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DESIGN AND OPERATION OF A ROTATING CYLINDER APPARATUS FOR RAREFIED GAS DYNAMICS RESEARCH

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FLUID FLOW AND
HEAT TRANSFER
AT LOW PRESSURES
AND TEMPERATURES

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1.0 INTRODUCTION

The problem of determining the flow conditions of a gas near a wall when the mean free path is small but not negligible compared to the body dimension has been considered experimentally and theoretically by many investigators. Theoretical investigations based on hydrodynamic theory (Ref. 1) and upon kinetic theory (Ref. 2) have developed the concept of a slip phenomenon and also have defined a slip coefficient used to describe the action of molecules impinging upon the wall. Early experimental studies by Maxwell (Ref. 3) and Mayer (Ref. 4), who observed the change in period of torsional vibration of disks located close to parallel fixed plates, verified theoretical deductions and provided a determination of an empirical constant over a moderate range of pressures at very low velocity. Kundt and Warberg (Ref. 5), who examined the flow of gases in a capillary tube at reduced pressures, made the first experimental determination of the coefficient of slip. Following these early developments Millikan (Ref. 6) observed the falling action of small drops of oil and determined a coefficient of slip for oil and air. This latter experimental program led to an examination of the slip phenomenon for various boundary conditions and resulted in the development of a slowly rotating cylindrical apparatus designed to determine slip coefficients by a new, accurate independent method at pressures as low as 0.001 mm Hg (Ref. 7). The results of an experimental program with this equipment was reported by Stacy and Van Dyke in Ref's. 8 and 9. More recent work with a rotating cylinder type of equipment has been reported in Ref. 10. This latter program, carried out with surface speeds of the rotor from 400 to 1,700 ft/sec and at pressures from 0.5 to 200 microns Hg, was concerned with the gross measurement of friction on a rapidly moving surface. Total drag measurements, using a concentric balance technique, were correlated on the basis of ordinary viscosity for high pressures, greater than 10 microns Hg, and on the basis of "free molecule viscosity" for low pressures, less than 10 microns Hg.

Recent increased interest in slip flow phenomenon as applied to high altitude supersonic flight problems (Ref. 11) has indicated that further experimental studies should be made with a rotating cylinder capable of operating at high rotational speeds. Such an equipment to be most useful should permit examination of all flow regions of interest in rarefied gas dynamics as defined in the following manner (Ref. 11):

(1) $M/Re < 1/100$ = continuum flow
(2) $1/100 < M/Re < 1/10$ = slip flow
(3) $1/10 < M/Re < 10$ = transition flow
(4) $M/Re > 10$ = free molecule flow

where M represents the Mach number based on the peripheral velocity of the rotor and Re indicates the Reynolds number of the flow where the characteristic length is the radial gap dimension between rotor and stator.

The need for further rotating cylinder studies arose from examination of the fundamental equations and boundary conditions describing rarefied gas flows. The Navier-Stokes expressions relating the viscous stresses and heat flux to gradients of velocity and temperature become incorrect. First order correction terms, the so-called Burnett terms, have been calculated theoretically for monatomic gases from kinetic theory (Ref. 12). Unfortunately for the rotating cylinder geometry, these first order terms disappear identically, at least so far as torque measurements are concerned. It is possible, however, that non-vanishing first order correction terms are present for diatomic gases or gas mixtures such as air. Higher order correction terms, as calculated in Ref. 13, are present even for monatomic gases, but are an order of magnitude smaller and hence very much more difficult to measure. For the determination of the correct slip-flow boundary condition and the evaluation of the empirical reflection and accommodation coefficients, however, the rotating cylinder geometry is excellent.

In addition to the studies noted above, a high speed rotating cylinder equipment would prove extremely useful in the development of "free molecule flow" probes. Such probes, with a characteristic dimension small compared to the mean free path, have been analysed recently (Ref. 14) for use in flow conditions where large shear stresses exist, such as in a boundary layer. Tests of such probes could best be carried out in a known shear flow such as generated by a suitable rotating cylinder equipment.

The Low Pressures Research group at Berkeley has designed and built a high-speed rotating cylinder equipment for the purpose of conducting the investigations outlined above. It is the aim of this report to describe this unit and the associated instrumentation that has been developed.

2.0 GENERAL CONSIDERATIONS

2.1 Flow Requirements

As indicated in Section 1.0, one use of the proposed rotating cylinder equipment was to determine slip coefficients for various gas-surface combinations over a wide range of flow conditions. Examination of the flow regions to be investigated, together with the requirement that substantial peripheral velocities ($0.1 < M < 1.0$) should be developed, indicated that a Reynolds number from 0.001 to 100 should be achieved to span all flow conditions from the continuum region to the free molecular flow region. To insure that this range of Reynolds number could be achieved and measurements carried out with sufficient accuracy for the investigations, a brief preliminary analysis was performed to determine the approximate size of the rotor, the required rotational speeds and the necessary pressure level within the vacuum chamber.

2.2 Design Considerations

A radial gap of one-half inch, the characteristic dimension used in computing the Reynolds number, was chosen as sufficient to allow for the test of small instrumentation in the shear flow between the cylinders. This dimension, once chosen, governs all other critical dimensions and limits the entire design.

The radius of the rotor is controlled by the gap dimension through the desire to minimize curvature effects in the flow and to retain a close approximation to a plane two-dimensional flow. Examination of the Couette flow equations (Ref. 15) indicated that a ratio of gap to radius of 0.0118, gap of one-half inch, radius of four and one-quarter inches, would introduce an error of only 0.38 per cent in the analysis of data, sufficiently small to be neglected in most cases.

For a cylinder with a radius of four and one-quarter inches to achieve the peripheral speeds necessary for the investigations, $0.1 < M < 1.0$, rotational speeds from 4,000 rpm to 40,000 rpm were required. Fortunately commercial centrifuge drives with precise speed control are available in this range.

With the radial dimension of the rotor and the rotational speeds thus determined and the Reynolds number range specified, one can calculate the pressure level required within the vacuum chamber. To cover all flow conditions it is necessary that the pressure be controlled from 3 mm Hg down to 10^{-4} mm Hg, a range that can be achieved and maintained with commercial vacuum equipment.

The length of the drag cylinder was determined by considering two factors. The first factor was the prediction of the drag forces developed by a unit length of inner rotating cylinder. The second factor was the estimation of the end effects upon the gross induced drag of a finite length of drag cylinder. Predictions of drag forces, based upon a theoretical analysis, indicated that forces from 200 mg to 3,000 mg would occur when measured at a radius of five inches for a cylinder length of six inches. To insure one per cent accuracies in the measurement of this range of forces, a system must therefore be sensitive to forces of approximately 2 to 30 mg. The previous success achieved with the use of quartz springs in a one-component balance (Ref. 16) led to the choice of a "floating cylinder" type of torque balance where the force required to restore the cylinder to a null position is measured. This force measurement can be carried out remotely by controlling and recording the extension of a spring with a known force characteristic. Commercial micrometer screws for extension of the spring, mechanical counters, properly geared, for measurement of the extension and inductive transducers for null position indication are available. Quartz springs with spring constants from 4 mg/mm to 600 mg/mm are available and permit a choice of springs for the various tests that will insure one per cent accuracy in the force measurements. The second factor, end effects due to a finite drag cylinder length, were minimized by mounting fixed drag cylinder extensions on each end of the floating unit. These cylinders, precisely located and concentric with the rotating cylinder, were each three inches long. The spacing between fixed and floating cylinders was approximately 0.030 inch, a gap that may introduce a second effect, increasing the induced drag by exposing an area on the end of the floating element. To minimize this possible added drag the ends of the floating cylinder were machined so as to expose only an annular width approximately 0.020 inch wide at each end. This area amounts to less than one per cent of the face area of the drag cylinder and therefore it may be assumed to be negligible for most investigations. Eccentricity of the rotating cylinder within the floating cylinder, if small compared to the radius of the rotor, can be neglected. Examination of the drag relationships, Ref. 15, indicated that an eccentricity of 0.047 inch would result in an error in induced drag of only one one-hundreth of one per cent.

3.0 DESCRIPTION OF EQUIPMENT

The rotating cylinder equipment was completed and placed in operation in September, 1951. Photos 249 and 248 illustrate the equipment as arranged for the initial tests to determine the slip coefficient and other drag characteristics for an air-oil covered surface geometry. The photographs indicate the general placement of the instrumentation relative to the rotating cylinder proper and also the concrete pit used to house the high-speed rotating system. The concrete enclosure is equipped with a hand-operated overhead hoist to handle the balance and drive mechanism prior to vacuum operation. During operation, all measurements of drag, pressure, and rotor velocity can be made outside of the enclosure.

3.1 Vacuum System

A schematic representation of the vacuum system, including pressure measuring devices, is shown in Figure 8. The vacuum chamber housing the rotor and drag balance consists of a cylinder

28 inches in diameter 24 inches long mounted on columns to permit access to the top, bottom and sides. Within the chamber and concentric with it a heavy, 2½ inch thick cylinder has been mounted as a safety precaution. This cylinder is supported by two sets of bumpers which will yield under extreme shock.

The primary pumping system consists of an MCF-700 D.P.I. (fractionating type) oil diffusion pump backed by a 2 H.P. Kinney mechanical pump. The same mechanical pump is used for roughing the chamber and also has an auxiliary vacuum connection to permit throttled pumping operation through a small line for maintaining constant chamber pressures up to 3 mm Hg. The oil diffusion pump is close-coupled to the vacuum chamber with only a six-inch Chapman valve and a refrigerated trap intervening. Isolation of other sections of the vacuum system is accomplished through the use of smaller valves of the Fulton Sylphon and Carotest variety. The structural materials used are mainly low carbon steel and copper. The major interior surfaces of the chamber have been treated with a low vapor pressure varnish to protect the surfaces from corrosion and to alleviate the problem of removing adsorbed and absorbed gas films. The lower plate of the chamber is fitted with instrumentation lead-throughs to permit measurement of pressures and temperatures and also to control electrical motors for the torque balance operation. The upper plate is designed to support the rotor drive and the torque balance. Both plates are easily removable and are equipped with conventional rubber cord vacuum seals.

3.2 Rotor

The experimental tests planned for the rotating cylinder equipment require rotational speeds which induce extremely high stresses in the rotor. The search for a rotor material which would have a high yield strength to specific weight ratio led to a consideration of aluminum forgings. On the basis of published data aluminum forging alloys such as 17S-T6 or 75S-T6 would permit a rotative speed of 53,000 rpm inducing a stress of 58,000 psi at the center of the cylinder. A 17S-T6 forging was selected after thorough inspection had been completed to determine soundness and absence of internal flaws. No inspection holes were drilled along the axis. This solid design should insure reaching the required design speed of 45,000 rpm (M=1.0). The finished rotor has a cylindrical center section 8.500 inches in diameter and 10.000 inches long. The end sections form truncated cones ending in a threaded coupling stud at the top end and a short cylinder at the bottom. The rotor weighs approximately 60 pounds. The critical speed of the assembly is located at approximately 1,000 rpm, a region which is passed quickly during starting and stopping procedures.

3.3 Rotor Drive and Speed Control

The rotor drive mechanism and speed control unit are commercial centrifuge components manufactured by the Specialized Instrument Company. The units are designed for adaptation to vacuum systems with an oil-sealed bearing provided for the shaft which enters the chamber. The drive unit is visible in Photo 248 while the control cabinet is shown in Photo 249.

The drive mechanism is equipped with a special 3 H.P. water-cooled AC motor which is designed to drive the rotor during operation and then to act as a generator to slow the rotation after completion of a test. The output shaft of the drive is 0.100 inches in diameter and is equipped with a coupling, threaded counter to the rotation direction, which can be engaged directly to the rotor. The vacuum seal around the shaft is accomplished through the use of a closely fitted double sleeve bearing which is force-lubricated from the drive gear case. A slight oil leakage into the vacuum chamber results from this seal.

The speed control mechanism utilizes a mechanical feed-back from the rotor drive, whose speed is compared to the speed of a separate synchronous motor. Comparison is achieved through a mechanical differential. By proper choice of gearing, attached to the synchronous motor output, the operator can select a proper comparison speed. The range of speeds over which control can be exercised extends from 12,590 to 74,070 rpm in conventional use and from 4,200 to 24,690 rpm when a reduction gear is used in the feed-back control. Thirty settings can be made within each range. Current control to increase or decrease the drive motor speed is then achieved by the action of switches which are tripped by the movement of the differential cage. Extremely sensitive control can be provided by setting the "on" and "off" switches close to each other. The internal precision of the control mechanism is better than one per cent, however, since comparison is made with a synchronous motor, the accuracy is determined by the frequency of the AC power. Records of the frequency of the commerical 60 cycle power indicate a variation of ± 0.5 per cent over long periods of time. This latter accuracy is probably a more true indication of the performance of this commercial drive.

3.4 Torque Balance

The torque balance is shown in Photo 249 and is illustrated schematically in Figure 7. The unit consists of three cylinders axially aligned and concentric to the rotor. The two end cylinders are fixed and located with a 0.030 inch axial clearance from the center drag cylinder. The drag cylinder is a ribbed thin-walled magnesium structure. The cylinder is partially supported by three floats symmetrically located and immersed in three separate vessels which contain a low vapor pressure oil (butyl phthalate). The buoyant lifting force can be adjusted by raising the oil level to the extent that the cylinder is completely supported. In addition to the restraint imposed by the floats within the oil vessels, three cantilevered thin phosphor bronze springs restrict the cylinder in radial movement. The three springs, 0.003 inch thick by 1.0 inch wide by 15 inches long, are fixed at their lower ends to the lower support ring and are fastened at their upper ends to arms attached to the drag cylinder. When the cylinder is supported by the oil floats, these springs afford moderate rigidity in a radial direction and negligible restraint in a tangential direction. The pertinent data for the drag cylinder are: inside diameter, 9.500 inches; height, 5.500 inches; weight, 2.33 pounds; the inside surface finish has a mean roughness of 125 microinches, determined by visual comparison to standard surface finish samples.

With the drag cylinder delicately supported, the problem of measuring the drag forces can be readily solved. A fine, 0.005 inch diameter wire is attached at its mid-point to one of the three spring attachment arms. One end of the wire is led over a conventional pivoted pulley to the metal core of a Shaevitz transducer and then on to a small pan which can be used for calibration purposes. The other end is led over another pivoted pulley to one end of a quartz spring whose other end is attached to a movable nut. The nut is translated vertically by a micrometer screw which is driven by a small induction motor. The motion of the nut is indicated by a five-place counter properly geared to the screw. In addition a 60 cycle AC selsyn generator is geared to the screw to provide remote counter information. The least count of the counter indicates a 0.001 inch movement of the nut.

With the above balance system induced drag forces could be counteracted and the drag cylinder returned to a null position as defined by the position of a small metal cylinder in the Schaevitz transformer. The induced signal from the transformer is brought out by shielded leads, through an electronic filter to decrease 60 cycle noise, to a Ballentine voltmeter. With these instruments a 0.00025 inch movement of the cylinder could be detected during calibration. In practice however, with counter data remotely received through an electro-mechanical relay system, the least count of the indicating system was of the order of 0.0005 inch. For a spring with a force characteristic of 300 mg/mm this least count corresponds to approximately 4 mg.

Initial tests of this torque balance revealed that the oil used to supply the buoyant force must be carefully treated to preclude violent release of occluded gases within the oil. Violent release of the gases within the oil had two effects: removing the buoyant force and coating the rotor and balance with oil films. This action of the gases was overcome by storing the oil used in the tests in a reservoir where the pressure could be reduced slowly to permit the gases to evolve. When the oil was thus stabilized, it could be drained into the oil vessels in the correct amount for the required lifting force. The oil used was carefully chosen for low vapor pressure characteristics to lessen the release of light oil components during the tests. The oil used was butyl phthalate, which has a vapor pressure of 3×10^{-5} mm Hg at 25°C.

3.5 Pressure Measuring Instrumentation

In section 2.2, consideration of the flow and design requirements indicated that pressure levels from 3 mm Hg down to 10^{-4} mm Hg must be achieved and maintained within the vacuum chamber. To achieve these pressures appropriate pumps were chosen and installed. Maintenance of a constant pressure level, that is a balance of in-leakage and evolved gas versus pumping rate, was insured by providing three channels of variable flow impedance and valving which could be adjusted to control the pumping rate. Measurement of the pressure level, however, is complicated by the fact that no one sensitive element is available which can measure pressures from 3 mm Hg to 10^{-4} mm Hg with an accuracy to satisfy the test requirements. For this reason three pressure-sensitive elements were chosen to measure pressures, each over a limited range. A fourth sensitive element, a Pirani type gage, was used to monitor the pressure level and detect gross changes but was not used for precision measurements. The three fundamental instruments were a precision differential manometer (Ref. 17), a mercury McLeod gage (Ref. 18) and a commercial ionization gage, D.P.I. VG1A.

The manometer, which with the McLeod gage can be seen in Photo 249, is normally used to measure differential pressures, comparing the unknown pressure to a negligible reference pressure supplied by a separate pumping system. The separate system in this case consisted of a D.P.I. VMF-20 oil diffusion pump backed by a Cenco Megavac mechanical pump capable of holding the pressure in a reference manifold to approximately 10^{-4} mm Hg. The limiting factor in the use of the manometer is the least count of the mechanical counter which is 0.001 inch of oil or approximately 0.002 mm Hg. Experience has shown that experimental scatter can be held to less than 0.0007 mm Hg. For one per cent accuracy, therefore, measurements should not be attempted below 0.1 mm Hg.

The ionization gage is a well-known instrument used mainly for measurements below 0.001 mm Hg. The gage used on the rotating cylinder equipment was checked against a secondary standard, an ion gage recently rigidly calibrated, and a maximum error of plus or minus five per cent was noted.

To span the gap between the useful range of the ionization gage and the oil manometer a special mercury McLeod gage was constructed to measure accurately pressures between 0.001 mm Hg and 0.250 mm Hg. This gage resembles well-known basic designs but is equipped with a capillary tube and reference volume selected to give a calibration constant of 1.10 mm Hg per $(cm)^2$ differential. The least count of the gage scale is 0.5 mm Hg and estimates are made within this interval using an enlarging lens mounted on the gage frame. Analysis based on a 0.2 mm length reading error indicates that the precision of this instrument is $\pm$ 0.0002 mm Hg at 0.025 mm Hg pressure, and $\pm$ 0.0006 mm Hg at 0.250 mm Hg. In addition to its use to measure chamber pressures, this primary instrument was used to calibrate the oil manometer and also to check the ionization gage in its upper ranges.

4.0 PRESENT STATUS OF EQUIPMENT

The first experimental use of the rotating cylinder equipment has been recorded in Ref. 15. Rotational speeds from $M = 0.14$ to $M = 0.55$ were used over a pressure range from 0.001 mm Hg to 0.220 mm Hg in a program that extended the results of previous investigators, Millikan, Stacy and Van Dyke, from the slip flow region through the transition region. In addition, an experimental check was made to determine the critical Reynolds number for the special cylindrical geometry described in this report. The success of the investigations was tempered by the action of oil vapors which issued from the oil vessels and which leaked into the chamber through the shaft bearing limiting the lowest pressure within the chamber. Also, excessive oil layers formed on the cool metal surfaces during the investigations limited the surface conditions that could be investigated. To alleviate this oil problem, a torsion wire balance is being constructed which will eliminate the oil vessels. Preliminary calculations indicate drag measurements can be made with a torsion wire balance with an accuracy equivalent to that proven for the older instrument. Further drag studies using other surfaces will then be instigated.

5.0 SUMMARY

A rotating cylinder apparatus has been designed and constructed for studies involving gas-surface interaction phenomenon. The instrument also can be used to provide a shear flow field for the development of instrumentation to be used in a non-uniform stream or in a boundary layer. Initial tests indicate the apparatus performs in a satisfactory fashion permitting tests to be made over a wide range of flow conditions from the continuum region, $M/Re < 1/100$, to free molecular flow region $M/Re < 10$.

GJM:JF/dms/150
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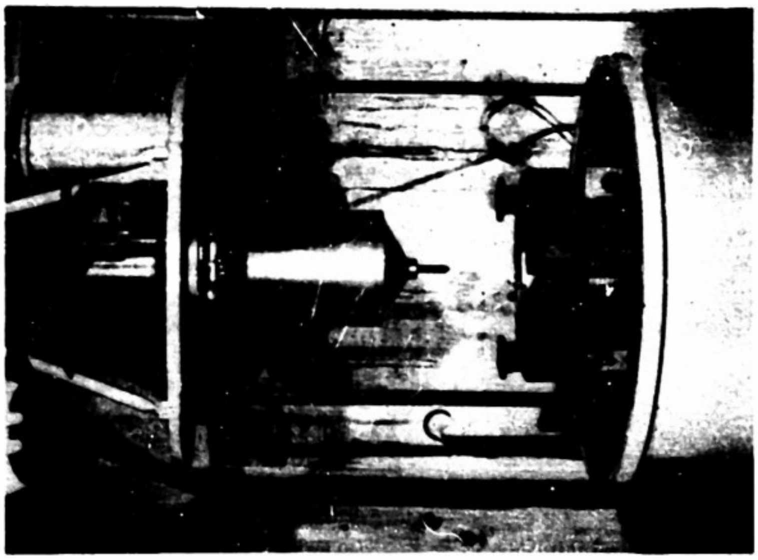
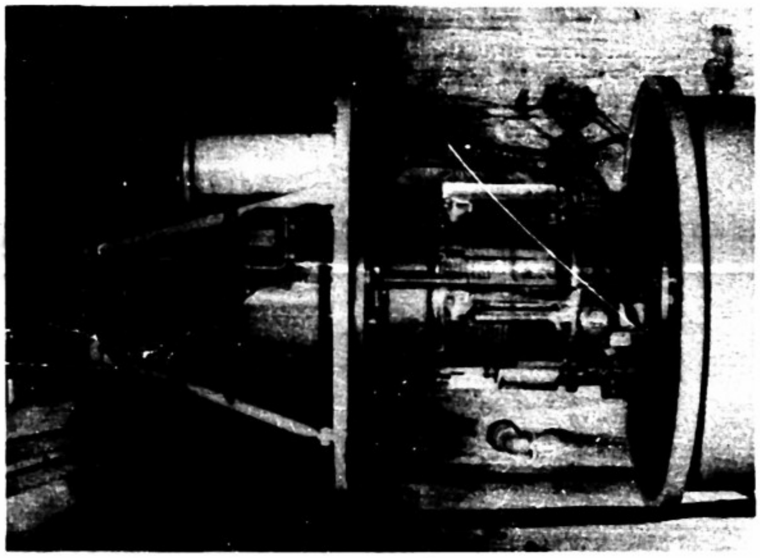




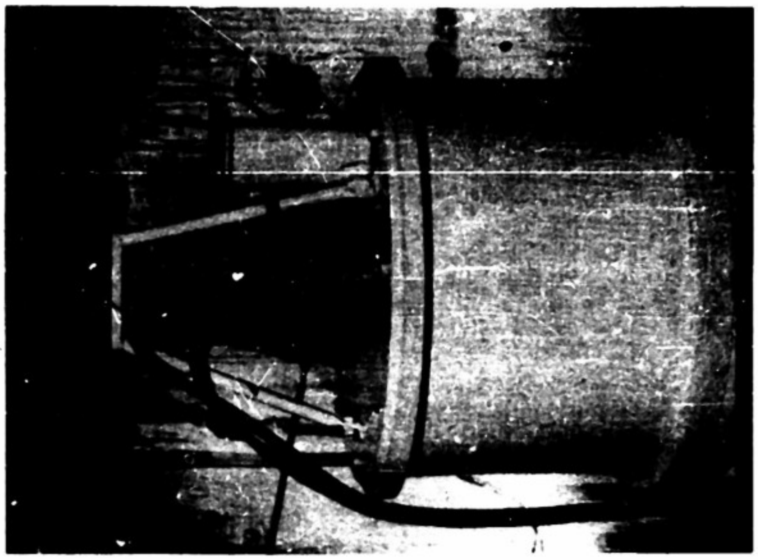
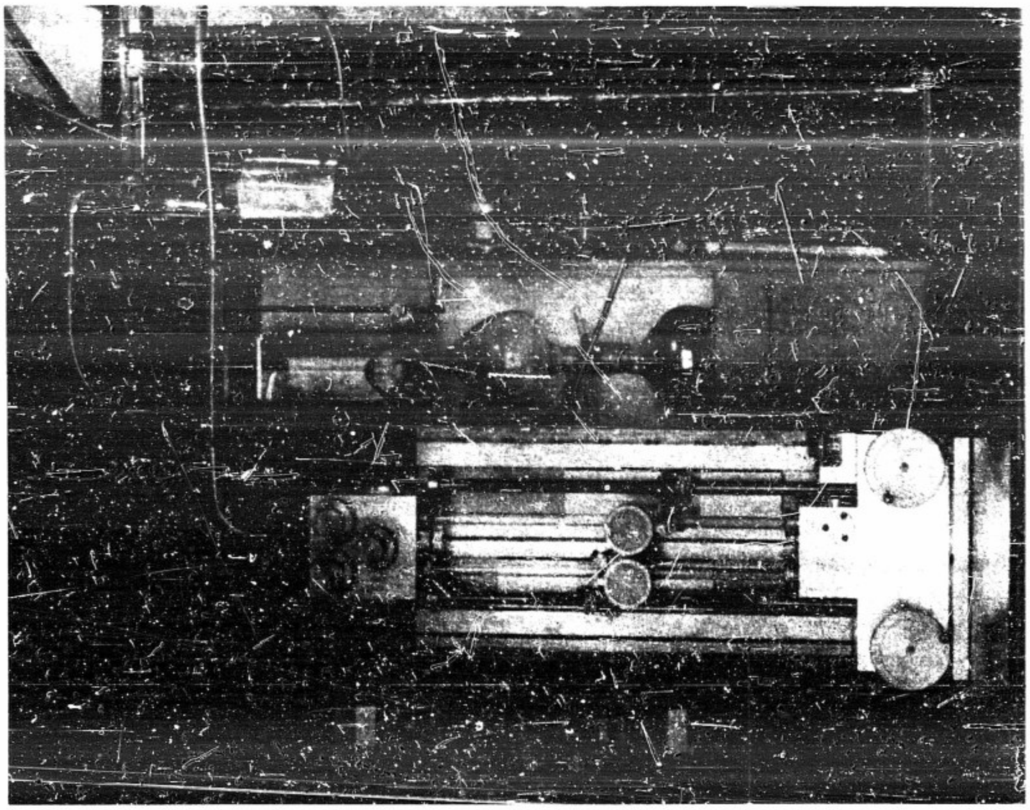
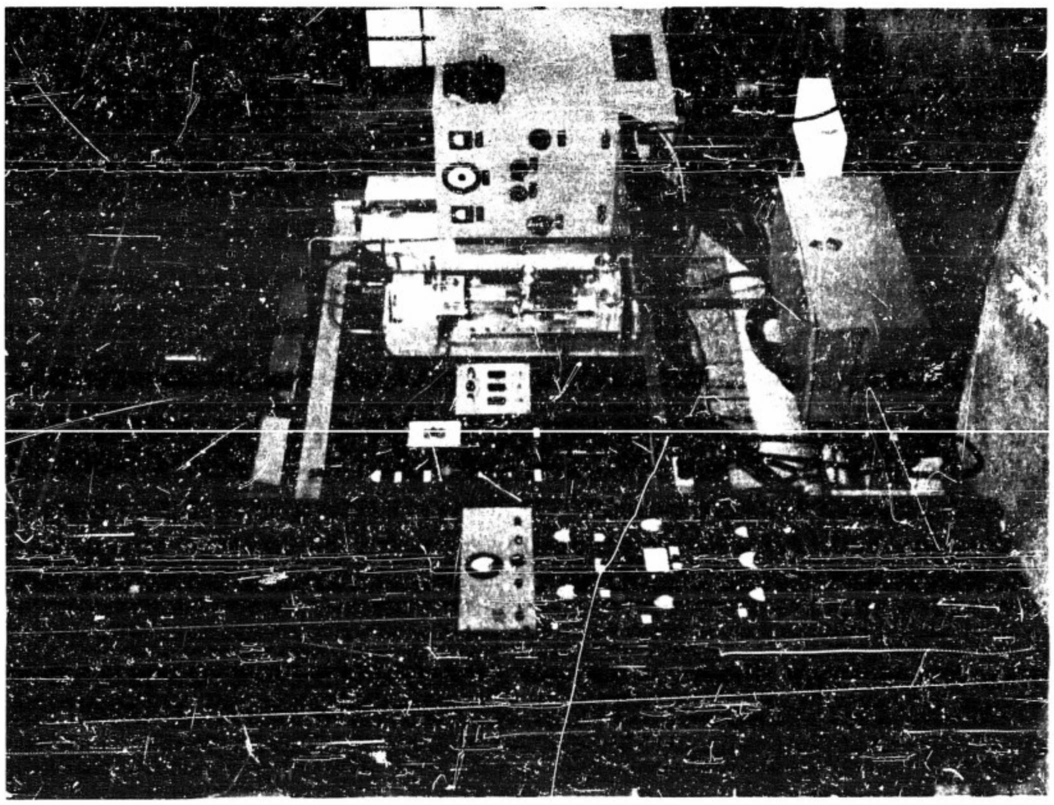


PHOTO 248





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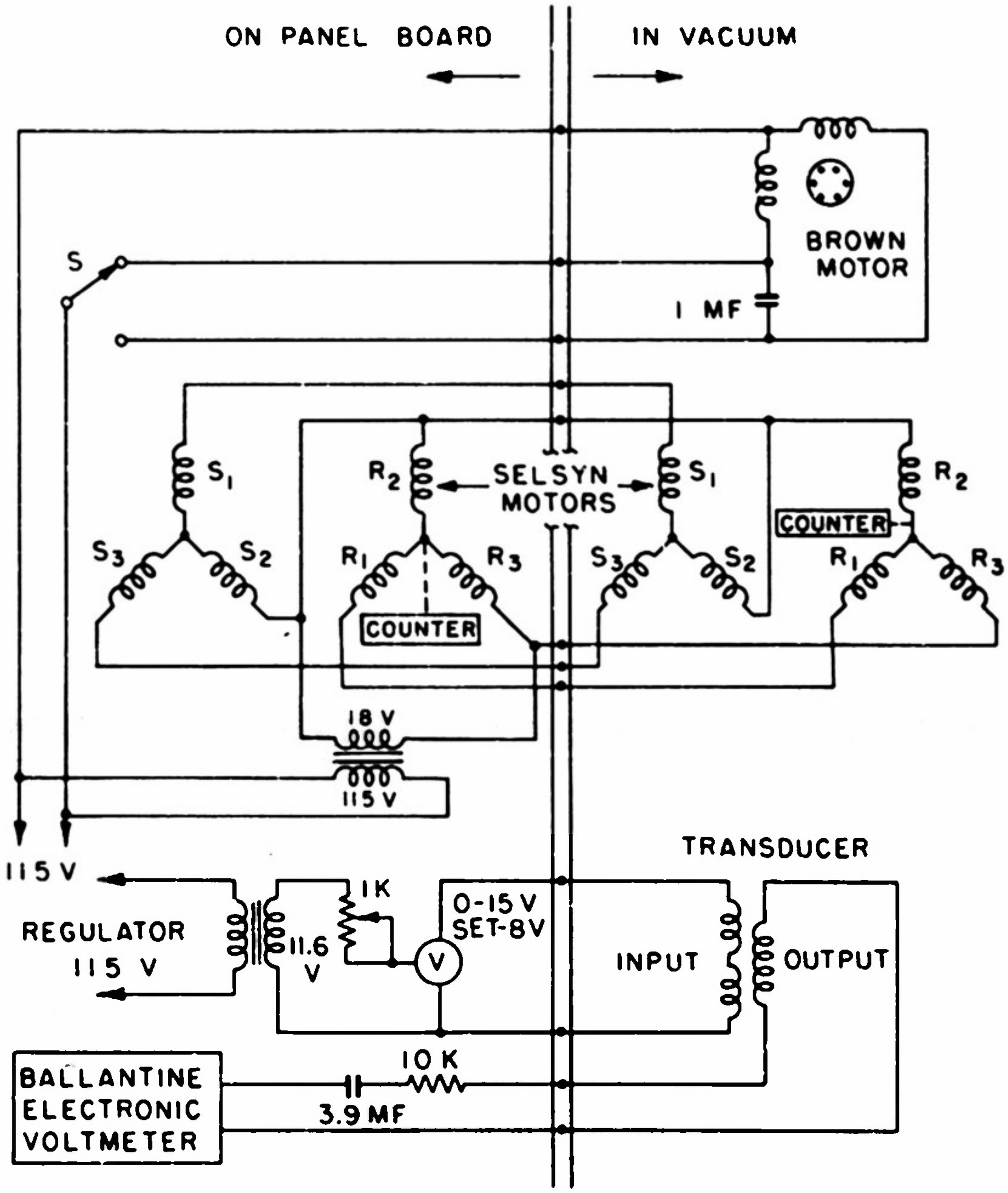

FIG. 6

TORQUE BALANCE ELECTRICAL CIRCUIT DIAGRAM

HYD-2740-150-0

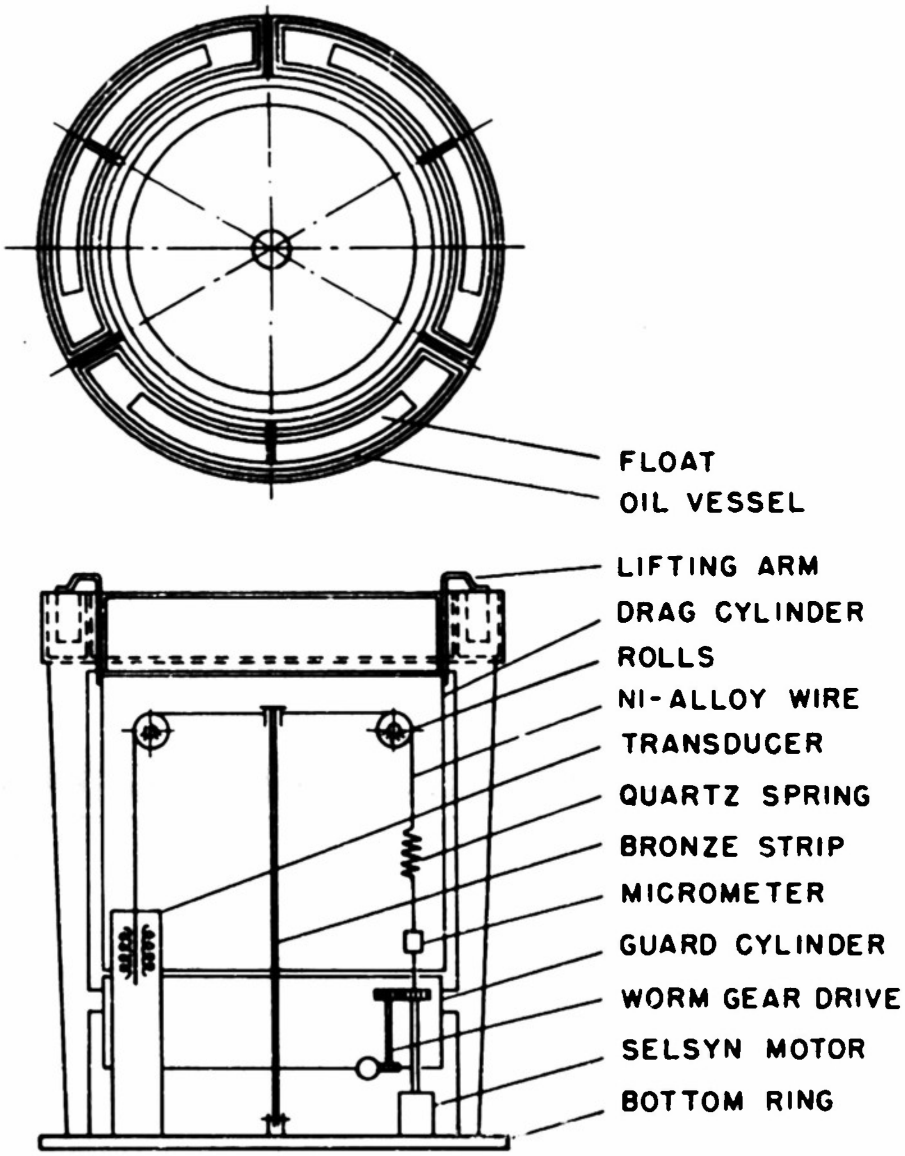

FIG. 7

TORQUE BALANCE - SCHEMATIC

HYD-2715-150-0

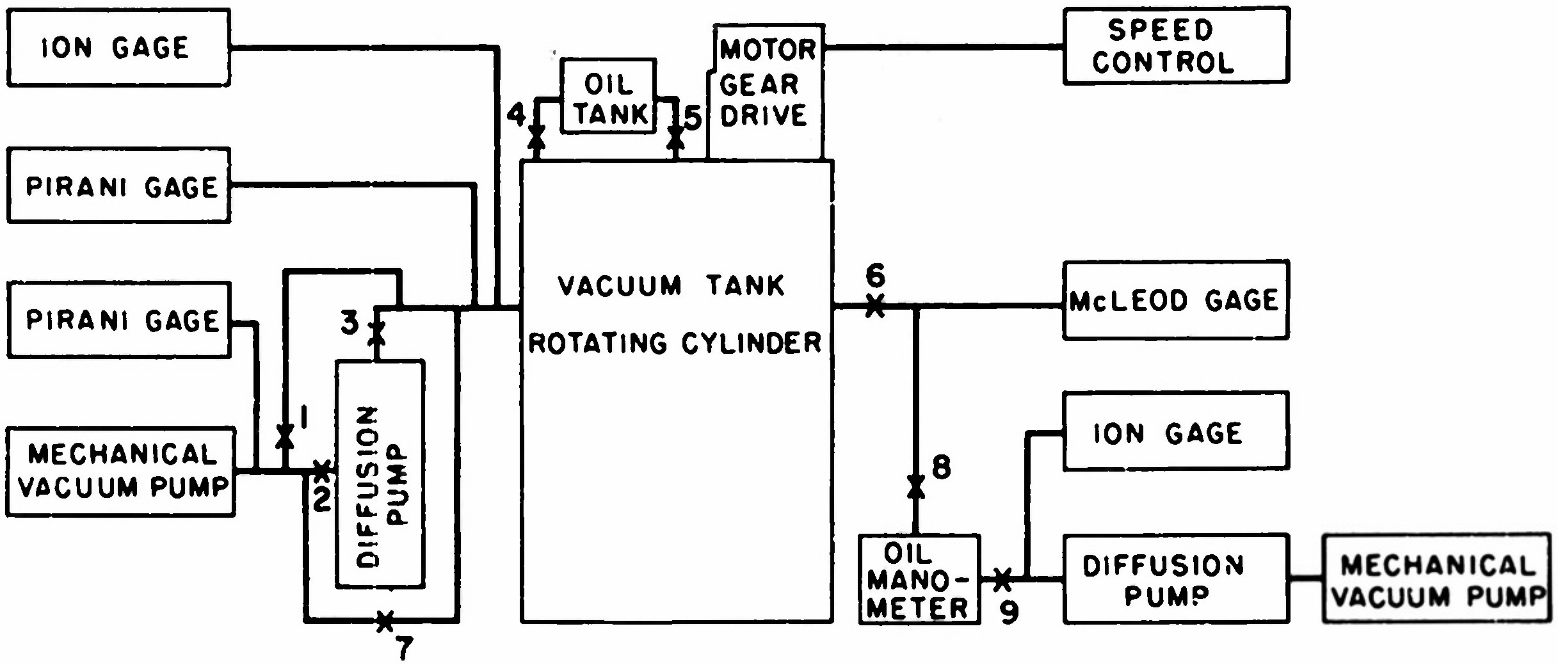

FIG. 8

VACUUM SYSTEM - SCHEMATIC

HYD-2716-150-0