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AIRCRAFT CARRIER TURBULENCE STUDY FOR PREDICTING AIR FLOW DYNAMICS WITH INCREASING WIND-OVER-DECK VELOCITIES

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PREPARED BY S. Frost

APPROVED BY

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An intensive review of literature pertinent to aircraft carrier air flow dynamics and an evaluation of experiments were conducted in order to determine the effects of turbulence on landing aircraft. Particular emphasis was given to the effects on carrier aircraft operations which occur as a result of increasing wind-over-deck (WOD) velocities, as well as carrier dynamics. Recommendations for future experimental and theoretical studies are given.

ABSTRACT

An intensive review of literature pertinent to aircraft carrier air flow dynamics and an evaluation of experiments were conducted in order to determine the effects of turbulence on landing aircraft. Particular emphasis was given to the effects on carrier aircraft operations which occur as a result of increasing wind-over-deck (WOD) velocities, as well as carrier dynamics. The effects of WOD velocities and carrier dynamics on air boundary layer were also considered. Recommendations for future, more exacting data acquisition, experiments, and theoretical studies are given.

SECTION I

INTRODUCTION

A major limitation to increasing wind-over-deck (WOD) resulting from augmented aircraft carrier velocities is the probability of increased aircraft accidents, hard landings, and bolters during landing operations. These effects are attributable to the nonpredictable characteristics of air flow dynamics, which affect aircraft during the approach to the carrier ramp and over the deck immediately before touchdown. With the advent of the high-speed aircraft carrier, the landing operation problem will become more acute. Thus a fuller understanding of carrier air flow dynamics is imperative.

This study program was undertaken primarily to determine if it is possible to land aircraft on carriers with WOD velocities beyond the maximum limits required under present procedures.

Many studies have been undertaken in previous years in which particular emphasis was given to the experimental aspects, while little or no consideration was given to the theoretical aspects of air flow dynamics. The initial considerations in this study were based on an intensive review of the literature on carrier air flow dynamics. Previous studies and experimental programs have indicated that the principal unknown factor pertaining to this problem is carrier air flow dynamics. Based upon the results of these studies, this investigation was concentrated on formulating a workable concept of general air flow properties around a carrier from which predictions can be made concerning air flow effects on aircraft carrier landing procedures. From this formulized concept, an experimental program has been outlined.

SECTION II

SUMMARY OF PROCEDURES AND RESULTS

The objective of this program was the investigation of all available information pertaining to the air turbulence properties within the wake of an aircraft carrier. From the information obtained, a prognosis was to be made concerning the flow field dynamics of the carrier wake. With increased wind-over-deck, these dynamics could prove to be detrimental to aircraft landing procedures. Where no satisfactory conclusions can be obtained, recommendations are made as to the methods to be used in acquiring the necessary information. Because of the program's requirements and because of the time limitations, analyses have not been carried out.

Previous programs have concentrated on the studies of air flow dynamic parameters that are involved with the present landing procedures. These experiments have been conducted within the wakes of carriers and, using scaled models of the aircraft carrier, within wind and water tunnels. The full-scale aircraft carrier wake measurements were obtained through the use of specially instrumented aircraft following normal landing procedures. The pilot's psychological reactions were obtained as well as control stability data of the aircraft. From analysis of these data, the turbulence properties were defined; however, these results are only applicable to the wind velocity at the time that the measurements were taken. They therefore cannot be projected to other wind velocity conditions.

Tunnel measurements were made within the wake of the carrier scale models. In these experiments, measurements were taken along the 4-degree glide path. Initial evaluation of the reduced data contributes little to the understanding of the air flow dynamics around the carrier that could be pertinent to aircraft operations. The preceding statement is based on the following: (1) The experiments and the subsequent analyses were not performed with the intent of making statistical correlation analyses (as was also the case for those programs using instrumented aircraft); (2) aerodynamic scaling factors between the carrier and its tunnel models are difficult to determine because of the lack of measurements within the carrier's wake; and (3) a formulization of a concept, or picture, of the carrier's wake, based upon known theoretical and experimental data, has not been undertaken.

As a result of extensive review of previous reports and documents and of theoretical wake analyses that have already been conducted, it is concluded that, based solely on these past efforts, reliable predictions of the effects that increased wind-over-deck velocities will have upon aircraft landing procedures cannot be determined. Thus, it was necessary to reappraise carrier air flow dynamics so that a workable concept could be formulated prior to considering any new measurement programs. To substantiate this concept, an initial experimental program, utilizing smoke tunnel facilities, has been recommended in order to demonstrate the effects of carrier dynamics upon flow field properties, particularly the turbulent wake. Upon the successful demonstration of these effects, a more detailed wind tunnel measurement program and a full-scale carrier measurement program can be developed.

SECTION III

CONCLUSIONS

In order to formulate a concept of the properties of the carrier's wake turbulence, it was necessary to re-evaluate the experimental data already obtained. One important conclusion derived from reviewing these data is that the flow parameters within the wake appear to be independent of the free stream velocity, the length of the carrier, and the kinematic viscosity (Reynold's number). This is in contradiction to known flying responses of aircraft entering the wake at different velocities of wind-over-deck (WOD). Steady state flow field data gathered in various experimental programs are basically the same with regard to steady state and turbulent flow properties.

Concurrently with this data re-evaluation a preliminary study was made of the boundary layer properties for fluid flow over a flat plate. The theoretical studies for laminar flow over a flat plate have not taken into consideration the pressure gradients within the fluid. As a result, these studies indicate that the boundary layer thickness (the region between the flat plate and the point at which the free stream begins to be affected) and the profile velocities (which decrease the closer they are to the plate) are independent of the velocity distribution immediately above the surface of the plate. Conversely, a given velocity distribution does not infer a given boundary layer thickness or velocity profile.

When the flow over the flat plate exceeds the critical Reynolds number, the boundary layer thickness increases with increasing fluid velocity. There are no indications that corresponding changes must occur within the turbulent regions immediately above the flat plate. From experimental data obtained aft of the ramp of model carriers, it appears that the same conclusions apply for carrier turbulent flow fields as for the flat plate; i.e., the turbulent properties are independent of the free stream velocity.

From the above conclusions and from known aircraft performance characteristics within the carrier's wake, a concept of the wake must be formulated prior to continuing experimental programs. This concept that is based on the premise that the carrier's wake turbulence consists of two different physical states. These states are:

- A steady-state dynamic pressure distribution around the carrier and within the wake, that maintains a fixed spacial relationship with the configuration of the carrier, is independent of time, and is independent of all velocities exceeding a critical value. This steady-state pressure distribution depends only upon carrier configuration and the relative direction of the wind to the carrier.
- Superimposed upon this steady state pressure distribution are the random turbulent flow fields. These are not stationary with respect to the carrier and fluctuate rapidly in time. This turbulence is independent for all wind velocities in excess of a critical flow velocity.

Around the moving carrier and within its wake, a major flow field is produced. This flow field and the free stream laminar regions are separated by a boundary layer. The division of the major flow fields are:

- From the surface of the carrier to the lower level of the boundary layer. Here, there is always a turbulent flow field superimposed upon the steady-state dynamic pressure distribution.
- Boundary layer that oscillates randomly between laminar and turbulent flow conditions. Within this layer there are no steady-state dynamic pressure distributions. With increasing WOD velocities, both the height and thickness of this layer increase. This intermittent boundary layer is believed to be the mechanism that complicates aircraft landing procedures.

- External laminar layer that extends from the top of the intermittent layer to infinity.

The thickness of the intermittent boundary layer increases not only with increasing WOD velocities, but will increase with increasing pitching and heaving motions of the carrier. When both pitch and heave motions are in phase, the intermittent boundary layer thickness will be maximum for a fixed WOD.

SECTION IV

RECOMMENDATIONS

Investigations should be continued into both the experimental and theoretical aspects of the aircraft carrier wake turbulence. The purpose of these investigations is to determine the properties of wake that will be pertinent to aircraft landing procedures with increasing wind-over-deck velocities.

The experimental program would consist of three phases. These phases are:

(1) Demonstration of the dynamic properties of the intermittent boundary layer with different wind velocities and carrier dynamics. This demonstration is to be initially attempted in a three-dimensional smoke tunnel. The first series of demonstrations will be to observe the intermittent boundary layer for two widely separated stream velocities. This demonstration is to be followed by a series of experiments in which the stream velocity is maintained constant and the model is dynamically disturbed in pitch or heave, or both, simultaneously.

(2) Successful accomplishment of the previous phase is to be followed by a series of wind tunnel experiments. These experiments are to be performed at higher wind velocities. Measurements are to be made to determine wake turbulence properties, particularly the growth pattern of the intermittent boundary with changing wind velocities and different conditions caused by the carrier's pitch and heave motions. All wind tunnel measurements should be taken so that statistical and correlation analyses can be carried out.

(3) Measurements are to be made within the wake and around the aircraft carrier. These measurements should be compared with those measurements obtained from the wind tunnel. From the comparison of these two sources of data, it will be possible to

arrive at significant scaling factors to be used in future tunnel testing of carrier models. The correlation analysis of measurements made on the full-size carrier will be similar to that performed with the wind tunnel measurements.

Continuation of the theoretical aspects of the properties of turbulence will require, in addition to a continued study of the literature, consultations with several authorities. The major emphasis of turbulence studies in recent years has been in the sonic and supersonic velocity ranges. Consequently, the technical literature is deficient with regard to both experimental and theoretical investigations for subsonic velocities.

The aspects of turbulence that should be pursued are: properties of the intermittent boundary layer, onset of turbulence, statistical correlation, and the spectral distribution properties of the turbulence as a function of time.

In addition to the continuation of the study of the turbulence, an investigation should be made of the dynamics of the carrier. The dynamic data required are the magnitudes and phase relationships of pitch, heave, roll, and yaw of the carrier as a function of carrier velocity.

SECTION V

TABLE OF CONTENTS

SECTION VI

LIST OF FIGURES

SECTION VII

DISCUSSION

A. GENERAL INTRODUCTION TO CARRIER FLOW CONCEPTS

As of 1965 the accident rate of carrier aircraft landing operations conducted during daytime operations,even under ideal conditions,greatly exceeded that of conventional airfield landings. The carrier rate is approximately 3 per 10,000 landings, which is surprisingly low in view of the difficult piloting task and the landing operating procedures required on aircraft carriers. To obtain this low accident rate it is imperative that the wind-over-deck (WOD) conditions remain below well-defined maximum limits that have been determined through trial and error. These limits are promulgated by means of appropriate aircraft recovery bulletins (Reference 7).

Experimental programs have been undertaken on both full-sized and scaled aircraft carriers at approximate WOD of 35 knots and 120 feet per second, respectively. Organized experimental programs have not been carried out with large differences of WOD velocities on either full or scaled models so as to enable an intelligent analysis of effects on aircraft operations caused by varying WOD conditions on full-sized vehicles.

Measurements with regard to landing characteristics of aircraft on aircraft carriers indicate that safety conditions strongly depend upon WOD properties, the angle of aircraft approach, the carrier design, and the type of aircraft. Figure 1, taken from reference 1, relates the approximate time prior to touchdown where the incoming aircraft encounters the initial effect of the "burble". This effect is primarily a dynamic updraft upon the incoming aircraft which is followed by a strong downdraft immediately aft of the ramp. To compensate for this effect addition of thrust and maneuvering are sometimes applied to the aircraft. With increasing WOD the available time required for this maneuvering is reduced. In order to keep this time within the operating capabilities of both the pilot and aircraft, the maximum WOD has been determined for each aircraft type.

References 1 through 6 appear to be the first experimental attempts to evaluate the dynamic parameters of aircraft landing characteristics. These are the only sets of experimental data available that give some insight as to what to anticipate under different WOD conditions and general flying parameters.

References 2 and 17, in particular, relate the minimum safe angle of aircraft approach with different WOD and aircraft types (see figure 2). Assuming a linear relationship between WOD and the approximate minimum safe glide angle, for a WOD of 50 knots the safe glide angles would be 8 degrees and 7 degrees for propeller and jet aircraft, respectively, and the time of the initial burble encounter will be from 2000 to 2700 feet prior to touchdown for aircraft with present-day approach and engaging speeds.

No conclusions have been arrived at concerning the differential flow directions and pressure gradient along the glide path as a function of WOD and attack angle. The linearity assumption of a linear turbulence velocity distribution is an over-simplification. Some analytical solutions can be arrived at for turbulences a large distance downstream from the wake of the carrier body, but no solutions are available for those close to the body (reference 8). Only a measurement program can yield information as to the flow patterns and turbulent spectral distribution close to the body.

Two types of flow dynamics are to be considered in this program. There is a steady state dynamic flow distribution which is stationary with respect to the aircraft carrier and which is the result of the combined effects of the vortex flow fields around the ship's hull and that produced by disturbances introduced by the design of the deck and the island. The second are the non-steady state flow fields that are superimposed upon the steady state patterns. The non-steady state flow fields may have no correlation with either any portion of carrier's design or the wind conditions. Since this is of major importance to aircraft performance, attempts must be made to determine if such a correlation does exist.

Measurements that have been carried out on scaled models at fixed WOD (figures 3, 4, and 5 of reference 11 and references 7 and 9 through 20) clearly demonstrate the steady state vortex-like flow patterns. From these patterns, taken along a glide path, it is observed that the aircraft will experience differences in flow field directions along its wings. These differences tend to rotate the aircraft. This rotating effect is experienced by pilots during landing operations (references 1, 2, 7, and 17) and is observed to increase with increasing angle between the center of hull line and the direction of the WOD.

With increasing glide angle there will be a correspondingly rapid increase of the accident rate and of the number of hard landings, bolters, and undershoots (reference 10). Similarly, an increase in the carrier's turbulence pattern and steady state dynamic pressure ratios will decrease both the aircraft and pilot's ability to respond. The pilot's response is determined by the Cooper's Index, which represents an accumulation of all the physiological and psychological reactions of the pilot to the dynamics of the landing parameters. Cooper's Index is less than four for present day carrier aircraft landing procedures. When the Index is equal to or greater than five, the pilot's reactions are regarded as unsafe.

Of the experimental literature investigated, with the exception of that of Systems Technology Incorporated (reference 10), only a minimum of investigations have been concerned with the use of statistical correlation analytical procedures for studying the interrelationships of the [illegible] properties to the carrier's design and dynamics. Data comparisons have been attempted to some degree between the full-size carrier and scaled models, but there is insufficient published, measured data on actual vehicles to determine procedures to be used for model scaling; therefore, these attempted comparisons are not valid. On scale models, correlation between simultaneous measurements has not been attempted, and it therefore becomes impossible to determine which parameters of airflow around the carrier are most dominant in influencing the characteristics of the carrier's wake. This is evident as one reviews the literature and observes the empirical procedures that were tried by various laboratories to reduce the burble effect.

In all cases only a minimal degree of the expected results was obtained. In the Dynasciences Corporation report (reference 9), good experimental data have been obtained and evaluated along the 4-degree glide path for the scaled model, but flow data were not evaluated to determine if the turbulent portion is random, and cross- and autocorrelation analysis was not attempted. From their data the turbulent portion of the velocity flow can have peak-to-peak variations equal to approximately eight to ten times the offset of the steady state mean flow rate. At approximately 100 feet aft of the ramp the steady state free stream flow of 125 feet per second is reduced by 20 percent, and, since the net flow rate cannot change, the root-mean-square of the turbulent flow must make up this difference. This data comparison has not been demonstrated in this report.

From their data and steady state flow patterns, it appears that the dominant influence on the dynamic pressure ratio distribution is the vortex flow generated around the hull in combination with WOD that perturbates this flow field. Various carrier modifications attempted, such as honeycombs in the vicinity of the island and numerous ramp modifications, have had only a small effect upon this pattern. (References 16, 17, and 9.)

Scaled models, approximately 1/110 to 1/150, for use in water tunnels, wind tunnels, and smoke tunnels have been employed to study the fluid flow characteristics. (References 9, 11, 15, 17, 18, 19, 30, 31, 32, 33, and 34.) Reynolds scaling, based upon carrier size and WOD velocities, has not been used for the following reason:

Reynolds number (Ne) is a measure of the distance traveled by laminar flow over a body prior to going into a transitional region that oscillates between laminar flow and three-dimensional unsteady turbulent flow. For a given free stream velocity U_o and fluid kinematic viscosity ν_k, Ne will be a direct measurement of L, as shown in figure 6. For a stream velocity of 35 knots (58 feet per second) and a carrier deck length of 1050 feet, the Ne is approximately 600 million. Maintaining a laminar flow for this condition will require an ideal non-viscous fluid, operating at supersonic speeds.

For a flat plate, the critical Ne of 330,000, as shown in figure 7, is the transitional value from laminar to turbulent flow. Many investigators are inclined to regard all turbulent measurements above this critical value as independent of Ne. They regard all turbulence properties as the same for all Reynold's Numbers greater than 300,000. When the data are compared between a 10-foot model and a full-sized aircraft carrier, the resultant data are believed to be equivalent. In wind and water tunnel testing performed at Ne between 300,000 and 1 million, the results appear to be independent of Ne. The same investigators are of the opinion that any difference in flow patterns around the full-sized carrier and around its model are not directly related to their differences in Ne. From this they have concluded that very large differences in Ne produce only a small effect on the flow field properties (references 20 and 25). This statement is in contradiction to known principles and will be elaborated upon in another section.

Another scaling factor that is often considered, particularly with regard to vortex shedding, is the Strouhal number. This factor represents the frequency of vortex shedding from the object. It is given as the product of the frequency of shedding times the object length divided by free stream velocity:

$$S = \frac{fL}{U_c}$$

Since the carrier length, velocities, and frequencies, L_c, U_c, f_c, are known, the model frequencies f_m can be readily determined. This factor does not affect the tunnel experimental conditions but does determine the frequency range that is measured and evaluated.

B. TUNNEL MEASUREMENTS

Since data derived from tunnel testing is of critical importance with regard to this study, the problems presented in using the tunnel techniques should be understood.

The principles of each technique apply equally well to air tunnels and water tunnels. The Image technique has the advantage over the Ground Plane technique in that the model can be supported within the center of the tunnel and will therefore be isolated from any wall turbulence. This technique is based upon the assumption that if a model is constructed with its mirror image, the resultant flow pattern (laminar and eddies) will be identical around an image plane. This can be clearly demonstrated for flow around a circular cylinder (Chapter XI of reference 8 and references 35 through 38) where the flow patterns are similar around both halves. As the stream velocity increases the vortices increase in size, become dynamically unstable, and are then carried away by the external flow. This detachment process is unstable, oscillates incoherently (references 8 and 39), and the pressure distributions are not predictable by potential flow theory. For this condition the Image plane technique will not have a plane of symmetry, and therefore the flow-pressure distributions will differ from that of the Ground Plane technique, that uses the model on a semi-infinite reference plan.

If there are unsteady vortex oscillations, the results of the Image technique will not be applicable to the study of carrier wake phenomena. A Water Cavitation tunnel apparatus, with either stroboatac visual observations or high-speed, pulsed photography, is the procedure used for observation in order to determine if this phenomenon exists for different flow conditions. Because of the uncertainty of the existence of unsteady vortex oscillations, the Ground Plane technique is used with an elevated reference plane.

At the wind tunnel speeds used, approximately 120 feet per second, the wall boundary layer is approximately 3 inches; i.e., one-half the height of the carrier model. To use a Ground Plane technique the model must therefore be placed on a reference plane 3 inches above the tunnel floor.

C. INTERPRETATIONS OF AVAILABLE DATA

A ubiquitous condition appears to exist for all data obtained and is clearly expressed in reference 9, page 32:

Dynamic pressure rates and flow angularity are independent of the carrier speed within the range of velocities tested.

From actual flight data of aircraft carrier operations, it has been established that the WOD has a major effect on flow fields and upon aircraft performance (references 4, 29, 40, 41, and 42). It may therefore be concluded that either the experimental programs are in error due to the combination of techniques and instrumentation procedures or that the observed experimental tunnel data are not indicative of the flow field properties around the full-scale carrier. A possibility for the discrepancy of these data may be misinterpretation of wind tunnel data. For a pitot-static tube the dynamic pressure ratio is given by:

$$\frac{P_D}{P_S} = \left[1 + \beta\left(\frac{\overline{V_i}}{V}\right)^2\right]^{-1}$$

where $\overline{V_i}^2$, is the velocity deviation from the average flow velocity V, and β is a factor that varies from one to three for small scale to large scale turbulences. In obtaining this measurement for a given $\left(\frac{P_D}{P_S}\right)$ either β or the ratio of $\left(\frac{\overline{V_i}}{V}\right)$ may vary, thereby introducing an unknown condition into the dynamic pressure ratio. The same principle applies to hot-wire anemometers. From some of the experimental results, there appears to be some discrepancy between the results of the hot wire anemometers and of the pitot-static tubes. The fluid velocity obtained from the pitot-static transducer $\left(\frac{2\Delta P}{\rho}\right)^{1/2}$, where ΔP is the differential pressure and ρ the fluid density, is considered as the average pressure which is compared with the average of that obtained from the hot-wire anemometer. This is in error in that it is the root-mean-square values that must be compared.

Fundamental concepts that have not been considered in any of the previous programs are the dimensional sonic wavelengths and the length of the aircraft carrier. For the carrier the critical cutoff frequency is approximately 1 cycle per second. At an air acoustical velocity of 1100 feet per second the wavelength is 1100 feet and approximately equal to the carrier length. From an acoustical concept, the air above the carrier has sharp discontinuities at the bow and stern and is therefore capable of generating within the air above the deck a standing wave pattern at 1 cycle per second. This wave effect is clearly evident in the reduced steady state data of the normalized velocity changes in reference 10. This effect is similar to the "Lee" waves of metereological aerodynamics. To simulate this condition in the wind tunnels, the stream velocity should be the same as for the full-scale vehicle, and the fundamental frequency that should be investigated within the turbulent wake is that having the same wavelength as the model (150 cycles per second for 7-foot model). Future tunnel tests must give consideration to this physical aspect in all data analysis.

As it is the prerogative of an investigator to doubt the validity of the experimental results obtained from various laboratories, there is also a responsibility to assume that the data are correct and that different conceptual approaches should be carefully undertaken.

In the classical Niavier-Stokes solution to flow over a flat surface (references 39 and 43 through 47), the computed boundary layer thickness is independent of the assumed velocity distribution for laminar flow regions (Ne less than 330,000) and the boundary layer thickness(es) is given as:

$$\left(\frac{\delta}{x}\right) = \frac{5.5}{\sqrt{Ne}}$$

where x is the distance measured along the flat plate from the leading edge (figure 6). Figure 7 is an experimental plot of the relationship of Ne and the dimensionless quantity $\delta\sqrt{Ne}$, as obtained from references 44 and 46. The ratio $\left(\frac{\delta}{x}\right)$ decreases with Ne within the laminar region. At the critical value, the boundary layer is at its minimum value and then increases with increasing Ne. Figure 8 is a plot of δ, as a function of x to a maximum value of 1050. Comparing these values of δ with that of an aircraft carrier must be done only in a descriptive manner and should be used only as a guide to further investigation. One conclusion is that measurements within the laminar region will not

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yield information pertinent to the turbulence, and for this reason low velocity wind tunnel experiments are not to be considered for this study.

Extending this two dimensional principle to a semi-infinite plane that terminates at 1050 feet (figure 9) and neglecting the effects of the ships' hull and the influence of the sonic wavelength (Lee waves), the distance that the aircraft is in the turbulent region is $\overline{AB}\left(\frac{\delta}{+}\right)\tan^{-1}\theta_{q}$. For a 3.5 degree glide slope angle and with δ equal to 10, 20, and 30 feet, the distances that the aircraft enters the turbulent regions are 164, 328, and 492 feet. The distances behind the ramp are 14, 178, and 340 feet (the touchdown point is 150 feet forward of the ramp). The strong burble effect is normally encountered at approximately 100 to 150 feet from the ramp. With increasing $\frac{\delta}{+}$, the spacial distribution of the turbulent region will change and will be elevated as is the boundary layer, and consequently the "heart" of the turbulence will approach the glide path.

The classical boundary layer δ for laminar flow is defined as a fixed percentage reduction of free stream velocity. In turbulent flow the classical boundary thickness is located within an intermittent region that fluctuates between laminar and turbulent flow (figures 6 and 9). The flow fields within this region change rapidly from position to position and, at any given position, change rapidly in time. The flow field patterns are random. For a flat plate the upper limit of this intermittent region is 1.2 δ, and for all distances larger than this value above the plate the flow fields are laminar. The lower limit is 0.4δ and for all distances above the plate less than this distance flow fields are turbulent. The layer thickness is approximately 0.8 δ.

Stabilities of these boundary layers are difficult to observe, measure, and interpret (references 39 and 48). With low speed smoke tunnels, fluctuations within the intermittent region are readily observed, and the size of this region is approximately equal to the boundary layer height. Air speeds of the smoke tunnel should be increased to approximately 20 feet per second in order to increase the effective Ne. Further growth of the boundary layer thickness may then be observed. To observe this effect, high-speed photography should be used in combination with high intensity microsecond light sources. Visual data can then be studied at slow speed projections.

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Experiments must be carried out at two widely different wind speeds so that predictions can be attempted at higher WOD velocities.

The effect of carrier pitch motion upon the steady-state dynamic pressure distribution is demonstrated in reference 11 and included in the studies of references 10 and 41. Carrier heave motion has never been included within any experimental program. It is felt that a simultaneous in-phase occurance of a strong heave with pitch will increase by several orders of magnitude the size of the boundary layer thickness and the pressure fluctuations within this layer. Referring to figure 8, the boundary layer height δ for a given model size, ℓ, increases with Ne within turbulent regions. These changes of δ can cause a corresponding increase of the intermittent regions. Thus, differences observed in flow dynamics will be proportional to differences of Ne. To predicate the changing flow dynamics that would occur with changing WOD velocities, experimental data at widely different Ne must be obtained. Higher speed wind tunnels have the advantage in that their parameters can be sufficiently varied so that a wide range of Reynolds numbers can be studied, and the resultant quantitative data are capable of analytical evaluation. For this study wind tunnels should be used. Water tunnel measurements are excellent for visualization over wide Ne ranges, and for measuring steady state flow parameters, but the instrumentation for measurements of turbulent properties is still in the development phase. If instrumentation capable of measuring up to 500 cycles per second is developed, the water tunnel should be considered for the study program. An operational disadvantage of the water tunnel is that experiments are more difficult to perform, and model modifications are more time consuming. Closely related to the above concept of the intermittent boundary line are the varied reactions of aircraft pilots during landings at high WOD velocities. Many investigators regard the pilot's explanations of their reactions with skepticism. During landing operations the aircraft passes through the intermittent region, which is unpredictable with regard to flow field properties, and, therefore, the time duration and turbulent magnitudes depends upon the time that the aircraft is in this region and thus vary.

From the proposed formulated concept of carrier wake turbulence, several procedures should be investigated with regard to modifying flow field distributions in order to accommodate increased WOD and still maintain safe landing operations. These methods are:

1. Delay boundary separation from the deck of the carrier by use of suction techniques. The reduction of the boundary layer thickness aft of the carrier ramp will be proportional to the distance between the bow and the suction section. In figure 10 four dashed lines (1), (2), (3), and (4) represent suction locations. At present operating WOD, no suction devices are employed. With increasing WOD number station (1) is turned on. Upon further increasing WOD, numbers (1) and (2) are on, and eventually all stations are on. Suction devices can also be used on the island to minimize and control its effects.

2. Use of fins at various locations to direct the air flow over the deck and thereby control and regulate the boundary layer profile.

3. "Suction" air to be exhausted in the aft portion of the hull to generate and control the vortex patterns aft of the carrier.

A major contributor to wake turbulence properties is the combined effect of the carrier's pitching and heaving motions. When these two dynamic parameters are in phase and of sufficient amplitude, the intermittent boundary thickness will markedly increase. Effects of the island, deck, and hull design upon wake properties will remain essentially unchanged with increasing WOD, beyond a critical speed.

D. MEASUREMENTS AND EXPERIMENTAL PROCEDURES TO USE FOR EVALUATING FUTURE AIRCRAFT LANDING CAPABILITIES ON AIRCRAFT CARRIERS AND MODELS AS A FUNCTION OF WOD

At the beginning of this section (paragraph A), an estimate was made of expected landing characteristics for 50 knots WOD. This was predicated on a linear assumption that has no experimental justification. Also, on the basis of experiments carried out in wind and water tunnels, it is not possible to make predictions of wake properties due to a lack of correlation data and analysis, questionable scaling factors, and because no data were obtained that demonstrated changes with increasing WOD. To obtain a reliable index of scaling factors and to correlate the geometry of the aircraft carrier with the dynamic wake parameters, measurements at a minimum of two different WOD conditions are recommended.

Turbulence is a statistically non-stationary property in both position and time, and has both a zero cross-correlation and auto-corralation function. This is equivalent to "white noise", as used in Information Theory, which indicates that the dynamics of the fluid cannot be related to any other physical process within the system (references 43 and 49). On the other hand, steady state flow fields are related to geometry of the model. Experiments on full-size aircraft carriers and scaled models have not been carried out with the objective of correlating experimental flow field data with configurations. To obtain cross-correlation, the experimental data at two different locations should be multiplied together and then integrated over a given time interval. For auto-correlation the experimental data taken at two different times in the same location should be multiplied and then integrated over a given time interval. These functions are.

$$R_{xx} = \frac{1}{T}\int_0^T f_x(t) f_x(t+\Delta t)\, dt$$

$$R_{xy} = \frac{1}{T}\int_0^T f_x(t) f_y(t+\Delta t)\, dt$$

where R_{xy} and R_{xx} are cross-correlation and auto-correlation, respectively (see figure 11). In the experimental program flow data within the wake will be compared and correlated with flow characteristics above the carrier ramp, along the ship's hull (particularly in the aft portion where strong vortex motions are anticipated, reference 5), and in the vicinity of the island. The physical parameters to be compared are velocity flow vectors and dynamic pressure ratios. From this experimental data the power spectral density distributions can be obtained. Steady state and vortex data must be clearly differentiated from the fluctuating turbulence data.

1. Tunnel Study Program.

Previous tunnel tests were performed to study the turbulent properties along the aircraft glide path and to investigate methods for reducing the effects of this turbulence upon aircraft performance and, more recently, to use these data to predict the turbulent properties at higher WOD velocities. In general, this accumulation of experimental data has contributed little to the overall understanding of the turbulent wake properties and indicates either that the experimental procedures and the corresponding data evaluations are in error, or that re-evaluation of the required measurements be made to determine which are pertinent to aircraft performance.

In a previous section emphasis was directed to the fact that within a laminar domain the boundary layer thickness decreases with increasing Ne up to the critical Ne. With increasing Ne, the boundary layer increases in thickness, turbulence ensues, and the intermittent portion of the boundary layer will change.

Aircraft carriers are operated at very high Ne which are impossible to match with scaled models. For flows over sharp edges, the implication of Ne has no meaning. Once a vortex flow has been generated and detaches itself from the body, the increase in fluid velocity has no effect other than to move the vortex at a faster velocity downstream. Thus, it is concluded that beyond a given Ne the turbulent portion of the wake is unaltered except for its free stream velocity. Increasing stream velocity will seriously affect the height and thickness of the boundary layer and the properties of the turbulent aspects of this region.

a. Smoke Tunnels. Attempts at visual observations, in combination with simple flow field measurements of the intermittent boundary layer should be made prior to initiating any extensive wind tunnel experiments and aircraft carrier measurement programs. The simplest method by which this can be accomplished is with the use of a three-dimensional smoke tunnel capable of working with two ranges of wind velocities. The velocities are to be approximately 7, 10 and 20 feet per second, which will give equivalent Reynolds numbers of 210,000, 300,000, and 600,000. In order to improve the data evaluation the following instrumentation must be incorporated:

(1) Motion picture camera moving at a rate of up to approximately 50-100 frames per second. This is to be used in combination with a synchronized pulsed light source.

(2) Hot-wire anemometers, preferably cross type.

(3) Mechanical assembly for pitching the model carrier about its center of pitch. A full-scale carrier will have a maximum

pitch amplitude of approximately 0.5 radian per second. To obtain an equivalent Strouhal number for a 5-foot model as compared to 1050-foot carrier, will require that the model be capable of oscillating up to 20 cycles per second, with an amplitude of ± 1 degree. Heaving motions of the carrier are approximately 15 db greater than that of pitch and are approximately the same frequency (reference 10). Considerations should be given to incorporate this motion with pitch after a satisfactory demonstration has been accomplished of the influences of the pitch dynamics.

(4) Multi-channel strip chart recorder. Simultaneous recording of hot-wire anemometer data and dynamic motion of model carrier. Because of the high turbulent oscillations, the standard mechanical recorders are not to be considered. Optical galvanometer recorders, useful to several hundred cycles per second, must be used.

(5) Thermocouple for measuring gas stream temperature.

Measurements and observations should be taken at distances equivalent to 125, 250, 600, and 1000 feet beyond the ramp, in the plane of the glide path, and perpendicular to the floor of the tunnel.

b. Wind Tunnels (Reference 50). After satisfactorily demonstrating the intermittent properties of the boundary layer and the influence of ship's dynamics upon the position and time distributions of the flow fields, a quantitative program should be carried out on larger size models (approximately 10 feet) with higher wind velocities. The primary objective would be to determine the physical aspects of the boundary layer; the second objective would be the determination of the fluid properties along the glide path. As in the smoke tunnel testing, two different wind tunnel velocities should be investigated. Wind velocities of 80 and 120 knots are recommended.

The initial set of measurements should be made on the plane perpendicular to the tunnel reference plane and passing through the glide path at a distance equivalent to 125, 250, 600 and 1000 feet beyond the ramp. Approximately four sets of measurements are to be obtained at each of these distances. All measurements are to be made above the height of the deck. In order to obtain correlation measurements several cross type hot-wire anemometers must be used simultaneously in both the wake and either on or around the carrier model. For steady state flow field investigations, pitot-static tubes must be used. From the steady state data the root-mean-square velocities can be obtained. These will be compared with the root-mean-square velocity measurements of the hot-wire anemometers.

Data must be recorded on magnetic tape in order to compute both the spectral power density of the turbulent flow and the cross- and auto-correlation functions. Optical real time recording should be used during the experiment as both an aid to the experimenter and as a check on the quality of the information on the magnetic tape at the time of data analyses. Measurements are to be concentrated on obtaining the profile of the intermittent boundary layer as a function of different wind velocities and of carrier pitch and heave dynamics.

To accommodate a 1/144 to 1/100 scaled-size model on a reflecting plane, the wind tunnel size should be approximately 5 feet by 7 feet. Provisions are to be incorporated onto the model so that the dynamic motions of pitch and heave can be introduced. To match the Strouhal number of the carrier, attempts should be made to vary the oscillations of the model up to a maximum frequency of 40 cycles per second.

Water tunnel measurements are satisfactory for evaluating the general pattern of flow fields, but, because of instrument limitations, turbulent data have not been obtained. When proven instruments, such as hot film anemometers, are available to measure the turbulent properties, the measurements should be carried out using both water and wind tunnels. The major advantage of the water tunnel is that the flow patterns can be photographed with high intensity short duration light flashes, similar to the process used for smoke tunnels.

Tunnel measurement data reduction differs from carrier measurements in that the frequency responses are considerably higher. This rules out the use of time-division multiplexing procedures. Data acquisition must be done with frequency-division multiplexing.

2. Full-Size Carrier and Wake Study Program.

a. Carrier Wake Measurements. The data to be taken from the full-size aircraft carrier will consist of movable and stationary probes that contain both flow and velocity sensors. Information received will be time-stationary; i.e., all measurements will be made at the same time relative to the ship, and therefore complete correlation analysis of the fluid dynamics can be computed. Measured data obtained within the carrier wake may or may not be position or time stationary. Time stationary data implies that many measurements in the ramp must be accomplished simultaneously. Therefore, at every position in the wake where a measurement is required, a helicopter must be available. For ten positions, an equal number of aircraft will be required. Such requirements are unfeasible. To fly an instrumental helicopter through the wake will give measurements as a function of position and time. Such measurements cannot be readily correlated. This is evident upon inspection of the Power Spectral Density distribution of the velocity turbulence (Appendix B of reference 10). The critical cutoff frequency is approximately 1 radian per second (6.28 seconds per revolution). In order to obtain reliable measurements along the flight path, all measurements should be taken within 0.628 second. For a distance of 1400 feet this will require a velocity of 5000 feet per second. The carrier wake measurements must therefore be carried out to insure that the relative position of the probe to the carrier remains fixed. According to the cutoff frequency response of 1 radian per second, within the turbulent flow, the estimated time at each location should be 30 seconds. This time duration will enable a better understanding of the steady-state versus the turbulent properties. The instrumented package at this location must be confined in a volume that will not change more than ±3 feet in any direction during the measurement time intervals. This dimension is determined by the scaling factor of 1/120 for the wind tunnel testing wherein the size of the pressure probe is 0.25 inch diameter. The helicopter carrying the sensor rack must therefore maintain its position relatively fixed with respect to the carrier. Figure 13 depicts the recommended measuring system.

Several problems are encountered in attempting to fix the rack's position with respect to the glide path. One of the possible configurations is to use the PLAT system and an optical range indicator to fix the position of the rack along the glide path. The difficulty with this approach is that a displacement from the desired position will require helicopter corrective action of either translation, pitch, or yaw. Roll motion is evident by observations of the horizontal and vertical portions of the rack. In most cases a combination of corrective maneuvers is required. Since rotational coordinate systems are antisymmetric, the corrective actions will be difficult and time consuming. If, instead, the rack is positioned on the glide path by the PLAT system and the optical range system is set at a prescribed angle to the deck for accurate positioning of the helicopter, the displacements of the instrument panel by pitch and yaw cannot be determined unless the PLAT system is capable of better then ±3 minutes of resolution. If .. o optical range instruments are set within a few feet of each other at a distance Do from the touchdown point at designated vertical angles ϕ_{OR} and ϕ_{OH} to the deck, both the helicopter and rack can be accurately positioned. Angles are given as:

$$\phi_{OR} = \tan^{-1}\left[\frac{\tan\theta_g}{\cos\theta + D_o/D_g}\right]$$

$$\phi_{OH} = \tan^{-1}\left[\frac{\tan\theta_g + L/D_g}{\cos\theta_g + D_o/D_g}\right]$$

R and H designate rack and helicopter; where

θ_K is the glide angle between the deck and the rack from the TD point,

D_K is the horizontal distance from touchdown to the rack, and L the distance from the rack's center to the helicopter's center of gravity. Translation of the helicopter's position is corrected from its optical range indicator and helicopter rotary motion from the rack's optical range indicator. When the rack's position has been fixed, i.e. ± 3 feet, recordings of data are initiated simultaneously on both the carrier and the helicopter.

In the previous section a concept was formulated in which it was concluded that both the boundary layer distribution and the turbulence properties had to be determined. The above helicopter measurements will give data that could be either within the turbulent or free stream regions. At each station aft of the ramp, three positions, in addition to the one on the glide slope, will have to be measured. Positions are to be vertically separated by approximately 10 feet. Locations aft of the ramp are to be approximately 125 feet, 250 feet, 450 feet, and 1000 feet. Measurements are to be taken at a total of 12 positions aft of the ramp.

Transducers on the rack are similar to those to be used on the deck and around the hull of the carrier. Figure 13 is a sketch of the helicopter carrying the instrumented rack. The rack will carry five transducer assemblies. Eight measurements are required per assembly for a total of 40 measurements for the entire rack.

All data are to be multiplexed onto multichannel magnetic tape from which information is then both recorded on standard strip chart recorders and computer processed for correlation data and power spectral density analysis.

b. Measurement of Fluid Dynamics on Full-Size Carriers. Measurement of flow characteristics around the carrier can be accomplished by installing sensors around the hull and on the deck as shown in figure 14. Data from these sources will consist of the following measurements:

(1) Four for cross hot-wire anemometer
(2) Two for sensor location
(3) One for temperature
(4) One for humidity

For 82 transducers the number of measurements required will be 336. To these must be added carrier roll, pitch, yaw, and heave. A total of 340 measurements is required for the carrier.

Measurement close to ramp can be accomplished by using an extendable tripod supported at the stern of the carrier (figure 15). This can be designed to measure the flow field to a maximum position of approximately 75 feet aft of the ramp.

A total of 348 measurements is required for flow measurements around the carrier and within the wake. To fulfill the requirements of the Shannon-Hartley Information Law, approximately four measurements must be made within the cycle at the highest frequency. A frequency of one cycle per second requires a minimum number of four samples per second per data point. For 348 data points the sampling, or multiplexing, rate is 1392. An eight-channel magnetic tape recorder will use one channel for time synchronization; another for general purpose information, such as instrumentation rack position, materological condition, aircraft carrier dynamic conditions, etc; and six channels for multiplex data at a multiplexing rate of 232 samples per second.

The above transducers on the deck and around the hull will give data within the turbulent layer. To obtain the boundary layer distribution, one instrument assembly on an adjustable length mount is required. This will be used to probe for the boundary layer contour around the carrier. Indications are that this layer can extend 30 feet above the deck. Since these measurements are not for correlation analysis, this experiment need not be run simultaneously with any other measurements of the program and can be simultaneously recorded on magnetic tape and strip chart recorders. Because of the simplicity in obtaining these boundary distribution measurements, it is felt that, if this phase is initially carried out, a clearer insight can be made of the conceptual picture of wake properties prior to proceeding to the use of the helicopter. Power spectral analysis will be required for all measurements.

c. Helicopter Instrument Rack Assembly. To measure the flow properties within the carrier wake will require that an instrumented rack, supported from a helicopter, be maintained within a fixed position. If the distance between the helicopter and the instrumented rack is not sufficient, the rotor's downwash will alter the local flow fields around the rack. Figures 16 and 17 illustrate this effect. With increasing airspeed the rotor downwash angle decreases, and therefore the instrumented rack can be placed closer to the helicopter. For a dynamic pressure ratio of 0.98, the separation at hovering conditions must be greater than one rotor diameter. With airspeed, this height is reduced by a factor of the sine of the air wake angle. For a 40-foot rotor at a minimum estimated forward speed of 25 knots, the separation must exceed 31.5 feet.

A preliminary analysis made of an aerodynamically shaped pod, with mounted instrumentation probes, towed by a helicopter with the aid of a 40-foot long cable proved to be unfeasible for this application. This pod would be particularly affected by changes in the free wind velocities that can give rise to large swaying motion. These uncontrollable motions could be disastrous if the motion of the pod becomes increasingly divergent. The helicopter would then be required to execute large and difficult maneuverings in order to maintain the pod's position. Combined with these swaying motions are the vertical gusts that will also affect forward flight. These gust actions would divert the helicopter off both the vertical and the azimuthal path.

If the pod configuration is 3 feet in diameter by 15 feet long, the lateral or side area would be approximately 45 square feet. The dynamic pressure for a 50 foot per second wind is 3 pounds per square foot, and this pressure will generate a side force of 135 pounds on the pod. For this condition the sway angle will be:

$$\sin^{-1}\left[\frac{\text{Side Force}}{\text{Gross Weight}}\right] \quad \sin^{-1}\left[\frac{135 \text{ lbs.}}{300 \text{ lbs.}}\right] = 27 \text{ degrees}$$

This will give a sway distance of 21 feet for a 40-foot tow line.

No control system would be able to stabilize this type of motion. It is therefore concluded that any towed object would not be feasible for this application.

However, the use of a rigid frame design (shown in figure 18) would be feasible for stabilizing an instrumented rack, and the stability would be determined by the helicopter's stability control capabilities. This frame concept would use a rigid boom extending 30 to 40 feet from the bottom of the helicopter. Several forms of the rigid boom were analyzed, including circular aluminum tubes and streamlined tubes, both hollow and honeycomb-filled. At 60 knots speed, the total wind force on a 6-inch-OD tube will be about 6.67 pounds per square foot. For a 3-inch-OD tube the wind force on the tube will be about 1/2 of this, or 3.34 pounds per square foot. The 6-inch rigid boom proved to be too heavy and it has too high a moment of inertia. The 3-inch tube will have appropriate inertia, but its radius of gyration is too small in columnar action.

In view of these difficulties, the initial concept of the suspension structure has been changed to one where the grid suspension member is subjected only to the tension due to the weight of the grid and its instrumentation and to any beam action due to transverse wind forces. Allowing the suspension member to pass through a pivoting collar having a hole with a clearance of 1/64 inch between suspension and ring will eliminate the buckling tendency of the boom. The collar in turn will be secured to the helicopter body by an A-frame. The collar will not support the suspension member in the horizontal plane, but, because of the slip fit in the hole, it cannot impose an axial load on the boom. The concept is shown in figure 18. This figure shows the A-frame supporting the grid structure and the pulling chords for positioning the entire assembly under the fuselage of a helicopter.

Preliminary assumptions made for this design are as follows:

(1) Critical frequencies of vibration of the helicopter will have no effect upon the structure.

(2) Critical stress points of the helicopter are known so appended structures can be adequately supported.

The moment of inertia of the frame assembly is approximately 350 slug-feet squared about its point of attachment, and 1.28 slug-feet squared about its center of gravity. The instrument frame, which weighs approximately 10 pounds, has moments of inertia around the A-frame attachment of 500 slug-feet squared and 9 slug-feet squared. Total J for the complete assembly is approximately:

$$J_y = 850 \text{ slug - feet squared}$$

$$J_x = 10.28 \text{ slug - feet squared}$$

For the helicopter the corresponding values for the moments of inertia are approximately:

$$\bar{J}_y = 27{,}500 \text{ slug-feet squared}$$

$$\bar{J}_x = 5900 \text{ slug-feet squared}$$

$$\bar{J}_z = 23{,}000 \text{ slug-feet squared}$$

Since the ratios of $\bar{J}_y/J_y$ and $\bar{J}_x/J_x$ are large, the frame assembly will have very little effect upon helicopter stability, and the positional accuracy of the instrument frame will depend upon the stability of the helicopter and the ability of the pilot to maintain a fixed relationship with the aircraft carrier. (See references 51 through 53.)

The position of the helicopter with respect to the carrier will be accomplished with a combination of the two Optical Range measuring systems and voice communications. Recording systems on the carrier and helicopter must be time-synchronized in order to correlate measurements.

d. Transducers. An investigation into the various methods for determining the velocity vector at prescribed locations in the turbulent wake and around the carrier has been performed. The application of existing instrumentation with known accuracy was of primary concern. Of the various devices available for the measurement of fluid flow parameters needed for velocity determination, the pitot-static tube and the hot-wire anemometer are the most promising. The following factors were also considered: methods for adapting these devices to the measurement of velocity, an evaluation of each method, and the determination of the most suitable method.

(1) Pitot-Static Tube. For flow data that must be obtained for a carrier operating at speeds between 30 and 50 knots, a pitot-static tube would have an accuracy of ± 0.5 percent. The tube would have to be oriented into the main velocity direction. This velocity vector orientation of a spherical-ended pitot-static tube can be misaligned as much as ±20 percent before the accuracy of the measurement becomes seriously affected. In the turbulent stream, where the velocity vector is random, the pitot-static tube must be continuously directed into the stream line. Simultaneous read-outs of both position and pressure differential must be made.

Figure 19 shows the concept for a pitot-static tube mounted in a gimbal system. A differential pressure transducer is used to measure the difference between the dynamic and static pressure. For the carrier wake measurements, the tube coefficient is taken as 1.00 and compressibility effects are neglected. The stream root-mean-square velocity is given as $\left[2\Delta p/\rho\right]^{1/2}$, where Δp is the transducer reading and ρ is the local air density. (See references 54 through 58.)

It should be noted that when making turbulent measurements with pitot-static tubes, two detrimental effects on probe performance occur. A minor effect is the variation of the probe's calibration constant with Ne. The major effect is that resulting from the turbulent fluctuations that occur with the moving medium. The turbulent fluctuations have velocity vector components of v_x, v_y, and v_z with an average value of zero. For a mean flow in the X direction, the fluid velocity components are respectively $V+v_x$, v_y, and v_z. Pressure measurements are the square of the root mean-square of the velocity. For incompressible fluid flow the pitot-static tube pressure measures:

$$p_t = p_s + \frac{1}{2}\rho V^2 + \frac{1}{2}\rho\left[\overline{v_x^2} + \overline{v_y^2} + \overline{v_z^2}\right]$$

and the static pressure is:

$$p_s = p_o + \frac{1}{2}\rho\left[\overline{v_y^2} + \overline{v_z^2}\right].$$

For isotropic turbulence $\overline{V_x^2}$, $\overline{V_y^2}$, $\overline{V_z^2}$ equal $\overline{V_i^2}$.

Dynamic and static pressures are reduced to

$$P_p = P_o + \frac{1}{2}\rho V^2 + \frac{3}{2}\rho\overline{V_i^2}$$

$$P_s = P_o + \rho\overline{V_i^2}$$

The pressure difference measured with the pitot-static tube is:

$$\Delta p = \frac{1}{2}\rho V^2\left[1 + \frac{\overline{V_i^2}}{V^2}\right]$$

and the dynamic pressure ratio is:

$$\left[1 + \frac{\overline{V_i^2}}{V^2}\right]^{-1}$$

When turbulence is considered as a statistical ensemble of eddies of different sizes and of different phases of rotation, the probe's performance is further affected. Small size eddies result in little or no correlations at the orifices, and, therefore, the static pressure reading will be high. For large size turbulence, the pressure at all ports is the same, but the tube axis will have a fluctuating angle of attack with the gas flow and the pressure measurement will be low. The previous equation is then modified by inserting a turbulence corrective factor, β :

$$\overline{\Delta P} = \frac{1}{2}\rho V^2\left[1 + \beta\frac{\overline{V_i^2}}{V^2}\right]$$

where

(Small scale turbulence) $1 \leq \beta \leq 3$ (large scale turbulence).

Since both the scale of turbulence and its direction are unknown, the mechanical support shown in figure 19 must be a gimbaled arrangement so that the probe can be directed into the stream. This instrument cannot be used for tunnel measurements because both the scale of turbulence and the nature of the fluctuations are not known. For carrier measurements the turbulent scale factor β can be set equal to unity. The gimbaled system must have a critical cutoff frequency of 1 cycle per second. Severe oscillations in the gimbaled systems will complicate the data reduction analysis. With this arrangement the general direction of the velocity vector would have to be known within 180 degrees from a plane through the fixed housing frame; that is, the determination of left to right or right to left flow would have to be known or determined by rotation of the instrument before data are taken. To circumvent this problem an elaborate arrangement of slip ring assemblies in both rotating axes are required.

(2) Hot-Wire Anemometers. To circumvent the difficulties of the mechanical pitot-static tube arrangement, the hot-wire anemometer instrument is to be considered as the primary transducer. (See references 59 and 64.) This anemometer consists of a fine electrically heated wire, stretched between two prongs, by which the air speed can be determined through the measurement of the change in the wire's electrical resistance due to the heat convection from the wire. This principle can be used in either of two ways: The wire can be heated by a constant current and the speed determined by measuring the resistance, or the wire can be maintained at a constant temperature and the speed determined from the measured value of the current.

The operation of the hot-wire anemometer is given by King's Law for heat dissipation:

$$H = K\theta + \theta(2\pi K C_v \rho V e)^{1/2} \approx C_0 + C_1(\rho V)^{1/2}$$

(Constant temperature)

C_0 and C_1 are constants, ρ is gas density, and V stream velocity. For incompressible media, where the stream velocity is less than 0.3M, the results of the hot-wire readings are acceptable for velocity measurements. These instruments have a 5-percent velocity error, and since the pressure is proportional to the square of the velocity, the pressure error will be 10 percent. For velocities greater than 0.3M, the gas can no longer be considered as incompressible, and H is now a function of the gas density. Usual spe[illegible]ations are 5 percent error for velocities up to [illegible]0 feet per second.

Hot-wire anemometer readings are more dependent on velocity directions than the pitot-static tubes. The effective cooling is a function of angle between the wire and the velocity vector. This angle correction is incorporated into King's equation as follows:

$$H = C_0 + C_1 (V)^{1/2} (\sin \theta)^{0.9}$$

If two hot-wires are placed perpendicular and in the same plane, the heat transfer will be expressed as the cosine for one wire and sine for the other. The ratio of the two measurements will give the tangent of the velocity vector. Use of one cross-wire set yields information that can be 180 degrees in error. Therefore, a moving gimbaled system will be required. To eliminate the requirement for a gimbaled system, two cross hot-wire anemometer sets, separated a small distance and directly in line with each other, can be used This method depends on the fact that cooling of one cross-wire set is influenced by the wake of the other set.

SECTION VIII

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SECTION IX

FIGURES

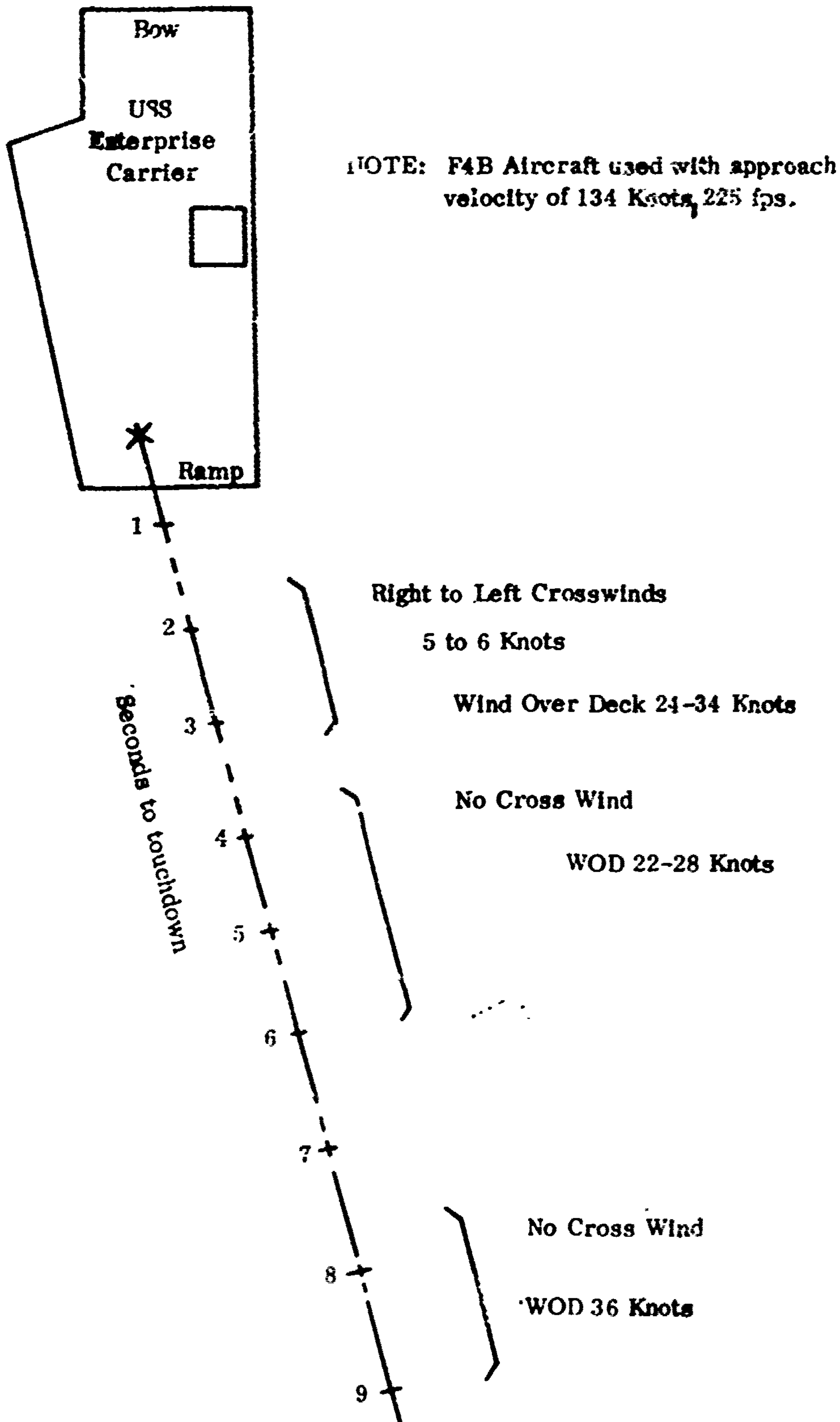


Figure 1. Approximate Times When Initial Burble Is Encountered for Various Approaches

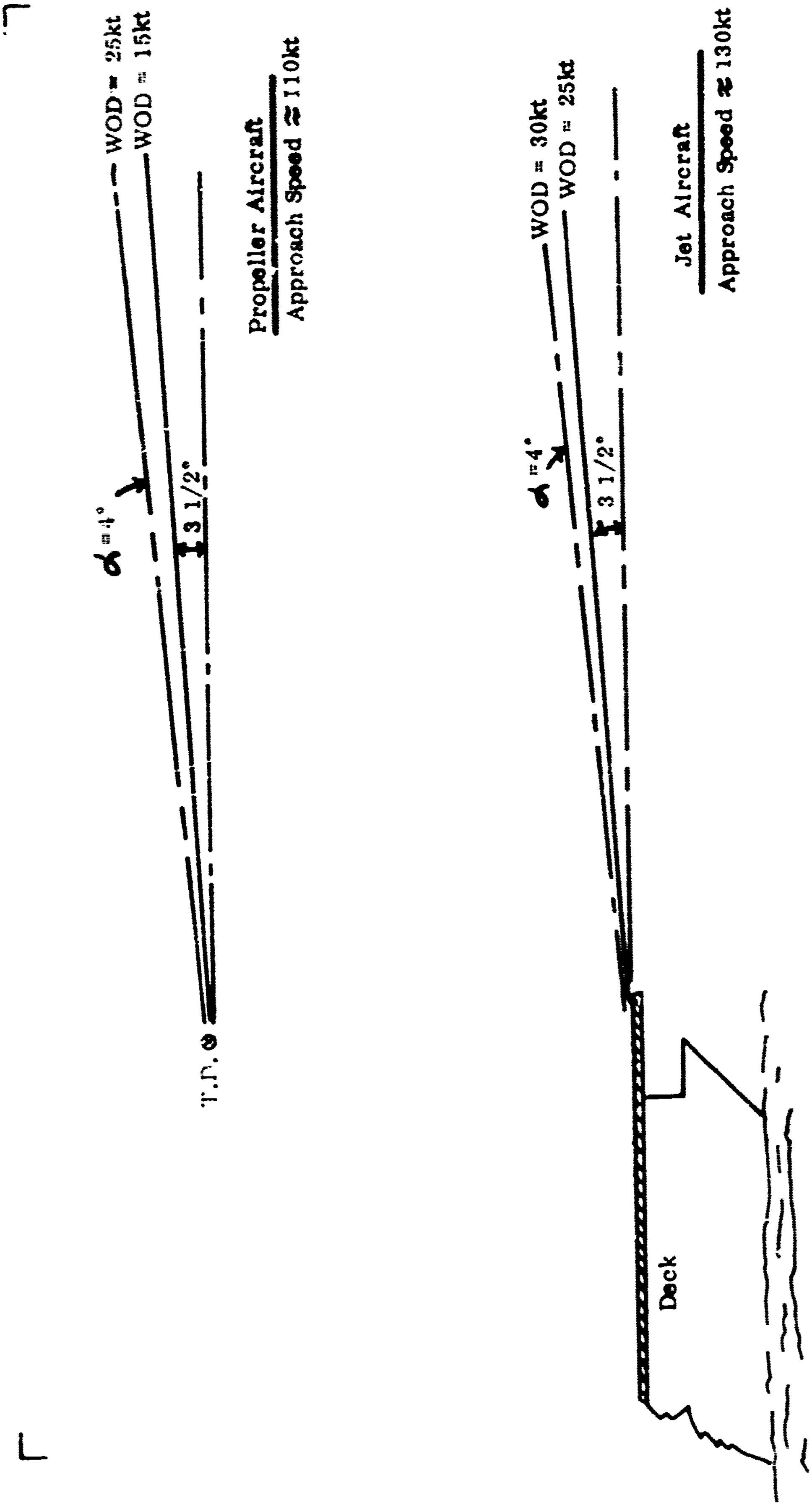


Figure 2. Minimum Safe Landing Angle with Different Wind Over Deck

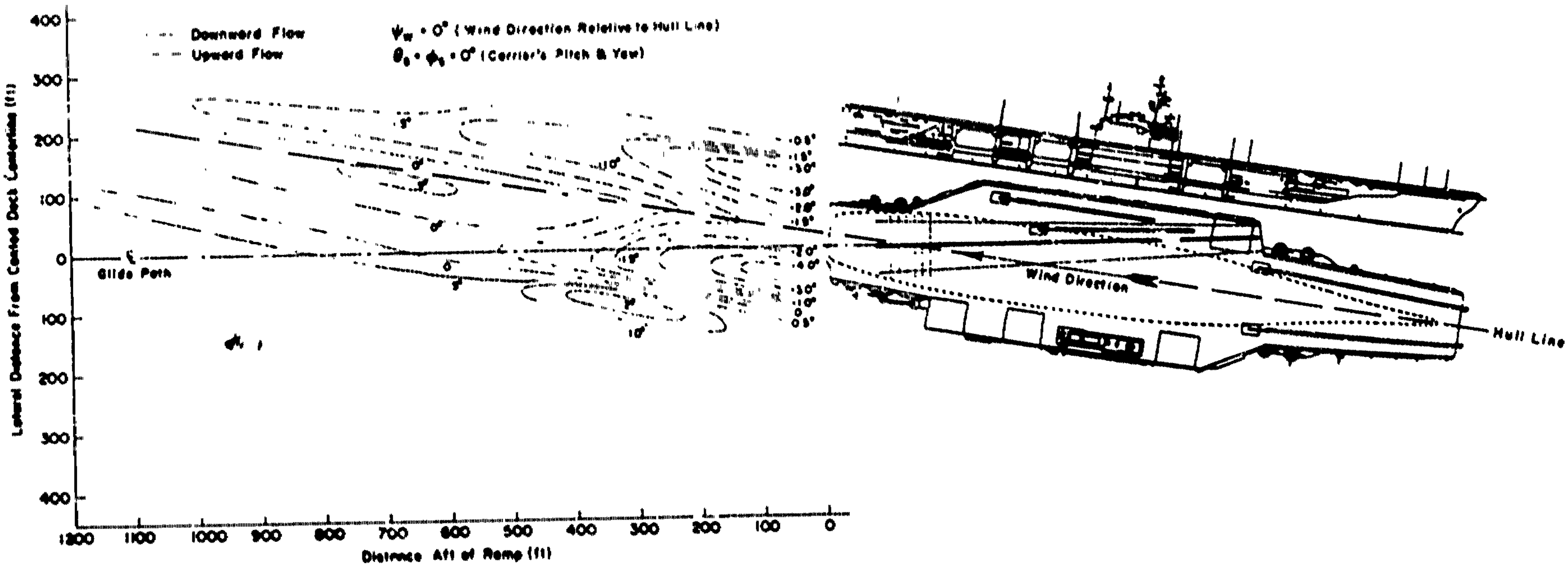


Figure 3. Lines of Constant Flow Angularity Astern the Carrier. Wind direction 0° to hull line and along a 4° glide path (reference 11)

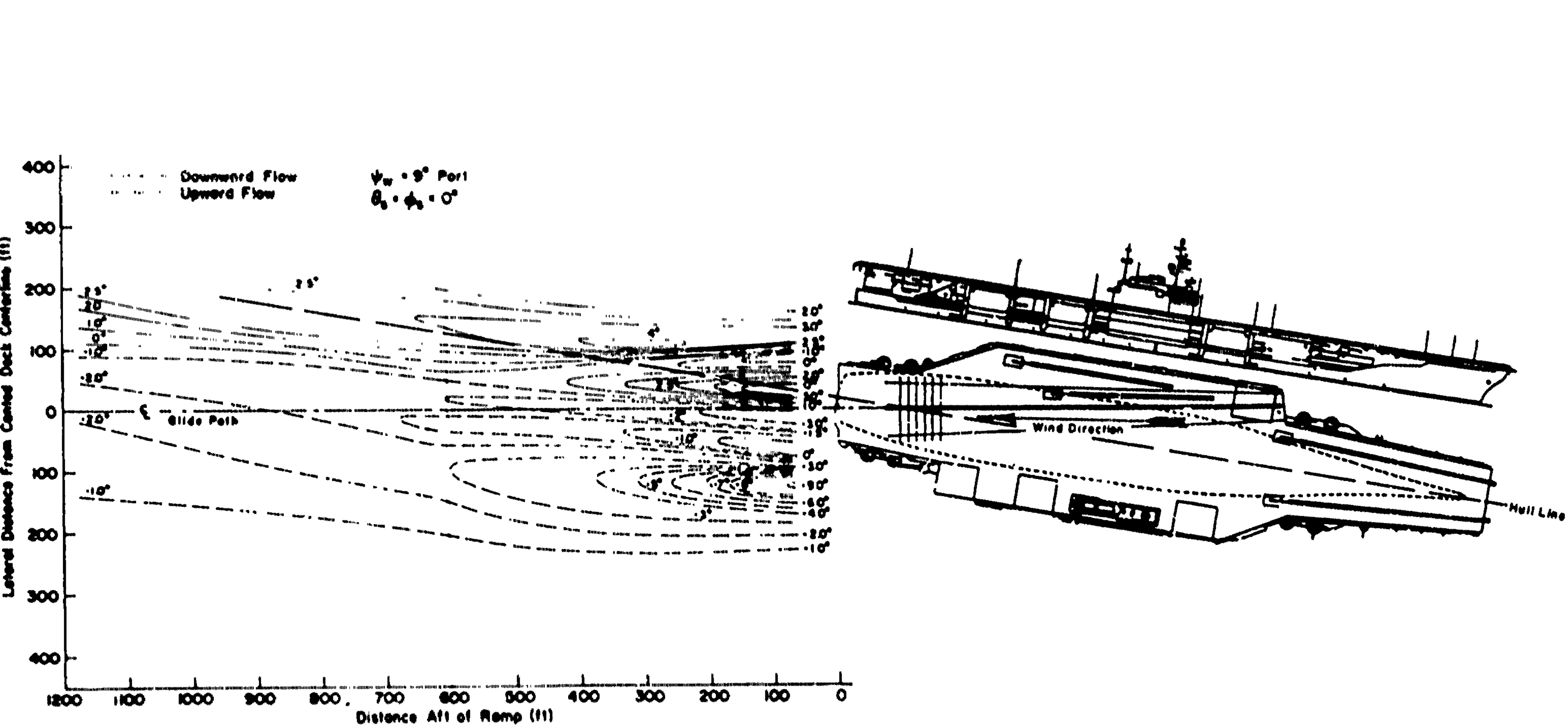


Figure 4. Lines of Constant Flow Angularity Astern the Carrier. Wind direction 9° to hull line and along a 4° glide path

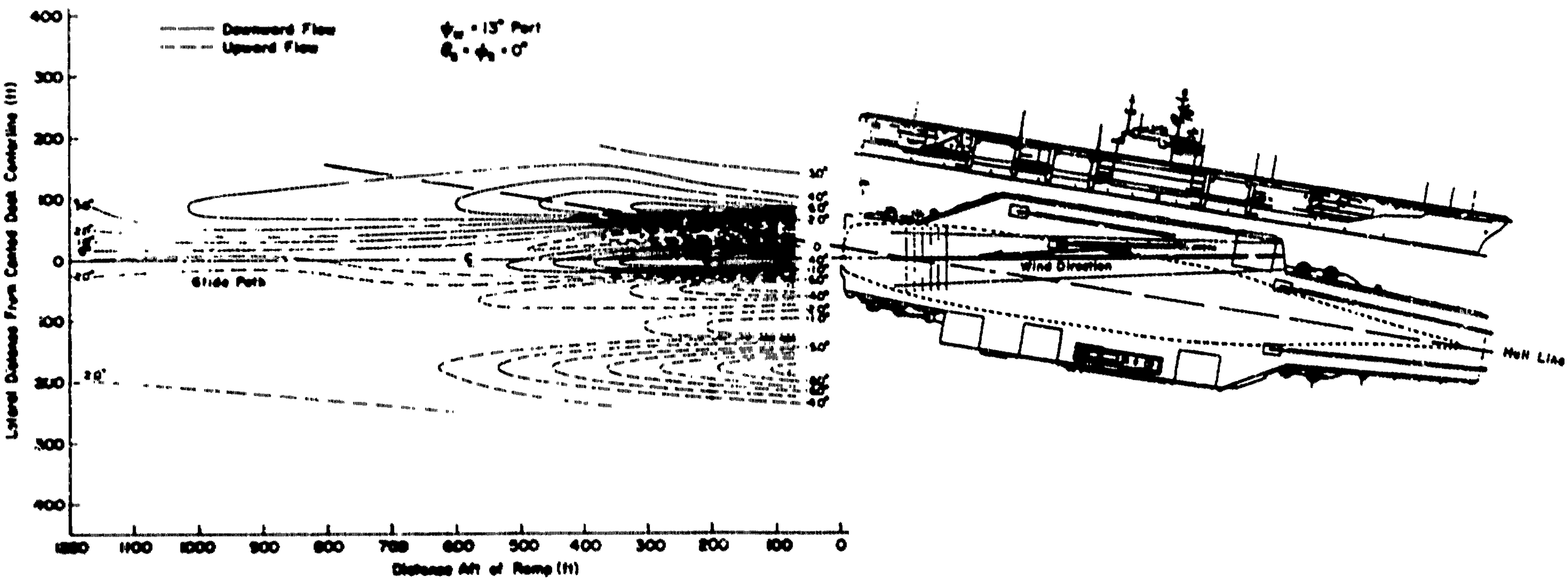


Figure 5. Lines of Constant Flow Angularity Astern the Carrier. Wind direction 13° to hull line and along a 4° glide path

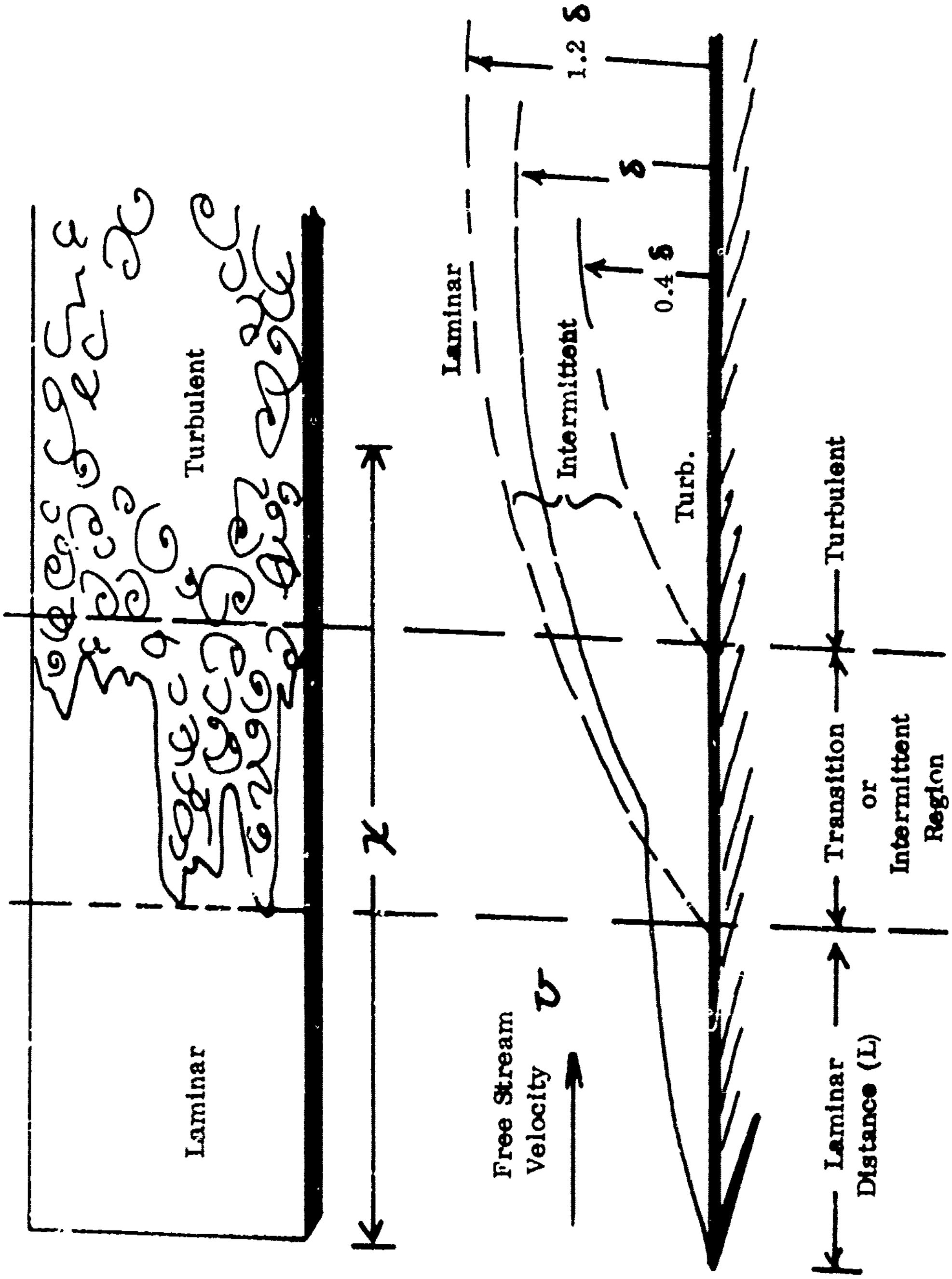


Figure 6. Laminar and Turbulent Flow Pattern Separations over a Flat Plate

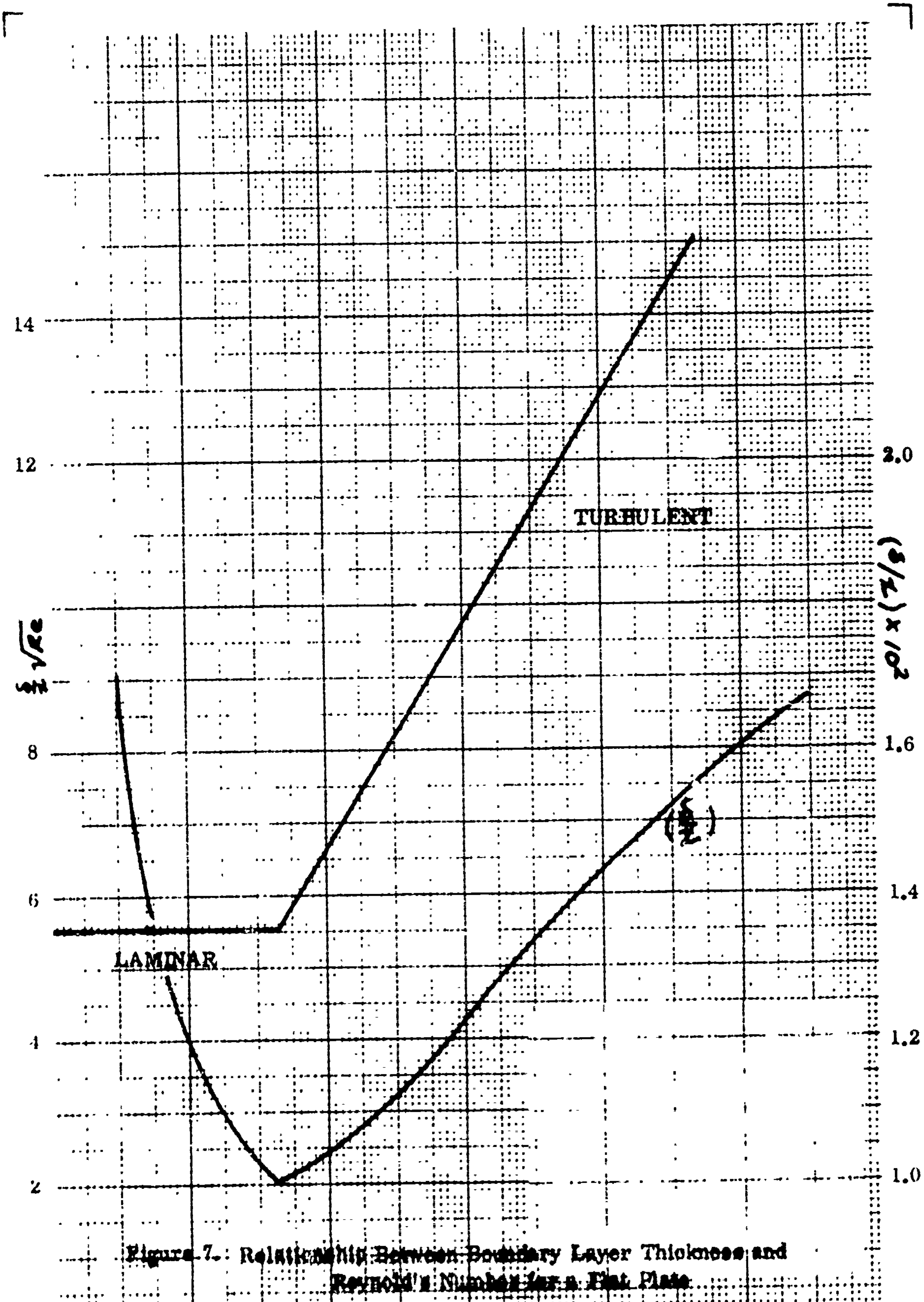


Figure 7. Relationship Between Boundary Layer Thickness and Reynold's Number for a Flat Plate

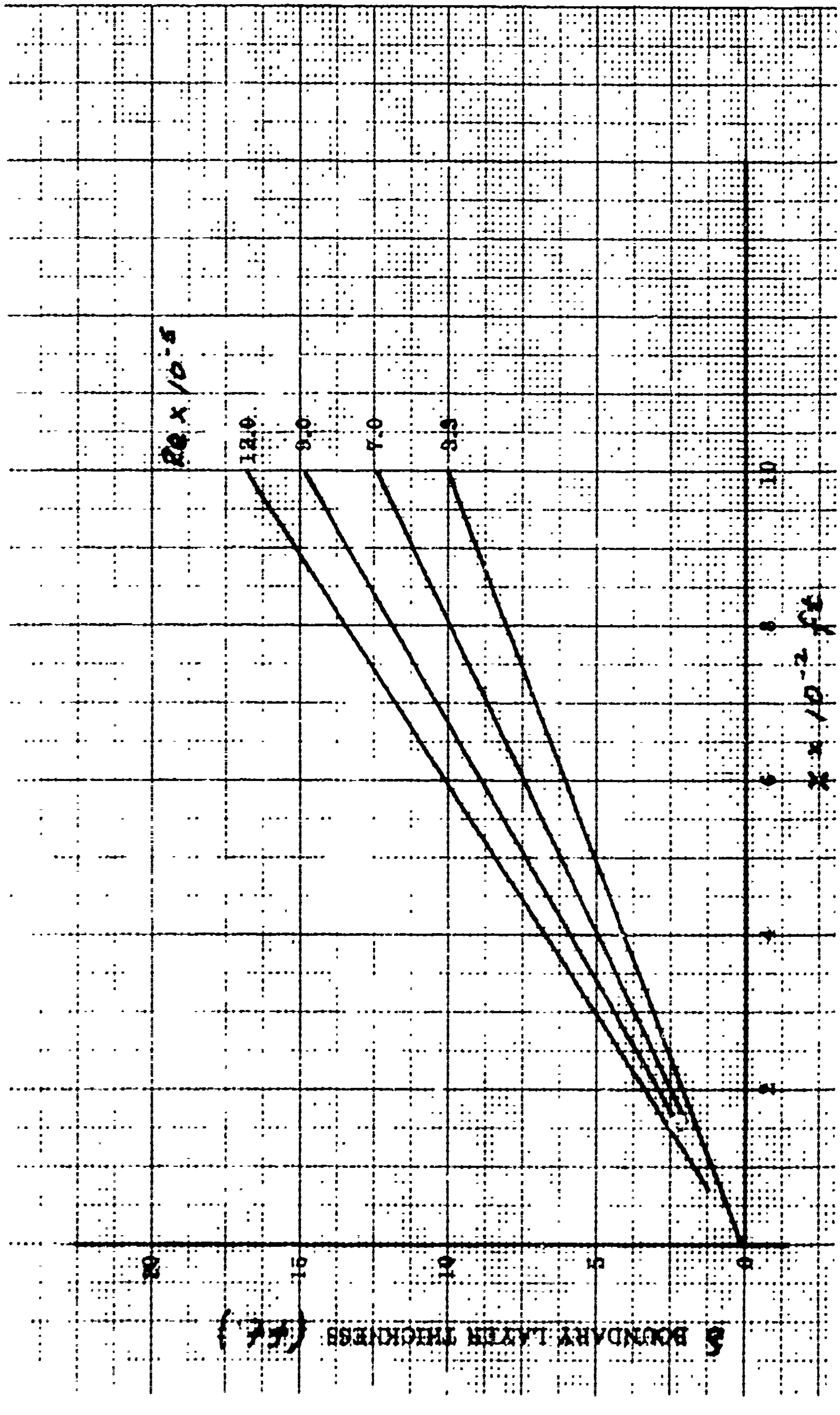
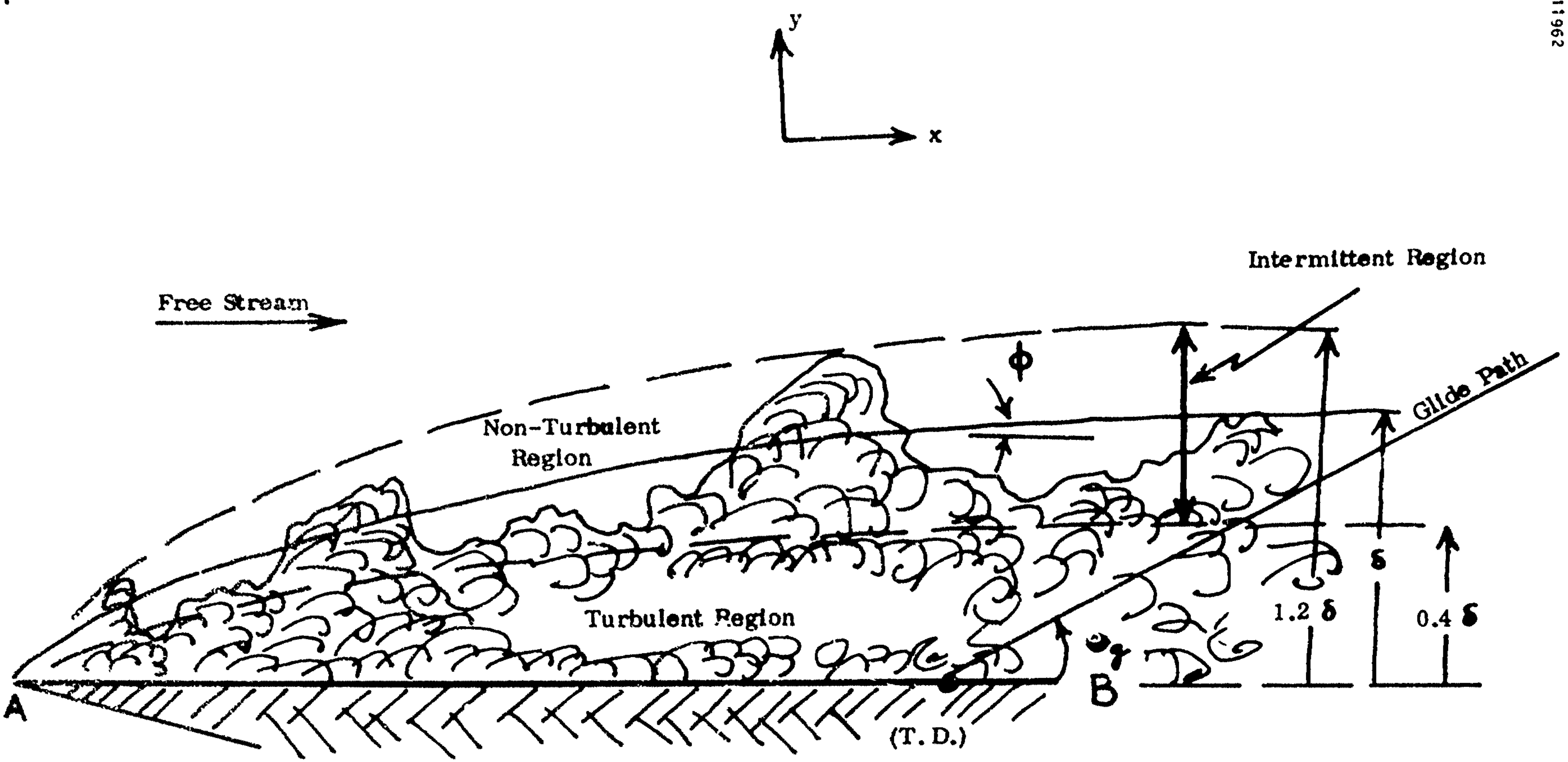


Figure 8. Relationship Between Boundary Layer, Distance, and Reynold's Number for a Flat Plate

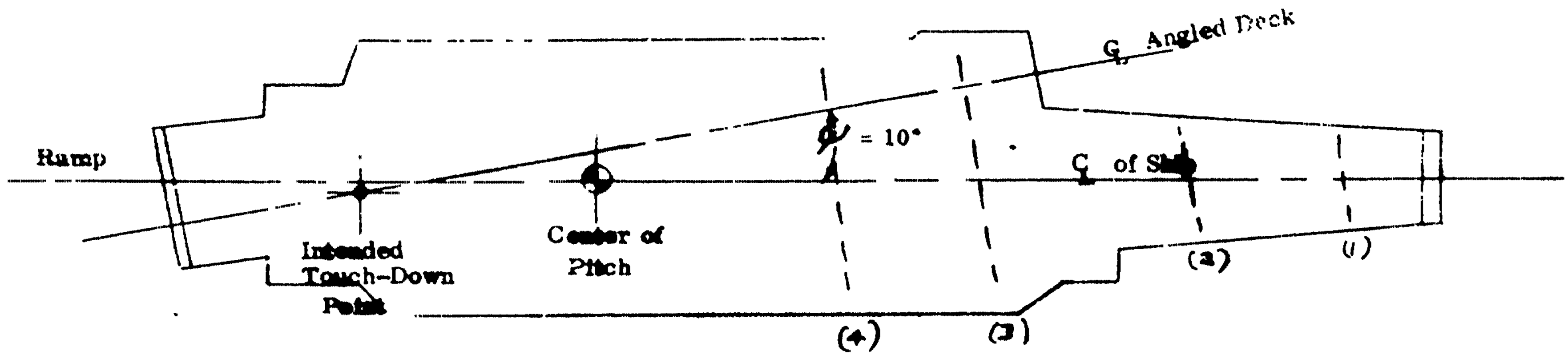


NOTE: Instantaneous time pattern of flow over a plate for $y < 0.4\delta$ Region is always turbulent, and non-turbulent when $y > 1.2\delta$. When $0.4\delta \leq y \leq 1.2\delta$ region is intermittent turbulent and the boundary between turbulent and non-turbulent is unpredictable in time and position.

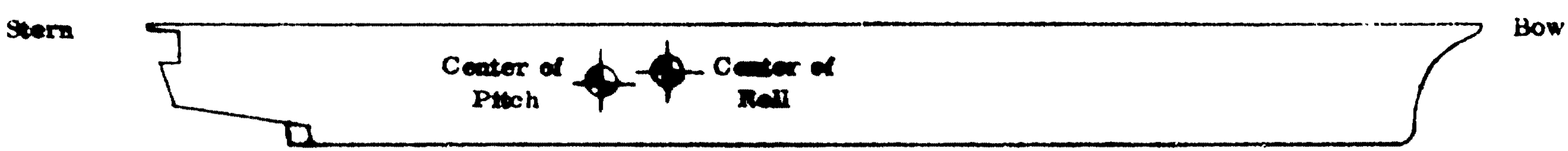
AB $\approx$ 1050 ft.
(T.D) B $\approx$ 150 ft.

θ_g = Glide Angle
δ = Boundary Layer Thickness
ϕ = $\sin^{-1}(\delta/x)$

Figure 9. Boundary Layers over a Flat Plate



FLIGHT DECK PLAN



PROFILE PLAN

Figure 10. Aircraft Carrier Geometry

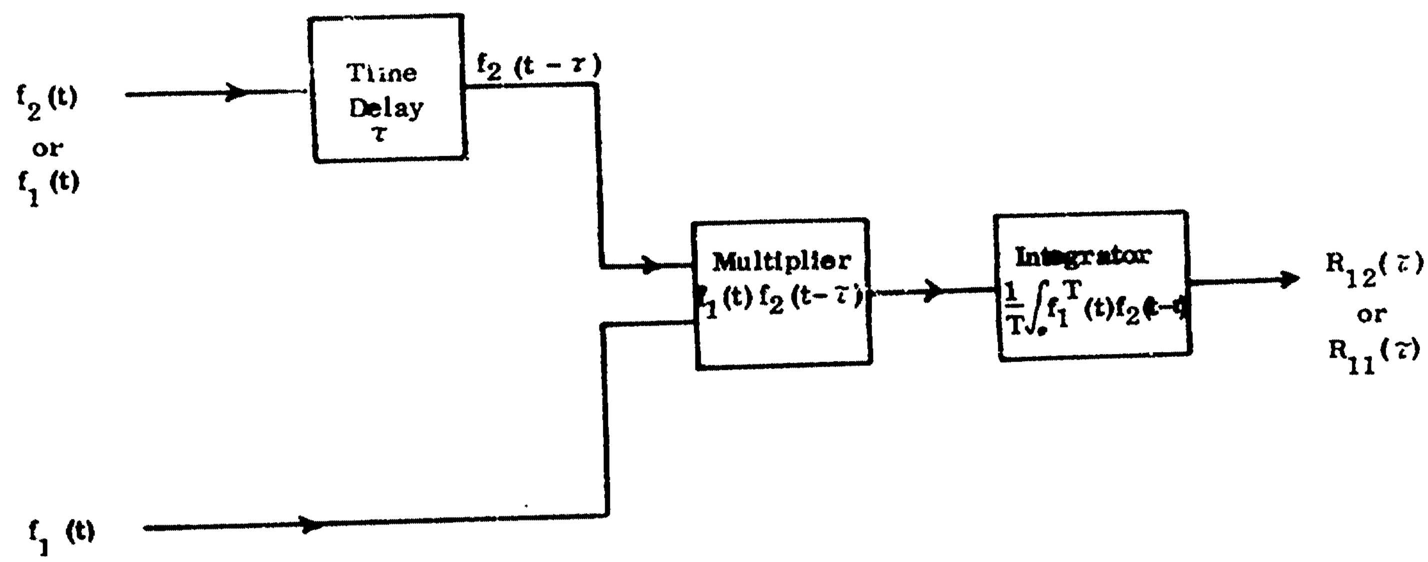


Figure 11. Basic Correlation Principle

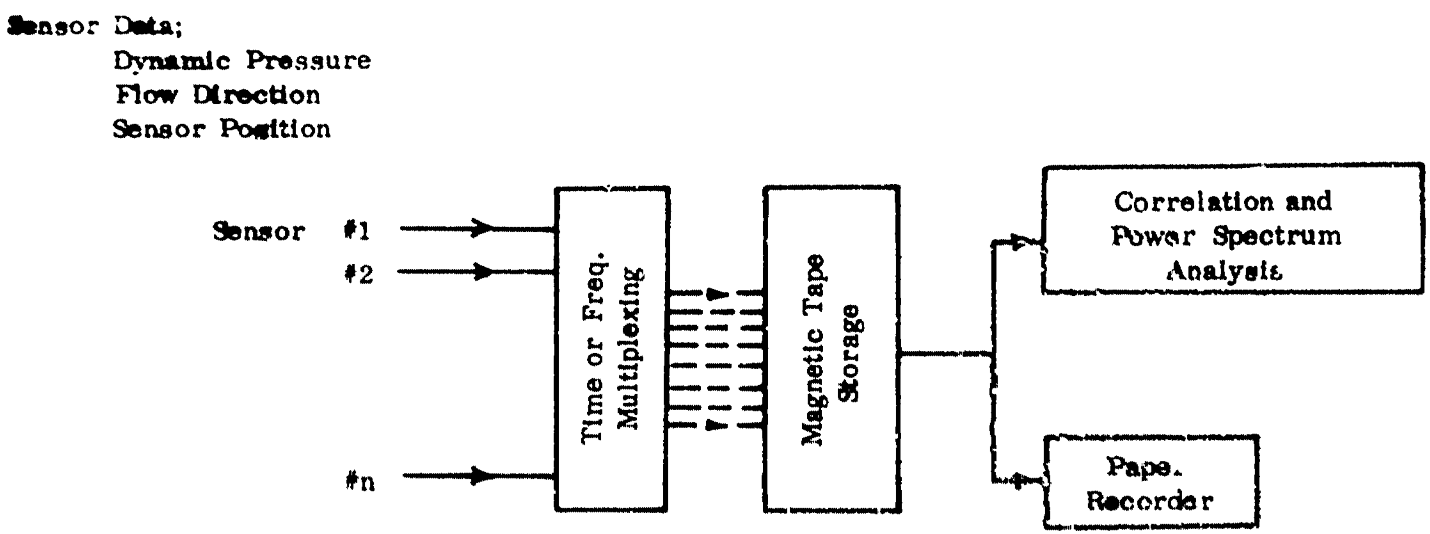


Figure 12. Block Diagram of Data Acquisition and Reduction

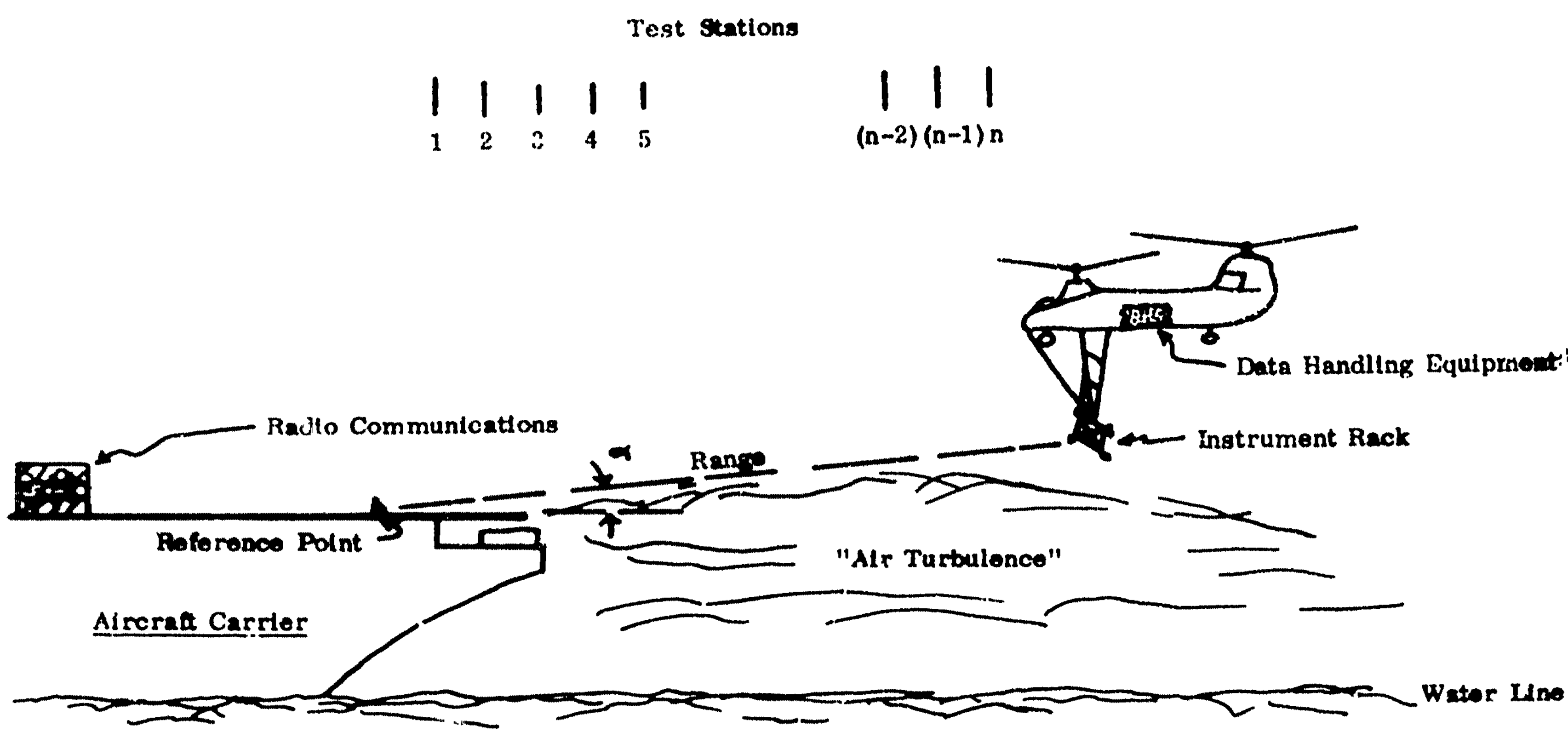
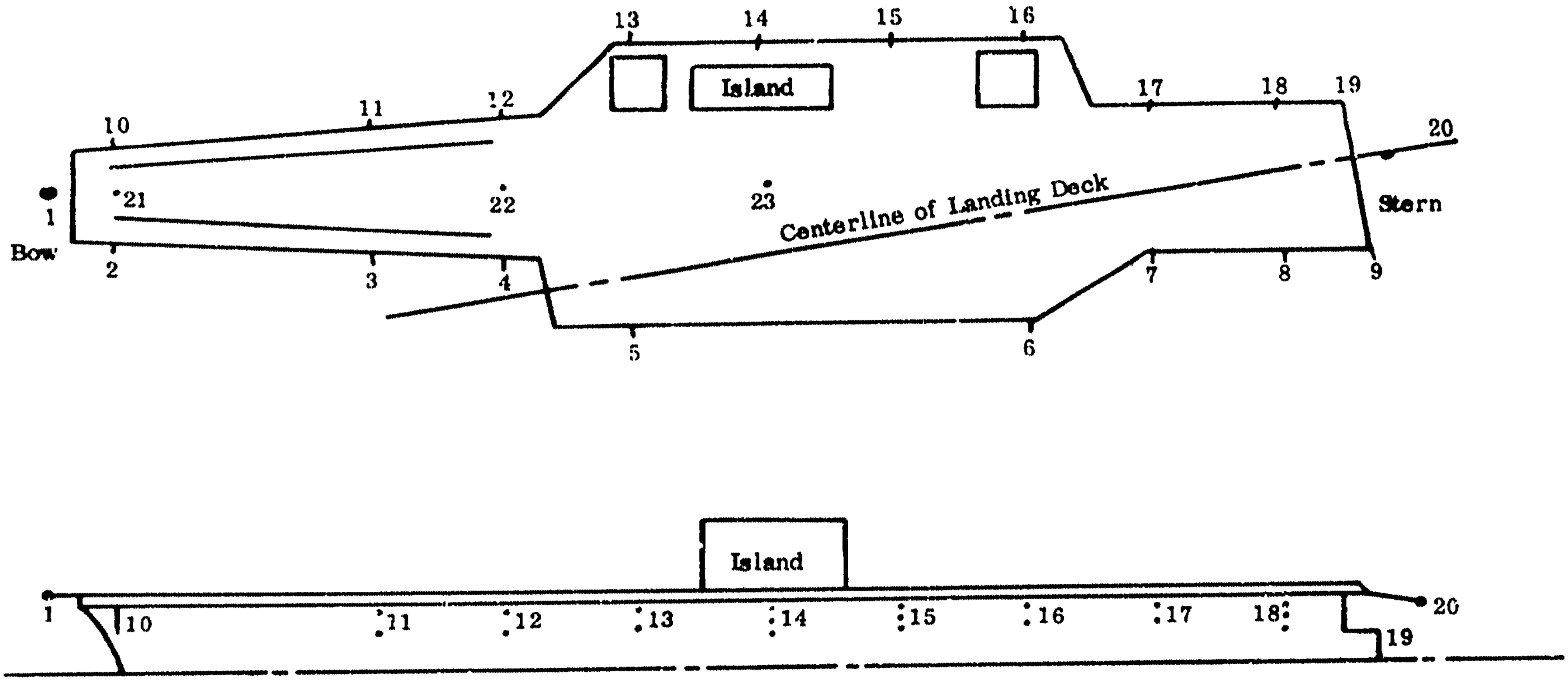


Figure 13. Helicopter-Rack Configuration for Measuring Flow Properties of Ramp Turbulence



Sensor groups separated approximately 100
Sensor #1 – Reference sensor
Sensors #2 thru 19 – Fixed positions
Sensor #20 – Variable positions
Sensors #21 thru 23 – Deck Sensors

Figure 14. Sensor Locations for Determining Flow Properties Around Aircraft Carrier

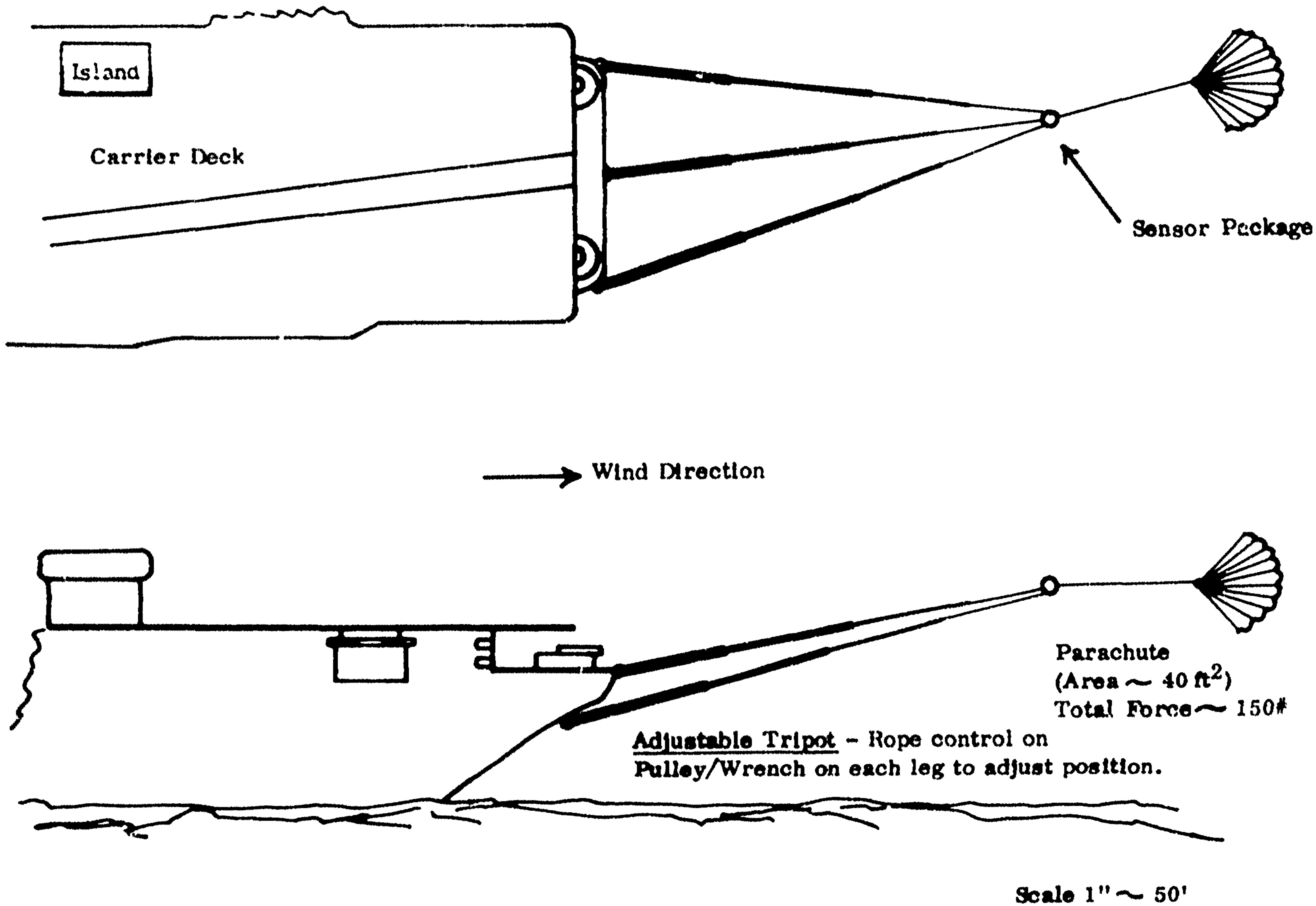


Figure 15. Adjustable Tripot for Sensor Package No. 20 (Figure 14)

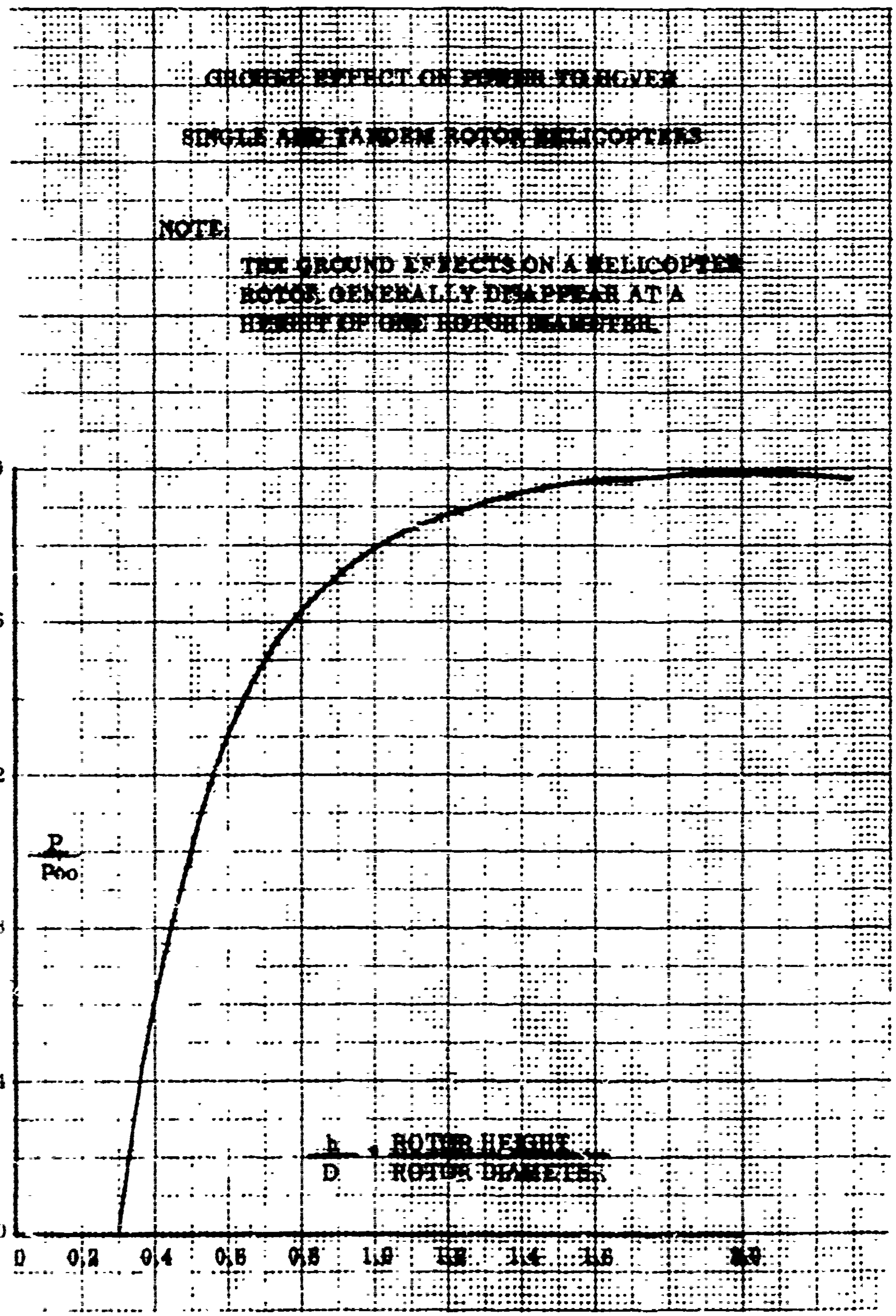


Figure 18. Ground Effect on Power to Hover Single and Tandem Rotor Helicopters

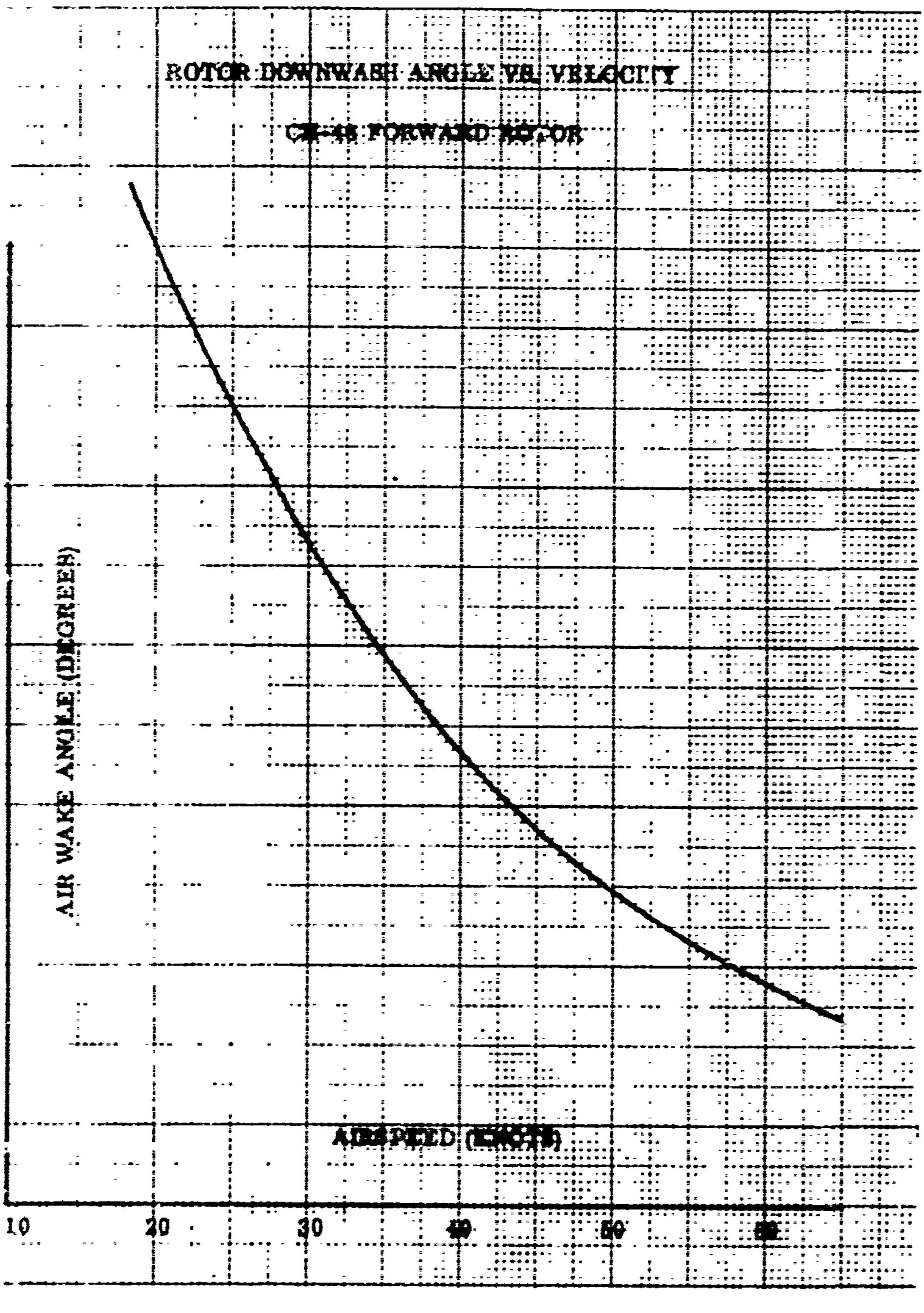


Figure 17. Rotor Downwash Angle vs Velocity

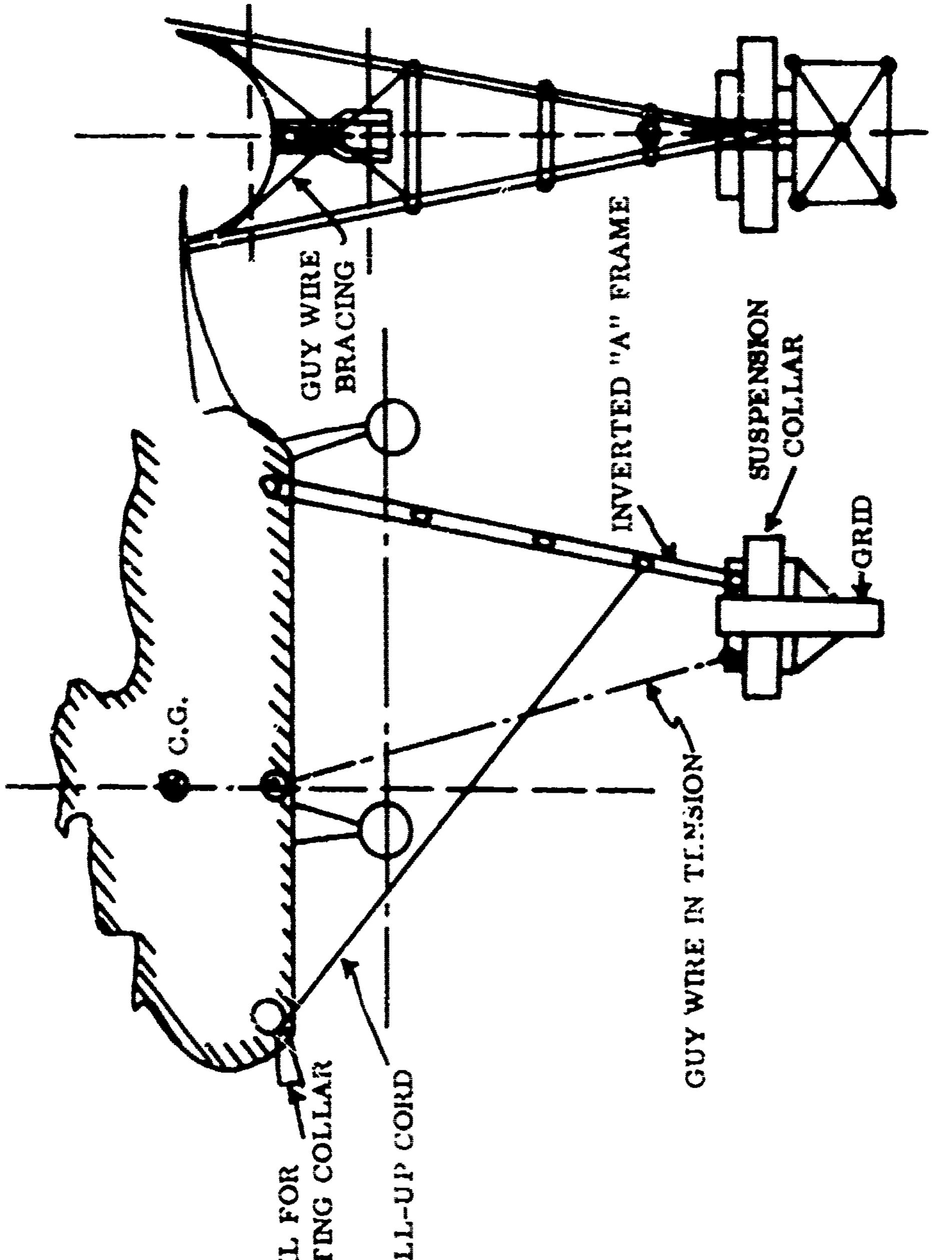


Figure 18. Helicopter - Instrument Frame Configuration (UH-2A\B)

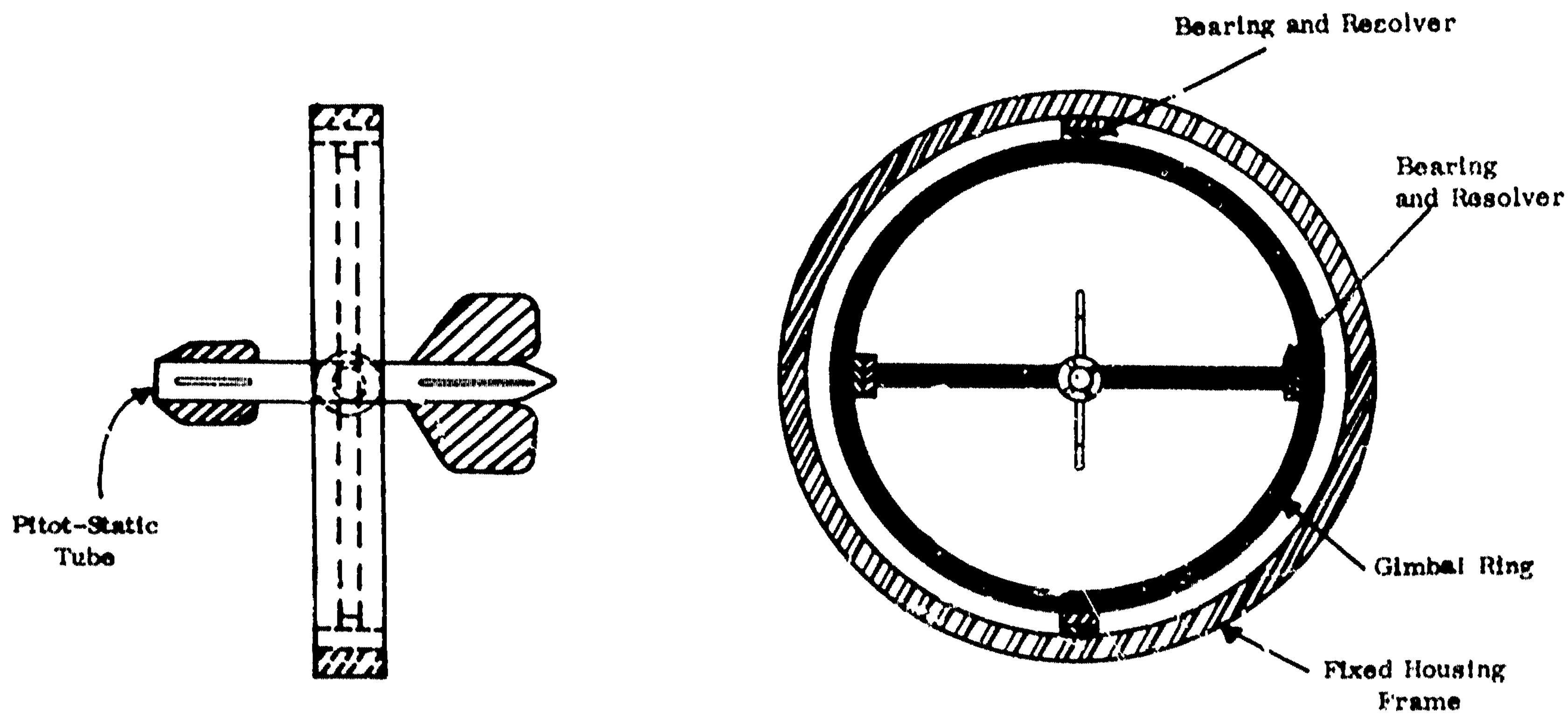


Figure 19. Schematic Sketch of Dynamic Pressure and Wind Direction Measuring Transducer (Scale ~ 1/2)

SECTION X

BIBLIOGRAPHY REVIEW

1. Durand, T.S., "Carrier Landing Analysis", Technical Report No. 137-2; Systems Technology, Inc; February 1967.

The objective of this study was to provide an analytic base for use in the development of improved carrier aircraft landing methods and systems.

Considered were the interaction of aircraft carrier motions, the optical landing system, the pilot-aircraft combination, air wake disturbances, and the landing signal officer. A quantitative mathematical description of the complete landing process was formulated. Methods are presented for determining terminal landing errors and resulting operational performance indexes. A new concept is described for stabilizing the optical landing systems against carrier motions. This concept is termed "Compensated - Meatball Stabilization" (CMS). This technique considers the dynamics of the carrier landing system elements and the optimization of the computer logic for controlling the FLOLS for improved landing performance. Simulator experiments to determine the potential accident rate reduction with this stabilization method show that there are significant effects related to the aircraft's lift-curve slope (C_{L_α}). These effects were analyzed, and the performance-limiting aspects for both manual and automatic control were delineated.

A description is given of the carrier air wake based on extensive data resulting from tunnel measurements. Carrier landing accident rates over a 10-year period are included, and description of the pilot's lead-generating capabilities using the FLOLS is also contained in this study.

The nominal margins available under steady deck conditions and for a perfectly controlled approach were found to be an 11-foot clearance of the ramp, 8-feet-per-second sink rate, and ±60 feet in touchdown point. Also, when the aircraft's inertial path is precisely controlled, the carrier's heave motion directly alters the ramp clearance by a 1 to 1 ratio and changes the touchdown point by a 14 to 1 ratio. Likewise, ±1 degree of carrier pitch produces ±9 feet of deck motion at the ramp and a ±80 foot change in the touchdown point. The heave and pitch motions also cause large vertical deck velocities and thus drastically reduce the availa npact velocity margin.

Because of the known importance of the carrier air wake, a representative model was sought. Wake data from the Oceanics, Incorporated, water tunnel tests were utilized to establish the mathematical descriptions of the air disturbance inputs to the complete system. These data consisted of measured water flow angularity (using a recirculating-type water tunnel) and dynamic pressure variations behind a 33-inch long model of a FORRESTAL(CVA-59) carrier. The three separate components of the air wake as identified and measured by Oceanics, consist of:

a. Steady-State Burble - A time-invariant and space-stationary component caused by the mere presence of the ship in a uniform air flow.

b. Pitch-Induced Wake - An oscillating airflow caused by the pitching cycle of the ship (velocity perturbations).

c. Carrier-Induced Random Turbulence - The non-deterministic and uncorrelated air disturbances resembling gusty air in an open environment.

The pilot-aircraft system responses to random vertical and horizontal turbulence gusts were analyzed for a WOD of 25 knots. The LSO model assumes (in combination with the pilot) that it is 90 percent effective in preventing both undershoots and hard landings. The LSO mathematical model used as a computer input was determined by probability theory. The "ninety-by-ten" average statistical model for wave offs operates on both potential ramp strike and hard-landing accidents, but this model did not influence the bolter rate. The accident and bolter rates per pass, assuming no LSO or pilot-initiated wave offs, were computed on the basis of Gaussian distributions of pertinent terminal motion parameters.

Results of the statistical analytical approach using water tunnel data, aircraft performance, ships dynamics, and instrument properties give a good explanation and performance capabilities of the FLOLS system. Results were directed towards obtaining conclusions for a maximum WOD of approximately 35 knots; however, predictions of performance above this speed cannot be made due to the lack of turbulence data, carrier dynamics data, and the interrelations between these two parameters.

2. "An Investigation of Means of Reducing Aircraft Carrier Air Turbulence to Facilitate Recovery of Planes", Report No. DCR-205, Dynasciences Corporation, Blue Bell, Pennsylvania; November 1966.

Existing carrier wake airflow data was analyzed to determine the relative importance of the various factors which contribute to wake turbulence. A number of ship modifications which reduce the degree of turbulence were investigated experimentally and analytically.

Wind-tunnel tests were performed with the CVA(N) 19, CVA 41, CVA 62, and CVA 65 carriers, and aerodynamic data (time-varying velocities, frequencies, and time-average velocity) were obtained in the carrier wake for the basic carriers and for various carrier modifications by the David Taylor Model Basin. Further studies including observations of the effects of carrier motions on the carrier wake flow were conducted with various models in a water tunnel. To obtain information concerning carrier wake turbulence along the aircraft approach path, instrumented aircraft made repeated landings on a carrier at various wind-over-deck (WOD) speeds and directions.

The results of the wind tunnel tests show that:

a. Wake turbulence is created mostly by the island, deck overhang, and hull.

b. WOD direction is an important factor in the determination of the carrier wake flow field.

c. Amplitudes of the time-varying fluctuations are of significant magnitude.

d. Predominant turbulence frequencies, using the Strouhal number for frequency scaling, are in a range which could affect the dynamics of the landing aircraft.

e. The most effective modification is a honeycomb screen located aft of the island.

f. Carrier modifications tested affect the wake flow only up to about 500 feet aft of the carrier.

3. Seckel, E., Miller, G.E., Nixon, W.B., "Lateral-Directional Flying Qualities for Power Approach", Princeton University Report No. 727; September 1966.

Simulated carrier approaches were flown by Navy carrier pilots in a variable stability Navion airplane. The approaches were visual, in daylight, and at a closure speed of 105 knots. The flight path used for this task was a simple lefthand racetrack pattern around the Princeton runway. The glide slope angle was set at 2.7°, and it intercepted the runway 850 feet from the threshold.

Moderate natural wind turbulence and the carrier turbulence wake were simulated. Lateral-directional handling qualities data in the form of Cooper rating number and pilot commentary were obtained for variations in control sensitivity, roll damping, dihedral effect, numerator transfer function characteristics, dutch roll damping, and magnitude of turbulence. The data are presented as iso-opinion graphs of the parameters involved. Turbulence was found to be a factor of commanding importance in the handling qualities of an aircraft configuration. The poor handling qualities were found to be chargeable to the large value of the dihedral effect and the associated sensitivity to turbulence. Very low values of dihedral effect were objectionable because of the yawing motions excited by turbulence.

These results of the test program are by no means the complete story on lateral-directional handling qualities for power approach landings on carriers.

This particular test concentrated on only one value of dutch roll period and spiral mode time constant. More values of dutch roll periods and spiral mode constants are needed in order to obtain a more complete evaluation with the various parameters involved.

4. Eney, John A., "Comparative Flight Evaluation of Longitudinal Handling Qualities in Carrier Approach", Princeton University Report No. 777, NONR-1858 (50); May 1966.

Simulated carrier approaches utilizing natural turbulence effects to simulate turbulence response of Princeton's variable stability airplane were evaluated. Frequency (W_{SP}) and damping (ζ_{SP}) of the short period mode were varied through augmentation of the M_{α} and $M_{\dot{\theta}}$ derivatives. Control sensitivity (stick-to-elevator gearing) was a third variable. These flights were all daylight operations with light to moderate air wake turbulence. The approach speed of 105 knots was used during these tests. The objective of this test was to determine the desirable short period characteristics for landing approaches aboard an aircraft carrier.

The tests were conducted with the aid of a Princeton variable stability navion aircraft. The aircraft was equipped with an extensively modified Minneapolis-Honeywell 3-Axis E-12 autopilot. The variable longitudinal feedbacks were angle of attack (α), pitch rate ($\dot{\theta}$), and airspeed (V). When fed into the elevator servo, these feedbacks effectively altered the M_{α}, $M_{\dot{\theta}}$ and M_V derivatives, respectively. The gain between stick motion and surface deflection was variable in flight. This allowed control sensitivity ($M_{\delta ES}$) to be an additional variable. A race track landing aircraft pattern was flown and investigated at Princeton's Forrestal airfield. Each run started in the downwind leg at an altitude of 800 feet. The configuration gains were set by the safety pilot on command from the ground.

Final approach began approximately 1 mile out. A 3 1/2 degree glide slope was maintained using a light-bar optical landing aid. In order to match computer response to the navion aircraft's response, three derivatives required adjustment. The airplane's open loop dynamics were altered for this study by varying M and M to achieve the desired valves of W_{SP} and ζ_{SP}. For the phugoid mode, high destabilizing gains on M and M were necessary to approximate the short period characteristics of current carrier aircraft. The speed stability derivative (M_V) would have had to have been so extremely large in order to keep the phugoid frequency low, that it was decided to eliminate the variable (M_V) from the study.

The results include pilot ratings (Cooper Index scale) versus control sensitivities. Comparisons were also obtained between pilot ratings and proposed short period criteria. Included in these test data results were proposed criteria to the current military specifications for aircraft handling, flying, and qualities (MIL-F-8785).

Since Princeton's Navion variable-stability airplane is limited for longitudinal simulation of heavy jet aircraft in the power approach flight condition, all the results are not conclusive.

5. Lehman, August F., "An Experimental Study of the Dynamic and Steady State Flow Disturbances Encountered by Aircraft During a Carrier Landing Approach", Report No. 64-16, Oceanics Incorporated, Prepared for Office of Naval Research Department, Washington, D.C.; September 1964.

Investigations were undertaken in a water tunnel to obtain greater insight into disturbances encountered by aircraft landing on a carrier. These studies were undertaken at Reynold's numbers higher than those normally achieved in wind tunnel investigations. Ground plane technique was used with a fixed water velocity.

The studies included observations of the dynamically disturbed flow patterns due to carrier motions induced by waves, using the cavitation technique and high speed movies. Two models of different sizes were used.

The downstream wake is periodic, with the periodicity having a direct relationship to the pitching and heaving motions of the ship. The overhang of the deck and the island are the two principal causes of the flow disturbances. Pitch motions produce flow disturbances more violent in nature than those occurring from pure heave motions.

Form and nature of disturbances and the downstream wake field vary markedly between models in a fixed position or undergoing pitching and heaving motions. Roll motions of the carrier have no significant influence on the flow disturbances.

The flow disturbances occurring from the deck and those occurring from the island tend to merge into a single major disturbance in the general region of about 500-feet aft of the carrier. Results obtained can be used as an input to study aircraft dynamics within the wake.

6. Lehman, August F., "Some Cavitation Observation Techniques for Water Tunnels and a Description of the Oceanics Tunnel", Cavitation Research Facilities and Techniques, Presented at Fluids Engineering Division Conference, ASME, Philadelphia, Pennsylvania; 18 May 1964.

A description and operational procedures, which are necessary in order to make an objective evaluation of the data acquired from flow patterns around a scaled model aircraft carrier, are given for Oceanics Incorporated water circulating tunnels. Such pertinent points as the size of "air bubbles" that are necessary for observations and still sufficiently small so as not to perturbate the flow fields are considered. Estimated size is believed to be approximately 0.002 to 0.004 inch.

A major short coming of the entire report that is of primary concern to the wake turbulent study is that no considerations are given to scaling factors and to the instrumentation used to measure dynamic flow properties.

7. Cantone, A., "Smoke Tunnel Studies on Wind Velocities Over the Deck of a Carrier", NAEL-ENG-7140; 3 March 1964.

The objective of this report is to establish a procedure to be used for measuring the relative wind velocity of the aircraft carrier. It involves a knowledge of the turbulent flow fields around the vehicle. Although the report gives no information that is of value to ramp turbulence, it does illustrate the variability of the turbulence profile at the carrier's bow with different wind over deck conditions.

8. Oldmixon, W.J., Lieutenant, USN, "The Acquisition, Reduction, and Analysis of Turbulence Data Associated with PA Configuration Approaches to Carrier Landings", Aeronautical Engineering, Princeton University; July 1963.

An analysis was made of flight test data to obtain information representing the turbulence inputs to the test aircraft. The basis of the method was the use of the linearized motion equations for aircraft, with the addition of certain terms representing the aerodynamic effects of the turbulence on the aircraft.

The equations were set up on an analog computer and verified by the technique of matching transient response flight data. Then, through the use of a feedback system, the desired turbulence quantities were obtained as system outputs. Inputs to the system were the aircraft response and control deflections, obtained from the flight test data. The method was found to be valid, assuming the aircraft analogue was correct. The resulting data appeared suitable for further analysis to determine its statistical qualities.

The approach to a carrier was simulated as closely as possible and included effects of atmospheric disturbances. The turbulence effects were to take the form of recorded signals applied as inputs to the electronic servos driving the control surfaces of the variable stability aircraft.

A suitably instrumented Navy fighter aircraft F4B from the Naval Air Test Center, Patuxent River, Maryland, made a series of 33 carrier approaches to the aircraft carrier USS ENTERPRISE under varying conditions of WOD.

The result of this investigation was that:

a. Representations of atmospheric turbulence may be obtained by the analysis method described in the report, assuming that the aircraft analogue is valid.

b. The consistent similarity in the magnitude of the angular velocity gust quantities and the similarity in the magnitudes of gust angular quantities indicated that the turbulence away from the immediate vicinity of the carrier was isotropic in character.

c. The turbulence in the vicinity of an aircraft carrier is characterized by a strong "burble" in the vicinity of the approach end of the carrier deck.

d. Based on these results, it is not possible to give a quantitative description of this turbulence, although it appeared that the character of the "burble" did not vary noticeably with changing relative wind conditions. However, the point at which the "burble" is initially encountered is a function of the relative wind conditions.

9. Barnett, William F., White, Herbert E., "Comparison of the Airflow Characteristics of Several Aircraft Carriers", Report 1908; David W. Taylor Model Basin, Aerodynamic Laboratory; May 1963.

A comparison of the airflow characteristics of several aircraft carriers was made with a view toward establishing correlations between configuration and airflow. Numerous surveys of the airflow patterns about various carriers have been conducted, both in full scale and model scale.

The sources of data are the results of wind-tunnel tests and full scale observations and measurements.. The wind-tunnel data consist of surveys of local dynamic pressure at various points in the wake of 1/100 scale models of the carriers CVA 62, CVA 64, CVA 65, CVS 36, and CVB 41 (references 1 through 6). Full-scale observations and measurements were taken aboard the CVA 61 by the Naval Air Test Center (NATC), Patuxent River. The NATC data consist of pilot observations. In addition Bendix carried out measurements of wind speed and direction on the flight decks of the carrier CVA 61.

Results show that correlations between major features of carrier geometry and airflow patterns can be established. However, prediction of the flow about one carrier from a knowledge of another is not very successful.

To optimize the carrier configuration from an airflow standpoint, a wind-tunnel program could be established wherein the effects of each carrier component could be investigated separately. This type of testing would utilize various components from which carrier models with various hull lines, islands, flight decks, and other features could be constructed.

Isolation of the contributing mechanisms of turbulent wake by studying the individual components is based on the assumption that when two effects are combined, the resulting effects are the sum of the individual effects. Studies of interference and diffraction have continuously demonstrated that such is not the case and that very rarely can results be obtained using summation concepts.

10. Ringleb, F.O., "Three Dimensional Smoke Tunnel of the Naval Air Engineering Laboratory in Philadelphia, Pennsylvania", NAEL-ENG-6818; July 1961.

A description of the wind tunnel (5-by-5-by-8 feet), its operations, and its measurement procedures and techniques for producing smoke tunnels is given.

A primary limitation of the tunnels' usefulness is the narrow range of wind velocities, which vary from 3 to 10 feet per second. These wind velocities produce low speeds because Reynolds scaling of superstructure (aircraft carriers) is so great that similarity can never be achieved. Also, dissimilarities of the flow fields are not believed to be directly related to differences in Reynolds number. (It should be noted that the author never considers other scaling factors; for example, Strandel, critical Reynolds, or velocity ratios.

Data are extremely difficult, if not impossible, to interpret. Photographic procedures were neither stereographic nor taken with pulse illumination techniques. All results appeared to be based upon the operators capabilities, and these results are not subject to data evaluation.

It is anticipated that in the past 6 years, considerable improvement in measurement techniques has been accomplished; if not, this apparatus is of little value for turbulent wake analyses.)

11. Ringleb, F.O., "Studies of the Airflow over an Aircraft Carrier", Report NAEL-ENG-6923; 7 September, 1962, Report NAEL-ENG-7019; 4 April, 1963.

The causes of strong turbulence of flow over an aircraft carrier and, in particular, near the landing area of aircraft have been determined by model studies in the three dimensional smoke tunnel of the NAEL laboratory in Philadelphia, Pennsylvania.

The following have been tested: (a) Model of Forrestal Island, (b) Model of Ranger With Streamlined Island, and (c) Model of Enterprise Island.

These studies furnished the following data: Two basic elements determine the airflow pattern in the environment of an aircraft carrier, namely, the vortex formation when a flow passes over a sharp edge, and the vortex formation associated with the circulation around a body under angle of attack, both phenomena being related to each other.

The flow passing over the island of a carrier forms a wing tip vortex behind the island which rotates in one or the other direction depending on the angle of attack and provides the strongest disturbance of the flow within the landing area of the aircraft. The numerous vortices forming at the edges of the ship and at the island provide further disturbances. However, not only the island but the total body of the ship contributes to the circulation which mainly disturbs the flow in the stern area.

From smoke tunnel observations two basic design rules for aircraft carriers can be derived: Sharp edges on the over water structures of the ship and especially at the deck should be avoided, and the aircraft carrier and, in particular, its island should be surrounded by an airflow without circulation (wing tip vortex).

12. Ringleb, F.O., "Smoke Control Studies for CVA-59 Class Aircraft Carriers" Report NAEF-ENG-6399; 28 May 1958.

Qualitative experiments have been carried out to find a means by which smoke emanating from stack of an aircraft carrier can be prevented from flowing downward and disturbing deck operation. It was observed that the sharp edge of the smoke stack creates a rotating vortex behind the edge which causes a downward motion of the smoke. The problem of smoke control, therefore, consists of finding devices which counteract the possibility of vortex formation.

A simple way to remove a vortex from a fixed position is to direct an airflow around the boundary of the vortex in order to blow the vortex away from its position. In the case of the smoke stack, this can be done by surrounding it with a parabolic shield which is open toward the wind. The air entering the shield flows around the smoke stack, and the air is blown out at its rear in an upward direction blowing away the vortex which otherwise forms behind the rear edge of the smoke stack.

A second method consists of a flat plate placed above the smoke pipe. A vortex is then formed behind the lower edge of the plate. The vortex draws the smoke and the air behind the smoke stack upward and removes the original vortex due to the fact that vortices which rotate in opposite directions attract each other. The newly created vortex is trapped behind the plate, and the original vortex can be removed in the upward draft.

The two devices for the smoke control around the island of an aircraft carrier using known principles of flow control are effective not only on scale models but also on full scale aircraft carriers. It is conceivable that airflow control at other parts of the aircraft carrier may be achieved by applying the two described flow control principles.

13. Hoover, C., "Carrier Airflow Analysis CVA-66 Glide Path Studies", BUWEPS WEPTASK RSSH 99-008/200/9.

The three-dimensional smoke tunnel of the Philadelphia Navy Yard was used to evaluate the flow field along the aircraft glide path.

Conclusions, that were obtained by the author for carrier design recommendations, such as island removal, rounding of decks, and movable flaps, are conclusions which are not based upon any experimental demonstration that can illustrate the effects of the above parameters.

14 Hoover, C., "Carrier Airflow Analysis Smoke Tunnel and Full Scale Comparison of CVA-61", WEPTASK RSSH-9S-008/200/9, Bureau of Naval Weapons; 1 June 1961.

The purpose of this report was to obtain a correlation of flow fields between the aircraft carrier and smoke tunnel models of the carrier. Deck measurement comparisons were the only tests made. The data comparison was that of larity of flow fields and the reference measurements that were carried out endix Aviation Corporation aboard several different types of aircraft carriers time these experiments were carried out, there was no desire among per- in this field of studies to make correlation data comparisons and spectral In lieu of this the author is unaware that the turbulence problem is a time fluctuating phenomenon that cannot be studied by the procedures used the smoke tunnel.

Hannegan, E.A., Badger, H.J., "Optimum Wind Over Deck for Shipboard Recovery Operations with Carrier-Based Airplanes", PTR-RSSH-31003, Naval Test Center, Patuxent River, Maryland; 1 February 1961; Final Report 21 uary 1962.

flow disturbance aft of the ramp and in the landing area is one of the most ificant adverse influences on the pilot's ability to make a precise carrier roach and landing and is primarily affected by the Wind-Over-Deck(WOD). s were conducted on board USS MIDWAY (CVA-41), USS RANGER (CVA-61), RAL SEA (CVA-43), and USS SARATOGA (CVA-60) in order to determine otimum WOD and to evaluate the significance of variation from an optimum anding parameters such as approach speed, sinking speed, off-center and bolter rates.

ests were carried out with the following fleet squadrons and model airplanes:

Fleet Squadrons:	Model Airplanes:
VA 216	FJ - 4B
VA 212	A4D - 2

Fleet Squadrons:	Model Airplanes:
VA - 125	A4D - 2
VAH - 123	A3D - 1/2
VF - 121	F3H - 2

Qualitative evaluation was made of day carrier approaches and landings under WOD conditions varying between 15 and 45 knots for jets and between 7 and 30 knots for propeller airplanes. Optimum WOD tests were conducted aboard the CORAL SEA with three model A4D and two model F8U airplanes in order to obtain a representative sample of quantitative data (307 landings) for WOD values of 25 knots and 35 knots. Each pilot and airplane combination was maintained throughout the tests in order to provide a statistical comparison between a 25-knot WOD with a 3 1/2-degree glide slope and a 35-knot WOD with a 4-degree glide slope for the following airplane landing parameters:

a. Approach speed

b. Actual and theoretical sinking speeds

c. Off-center distance at both the ramp and at touchdown

d. Actual and theoretical touchdown distances from the ramp

e. Main gear to ramp clearance

f. Roll angle at touchdown

All data for the above parameters were obtained from camera coverage of the landing area, except for airplane approach speed which was obtained from the ship's radar.

Airflow disturbance aft of the ramp, or "burble", is generally described as a downdraft of varying intensity immediately aft of the ramp, followed by a resultant updraft of varying and shifting location in the vicinity 1000 feet astern. Airflow disturbances in the landing area are caused by the relationship of fixed and variable factors. Ship design characteristics vary considerably among classes and exert a significant influence on the air mass through which the pilot must fly.

Test results show that for a given magnitude of WOD the airflow in the landing area is steadiest when the relative wind direction is parallel to the angled deck centerline. Airflow conditions in the landing area improve when the magnitude of the WOD is reduced.

The "burble" aft of the ramp becomes stronger when the magnitude of WOD, the angle between relative wind and the angled deck centerline, and natural wind component increase.

The results of these tests were as follows:

a. From the pilot's viewpoint alone, 25 knots WOD for all jet airplanes and 15 knots WOD for all propeller airplanes (WOD parallel to the angled deck centerline) is optimum;

b. For jet airplane recoveries, a 3 1/2-degree glide slope is required for 25 knots WOD while a 4-degree slope is required for WOD values in excess of 30 knots.

c For propeller airplane recoveries, a 3 1/2-degree glide slope is satisfactory for 15 knots WOD, while a 4-degree glide slope is satisfactory for a 25-knot WOD.

This is the only report available that clearly demonstrates the effect of turbulence upon the aircraft's performance as a function of wind over deck (WOD).

16 Corcos, G.M., Symposium of Measurements in Unsteady Flow, National Science Foundation, (ASME Meeting - Worcester, Massachusetts); 23 May 1962.

The purpose of this symposium was to present the state of the existing knowledge and some recent developments in the techniques of unsteady flow measurements.

This paper discusses the measurement of the statistical properties of turbulent pressure fields and dictates that flow and measuring equipment fulfill a certain number of requirements. These requirements include the isolation of the local flow pressure field of interest from other sources of pressure fluctuations and from radiated noise. The sensitivity of the measuring equipment to other signals, such as vibrations and linearity, over a wide frequency range is also required.

The most fundamental difficulty attending the measurement of pressure, within a turbulent flow, is that it is difficult to introduce a probe in the stream without altering the velocity and the pressure fields. In a steady, locally uniform stream it is relatively easy to ensure that the static pressure at the holes is equal to the static pressure of the stream once the probe is removed. But, for a turbulent flow, the instantaneous velocity is a vector whose direction and magnitude change at random, so that the probe instantaneously experiences a cross-flow which will cause an additional pressure field. The relative order of magnitude of this effect depends on the probe geometry and on the scale of the turbulence.

In pressure measurements another problem, although less fundamental but important nevertheless, is that of vibrations. In a turbulent flow, sources of excitation abound, and the result is usually a very large signal due to vibrations.. In the case of a statistical pressure proble, since it is a cantilever structure required by aerodynamic considerations to be slender, it is therefore not very rigid in a strong vibrating flow. Good pickup response can be achieved with piezo-electric elements (for transducer faces directly in contact with the pressure field) up to a frequency equal to perhaps two-thirds of the first natural frequency of the element.

Velocity fluctuations in any flow field produce pressure fluctuations. Turbulent pressure fluctuations are random functions of time and space.. Some quantitative information is presented. Finally some of the results of measurements in the fully turbulent flows of air in a pipe are presented as an illustration of the techniques discussed.

17 Lippisch, A.M., "Flow Visualization in Two and Three Dimensional Flow Fields by Use of Smoke Filaments", The American Society of Mechanical Engineers Symposium on Flow Visualization; 30 November 1960.

This paper describes the construction and operation of two and three dimensional smoke tunnels. The system used today to produce the smoke has smoke generator where the oil is soaked up by wicks which are led through heating coils. The use of oil smoke has the advantage that the lines and thin tubes are kept open and can be cleaned easily. Model dynamics can be incorporated into the testing facilities to demonstrate actions of propellers and the influence of the angle of attack upon flow fields.

A fluid, whose flow potential is known, can be used to determine the theoretical course of the stream lines. It is then necessary to transform the flow potential. Observation and photographic recording of the flow patterns are all that is required to indicate the course which an investigation of a special problem should follow. Since most theoretical treatments of aerodynamic problems require some simplification to obtain a useful solution, the flow observation indicates in such cases which terms of the analytical equations can be neglected. Boundary layer phenomena with low turbulence have been observed in three-dimensional smoke tunnels.

18. White, Herbert E., Blalock, James, E., Foster, John J., Anderson, Arnold W., Nickols, Frank, A., "Wind-Tunnel Tests to Determine the Air-Flow Characteristics in the Wake of Five Aircraft Carrier Models", conducted in the Wind-Tunnel of the David Tyalor Model Basin during the time from 1953 until 1959.

Wind-tunnel tests wer made on scale models of various aircraft carriers in order to obtain data in the form of ratios of dynamic pressures at various local points in the approach zone of aircrafts to the free-stream dyanamic pressure. Also, attempts were made to obtain velocity ratios in the wake of an aircraft carrier by using an instrumented trailing bomb which was towed from a helicopter. This full scale test was cancelled because the data obtained were unsteady and unreliable, and only wind tunnel tests were conducted.

The wind-tunnel tests were performed on 1/144 scale models in the 8-by-10-foot wind-tunnel of the David Taylor Model Basin. Yaw angles of 0 degrees and 10 degrees were tested for the straight deck and yaw angles of 0 degrees, 10 degrees, and 20 degrees were tested for the center deck. Special racks had been used, consisting of 42 pitot-static tubes for dynamic pressure measurements in the wake of the carriers up to 1440 feet aft the ramp and one reference pitot-static tube located outside the model's field of influence. The pressures sampled by the pitot-static tubes were indicated on vertical manometer boards and photographed for later evaluation.

Data analyses showed considerable scattering of the dynamic pressure ratios and also these ratios above and aft of the flight deck were flatter than expected. There was a sharp change in the dynamic pressure pattern between 10 degrees and 20 degrees of the crosswind.

The scatter of the data was attributed to errors in film readings. The flattening out of the curves was assumed to be due to the fact that the airspeed of the aircraft is much greater than that of the aircraft carrier. The scope of the test did not permit a determination of the angle between 10 degrees and 20 degrees crosswind which would give the maximum dynamic pressure pattern.

Frequency response characteristics of the instrumentation was a limiting feature for determining reliable wind tunnel turbulence measurements.

19. Kiellmann T.K., Colt, R.B., "Survey Report of Wind Direction and Speed Across the Flight Deck of the U.S.S. TICONDEROGA CVA 14 (CVA 19 Angled Deck Class)". Index No. NS(illegible)-0201, Contract Nobs 72137, Bendix Aviation Corporation, Friez Instrument Division, Baltimore, Maryland; August 1957.

Fifty-six tests were conducted aboard the USS TICONDEROGA to determine how the relative wind velocity differs at various locations on the carrier. Test conditions were chosen to represent wind significant for aircraft operations, helicopter operations, and true meteorological wind computations. Data presented show the relative wind variations between stations.

It is suggested that the present yardarm wind detector locations are unsuitable for measuring deck winds or for computing true meterological wind. Alternate wind detector locations are recommended for optimum accuracy for all operating conditions. The measuring equipment used for evaluating the winds at the various locations on the ship consisted of eight wind detectors and eight recorders.

The following eight stations were selected for the installation of the wind detectors:

a. Station 1 represented the touchdown point for landing operations.

b. Station 2 was selected to observe eddy wind effect from the island structure.

c. Station 3 represented the take-off point when a full landing is not accomplished.

d. Stations 4 and 5 represented the catapult take-off points.

e. Station 6 was selected as a better position for wind sampling than the yardarm wind detectors "A" and "B" being mounted fairly close to the island structure.

f. Stations 7 and 8 were added to observe the wind effects over the bow and forward edge of the angled deck at various heights above the deck.

All wind detectors were mounted 7 1/2 feet above the flight deck except Station 6 which was supported 52 feet above flight deck and yardarm detectors "A" and "B" which were supported 64 feet above flight deck.

A constant ship speed of approximately 18 knots was maintained and for each 30-degree course, five minute records were taken for relative wind velocity and absolute ship's velocity. From this data, the true meterological wind for each detector of interest was computed.

The test results indicated that at most deck stations the wind velocity during the test periods was not steady and it varied markedly in both speed and direction. The velocity varied considerably in direction and magnitude. These variations became exaggerated by the presence of the island superstructure.

Furthermore, it was found that the location of the present yardarm wind detector did not give representative wind conditions for flight deck operations. Station 6 will give the most reliable relative wind measurements, when directional correction factors are considered for obtaining the correct relative deck wind velocity. Also true wind computations for relative bow winds would be more accurate if station 6 rather than the yardarm detectors "A" or "B" would be used.

The data supplied should be considered representative of wind conditions for the CVA 19 class carrier only.

20. Kjellman, T.K., Colt, R.B., "Survey Report of Wind Direction and Speed Across the Flight Deck of the USS RANGER CVA 61 (CVA 59 Class)", Index NS 681-026-03, Contract NObs 72137, Bendix Aviation Corporation, Frietz Instrument Division, Baltimore, Maryland; April 1958.

Sixty tests were conducted aboard the USS Ranger CVA 61 to determine how the relative wind velocity differs at various locations on the ship with respect to the yardarm wind detector. Test conditions were chosen to represent winds significant for aircraft operations, helicopter operations, and true meteorological wind computations. Data presented show the average relative wind variation at these locations. Measuring equipment used for evaluating wind at various locations consisted of eight wind detectors and eight wind recorders.

The detector locations were chosen and numbered as follows:

a. Stations 1 and 2 represent touchdown points for landing operations.

b. Station 3 gaged wind conditions at the angled deck catapult take-off point.

c. Stations 4 and 5 represent the forward catapult take-off points.

d. Station 6 was selected as a possible alternate location of the existing yardarm wind detectors P and S.

e. Stations 7 and 8 gaged vertical wind direction forward of angled deck and the bow.

All wind detectors were mounted 7 1/2 feet above the flight deck, except Station 6 and Stations P and S which were supported 54 feet above flight deck.

The resulting data indicated that the present yardarm wind detectors do not give the reliable data for all flight deck locations. The velocity varies up to ± 7 degrees and ±3 knots. The relative wind is distorted by varying amounts at all stations measured. due to the geometry of the carrier. Average correction factors may be applied to the yardarm wind detectors to determine the relative winds on deck. These factors will vary with the relative wind speed and direction.

21. "Wind Survey of CVA Type Carrier-Final Report", Nobs-72137, NS-681-026-1-213. Frietz Instrument Division, Bendix Aviation Corporation. Navy Department-Bureau of Ships; June 1956 to May 1958.

This report is a summary of measurements carried out on different model aircraft carriers. Conclusions are that the location of wind detectors on the ships deck are unsatisfactory for operation use.

22. Thom, A. Swart P. "The Forces on an Airfoil at Very Low Speeds", Journal Royal Aeronautical Society Page 761; 1940.

The forces on an airfoil were measured at various angles of attack for Reynold's numbers from 0 to 2000. These experiments were undertaken to study the general behavior of an airfoil at low speeds. The experiments were made to determine what effects Reynolds Number reduction would have on changes expected in cirulation or on lift when the point was reached where viscosity prevented the formation of eddies. These measurements were made in a 5-inch by 5-inch channel using either water or oil as the fluid medium.

Several arrangements were tried during the course of this experiment, and, due to difficulties that had been encountered in dealing with these small Reynold's Numbers, no definite conclusion was determined on forces on airfoils for low Reynold's Number.

23. Schubaur, G.B., Skramstad, H.K., "Laminar Boundary - Layer Oscillations and Stability of Laminar Flow", NACA Technical Report 909; February 1947.

An account is given of an experimental investigation conducted at the National Bureau of Standards in 1940 and 1941 in which sinusodial velocity fluctuations were discovered in the laminar boundary layer of a flat plate. The characteristics of these fluctuations were studied in detail and found to agree with the characteristics predicted earlier by the Tollmein stability theory. The fluctuations are termed "Laminar Boundary-Layer Oscillations" to distinguish them from the irregular velocity fluctuations previously observed by other investigators.

This present investigation was conducted in a wind tunnel having a turbulence of less than 0.1 percent of the free stream velocity. The oscillations were detected and studied by means of the hot-wire anemometer.

A description is given of the methods used to produce and study boundary-layer oscillations By these methods the oscillations were found to consist of a wave motion in the boundary-layer. These results were all obtained with zero pressure gradient.

Aircraft Carrier Turbulence Study For Predicting Air Flow Dynamics With Increasing Wind-Over-Deck Velocities

NAEC-ENG-7467

An intensive review of literature pertinent to aircraft carrier air flow dynamics and an evaluation of experiments were conducted in order to determine the effects of turbulence on landing aircraft. Particular emphasis was given to the effects on carrier aircraft operations which occur as a result of increasing wind-over-deck (WOD) velocities, as well as carrier dynamics. Recommendations for future experimental and theoretical studies are given.

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