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FROM:	**restricted**
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DSTL ltr dtd 15 Feb 2007 xxxx; DSTL ltr dtd 15 Feb 2007 xxxx	

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JOURNAL

OF THE

ROYAL NAVAL

SCIENTIFIC SERVICE

| Vol. 23 | ★ | MAY 1968 | ★ | No. 3 |

Journal of the Decl OADR $C/00,157$
ROYAL NAVAL SCIENTIFIC SERVICE

AD-398598

CONTENTS

THE DEFENCE ESTIMATES 1968

On February 22nd the Government announced in the Defence White Paper that as a result of the detailed review of Defence Expenditure instigated in January, a cut of £110m. will be made in the forecast estimates for 1969 and that by 1972-73 the defence budget will be reduced by a further £210m. - £260m.

Among the major decisions taken by the Government to achieve these reductions are, Britain's future defence effort will be concentrated mainly in Europe and the North Atlantic area, the withdrawal of our forces from Malaysia, Singapore and the Persian Gulf to be completed by the end of 1971 and no special capability for use outside Europe will be maintained after that date. The carrier force will be phased out as soon as the withdrawals from Malaysia, Singapore and the Persian Gulf have been completed, and the rate of some new naval construction will be reduced. The manpower of the Services will be eventually reduced by more than the 75,000 forecast last year and the reduction will be spread over a shorter time.

It is however stated in the White Paper that the garrison and naval base in Hong Kong will continue to be maintained and it is intended to retain a general capability based in Europe including the United Kingdom which can be deployed overseas as, in the Government's judgment, circumstances demand and can support United Nations operations as necessary. The Government recognises that the re-organization of the Services will involve difficult readjustments and it will be one of their major aims to reduce individual hardship and to maintain efficiency during the period of transition and it is their intention to have balanced and effective forces which offer a good career to those who serve in them.

Among the changes in organization announced in the White Paper is that the naval shore commands in the United Kingdom will be brought under a single Commander-in-Chief based in the Portsmouth area. In addition to his own area he will control three other Flag Officers *i.e.* Plymouth, Scotland and Northern Ireland and the Medway, and also superintend certain aspects of shore training and administration throughout the United Kingdom. The responsibilities of the Area Flag Officers will include those now carried out by the Admirals Superintendent of the Royal Dockyards in their areas. The separate posts of the Admiral Superintendent will in due course be abolished.

In the equipment field the Government are reviewing the eventual rate of building of the three new classes of ships announced in last year's Supplementary Statement on Defence Policy. The three classes are frigates to succeed the Leanders, destroyers to carry *Sea Dart* and the cruisers to follow the converted *Tiger* class. The design work on these however is going ahead. Work is proceeding on the conversion of H.M.S. *Blake* and H.M.S. *Tiger* to carry *Sea King* helicopters and it is planned to convert H.M.S. *Lion* later. Some of the existing Leanders will be modified to carry the *Ikara* anti-submarine weapon system.

It has also been stated that all ships of frigate size and above will carry helicopters and that *Wasp* helicopters will be replaced by the *WG13* in the mid-1970s. An order for a nuclear powered submarine of an improved design was placed at the end of last year and six more minesweepers are being converted to minehunters. The future rôle of support ships in the light of our reduced commitments overseas is under examination. The major Research and Development projects on which work will be carried out include Nuclear propulsion, gas turbine development for ship propulsion, automation of ships data handling systems, anti-submarine torpedoes and launching and fire-control systems associated with *Sea Dart* and other guided naval-weapons.

As the present statement on Defence Policy cannot reflect the full effect of the decisions that have been taken, the Government intend to present a supplementary statement in which they will report progress later in the year.

AN HISTORICAL SURVEY OF WATER ENTRY RESEARCH AT THE ADMIRALTY RESEARCH LABORATORY

W. L. Borrows, B.Sc., D.I.C., R.N.S.S.

HEN Dr. Hartmann* invited me to take part in these ceremonies and to give one of the addresses, I was somewhat at a loss in choosing a suitable subject on which to speak. However, the dedication of the Naval Ordnance Laboratories' new Hydroballistics Research Facilities seemed to me to mark the threshold of a major step forward in a subject which in the past has been a mixture of art and science—and often just plain magic. Consequently it may be thought to be not inappropriate if I attempt to make a brief survey of the history of water-entry research in my own country and, in particular, at the Admiralty Research Laboratory.

My story begins in the late '20's when Stephen Butterworth—an extremely versatile scientist and an applied mathematician of outstanding ability—began to take an interest in the stability, or their instability, of torpedoes when running in a swell and when dropped from the air. Full scale trials had been conducted by H.M.S. *Vernon* in a rather desultory fashion over the years following the end of World War I and the problem posed by the rather random results obtained seemed just the thing to hand over to the small group of scientists who were slowly but surely gaining acceptance by the sailors, particularly those in the newer and more technical branches. Thus started hydroballistics research at the Admiralty Research Laboratory.

Since background knowledge was scanty and money scarce, the early experiments were simple and the facilities primitive. The first tank was some 24 ft long and 2 ft by 2 ft in cross section, made of steel and came into operation in 1930. Initially it was used to study the behaviour of torpedoes at water entry. The models were 1 in. in diameter made of wood and fitted with a steel spike in the nose, and were " fired " by the release of a flat strip steel spring. A slab of wood making a false bottom to the tank represented the " target "

and a typical experiment consisted of comparing the initial angle of discharge with the angle (that is the attitude) shown by the model when it was fixed by its spike to the submerged wooden target. Presumably by changing the depth of the target for a constant angle of discharge a crude idea of the trajectory immediately following entry could be obtained. Cine photographs were also taken during the experiment and showed that the entry of the model into water gave rise to a complex " splash and cavity " phenomenon which had an important effect on the subsequent behaviour of the projectile.

During the period from 1930 to the outbreak of World War II the experimental work proceeded steadily and was expanded to include the effect of head shape on water-entry; scale effects using 1 in. and $\frac{1}{2}$ in. diameter models, measurement of impact stresses and of resistance coefficients.

In some of the very first simple experiments, observations had been made on the cavities formed when spherical models were dropped into water, when it was found that the initial cavity was conical in form, the angle of the cone being approximately 12°. Accordingly a series of 12° conical heads terminating in spherical ends of various diameters were tested, these giving a splash free entry but either diving deeply at high angle of entry or following an upward turning trajectory at low entry angles. It is interesting to speculate in which direction this work would have continued if even one flat nose end had been included in the series. In the event, since the 12° cone was a quite impracticable configuration, the experiments were continued with larger cone angles and eventually led to the design of ogival forms with their

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* Dr. G. K. Hartmann, Technical Director, U.S. Naval Ordnance Laboratory.

generally much improved performance. Although this phase of the work was more or less completed by 1938 so far as I am aware no torpedoes to this design were used in Service during the following war years. A few experimental full-scale models were made but controlled trials were extremely difficult to carry out and the discrepancies between the results obtained in model and full scale tests were even then only too well known. Something of an understatement appears in a report written at that time which concludes " the factors involved are by no means simple and further investigation may be required."

Excellent correlation was, however, shown with the data obtained in full scale trials of parachute controlled torpedoes and in the laboratory experiments with 1 in. models fired from the catapult.

About the middle of this period modifications were made to the original water entry tank so as to enable it to be used for horizontal entry and torpedo resistance measurements. A compressed air gun was fitted at one end of the tank with its muzzle projecting into a small air chamber inside the tank. This chamber was sealed from the water by a rubber partition with a central cardboard burster disc. The 2 in. diameter wooden models were carried on a taut wire stretching from the gun to the opposite end of the tank. A magnet fitted in the model produced an impulse in equispaced circular coils at the moment of passage through the coils, so giving velocities and hence resistance coefficients. Speeds of up to 150 f.p.s. were obtained and by heating the water in the tank the viscosity—and consequently the Reynolds number—could be changed. Discrepancies of the order of 2 to 1 between the 2 in. model results and those obtained using much larger models in a towing tank were resolved by an examination of the cine film records which clearly showed the onset of nose cavitation and its apparent correlation with increased drag.

The limitations of the first water-entry tank had long been realized and with the coming of the re-armament period the procurement of a second tank was hastened. Its design was generally governed by the requirement to study torpedo bombing attacks on shipping in harbour. This tank was about 8 ft long, 3 ft 6 in. high and 2 ft wide. One of the long sides was effectively a plate glass window through which the shots were observed and photographed. A compressed air gun could be fitted either at one end of the tank for horizontal shots or on trunnions above the tank for air-water shots. A " flat " entry could be made by imparting a parallel motion to the gun at the moment of firing. The " gun " itself was simply a length of 1 in. commercial brass tubing which was given a smooth bore by forcing through it a 1 in. diameter

steel ball. A rough idea of the behaviour of the model in a horizontal plane could be obtained by placing a mirror, inclined at 45°, in the tank when the image of the model in the mirror appeared in the same photograph as the model itself. (It may be of interest to note that this tank is still in use although not for hydroballistics research. When last heard of it was being used at a Naval Pathology Laboratory for growing cultures).

The models themselves were made of magnesium and were held in position in the gun by an electromagnet clamped outside the gun, the poles of the magnet coinciding with soft iron inserts in the walls of the gun. The models were fitted with a mild steel ring at the intersection of the body and tail components which completed the magnetic circuit.

The whole arrangement was extremely simple but proved to be highly effective.

During the stress of the war years anything resembling a long-term logical research programme was clearly impossible and the investigations were often of an ad hoc nature, including such items as the determination of the characteristics of captured enemy material. One particular piece of work which I should like to mention concerns the development of the Naval anti-submarine weapon *Squid*. In October 1941 the Admiralty Research Laboratory was asked to assist in increasing the stability and rate of sinking of the standard Mark VII depth charge and to develop the design of an entirely new forward thrown weapon. The Mark VII depth charge rather resembles a 50 gallon oil drum and its underwater behaviour had been described as that of a falling leaf, but eight months later the weapon had been stabilized and its terminal velocity increased nearly three times. Also, building on the same cylindrical form, the prototype design of an entirely new forward thrown weapon was well advanced: this was later known as the *Squid* and, by working on the principle that it is better to get a reasonably efficient weapon into service quickly than spend a long time on changes which might only slightly improve its performance, its first " kill " occurred in August 1944 when H.M.S. *Loch Killin* sank the submarine *U736*.

I am rather inclined to believe that this war-time principle could with advantage be applied on occasion at the present time.

The *Squid* projectile was designed with a flattened nose, following work on models at the Royal Aircraft Establishment at Farnborough which had demonstrated the stability of this configuration during the water path of air launched A/S bombs. It was also claimed to be easier and cheaper to make than a spherical nose !

I have earlier referred to the difficulties encountered in correlating the model and full scale results, these difficulties not being made any less by problems involved in making accurate observations at full scale.

The general trend during the early part of the war was towards increased aircraft speeds and low altitude bomb and torpedo attacks against both surface ships and submarines. These changed conditions of attack required shallow entry of the projectile and posed a number of new problems, not the least being that of ricochet. The Admiralty, therefore, decided to proceed in 1943 with the construction of a full-scale torpedo water-entry launcher at Coulport on Loch Long. This action was, however, anticipated by the Air Ministry, who, the previous year, commenced construction of a large tank at Glen Fruin only a few miles away. The main interest of the Air Ministry was in A/S bombs and depth charges, and much work, particularly on missiles with flat noses, had been done in the immediate pre-war years at the Royal Aircraft Establishment, Farnborough, using models in a tank similar to, although rather deeper than that at the Admiralty Research Laboratory. The large Glen Fruin tank was built to examine the perforamnce of these types of missile at full scale, but there was also a small tank for continuing the model work. The full-scale Coulport design consisted essentially of a 300 ft long beam mounted on trunnions at the water end with the inshore end supported in a cradle which could be lifted in a 200 ft high tower to give a maximum angle of launch of approximately 30°. Standard service rocket motors attached to the missile carriage were to give a launching velocity of up to 250 ft per second with missiles weighing up to 2,000 lbs.

The large Glen Fruin water entry tank was some 150 ft long, 30 ft wide and 40 ft deep, one side consisting of armoured glass panels to enable high speed photographs to be taken of the water-entry and underwater phenomena. The tank had no roof so that, on those occasions when the Scottish weather permitted, sunlight assisted in the overhead illumination. The missiles to be fired were mounted on a launching carriage propelled by rocket motors down a catapult track. Maximum velocities of up to 300 feet per second for projectiles weighing up to 400 lbs could be achieved, with lower velocities for heavier missiles.

The Coulport launcher did not come into operation before the end of the war but the Glen Fruin tank was used extensively particularly in the development of high speed projectiles with a terminal underwater path. The projectiles included rockets, shell and shell-type missiles and extensive model experiments were carried out at Teddington and

Farnborough as well as Glen Fruin. Interest thus became centred on relatively long shallow trajectories where the missile was actually predisposed to ricochet. Research was stimulated by the requirement for a " large " rocket projectile, *Uncle Tom,* which could be used to attack snorting submarines or " soft " surface targets. As so often happens, operational demands had again outstripped experimental facilities and even the large Glen Fruin tank was inadequate for full scale testing of the new missiles and a rocket range was set up in the Alwen Reservoir. This consisted of an array of parallel nets suspended vertically in the water from booms floating on the surface and extending to a depth of 40 to 50 ft. The nets were accurately placed at regular and known spacings and the projectiles were fired approximately at right angles to them. The point at which a projectile penetrated the nets could be determined quite accurately by counting meshes, whilst the entry point was determined photographically, which also gave entry speed and angle. The time element was measured by means of an electrical screen consisting of twin sheets of metal foil insulated from each other and enclosed in a watertight envelope. Suspended in the same way as the nets and connected to an oscillograph recorder, it indicated the short-circuit caused by the passage of the projectile, so allowing calculation of velocity and overall drag coefficient.

Together with the model experiments and theoretical studies the general behaviour of a high speed projectile after water entry was determined in terms of drag, lift, stability, underwater dispersion, angle of ricochet and seale effect. As regards total drag it was established that the essential variables in order of importance were (i) head shape, (ii) ratio of tail to head diameter, (iii) position of centre of gravity and (iv) virtual mass and rotary effects. Like drag, lift is dependent on all the projectile characteristics and is markedly influenced by (i) head shape, (ii) length to diameter ratio, (iii) position of centre of gravity and (iv) tail shape. Only qualitative conclusions were drawn about the behaviour of the projectile in a cavity and the underwater dispersion, but the importance of the cavity, and tail oscillations in it, as a cause of exceptional behaviour and of non-uniform entry conditions (pitch and yaw) on dispersion was clearly recognized. On scale effects, the general conclusion was that although a gross assessment could be made a systematic research programme would be needed before these could be established with any confidence.

After all this work, it did seem rather a pity that, to the best of my knowledge, *Uncle Tom* never went into service. But a vast amount of data had been accumulated which could have been of

real value to the succeeding peace time hydro-ballistics research programme. I say " could ", because I believe that in fact in the rather chaotic (research and development-wise) conditions which followed the ending of the war, much of the data—which often had not been formally recorded—was lost when the war-time research teams disbanded and the newcomers perhaps even preferred to start afresh.

Before, however, speaking of the post 1946 era, I should like to mention briefly the *Shark*. The *Shark* was a shell-type missile designed to meet a requirement for the self defence of merchant shipping against surface submarines at close range. The requirement to inflict lethal underwater damage involved water-entry at very shallow angles (less than 5°) so that prevention of ricochet was important as also was underwater stability. The entry problem was one of substantial difficulty and the Admiralty Research Laboratory took as its starting point in model scale work the German "Kopfring". This was simply a collar of triangular section fixed round an ogival head forward of the shoulder. In an evaluation of captured material it had been shown that the Kopfring had the following effects: (i) the angular momentum in the entry phase was reduced (since the Kopfring partially introduces flat-head characteristics), (ii) in the cavity phase, the Kopfring reduces the unstable nose moment of yaw by imposing parallel break-away above and below so inhibiting the differential flow pattern that would give rise to pronounced lift and (iii) it increases the axial component of the nose force which tends to stabilization. Experiments with *Shark,* and subsequently, showed that by suitable choice of the size and disposition of Kopfrings satisfactory water entry could be obtained at angles as low as 1·5°. In this case, at least, the *ad hoc* model testing of enemy material paid off very handsomely.

The years immediately following the end of the war were largely concerned with " tidying up " operations, with a re-assessment of the problems in underwater ballistics research and a material improvement in the available research facilities. The Coulport full-scale launcher was completed in 1947 and in the same year it was combined with the Glen Fruin establishment to form the Admiralty Hydro-Ballistic Research Establishment. But rationalization of administration did not produce a rational research programme and for the next four or five years the function of the establishment degenerated into one of providing facilities for the *ad hoc* tests of other organizations. It was producing no basic information on which the future design of weapons with a water-entry requirement could be based. An investigating committee urged that there was an urgent need for " . . . at least

enough research . . . to arrest the present steady growth of our underwater ballistic ignorance ". But the Admiralty was not alone in this neglect, since proposals to build a large open hydroballistics tank at the Ministry of Supply Armament Research Establishment at Shoeburyness were abandoned. A companion facility at the same organization's Fort Halstead site was, in fact, completed, but so far as I know was never used effectively. This tank was, at the time, a very ambitious design which was intended to allow the control of at least three of the fundamental non-dimensional parameters involved in water-entry research. These were, of course, the Froude number, the local cavitation number and the gas-water density ratio. The Froude number was easily controllable through changes in entry velocity and size of model, but for control of the cavitation number a closed tank was required in which the pressure at the water surface could be varied. Further, if the gas-water density ratio was to be controlled it was necessary that gases of high density, such as the Freons, be injected into the space above the water surface.

The size of the tank was approximately 46 ft long and 10 ft wide with a water depth also of 10 ft. It was thus not too dis-similar from the Naval Ordnance Laboratory Pilot Facility.

However, there were considerable teething troubles in bringing the tank into operation and before these had been satisfactorily resolved, changes—and cuts—in the research programme hastened its premature end.

Returning now to the Admiralty scene, I have mentioned the pre-occupation with ad hoc testing of missiles, many of which were as remarkable for their names as for their design. Thus this was the era of Z-weapons, Blue Eggs and Green Cheese. One particular example with a pointed ogival nose was a particularly vicious brute, its trajectory very nearly having a 4π dispersion. Certainly the safest point from which to observe events posed a considerable problem and was generally solved by adopting the theory that, like lightning, it would never strike in the same place twice ! To add variety to the work, some measurements were made on tail-first water-entry, but this never became a preferred method !

Although by 1950 over 4,000 shots had been made in the Glen Fruin tanks alone, and very many more in the Teddington tank, it had become only too apparent that no basic information was being obtained and in 1951 the Admiralty Hydro-Ballistic Research Establishment came under the control of the Admiralty Research Laboratory and a co-ordinated programme of research was drawn up. Thus in one Establishment there was now the ability to make tests at full-scale, quarter-scale and

down to 1/20 scale. It was also clear that much more precise measurements must be made and special instruments developed for this.

About this time, as part of the extensive fluid dynamics facilities, a new water-entry tank was installed at Teddington. This was still quite small, being 29 ft long, 9 ft deep and 5 ft wide, but a major innovation was the slotted cylinder catapult. Missiles released from aircraft at the moment of water-entry are generally, to a greater or lesser degree, pitched or yawed off the actual line of fire, so that, although a smooth bore gun is quite suitable for shots on trajectory, for the off-trajectory shots it would be better to fire the models from a carriage mounted on a catapult. The new slotted cylinder compressed air catapult was similar to the steam catapult used for launching aircraft from Carriers—indeed it was designed by the same man. The whole catapult was mounted on a variable angle platform so arranged that models could be fired at any angle between near horizontal and vertical and enter the water at almost the same position in the tank. Using air pressures of 700 lbs per sq in., maximum entry velocities of 300 feet per second could be obtained with models 2 in. in diameter. Basic recording of data was still by high speed photography, but the introduction of colour film produced a marked improvement in definition and allowed a more accurate interpretation to be made of the phenomena.

At Coulport and Glen Fruin many attempts had been made to obtain satisfactory photographic records of the full-scale water-entry phenomena and underwater trajectories but with indifferent success. The Flare camera technique and the Rule optical method were alike found to be insufficiently accurate for detailed studies, since determination of bending frequency in the larger models showed that experimental results relying on measurements of the motion of the tail of the projectile were liable to serious error. In actual tests it was found that the tail of a projectile 12 ft long did not begin to react to the transverse effects of the head hitting the water until some $2\frac{1}{2}$ milli-seconds later, a long time by water-entry standards. Consequently it was decided to try and measure the time-variation of the total forces acting on the model by using suitably positioned accelerometers, the output from these being conveyed to the recording equipment through a very light and flexible cable. This trailing cable technique was used first of all with the full-scale launcher most successfully since it allowed observations to continue after the tail was buried beneath the surface, something previously impossible with optical methods in the murky open waters of Loch Long. Continuous measurements showed that some of the most important features

of entry appeared just after the projectile tail had disappeared below the surface. For example, for a projectile with a hemi-spherical head, it was not until both tail and body rode on the side of the surrounding air cavity, several lengths from entry, that the trajectory got its main upward deflection and angular motion started to be damped out.

The trailing cable method was now adapted for use in the smaller, *i.e.* down to 4 inch diameter, models used in the Glen Fruin tank. By making possible a direct comparison of the timing direction and magnitude of the forces acting on full scale and model projectiles at and immediately following water-entry, this technique, I believe, achieved a small revolution in the study of scale effects.

Rather earlier than this, a new high velocity slotted cylinder launcher based on experience with the smaller but similar device at Teddington, had been installed in 1954. This provided really accurate launching of 50 lb models (4 - 8 in. in diameter) under conditions of controlled pitch and yaw at velocities of up to 500 ft per second and with an entry angle range of 0° to 90°.

An extensive research programme was now instituted to study water-entry shock, deceleration and angular motion of a family of head shapes at full scale at Coulport with a comparative programme at $\frac{1}{4}$ and $\frac{1}{8}$ scale at Glen Fruin. It soon became apparent that at low angles and velocities of entry the model results were in considerable error and that this was due to under-pressure effects. Generally speaking, Froude scaling of the inertia forces gave satisfactory results provided that no attempt was made to extend it to conditions beyond the cavity forming stage and provided that some method is adopted for correcting the atmospheric pressure differential. The great sensitiveness to atmospheric pressure is, of course, due to the fact that for a very short period during the first penetration of the water surface by the projectile head, a small low pressure cavity—in fact cavitation—is formed around the underside of the head just at the critical time when the conditions of pitch, which will largely control the resulting trajectory, are being built up. For a 1/10 scale model, the uncorrected atmospheric pressure would be ten times too large and the forces tending to tilt the projectile nose downwards correspondingly high. Accelerometer measurements also showed that these under-pressure effects are extremely sensitive to small variations in flow, such as those caused by small changes in initial pitch, so making a projectile at model scale appear to be much more sensitive to pitch than in fact is really the case.

The direct and ideal solution is, of course, that now adopted by the Naval Ordnance Laboratory, but such facilities were beyond our limited means

and various palliatives were tried instead. We are still actively pursuing this objective.

As an economy measure, in 1957 the Coulport establishment was reduced to care and maintenance but not before a very large amount of full-scale data had been obtained within the limitations of its entry angle and velocity range. Indeed it was partly because of these limitations that this facility was sacrificed and the decision made to concentrate on model scale experiments at Glen Fruin and Teddington.

Before discussing these, however, I should like to mention a somewhat unusual use to which the Glen Fruin tank was put.

Following, in the late 1950's a number of fatal accidents in aircraft which had crashed into the sea, a rather novel series of experiments was started which might perhaps be described as water-exit measurements—at full-scale this time. These first experiments involved the underwater jettisoning of the cockpit canopy of naval aircraft under various conditions and at various depths. Trials were also made to determine whether it was practicable—and safe—to use under water the ejection mechanism intended for use in the air. Both dummy and live subjects were used, one of the latter being a member of the United States Marine Corps. As a variant, further tests were made in which the seat, complete with occupant, was fired *through* the canopy. This proved to be not so desperate a remedy as might have been thought and, after some small modifications had been made to the standard ejection equipment, it was shown that a pilot could escape from the aircraft cockpit under water by power ejection as in air.

Returning now to the missile research, it was decided to concentrate mainly on a study of the scaling factors involved in water-entry whip using the accelerometer techniques at Glen Fruin and an optical method at Teddington in which a parallel beam of light, chopped by a rotating shutter at $\frac{1}{3}$ of a millisecond intervals, was reflected from a $\frac{1}{4}$ in. square mirror attached to the model on to an appropriate photographic plate. This optical technique was reasonably satisfactory for very small models, but not so for larger ones, and it was eventually abandoned in favour of measurement by accelerometer.

One of the methods of overcoming the unwanted under-pressure effects is that of " venting ". This consists of the provision of air ducts in the head of the model so as to equalize the pressures above and below the head. Unfortunately the requirement for correct modelling is not to remove the pressure differential completely but to reduce it to the correctly scaled level. This we have not found to be practicable with the venting technique. A new method was therefore tried. In this, a high vapour pressure liquid was run onto the water surface, so that the under-pressure would be materially increased and the correct scaled pressure differential with the atmosphere obtained. For quarter-scale modelling the high vapour pressure liquid should have a vapour pressure equal to three-quarters of an atmosphere at normal temperatures and also have the same density as water. A mixture of Pentane and Freon was devized which had these characteristics and in early experiments was used quite successfully. These early results were obtained with relatively large models having hemi-spherical heads. However, with flat heads much less satisfactory results were obtained and a modi-fied method was developed in which the tempera-ture of the water was raised locally to provide the high vapour pressure. Using this ' hot water ' technique comparable results to those previously given by the Pentane/Freon mixture were obtained with hemi-spherical heads and much improved modelling with flat cylindrical heads. However, very recent work has shown that even the ' hot water ' method is unreliable for models 2 in. in diameter or less.

Nearly all of our recent work has been concerned with underwater stabilized bodies, that is tor-pedoes, but occasionally we have branched out into related fields particularly where our accumu-lated experience could be of particular value. One example of this almost extra-mural activity has been in the development of an anti-submarine bomb which had to enter the water at a high velocity and over a wide range of angles. A satis-factory form was very quickly chosen and its per-formance confirmed in a comprehensive series of tests.

Over the past few years our programme has been concerned with a continuation of the whip research, with the development of an ideal head for water-entry—this may be nearly as frustrating as the search for the alchemists stone—with fran-gible heads for missile water-entry and frangible canopies for pilot water-exit and various *ad hoc* work for which our hydroballistics facilities are particularly well suited. In fact so far as facilities are concerned the wheel has now turned nearly full circle and we are presently building at Coul-port a new full-scale launcher, with a cordite fired slotted cylinder catapult having a maximum ter-minal velocity of 450 ft per second and a $\pm$ 10 degree pitch and yaw controlled water-entry angle of from 3° to 90°.

Although I have dealt exclusively with work carried out in my own country, it is only proper for me to acknowledge the material benefits which have accrued to our work from association with workers in other countries, particularly the United States. I hope that these close and happy relation-ships will long continue.

A BLAST SIMULATOR FOR STRUCTURAL RESPONSE STUDIES

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Introduction

The Defence Research Establishment Suffield (DRES) Shock and Blast programme started in 1956 when teams were sent to Australia to measure the shock wave overpressures from the British Atomic Tests. Since then the programme has developed along two complementary lines: Field trials using TNT charges with yields up to 500 tons[1], and shock tubes or blast simulators.

To establish structural design methods and the blast loading at which a structure yields or fails, it is usually necessary to test the structure under blast conditions. The testing can be done by exposing a large number of structural models at various overpressure levels in a field trial, or a single model can be exposed to increasing overpressures in a shock tube or blast simulator. Experience to date shows that the most economical method is to test the model in a shock tube to establish the critical blast pressure levels, and then confirm this data by exposure in a field trial.

From 1955 to 1964 a number of compressed air driven shock tubes were developed at DRES[2, 3, 4]. These were used for fundamental studies of the physical parameters of shock waves, investigation of interactions between shock waves and targets, and tests on small items of military equipment. By 1964 it was apparent that there were other targets of interest which were too large for the existing tubes, or which could not be modelled accurately enough to warrant testing in the small shock tubes. Consequently two large blast simulators, one six feet in diameter and one three feet in diameter, were designed and built[5]. These tubes are explosively driven using RDX-TNT charges, and are housed in the Blast Simulation Laboratory at DRES shown in Fig. 1. The six-foot blast simulator, near the top of the figure, and the dynamic tests of the RCN Bridge Windows will be described.
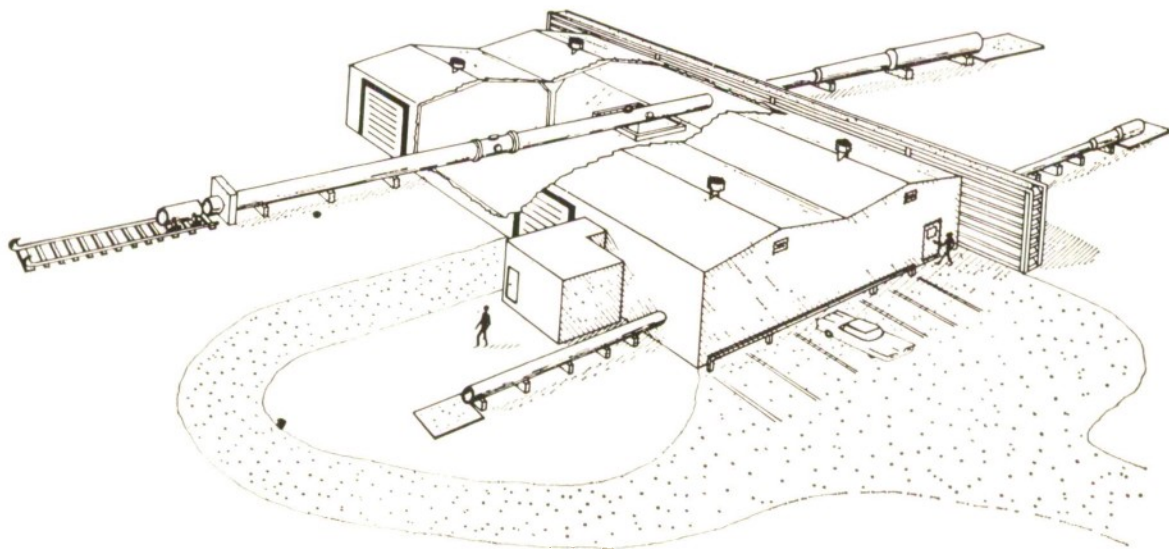

FIG. 1. Artist's Conception of the Blast Simulation Laboratory.

SIX-FOOT DIAMETER BLAST SIMULATOR

It was established that the six-foot blast simulator should produce a shock wave having a peak overpressure of 50 pounds per sq in. and a duration of about 100 milliseconds in a six-ft. diameter working section. These requirements precluded the use of compressed air as a driver since the limited practical pressures and volumes were exceeded and because there are many problems associated with the design and operation of large mechanical systems.

A survey of existing facilities indicated that the most economical method would be to construct an explosively driven blast simulator. A small conical tube was in use at the Naval Ordnance Laboratory[6, 7] and it was known that the Atomic Weapons Research Establishment was considering construction of a similar type of large blast simulator[8].

FIG. 2. General layout of 6ft. blast simulator.

Design and Construction Details

In order to reduce the expense of fabrication of the blast simulator, it was decided to use a constant cross-section expansion chamber. A prototype tube was built using 6 ft diameter rolled sections with a three-eighth in. wall thickness for the expansion chambers and a 14 in. naval gun liner as the compression chamber. Use of this prototype tube proved that the cylindrical expansion chamber gave reasonable pressure-time histories at the working sections. The final tube uses 6 ft diameter rolled sections with half-inch wall thickness and a 16 in. naval gun for the compression chamber.

Two 16 in. naval guns, each 68 ft long and weighing about 120 tons, were obtained with the co-operation of the Defense Atomic Support Agency, U.S.A. They were transported by barge from Dahlgren, Virginia to Baltimore, Maryland and then by rail to Suffield. The gun is used without a breech block so that there is no recoil; this simplifies the mounting procedure. The conical expansion section, Fig. 2, connecting the gun to the constant cross-section expansion chamber, was fabricated from heavy sheet metal rolled into a 10° half angle cone and installed inside the expansion chamber entrance. Reinforced concrete was poured between the 10° half angle cone and the expansion chamber wall.

The expansion section, Fig. 2, contains three working areas: a pit test area for use with underground structural models; a model test area which has windows for high speed cameras; and a recoil test area in which large models are mounted. When large targets or structures are tested, a high pressure region is formed at the upstream face of the target and the resulting force must be taken up by some means. To simplify the design it was
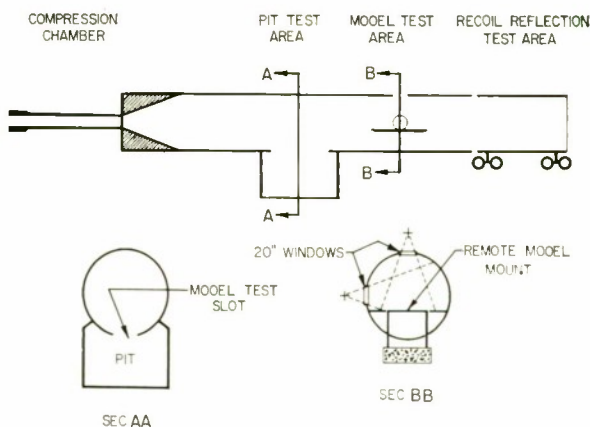
decided to use a section of the tube mounted on rails to absorb this energy. Fig. 3 shows the 6 ft tube that was originally constructed. The final tube is of the same configuration but has a 166 ft long expansion section.

High Pressure Driver

One of the major problems in the development of an explosively-driven blast simulator is the containment of the explosion in the driver or compression chamber. A pressure of several million pounds per square inch exists, for a short time, at the detonation front in solid high explosives. Therefore, in order to prevent failure, direct contact between the explosive and the gun barrel must be avoided.

FIG. 3. Prototype 6ft. blast simulator with 14in. Naval gun liner.

FIG. 4. Charge loading system.

Charge Design and Firing Procedures

The charges used are 60/40 RDX/TNT cylinders, cast at DRES. To allow the use of long lengths of this brittle material, a cylinder of 0·005 in. celluloid is placed in the mold prior to casting. The explosive bonds to this material and hence, if any cracks occur during handling of the explosive in t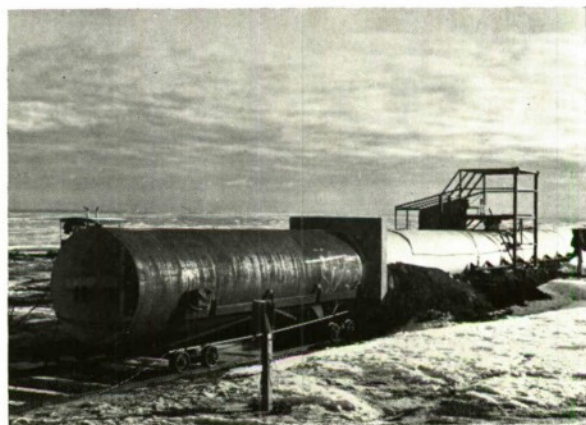he field, the celluloid cylinder prevents it from breaking into small sections. At present 40 in. long charges are being cast in celluloid successfully.

To support the charge in the centre of the compression chamber bore, a system was developed which enabled the complete charge and styrofoam holder to be assembled on a loading frame outside the gun. This assembly is then inserted into the driver chamber (Fig. 4) and when the charge

Tests were carried out by the Naval Ordnance Laboratory during their development programme to determine the maximum charge size that could be used. These tests covered a wide range of gun sizes and the conclusion was that the critical charge-to-bore size ratio for the start of plastic deformation was about one-to-four. They have since fired many hundreds of shots in their 180 ft conical tube using charge-to-bore diameter ratios up to one-to-five without any apparent deterioration of their gun barrel.

Based on this work, it was decided to limit the charge-to-bore diameter ratio to one-to-seven to prevent overstressing the gun barrel. To date the maximum charge diameter has been $1\frac{1}{2}$ in.
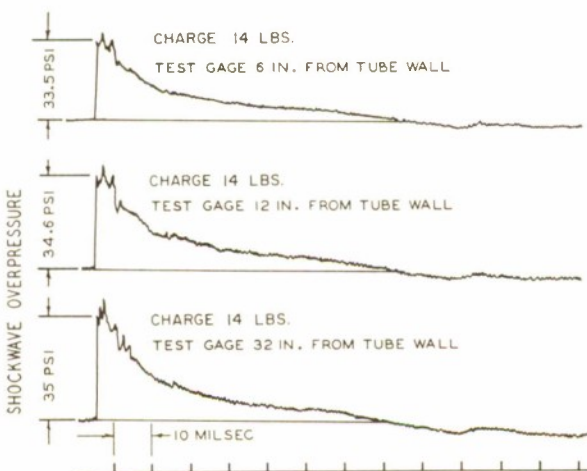
TABLE I
Six foot Blast Simulator Performance

	RDX-RDX-Charge Weight (pounds)	Peak Over-pressure p.s.i.	Duration (m sec.)
Ground Shock Test Section	2 6 10 14	10 22 28 37	30 38 60 65
Modet Test Section	2 6 10 14	8 16 21 32	30 35 60 65
Rolling Mount Test Section	2 6 10 14	6 10 13 21	25 30 50 55

is positioned 12 in. in from the breech end of the driver, the loading frame is pulled from the chamber, the styrofoam rests on the inner wall of the barrel with the charge centred in the bore. Using this system, it has been possible to install charges up to 280 in. in length.

After installation of the charge, a C.E. booster is attached to the outer end of the charge and a No. 8 Seismocap electric detonator is inserted into the booster. The firing pulse is initiated from a standard firing box controlled by a sequence timer in the bunker.

Instrumentation and Calibration

Pressure-time and shock velocity records are obtained at various locations along the tube length for all shots. These, together with measurements made on the models or structures being

CHARGE 14 LBS.
TEST GAGE 6 IN. FROM TUBE WALL

CHARGE 14 LBS.
TEST GAGE 12 IN. FROM TUBE WALL

CHARGE 14 LBS.
TEST GAGE 32 IN. FROM TUBE WALL

10 MILSEC

FIG. 5. Typical pressure time records.

tested, are recorded on a magnetic tape recorder installed in the control bunker. A sequence timing system is used to start the tape recorder, cameras, etc., and then to turn off all systems after the data are recorded.

Over one hundred shots have been fired in the 6 ft blast simulator, with the results which are summarized in Table 1. Typical pressure-time records taken 42 ft from the conical section are shown in Fig. 5. Although most of the shots fired have been for calibration purposes, several projects for the Canadian Forces have been carried out. One of these was the dynamic test of RCN bridge windows, which was carried out in the blast simulator and in the field.

For complete simulation of a free-field explosion, the pressure impulse (i.e. the peak overpressure and the positive phase duration) obtained in the simulator must be identical to that in the field. However, for pressure-type targets, it is usually sufficient to provide an impulse which will excite the natural frequencies of vibration of the target. This means that, for most structural work, meaningful results can be obtained in a simulator even though the impulse is less than that from large chemical explosions or nuclear detonations. For drag-type targets the shock wave velocity and particle velocities should also be identical, but at present this cannot be accomplished in a simulator.
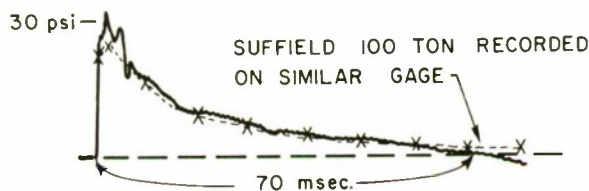

FIG. 6. Comparison of pressure records obtained in simulator and a 100 ton TNT field trial.

Fig. 6 shows a typical pressure-time curve obtained in the 6 ft blast simulator compared with a pressure-time curve from a 100-ton TNT field trial. For pressures greater than 30 pounds per sq in. this tube can be used to simulate completely free-field explosions of about 500 tons of TNT. In free field explosions, as the pressure behind the shock wave is reduced (with distance from the charge), the length of the pressure pulse increases; however, in the explosively driven blast simulator, the pressure pulse length decreases with decreasing pressure in the working section (Table 1). Therefore, for pressures below 30 pounds per sq in., the size of the charge exactly simulated decreases with decreasing pressure. Modifications to the blast simulator are presently being considered to improve this situation.

DYNAMIC TESTS OF RCN WINDOWS

A human-engineering study of command and control functions aboard RCN ships recommended, among other things, that the ship's bridge should have increased visibility. To provide this visibility large (four-foot square) windows were designed. Since it was also desired to include the bridge within the citadel, these windows would have to meet the Quadripartite design criterion for blast resistance to an incident overpressure of 10 pounds per sq in.

No design or empirical data on the blast resistance of these windows were available, so Suffield was asked by the RCN to conduct the necessary trials. Six large windows, two from each of three manufacturers were supplied. These windows were nominally 4 ft square and were made of laminated toughened glass with internal heating coils and stainless steel frames. In addition, we contracted with one of the manufacturers for six small panels (1 ft square) of the same glass. Mild steel frames for these were built on site.

Both sizes of windows were instrumented and tested in our shock tubes[9], the large windows in the 6 ft blast simulator and the small windows in the 17 in. shock tube. The small windows were also tested under static hydraulic pressure. Both sizes of glass panels were replaced with aluminium sheet (2S alloy, $1\frac{1}{2}$ in. thick) and the dynamic and static pressure tests were repeated to determine the effect of the material properties and the effect of the laminations. The large windows were subjected to two further trials: a cold-weather blast simulator trial, and two 20-ton TNT field explosions. The cold-weather trial was to determine the effect of ambient conditions on the electrical continuity of the heating coils and temperature sensors. The field trials were to confirm the shock tube results and to confirm predictions of the strength of the window mounting structure.

Large Windows Dynamic Trials

The rolling mount test section of the 6 ft blast simulator was used for these tests. This section was modified by welding a frame of 6 in. × 8 in. I-beams and $\frac{1}{2}$ in. plate steel into the tube, completely blocking it except for the $45\frac{1}{2}$ in. × 47 in. hole required for the window. Each window was assembled in its frame and installed in turn in the tube, Fig. 7. Each window was subjected to four tests without the frame gasket and four with the frame gasket installed. These tests were nominally at 4, 6, 9, and 12 pounds per sq in. incident overpressure.

Strain Measurements

From the analysis of the frame, Fig. 8, it was evident that the critical point was the web of
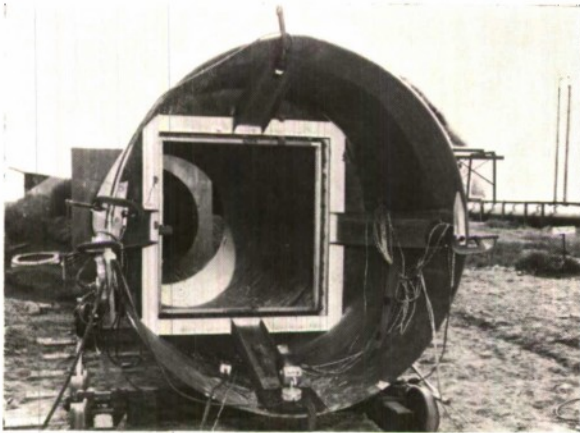
FIG. 7. A Naval window mounted
in the rolling test section.

the Z-section, where the combined stress
approached yield. Four strain gauges were
applied on the web at the mid-length of one
side, two connected to measure double the bend-
ing strain and two connected to measure double
the tensile strain. These foil gauges were Budd
C6-141-B1350, with a gauge length of $\frac{1}{2}$ in. and a
gauge factor of 2·06.

Two gauges of the same type were applied in
the centre of the window panels on the "inside"
face, oriented at 90° to each other.

Deflection Measurements

Two linear potentiometers, Bournes Linipot
No. 141221 - .44 - 102, were mounted at the mid-
length of one side of the window to measure
the deflection of the window frame at the inner
edge of the inner flange, relative to the rigid
mounting frame, and of the window panel adja-
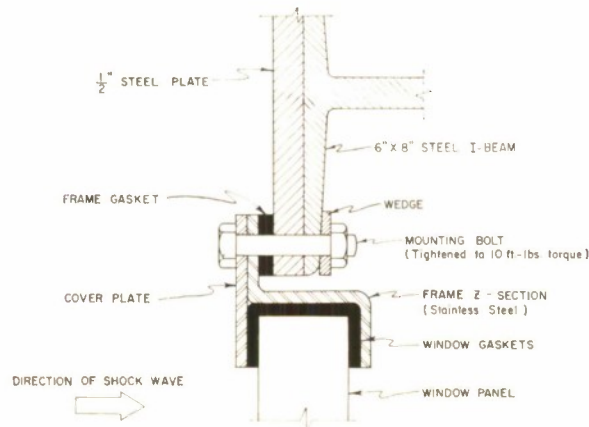cent to the frame. The potentiometers were

modified by the addition of a compression spring
and a teflon tip on the shaft; this allowed the
potentiometer to follow deflections in both direc-
tions without being attached to the window.

Pressure Measurements

The pressure in the shock tube was measured
by two methods, piezoelectric gauges being used
for both. Pairs of gauges were used to determine
the shock wave velocity and the peak shock wave
overpressure was calculated using the Rankine-
Hugoniot relations, and the pressure-time profile
was obtained using a single gauge. All gauges
were mounted in the shock tube wall, but physic-
ally isolated from the tube wall, so that they saw
the shock wave in a side-on orientation. These
gauges were piezoelectric compression tubes and
were $\frac{1}{2}$ in. in diameter[10]. The gauge was inserted
in a teflon adapter which was mounted remotely
from the tube wall to minimize noise in the gauge
signal.

Experimental Results

All the windows and frames were capable of
withstanding the required 10 p.s.i. free-air over-
pressure. One window did shatter on the maxi-
mum-pressure shot. The glass which was held
together by the plastic between the laminations
travelled 94 ft before coming to rest (Fig. 9). The
fracture appeared to have been initiated at the
mid-point of one side where there was a small

FIG. 8. Window test section
in the 6ft. tube.

FIG. 9. Overall scene after fracture
of the window.

bearing block on the inside of the frame. This failure could probably be avoided by a redesign of the frame without bearing blocks.

There was no possible correlation between the static and dynamic tests on the small windows nor between the dynamic tests on the small and large windows. However, the prediction method used[11] gave reasonably accurate presentation of the panel stresses (see Fig. 10), so that it may be used in future as a design tool. The predictions of frame stresses using standard beam formulae and a dynamic load factor of two did not give reasonable results.
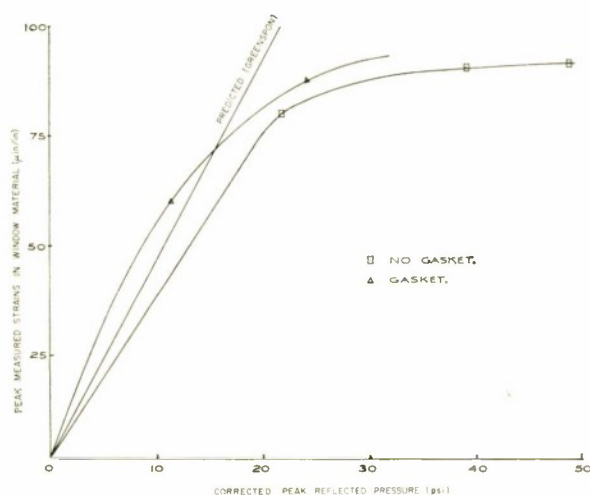

FIG. 10. Measured peak strain in a 12in. × 12in. window mounted in a 17in. shock tube.

It was apparent, during the static tests, that the $\frac{1}{4}$ in. rubber gasket between the frame and the mounting allowed rotation of the frame. Thus all the windows were tested in the Blast Simulator both with and without this gasket installed. There was no significant variation in the panel stresses, but the windows and frame deflection were about twice as large when the gasket was in place (Fig. 11). In the field trial this was further emphasized. The two windows in the deckhouse section were installed one with and one without the frame gasket. After exposure to a 10 p.s.i. blast wave the window with the gasket was damaged, whereas the other, without the gasket, was not damaged even though the front face of the deckhouse was visibly deformed.

There was no apparent difference in any of the quantities measured despite the large change in ambient temperature between the original tests and the cold weather trial.

It is interesting to note that the panel stresses were similar for the toughened laminated glass and the aluminium plate. The material properties were not significantly different, and the laminations in the glass windows seemed to have very little effect. This was shown also by the similarity between the stresses shown by window C and by windows A and B (Fig. 10). Window C had one thick and two thin laminations while windows A and B had three almost equal laminations.

Summary

Field trials, using large quantities of high explosives, are essential to confirm predictions of structural strength and dynamics when a structure is exposed to a blast wave. However, to establish the blast loading at which a structure will fail or be badly deformed, it must either be tested in a blast simulator or large numbers of the item must be exposed to a wide range of pressures during the blast trial. From the work carried out to date, it has been shown that, in order to obtain the most useful information for these large field trials, the structure should first be tested under controlled conditions in a blast simulator.
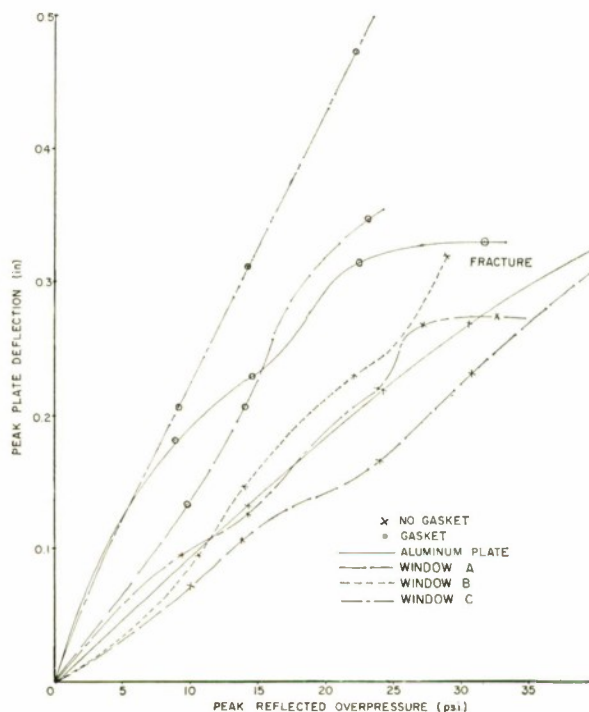

FIG. 11. Peak window deflection versus peak reflected over pressure for window in simulator.

The blast simulation facility at DRES is the only one of its kind in Canada and it is large enough and versatile enough to test the majority of items of interest to the Canadian Forces, the Emergency Measures Organization, other Government Agencies and the Canadian Universities.

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Miss L. M. Piggott, A.E.O., and Mr. J. H. Norton, S.O., taking measurements at the SINS Gyro Test Centre at the Admiralty Compass Observatory.

This new facility will be described in a forthcoming issue of the Journal.

ELECTROCHEMILUMINESCENCE

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SUMMARY

This article reviews recent research into electrochemiluminescence with some reference to the work being carried out on the subject at the Admiralty Materials Laboratory. Types of systems capable of exhibiting electrochemiluminescence and the theoretical basis of the effect are discussed.

Chemiluminescence has been defined as the production of light from a chemical reaction in excess of black body radiation[1]. Until recently, all known chemiluminescent reactions have involved the oxidation of a molecule with an oxidizing agent, commonly hydrogen peroxide, the most familiar such reaction being the oxidation of luminol which typically falls into this category. However, in 1964, Chandross and Sonntag[2] reported the discovery of a new type of chemiluminescent reaction in which an electron is added to a fluorescent hydrocarbon by treatment with potassium in tetrahydrofuran to form the radical anion of the hydrocarbon. Addition of an oxidant to the solution resulted in the production of the hydrocarbon in the first excited singlet state, with subsequent emission of light of spectral distribution identical to the normal photo-excited fluorescence. As it happens, this is a rather curious result, since, if the oxidant functions as an electron acceptor, it must accept an electron from an orbital lower in energy than the highest occupied orbital.

| ground state | radical anion | first excited singlet state | ground state |
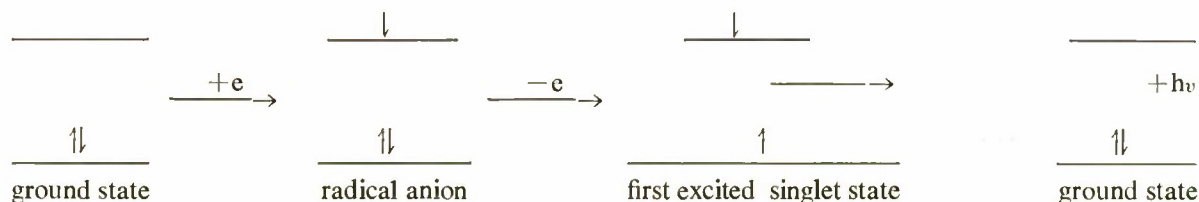
In the diagram, the ground state is represented by a pair of electrons in the highest occupied orbital of the hydrocarbon, the upper level representing the unoccupied next highest energy level. Formation of the radical anion involves the occupation of the latter level by one unpaired electron. In order to produce a first excited singlet state, an electron must be removed from the lower orbital, which is then re-occupied from the upper level with the emission of light. The net result is the production of the hydrocarbon in its ground state.

Cyclic Electrolysis

Several workers[3, 4, 5] developed the above work further and observed electrochemiluminescence by generating the hydrocarbon radical anions by electrolytic reduction at an inert electrode and then varying the potential so that the anion could be oxidized either by oxidation products of the solvent, or by the radical cations through an ion combination reaction:—

$$\overset{+}{R} + \overset{-}{R} \rightarrow \overset{*}{R} + R \qquad \dots (1)$$

The latter reaction is believed to occur when hydrocarbons in a rigid matrix at low temperature are irradiated with gamma rays and allowed to warm[11]. If this reaction occurs in electrochemiluminescence, then a *direct conversion of electrical energy into light* could be achieved, since no net chemical change occurs in the system. Unfortunately, while it is possible to produce radical cations by electrolytic oxidation[15] they are in general very unstable, and so far it has not yet been proved beyond doubt that radical-radical combination does occur in electrochemiluminescence, although evidence has been obtained that a major proportion of the emitted light arises from process (1) in at least one case[12].

Technique

The experimental technique needed to demonstrate electrochemiluminescence is very simple. Two platinum electrodes are suspended in a deoxygenated solution of a hydrocarbon in an aprotic ionizing solvent such as acetonitrile or dimethylformamide. A quaternary alkylammonium salt, *e.g.* tetraethylammonium perchlorate, acts as a supporting electrolyte. An alternating voltage of 2 - 3 volts which can be sine wave obtained directly from the mains voltage supply *via* a transformer, excites light emission. Generally, a highly fluorescent hydrocarbon such as rubrene[7] or 9 : 10 diphenylanthracene must be used[5], because the total light output will be a function of ϕ_f, the quantum efficiency of fluorescence of the solute. The resulting light output for the more efficient systems is easily visible to the eye and increases rapidly with increasing voltage up to a maximum of 5 - 6 volts. The signal displayed on an oscilloscope *via* a photomultiplier is found to be modulated at exactly twice the frequency of the exciting voltage. For research into the electrochemical properties of the system however, greater control is required over the actual potential of the electrodes, which makes it necessary to incorporate a reference electrode. Such an electrode remains at a constant potential, and in conjunction with the potentiostatic device enables the potential of one electrode (the working electrode) to be kept at any desired value. If a triangular wave form is now fed into the potentiostat, the working electrode will vary linearly with time in a cyclic fashion and the resulting current flowing in the circuit can be displayed versus the electrode potential on an X - Y recorder or oscilloscope. This is the technique of cyclic voltammetry[8]. Using this technique, the various oxidation and reduction reactions occurring at the electrode can be followed. Each reaction results in a peak in the voltammogram from which information about the reversibility of the reaction, the number of electrons involved and the lifetimes of the transient species can be deduced. A cyclic voltammogram of 9 : 10 dimethylanthracene in acetonitrile is shown in Fig. 1. Light emission is obtained from this system when the potential scan is greater than the limits denoted by points A and C. These points coincide with the production of radical cations and radical anions respectively. Similar results have been obtained for pyrene, rubrene, 9 : 10 diphenylanthracene and many other hydrocarbons.
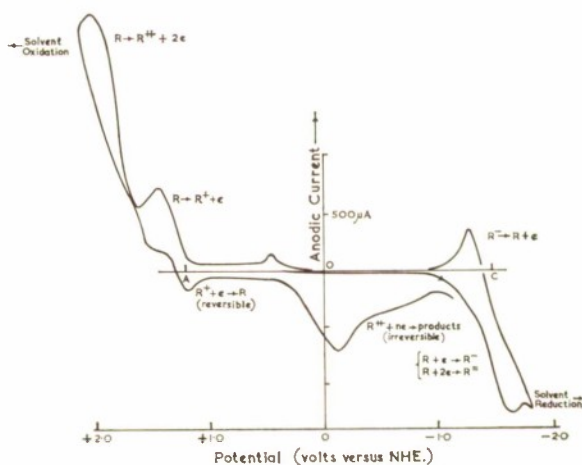

FIG. 1. Cyclic voltammogram of 10^{-3}M 9 : 10 dimethylanthracene in acetonitrile. (Electrode area 0·25 cm^2, Scan rate 0·16 volt sec^{-1}, supporting electrolyte 0·1M tetraethylammonium perchlorate).

Excited Dimers

The electrochemiluminescence spectra of certain hydrocarbons, notably anthracene, have been reported [9] to possess a long wavelength component which has been attributed to excited dimer emission (an excited dimer is a short-lived complex formed between a ground state molecule and an excited singlet state molecule, denoted by R_2^*). This work is especially interesting because two points can be raised. First, since excited dimer emission of anthracene has never been obtained by normal photoexcitation, the method of electrochemiluminescence seems to be a route to observation of new excited dimers. Second, the observation of excited dimer emission with an intensity greater than that observed by photoexcitation automatically implies that a prior step in the mechanism must involve a bimolecular collision leading directly to excited dimer formation, *in addition* to the normal association reaction:

$$R^* \; + \; R \; \underset{K_d}{\overset{K_a}{\rightleftharpoons}} \; R_2^*$$
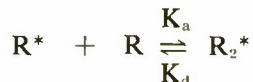
The immediate inference is that radical-radical annihilation can proceed *via* the excited dimer in those compounds capable of forming them, *e.g.*

$$\overset{+}{R} + \overset{-}{R} \begin{cases} \nearrow R^* + R \\ \searrow R_2^* \end{cases} \qquad \dots (2)$$

Alternatively it is possible that a radical ion could react with a degradation product of the hydrocarbons or that two such degradation products (oxidized and reduced forms) could react together. In the case of dimethylanthracene in dimethylformamide solution, the balance of evidence is in favour of the radical-radical reaction predominating, because analysis of the solution after prolonged cyclic electrolysis shows that little degradation has occurred, while at lower voltages light emission can be observed over periods of several hours without loss in intensity. Most other hydrocarbons as well as yielding radical ions on electrolysis, also participate in side reactions with the result that a complex mixture of oxidation and reduction products is quickly built up in the solution, light emission is quenched and the electrodes themselves become coated with insoluble material.

Triplet Mechanism

A third explanation for enhanced excited dimer emission has been proposed. This postulates that the initial species formed in solution as a result of the radical reactions is the triplet state of the hydrocarbon. Thus:

$$R \xrightarrow{. - \text{oxidant}} {}^3R \qquad \dots (3)$$

Two triplets can then react together, in a well established annihilation reaction [10] to yield either excited dimer or excited monomer:—

$$^3R + {}^3R \begin{cases} \nearrow R^* + R \\ \searrow R_2^* \end{cases} \qquad \dots (4)$$
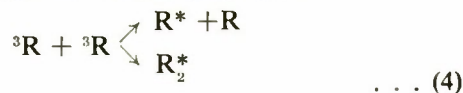
This is the process giving rise to P-type delayed fluorescence [11] and has been observed for a large variety of compounds. The intensity of the excited dimer fluorescence relative to monomer fluorescence is larger than that observed for prompt fluorescence where only an excited monomer is formed initially. In theory, the ratio of dimer to monomer emission for delayed fluorescence can be compared with the same ratio obtained from electrochemiluminescence and could provide a means for distinguishing between the two mechanisms. So far this has only been possible in the case of 9 : 10 dimethylanthracene, since this is the only compound which not only electrochemiluminescences efficiently but is also known to be capable of forming excited dimers on photoexcitation [13]. It was found that electrochemical excitation yielded appreciably more dimer emission than could be accounted for by a triplet mechanism [12]. In addition the ratio was found to increase rapidly with decreasing temperature whereas in delayed fluorescence, the ratio reaches a maximum value and then declines with decreasing temperature. This seems to indicate that only a small proportion of the reaction can involve the triplet state and that a major contribution to the light emitted is made by a reaction such as (1). On the other hand, Weller [14] has recently shown that oxidation of ethereal solutions of hydrocarbon radical anions with Wursters blue perchlorate (a stable amino cation) results in a strong luminescence emission from the excited singlet state of the hydrocarbon, even though there is insufficient energy available for this state to be reached by a one step ion combination reaction. Hence ion combination must result in the formation of the triplet state of the hydrocarbon followed by triplet-triplet annihilation. It appears therefore that much depends on the relative energy levels of the triplet states involved as well as the energetics of the ion combination reaction itself.

Electrochemiluminescent Materials

There are several criteria involved in the choice of a suitable molecule for electrochemiluminescence, each of which must be satisfied in order to obtain a reasonably efficient light-producing system.

(a) Anion and cation formation must take place at potentials within the solvent-breakdown region.

(b) Both anions and cations must have reasonably long intrinsic lifetimes in the solvent, preferably > 5 secs.

(c) Both the radical ion and neutral molecule must be stable with respect to the medium so that side reactions are absent.

(d) The parent molecule must possess a high fluorescence quantum efficiency and fluoresce in the visible region of the spectrum.

(e) The substance must be reasonably soluble ($>10^{-2}$M).

At present there is no molecule which fully satisfies all the above criteria. While there are a great many substances which have been found to exhibit electrochemiluminescence, the emission is generally dim and brief, due mainly to the effect of side reactions. It is significant that the most efficient materials known are substituted with nucleophilic groups in the positions of the nucleus most susceptible to electrophilic attack. For example, rubrene [7], (9, 10, 11, 12 tetraphenylnaphthacene), 9, 10 diphenyl [5] and dimethylanthracene [12], 1, 4, 5, 8 tetraphenylnaphthalene [15], and various substituted isobenzofurans and isoindoles [16], are the only materials which have been observed to electrochemiluminescence brightly for long periods. Future development of electrochemiluminescent systems will involve further substitution into ring systems of known stability and high fluorescence efficiency.

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Dr. Ralph Benjamin, Ph.D., B.Sc., A.C.G.I., C.Eng., F.I.E.E., R.N.S.S., the Director of the Admiralty Underwater Weapons Establishment presented the Imperial Service Medal to Mr. Cornelius McCarthy, Head of the Drawing Office of the Admiralty Experimental Diving Unit, on Wednesday, 14th February, 1968.

Mr. McCarthy, an Old Boy of Southern Grammar School, and an ex-dockyard apprentice, joined the Unit when it was first formed in 1947, after twenty years in various Dockyard Drawing Offices, and spent the next twenty years as the Head of the Unit's Drawing Office, designing diving gear for frogmen in the Royal Navy. He retired recently on reaching 60 years of age and the award of the Imperial Service Medal is a fitting crown to a long service career in Royal Naval research and development.

COMPUTERS IN THE ROYAL NAVY.

Instructor Lieutenant R. W. Sudweeks, B.Sc., M.I.E.E.E., R.N.
H.M.S. *Neptune*

Introduction

In the course of this paper it is proposed to deal with three types of computer, all acting as special purpose computers. They are:—

(1) *T.G.C.U. Mk. 2 (Torpedo Guidance Control Unit)*—used in the solution of relative velocity triangles, and concerned with guiding a controllable torpedo from a moving firing vessel to a moving target.

(2) *D.A.A.—used in the A.D.A. (Action Data Automation)* concept to control the launching, direction, and recovery of carrier-borne aircraft from an aircraft carrier in an air-defence system.

(3) *The Polaris Computers*—used
   (a) in controlling the navigation of a submarine in conjunction with S.I.N.S. (Ship's Inertial Navigation System)
   (b) in launching on to a correct trajectory a missile towards a target.

Most computers used in Service applications are used in a special purpose manner. The *T.G.C.U.*2 is in fact a pure special purpose computer in that it is only capable of solving relative velocity triangles, and has a fixed, hard-wired program allowing it to do this.

D.A.A. is a general purpose computer used with a " plug-in " tactical program. This is a special purpose program written to deal with aircraft direction and tactical decision-making, and as such is fixed for a given tactical situation. However, since the computer is itself a general purpose machine, *i.e.* it need not always use the same tactical program, the program can be re-written

or tailored to meet changing tactical situations should minute or overall objectives change.

The *Polaris* Computers broadly come under the same classification as *D.A.A.*, and are used in two applications:—

(a) Navigation, in which the function of one of the computers is to monitor outputs of a stabilized gyro platform, and to compute corrective torquing signals to maintain the platform in the local horizontal regardless of current latitude and longitude, whilst the other monitors the behaviour of the entire navigation system.

(b) Weapons, in which one computer compares current latitude and longitude with target latitude and longitude and from these computes a launch bearing and range for each missile, whilst another takes account of submarine movements during launch, and a third computer—in each missile— monitors the in-flight behaviour of the missile.

Of these *Polaris* computers, all the Navigation and Weapons computers, with the exception of the computer in the missile, are general purpose machines used with special purpose tactical programs. The missile computer is a special purpose device with a hard-wired program.

From this layout of three computerized systems, used in conventional submarines, carriers and guided missile destroyers, and in *Polaris* submarines it will be evident that there is a large requirement for computer maintainers, operators and programmers in the Royal Navy. Personnel are required to maintain and to oversee the main-

tenance of the electronics and mechanics of computers. More personnel are required to teach the principles and practice of computation. Others are required to actually operate the computers in the various tactical situations, and still others to write the " computer's rules of operation " *i.e.* the tactical programs. In the first two Naval applications mentioned the distinction between maintainer and user was relatively clear cut. With the advent of Polaris the rôle of maintainer and user have been somewhat fused, and so a new all-round computer systems engineer is called for; one who understands the problems being solved, the basics of their solution, and the solution applications, together with the implications for the system as a whole should one component part of it be unserviceable.

The Torpedo Guidance Control Unit

The function of this machine is to solve relative velocity triangles, using as data constantly updated own ship and target positions and velocities, and it was decided that a fixed program, special purpose device was best suited to the solution of this problem. Influencing the design were the facts that only one function for the computer was required—it was to be used solely as a unit for the control of torpedo guidance, and was not to be used as a maid-of-all-work, and that it must be small and rugged, for use in a submarine possibly itself under attack from torpedoes or depth charges.

The solution to the problem requires as input data several parameters—own course and own speed (obtainable from components of the ship subsystem), target course and target speed (obtainable from the surveillance system, sonar, radar, *etc.*), and weapon data (available as constants of performance). From these sets of vectors a target bearing vector can be calculated, and when coupled with target range an intercept bearing can be calculated which assumes no change in target course and speed. These calculations involve only simple trigonometrical relationships.

The computer also has available weapon performance data, *e.g.* weapon speed, and maximum range, and is capable of communicating with the weapon after launch to issue guidance commands and to receive current weapon data in return.

The problem then has simplified to the production of a weapon intercept vector and the issue of guidance commands to the weapon to maintain the actual weapon vector aligned with the theoretical intercept vector. Since the target may alter course and/or speed at any time during the intercept, and the weapon launching submarine may also be manoeuvring (within the limits imposed by the guidance problem) constantly updated sub-

marine and target data are required to produce the constantly updated theoretical intercept vector, and to allow the issue of updated guidance commands to the weapon.

The tactical program has been written such that new data and the updated intercept vector are used and produced every two seconds. This time is considered to be within the limits imposed by:—

(a) the minimum time required to perform the computation,
(b) the staff requirements on the monitoring of the attack.

The computer produces for the user three displays:—

(a) a tactical operator's display,
(b) a weapon operator's display,
(c) a numerical tabulation of current data.

All three displays are produced on C.R.T.s on the computer console. The Tactical Operator's Display provides in trace form updated own ship's position, target intercept vector, and weapon position (after launch). The weapon position is controlled by a joystick and the object of the " game " is to position the weapon marker on the intercept vector at all times, and preferably headed towards the target. The joystick movements are interpreted by the computer as guidance commands every two seconds, and are transmitted to the weapon which obeys them and indicates to the computer that it has done so. The tactical display is then updated and the procedure repeated.

The Operator's Display provides information on the weapon heading, again in trace form, and indicates the weapon state, *i.e.* whether it is under guided control or is in an auto-homing state. Once the weapon is within a certain range of the target it sends back to the computer a request for guidance to be terminated, and if this request is granted the weapon switches to a homing attack mode listening to target noise in its transducer channels and issuing its own guidance commands until contact is established and the intercept completed.

The Numerical Display provides in numerical decimal form, on the surface of a C.R.T., a constant display of the important data currently being processed for the benefit of the command team. The data, such as own course and speed and target course and speed, weapon range *etc.*, are rewritten on the tube every two seconds, and a large part of the tactical program is involved with the production of this display.

The computer used is a special purpose, fixed program serial computer operating in the twos complement form. Computer wordlength is 20 bits and single address format is used in the instructions. The memory unit of the machine is a magnetic drum rotating at 6,000 r.p.m. and having an

access time of 10 millisecs. The basic clock frequency comes from the timing track engraved on the drum is around 90 kHz, while the computer clock frequency is around 60 kHz. The drum has 32 tracks with basically 32 words per track. Two of the tracks are used to provide drum timing pulses and a drum revolution marker, and 16 tracks are used to form a library of trig. tables. These are used in preference to using subroutines to generate trig. functions since they are used so often, and in any case even a severely truncated series calculation for the trig. functions would involve more computing time and memory space than the tables require. Thus a sequential table look-up routine is used, and fully half of the memory space is used as the library. One track of the drum is used for permanent data, and four tracks for temporary data. Five tracks are used to store the program and the remainder of the tracks are spare. The program, tables and permanent data are engraved on the drum so that the machine is truly a fixed program machine. Program change is a major operation involving policy and tactical decisions and means that the entire drum must be replaced.

Typical operation times on the computer are of the order of 0·35 millisecs for addition, 7 millisecs for multiplication, and 10 millisecs for division.

The largest part of the computer's efforts is devoted to producing the up-dated operator's, tactical and numerical displays, and in a Service application this is not unreasonable. This is quite different from the normal run of commercial or scientific computers where the effort goes into producing as many results as accurately as possible in the shortest possible time, and decisions concerning these results are made off-line, and later reprocessed. In its military rôle the prime purpose of the computer is to give a rapid display of a situation in which the display itself allows an instant command analysis to be made, and the tactical response developed. The processing rate need only keep up with the " command policy " treatment rate, providing an effectively constantly up-dated picture.

A cabinet approximately 7 ft high, 2 ft wide and 3 ft deep houses all the sections of the machine. including the display screens and associated display electronics. It is interesting to note that a drum memory is used even where the entire computer may be subjected to relatively severe shocks and operational disturbances.

D.A.A. and Action Data Automation

The A.D.A. concept, used in the aircraft carrier *Eagle* and, in a modified form, in the new guided missile destroyers, provides a means of rapidly assimilating surrounding data, analyzing it and, on the basis of a set of pre-formulated rules applied to the analysis, developing a response to a given situation.

The main input to the system comes from a three-dimensional radar installation which provides a picture in depth of the surrounding area, from sea level up to normal aircraft operational levels. A three dimensional picture is provided and the radar contacts are classified and fed as input data to the computer system. Once the computer has accepted these classified contacts they are continuously tracked and the current positional display maintained. Other inputs to the computer system come from other peripheral equipment such as further radar, sonar *etc.*, and from other ships in company by means of digital Tactical International Data Exchange links. These escorts provide an extension of the effective screen range of the system. The composite picture assembled from data supplied by all sources is then available and tactical decisions are made.

The tactical program used is concerned with:—

(a) data obtained from the sources already discussed,

(b) data concerning the defensive armaments and capabilities carried by this force,

(c) decisions, written as the program, based on tactical experience as to how best to utilize the capabilities of this force to counter an attack.

The data on defensive armaments and capabilities includes information on the type of aircraft carried, its performance figures, its fuel capacity and its armament capacity.

The tactical program makes decisions as to how best to deploy these aircraft against attacking aircraft using a weighting technique—rather like a program written to play chess—and continuously monitoring fuel and armament states of defending aircraft. For example, the decision must be made as to whether to deploy against a marauder an aircraft with a half load of fuel and two rockets or a plane with a quarter load of fuel and six rockets, when in both cases one eighth load of fuel will be required to successfully recover these planes and this fuel is being used now, while the decision is being made. When you consider that in an attack of any reasonable size many such decision pairs and triplets may be required simultaneously and continuously from a command team itself under attack then it is apparent that a more acceptable solution can be achieved by giving the whole problem to a computer, programmed to make the same decisions as would normally be made by the command team, faster, continuously and impervious to stress or fatigue. When you further consider that at the same time as the air situation has been
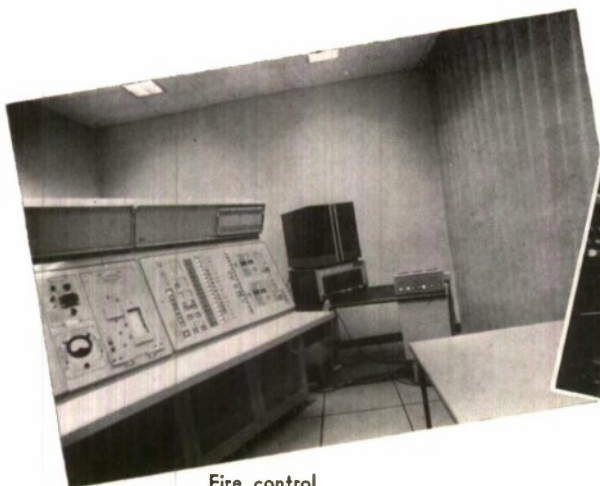
Fire control
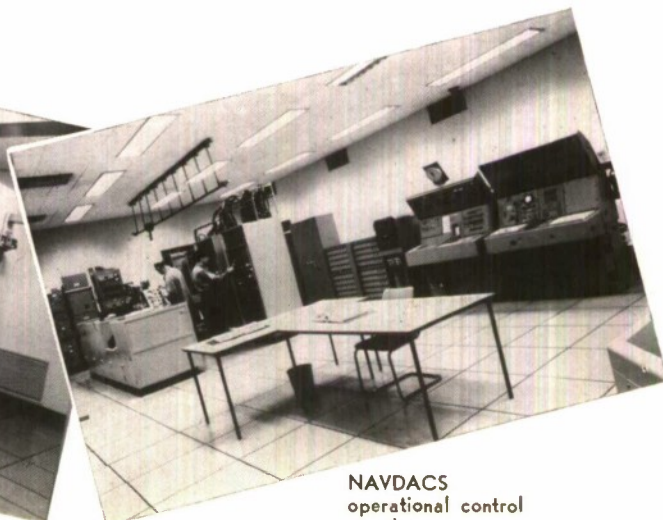Console trainer run by
PDP8 computer.

Nav centre
Simulator control run
by Mardan computer.

Two SINS binnacles
and Mardan.

Fire control
computer D.G.B.C.

NAVDACS
operational control
panel.

developing a sea situation may have been developing, and the ship and escort vessels still require normal handling then a computerized solution is the obvious answer.

The computer used to mechanize the A.D.A. concept is the Ferranti *Poseidon*. This is essentially a paralled mode computer operating at 500 kHz, and using a random access core memory. The whole computer is transistorized and uses NOR logic, and uses a wordlength of 24 bits. This is considered to be of sufficient size to allow solutions to be processed to the required degree of accuracy. The core store of Poseidon is unusual in that two cores per bit are used. Eight thousand one hundred and ninety-two words of data store are provided and the program store is provided in sections of 4,096 words, capable of expansion up to a total of 16,384 words. The program store is separate from the data store in this machine for normal tactical purposes, and the program is held on punched magnadur sheets: punched holes on these sheets in line with the core bits being used to store the program. Program changes merely involve removing one sheet and inserting another. Using this system the core cycle time is 6 microsecs. and this is used in conjunction with a basic bit time of 2 microsecs. from the 500 kHz clocks. During program development programs may be written into the data store to avoid the need for repetitive punchings of magnadur sheets. (This does reduce the overall operational speed of the machine, but this is unimportant during the development phase of program writing and proving.) The average instruction time for the machine is around 6 microsecs assuming an average of 10% multiplication time, and this figure compares well with the core cycle time.

Poseidon has a very powerful order code, being in fact a commercial computer re-engineered to meet the service requirements. It can be programmed in either machine code (Inner Code), or in Autocode (Outer Code). Each autocode step calls up the appropriate machine code step using a compiler routine, and from this it follows that autocode is used during program development to simplify the tactical programmer's task, and from the final tested version of this a machine code program is produced to ensure that the computer can process the program at as high a rate as possible.

Poseidon has been designed so that it can act as part of an on-line computer system. *Proctor* is the control unit which controls data transfers between various parts of the system in a parallel transfer mode. Bearing in mind that *Poseidon* is an early second generation computer this interrupt and data transfer system is fairly sophisticated, as it is only really now in the third generation of computers that computer systems using inter-computer data exchanges have been developed.

Displays from the system are used in two areas:—

(a) operator/maintainer displays on the control console, used by the direct operator to ensure correct operation of the computer and associated peripheral equipment.

(b) user displays in the operations room, where aircraft directors relay the results of the computer's analyses to the defensive aircraft and outstations.

The data flow in the system is then:—

(a) detection and classification of hostile aircraft and targets in an area, and the classification of friendly aircraft and support vessels.

(b) assimilation in the computer of this data.

(c) computer-proposed course of action developed and displayed to the user.

(d) proposed course of action relayed to the defensive aircraft.

(e) continuous monitoring of the development of the course of action, with modified proposals and alternative proposals available at all times.

This last step in the flow is important, since it does bring out the over-ride concept (or Gold Braid Modulator). If at any time the controller decides, intuitively perhaps, or because he has access to information not available to the computer, that he wishes to over-ride the computer proposal, or that he wishes to see an alternative course of action proposed before making the final decision, then this option is available.

The actual computer section is fairly small, being housed in three cabinets, each 5 ft 6 in by 1 ft 10 in by 1 ft 5 in. The overall system, excluding the user displays requires a space equivalent to a small living room.

The Polaris Weapon System

As was mentioned in the introduction the *Polaris* Weapon System uses three types of computer—two concerned with the accurate navigation of the submarine, and one concerned with the calculation of launch bearings and target ranges.

As early as the late 1950s a computer was being used to assist in navigation. The problem was precipitated by the ever increasing speeds of flight and the correspondingly shorter times available in which to perform the classical navigational evolutions. *VERDAN*, a versatile differential analyzer, was developed and was used in conjunction with accelerometer outputs to compute current position relative to some previous fix position by mechanizing *Simpson's Rule*. Accelerometers were mounted so as to have them maintained in the local horizontal by means of a gyro-stabilized plat-

form. However, since the gyro-stabilization caused the platform to be referenced to inertial space it was necessary to torque the platform gimbals *via* the gyros so as to keep them earth-referenced rather than space-referenced. The outputs of the accelerometers were then used:—

    (i) to allow computation, by means of double integration, of the distance travelled since last fix, and thus to allow computation of a new latitude and longitude.

    (ii) to allow the computation of torquing signals, in accordance with the current latitude and longitude, to keep the platform aligned in the local horizontal.

(It will of course be obvious that if the platform is not kept in he local horizonal then the accelerometers will sense a component of gravity, thus invalidating the pure acceleration reading required from them.)

Exactly the same set of conditions prevailed when it was decided to build the *Polaris* submarines, and earlier the nuclear submarines. Three-dimensional navigation was required to a high degree of accuracy, but whereas in the flight situation the system had to be maintained in accuracy for only a few hours, and system gyro drifts and biases were not critical, the undersea navigation system had to be maintained in stability for a considerable number of weeks, and over this period drifts and biases could have considerable effect.

MARDAN, a marine differential analyzer, was built by Autonetics—a subsidiary of North American Aviation Company, and thus a particularly apposite choice of company to achieve the transfer of ideas—as a general purpose computer capable of being tied in to the navigation system. In addition to handling the normal minute-by-minute navigation problem the effects of drifts and biases could be programmed out by including offset figures in the torquing commands, and so *MARDAN* was tied in with SINS to provide a highly stable navigation system. Fixes, or as they are known resets (*i.e.* verifications developed from external sources of the submarine's true position) are required at set intervals, and the overall computation of new distance travelled is then re-started from this new fix point. Again, acceleration signals processed through double integration give distance travelled, and torquing and resultant position signals are developed.

MARDAN is mechanized using a disc memory on which are the registers of the digital differential analyzer (*DDA*) section, and associated stores. The memory capacity is approximately 6,000 words and has a maximum access time of 10 millisecs. Its program takes into account the effects of earth rotation (different tangential velocities for different

degrees of latitude) and movement across a round earth (stabilization of the platform in the local horizontal from the computed latitude and longitude). Its display system is limited to a switchable, generalized nixie-tube display capable of displaying all interesting quantity locations, since its primary function is to produce torquing signals, not displays, and the whole computer occupies a space of only 3 ft $\times$ 3 ft $\times$ 1 ft. The input to the machine is by means of a fan-folded paper tape in a pre-loaded casette—a rather novel feature for a computer, the casette being loaded off-line.

The overall navigation system performance, and the tie-in of the navigational aids is monitored by a Navigational Data Assimilation Computer (*NAVDAC*). There was a requirement for the computation and/or verification of reset quantities, prior to their use on *SINS*, and to achieve this a high resolution digital computer was thought to be the best solution. *NAVDAC* is such a computer, operating in serial mode and being quite general purpose. It was available as an off-the-shelf general purpose computer from Sperry Company, and by means of a special purpose navigation system program meets the requirements for an accurate system monitor. Its main store is a drum having a capacity of 18,000 words, and it also has access to a small core memory for fast access as a " scratch pad " memory. The drum access time is a little better than 10 millisecs, while the core can be accessed in around two microseconds. Its inputs are achieved from the navigation system peripheral equipment and from *MARDAN*, and its principal outputs are to *SINS* and to an *IBM* typewriter. It has however a full front panel display system for maintenance purposes, and for training can be used as a G.P. computer under front panel control.

Both of the navigation computers are fractional machines, and both have clock rates below 500 kHz. They are late first generation computers, fitting comfortably into a second generation application.

The Weapon System computer is the Digital Geo-Ballistic Computer (*DGBC*). This is a sophisticated second generation computer system using as its computer the Digital Control Computer (*DCC*), which is a militarily re-engineered version of a standard, commercial computer manufactured by Control Data Corporation. It is a high speed, parallel mode machine with a core memory of 16,000 words, and a clock rate of 5 MHz.

Its task is to compute, for each of 16 missiles, a launch bearing and range from a knowledge of current submarine position supplied by the navigation system, and of the target positions. There are various means by which a ballistic missile may be delivered to a target, and, using the *Polaris*

guidance system, *DCC* computes from the range and bearing figures the correct quantities for the guidance system actually used. The tactical program is an interesting problem in itself since it must calculate quantities to enable a missile to be lifted from below the surface of the sea, out into space, and to be successfully re-entered into the earth's atmosphere and delivered accurately on to the target. The tangential velocity of the earth at the launch point may be different from the tangential velocity being experienced by the target, due to the fact that the effect of earth rotation is different at different latitudes. Thus the fact that the target is not at the same point when the missile arrives as it was when the missile was launched must also be taken into account. Coriolis effects during the time of missile flight must also be accounted for, as indeed they were in the navigation program to account for computed positional anomalies due to the actual movement of the submarine.

DCC is a conventional general purpose computer and has the normal range of interrupt facilities. Normally in a commercial application these would be connected to back-up tape decks, and to flexowriters, and even to other computers. In the tactical configuration in which it is used for *Polaris* the interrupts are coupled to external events, and the computer is programmed by means of subroutines to make the correct type of response for each interrupt's occurrence. Similarly the internally generated interrupts are used to allow the computer to communicate at will with the remainder of the weapon system. This set-up, in conjunction with the tactical program is what converts the essentially general purpose machine into a quasi-special purpose device—hence the title of digital control computer insomuch that it controls the system by making conditioned responses to external events.

To provide a highly reliable computing system for this weapon fire-control problem two *DGBCs* are used in parallel, each having access to a back-up drum store of capacity 16,000 words. This drum allows inter-computer data transfers since either computer can transfer data to, or request data from, the drum, and it is this 'computer system' concept that makes the fire-control computers so flexible. The memory access time using a 5 MHz clock is two microseconds for the core memory. Access to the drum store is much slower but this is not so important as it is not single-word transfers but bulk data transfers which are made between the two. Input to the computer comes from punched mylar tape and manual injections, and output from the computer is direct to the individual missile computers and to the servos indicating computed launch bearing.

The fire control problem is further complicated by the fact that the missile is not being launched from a stable launch pad. The pad may be feeling, rather severely, the combined effects of submarine roll, pitch and yaw, and the actual amount of each effect will differ from missile to missile due to their placings down the length of the submarine's hull. An analog missile motion computer computes correctives quantities to allow the *DCC* to proceed with each missile's calculations as if it were computing for a hard-site missile.

Conclusions

These then are three examples of the ways in which computers are being used in the Royal Navy to-day. The tasks performed are complex and the results are required continuously and accurately. The human operator is still required for system operation, analysis and for maintenance, but, most important, he still retains overall command of the system despite the computers. The computer can only calculate from the data available. The application of the results of these calculations, their interpretation and translation into policy and command decisions is still the function of the Naval Officer.

A GaAs LASER ARRAY FOR COMMUNICATIONS

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Introduction

In any communications system employing light as a transmitting agent, ship to ship signalling being a good example, the laser can replace the normal forms of illumination such as filament or arc lamps with considerable advantages.

It is by far the brightest light source available, and can increase the daylight range of optical signalling up to the horizon given suitable weather conditions.

The light is emitted over a very narrow spectral bandwidth, and therefore a good signal to noise ratio can be achieved easily by filtering out unwanted light at the receiver.

Of the forms of laser available the gallium arsenide laser is the smallest and most rugged, it has the best power to light conversion factor, and its light can be modulated at high frequencies simply by modulating the current supply.

The wavelength of the emitted light is 8,500 Å and at this wavelength the receiver must be some form of infra-red detector. This is conveniently and readily available as the silicon P-I-N photodiode [1] which is also small and rugged.

Two small compact units then, each consisting of a GaAs laser transmitter and a silicon photodiode detector can form a highly efficient signalling system. In the type of system quoted as an example its small size would enable it to be placed at the masthead thereby reducing still further the limitations imposed on range by the horizon.

It is unfortunate that the GaAs laser cannot be used in foggy or inclement weather, but then neither can any other form of light signalling. In conditions when it can be used, however, it has the advantage that it is not easily subjected to either jamming or tapping.

For research and development purposes such a system is plainly divisible into two major components, and as the silicon photodiode is currently —and conveniently—being developed in this Laboratory, this paper deals only with the transmitter.

Constructional Details

Fig. 1 shows the transmitter in sectional side elevation, from which the main constructional layout is evident. There is a central tube which carries the cooling system, and which is surrounded by thermal insulation. To this is fastened the unit carrying the laser and electrical system. This central unit is surrounded by an outer case into which is built the lens system. The complete unit is then surrounded by a protecting perspex tube which is continuously flushed with dry gas to prevent frosting of the lens.

Design Considerations

(a) *The cooling system*

Although GaAs lasers can be made to work satisfactorily at room temperature [2] the increase in efficiency obtained by working at or near the temperature of liquid air is so large that the mechanical problems associated with this degree of cooling are worth solving. Apart from the supporting plant necessary to supply clean air at high pressure to the cooling element, there are the problems of thermal insulation and the frosting of lasers and lenses in the capsule itself.

Attempts have been made in the past to encapsulate lasers in vacuo in the same manner as thermionic valves [3] in an effort to overcome these last two disadvantages. For various reasons, but mainly due to the difficulties of providing efficient seals and of vacuum baking this has so far been found not to be the best approach. A simpler

scheme was used for this transmitter which proved that vacuum enclosure is not strictly necessary. The thermal loss problem has been reduced to manageable proportions by the use of thin-walled stainless steel components and the provision of ample insulation of expanded polystyrene wherever possible. By arranging the lasers in a virtually airtight compartment, and assembling in dry air, frosting of the lasers and the inside of the lens has been prevented. The clean dry air exhausted from the cooling system is directed over the outer face of the lens by an outer perspex sleeve. The resultant gradual thermal gradient between the lens and the case prevents frosting either of lens or sleeve.

The laser units are mounted radially on a bucket which forms the liquid air container, and to which they are held in good thermal contact, by flat springs which also form the electrical contacts (Fig. 2). This component is made of aluminium not only because of its excellent thermal conductivity between liquid air and laser block, but also because it can be anodized to form a good electrical insulator without impairing its thermal conductivity. This obviates a lot of complicated insulation of the laser blocks.

The bucket is machined to accommodate two full rings of laser blocks *i.e.* 20 spaces to cover 360° in azimuth. The present application requires only 10 spaces to be occupied to cover 180° in azimuth, but the extra spaces not only allow for any future research and development requirements, but also make the bucket symmetrical in shape. At the same time it reduces the thermal mass to the lowest possible level, the finished bucket weighing less than 12 g. A dummy laser block mounted on a disused section of the bucket carries a thermo couple which gives the best possible indication of laser working temperature.

The joint where the aluminium bucket meets the stainless steel cooler housing is subject to large temperature fluctuations, and in view of the large expansion mismatch between these two materials, some flexibility at this point is essential. By making the neck of the bucket only 0·005 in. thick the joint works in much the same way as the well-known " Housekeeper " glass to metal seal, and at the same time this thin section forms a further barrier to unwanted thermal conduction.

The cooler itself is a Hymatic Joule-Thomson expansion type gas liquefier model MAC 217. This unit is capable of a maximum dissipation of 25 W, but works quite well in this application at a rating of 10 W, where it uses 1 cu. ft per min of free air at 2,000 lbs per sq in. It is mounted in a central stainless steel sheath which has a wall thickness of 0·007 in., giving the best possible longitudinal thermal insulation consistent with adequate mechanical strength.
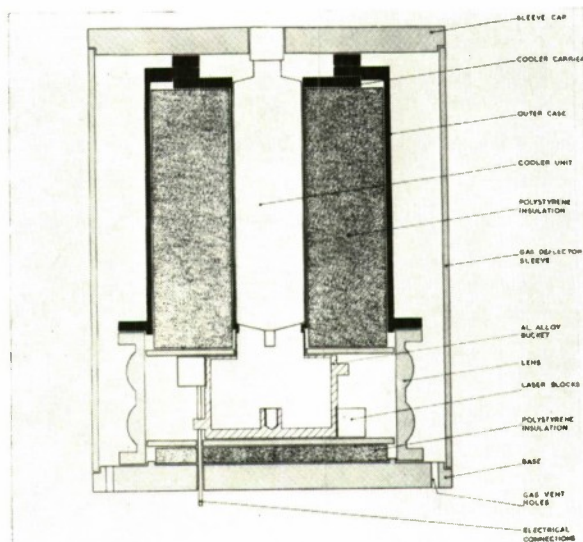

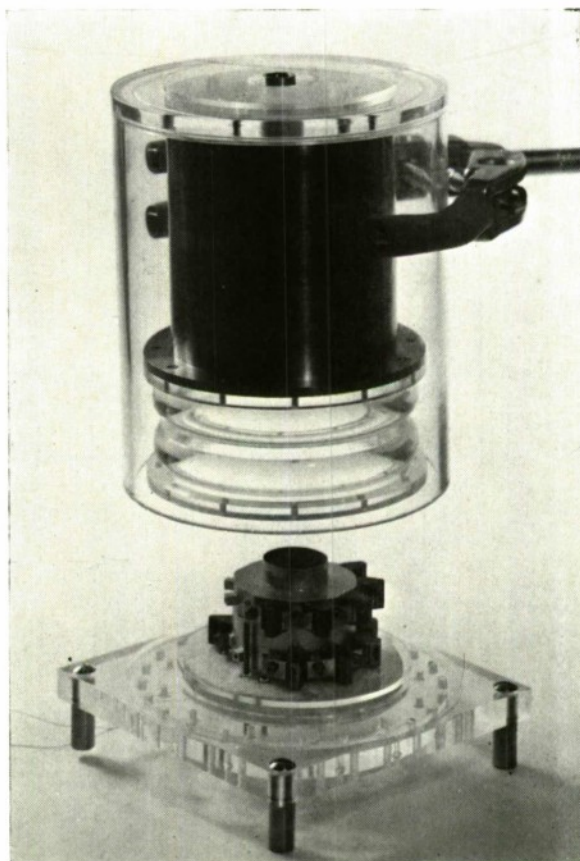
FIG. 1. Sectional side elevation of capsule.

FIG. 2. Capsule dismantled for access to lasers.

(b) *The optical system*

For the system envisaged it was necessary that the transmitted beam should cover a field of 180° in azimuth and 3° in elevation. The commercially available laser assemblies that it was proposed to use would have a half-power beamwidth of about 20° parallel to the junction and 15° normal to the junction. An array of 10 lasers therefore arranged in a semi-circle and facing radially outward would cover the proposed field of view in azimuth and could be focused in elevation by a plano-cylindrical lens.

The lasers are arranged in two staggered rows of five, which keeps the outside diameter of the capsule as small as possible without altering the optical layout. In the interests of simplicity and ruggedness it was decided not to have an adjustable lens for each laser, but to have a single pre-focused lens in the form of a ring, common to each row of five. This decision put a premium on concentricity of lasers and lenses, and on longitudinal positioning of the bucket assembly. This last can be adjusted during manufacture, but the former depends entirely on accuracy in manufacture and design.

The two ring-shaped lenses are built into one unit (Fig. 2) which also forms part of the outer case. It is made of perspex, which is quite suitable optically and which allows of simple flange design and ease of manufacture.

(c) *The electrical system*

Since the lasers have a very low electrical impedance and require high current pulses to drive them it is best to connect them in series. This method of connection enables the spring clips securing the laser blocks to the bucket to be used also as electrical connections. The terminal leads are copper wires which must be big enough to carry the heavy current involved, but also as small as possible to prevent unnecessary thermal conduction.

In view of the possibility that a successful transmitter might go into production it was considered essential that it be designed around a commercially available laser unit. The unit selected has a peak light output of 50 W and a power-to-light conversion efficiency of approximately 10%. They are driven by a standard power pack at 200 A and approximately 30 V. The pulse repetition frequency is 500 Hz average and the pulse length is 3 μs. This means that for an array of 10 lasers there is about 8 W to be dissipated by the cooling system. As the cooler is capable of a maximum dissipation of 20 W there should be ample in reserve for thermal loss in the casing.

The laser units used in the transmitter are basically rugged and reliable, but in the unlikely
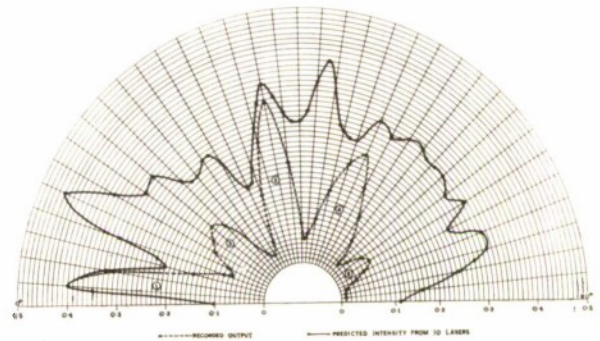

FIG. 3. Polar diagram of laser light intensity in azimuth.

event of one laser failing it is usually due to a short circuit and therefore the array as a whole continues to operate at lower power. It is essential however that access for repair or replacement is simple and quick. Fig. 2 shows the capsule exploded for servicing. This is achieved by removing one row of screws from the lens to base joint, when the whole bucket and laser assembly can be withdrawn attached to the base. Re-assembly should be carried out in clean dry air to prevent internal frosting when working.

Conclusion

The capsule has been tested using only one row of five lasers, the other five spaces being occupied by dummies. The polar diagram of light intensity in azimuth, Fig. 3, shows not only the actual recorded values, but also a compounded diagram composed of two sets of recorded figures displaced to simulate the expected output from 10 lasers. The five lasers used were taken at random and a flatter curve might result from using 10 selected and matched lasers. The polar diagram in elevation, Fig. 4, was taken across laser No. 4, and shows that the lens is working at the predicted beamwidth. It will be noted that the actual diagram in elevation is depressed by 4°. This is due to the laser and bucket
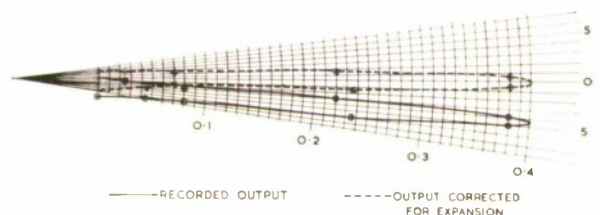

FIG. 4. Polar diagram of laser light intensity in elevation.

assembly moving upwards out of position due to contraction of the cooled portions at working temperature. This was expected, and now that the actual contraction figure is known, can be corrected, so that the beam comes into the correct position at working temperature. This movement could be prevented by fastening the lens to the bucket, but this would increase the thermal conduction where it is least wanted, and would lead to complication and lack of ruggedness.

Working temperature was reached in 13 to 15 minutes and was easily maintained with about 10 W cooling. Although only one row of lasers was being used, it is obvious that the cooling system would be adequate for the full array of 10 lasers.

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WHAT PRICE STERILIZATION?

Lieutenant Commander W. A. Harris, R.N.

H.M.S. Rothesay

With the introduction of a new weapon into service it is necessary to conduct a Radio Hazard trial to ensure that the fuze initiator remains unaffected by all the various RF transmissions likely to be encountered in service. Such a trial had to be conducted for the Mk 24 Torpedo which is a 21 in. diameter 22 ft long submarine fired weapon incorporating an N5 fuze.

A.S.W.E. wrote a trials specification and considered that the trial should be conducted using a Leander Class Frigate, these ships being fitted with the same radio/radar equipment as proposed for the new Depot Ship.

The R.N. Application Officer attached to the project at A.U.W.E. arranged the trial and requested C. in C. Western Fleet for the services of a frigate. The following narrative describes the problems encountered before the trial was completed and illustrates the fact that the contribution which the Naval Application Officer can make within the project team sometimes requires " push, persuasion and perseverance ".

Unfortunately, C. in C. Western Fleet was unable to give more than one week's notice of the frigate allocation and so the Trials Officer went to the Dockyard to finalize arrangements personally and to talk to the ship's officers concerned. It was soon discovered that, although previous checks had shown the ship to be at a crane berth, the crane was inoperative. Indeed, it had apparently been constructed two years before but had not yet been accepted by the Dockyard because of a most unusual phenomenon: the back lifted whenever a load was applied to the jib!

Discussions then proceeded with the Dockyard with a view to obtaining the services of a floating crane (mobile cranes not being large enough for our purpose) and a tug to tow it. Unfortunately, the First Lieutenant was storing ship from barges alongside; but the floating crane could not be obtained anyway, so full stop from all directions.

Further discussions were then started for some other crane but the only one available was two berths up the jetty. This could be used for our

purpose if the ship in that berth could be moved and the trials ship moved there in its place. Negotiations with the Captain of the trials ship were not very successful at first (he would not have taken on the trial if he had known !) but he succumbed to some gentle persuasion and agreed. It should be pointed out here that the ship had a tight schedule of storing, A.A. exercises requiring the ship to be facing a certain direction for clear tracking runs and main engine basin trials requiring the ship to be lashed firmly to the jetty with many heavy wires while the engines are turned. It was little wonder therefore that the Captain was reluctant to move.

Negotiations were then started between all interested parties to arrange a time for moving and this was arranged for 0730 on the Wednesday morning i.e. the first day of the trial, much against the wishes of the ship's Engineer Officer who wanted to get on with his basin trial.

Meanwhile, the lorry from A.U.W.E. was due to arrive with the weapon Tuesday p.m., but of course, there was no crane to lift the box off the lorry and on to the ship. A telephone call to A.U.W.E. established that the lorry would come on Tuesday willy-nilly and that the driver and his mate would stay overnight. The Dockyard police however were reluctant to look after the lorry all night and only agreed after the Trials Officer had negotiated personally with the senior police officer.

The ships were moved by tug and the lorry came alongside early a.m. on the Wednesday and all systems appeared to be at " GO ".

The crane driver at the new berth however, did not like the idea of being sterilized by radiation (he'd heard it was a radiation hazard trial !) and was very reluctant to mount his cab. After much gentle persuasion however, he agreed to co-operate and went up the ladder. This was not the end of the matter though as the Trials Officer's frantic arm waving and signalling produced no movement from the crane. It refused to start. This required the Dockyard electricians to be called in who, when they arrived much later, diagnosed water in the junction box. Nothing could be done

except call out a team of E.Ms from the ship to hump the cables along to the next junction box and try there. The ship's Chief Electrician was very sympathetic and organized the necessary party of humpers.

By this time, quite naturally, the buzz had got around that something was going on and soon there was a gaggle of Dockyard mateys in conference on the jetty (it was a nice sunny morning!). From a quick sensus of opinion it became apparent that the boxes were connected in series and that, rather than strip out the defective box in order to make the next in line work, it would be easier to revert to the initial condition and insert sheets of rubber as insulation between the cables. This was organized, but meanwhile the lorry driver and his mate were getting extremely agitated about a further appointment. A mobile crane was therefore arranged to come and lift the crate off the lorry so that it could get on its way. Meanwhile, down at the big crane, the rubber sheets were put in place and the juice switched on. Almost unbelievably the crane worked.

The DAS(N) man from the Armament Depot who was to carry out tests on the initiator bridge wire arrived, but he had no bridge wires, wax, microscope or melt test set. " Oh ! It should have arrived yesterday by Pussers Transport ", was his reply to a few piercing questions. Frantic telephone calls across the country tracked the gear down to R.N.A.D. Frater and a lorry was arranged to bring it forthwith.

Miraculously, all the ships transmitters were operational when the trial finally got going but halfway through, the overheating buzzers started up. The Trials Officer was just beginning to think that Murphy's Law had finally got the better of him, when it was discovered that the Engine Room Department had switched off all the cooling water to the transmitter heat exchangers !

The trial was eventually completed but it does bring to mind the moral which is: " Don't expect your Application Officer to perform miracles immediately—it does take a little longer ".

THE ENHANCEMENT OF SPURIOUS SIGNALS IN NON-LINEAR FREQUENCY MULTIPLIERS

R. G. Still, R.N.S.S.

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SUMMARY

An inherent disadvantage of non-linear frequency multipliers when fed from a signal source containing spurious signals, is the enhancement of the spuriae in the multiplier pass-band as a function of the degree of multiplication. An analysis showing the enhancement effect is given, and some experimental results are described.

Introduction

Where a requirement exists for rapid microwave frequency changing, such as in a frequency agile coherent radar, it is expedient to carry out the switching operation at low frequency and then multiply up to the transmitter frequency.

Most considerations of non-linear frequency multipliers assume that the frequency to be multiplied is pure; in every case, however, the purity is a matter of degree. For example, should the frequency be obtained from a high grade signal generator the spuriae would consist of the inherent noise of the source, probably 120 - 160 dB below the level of the signal frequency. If, however, the signal is derived from a frequency modulator or mixing circuit, the spuriae in the multiplier pass-band will consist of sidebands as well as harmonics of the local oscillator and of the signal frequencies. In practice the amplitude for these frequencies would be 30-40 dB below the signal frequency level.

Analysis

Frequency multipliers in general employ non-linear input/output characteristics to produce harmonics of the input signal frequency. The characteristic is of the form:—

$$E_{out} = aV_{in} + bV_{in}^2 + cV_{in}^3 \quad \ldots \text{etc.}$$

The a, b, c terms in the expression represent respectively 1st, 2nd and 3rd harmonic **frequency** contents, and the desired order of multiplication is selected by filtering out the unwanted harmonic orders.

Consider a x2 frequency multiplier:

Let V_{in} consist of two frequencies separated *by a small* amount. $E_1 \sin \omega_1 t$ is the main signal and $E_2 \sin \omega_2 t$ the unwanted or spurious signal.

A simple analysis considering only those terms up to and including 2nd order shows:

$$V_{in} = E_1 \sin \omega_1 t + E_2 \sin \omega_2 t.$$

$$E_{out} = a[E_1 \sin \omega_1 t + E_2 \sin \omega_2 t] + b[E_1 \sin \omega_1 t + E_2 \sin \omega_2 t]^2$$

$$E_{out} = a[E_1 \sin \omega_1 t + E_2 \sin \omega_2 t] + bE_1^2 \sin^2 \omega_1 t + 2bE_1E_2 \sin \omega_1 t . \sin \omega_2 t . + bE_2^2 \sin^2 \omega_2 t.$$

$$= bE_1^2 \sin^2 \omega_1 t + bE_2^2 \sin^2 \omega_2 t + 2bE_1E_2 \sin \omega_1 t . \sin \omega_2 t + \text{first order term } (F_1).$$

$$= bE_1^2 \left(\frac{1 - \cos 2\omega_1 t}{2} \right) + bE_2^2 \left(\frac{1 - \cos 2\omega_2 t}{2} \right) + 2bE_1E_2 \sin \omega_1 t . \sin \omega_2 t + F_1.$$

$$= \frac{b}{2}(E_1^2 + E_2^2) - \frac{b}{2}(E_1^2 \cos 2\omega_1 t + E_2^2 \cos 2\omega_2 t) + 2bE_1E_2 \sin \omega_1 t . \sin \omega_2 t . + F_1.$$

Now $\sin\omega_1 t.\sin\omega_2 t.=\dfrac{\cos(\omega_1-\omega_2)t}{2}-\dfrac{\cos(\omega_1+\omega_2)t}{2}$

$\therefore E_{out}=\dfrac{b}{2}(E_1{}^2+E_2{}^2)-\dfrac{b}{2}$

$(E_1{}^2\cos2\,\omega_1 t+E_2{}^2\cos2\,\omega_2 t)$

$+\,bE_1 E_2[\cos(\omega_1-\omega_2)t-\cos(\omega_1+\omega_2)t]+F_1.$

From the above it is seen the output consists of several terms, besides the first order term, the significance of each being as follows:—

(i) $\dfrac{b}{2}(E_1^2+E_2^2)$ a fixed term which can be ignored as it is not related to frequency.

(ii) $\dfrac{b}{2}(E_1{}^2\cos2\omega_1 t)$. the 2nd harmonic of the input signal frequency *i.e.* the input frequency x2, this being the *wanted* frequency.

(iii) $\dfrac{b}{2}(E_2{}^2\cos2\omega_2 t)$. the 2nd harmonic of the input spurious frequency; this lies close to the wanted frequency, but its relative amplitude is greatly reduced compared with the input conditions, *i.e.*

ratio of input signal to input spuriae $=\dfrac{E_1}{E_2}$ and ratio of the *wanted* 2nd harmonic signal to spurious 2nd harmonic $=\dfrac{E_1{}^2}{E_2{}^2}$.

(iv) $bE_1 E_2\cos(\omega_1-\omega_2)t$. the difference frequency. In the case of a frequency multiplier containing 1st and 2nd harmonics only, the difference frequency component lies well outside the operating band and therefore has little effect; however, some of the difference frequency components of higher harmonics fall into the wanted band and have significant effect as explained later.

(v) $bE_1 E_2\cos(\omega_1+\omega_2)t$. the sum frequency. ω_1 and ω_2 are close together and their sum lies close to the frequency we are considering, the actual separation being $2\omega_1-(\omega_1+\omega_2)=\omega_1-\omega_2$.

The amplitude coefficient of the 2nd harmonic term of the signal frequency $=\dfrac{b}{2}E_1{}^2$.

The amplitude coefficient of the frequency summation term $=bE_1 E_2$.

$\therefore$ The ratio of these two amplitude terms $=\dfrac{E_1}{2E_2}$.

But the ratio of the original signal amplitudes $=\dfrac{E_1}{E_2}$.

Thus at the multiplier output the required 2nd harmonic is produced as expected and also an unwanted frequency which is separated from the wanted one by the original frequency difference.

Furthermore the amplitude of the output spuriae has increased by 6 dB relative to the input conditions[2].

If the coefficient " b " should not be the same for the two terms because of the difference in signal levels, the 6 dB figure would be modified; experimental evidence, however, has confirmed this figure.

Analyzing the expression further to include the cubic terms, *i.e.* third harmonic content, we find the coefficients are:

3rd harmonic coefficient $\dfrac{CE_1{}^3}{4}$,

3rd order summation coefficient $\dfrac{C3E_1{}^2E_2}{4}$,

the ratio of these two terms becomes $\dfrac{E_1}{3E_2}$ for a tripler.

It is apparent that in this case the unwanted signal amplitude is enhanced by a factor of three, *i.e.* 9·5 dB. It can also be proved that the 4th order harmonic terms resolve down to $\dfrac{E_1}{4E_2}$, *i.e.* an enhancement of 12 dB for a quadrupler.

So far only summation terms have been considered to be significant spuriae within the band. Difference terms, however, also fall within the required band when they exist as differences between the higher harmonics of the fundamental and the spurious input frequency or its harmonics.

In general the summation and difference frequencies are of the form $n\omega_1\pm m\omega_2$: and sum and difference spuriae will appear respectively on either side of any one of the output harmonics of the fundamental.

The number of sum and difference terms increases in proportion to the number of harmonics the multiplier is capable of producing. For example, referring to Fig. 4, the frequency difference associated with the cubic term is $2\omega_1-\omega_2$ which results in a spurious frequency component separated from the main fundamental by the same amount as the spurious input, but appears on the other side of the fundamental. Similarly the spuriae on either side of the main 2nd harmonic output are $\omega_1+\omega_2$ and $3\omega_1-\omega_2$ *etc.*

The analysis has shown the amplitude coefficient of the sum and difference terms to be the same. Therefore the difference term frequency component will also be enhanced 6 dB per octave of multiplication.

This note does not attempt a complete analysis of the non-linear characteristics of frequency multipliers but in general it can be stated that the unwanted frequencies in the pass-band of a multiplier increase by 6 dB per octave of multiplication,

FIG. I.
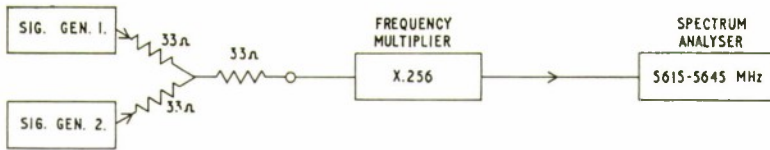
Main signal IN	22MHz	Amplitude	−6dB
Spurious signal IN	23MHz	Amplitude	−56dB
Main signal out	5632MHz	Amplitude	+50dB
Spurious signal out	5632±1MHz	Amplitude	+48dB
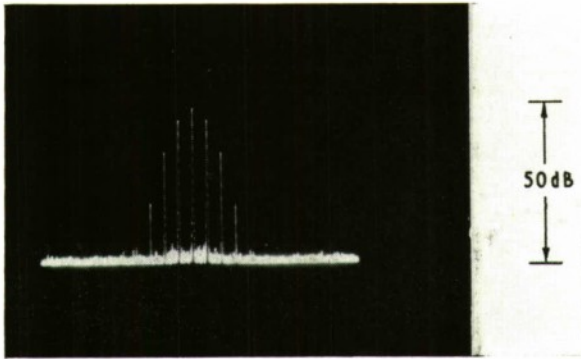
FIG. 2. Eight octave multiplier.

Main signal in	22MHz	Amplitude	−6dB
Spurious signal in	Nil		
Main signal out	5632MHz	Amplitude	+50dB
Spurious signal out	Nil		
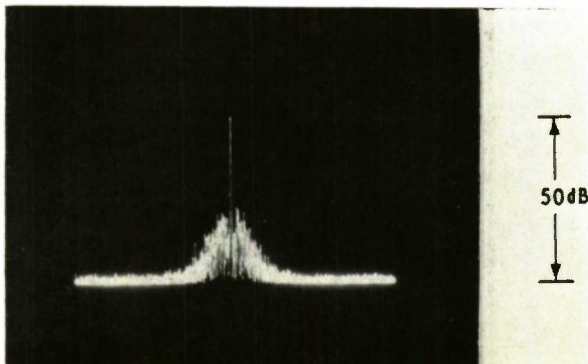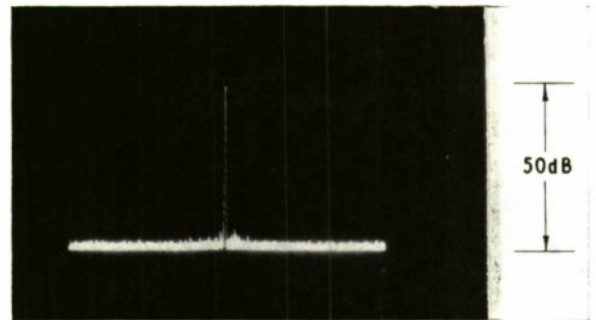
FIG. 3. Eight-octave multiplier.

Main signal in	22MHz	Amplitude	−27dB
Spurious signal in	Nil		
Main signal out	5632MHz	Amplitude	+50dB
Spurious signal out			
	Enhanced Multiplier Noise	Amplitude	+20dB

FREQUENCY
MULTIPLIER

SPECTRUM
ANALYSER

SIG GEN 1

SIG GEN 2

×8

300 — 1800MHz

50 dB
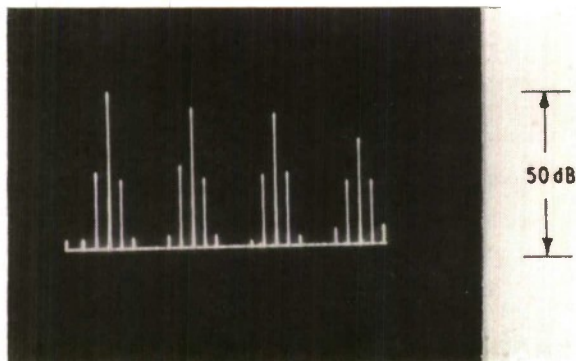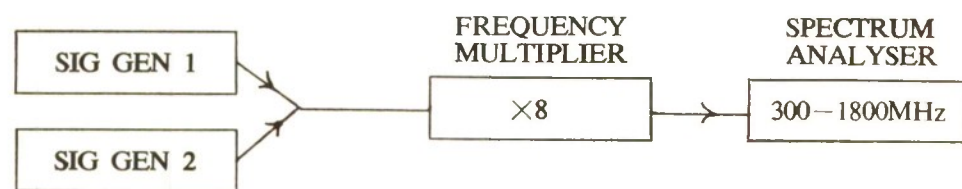
FIG. 4. Step recovery diode
multiplier.

Main signal in 400MHz.

Spurious signal in 340MHz Amplitude 25dB below main signal

4th harmonic of main signal   1600MHz   Amplitude +34dB

⎡ Spurious   signal   (accompanying   4th   harmonic) ⎤
⎢ 1600MHz ± 60MHz. Amplitude +21dB. i.e. 13dB ⎥
⎣   below main signal 4th harmonic   ⎦

and the frequency difference remains the same. Also the higher the order of harmonics selected (*i.e.* the greater the multiplication factor) the greater the number of other frequencies produced from the original input spuriae and these are separated by multiples of the original frequency differences.

Further analysis also shows that slight changes of the ratio $\dfrac{E_1}{2E_2}$ are caused by contributions from the higher even order terms, *i.e.* V_{1n}^6, V_{1n}^8, *etc.*, should these exist in the multiplier.

Experimental Results

The following experimental results were obtained using two types of frequency multiplier. The first consisted of eight separate doubler stages, the output of each stage being filtered and the second harmonic only passed to the input of the succeeding stage. The first two of the eight stages were overdriven transistor amplifiers and the remaining six were varactor stages with mixed self and external bias.

The second multiplier was a single step-recovery diode capable of a multiplication of x15. The first three harmonics plus the fundamental only are shown in Fig. 4.

Reference to Fig. 1 shows the output frequency spectrum of an eight octave (2^8) frequency multiplier when fed with two frequencies as shown. As predicted by the previous analysis the spurious signal enhancement is 48 dB, *i.e.* 6 dB per octave. Some of the other spurious frequency components are also evident.

Reference to Fig. 2 shows the frequency multiplier output spectrum with no spurious input present. The absence of output spuriae is evident.

There is, however, noise generated in the multiplier and Fig. 3 shows the multiplier output spectrum again without the spurious frequency input but with the amplitude level of the input reduced by 21 dB. The effect of this is to reduce the signal-to-noise ratio. Due to the 48 dB enhancement of the multiplier, the noise now appears as the spurious signals on the output spectrum.

Reference to Fig. 4 shows the output frequency spectrum of a step-recovery diode multiplier when fed with two frequencies as shown. Three of the main signal harmonics plus the fundamental, together with the spurious frequencies are shown. The main input frequency is 400 MHz and the input spuriae 340 MHz.

The sum and difference term frequencies are seen on either side of the main harmonic frequencies and, from inspection, these clearly show an increase relative to the main harmonic they accompany, as the harmonic order increases. Measurement of the relative amplitudes indicates an approximate 6 dB per octave enhancement.

Conclusions

In general any form of frequency multiplier poses this problem of spuriae enhancement. If the spuriae lie outside the multiplier pass-band they can be filtered out but nothing can reduces the in-band spuriae. If a multiplier output spectrum of high purity is required it is necessary to (a) start with a very low level of input spuriae, and (b) keep

the order of multiplication as low as possible.

If the multiplier consists of low harmonic stages cascaded with inter-stage filters the spuriae outside the wanted band are filtered out at each stage and therefore prevented from generating additional sum and difference terms which may appear as in-band spuriae: such a system is believed to be preferable to one in which all the filtering is carried out at the multiplier output only.

Increasing use of step-recovery diodes as frequency multipliers is being made, the advantage being the efficiency with which they produce high order harmonics, hence a high multiplication factor can be achieved in one device. The exploitation of this advantage precludes the use of inter-stage filters. Also many applications involving frequency multiplication require the multiplier to have considerable bandwidth, *i.e.* 10 - 20%, in which case, of course, very high order harmonics cannot be used with the Step Recovery Diode. If any spurious signals lie within the required bandwidth, filtering is of no avail, it then becomes necessary to resort to either (a) or (b) or both, as mentioned above.

As an example a radar system may require a transmitter ouput spectrum with spuriae at least 50 dB below the signal frequency level. If the signal frequency is to be derived from an 8 octave multiplier, *i.e.* x256, the level of the input spuriae must be $50 + (8 \times 6\,dB) = 98$ dB below the level of the main frequency.

Modern practice is to start the multiplier with as high a frequency as possible, but other precautions will become apparent in use such as the great care necessary in anti-shock mounting of the signal source particularly if this is a crystal[1].

Acknowledgements

References

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H.R.H. The Duke of Edinburgh came to A.S.W.E. on the 16th February and was shown around the laboratories and workshops by the Director Mr. D. Stewart-Watson. He was accompanied by Rear Admiral C. D. Bonham Carter an old friend of A.S.W.E. from the days when he was Director of Radio Equipment Division of Admiralty. The particular demonstrations which had been chosen for this occasion were:—

Satellite Communications by Dr. Glanville Harries. C-Band Radar Work, Anti Clutter research by Mr. J. Alvey and a very Comprehensive display of a wide range of techniques by the workshops, by Mr. K. A. G. Taylor.

After lunch His Royal Highness spoke to the gold and silver medal winners of his Award Scheme and to Mr. D. Le Feuvre who is the principal organiser of this activity at A.S.W.E. During the whole day the Duke of Edinburgh delighted the staff of A.S.W.E. who had gathered at a number of vantage points to cheer him; he often left the programmed route of the visit to talk informally to many on their work and on the contribution they were making to the Establishment's work.

PROBABILITY, JUDGMENT AND MIND

I—The Relevance of Mind to Probability and Judgment

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The explanation and discussion of Subjective Probability is a movement with practical implications for statistical theory and applications at all levels, from the most elementary classroom to the most sophisticated research. Professor L. J. Savage[1] remarks that it is becoming more and more clear that the concept of subjective probability is capable of suggesting and unifying important advances in statistical practice. He even suggests that every topic in statistics ought to be reviewed in the light of this concept.

This opinion is not shared by all statisticians. Some like to use the word probability to cover all quantitative measures of uncertainty, distinguishing the different kinds of adjectives such as " subjective ", " physical ", " rational ", " pistimetric ", and so forth. Others feel that the differences are so important, and require such emphasis at the present time, as to be best dealt with by the use of different nouns, such as " likelihood ", "acceptability", and " long-run frequency ", as well as by probability itself. There are those who maintain that the word " probability " is best reserved for the context of games of chance, or for the most precisely measurable kinds of uncertainty, suggesting that other forms of uncertainty are best referred to as " plausibility " or " credibility ".

Professor Bartlett[1] who favours the frequency theory, prefers to base his arguments on such generally accepted probabilities as those historically associated with populations and aggregates rather than subjective or " degree of belief " types of probability. Statisticians holding these views prefer to keep the two types of probability separate. Connections between the two types of probability, provided by the logistic function, have already been noted[2,3,4]. Further comment on the implication of this for statistical theory—particularly with regard to biology—will be the subject of a separate paper.

Subjectivists claim that it is unnecessary to divorce different kinds of probability, one from the other. They maintain that all should be subsumed under one general subjective theory, while admitting that other names might be more appropriate for the resulting measures. Certainly, the wide use we have made of measures from a subjective theory[2-5] appears to justify its claim for comprehensiveness: it has also emphasized the element of subjectivity in the assessment of radar performance. This subjectivity has been accentuated in two ways. Firstly, in several cases, a choice of models has been shown to exist, selection from which is influenced by utilitarian motives:

secondly, relationships, which in use are selected by personal judgment, have been put into quantized forms for comparison, in the manner suggested by subjective probability theory.

In this present paper it will be shown that personal judgments are unavoidable; that is to say, a subjectivist viewpoint will be presented. Sometimes subjective judgments involve conceptual difficulties which may present real and serious obstacles to scientific inference in general. Methods advocated by statisticians and philosophers of science to overcome these obstacles will be described and a residual amount of subjectivity, which cannot be eliminated as a source of error, will be explained.

On choice of model, Professor Savage vindicates our utilitarian approach by declaring that probabilities assigned to models are not really objective; they are expressions of opinions. In practice, they are seldom even taken seriously as realistic opinions by experienced statisticians, but are regarded as rather rough practical ways to get on with the problem until more realistic assumptions prove necessary. In short, he says, simple models do not often fully represent our opinions about the possible outcomes of an experiment. Useful though such models are, the danger of accepting them literally cannot be overemphasized.

He quotes, as an example, the counsel we receive from statistical theory to choose among the many operating characteristic functions that reflect the choice of an experiment and an analysis or the choice of an experiment alone. This choice among available operating characteristics is recognized almost universally to be a subjective matter, depending on the judgment of the person, or of each person, concerned. The theory of subjective probability shows these necessarily subjective judgments to be far less arbitrary or free than they have heretofore superficially seemed, and therein lies much of the value of this concept of subjective probability for statistics.

At the same time Professor Savage admits the concept has real and serious defects. He suggests that these can be instructively appraised by exploring the close analogy between the odds that you would offer on an event, and the price at which you would buy or sell some valuable object. Both concepts are afflicted with vagueness and temptation to dishonesty. Common sense and ingenuity, he claims, will mitigate some of the inadequacies; and he offers hope that distinct improvements will be made on such concepts some day.

The theme of this, and subsequent, papers is that subjective probability judgments are even less arbitrary or free than is generally allowed, because they are swayed by *unconscious* mental

processes; that *insight* is necessary as well as common sense and ingenuity. If we can recognize unconscious biases, or even make it more widely known that they exist, we may be able to eliminate some of the causes of vagueness and dishonesty.

When we wish to decide whether to adopt a particular course of action, our decision depends on the values to us of the possible alternative consequences. A rational decision depends also on our degrees of belief that each of the alternatives will occur. The values of the consequences and our degrees of belief that they will occur are liable to be influenced by our state of mind.

It is important to note that present values of the alternative consequences, and present degrees of belief that they will happen, are the consequences of past states of mind. These may not be remembered but, nevertheless, they influence our present state of mind and, consequently, our judgments. Unless relevant contributory effects of this kind can be appreciated and allowed for in the judgment, conceptual difficulties may arise. Difficulties of this type may be circumvented only by intellectual insight and clarity of thought, *e.g.* the " aperçu " of Goethe and Einstein's " feeling for the order lying behind the appearance ".

Appreciation of the importance of these qualities will be aided by an awareness of the nature of a belief and of the mind that produces it. These matters have a relevance to all scientific inquiry and, indeed, to everyday life. The aim of the present work is to provide a description of mind and mental activity which is complementary to abstract theories of probability and necessary for the construction of theories of scientific induction.

The question of how to apply abstract theories of probability to problems involving judgment and belief arouses much controversy among statisticians and philosophers of science. Dr. I. J. Good, a leading exponent of " subjective " probability observes that ordinary logic seems to be inadequate by itself to cope with problems involving beliefs; in addition a theory of probability is required. He offers a theory of probability which is concerned with ' those mental phenomena called *degrees of belief* '. His aim is to provide a consistent theory of probability that is mathematically simple, logically sound and adequate as a basis for scientific induction, for statistics, and for ordinary reasoning. Probability (in his theory) is the logic (rather than the psychology) of degrees of belief and of their possible modification in the light of experience.

There have been various attempts to eliminate the necessity for subjective probability judgments by employing instructions that are outside the theory adopted in Good's book[1]. These he dis-

misses as either imprecisely stated or, when they are precise, applying only to ideal circumstances, so that they can be used only in some unspecified approximate sense. Dr. Good argues that some adherents of objective techniques are now at loggerheads because in small sample work in statistics the rival objective procedures do not lead to identical results. His theory abandons the attempt to obtain unique results—it leaves a little freedom of choice to the individual. Our brief review of the psychological background of belief will show that Good's conclusion—in the last resort one must define one's concepts in terms of one's subjective experiences—is well-founded.

The conceptual aspects of research and discovery have been discussed by Professor N. R. Hanson in " Patterns of Discovery "[7]. In this, he considers differences between the ways in which two people may see the same thing and different things, the connection between seeking and knowing, the relation between facts and the language in which they can be stated; and he gives examples from history of the great obstacles to progress that conceptual difficulties can present. A contemporary example of the type of mechanism involved is to be found in a recent issue of " Nature "[8]. This is to the effect that experimental evidence has been found to support the theory of two different mechanisms by which words are perceived by the hearer. One mechanism may prevent the operation of the other to an extent depending on whether the words are pleasant, neutral or bad. The number of correct responses is found to be greatest for neutral words and least for bad words. This is consistent with certain aspects of Freudian psychology.

Differences between individuals is mentioned, also, by Professor Braithwaite in " Scientific Explanation"[9] who says that what we call the laws of nature are conceptual devices by which we organize our empirical knowledge and predict the future. He suggests that what is demanded of a " why ? " question is intellectual satisfaction of one kind or another and this can be provided, partially or completely, in different ways. What gives partial or complete intellectual satisfaction to one person may give none whatever to a person at a different stage of intellectual development.

The question of degrees of belief is also discussed by Professor Braithwaite. He takes the view that the question of the reasonableness of an inductive belief is bound up with the validity of the inductive inferences by which it has been or could be derived—thus leaving no room for the comparison of the reasonableness of different inductive beliefs. The notion of a scale of probabilities of a hypothesis with a corresponding scale

of degrees of reasonableness of belief in the hypothesis is, he believes, a philosopher's myth. The myth has arisen partly from the desire to subsume the " probability " of hypotheses under a unified theory of probability which will also include the numerically measurable probabilities of events, but also partly from a comparison between the notion of degrees of *reasonableness* of belief and the quite different notion of degrees of *belief*.

Professor Braithwaite recognizes that there is a sense to be found in the variations in tenacity with which beliefs are held which allows a form of " subjective " probability to be defined. Several of his views are characteristic of certain " mechanistic " philosophies which feature " conditioned reflexes " as a major justification of their creeds. He justifies his opinions on teleological causation by suggesting that the neurologists or the experimental and clinical psychologists may in time discover satisfactory independent evidence for cerebral traces or for a persistent unconscious. While these are perfectly legitimate opinions in our present state of knowledge, and are shared with others, as Dr. Good has remarked, if we do not accept subjective probability the opposite view is that degrees of belief can be interpreted only by the methods of experimental psychology: there is some evidence, as we shall see, that these methods are not enough.

Many of the personal aspects of belief, or judgment, are allowed for in their different ways by these three authorities. Dr. Good refers to the state of mind (M) of the person who is doing the believing (M depends on who "you" are and on the moment of believing) and specifies conditions for a consistent " body of beliefs " (β). In his theory the fundamentals of probability are classified into axioms, rules and suggestions. The mathematical theory depends only on the axioms. The rules are not purely mathematical but they are precisely stated in terms of the primitive notion of the comparison of pairs of beliefs. They enable the mathematical theory to be applied to a given body of beliefs. The " suggestions " are liable to affect your body of beliefs without directly using the theory. It does not seem to be possible to formulate the suggestions with the same precision as the axioms and rules. Non-mathematical words like "honesty" are used. The suggestions are natural modes of procedure for forming bodies of belief. There is no compulsion to accept the suggestions in order to be able to use the theory, and the list of suggestions is not exhaustive—it can be added to. Dr. Good calls the consequences of accepting the axioms, rules and suggestions the " technique of probability " and adds that the technique will not be completely defined since no complete list of suggestions is given. He adds, further, that the

trichotomy into axioms, rules and suggestions is perhaps the ideal for any scientific theory.

Professor Hanson explains conceptual clarity of language by the use of theory-loaded words. He differentiates between "cause"-words and "effect"-words. "Cause"-words are charged: they carry a conceptual pattern with them. Conceptual organization and clarity of thought may be obtained by referring events to their "context of utterance". Sometimes drastic and complete rethinking is necessary.

Professor Braithwaite suggests a search for intellectual satisfaction and offers "biotic laws" for living systems which are not necessarily irreducible to physical and chemical terms. These, he hopes, will settle the dispute between the biological "mechanists" and the biological "teleologists" and thus lead to intellectual satisfaction. He stakes his acceptance or rejection of the legitimacy of comparing reasonableness of beliefs on whether their admission to or rejection from the "rational corpus" is an all-or-none process: but freely admits there is much more to be done on this subject.

There is, however, an element in judgment which cannot be allowed for entirely in their schemes and this is responsible for the freedom of choice which, we aver, must be allowed the individual. This part of judgment is a consequence of the personal history of each individual and much of it is "unconscious". Little specific attention has been given to judgment and even less has been given (in this context) to the unconscious processes which shape our judgments. The intangible and nebulous beliefs and concepts of every individual are shaped, modified and retained by unconscious processes in the mind. We shall in this series of papers consider the ideas of various authorities on the nature of mind, its purpose, and the way it functions. Our approach will be to view these ideas through the lens of contemporary thought. This, purely by chance, is somewhat similar to the approach used by Professor Hanson in "Patterns of Discovery". In particle physics today there is an emergent conjectural picture of a physical "substratum" which corresponds to the "psychical" substratum of the unconscious portrayed by certain schools of psycho-analytical thought; therefore this approach seems particularly suitable.

In works on Statistics and the Philosophy of Science there is reference to "reasonableness" and "rationality", but in the same way that "precision" in an estimate does not ensure "accuracy" so "reasonableness" in a body of beliefs does not guarantee Truth. Professor Hanson makes the point that we cannot confidently judge ideas of today because we have no hindsight but we *can* note that conceptual "obstacles" affect the entire organization of one's data, observations, facts and subsequent theories. Professor Braithwaite remarks that theories on the same subject need not be incompatible because they are couched in different terms. They may be amenable to translation. He cites the work of those psychologists and psychiatrists who, following Freud, refer to theoretical concepts such as "unconscious wishes"; and remarks that the best of these (including Freud himself) insist that to give an explanation in terms of processes in an "unconscious" does not preclude the possibility of also giving an explanation in terms of physico-chemical processes in the brain (or, more generally, in the body).

It is natural to consider whether any "bias" may be overcome by incorporating into Good's theory of probability some combination of personal qualities such as intellectual development, education, insight, introspection, craving for intellectual satisfaction, detachment, *etc., etc.* To indicate that the holder of the body of beliefs is not only rational but has achieved sufficient "insight" or "detachment" for his technique of probability to be of value, either to himself or to science, perhaps, it might be argued, M could bear a suffix; and a "satisfactory" state of mind could be denoted by M_1. This would also have the advantage of providing some sort of linkage between M and β. How then would we allow for "flashes" of genius in otherwise unpretentious and mediocre bodies of belief? Could we overcome this by specifying a distribution of degrees of insight, or distribution of potential usefulness? In that case how could we allow for fruitfulness and productivity in an M_1 which could not be classified satisfactorily. For example, how could we categorize the bodies of belief or the states of mind of Leverrier? He raised classical mechanics to a peak by predicting the unseen Neptune as being responsible for observed aberrations in the orbit of Uranus; yet by the same argument be postulated the "planet" Vulcan to explain Mercury's precessions at perihelion, and classical mechanics met a most telling failure. In any case, these are merely theoretical devices of little practical value. In truth we cannot overcome these obstacles. We cannot allow for this individual and irreducible element of judgment.

D. V. Lindley[1] maintains that we can. He allies himself with Keynes and Jeffreys[10, 11] and disputes Savage's claim that probabilities are "personalistic", that is they are a property of the individual and not of society. Lindley agrees with Jeffreys in saying that in scientific questions they are objective. He argues that they only differ between individuals because the individuals are differently informed (cf. Hanson's "education", Braithwaite's "intellectual development", *etc.*): but with common knowledge we have common Bayesian probabilities. However, Professor Savage's argu-

ment that subjective probability refers to the opinion of a person as reflected by his real or potential behaviour retains its compelling force. We shall shortly consider Dr. Good's answers to the proposals of these " objectivists ".

Keynes and Jeffreys assume that there is a " reasonable " (degree of) belief which is independent of M. This may be called an " objective " belief but their meaning for " probability " is not quite the same as the one adopted by Dr. Good. Jeffreys' theory may be regarded more or less as a special case of Good's theory with the various possible bodies of belief replaced by a fixed objective one β^*. A similar kind of objectivity would be the consequence of complete and universally successful psycho-analysis in our proposal for an amended state of mind M_1, or in those philosophies where all learning is attributed to conditioned reflexes. Dr. Good's objections apply equally well to these situations as to Jeffreys' β^*. One of the purposes of the more general theory is to avoid the assumption that β^* exists. Even if β^* does exist it is still necessary to fall back on subjective judgment in practice.

A truly objective theory or technique which could always be applied in practice, may be impossible of attainment. Such a theory might involve an extensive β^*, or possibly a " complete " list of rules and suggestions, so that no β would be required at all. While this seems to be quite beyond our powers, there does remain the possibility of adopting extra suggestions. Just as the purpose of the theory is to introduce some measure of objectivity into our bodies of beliefs, the purpose of introducing new suggestions would be to increase this objectivity still further. It is with this ambition that the following outline of mind in terms of speculative thought in particle physics is offered, *i.e.* as an additional suggestion.

Before embarking on a description of the opinions of physiologists and psychologists on the nature of mind we shall consider a few examples of the kind of phenomena we are trying to illustrate and explain, wherein the unconscious part of the mind may influence our conscious judgment. Professor Hanson's book is profusely illustrated with examples and furnishes several which are eminently suitable for our purpose.

In " Patterns of Discovery " the meaning of the " context of utterance " is explained by a discussion of the word " Fire ". It is maintained that in the context of a blazing dynamite warehouse the word has a clear propositional force; in other contexts it has other meanings. To cite a case where it has *no* propositional force and is "neutral" Professor Hanson suggests that " Fire " written in the place reserved for St. Valentine's day and found in the blank pages of a next year's diary would suggest no action to an observer. The point we wish to make is that the conversion of the " context of utterance " into action is also dependent upon the " context of experience " of the observer. If, in the above example, the observer had a background of Freudian psychology an action might well suggest itself to him. After he had considered (a) the blankness of the page, (b) the nature of the day, and (c) the voracious, destructiveness of fire, his action could be to recognize a possible causal relationship between the sexual impulses of the author and the placing of that particular word in that particular location.

If each observer had the same background, " Fire " might have a clear propositional force (in most cases, and depending upon the context of utterance). Not so if each observer has a different background. The clarity of the proposition is apt to become blurred, or re-orientated, by the context of experience. In the majority of cases meanings are exchanged satisfactorily in languages that are " many-levelled in explanatory power ", or by " interlocking patterns of concepts ", or " Gestalts ", to quote Professor Hanson. But not even by reducing observers to automata could we *guarantee* to eliminate the chance of disagreement about the clarity or interpretation of the proposition or about its force. There would still be differences in background and structure.

Regarding the blazing dynamite warehouse, it is pointed out in " Patterns of Discovery " that part of the force of the shout " Fire " is that he who hesitates is lost. The question is asked: Who could hear and understand such an alarm and fail to run ? The point of this example is that no other words are necessary in this context to convey the clear and urgent message that to tarry in the vicinity would be dangerous. The question is rhetorical. We will seize the opportunity, however, to do in particular what we are attempting to do in general; that is to continue further with Professor Hanson's attack on conceptual obstacles to scientific progression by elaborating specifically to include the unconscious. To this end a list of people could be furnished in answer to the rhetorical question. Many of these would be psychologically unbalanced, but not necessarily all. (Those who were unbalanced might nevertheless, be in a position to make scientific, or some other, judgments which could appear " reasonable ".) There is, for example, the type of individual, commonly met in everyday life, who might fail to react immediately because his temperamental make-up (influenced by past states of mind) prevents him from immediately accepting any statement—even an imperative one like this—without an immediate but opposite reaction. In this case it might cost him dear. Alternatively, another person, realizing

in full the implications of the cry, might elect to head towards the fire in an attempt to rescue or salvage somebody or something of great value or importance to him—this action could be the consequence of a variety of *misconceptions*. We might think of the case, similar to that of the two mechanisms for perceiving words, of professional drivers and professional sportsmen who undergo a self-imposed restriction of awareness (which is accompanied by a great increase of concentration) while committed to a particular course of action. Their reaction to the cry in this context, clearly, would depend upon their state of mind.

The fusion of the context of utterance with contexts of experience to result in a range of possible actions is the basic philosophy of subjective probability. It is the reason why conceptual clarity does not guarantee conceptual " accuracy ".

Another example chosen by Professor Hanson concerns his winding his clock and then going to sleep. There is, he professes, no causal relationship between the events, although no two events occur with more monotonous regularity. One could predict his going to sleep from watching him wind the clock, or retrodict his having wound the clock from observing him asleep: but no conceptual issue would be raised by the failure of such a prediction or retrodiction.

However, this is conceptual. He does not conceive any causal connection; but for many people (including himself) there might be one. There must be a great many householders who at some time, have lain awake at night, unable to sleep, wondering if they had bolted the door, or checked the windows, or put the cat out, or wound the clock. Conversely, a great many people must have felt a glow of satisfaction and thought to themselves " Good, that's done " before relaxing into immediate sleep. We could look for a causal relationship by observing his reaction nightly after winding the clock. Perhaps, to expedite matters, we could contrive to make him forget to wind it one night and then look for restiveness when he settles for slumber. Conceptual issues would be raised by the outcome. In Professor Hanson's own words " Only by seeing what sorts of things make a man fail to explain a phenomenon or fail to make a certain observation can we appreciate what is at work when he succeeds at these things ".

These examples illustrate how conceptual issues involve the unconscious. To obtain maximum conceptual clarity recognition of the unconscious should be made. To quote again from Professor Hanson's book, " It is too easy to say that scientists may make the same observations but use them differently. This does not explain controversy in research science. Were there no sense in which they were different observations they could not be used differently. This may perplex some: that researchers sometimes do not appreciate data in the same way is a serious matter . . . It is important to realize that sorting out differences about data, evidence, observation, may require more than simply gesturing at observable objects. It may require a comprehensive reappraisal of one's subject matter. This may be difficult, but it should not obscure the fact that nothing less than this may do ".

In subsequent papers we examine theories of the unconscious. The theories are based on scientific observation and logical thought by some of the greatest men of science the world has known. They are justified by psychological and psychoanalytical success. We view the theories in the light of speculative thought from eminent physicists and philosophers on the future of physics. If we conduct our examination with due regard for unemotional thought and consistency we begin to appreciate Dr. Good's observation that all probabilities seem to be to some extent metaphysical.

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STABILITY AND CONTROL OF SUBMARINES

Parts I-IV

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Introduction

Although an enormous amount of effort has gone into the development of the modern submarine, knowledge of the theoretical aspects of the stability and control of these multi-million pound vehicles is limited to very few people. Anyone conversant with the study of aircraft stability and control would, however, be immediately aware that the techniques adopted in the study of submarines are those that have been in use for many years in the field of aviation. There are, of course, particular problems peculiar to each application, but in the initial development of the equations of motion the only difference between the submarine and the aircraft is the surrounding medium, thus terms that are in one case negligible are not in the other.

The following contribution is an introduction to the theory of the stability and control of the submerged submarine, dealing mainly with the initial application to underwater vehicles of the techniques developed in the study of aircraft. Part I is a brief history of the development of the submarine to its present day form, and Part II a general discussion of the meaning of stability and control. The equations of motion of a rigid body moving with six degrees of freedom are developed in Part III, although not rigorously since this theory has been dealt with extensively elsewhere. Parts IV and V deal with the motion of the submarine in more detail, in the vertical and horizontal planes respectively. Some attempts at the derivation of the hydrodynamic forces on a submarine are described in Part VI, and the now widely used experimental techniques are described in Part VII. Up to this point it is assumed that the motion of a submarine can be adequately described by the simplified equations of motion, this approach is extended in Part VIII where non-linear characteristics are considered. A number of general topics are discussed in Part IX including automatic control and display systems. Some possible means of checking theory and experiment by analysis of full-scale trials are introduced in Part X, before a brief summary in Part XI.

I feel there is a need for a wider dissemination of this information and it should be of value to those who may find themselves working in this field. Hitherto there has been no publication that brings together all the aspects of submarine stability and control, although the paper by Arentzen and Mandel[1] entitled "Naval architectural aspects of submarine design" contains a wealth of information with particular reference to American submarines.

(Parts V - VII will be published in July, Parts VIII - XI in September issues—Ed.)

PART I—DEVELOPMENT OF THE
SUBMARINE

Although the pages which follow are concerned with the mathematical theories of the stability and control of submarines, it is of some interest to consider very briefly the history of the development of the submarine.

Historical records indicate that from the earliest times man has been fully aware of the advantages to be gained by being able to remain under water for long periods of time. Xerxes employed divers to recover treasure from wrecked Persian ships, Thucydides refers to the use of divers against the harbour defences of Syracuse in 414 B.C., and Alexander the Great used men in a similar rôle at the siege of Tyre in 333 B.C. Sorties such as these were undertaken by men without artificial aids, and it was comparatively recent times before it was found possible to supply the man under-water with the air he needs to survive. Designs for diving suits began to appear in the 15th century, and as one might expect Leonardo da Vinci was the originator of many designs. The modern diving equipment has developed from these early beginnings.

Descriptions of diving bells appear in the literature of the 16th and 17th centuries, and a design by Edmond Halley (of comet fame) in 1690 was probably the forerunner of modern equipment. It was first demonstrated by use of the diving bell that men could work under water in suitably designed vessels, and that air could be supplied to them. Following this development inventors turned to the possibility of submerged ships capable of operation remote from any surface connection.

Cornelius Drebbel has the honour of being the constructor of one of the first submarines, his boat was on trial in the Thames during the reign of James I. Robert Boyle (known for the law bearing his name) refers to the trials in his book *New Experiments, Physico-Mechanicall* published in 1660. Boyle thought that Drebbel's major discovery was " the composition of a liquid that would speedily restore to the troubled air such a proportion of vital parts as would make it again for a good while fit for respiration ". The composition of this liquid has never been revealed. A whole chapter of *Mathematicall Magick* by Bishop Wilkins published in 1648 was devoted to " the possibility of framing an Ark for Submarine Navigation ". Wilkins considered submarines as a practicable proposition despite the difficulties, and recounts their advantages in security from pirates, naval warfare and philosophical experiments.

The greatest success in these early experiments was achieved in 1775 by a gentleman named Bushnell from Connecticut. His submarine was designed for naval warfare, was screw-driven, and could remain submerged for about half an hour. In 1800 another American, Robert Fulton, built a vessel in which he dived to a depth of 25 ft and stayed manoeuvring at that depth for four hours. His most successful trials were carried out in France, but neither the French, British nor American governments were prepared to finance further developments, even though he demonstrated the value of submarines in warfare by blowing up a ship in Brest harbour. Yet another American is noteworthy for his method of depth control. This is Delany of Chicago who in 1859 used two tanks in a vessel, one filled with compressed air, and the other openable to sea water.

The first naval action involving submarines was undertaken in 1863 by the Confederates against a blockading Federal ship. The submarine was propelled at about four knots, by eight men driving a screw. When in motion, moveable surfaces (hydroplanes) were used to control the vessel in depth. Vessels built to this design were named *David*, and unfortunately they failed on initial trials taking their crews to their death. However at the fourth attempt a submarine succeeded in breaking out of Charleston harbour and sinking the *Housatonic*. This time the submarine was carried down by the sinking ship. Although this encounter was not altogether successful it undoubtedly indicated the potential of the submarine.

Further development followed, and it was probably the French that saw the emergence of the submarine as a serious proposition in naval warfare. The *Goubet* (named after her designer) completed in 1885 was 16 ft 5 in. in length and driven by electricity. Tanks which filled with water were used to submerge, and a pump was carried to pump the water out. A " fail-safe " weight which could be released in an emergency was carried outside the vessel. A much larger vessel, the *Gymnote*, was constructed in 1888. She was 56 ft 5 in. long, and had a radius of action of 32 miles at eight knots. Eleven of these vessels were completed.

The year 1898 saw the completion by the Holland Torpedo Boat Company in America of the submarine named *Holland*. This vessel incorporated virtually all the features found in modern submarines, and recent studies have shown that many of them were close to the optimum for

underwater performance. Five *Holland* boats were ordered by the British Admiralty from Vickers Sons and Maxim in 1901. These ships were 63 ft 4 in. long with a beam of 11 ft 9 in., displacing submerged some 120 tons. They were driven on the surface by a four cylinder petrol engine at about 12 knots; electric motors took over when submerged and eight knots could be achieved. Hydroplanes and a rudder were fitted for control, and five torpedoes were carried capable of being discharged through a tube in the bow.

Many more and larger submarines were built in the succeeding years, and by 1914 the Royal Navy had 96 submarines. However, the time a submarine could spend submerged was still very short, and the vessels were still designed largely for surface operation. The first world war ensured that above all the fighting qualities of submarines were developed, although a 1,600 ton vessel carrying a 12 in. gun was not particularly successful. Large boats were also developed by the Germans, and their cruiser-type submarines appeared towards the end of World War I. These German vessels were 302 ft long displacing 2,500 tons submerged and were capable of 15·8 knots on the surface, but only 7·7 knots submerged. Four V-boats of the large cruiser-type were also constructed in the U.S.A. These vessels were 371 ft long and had quite good surface characteristics, but high resistance submerged, and inadequate electrical power resulted in poor underwater performance.

Between the two world wars submarine construction continued to advance, and by 1939 development appeared to have finalized on two particular types. These were vessels of 500 - 700 tons surface displacement with four to six torpedo tubes, and larger boats of 1,000 - 1,500 tons surface displacement with six to eight tubes. Emphasis was still on surface performance and most ships carried a four-inch gun. During the Second World War the Germans developed what was probably the greatest submarine fleet ever to be seen. The U-1 was launched in 1935 and this was followed by the allocation of numbers up to U-6351, although some were projected designs which were not built.

One of the more interesting developments considered by the Germans was a variation of the Type III which carried two small motor torpedo boats in a hangar on the deck. These could be floated out with the submarine partially submerged. There were many other intriguing developments, but the most important for the purposes of this brief survey were those that were aimed at making the submarine independent of surface operations. By 1943 all German submarines were fitted with the schnorkel, a tube which carried an inlet and exhaust to the diesel engines, and it did allow the submarine to charge its batteries whilst still submerged, although, of course, the end of the tube had to be above the surface. Complete independence of the surface was brought within the realms of practicability by use of the Walter turbine. As early as 1940 an experimental submarine, V80, had undergone trials, although not too successfully, with this installation. The Walter system depends upon the decomposition of hydrogen peroxide producing thermal energy to drive a turbine. It is quite independent of the external air, but great difficulties were encountered in the manufacture and storage of the hydrogen peroxide. The U-791 was the first naval boat to be fitted with the Walter system, but it was the Type XVII that really marked a significant advance in submarine development, the hull form being designed for continuous submerged operation.

German submarine development was forced along by the increasingly severe anti-submarine warfare mounted by the Allies. Fortunately for the Americans the Japanese were not able to mount such a concentrated attack, and although the cruiser type vessel developed in the U.S.A. had poor submerged characteristics, they were able to escape without serious losses. At the end of World War II the German designs passed into American hands and submarine development continued on the lines of the Type XXI. The Type XXI was an ocean going submarine using diesel/electric propulsion and only capable of extended submerged operation by use of the schnorkel. The continued development of this type of vessel indicated that difficulties with the Walter turbine had not been overcome. The *Tang* class built in the U.S.A. were very similar to the Type XXI.

The development of the nuclear power plant brought about a minor revolution in submarine design, and the first nuclear powered submarine was the U.S.S. *Nautilus*. The *Nautilus* was developed specifically to test the pressurized water nuclear power plant at sea, and although many new ideas were built into her structure, her hull form was not unlike the conventionally powered submarine of the time. However, while development of the *Nautilus* was proceeding a submarine designed to investigate a new hull form was being built. This was the U.S.S. *Albacore* which was conventionally powered but had a body of revolutionary hull form (commonly whale or dolphin shape) with a single propeller. The purpose of the *Albacore* was to demonstrate the big improvements that could be made in submerged performance, if the design was undertaken with this aim in view. Both *Nautilus* and *Albacore* were highly successful. The one demonstrated that by using nuclear power

a submarine could remain submerged almost indefinitely, the other showed that by suitable design greater manoeuvrability and higher underwater speeds could be achieved. The outcome was naturally to combine these desirable aspects into one submarine, and the result was the U.S.S. *Skipjack*.

British submarine design proceeded on similar lines to the American development immediately following the Second World War. The 'O' class of submarines are probably the most advanced conventionally powered vessels. Financial considerations undoubtedly restricted nuclear powered development in this country, and there was no progress beyond the paper stage. However, the great success achieved by the Americans did lead ultimately to the construction in Britain of H.M. S/M. *Dreadnought*. The design of this submarine relied heavily on American experience, and indeed much of the equipment, including the reactor, was American manufacture. Since then British development of submarines has proceeded along independent lines, and H.M. S/M. *Valiant* and future ships incorporate practically all British equipment.

The development of submarines for different rôles has again been largely an American preserve, although there has obviously been similar development in the U.S.S.R. The most important development has been the vessel for carrying *Polaris* missiles, and these are the submarines which form the backbone of the defences of the western world. These boats are effectively of the *Skipjack* type with an additional cylindrical section amidships which houses the 16 missiles. Britain has again benefited from American experience and has built *Polaris* submarines.

This brief introductory survey is by no means a complete history of the submarine; it has been included to indicate how the present-day vessels have evolved. At the time

of writing, construction is limited to the two types of submarine, the hunter-killer and the missile carrying vessels, and irrespective of their operational rôles their design is basically similar. The boats are nuclear powered, and the hulls are designed for optimum underwater performance, being very nearly bodies of revolution about the longitudinal axis. Propulsion is by a single propeller at the rear of the vessel, and control surfaces for manoeuvring the submarine are mainly at the stern, and are generally of cruciform arrangement. The rudders are above and below the hull just forward of the propeller, and the hydroplanes are at either side of the hull at much the same position. The rudders are usually all-moveable, but the stern hydroplanes which are moveable are often part of a split combination, the stabilizers being fixed portions just ahead of the hydroplanes. Submarines still carry a bridge fin (or sail) on the upper surface of the hull. This appendage is not really necessary for underwater performance, but is necessary for conning the vessel when on the surface. (It also houses the periscope and does ensure that the main hull of the submarine is not so near the surface when operating at periscope depth). Forward hydroplanes, usually all moveable, are also carried, and here is one marked difference between the present versions of British and American vessels. The American submarines have the forward hydroplanes on the bridge fin, whereas the R.N. ships have them on the hull forward of the bridge fin.

The submarine of to-day is thus designed primarily for operation below the surface, although it must still enter and leave harbour on the surface and must not be unseaworthy when in this condition. However it is the vastly superior manoeuvrability and the greater underwater speeds that have raised a number of control problems, and it is the theoretical study of submerged performance with which the remainder of this note is concerned.

PART II—GENERAL DISCUSSION

Nomenclature

Throughout this contribution the notation is defined as it arises; some of it is peculiar to particular chapters, and is not included in this general list. However it is important that anyone studying stability and control should be conversant with the following nomenclature.

System of Axes

A right-angled system of axes fixed in the submarine and moving with the vessel. Centre of gravity O, axis Ox forward, Oy to starboard, Oz downwards.

U, V, W velocity components along the x y, z axes respectively.

U_o, V_o, W_o initial values of the velocity components.

u, v, w small disturbance values of the velocity components.

p, q, r angular velocity components about the x, y, z axes respectively.

ϕ, θ ψ angular displacements of the axis system with respect to its initial position, *viz.* angles of roll, pitch, yaw respectively.

X, Y, Z components of force along x, y, z axes.

K, M, N moments of force about x, y, z axes.

The subscripts h, g applied to X, Y, Z, K, M, N refer to the hydrodynamic and gravitational forces respectively.

X(t), Y(τ), *etc.* components of force (or moment) dependent upon time t, or τ non-dimensional time

The Derivative Notation

X_u, $Y_{\dot{v}}$, Z_w, *etc.* where velocity or acceleration components appear as subscripts to the force and moment components, these terms are the so-called hydrodynamic or stability derivatives, and

$$X_u = \frac{\partial X}{\partial u}, \quad Y_{\dot{v}} = \frac{\partial Y}{\partial \dot{v}}, \text{ } etc.$$

Body Characteristics

m   mass of the submarine.

I_x, I_y, I_z moments of inertia of body about x, y, z axes.

I_{yz}, I_{zx}, I_{xy} products of inertia.

L   length of submarine.

$\overline{BG}$ distance between centre of buoyancy and centre of gravity.

$$\gamma = \frac{g\overline{BG}}{U^2}$$

δ representative hydroplane angle.

δr rudder angle.

ρ density of sea-water (approximately = 2).

A comprehensive nomenclature in fairly general application is given in Technical and Research Bulletin No. 1 - 5 issued by S.N.A.M.E. in 1950.

Considering the fact that the navies of the world have used submarines for a number of years, it is surprising that the detailed investigation of stability and control has only been undertaken in recent years. Of course, until the advent of nuclear power, submarines spent a greater time on the surface than submerged, and when submerged the hull form did not allow much manoeuvrability. Underwater speeds were quite small, and the design and manufacture of pressure hulls restricted the depths to which the submarine could operate without fear of collapse. The rapid development in design and manufacturing techniques over the past 20 years quite suddenly increased the capability and three-dimensional operating range of the submarine. The study of stability and control thus became a necessity, stability being of importance from a safety point

of view, and control being important from a desire to make the most of the possibilities provided by the new designs.

It was perhaps fortunate for those embarking on the study of the stability and control of submarines that they could make use of the work done on similar problems in connection with airships and aircraft. In fact the methods adopted in the study of submarine problems rely heavily on, and are almost identical to those still used by aerodynamicists. The technique was first described by G. H. Bryan in 1911[2], and he pioneered the adaptation of the principles of theoretical mechanics to the motion of an aircraft. The theoretical methods will be introduced in later chapters. The remainder of this chapter discusses the problems in rather more general terms.

Stability defines the ability of a submarine to return by itself, after a disturbance, to an equilibrium state of motion, without any corrective action, such as the use of control surfaces, being taken. Control could be defined as the capability of the vessel to carry out specific manoeuvres. Considering initially the vertical plane of motion, despite improved design and manufacture submarines are still restricted to an operating depth that is probably no more than perhaps just a few ship lengths. This is a relatively thin layer of water, and at high underwater speeds the problems of stability and control are obviously of vital importance. Furthermore, stability and control problems must always be considered simultaneously because the solution of them is of necessity a compromise. It is not possible to have excessive stability, otherwise the control surfaces would have to be excessively large to undertake even the smallest manoeuvres.

In fact, it is not essential for an uncontrolled submarine to be stable, the hydroplanes and rudder are able to overcome a certain amount of instability, and thus ensure that the vessel is controllable. For instance, in an uncontrolled unstable vessel the deviation due to a disturbance builds up exponentially, the control surfaces have a fixed maximum deflection, and thus the effect of any instability must not be so large that it cannot be " caught up " by the effect of the opposing force produced by the control surface, allowing for the fact that there is a delay in the initiation and build up of this opposing force. However it is obvious that a vessel which is unstable in an uncontrolled state is going to require much more use of its controls than a ship which is stable when uncontrolled. Thus from the point of view of safety and ease of handling it is to be expected that some degree of uncontrolled stability has been found desirable. Nevertheless, as has already been stated, this stability must not be too great other-

wise the submarine will not easily be deflected from its given path by accident or design.

Controllability of the submarine with its control system active is thus a necessary condition, but stability of the uncontrolled vessel is not. In the consideration of the uncontrolled submarine the two different states or conditions of stability are described by the use of aircraft terminology, namely " stick-fixed " and " stick-free " stability. As the terms imply, stick-fixed stability refers to the case where the control surfaces are fixed, and stick-free stability describes the situation where the control surfaces are free to move under the action of the mechanical and hydrodynamic forces acting upon them. Thus for any required motion of the submarine the control surface displacements (or stick movements) that have to be made are related to stick-fixed stability, whereas the forces necessary to move the control surfaces (or stick forces) are related to stick-free stability. For this reason aircraft pilots, who in the past were directly connected to the control surfaces, were more interested in stick-free stability. Even with the introduction of power operated controls the pilot has been given " artificial feel ", and he is still more interested in the forces he has to apply rather than the stick movements required. In submarines the operator has simply manipulated the position of valves controlling hydraulic systems, and the control surfaces do not, in fact, become free at any time in normal operational conditions, even if the operator takes his hands off. Hence stick-fixed stability has been the main consideration in submarine studies, and this is perhaps fortunate since stick-free stability is a more complex investigation requiring knowledge of the dynamics of the control system.

Even within the confines of stick-fixed stability there are different grades of stability. The submarine must first of all possess static or metacentric stability, so that it is able to remain upright when at rest. Furthermore the submarine is a special case in that it should be statically stable on the surface, when completely submerged, and if possible in all conditions of partial submergence. This problem of metacentric stability is largely one for the naval architect who is responsible for the weight distribution in his design. For the purposes of this note only the completely submerged vessel will be considered, and in this condition metacentric stability requires that the centre of gravity of the submarine is vertically below the centre of buoyancy.

The satisfaction of this requirement ensures that the submarine is stable when at rest since any disturbing force in pitch or roll will be opposed by a metacentric restoring moment. This is illustrated in Fig. 1 where B is the centre of buoyancy, and G is the centre of gravity.

For the neutrally buoyant submarine the restoring moment is obviously a couple, and for a roll angle ϕ the restoring moment is mg BG sin ϕ, and similarly for a pitch angle θ the restoring moment is mg BG sin θ where m is the mass of the submarine. There is no metacentric stability in yaw.

Metacentric stability is essential when the submarine is at rest, also when the vessel is in motion at very low speeds. However as speeds increase the metacentric restoring moment which is speed independent is overshadowed by the hydrodynamic forces on the vessel which increase in proportion with the square of the velocity. The distance of the centre of buoyancy above the centre of gravity is known as the metacentric height, and it is very difficult to ascribe a criterion or to establish limits for a desirable metacentric height; neither is it a distance that is amenable to measurement. A large metacentric height would perhaps improve stability, and reduce the roll angles experienced by a submarine in a turn, although manoeuvring would be difficult at low speeds due to the large restoring moment, and the response to a disturbance in roll might be uncomfortably fast. A compromise must be achieved by considering the operational requirements; according to Reference[1] many submarines have operated with a metacentric height as low as 3 in.

Considering now the submarine in motion, its response to a disturbance will take different forms dependent upon its degree of stability. If an uncontrolled stable submarine travelling in a straight and level path is subject to a disturbance in yaw, and its final path is straight, the vessel is said to possess straight line stability. The final path will not have the direction of the initial path because there is no restoring moment. However, if the same stable submarine is subject to a disturbance in pitch the final path will not only be straight, but also level because of the metacentric restoring moment. This is termed directional stability, and is a degree of stability that cannot be achieved by an uncontrolled submarine in yaw. The final path of the stable submarine disturbed in pitch was straight and level but at a different depth from the initial path, if the final path had been at the same depth as the initial path the submarine would have had positional motion stability. It is, of course, not possible for the uncontrolled submarine to have positional motion stability; following a disturbance the vessel can only be made to return to its initial path by using control surfaces.

It is thus essential that all submarines have metacentric stability, and also that when using hydroplanes and rudder they have positional
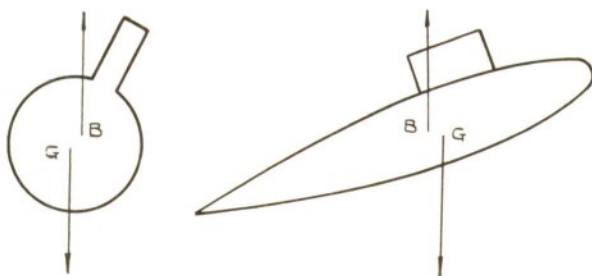
FIG. 1. Illustration of metacentric restoring moment in roll and pitch.

and at the same time provide the manoeuvrability demanded by operational requirements. Thus the forces generated by the control surfaces must be sufficient to counteract any instability, and also large enough to overcome any stability possessed by the uncontrolled submarine. There are, however, limits to the size of the control surfaces, for instance; large surfaces would require excessively large power supplies to move them, and also to simplify docking procedures it is desirable that the tips of the hydroplanes and rudder do not extend beyond the maximum beam and depth of the submarine. Consequently, there are limits of stability or instability that can be tolerated, although these limits are not easy to ascertain.

Criteria of stability and control will be discussed in later pages, sufficient has been said in this chapter to appreciate that some compromise is involved. In the following chapters the mathematical and experimental techniques used in the study of the stability and control of submarines will be dealt with in some detail.

motion stability. The uncontrolled submarine does not necessarily need to have straight line stability, although this may be desirable. If the vessel has straight line stability in the vertical plane, because it also has metacentric stability it will perforce have directional stability. The control surfaces must obviously have sufficient power to give the controlled submarine positional motion stability,

PART III—THE EQUATIONS OF MOTION OF THE SUBMERGED SUBMARINE

Introduction

The first requirement in the theoretical investigation of stability and control is the derivation of the equations of motion of the submarine. The method adopted is one that can be found in many treatises on classical dynamics, where the general dynamical equations for a rigid body are obtained. Because the method is well-known, treatment in this instance is not described in minute detail, nor is it entirely rigorous. The technique is used whereby small perturbations about the equilibrium position are considered, the resulting equations are then simplified, linearized and separated into lateral and longitudinal modes.

General Dynamical Equations for a Rigid Submarine with Respect to Moving Axes

Consider a set of rectangular axes with origin O at the centre of gravity of the submarine. As shown in Fig. 2 the axes are fixed in the body moving with it, Ox and Oz are in the plane of symmetry (Oz downwards) and Oy is to star-

board. U, V, W are the velocity components parallel to Ox, Oy, Oz repecively, and p, q, r are the angular velocity componentts about Ox, Oy, Oz respectively. Thus p is the rate of roll of the submarine, q is the rate of pitch and r is the rate of yaw.
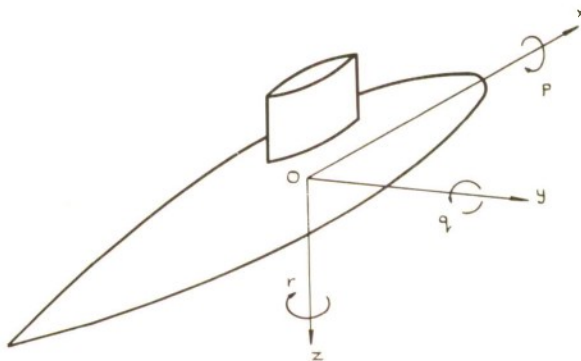

FIG. 2. Orientation of the moving axes.

If the submarine is of mass $\underline{m}$ and is acted on by forces X, Y, Z along Ox, Oy, Oz respectively, then by the theory of moving axes[3]:—

$$m(\dot{U}-rV+qW)=X$$
$$m(\dot{V}-pW+rU)=Y$$
$$m(\dot{W}-qU+pV)=Z$$
$$\ldots (1)$$

If K, M, N are the moments of the external forces about Ox, Oy, Oz respectively and I_x, I_y, I_z denote the moments of inertia about Ox, Oy, Oz then:—

$$I_x=\Sigma\ (y^2 + z^2)\delta m$$
$$I_y=\Sigma\ (z^2 + x^2)\delta m$$
$$I_z=\Sigma\ (x^2 + y^2)\delta m$$

and the products of inertia are given by:—

$$I_{yz}=\Sigma yz\ \delta m$$
$$I_{zx}=\Sigma zx\ \delta m$$
$$I_{xy}=\Sigma xy\ \delta m$$

Again by the theory of moving axes:—

$$I_x\dot{p} - (I_y-I_z)qr+I_{yz}(r^2-q^2)-I_{zx}(pq+r)$$
$$+I_{xy}(pr-\dot{q})=K$$
$$I_y\dot{q} - (I_z-I_x)rp+I_{zx}(p^2-r^2)-I_{xy}(qr+\dot{p})$$
$$+I_{yz}(qp-\dot{r})=M$$
$$I_z\dot{r} - (I_x-I_r)pq+I_{xy}(q^2-p^2)-I_{yz}(rp+q)$$
$$+I_{zx}(rq-\dot{p})=N$$
$$\ldots (2)$$

Equations of Motion for Small Disturbances

Equations (1) and (2) could be solved by modern computing techniques, provided, of course, that the basic data applicable to a particular submarine were known. In particular an adequate and realistic representation of the forces and moments X, Y, Z, K, M, N is required, and, as will be seen, this is the crux of the problem. The most convenient approach to the solution of equations of the type of (1) and (2) has been found to be their linearization by the small perturbation technique.

Consider small disturbances from a steady rectilinear motion with no roll, sideslip or yaw in the steady state. Ox and Oz lie in the vertical plane, and the submarine is moving forwards with uniform velocity and with no angular rotation. Let U_o and W_o be the velocity components of the centre of gravity, and since there is no sideslip $V_o=O$. Let $U_o + u$, v, $W_o + w$ be the velocity components of the centre of gravity in disturbed

motion, and p, q, r be the disturbed angular velocity components about Ox, Oy, Oz. Assume that, in accordance with the usual small perturbation theory, u, v, w, p, q, r are small quantities of first order compared with U_o, and neglect terms of second degree and higher order.

The external forces and moments can be classified as hydrodynamic forces and moments (X_h, Y_h, . . . *etc.*), and gravitational and buoyancy forces and moments (X_g, Y_g, *etc.* . . .). There is no moment due to gravity or buoyancy about the yawing axis and thus $N_g=O$.

Incorporating these assumptions equations (1) and (2) reduce to:—

$$m(\dot{u}+qW_o)=X_h+X_g$$
$$m(\dot{v}-pW_o+rU_o)=Y_h+Y_g$$
$$m(\dot{w}-qU_o)=Z_h+Z_g$$
$$\ldots (3)$$

$$I_xp-I_{zx}r=K_h+K_g$$
$$I_y\dot{q}=M_h+M_g$$
$$-I_{zx}p+I_z\dot{r}=N_h$$
$$\ldots (4)$$

A further assumption being that since the submarine is symmetrical about the Oxz plane the products of inertia I_{yz} and I_{xy} are zero.

In the above analysis the axis Ox was not fixed in any specific direction; in fact there are two systems of axes in common use. In one system the undisturbed direction of Ox is taken to coincide with the undisturbed direction of motion of the submarine, these axes are often referred to as stability or wind axes. Alternatively the axes are chosen to be the principal axes of inertia of the submarine. Either of these systems leads to some simplification in the equations of motion, but in general wind axes are more commonly used in stability and control investigations. Using wind axes in equations (3) and (4) $W_o=0$ and $U_o=U$ the initial velocity of the submarine.

Representation of the External Forces on a Submarine

Once more equations of the type (3) and (4) could readily be solved, provided the right-hand sides could be specified. There is no great difficulty in deriving mathematical relations to represent the gravitational and buoyancy terms (X_g, Y_g *etc.* . . .), the problem is to find an adequate representation of the hydrodynamic forces and moments (X_h, Y_h, *etc.* . . .).

Consideration is given at this stage only to the case of a submarine deeply submerged in water

everywhere at rest except insofar as motions are induced in it by the motion of the submarine. Obviously the flow of water through the propeller considerably affects the flow over the rearward half of the submarine, for present purposes these effects are included in the hydrodynamic terms X_h, Y_h *etc.*

It is fairly obvious that the forces and moments induced on a submarine by its own motion depend to some extent on the past history of the motion, since this has determined the wake formation which in turn has influenced the flow over the hull. However the approach on these lines to the determination of the hydrodynamic forces and moments leads to problems of great complexity. Consequently it has been assumed that the forces and moments do not depend on the past history of the motion, but that they depend only on the instantaneous values of the velocities and accelerations. Duncan[4] attempted to justify the applicability of this assumption with respect to aircraft, and this exercise could be repeated for submarines on exactly similar lines. This assumption is now widely accepted in aircraft and submarine studies.

Independence of Longitudinal and Lateral Modes

Intuitively one would expect that due to the symmetry of a submarine about the plane Oyz, motion in the longitudinal plane would be unlikely to produce any lateral motion. In fact this is quite a reasonable assumption. It is not so reasonable to assume that motion in the lateral plane does not induce motion in the longitudinal plane; it is well-known that submarines in turn induce quite large cross-coupled effects in the vertical plane. However, it has been argued that since a disturbance in v, p or r in the lateral motion produces in the longitudinal plane the same effect whatever the sign of v, p or r, then the coupling must not be of first order. Hence in an investigation which is considering deviations so small that their squares can be neglected, it is reasonable to assume independence of the longitudinal and lateral modes.

This assumption is probably the most unrealistic that has had to be made so far, and this aspect will have to be re-investigated as the studies proceed.

Longitudinal Symmetric Motion

Using wind axes and assuming the independence of longitudinal and lateral motion, the equations (3) and (4) provide the equations of longitudinal symmetric motion for small disturbances:—

$$m\dot{u} = X_h + X_g$$
$$m(\dot{w} - qU) = Z_h + Z_g$$
$$I_y\dot{q} = M_h + M_g$$

$$\ldots (5)$$

A submarine is usually operated in a condition of neutral buoyancy, and is balanced so that it is in level trim when at rest.

Thus $X_g = Z_g = O$; $M_g = -mg\,\overline{BG}\sin\theta$

Where $\overline{BG}$ is the metacentric height, the distance between the centre of buoyancy and the centre of gravity, and θ is the inclination of the x-axis with respect to its initial condition, and $\dot{\theta} = q$.

Using now the assumption that the hydrodynamic forces and moments depend on the instantaneous values of the velocity and acceleration components:—

$$X_h = \frac{u\partial X}{\partial u} + \frac{w\partial X}{\partial w} + \frac{q\partial X}{\partial q} + \frac{\dot{u}\partial X}{\partial \dot{u}} + \frac{\dot{w}\partial X}{\partial \dot{w}} + \frac{\dot{q}\partial X}{\partial \dot{q}} + X(t)$$

or in the notation introduced by Bryan[2]:—

$$X_h = uX_u + wX_w + qX_q + \dot{u}X_{\dot{u}} + \dot{w}X_{\dot{w}} + \dot{q}X_{\dot{q}} + X(t)$$

and similarly for Z_h and M_h

Thus equations (5) become:—

$$m\dot{u} = uX_u + wX_w + qX_q + \dot{u}X_{\dot{u}} + \dot{w}X_{\dot{w}} + \dot{q}X_{\dot{q}} + X(t)$$
$$m(\dot{w} - qU) = uZ_u + wZ_w + qZ_q + \dot{u}Z_{\dot{u}} + \dot{w}Z_{\dot{w}} + \dot{q}Z_{\dot{q}} + Z(t)$$
$$I_y q = uM_u + wM_w + qM_q + \dot{u}M_{\dot{u}} + \dot{w}M_{\dot{w}} + \dot{q}M_{\dot{q}} + M(t) - mg\,\overline{BG}\,\theta$$

$$\ldots (6)$$

Where X_u, X_w *etc.* are the hydrodynamic derivatives, $X(t)$, $Z(t)$ and $M(t)$ are the contributions to the hydrodynamic forces and moments which are a result of some externally applied disturbance. The externally applied disturbances are time dependent, and in many cases will be due to control surface deflections; they could also be disturbances due to waves, changes in ballast, or power.

If now it is assumed that the submarine is of slender form, and symmetrical about both vertical and horizontal planes, it can be shown that:—

$$X_{\dot{w}} = X_{\dot{q}} = Z_{\dot{u}} = M_{\dot{u}} = 0$$

It is also convenient from the point of view of simplification to assume that a change in forward speed produces instantaneous changes in drag and

thrust that are exactly compensating. Thus it is assumed that the speed of the submarine is in a state of neutral equilibrium. The effect of the speed change on the stability derivatives can also be neglected, thus:—

$$X_u = X_w = X_q = Z_n = M_n = 0$$

A consequence of these assumptions is that following a disturbance in the direction of the initial steady state motion there is no change in w or q; henceforth further discussion of the motion in the vertical plane will be concerned only with deviations in w and q following application of a normal force or pitching moment. In general, it has also been found that for small disturbances $Z_{\dot{q}}$ and $M_{\dot{w}}$ can be neglected, thus equations (6) reduce to:—

$$(m - Z_{\dot{w}})\dot{w} - (mU + Z_q)q - wZ_w = Z(t)$$

$$(I_y - M_{\dot{q}})q - qM_q - wM_w + mg\,\overline{BG}\,\theta = M(t)$$

$$\dots (7)$$

$$\text{where } \theta = \int q\,dt$$

Many assumptions have been made in arriving at these simplified longitudinal symmetric equations, although in later pages some of them will be relaxed. However, to use these equations realistic estimates of the values of the hydrodynamic derivatives are required, and, even though there are only a few remaining, determination of their values is not a simple process either theoretically or experimentally. In the following pages some of the difficulties involved will be described.

Lateral Symmetric Motion

An exactly similar process to that used above can be used to derive the simplified lateral equations of motion. Assuming once again that the speed of the submarine is in a state of neutral equilibrium, the equations of lateral symmetric motion for small disturbances become:—

$$m(\dot{v} + rU) = vY_v + pY_p + rY_r + \dot{v}Y_{\dot{v}} + \dot{p}Y_{\dot{p}} + \dot{r}Y_{\dot{r}} + Y(t)$$

$$I_x\dot{p} + I_{zx}\dot{r} = vK_v + pK_p + rK_r + \dot{v}K_{\dot{v}} + \dot{p}K_{\dot{p}} + \dot{r}K_{\dot{r}} + K(t) - mg\overline{BG}\,\phi$$

$$I_z r - I_{zx}p = vN_v + pN_p + rN_r + \dot{v}N_{\dot{v}} + \dot{p}N_{\dot{p}} + \dot{r}N_{\dot{r}} + N(t)$$

$$\dots (8)$$

$$\text{Where } \phi = \int p\,dt$$

The first of many assumptions will be that which assumes that the direction of the initial state motion (and thus the x-axis) lies along the principal axis of the submarine. Hence the product of inertia $I_{zx} = O$.

On the assumption of symmetry and slender form:—

$$Y_{\dot{r}} = N_{\dot{v}} = K_r = N_{\dot{p}} = Y_{\dot{p}} = K_{\dot{v}} = 0.$$

At this stage it will also be assumed that the motion is "roll-independent". This assumption implies that although rolling is dependent on the sideslip and yawing of the submarine, sideslip, or yawing are not affected by rolling. Thus:—

$$Y_p = N_p = 0$$

and equation (8) reduces to:—

$$(m - Y_{\dot{v}})\dot{v} - vY_v + (mU - Y_r)r = Y(t)$$

$$(I_x - K_{\dot{p}})\dot{p} - vK_v - pK_p - rK_r + mg\,\overline{BG}\,\phi = K(t)$$

$$(I_z - N_{\dot{r}})r - rN_r - vN_v = N(t)$$

$$\dots (9)$$

$$\text{where } \phi = \int p\,dt$$

As was the case in the vertical plane a large number of assumptions have been made in the derivation of these simplified equations of motion. Whereas, however, in the vertical plane even the most violent manoeuvres in the restricted layer of water cannot involve large deviations, in the horizontal plane the changes of direction are virtually unlimited. Consequently the assumption of small displacements is not so realistic in the description of the motion in the horizontal plane. Furthermore these simplified equations take no account of the asymmetry of the vessel about a horizontal plane (largely due to the bridge fin), nor do they take into account the speed reduction in turns. Making the same assumptions in the horizontal plane as were made in the study of the vertical plane is thus not such a realistic procedure. Nevertheless, the simplified lateral equations of motion are useful in the study of stability in the horizontal plane since this falls within the scope of a small disturbance theory.

Both the lateral and longitudinal simplified equations of motion will be developed and examined in more detail in the following parts, but it is worth noting now that these equations cannot adequately represent a submarine that does not have straight line stability. Equations of this form for a submarine without straight line stability produce a divergent response to any disturbance, which is clearly unrealistic.

PART IV—STABILITY AND CONTROL
IN THE VERTICAL PLANE OF MOTION

Introduction

The stability and control investigations undertaken in this part will use the simplified longitudinal symmetric equations of motion. Initially the form of the equations will be examined in more detail, and then the non-dimensional equations developed. Criteria for stability will then be determined. There are no control criteria, but various performance indices will be discussed. Finally a brief mention will be made of the use of normalized equations.

The Nature of the Simplified Longitudinal Symmetric Equations of Motion

The longitudinal symmetric equations were derived in the last chapter:—

$$(m - Z_{\dot{w}})\dot{w} - (mU + Z_q)q - wZ_w = Z(t)$$

$$(I_y - M_{\dot{q}})\dot{q} - qM_q - wM_w + mg\,\overline{BG}\,.\,\theta = M(t)$$

$$\text{where } \theta = \int q\,dt$$

. . . (10)

In the above equations there are two derivatives with respect to accelerations—$Z_{\dot{w}}$ and $M_{\dot{q}}$—and it is seen that these are associated with the mass and inertia respectively. They are thus referred to as the added mass, and the added inertia, and the terms $(m - Z_{\dot{w}})$, $(I_y - M_{\dot{q}})$ are often referred to as the virtual mass and the virtual inertia. These terms arise because a body moving through a fluid appears to have a greater mass than is actually the case. In its passage through an otherwise stationary fluid a body induces motion in the fluid, which thus has kinetic energy it would not have had but for the motion of the body, and the equations of motion must take this kinetic energy into account. Work is only done if the kinetic energy is changing, and thus the added mass and inertia are associated with the acceleration of the body.

Treatises on classical hydrodynamics[5] have determined values for the virtual masses and inertias of regular solids in motion through ideal fluids. It is obvious that for a particular direction of motion a streamlined body will have less influence on the surrounding fluid than a bluff body, and hence less added mass. This applies to the submerged submarine which, if treated as a solid of revolution with a high length/beam ratio, will have a very small added mass for motion along the x-axis, but an added mass approximately equal to the actual mass for motion along the y

or z axes. In aircraft studies these derivatives are often neglected, because the mass of the air to which kinetic energy is imparted is very small in comparison with the mass of the aircraft. There are experimental methods for the determination of these acceleration derivatives, and these will be described in the chapter on experimental techniques.

Also in equations (10) there are two derivatives dependent upon a linear velocity; these are Z_w and M_w. Z_w is the shorthand notation for $\dfrac{\partial Z}{\partial w}$ and represents the variation in normal force Z with respect to the normal velocity w. The assumption of small disturbances in the derivation of the equations of motion was made partly to ensure that the coefficients such as Z_w have constant values (for a particular value of the forward speed). In order to appreciate the physical significance of Z_w, assume that a submarine is travelling at constant forward speed, U, and is subject to a small disturbing normal velocity w. As can be seen from Fig. 3 the result of this disturbance in normal velocity is effectively equivalent to that produced by the submarine travelling at an angle of incidence $\dfrac{w}{U}$ to the direction of motion.
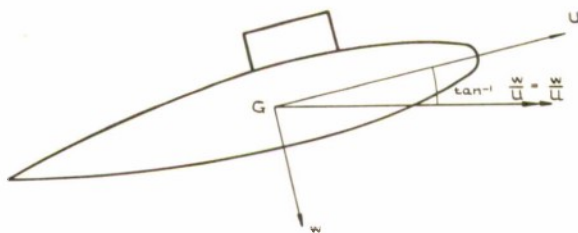

FIG. 3. Illustration of the equivalence of a normal velocity perturbation to an angle of incidence.

At an angle of incidence to the direction of motion the water flow over the upper surface of the hull has greater velocity than that along the lower surface. Hence there is a differential pressure produced, the resultant effect of which is a normal (or lift) force on the hull of the submarine. The lift distribution is similar to that shown in Fig. 4.

If the resultant lift force is measured for a number of angles of incidence (experimental and theoretical methods are described in later pages), it is found to vary linearly with the angle of incidence for small angles. The slope of the line obtained by plotting the lift force against the angle of incidence for small angles at a particular velocity
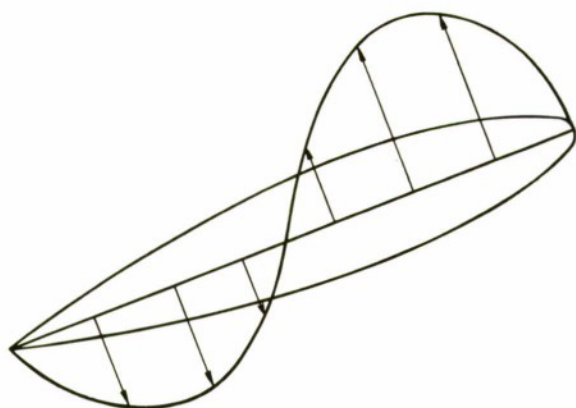
FIG. 4. Typical pressure distribution on a submarine hull.

provides a value for the derivative Z_w at that particular speed. For larger angles of incidence the variation is no longer linear (compare the aircraft wing which approaches the stall as incidence is increased); the extent of the linearity gives some indication of the limits to which the small disturbance theory can be extended. If for a particular small angle of incidence the forward speed is varied, the lift force, and hence the derivative Z_w, is found to be proportional to the square of the forward speed. The resultant lift force, of a distribution such as that shown in the above diagram, passes through the centre of pressure of the hull of the submarine, a point sometimes referred to as the neutral point. The position of the centre of pressure is dependent upon hull shape, but obviously it is not necessarily coincident with the centre of gravity. The moment of this force about the centre of gravity provides a value for the derivative M_w. M_w is also thus linearly dependent on incidence for small angles, and is directly proportional to the square of the forward speed.

The derivative values which have been assumed to depend only on the instantaneous values of the velocities and accelerations are measured for steady state velocities and accelerations, and the derivatives obtained used in the calculation of transient motions. This approach, which is justified by its use in aircraft studies, is known as the quasi-static approach.

There are two rotary derivatives in equations (10) so-called from their dependence upon an angular velocity q; these are Z_q and M_q. In this case the determination of values requires some knowledge of the variation in normal force and pitching moment for small increments in angular velocity q. Experimentally models can be towed in a circular path with constant angular velocity, and the normal force and pitching moment measured. Repetition with different values of q and U provides the values of Z_q and M_q and shows their

dependence on the square of the forward speed.

$Z(t)$ and $M(t)$ represent any external time dependent force and moment. Initially the most important consideration will be the effect of a deflected control surface such that:—

$$Z(t) = \delta Z_\delta$$
$$M(t) = \delta M_\delta$$

Where δ is the angular deflection of the control surface, and Z_δ M_δ are the coefficients representing control surface effectiveness. The control surface in the vertical plane could be either forward or after hydroplanes. Analogous to the other derivatives, Z_δ and M_δ are the slopes of the linear sections of the force and moment curves produced by deflection of the control surfaces. These derivatives also depend upon the square of the forward speed.

For a particular value of the forward speed U the equations (10) are thus differential equations with constant coefficients, provided that the disturbances are small and within the range of linearity. However, in the form given above the equations would require different derivative values for different velocities since they depend upon the speed squared. In order that constant values can be used for a particular submarine, applicable at all speeds, the equations are non-dimensionalized, as outlined in the following section.

Non-dimensional Simplified Longitudinal Symmetric Equations

The non-dimensionalizing of the equations of motion is largely a matter of convenience, although at one time it was thought that suitable non-dimensionalizing parameters might lead to the possibility of directly comparing derivative values for submarines of different size and shape. There have thus been various methods used in attempts to achieve this aim, but none of them quite satisfactory. The following method is one that is used quite frequently.

It is obviously convenient to non-dimensionalize with respect to U^2, since the derivatives depend upon the square of forward speed. This factor alone ensures that the coefficients of the non-dimensional equations are not speed dependent. It is also found that derivative values for different size submarines are of the same order if the length of the submarine is used as a parameter. Forces are thus divided by $\frac{1}{2}\rho U^2 L^2$ and moments by $\frac{1}{2}\rho U^2 L^3$. The velocity components are divided by U and the angular velocity components by $\frac{U}{L}$. A further simplification is obtained

if non-dimensional time is introduced such that real time $t = \dfrac{L\tau}{U}$

Equations (10) in non-dimensional form thus become:—

$$(m' - Z_{\dot{w}}')\dot{w}' = (m' + Z_q')q' + w'Z_w' + Z'(\tau)$$

$$(I_y' - M_{\dot{q}}')\dot{q}' = q'M_q' + w'M_w' - m'\gamma \int q'\,d\tau + M'(\tau)$$
$$\dots (11)$$

Where the dot now denotes differentiation with respect to τ, and the dash (or prime) denotes non-dimensional quantities given by the following relations:—

$$w' = \frac{w}{U} \quad ; \quad q' = \frac{qL}{U} \quad ; \quad t = \frac{L}{U}\,\tau$$

$$m' = \frac{m}{\frac{1}{2}\rho L^3} \quad ; \quad Z_{\dot{w}}' = \frac{Z_{\dot{w}}}{\frac{1}{2}\rho L^3} \quad ; \quad Z_q' = \frac{Z_q}{\frac{1}{2}\rho U L^3}$$

$$Z_w' = \frac{Z_w}{\frac{1}{2}\rho U L^2} \quad ; \quad Z'(\tau) = \frac{Z(t)}{\frac{1}{2}\rho U^2 L^2}$$

$$I_y' = \frac{I_y}{\frac{1}{2}\rho L^5} \quad ; \quad M_{\dot{q}}' = \frac{M_{\dot{q}}}{\frac{1}{2}\rho L^5} \quad ; \quad M_q' = \frac{M_q}{\frac{1}{2}\rho U L^4}$$

$$M_w' = \frac{M_w}{\frac{1}{2}\rho U L^3} \quad ; \quad \gamma = \frac{g\overline{BG}}{U^2} \quad ; \quad M'(\tau) = \frac{M(t)}{\frac{1}{2}\rho U^2 L^3}$$

All the coefficients of equations (11), with the exception of γ, are now independent of speed. Having obtained numerical values of the derivatives by theoretical or experimental methods, equations (11) would be quite amenable to solution by classical methods for a variety of forcing functions $Z(\tau)$ and $M(\tau)$. Repeated calculations for different speeds would only involve using different values of the coefficient γ, the non-dimensional time would, of course, bear a different relation to real time for each speed considered. Nowadays it is usually much more convenient to programme a computer to solve the equations.

Stability—Stick Fixed

In this section it is proposed to investigate the stick-fixed stability of the submarine using the equations derived above (11). In this application equations derived by using a small disturbance theory should be entirely adequate, since stability is the consideration of the reaction to a small disturbance.

A dynamical system is said to be stable when in the free motion following a disturbance the effect of that disturbance ultimately becomes vanishingly small. This concept of stability only applies to systems in equilibrium at rest or in some steady state motion. It was noted in Part II that the stability of the submerged submarine at rest was entirely dependent upon the disposition of the

gravitational and buoyancy forces. It will be assumed that the submarine is stable at rest (*i.e.* has metacentric stability). The more difficult problem of dynamic stability will now be discussed.

Stick-fixed stability implies that the controls are not used to correct any disturbance, and thus following a disturbance the motion of the submarine must satisfy the following equations:—

$$(m' - Z_{\dot{w}}')\dot{w}' - w'Z_w' - (m' + Z_q')q' = 0$$

$$(I_y' - M_{\dot{q}}')\dot{q}' - w'M_w' - q'M_q' + m'\gamma \int q'\,d\tau = 0$$
$$\dots (12)$$

The solution of these equations takes the form:—

$$w' = a_1 e^{\sigma_1 \tau} + a_2 e^{\sigma_2 \tau} + a_3 e^{\sigma_3 \tau}$$

$$q' = b_1 e^{\sigma_1 \tau} + b_2 e^{\sigma_2 \tau} + b_3 e^{\sigma_3 \tau}$$
$$\dots (13)$$

where σ_1, σ_2, σ_3 are the roots of the characteristic equation:—

$$A\sigma^3 + B\sigma^2 + C\sigma + D = 0 \qquad \dots (14)$$

where

$$A = (m' - Z_{\dot{w}}')\,(I_y' - M_{\dot{q}}')$$

$$B = -\left[M_q'(m' - Z_w') + Z_w'(I_y' - M_{\dot{q}}') \right]$$

$$C = Z_w' M_q' - M_w'(m' + Z_q') + m'\gamma(m' - Z_{\dot{w}}')$$

$$D = -m'\gamma Z_w'$$

For stability w' and q' must decay to zero with increasing τ, hence considering the solution (13) σ_1, σ_2, σ_3, must either all be negative or their real parts must be negative. Any positive value would result in a divergent solution. Equation (14) can be solved to obtain the values σ_1, σ_2, σ_3, it will be appreciated that these values will vary with the speed U because coefficients C and D include γ which is inversely proportional to U^2. The expected solution for a submarine is shown in Fig. 5 which is seen to be similar to Fig. 40 of Ref. [1].

The characteristic equation (or stability cubic) can either have three real roots, or one real root and a complex conjugate pair. The existence of a complex pair of roots indicates an oscillatory solution. At low speeds γ is large in comparison with the other terms and stability is governed by the metacentric height, the motion is almost certain to be oscillatory. As the speed is increased so the effect of γ decreases, and the stability depends more on the hydrodynamic derivatives, the motion can still be oscillatory and stable. It is most likely that some value of the speed U is eventually reached where the roots of the stability cubic are all real, and the oscillation has disappeared. The submarine will still be stable if the roots are all negative. At still higher speeds $\gamma \to 0$ and since $D \to 0$ equation (14) becomes a quadratic. This

implies that the solution is no longer dependent on the value of the pitch angle, and the controls fixed submarine can have only straight-line stability. As was indicated in Chapter II the submarine can only have directional stability in the vertical plane while the influence of the metacentric stability is still of consequence.

The solution (Fig. 5) illustrates these points; the submarine is oscillatory and has directional stability at low speeds. At a speed in the region of 20 knots the roots of the stability cubic become all real, and as speed is furher increased one of these roots tends to zero, as γ tends to zero. Directional stability gets less at the higher speeds, noted in the submarine by the increasing inability to pull out from a dive without the use of control surfaces. At infinite speed the submarine has only straight-line stability.

Actually it is not necessary to complete the solution of the stability cubic in order to investigate the stability of the submarine. The techniques of Routh and Hurwitz can be used to obtain criteria which must be satisfied if the roots are negative (or their real parts are negative). Their method states that if the roots are all negative or have negative real parts then the coeffiients of the stability cubic must satisfy the following relations:—

$$\frac{B}{A} > 0 \; ; \; \frac{BC-AD}{A^2} > 0 \; ; \; \frac{D}{A}\frac{(BC-D)}{A^2} > 0$$

The coefficient A is virtual mass multiplied by virtual inertia and is at all times positive, thus the above criteria reduce to:—

$$B > 0 \; ; \; D > 0 \; ; \; BC > AD \qquad \ldots (15)$$

These are the necessary and sufficient conditions for stability. It will be seen that the third condition considered in conjunction with the other two also implies that $C > 0$. At very low speeds γ becomes indefinitely large and $C > 0$ only if $\gamma > 0$; in other words if:—

$$\overline{BG} > 0$$

This is the well-known condition for metacentric stability, that the centre of buoyancy is above the centre of gravity. This is a mandatory condition for submarine operation, and using this condition in the inequalities (15), the following conditions must also be satisfied:—

$$Z_w' < 0 \text{ and } M_q' < 0$$

The first of these conditions provides for stability against a force acting through the centre of gravity, and the second provides for stability against a moment about the centre of gravity, because in both cases, if the inequalities are satisfied, forces are generated which oppose the disturbances.
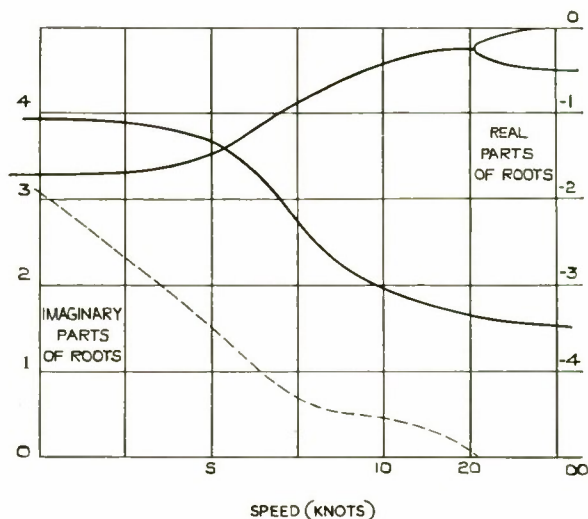
At high speed $\gamma \to 0$ and the criteria (15) also

FIG. 5. Routes of the stability cubic for a stable submarine.

provide the following inequality which must be satisfied:—

$$M_w'(m'+Z_q') - Z_w'M_q' < 0$$

This is sometimes referred to as the high speed stability criterion, and it is necessary to provide stability in the motion following application of either a force or a moment.

The necessary and sufficient conditions for stable motion following a disturbance at any speed are thus:—

$$\overline{BG} > 0 \quad Z_w' < 0 \quad M_q' < 0$$
$$M_w'(m'+Z_q') - Z_w'M_q' < 0$$
$$\ldots (16)$$

The above inequalities (16) indicate whether a submarine is stable or not, but they give little or no indication as to the degree of stability. As has been previously noted, a measure of stability is desirable but too much stability can result in difficult control. Fortunately analogous equations have been analyzed in great detail in other fields, and a number of " stability indices " proposed, which are of course directly applicable to these equations. A typical stability index is the algebraically largest real part of the roots of the stability cubic expressed in non-dimensional terms. This index varies with speed, and referring to Fig. 5 it is seen that for the stable submarine it corresponds to the value of the root that approaches zero for large values of U. It is obviously undesirable for this root to be too small since a small value would indicate low directional stability.

Another approach commonly used in the study of servo-mechanisms is that of the determination of the damping ratio; this method is applied to the submarine equations in the next section.
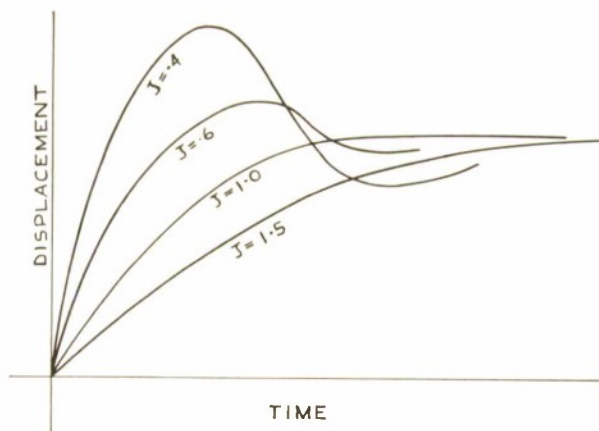
FIG. 6. Transient response of a second-order system with different values of the damping coefficient.

The Damping Ratio

The stability cubic (14) can be written as follows:—

$$\sigma^3 + \frac{B}{A}\sigma^2 + \frac{C}{A}\sigma + \frac{D}{A} = 0$$

and can be factorized thus:—

$$(\sigma - \sigma_2)(\sigma^2 + E\sigma + F) = 0$$

where σ_2 is the root which is always real, and σ_1, σ_3 are the roots of $\sigma^2 + E\sigma + F = 0$, and can be complex (*i.e.* an oscillatory solution), or real.

The equation $\sigma^2 + E\sigma + F = 0$ is in effect the characteristic equation of a second order servo-mechanism, and will be analyzed as such.

The roots σ_1, σ_3 are given by:—

$$\sigma_1, \ \sigma_3 = \frac{-E \pm \sqrt{E^2 - 4F}}{2}$$

Thus the roots have an imaginary part and hence the solution is oscillatory if $E < 2\sqrt{F}$, the roots are real if $E > 2\sqrt{F}$, and the critical solution occurs when $E = 2\sqrt{F}$.

The coefficient E is said to represent damping, since clearly if E is zero then $\sigma^2 + F = 0$ which is the well-known equation for simple harmonic motion of undamped natural frequency $\sqrt{F}$. For small values of E the solution is still oscillatory but damped; however, for $E = 2\sqrt{F}$ the solution is just and only just no longer oscillatory. This is the condition of critical damping.

The damping ratio is the ratio of actual damping to critical damping; it is usually denoted by ζ and is thus given by:—

$$\zeta = \frac{E}{2\sqrt{F}}$$

or in terms of the roots σ_1 and σ_3:—

$$\zeta = -\frac{(\sigma_1 + \sigma_3)}{2\sqrt{\sigma_1 \sigma_3}} \qquad \ldots (17)$$

or if the roots σ_1 and σ_3 are complex and can be represented by $R \pm iI$ then:—

$$\zeta = -\frac{R}{\sqrt{R^2 + I^2}}$$

If the natural frequency $\sqrt{F}$ is denoted by ω_n then the equation $\sigma^2 + E\sigma + F = 0$ can be re-written as follows: —

$$\sigma^2 + 2\zeta\omega_n + \omega_n^2 = 0$$

The typical transient response of a second-order servo mechanism with different values of the damping coefficient is shown in Fig. 6.

When $\zeta > 1$ it is seen that the response to a disturbance is comparatively sluggish, and non-oscillatory, it is said to be over-damped. Critical damping occurs when $\zeta = 1$ (that is $E = 2\sqrt{F}$), this is the boundary between oscillatory and non-oscillatory responses, and corresponds to the point where the solution of the characteristic equation resolves into three real roots. If $\zeta < 1$ the response is oscillatory and is said to be underdamped. It can be seen from Fig. 6 that a certain amount of under-damping may be found desirable, since the response is quicker and the overshoot and subsequent oscillation quite small. In fact this is the case and for servo-mechanisms the most suitable solutions are often found to be for values of ζ between 0·6 and 0·85.

There is no reason to doubt that similar reasoning cannot be applied to the submarine characteristic equation. Clearly the damping ratio for a submarine can be found by using equation (17) if the roots have previously been obtained. Since the roots vary with the speed of the submarine, so does the damping ratio, and an expected variation is shown in Fig. 7. If the submarine is analagous to a servo-mechanism then a damping ratio of 0·6
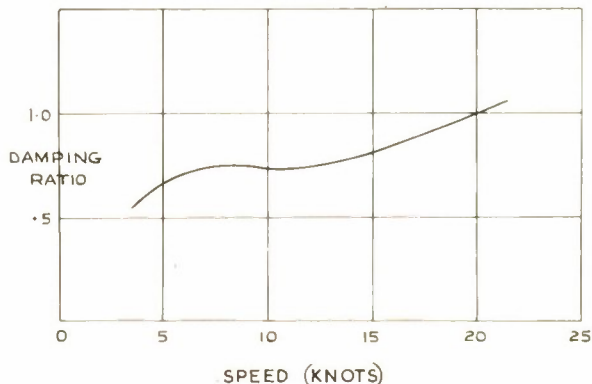

FIG. 7. Typical variation of damping ratio with submarine speed.

to 0·85 should provide adequate stability, and ensure that over-frequent use of the controls is not necessary to maintain depth.

Control in the Vertical Plane

The simplified longitudinal symmetric equations (10) can be re-written as follows:—

$$(m-Z_{\dot{w}})\dot{w}-wZ_w=(mU+Z_q)\dot{\theta}+\delta Z_\delta$$

$$(I_y-M_{\dot{q}})\ddot{\theta}-\dot{\theta}M_q+mg\,\overline{BG}\theta=wM_w+\delta M_\delta$$

$$\dots (18)$$

Where the dot now denotes differentiation with respect to real time, δ is the deflection of a control surface, and Z_δ and M_δ are the force and moment coefficients of the control surface with respect to δ.

In sea water it is quite reasonable to assume that $\rho=2$, using this assumption, and using non-dimensional coefficients, equations (18) can be re-written as follows:—

$$\dot{w}+a_1w=a_2\dot{\theta}+a_3\delta$$

$$\ddot{\theta}+b_1\dot{\theta}+b_2\theta=b_3w+b_4\delta$$

$$\dots (19)$$

where $a_1=\dfrac{-Z_w'}{(m'-Z_{\dot{w}}')}\cdot\dfrac{U}{L}$; $a_2=\dfrac{(m'+Z_q')}{(m'-Z_{\dot{w}}')}\cdot U$;

$$a_3=\dfrac{Z_\delta'}{(m'-Z_{\dot{w}}')}\cdot\dfrac{U^2}{L}$$

$b_1=\dfrac{-M_q'}{(I_y'-M_{\dot{q}}')}\cdot\dfrac{U}{L}$; $b_2=\dfrac{m'g\,\overline{BG}}{(I_y'-M_{\dot{q}}')}\cdot\dfrac{1}{L^2}$

$b_3=\dfrac{M_w'}{(I_y'-M_{\dot{q}}')}\cdot\dfrac{U}{L^2}$; $b_4=\dfrac{M'_\delta}{(I_y'-M_{\dot{q}}')}\cdot\dfrac{U^2}{L^2}$

Solving equations (19) it is possible to obtain equations showing the relationships between w and δ, and θ and δ; in other words the effect of control surface movement on w and θ. The most convenient method of solution is by the Laplace Transform Theory.

The transforms of equations (19) are:—

$$(s+a_1)\,w(s)=a_2s\theta\,(s)+a_3\delta(s)$$

$$(s^2+b_1s+b_2)\,\theta(s)=b_2w(s)+b_4\delta(s)$$

and solving for w(s) and θ(s):—

$$\frac{w(s)}{\delta(s)}=\frac{a_3s^2+(a_3b_1+a_2b_4)s+a_3b_2}{s^3+(a_1+b_1)s^2+(a_1b_1-a_2b_3+b_2)s+a_1b_2}$$

$$\dots (20)$$

$$\frac{\theta(s)}{\delta(s)}=\frac{b_4s+(a_1b_4+a_3b_3)}{s^3+(a_1+b_1)s^2+(a_1b_1-a_2b_3+b_2)s+a_1b_2}$$

$$\dots (21)$$
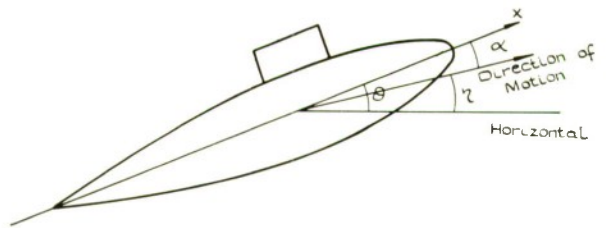

FIG. 8. Definition of angles α, θ and η.

If α is the angle of incidence of the submarine, which for small displacements is equal to $\dfrac{w}{U}$, and θ is the pitch angle, then the angle of the path of the submarine with respect to the horizontal is η where:—

$$\eta=(\theta-\alpha).$$

The relation between these angles is illustrated in Fig. 8.

The rate of change of depth (positive for increasing depth) is thus given by:—

$$\dot{z}=U(\alpha-\theta)$$

or for small displacements:—

$$\dot{z}=w-U\theta \qquad \dots(22)$$

Using equations (20), (21) and (22):—

$$\frac{\dot{z}(s)}{\delta(s)}=$$

$$\frac{a_3s^2+(a_3b_1+a_2b_4-Ub_4)s+(a_3b_2-U(a_1b_4+a_3b_3))}{s^3+(a_1+b_1)s^2+(a_1b_1-a_2b_3+b_2)s+a_1b_2}$$

$$\dots (23)$$

If now it is assumed that the control surface angle δ is set to some fixed angle δ_m and held there, then:—

$$\delta(s)=\frac{\delta_m}{s}$$

and by the final value theorem of Laplace Transform theory as $t\to\infty$ the steady state value of $\dot{z}$ will be given by:—

$$\dot{z}\text{ steady state}=\delta_m\frac{\left[a_3b_2-U(a_1b_4+a_3b_3)\right]}{a_1b_2}$$

$$\dots (24)$$

provided that $s^3+(a_1+b_1)s^2+(a_1b_1-a_2b_3+b_2)s+a_1b_2$ has negative roots. In fact this relation (the denominator of equation (23) is the stability cubic, and the provision that it should have negative roots is the one required for a stable submarine.

Equation (24) shows that if

$$U=\frac{a_3b_2}{a_1b_4+a_3b_3} \qquad \dots (25)$$

then a control surface held at any fixed angle will, in the ultimate steady state, be found to have had no effect on the depth of the submarine. Substituting the original coefficients, equation (25) in derivative form is as follows:—

$$U^2 = \frac{m'g\ \overline{BG}}{Z_w'\left[\dfrac{M_w'}{Z_w'} - \dfrac{M'_\delta}{Z'_\delta}\right]} \quad \ldots (26)$$

From the description given earlier it is seen that the ratio $\dfrac{M_w'}{Z_w'}$ gives the moment arm (in this case non-dimensionally) of the centre of pressure of the submarine, with respect to the centre of gravity. Similarly the ratio $\dfrac{M'_\delta}{Z'_\delta}$ gives the non-dimensional

location of the centre of pressure of the control surface, with respect to the centre of gravity. The term in square brackets in the denominator of equation (26) thus represents the distance between these two centres of pressures, or is effectively the non-dimensional location of a control surface (*i.e.* hydroplane). Equation (26) can thus can be used to determine for any particular speed the position along the length of the hull at which a deflected hydroplane would have no ultimate effect on the depth of the submarine. This point is referred to as the critical point, its position is speed dependent, and a typical location along the hull of a submarine was given in Reference [6], a similar example is shown herein in Fig. 9.

It can also be seen from equations (26) and (24) that a control surface aft of the critical point deflected trailing edge down (*i.e.* positive δ) will produce an increase in depth, whereas a control surface forward of the critical point deflected trailing edge down will produce a decrease in depth. Hence the critical point has sometimes been referred to as the reversal point. Alternatively, since the location of the critical point varies with the speed of the submarine, for a control surface in any one position there is a particular speed at which reversal of its effect takes place. From Fig. 9 it is seen that a hydroplane at the stern has a low reversal speed, and a forward hydroplane a high reversal speed. This reversal of effect of the after hydroplanes is said to occur at the critical speed, and is a phenomenon well known to submariners. It is, of course, due to the fact that although the after hydroplane still produces a bow down attitude on the submarine, at low speed this change of direction is insufficient to overcome the force on the hydroplane tending to decrease depth.
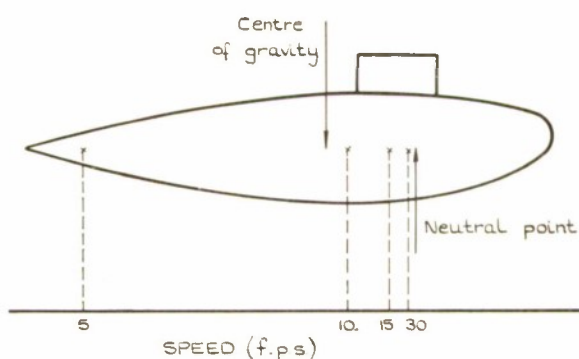

FIG. 9. Typical variation of critical point with speed.

Applying similar analysis to equation (21):—

$$\theta\ \text{steady state} = \delta_m\left[\frac{a_1b_4 + a_3b_3}{a_1b_2}\right]$$

$$= \delta_m\left[\frac{M'_\delta}{Z'_\delta} - \frac{M'_w}{Z'_w}\right]\frac{Z'_\delta}{m'g\ BG} \quad \ldots (27)$$

Thus a control surface does not produce any pitch angle in the steady state if:—

$$\frac{M'_\delta}{Z'_\delta} = \frac{M'_w}{Z'_w}$$

This result might well have been expected; it states that no pitch angle results from the deflection of a control surface located at the centre of pressure of the submarine (or the neutral point). A control surface aft of the neutral point will produce a bow down pitch angle for a trailing edge down deflection (positive δ), whereas a control surface forward of the neutral point will produce a bow-up pitch angle for a trailing edge down deflection.

Typically the neutral point of a submarine is 0·24L forward of the centre of gravity, and the centres of pressure of the control surfaces are 0·47L aft of the centre of gravity for after hydroplanes, and 0·33L forward of the centre of gravity for forward hydroplanes. In the above notation:—

$$\frac{M'_w}{\left|Z'_w\right|} = 0\cdot24\ ;\ \frac{M'_\delta\ (\text{aft})}{\left|Z'_\delta\right|} = -0\cdot47\ \ \frac{M'_\delta\ (\text{fwd})}{\left|Z'_\delta\right|} = 0\cdot33.$$

For the aft location of the hydroplanes critical speed is of the order of 5 ft per second, and since the location of the forward hydroplanes is ahead of the neutral point they have no reversal speed. This may not be the case when forward hydroplanes are located on the bridge fin which may be just aft of the neutral point. However in this situation the reversal speed is high, and often

greater than the operating speed of the submarine.

It has already been pointed out that a control surface at the neutral point produces no pitch angle, control surfaces in the typical positions considered above would produce the following deviations:—

θ steady state $= -\cdot 01 \, \delta_m$ for the aft location

θ steady state $= \cdot 001 \, \delta_m$ for the forward location

The change in sign of the effect of the location of the control surface with respect to the neutral point was noted above, and it is obvious as the above relations show that the farther removed the control surface is from the neutral point the more effective is the surface in producing pitch angle.

Note on the Location of Control Surfaces

The reasons for the time-honoured submarine practice of using forward hydroplanes to control depth, and after hydroplanes to control pitch angle should now be quite clear. The after hydroplanes are most effective in producing pitch angle, and always operate in the same sense, whereas in the control of depth they undergo reversal at low speeds. The forward hydroplanes are not so effective in controlling pitch angle being close to the neutral point, but in the control of depth they are not subject to reversal. Nevertheless it is not true to say that the forward hydroplanes are necessarily more effective in the control of depth. The steady state rate of change of depth was given by equation (24) which on substitution becomes:—

$\dot z$ steady state $=$

$$\frac{UZ'_\delta}{Z'_w}\left[\frac{U^2 Z'_w\left[\dfrac{M_w'}{Z_w'} - \dfrac{M'_\delta}{Z_\delta} \right] - 1}{m'g \, \overline{BG}} \right]\delta_m$$

but the critical or reversal speed is given by:—

$$U_c^2 = \frac{m'g\,\overline{BG}}{\left[\dfrac{M'_w}{Z'_w} - \dfrac{M'_\delta}{Z'_\delta} \right] Z_w'}$$

and thus:—

$$\dot z \text{ steady state} = \frac{UZ'_\delta}{Z'_w}\left[\frac{U^2}{U_c^2} - 1 \right]\delta_m \quad \dots \ (28)$$

Thus for example:—

$\dot z$ steady state is proportional to $\left[\dfrac{U^2}{25} - 1 \right]\delta_m$ for after hydroplanes

whereas $\dot z$ steady state is proportional to

$\left[-\dfrac{U^2}{218} - 1 \right]\delta_m$ for forward hydyroplanes

Using these relations it can be found that in many cases the after hydroplanes are equally and increasingly more effective than the forward hydroplanes at speeds of 8 ft per second and above. Thus forward hydroplanes are only more effective in depth control in a small speed range near the reversal speed.

Performance Indices

If the controls fixed submarine is unstable then it is absolutely essential that the hydroplanes have sufficient power to ensure that the vessel is controllable. The control surfaces are restricted in size and speed of operation and hence the submarine cannot be too unstable or it would be uncontrollable even with the maximum permissible size of hydroplanes. On the other hand the submarine must not be too stable or the maximum permissible size hydroplanes will be unable to achieve the required manoeuvrability. Hydroplanes are required for the maintenance of depth during disturbances (e.g. wave forces), and for depthchanging and their performances in these rôles must be assessed.

In Reference [1] a parameter is given for the assessment of control effectiveness which is the ratio of the moment on the vessel produced by unit deflection of a control surface to the longitudinal moment of inertia of the submarine. In dimensional derivative notation this parameter is $\dfrac{M_\delta}{I_y}$ and it is of course speed dependent. Perhaps the greatest value of this parameter is in the comparison of the "powers" of hydroplanes on different submarines. Another index of performance is the measurement of the non-dimensional time to attain 10° of pitch angle following the application of maximum hydroplane angle to the submarine which was initially in equilibrium with zero pitch angle and neutrally buoyant. This parameter is designed to assess the ability of the controls to initiate a dive.

The measurement and comparison of results on a number of specific manoeuvres also gives an indication of control effectiveness; one such manoeuvre is the overshoot manoeuvre. This manoeuvre begins with the submarine proceeding straight and level in neutral trim, the hydroplanes (any combination suitable for comparison) are then set to some predetermined dive angle, and held until the pitch angle of the submarine reaches some predetermined angle (denoted the execute angle). At the execute angle the hydroplanes are reversed to the equal and opposite rise angle, and held until the maximum depth change has been recorded. Three principal parameters (shown in

Fig. 10) are measured on each manoeuvre. These are:—

    (i) the time from the commencement of hydroplane movement until the execute pitch angle is reached.

    (ii) the difference in pitch angle between the maximum reached and the execute angle, known as the overshoot angle.

    (iii) the difference in depth between the maximum attained and that recorded at the execute, known as the overshoot depth.
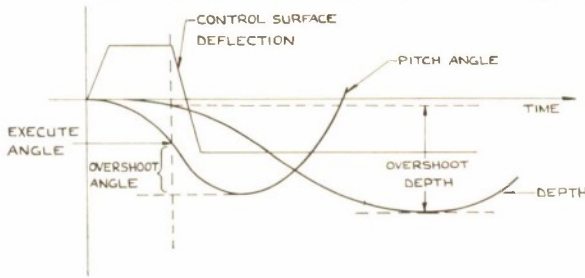

FIG. 10. Illustration of overshoot manoeuvre.

For the purposes of comparison a variety of hydroplane and execute angles, and submarine speeds can be considered; such a comparison is tabulated and analyzed in Reference [1]. The theoretical response of a submarine to such a manoeuvre as this is quite easily calculated using the equations developed in this note, but because of the assumption of small disturbances one could not expect an accurate prediction for large angular displacements.

Satisfactory performance in the overshoot manoeuvre does not necessarily mean that a vessel will have good depth-keeping ability. By comparison with servo-mechanisms it would appear that a boat with a damping ratio of between 0·6 and 0·85 should be satisfactory. A more realistic assessment of depth-keeping ability can be undertaken by setting up a computer as a simulator representing the submarine, its control system and representative wave disturbances. Attempts at maintaining depth by either human operators or automatic controls can be recorded and analyzed by statistical methods.

Normalized Equations

When non-dimensional equations were introduced it was stated that one of the original purposes for non-dimensionalization was the elimination of dependence of the derivatives on speed, size, and form of the submarine. However as no method had proved entirely satisfactory the one described involved non-dimensionalizing with respect to speed and length only. Nevertheless, the concept is of interest and efforts have been made to reduce the number of coefficients in the

equations of motion to a minimum, and in so doing eliminate all superficial dependence between parameters. In other words, by this means it is hoped to obtain a one-to-one correspondence between the coefficients depending on hull form, and the coefficients defining the response of the submarine. The following method is described as an example of the normalizing process, but no claims are made as to its value.

In the manipulation of the non-dimensional equations of motion it is noticeable how often the ratio $\dfrac{m'-Z_{\dot{w}}'}{Z_w'}$ appears. It is assumed that this ratio is an important parameter, and the non-dimensional equations are normalized by using $\dfrac{m'-Z_{\dot{w}}'}{Z_w'}$ as the base for a new time scale.

The non-dimensional equations (11) are:—

$$(m'-Z_{\dot{w}}')\dot{w}' - w'Z_w' - (m'+Z'_q)q' = Z'_\delta \delta$$

$$(1_y'-M_{\dot{q}}')\dot{q}' - w'M_w' - q'M'_q + m'\gamma\int q'd\tau = M'_\delta \delta$$

$$\dots (11)$$

where the dot denotes differentiation with respect to τ, where $t = \dfrac{L}{U}\tau$

Divide the first of equations (11) by $-Z_w'$:—

$$\frac{(m'-Z_{\dot{w}}')}{-Z_w'}\ \dot{w}' + w' + \frac{m'-Z_q'}{Z_w'}q' = \frac{Z\delta'}{-Z_w'}\ \delta$$

Now the coefficient of w' can be eliminated by using a new time scale such that:—

$$\hat{t} = \left[\frac{-Z_w'}{m'-Z_{\dot{w}}'}\right]\tau$$

Applying a similar process to the second of equations (11) also, the normalized equations became:—

$$\frac{dw'}{d\hat{t}} + w' + \frac{m'-Z_q'}{Z_w'}\ q' = \frac{-Z'_\delta}{Z'_w}\ \delta$$

$$-Z_w'\left[\frac{I_y'-M_{\dot{q}}'}{m'-Z_{\dot{w}}'}\right]\frac{dq'}{d\hat{t}} - w'M_w' - q'M'_q -$$

$$m'\gamma\left[\frac{m'-Z_{\dot{w}}'}{Z_w'}\right]\int q'd\hat{t} = M'_\delta \delta$$

References

[1] Naval Architectural Aspects of Submarine Design. Capt. E. S. Arentzen, U.S.N., and P. Mandel. *Trans.* S.N.A.M.E. (1961).

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[3] Automatic Control of Aircraft and Missiles. J. H. Blakelock, Wiley (1965).

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[6] The Stability and Control of Deeply Submerged Submarines. T. R. F. Nonweiler. *Trans R.I.N.A.* (1961).
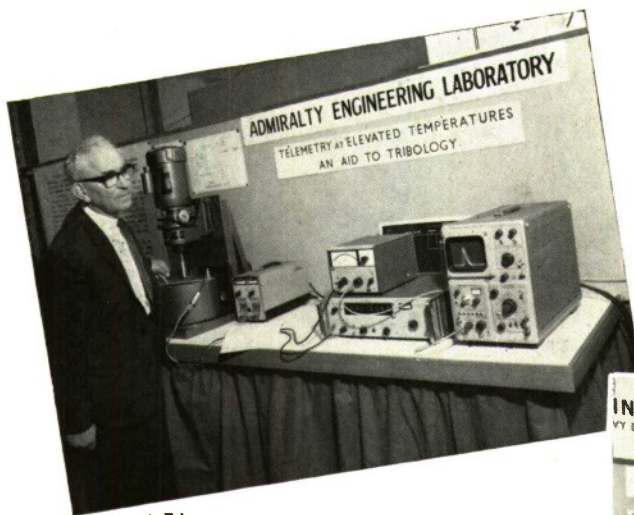
A.E.L.
Telemetry at high
temperatures.

A.U.W.E.
Hydrophone calibration.
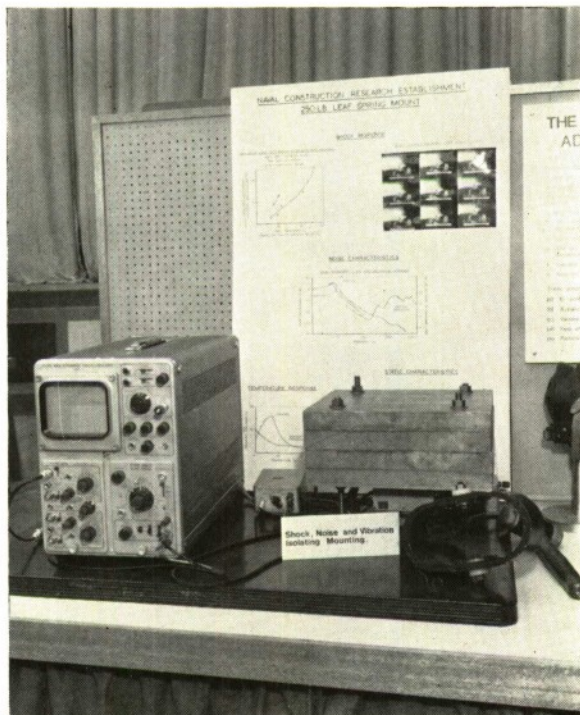
N.C.R.E.
Shock, noise
and vibration mounting.

Navy
Department
Exhibits

A.S.W.E.
X-Band radar
beacon.

S.E.R.L.
Ion implantation

Physics
Exhibition
1968

PHYSICS EXHIBITION
1968

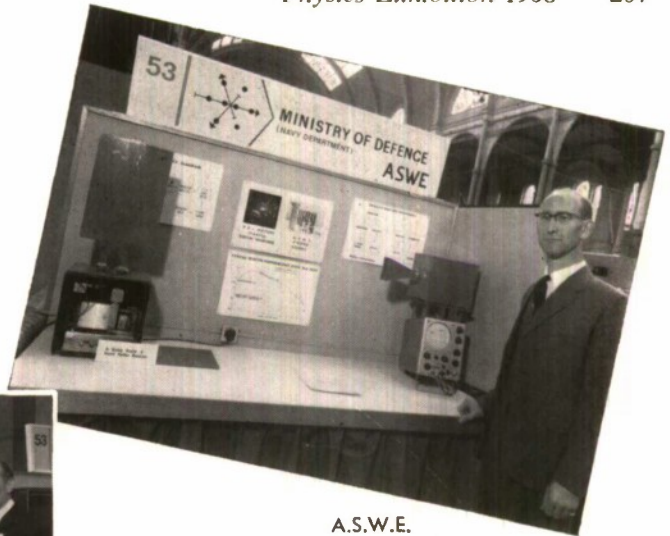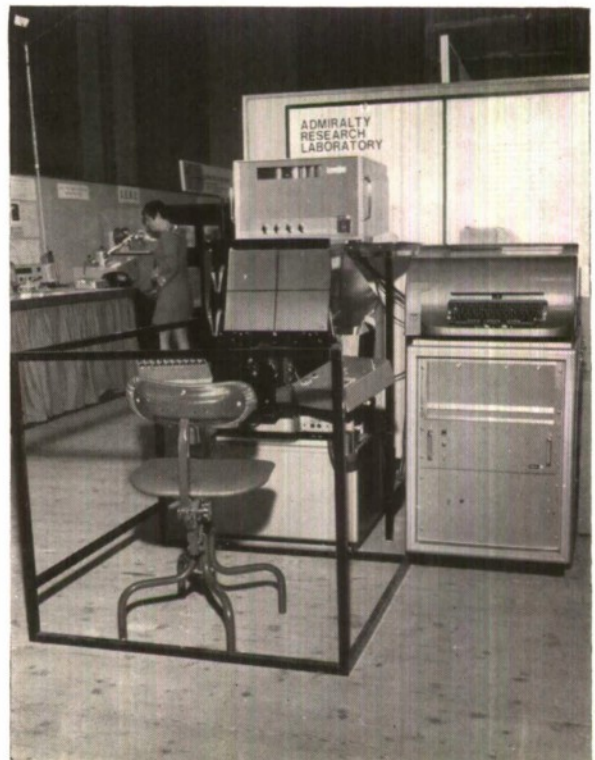The Navy Departments' Research and Development Establishments again exhibited at the Physics Exhibition, held this year at Alexandra Palace, London, on 11 - 14th March. Six establishments participated, each with exhibits which aroused considerable interest amongst the large number of visitors to the exhibition during the three days it was open.

Illustrations of the stands are shown on the previous pages and very brief technical descriptions are given below.

ADMIRALTY ENGINEERING LABORATORY

Telemetry at elevated temperatures (Int. Telemetering Conf., Washington, September 1967, Session VIII, paper 2). Studies of the load-bearing properties of lubricant-gear-material combinations (Inst. Mech. Engrs, Lubrication and Wear Symp., 1963, paper 12) as investigated on an edge-type disk machine are assisted by information on the temperature of the rubbing surfaces.

A sensor in the form of a thermistor is inserted in a 15×10^{-3} in. hole close to the periphery of one of the disks. The thermistor resistance is sensitive to temperature and can change, typically, from 2000 to 50 Ω for a rise in temperature from ambient to 300°C. A clamping nut contains a transmitter whose frequency is controlled by the thermistor resistance. This frequency changes from 2 to 3·5 MHz for a sensor temperature change from ambient to 200°C. The transmitter ring-type aerial couples the signal to the receiver via the arc-shaped aerial.

The transmitter is frequency/temperature stable in its own right up to 100°C at the controlled frequency and it is sited where the temperature does not, in fact, exceed 80°C.

ADMIRALTY RESEARCH LABORATORY

A ciné film analyzer. An instrument for the routine measurement and semi-automatic recording with speed and accuracy of up to ten co-ordinates and other data relating to each of a series of similar photographic images was exhibited.

The film, viewed on the screens of a conventional back projector ('Shadomaster' Type BC 1512), may be moved in its plane over a 1 in. square so that any part of its projected image may be brought into coincidence with a fixed datum. Film position is sensed to the nearest 0·0001 in. by two mutually perpendicular transducers (Sogenique (Electronics) Ltd., Type C), the numerical outputs of which are continuously displayed and may be printed in tabular form by a Creed Model 54 teleprinter and punched on to paper tape for direct input to a computer. A keyboard is provided for editing and the insertion of supplementary information.

The equipment has been developed for the routine measurement of displacements recorded by a high speed camera.

ADMIRALTY SURFACE WEAPONS ESTABLISHMENT

A solid-state X-band radar beacon. Radar transponder beacons or Racons have a variety of possible marine applications and are already used as an aid to navigation in identifying lighthouses and lightships. The present designs of beacon use a magnetron transmitter and klystron local oscillator. The experimental beacon exhibited uses only solid-state components, including the X-band transmitter. The power output is much lower than in the magnetron equipments as this beacon is intended to have shorter-range applications such as marking harbour entrances. Owing to its small size and power requirements it could be mounted on a light buoy.

The beacon transmitter consists of a continuous-wave operated solid-state multiplier which delivers 150 mw over the marine radar band from an input power of about 5½w. The frequency is swept electronically through 150 Hz by a 75 s duration sawtooth waveform applied to a varactor diode in the oscillator circuit. The output of the transmitter is controlled by a p-i-n diode switch. In operation the transmission from the ship's radar is received by the omnidirectional aerial of the beacon and amplified in a crystal video receiver which uses integrated circuits. The output from the receiver operates the p-i-n diode switch to give a transmitted pulse of 12 μs duration (1 nautical mile), which is fed to the omnidirectional transmitting aerial. A single biconical horn and circulator could be used in place of the aerial exhibited. The beacon response appears as a radial line on the radar plan-position indicator. In order to ensure a response the sweep rate must be such that the frequency is within the receiver bandwidth of the radar for a complete rotation of the aerial. To cover X-band marine radars a 75 s sweep is required.

ADMIRALTY UNDERWATER WEAPONS ESTABLISHMENT

Electrostatic calibration of hydrophones. Hydrophones for underwater sound measurements are normally calibrated in a large body of water in 'free-field' conditions. Obtaining an accurate voltage-to-sound-pressure calibration over a wide frequency range is a complicated and time-consuming procedure. The apparatus shown was developed for calibrating small hydrophones in air by applying a periodic electric force to the hydrophone face. It is quick and convenient in use, and readings may be taken at any frequency up to 60 kHz.

The hydrophones which are calibrated in this apparatus are small flush-mounting units used for measurements of pressure fluctuations associated with the hydrodynamic flow around experimental underwater vehicles. These hydrophones have sensitive faces ranging from $\frac{1}{8}$ in. to 1 in. in diameter. For calibration the front of the hydrophone is ground flat and then positioned accurately 0·01 in. from a flat counter-electrode. This electrode is energized with an alternating voltage plus a d.c. bias of 500 v. The ratio of the hydrophone output voltage to the alternating drive voltage is determined with a variable attenuator and the hydrophone sensitivity is derived very simply from this ratio.

The accuracy of the method depends mainly on the precise setting of the air gap and adequate

rigidity of the hydrophone and electrode mountings. Comparative measurements with the apparatus in air and in helium have shown that errors due to the impedance of the gas in the gap are insignificant over a frequency range of 1 to 60 kHz.

The method is particularly suitable for calibrating flow-noise hydrophones because the sensitivity to be determined is the sensitivity to local pressure fluctuations, not the free-field sensitivity. Conventional calibrations of these hydrophones in free-field in water require a large correction for diffraction by the hydrophone housing, with some uncertainty in the final answer; the electrostatic method avoids this difficulty, and at the same time makes it possible to complete in half an hour a calibration which formerly took about two days by conventional methods.

NAVAL CONSTRUCTION RESEARCH ESTABLISHMENT

Noise, shock and vibration isolating mounting. Essentially the mounting, which is dissipative in action, is made from four U-shaped metal leaves riveted together at top and bottom with spacers and faceplates holding the leaves in position. The production prototype mounting is made of stainless steel, but mountings constructed from maraging and high-carbon steels, as well as from beryllium copper, have been evaluated.

The space between the leaves is filled with an epoxy resin damping compound developed at the Admiralty Materials Laboratory and the whole is coated with a neoprene paint. The high energy dissipation in the damping material is obtained as a result of the strain induced in this material as the space between the metallic leaves expands or contracts during mounting deflection. High-impact nylon washers backed by high-strength metal washers are provided for load bearing and improved noise attenuation.

The mountings were developed primarily to protect delicate ship-borne electronic equipment against shock from underwater explosives. Low transmitted shock accelerations are obtained by combining a large permitted deflection in every direction with a high energy loss within the mounting. In addition to these shock characteristics, a noise isolation comparable with that of the best rubber mountings having the same natural frequency has been obtained. At the lower frequencies the magnification at resonance is limited by the large amount of damping in the mounting, values of 15% to 30% critical damping being typical.

As the damping material has a very low static stiffness, the load-bearing characteristics are deter-

mined entirely by the metallic parts of the mounting. Thus high damping is combined with a minimum amount of creep. In addition the materials from which the mounting has been constructed have been selected to give a good life under fatigue and not to deteriorate unduly when exposed to oil or salt water.

SERVICES ELECTRONICS RESEARCH LABORATORY

Ion implantation and its application to semiconductor devices. Semiconductors are normally doped by diffusion or by incorporation of impurities into the host lattice during the growth of the crystal. The exhibit showed an alternative technique in which the impurities are produced in the form of ions, accelerated in high electric fields and allowed to impinge on the crystal to be doped. The beam penetrates the lattice to fairly discrete depths depending on the particle energy and the direction of the beam relative to the major crystal axes. Damage to the crystal can be minimized by subsequent heat treatment, usually in the temperature range 600 - 800°C, and during this process a high percentage of the impurities can take up substitutional positions in the lattice, thereby becoming electrically active.

The main advantages of this process are as follows:

  (i) The high degree of control of doping level and doping depth that can be achieved.
 (ii) Doping profiles can be obtained that are not normally possible by other means.
(iii) The annealing is carried out at relatively low temperatures.
 (iv) Impurities can be introduced that are not normally chemically soluble.

The assessment of ion implantation as an additional technique in the manufacture of semiconductor devices is part of a programme being carried out at S.E.R.L. in close co-operation with Industry. Some fundamental concepts of ion implantation, such as the dependence of range on the alignment of the crystal, were demonstrated together with methods for determining the electrical properties of implanted layers. Results of electron microscope examination, carried out by the Plessey Co. Ltd., of damage caused by the passage of heavy ions through silicon was also shown.

The use of ion implantation in the manufacture of advanced devices was demonstrated by presenting results of research programmes currently being carried out at S.E.R.L. and by Associated Semiconductor Manufacturers Ltd. These devices included avalanche photodetectors, variable-capacitance diodes and high-frequency bipolar transistors.

OBITUARY

J. CLARKSON, B.Sc., A.M.R.I.N.A.

James Clarkson of the Naval Construction Research Establishment, died in an accident on Ben Nevis on 17th March, 1968, at the age of 40.

He was by training a Civil Engineer, going on from Cheltenham Grammar School to Bristol University in 1945 where he graduated with First Class Honours in 1948. It is understood that the examiners never solved the problem of devising papers in Engineering Mathematics in which he would get less than 100% without automatically causing most of the other candidates to fail. After a short spell with Bristol Aeroplane Company Limited the joined the R.N.S.S. as a Scientific Officer in early 1951 and joined N.C.R.E where he remained throughout his career. He was promoted rapidly and became an S.P.S.O. (Special Merit) in 1965.

He early showed himself to have a rare combination of theoretical and experimental insight and a series of fruitful investigations in structural mechanics was carried out, with a meticulous insistence on experimental confirmation of all theoretical results. He established an international reputation in the ship structures field, his book " The Elastic Analysis of Flat Grillages " being
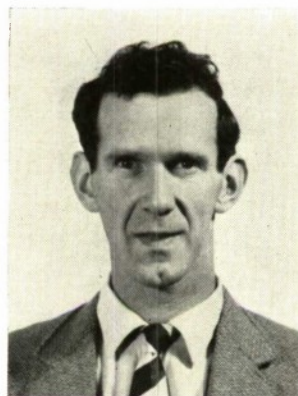
published in the Cambridge Engineering Series in 1965. He was, at the time of his death, Chairman of a Sub-Committee of the International Ship Structures Congress dealing with the design of stiffened plating. Apart from these specialist interests, he most competently worked and advised on many aspects of ship structural design. In recent years he had been interested in the use of glass reinforced plastics as a material for ship structures and he quickly established himself in this area as a man with something worthwhile to say.

Jim Clarkson delighted in the outdoor activities for which Scotland offers opportunities. He enjoyed canoeing and ski-ing, in the latter having a healthy disrespect for those who regard skis as a useful means of transport from the top to the bottom of a chair lift. He was also the prime mover of a band of colleagues who went swimming regularly in the lunch hour, only resorting to the Baths when the pack ice appeared likely to invade the Forth. But his main love was mountaineering. He was at one time Secretary and currently Treasurer of the

Junior Mountaineering Club of Scotland and led its expedition to Greenland in 1961. He was an experienced and responsible climber and the tragedy of his death is enhanced by the fact that he was the last person to take unnecessary risks and was not climbing when he fell to his death in very bad gale conditions.

He had long appeared to his colleagues to be an incorrigible bachelor when five years ago he married. The years that followed gave great pleasure to all his friends who saw him revealed as a devoted husband and father, adding gardening and other home loving skills to his repertoire.

To his wife, Mary, and to Alastair, aged two, goes the heartfelt sympathy of a very wide circle of friends and colleagues both in work and play.

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N. WOOTTON, R.N.S.S.

The start of Christmas 1967 was a sad one for the colleagues of Nelson Wootton, whose sudden death occurred in his office at A.S.W.E. on the afternoon of December 22nd.

Nelson Wootton joined the Government service as a test inspector with the Air Ministry in September 1940 after spending the previous nine years of his working life as a radio and television maintenance engineer with his own business in Surrey.

Whilst employed by the Air Ministry he was engaged on the final test inspection of radio transmitters and

receivers at various factories and in aircraft at Vickers Armstrong, Weybridge.

In April 1942 he was appointed as a T.E.A.III in what was then the Admiralty Signal School at Eastney Barracks where he joined the team, led by Dr. Landale, engaged on the development of the transmitter for the Type 274 radar. He remained in this group until after the war and was employed on the development of the transmitter and modulator for Type 980 and on its ultimate fitting at the trials site at Tantallon in 1945.

Nelson Wootton had been promoted to a T.E.A.II in 1944 and was appointed as an established Senior Scientific Assistant following the re-organisation of the Scientific Civil Service in 1946.

The next move was to the project group formed to develop a tracking radar for a long range gunnery system, and which later became the *Seaslug* Tracking and Guidance radar. Though he remained in the G.W. radar division for the rest of his life, he was employed on a wide variety of work including the development of equipment for trials recording and analysis. The work covered the field of optical, magnetic and teleprinter systems, and Nelson took part in many of the trials at the guided weapons range at Aberporth.

Following the completion of the *Seaslug* I programme, Nelson Wootton remained on the development of equipment for the *Seaslug* II radar trials. Finally for his last four years he worked in the project team responsible for the development of the Tracker Illuminator Radar for the *Sea Dart* weapon system.

To all his colleagues at A.S.W.E., Nelson Wootton will be remembered as a helpful and willing member of their team who would " fix " any piece of equipment for them, be it electronic, optical, or electro-mechanical. Nelson, whose age was 54, leaves a widow and one son.

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CORRESPONDENCE

To The Editor,
Journal of the Royal Naval Scientific Service

Dear Sir,

I would like to congratulate you on the account of Dr. C. D. Lawrence's career in the last number of the Journal and would like to add a tribute, as a member of his staff, to his outstanding qualities. He had that indefinable quality of being able to arouse the loyalty of his staff which was in part attributable to his concern for their personal problems, as well as with the efficient running of his laboratory and outstations. He was blessed with the ability to recognise the good qualities of his staff and to coax from them their very best efforts, often creating the impression that he had some special source of recruits.

Dr. Lawrence was retiring by nature and never sought the limelight. It was, however, often thrust upon him by his own abilities. He would work quietly and conscientiously at every problem and pursue it through to a successful conclusion.

He was always ready to listen to both points of view in any matter and would weigh the facts carefully before making his decision. Despite the fact that sometimes individual members of staff disagreed with him, he had an uncanny knack of being right, when the matter was viewed in retrospect.

I am sure I echo the sentiment of his staff in wishing him and Mrs. Lawrence a happy retirement in their delightful home on the Isle of Wight.

Yours faithfully,

D. R. Houghton
Central Dockyard Laboratory
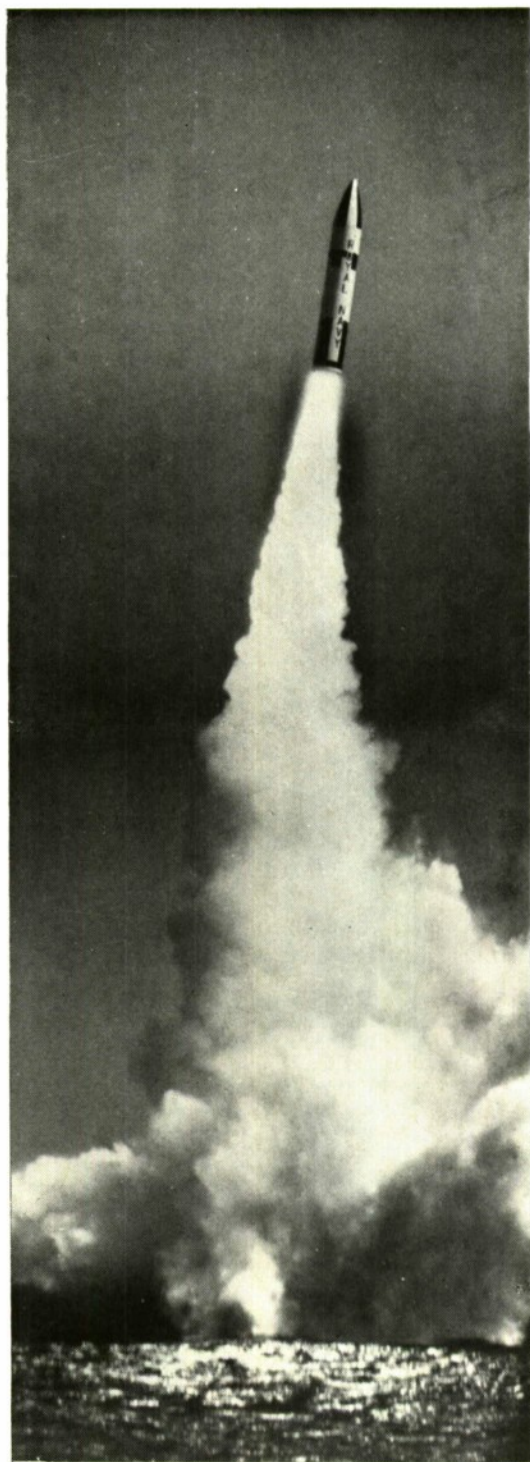
Britain's first Polaris missile
launch from H.M.S/M. Resolution
off Cape Kennedy, Florida,
on 15 February 1968.

Notes

and

News

Admiralty Engineering Laboratory

A visit was recently made to A.E.L. by Mr. Roy Mason, Minister of Defence (Equipment) when he was briefed on the projects under development and the research programme by Captain W. A. Humphrey, R.N., Superintendent and Head of the Mechanical Department, and Mr. F. R. W. K. Mansell, Head of the Electrical Department.

During a busy forenoon, Mr. Mason was conducted around the Laboratories where he talked with Project Leaders and their teams; he also visited the apprentice group training centre. The photograph shows (L. to R.) Mr. J. Peters (private secretary), Mr. Mason, Mr. W. Fearon (Chief Scientist), Mr. Mansell and Captain Humphrey.

During January, a welcome was extended to Sir Alfred Sims who was making his farewell visit to A.E.L. as Director General Ships. Sir Alfred relinquished his post at the end of April and was succeeded as Director General by Rear Admiral R. G. Raper.

Quaver—a new concept in automatic voltage control for brushless a.c. generators developed by the Electrical Laboratory, was shown as a working display on the Royal Naval Stand at the 14th Exhibition of the Association of Supervising Electrical Engineers held March 27th to April 3rd, 1968. This exhibit attracted large numbers of visitors and aroused tremendous interest. Technical representatives of the Central Electricity Generating Board

attended a private conference at the Royal Naval Stand to discuss the system with Capt. D. A. Craddock (R.N. retired) who originated the system. The C.E.G.B. have decided to revise their specifications in the light of this work. During the exhibition many other experts, including overseas representatives from France, Germany and Italy attended discussions on the operation of the *Quaver* system.

Technical explanations and answers to queries were given by Mr. C. K. Aked, Senior Experimental Officer and his colleague Mr. A. W. Smith, Experimental Officer, both of whom have been engaged on the development of *Quaver*.

Quaver will be evaluated under sea-going conditions later this year and is expected to make a fundamental contribution to the stability of ships' electrical supplies.

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Central Dockyard Laboratory

Dr. E. N. Dodd assumed the duties of Superintending Scientist of C.D.L. on 1st April, 1968 following the retirement of Dr. C. D. Lawrence.

The staff of C.D.L. and its outstations, marked the retirement of Dr. C. D. Lawrence, Superintending Scientist, by dining him and his wife, at the Royal Beach Hotel, Southsea, on the 28th March, 1968. The Dockyard was represented by Mr. H. J. Fulthorpe, general manager, and the R.N.S.S. by Mr. N. L. Parr, Director of Materials Research (Navy), who presented Dr. Lawrence with a transistorised tape recorder on behalf of the staff and his colleagues in the R.N.S.S.

An article entitled "Modern Cathodic Protection Practice" by Dr. R. Holland was published in *The Engineer* (2nd February, 1968), 210 - 213. Dr. Holland also delivered a lecture on "The application of cathodic protection to painted steel with particular reference to ships' "hulls" to the Joint British Corrosion Group at the Society of Chemical Industry on 20th March, 1968.

Mr. J. C. Rowlands gave a lecture on "The effect of Alloying on Corrosion", at a symposium on Corrosion Phenomena held at Woolwich Polytechnic, 13th March, 1968.

Mr. D. R. Houghton, was nominated as one of the two vice-presidents of the Permanent International Committee for Research on the Preservation of Materials in the Marine Environment, at their last meeting on the 25th/26th March, 1968.

A "workshop" run by the O.E.C.D. Group on the Preservation of Wood in the Marine Environment, was held in Portsmouth from the 27th March - 3rd April, 1968, at which Mr. D. R. Houghton presented a paper on "Barnacles and the Importance of Environmental Factors".

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Services Electronics Research Laboratory

Mr. M. Hillier attended the North Herts Productivity Association Seminar on "Capital Investment Appraisal" in Letchworth on 7th February, 1968.

A party of undergraduates from the Cambridge University Physics Society visited S.E.R.L. on the afternoon of March 6th. Projects in the establishment which were demonstrated to them included neutron tubes, gas lasers, holograms and gallium phosphide lamps. This visit was organized by Mr. J. W. Allen.

Applications of the carbon dioxide laser were demonstrated on the S.E.R.L. stand at the Industrial Exhibition of the North Hertfordshire Productivity Association at Stevenage.

Mr. M. Hillier was responsible for the laser exhibit in which the cutting of complex shapes in materials such as paper and fabrics was exhibited. This attracted considerable interest from those who attended the exhibition.

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Seminar on Deep Diving Technology

The Navy Department, in association with the Ministry of Technology and the Construction Industry Research and Information Association held a Seminar on Deep Diving Technology, on 12th March, 1968, at the Royal Naval College, Greenwich.

The Seminar was opened by the Right Honourable Roy Mason, M.P., Minister of Defence Equipment. The meeting was chaired by Mr. A. W. Ross, O.B.E., Director of Naval Physical Research and addressed by Mr. W. J. Charnley, Head of Research Planning, Ministry of Technology.

The aim of the meeting was to discuss the release to Industry of information obtained by the Royal Navy in the course of its experimental deep-diving programme and to examine the possibilities of Ministry of Defence and Industry collaborating in future research and development in this field in order to obtain, economically, further information and equipment to meet common requirements.

The morning session was devoted to the current status of deep diving in the Royal Navy and included papers on the techniques and equipment required, physiological problems involved, and medical and safety aspects of diving to depths down to 800 feet.

In the afternoon speakers covered the immediate and future requirements for research and development of both the Royal Navy and Industry, and Ministry of Defence and Ministry of Technology views of the advantages to be gained from collaboration in research and development in this field. This was followed by an open discussion on the desirability of collaboration and ways of bringing this about.

Invitations to attend the Seminar were issued to 69 firms, covering broad interests in underwater technology, 22 Government Departments, seven Societies and Institutions, and six Universities and Colleges, as well as to representatives of the Scientific and Technical Press. These resulted in some 120 representatives attending the Seminar, many of whom participated in the discussions which took place after the various papers had been presented.

Those papers presented by members of the Navy Department are to be published in our next issue.

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Britain's First Polaris

A *Polaris* missile was successfully launched on February 15th for the first time from a British submarine. H.M.S. *Resolution* was cruising submerged about 30 miles off Cape Kennedy, Florida, when she launched the 2,500 nautical mile range *Polaris* to the target area down the Atlantic Missile Test Range.

The launching and test flight was evaluated as successful in meeting test objectives. The entire operation was carried out by the *Resolution's* Port Crew under the command of Commander M. C. Henry, Royal Navy. The second successful test *Polaris* flight was carried out on March 4th by the Starboard Crew under the command of Commander K. Frewer, Royal Navy.

H.M.S. *Resolution* goes operational in the middle of this year in accordance with the programme. The building of this force has been kept under a firm budgetary control by adopting both in Industry and in the Navy the most up-to-date management methods and to get the first submarine operational in under five years is a considerable achievement.

Book Reviews

ABC's of Fluid Power. By H. L. Stewart and J. M. Storer. Pp. 128. Slough; W. Foulsham and Co. Ltd. 1967. Price 22s.

This book is for the young man commencing a career in hydraulic engineering. It might also be a worthwhile addition to sixth form school libraries.

At the conclusion of each chapter there are review questions which the student may choose to answer.

Being of American origin, there is an introduction for " English " readers. This tends to be on the defensive as if fluid power is thought to lack appeal to the teenage student because it has not the glamour of modern electronics. A better approach would be to point out the potential of fluid power with proportional electronic control. Then if glamour is needed, mention could be made of some of the more exacting applications of remote power control.

Hydraulic and pneumatic components are described in some detail and there are numerous sectioned photographs and drawings. There is a very useful chapter on Fluid Lines and Fittings containing data for selection of the correct bore of pipe for various flows and pressures and also how to determine the maximum permissible bend of flexible hose. Another chapter deals with Filters, Lubricators and Dryers but the need to avoid contamination of components and fluids is not clearly stressed.

This book shows the reader what most hydraulic and pneumatic components look like and what is inside them. It does not show him how to combine them into a working system. Yet the last chapter presumes that the student can determine whether to use a pneumatic or hydraulic system for a given application when armed with the academic knowledge gained so far.

I would prefer the last chapter to have been devoted to pneumatic and hydraulic circuitry to instill a basic working knowledge of conventional systems.

A useful but not outstanding book.

D. V. Cross

Direct Readout Meters. By John D. Lenk, Pp. 144 + two pull out diagrams + four introductions. Slough; W. Foulsham & Co. Ltd. 1967. Price 26s.

This is the latest in the series of Foulsham-Sams joint Anglo-American technical publications.

The volume describes the classification and operation of the main types of digital voltmeters and also includes two analogue voltmeters using similar techniques. The first three chapters are devoted to the simple theory, at block diagram level, of the successive approximation, continuous balance, ramp, integrating and potentiometric methods of converting voltage input to digital readout. The advantages and disadvantages of these types are discussed together with such digressions as clip-on meters, sampling, average, peak and rms measurements. This basic theory is well described at a qualitative level and is suitable for equipment operators or for laboratory technicians at an early stage of their training.

The remaining four chapters give detailed circuit descriptions and theory of operation of six production meters of United States origin as examples of the main types of meter. In one case, at least, and, it is suspected, in all, the description given is a direct copy of the relevant section of the makers handbook on the instrument and as such is not the ideal description for a book of this type. This short cut to book writing causes one to have doubts as to the qualification of the author to write this book. As is regrettably common with makers descriptions, the prime object appears to be to mention every component in the description, giving all equal weight, regardless of whether their function is of primary or secondary importance to the signal flow. Because of this, some descriptions are hard to follow, particularly when they relate to a wiring diagram rather than a circuit diagram as is the case for one instrument described.

There is evidence of sketchy proof reading shown by several errors in both print and diagrams. Some of these errors are serious as they may be accepted by the reader at whom this book is aimed. Examples are, reversal of waveform, numerator and denominator reversed, " up pulses " labelled " down pulses " etc. The author also appears to use his own logic symbols for which there can be no justification when MIL-STD symbols are in general use in the U.S.A. To make matters worse, having defined his symbols in chapter 4, they are then incorrectly applied in succeeding pages.

As is standard in this series, the contents are prefaced by several pages entitled " It is essential that the English reader should read this chapter " which contribute nothing to the book apart from defining VOM and VTVM which could well have been inserted in the glossary at the end.

The general impression is of a book useful in conception but marred in execution by the several faults outlined above.

J. D. Locke

101 Questions and Answers About Transistors. By L. G. Sands. Pp. 108. Slough; W. Foulsham & Co. Ltd., 1967. Price 21s.

Transistor techniques are now approaching international standardisation and although this book is American in origin, its usefulness in British hands is not impaired.

The text begins with an excellent chapter by W. Oliver (G3XT) in which differences between European and Transatlantic terminology and application are explained and discussed in some detail where necessary.

The contents are divided into five parts. The first part deals with the construction and characteristics of transistors, starting with basic transistor operation. Parts 2, 3 and 5 carry the basic operation into AF, RF and Control applications and Part 4 is devoted to oscillators. The inclusion in Part 4 of a table showing the most suitable oscillator for a given application would be a helpful adjunct.

Most of the answers are accompanied by an illustration or explanatory circuit. These circuits naturally do not have the component values given. The experimenter and technician could determine the values of Rs and Cs if he desired to construct a demonstration circuit but the layman would be in some difficulty. Fig. 2-20 gives component values for a magnetic pick up preamplifier but Fig. 2-19 does not give values for the high-impedance pick up preamplifier. This seems illogical. The use of a " field effect transistor " as a high impedance input device should be explained in Answer 51.

Some knowledge of electronics is essential to get the most out of this book. Armed with this, the student can identify each transistor module and its function and

then recognise it in a more complex circuit. In this way a better understanding of the functioning of a complete piece of apparatus can be obtained. To those who find the jargon of modern electronics confusing this book is also a dictionary.

A worthwhile and useful book.

D. V. Cross

Wave Propagation and Turbulent Media, By R. N. Adams and E. D. Denman. Pp. viii + 126. New York; American Elsevier Publishing Company, Inc. 1966. Price 65s.

This book is Volume 6 in a series entitled " Modern Analytic and Computational Methods in Science and Mathematics " and, like Volumes 1 and 2, is primarily concerned with the solution of the wave equation by the " Invariant Imbedding " Technique. This is an iterative method, well-suited to a computer, by which solutions of increasing complexity are built up by the use of recursive functions.

In the problem discussed here—the passage of plane waves of electromagnetic noise through a medium of stratified refractive index—the " complexity " is the number of strata into which the medium is divided. Turbulence is simulated by a Monte Carlo type of computation, in which refractive indices are varied according to a quasi-random Gaussian law. The results are presented as 70 histograms of computed distributions of reflection and transmission coefficients, for various types of white and band-limited noise.

This part of the book, in context and length, would form by itself a reasonable paper in a journal. To expand it into book length, the authors have added a short (but well written) introduction on the known methods of solving the wave-equation in non-isotropic media (WKBJ approximation, etc.); a comprehensive bibliography; and a number of appendices, most of which simply reproduce elementary book-work e.g. a description of the χ^2-test and the generation of pseudo-random numbers, while the last gives the Fortran computer programme *in extenso*.

The style and presentation cannot be commended. Nomenclatures in text, formulae and figures often do not agree, and the English is at times almost incomprehensible (Example: "Although the total thickness is $0.40\lambda_0$, the results given illustrate the effects of turbulence at a greatly reduced computation time compared to a total thickness of several wavelengths "). In fact, though the authors claim that study of the histograms presented will give the reader a " general feeling for the contribution of turbulence to electromagnetic scattering ", the reviewer obtained an equally intense understanding of turbulence simply by struggling through the text !

It is clear that, although the specialist in this rather limited field may find it worthwhile adding this book to his collection of references, it is unlikely to be of much use to the general reader, who would be paying rather dearly for the 20 pages or so that would suit his needs.

M. J. Daintith

The Journals of Captain James Cook—The Voyage of the " Resolution " and " Discovery ", Vol. III. 1776-1780, edited by J. C. Beaglehole. Parts I and II. Part I. 718 pages + ccxxiv, 68 illustrations, 13 sketch maps; Part II, pp. 719-1647 + viii, illustrations 69-78, two figures. Cambridge; Cambridge University Press (for the Hakluyt Society), 1967. Price 315s.

These truly majesterial volumes must contain what is the definitive account of Cook's tragic last voyage in the Pacific. His first two voyages of exploration in 1768-1771 and 1772-1775 delineated the modern chart of the South Pacific and had initiated the discovery of Antarctica. These voyages were the subject of Dr. Beaglehole's Volumes I and II of Cook's Journals. This third voyage in which Cook set out in 1776 was designed to be concerned primarily with the northern hemisphere. Its objective was the discovery of " a Northern Passage by sea from the Pacific to the Atlantic Ocean ", that Northwest Passage which had been sought by the English since the end of the 15th century. Its discovery would, of course, have changed the pattern of world trade and this was the object behind the English endeavours. It would have short-circuited the great Cape route to the east. The search took Cook into high latitudes and into the problem of navigating in ice, this time Arctic instead of Antarctic. In 1778 sailing from Tahiti Cook discovered the Hawaiian Islands and in March, sighting the coast of Oregon in 44° N., he then carried out a remarkable voyage exploring the hitherto unknown coast of what is now British Columbia and Alaska. Passing through the Behring Strait he got as far north as 70° and almost proved that there was no such thing as a North-west Passage. He returned to Hawaii to refit and here he was killed in a stupid clash with natives whose reactions to his preparations to use force in order to recover a stolen boat he misjudged. Cook's death did not result in the voyage of exploration being abandoned but Captains Clerke, and after his death Gore, doggedly made their way to Kamchatka, through the Behring Strait and into the Arctic Ocean, once again, finally returning, by way of Japan and Macao, through the South China Sea to an England almost apathetic at their return for the news of Cook's death had been sent overland from Petropavlosk in Kamchatka before the second exploration beyond the Behring Strait.

Dr. Beaglehole's thesis is that while no one can study attentively the records of Cook's third and last voyage without being convinced that it was of the same order of greatness as its two predecessors, it was a mistake for Cook to have been sent on the voyage so soon after his return from the two previous most exacting voyages. In his opinion the authorities underestimated, if they indeed considered, the tremendous mental strain placed upon the commander of such voyages and in his admirable and engrossing introduction Dr. Beaglehole illustrates by example where it would seem that Cook was suffering from nervous strain, just the sort of strain which might lead him, as in fact it did, to misjudge a critical situation with fatal results. The reviewer's mind immediately leapt to the lack of appreciation of the Admiralty in the last war of the strain placed upon the late Captain Walker, the great U-boat killer which led to his premature death. It is an analogy which, it is hoped, will not escape those in the Ministry of Defence in years to come when they have some brilliant officer in their service whom they are tempted to work to death.

It is perhaps needless to say that these two volumes are magnificently produced with immense learning which is, however, transmitted to the reader with most felicitous phrases.

D. W. Waters

A Manual for Capstan Computer Analysis of Projects.
By United Kingdom Atomic Energy Authority
Research Group. Pp. iii + 54. Oxford University Press.
1967. Price 15s.

The Capstan computer programme is one of several
proprietory programmes available for dealing with
Project net-work analysis. The name Capstan is formed
from Computer Analysis of Projects and the initials of
the names of the members who originally developed it
at Harwell. In fact, the Capstan programme is the hub
of a very good three-day course on The Critical Path
Method organised by the Post Graduate Education
Centre at Harwell, a course that your reviewer was for-
tunate enough to attend.

The programme has the following characteristics:—
(a) Only a few minutes of computer time is necessary
on the IBM 7030 computer to handle a net-work of
1,000 activities, the maximum capacity being 3,600
activities for this particular computer (versions of
the programme are available for certain other
computers, but with a lower maximum capacity).
(b) A choice of several different forms of print-out,
selected by punching one master-card, and
(c) The output consists of ordinary and classified
listings, bar charts and allocated resource
histograms.

The main virtue is that the programme is so easily
operated that little basic initial tuition is needed, and
it is not necessary for the user to understand the working
details of the system.

The manual deals with how the Capstan programme
is applied to project net-work analysis, and the main
lay-out covers the principles of Capstan illustrated by a
worked example of net-work analysis, how the cards are
assembled and their punching, and analysing the outputs.
There are three appendices giving examples of computer
printouts and specimen punch cards.

Whilst the manual is written primarily for those who
wish to use Capstan, the worked example of net-work
analysis is worth reading for its own sake.

W. E. Silver

Manual of Mathematics. By G. A. and T. M. Korn. Pp.
xii + 391. New York and London; McGraw-Hill Book
Co. 1967. Price 40s.

This small handbook (approximately 8 in. × 6 in.)
has been written as a condensed form of an advanced
mathematical syllabus for scientists and engineers of
graduate level. Space has been saved by the exclusion
of proofs, and for ease of reference the more important
formulae and definitions have been presented in tabular
form or boxed groups. Each subject is reviewed in the
main text of the relevant chapter, while the more detailed
and advanced topics are presented in small print.

Because of the lack of proofs, the manual cannot be
regarded as a text book, nor is it intended to be. How-
ever, many of the sections are sufficiently comprehensive
to be used without reference to other texts, and when
further reading is found necessary, the reader may be
guided by the bibliography at the end of each chapter.
British readers may find this of doubtful value for the
references are almost exclusively to American texts,
many of which will not be readily available in the U.K.

The first seven chapters are on subjects of long-standing
importance which will be familiar to anyone who has
taken mathematics at undergraduate or National Certi-
ficate level. Complex numbers, analytical geometry and
vector analysis are each treated separately, and calculus
is subdivided into chapters on differentiation and inte-
gration, maxima and minima, differential equations and
functions of a complex variable.

The remaining chapters cover a number of theories
and concepts that have reached positions of importance
in the past decade partly due to the development of
statistical analysis and computers. The theories of proba-
bility and statistics are given a thorough treatment, and
the chapter on modern algebra contains the fundamentals
of abstract models, matrices, linear transformation and
Boolean algebra.

Lists of formulae and numerical tables are given in
the six appendices, the value of which may be deduced
from the fact that more than six hundred standard
integrals are given. The numerical tables consist of the
usual four figure logarithms, power and trigonometric
functions, although the latter are limited to angles at
intervals of ten minutes. There is also a useful list of
units, conversion factors and physical constants, and an
extensive index which will form the basis of an excellent
mathematical dictionary. Even though the graduate
scientist or engineer may already possess much of the
information contained in the Manual, it is doubtful
whether such a wide syllabus is presented in a single
volume in an equally comprehensive yet compact and
well arranged form. Within its particular field, therefore,
the Manual is extremely good value.

D. W. Butcher

Lasers. By K. Patek. Pp. 288. London; Iliffe Books Ltd.,
1967. Price 45s.

As might be expected, the advent of the laser has
resulted in a flood of books mostly intended to acquaint
the non-specialist with the principles of coherent light
sources. Patek's book, however, can be described as a
serious introductory textbook.

The first four chapters deal with physical principles
including stimulated emission, resonant cavities and the
properties of coherent radiation. The next four chapters
describe the different types and design of laser in some
detail, while the final third of the book outlines applica-
tions. A valuable list of some 600 references is included
at the end of the book. If only all authors would emulate
this practice.

The first chapter requires a good knowledge of higher
mathematics as it deals with the quantum mechanical
analysis of non-stationary states. The first and third
chapters suffer from too much statement of fact. A little
more explanation and classification would have been
very welcome, otherwise degeneration into a re-hash of
published papers can easily happen. The lasers them-
selves are well covered although inevitably outdated by
rapid advances in the field. The chapters on applica-
tions are somewhat sketchy and no mention is made
of holography; a curious omission considering the many
papers published on the subject in the last four years.

Despite its shortcomings, which could have been
largely overcome by enlarging the volume slightly, this
book deserves a place on the bookshelf of anybody
whose work involves lasers or desires a serious acquaint-
ance with the subject.

M. J. Beesley

[dstl]

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Record Summary:
    Title: Journal of the Royal Naval Scientific Service
    Covering dates 1968 May
    Availability Open Document, Open Description, Normal Closure before FOI
    Act: 30 years
    Note Vol 23 No 3
    Held by The National Archives, Kew

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Illustrations are in most cases a desirable addition. Photographs should be of good quality, glossy, unmounted, and preferably between two and three times the size of the required final picture. Graphs and line drawings should be made on a similar large scale, with bold lines to permit reduction in block making.

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