An Experimental Study of the Dynamic and Steady-State Flow Disturbances Encountered by Aircraft during a Carrier Landing Approach

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The processes involved in landing an aircraft on a carrier are extremely complex. The landing deck is not a stable platform in space, but constantly is changing its orientation owing to the pitching, heaving, and rolling motions of the ship. Jet aircraft response is somewhat slow or sluggish in the landing attitude; thus, disturbances existing in the air wake along the glide path which affect the aircraft are of considerable importance to the pilot. This study, which was undertaken in a water tunnel, was concerned with identifying the cause and nature of the major dynamic disturbances existing about the glide path area, measuring the steady-state velocity magnitudes and directions in this area, and measuring the dynamic horizontal and vertical velocities in this area. Major conclusions are the following: the overhang of the deck is the major source of the disturbances; dynamic vertical velocity fluctuations are stronger and persist longer than horizontal velocity fluctuations; and stronger disturbances are produced when the wind is along the landing deck than when the wind is aligned more closely with the keel line.

Introduction

THE processes involved in landing an aircraft on a carrier are extremely complex. One must consider aircraft approaching at speeds in excess of 100 knots with a touchdown length in the neighborhood of several aircraft lengths. Add to this the fact that the carrier will be undergoing various degrees of pitching, heaving, and rolling, thus constantly changing the orientation of the landing deck in space. Include also the fact that the response of a jet aircraft tends to be somewhat slow or sluggish in the landing attitude, so that disturbances existing in the air wake along the glide path and affecting the aircraft are of considerable concern to the pilot who is attempting to make a satisfactory approach and touchdown. A touchdown that is "short" of the landing deck is extremely hazardous to the aircraft and pilot as this results in an encounter between the aircraft and the stern of the vessel. An overshoot of the arresting cables requires the aircraft to become airborne again within several aircraft lengths, a procedure that can be fairly hazardous where jet aircraft are concerned.

It is the cause and nature of the disturbances affecting the aircraft in the glide path which have been investigated and will be described in this paper. But, before doing so, perhaps a paragraph or two of additional background material applicable to the aircraft landing problem might be helpful.

The Fresnel Lens Optical Landing System is one of the systems currently employed to indicate to the aircraft pilot whether or not his approach to a carrier in the landing process is proper. With this system or with a similar signal system three elements are involved: 1) ship dynamics, 2) aircraft dynamics, and 3) pilot response. Of these three, two (aircraft dynamics and pilot response) will be affected by disturbances in the glide path.

Major disturbances do exist in the glide path and are collectively identified by carrier based pilots as a "burble." The disturbances of concern to the pilot are encountered within the last several seconds before touchdown; the significance of this encounter is, normally that the pilot has only between 1 and 2 sec after emergence from the disturbance to commit himself to a landing or an abort. Such decision making creates considerable strain on the pilot, in view of the possible, serious consequences resulting from a wrong decision.

Program Objectives

The primary purpose of this program concerned an investigation of the flow conditions existing in the glide path or approach area of a carrier. To satisfy this purpose, four objectives, all involving model studies, were established: 1) to observe visually and photographically the vortex formations representing and comprising the major characteristics of the air wake disturbances existing in the glide path area; 2) to measure the steady-state velocity magnitudes and directions at a number of axial stations downstream of the model, extending far enough aft to include all reported major flow disturbances; 3) to measure the dynamic velocity fluctuations in both the axial and vertical directions existing in the glide path area; and 4) to analyze and interpret the dynamic velocity fluctuation data to permit their utilization in system analysis computer studies† concerned with the Fresnel Lens Optical Landing System.

General Approach to the Problem

Perhaps the dominant consideration in satisfying the program objectives was that the studies should be undertaken with a model undergoing heaving, pitching, and rolling motions, as it was believed that the wake created with model motions would be different significantly in character than the wake existing with the model stationary. Another important consideration was the desire not only to observe easily the downstream disturbed flow pattern, but also to identify the

Presented as Preprint 65-332 at the AIAA Second Annual Meeting, San Francisco, Calif., July 26-29, 1965; submitted August 24, 1965; revision received January 17, 1966. This work was supported by the Office of Naval Research under Contract Nonr-4186(00) with the technical direction under Code 461. Appreciation is expressed to that code, particularly to G. Flohil. The contributions of Systems Technology, Inc., in examining the data in light of their computer studies is recognized, particularly the efforts of T. S. Durand and R. J. Wasicko.

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† The system analysis studies were undertaken by Systems Technology, Inc., Hawthorne, Calif.

source creating these flow disturbances when the model was in motion.

Because of these two considerations, it was decided to undertake these studies, which involved an investigation of air wake disturbances, in a water tunnel. This technique is much more reasonable than it initially appears. At full scale wind-over-deck velocities, air acts as an incompressible fluid, i.e., the compressibility effects are negligible. Because the air acts as an incompressible fluid, water, which is an incompressible fluid, can be substituted satisfactorily. (Conversely, problems involving water flow can be, and often are, studied in low velocity air flows.[1,2]) Thus, water tunnel studies are as valid as air tunnel studies. In fact, from Reynolds number scaling considerations, water tunnel studies have an inherent advantage over air tunnel studies because of the difference in the kinematic viscosity of the two fluids. The wall effects in water tunnel studies are no larger than those in air tunnel studies. Boundary-layer growth has a direct relationship with Reynolds number; thus the same boundary layer exists in either an air or a water tunnel if the tests are run at the same Reynolds number.

Another advantage of water tunnel investigations is that flow disturbances (vortex formations) that may exist in any fluid can be observed easily through the phenomenon known as cavitation. Cavitation is defined as the formation, growth, and collapse of vapor or gas-filled voids (bubbles); thus these vapor bubbles permit the observation of the disturbed flow and vorticity patterns.

In analyzing the over-all problem it was recognized that disturbances (other than free air turbulence) encountered by landing aircraft must originate from portions of the ship hull, deck, or island. All of these major components will produce flow disturbances either having well established vorticity patterns or with vorticity tendencies. For example, depending upon the relative wind direction, the leading edges of the bow and landing deck can act much as the leading edges of wings. Thus, the "tips" (or corner edges) would shed the well-known tip vortices commonly observed from aircraft wing tips. This type of vorticity can be extremely strong and has a long life. Figure 1 illustrates a tip vortex forming from a wing at an attack angle (water tunnel investigation). For the problem under consideration, the cores of the vortices essentially would travel parallel to the wind direction. (Some recent work by Batchelor[3] discusses the strong velocity gradient that can exist parallel to the core of a vortex of this nature.) The leading edges of the bow and landing deck also can shed Karman type vorticity, that is, vorticity in which the core of the vortex essentially is parallel to the edge of the shedding structure. This type of shedding is shown in Fig. 2. It was easy to postulate that this type of shedding would be intermittent owing to the cross flow of the wind along the deck edges caused by the pitch and heave motions of the carrier. How correct this postulation was will be noted later.

As the island is located on the deck parallel to the longitudinal center line of the ship's hull, it is therefore at an angle to the landing deck. Since the relative wind is normally oriented along the landing deck, the island is at an effective attack angle. Because of this orientation, the island will produce disturbances associated with such a blunt structure at an

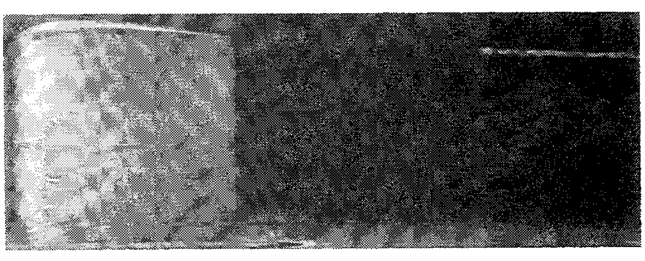

Fig. 1. Tip vortex.

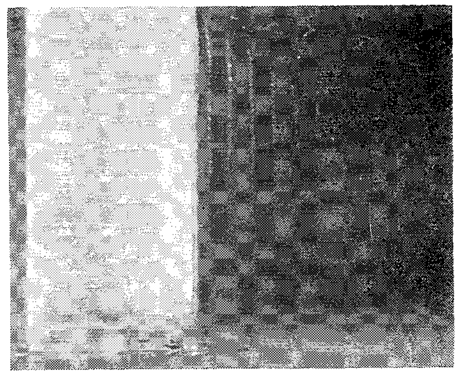

Fig. 2 Karman type vorticity.

attack angle. Also, the hull itself, projecting as it does from the water, will create an air wake aft of it.

Test Arrangement

The tests were undertaken in the Oceanics water tunnel. This tunnel is a closed jet recirculating type having both velocity and pressure variable (see Fig. 3). The maximum test section velocity is about 40 fps, whereas the test section pressure, which can be controlled independently of the test section velocity, covers a range from about -0.9 to $+1.0$ atm using atmospheric reference. The test section itself is about 20 in. on a side and has rounded corners. The over-all length of the test section is 7 ft. There are eight viewing windows, two on each of the four sides; each window has a viewing area of 10×30 in.

The test arrangement consisted of a flat horizontal plate extending across the width and length of the test section. This plate represented the sea surface and divided the flow passing through the test section. The flow of water passing over the upper portion of the plate represents air flow in the real case. This is the portion of the flow which is of interest in this program. (The flow below the plate has no significance in this study.)

The model, which was 33 in. long, was positioned near the forward end of the test section and the hull passed through an opening in the plate. This opening was just large enough to permit the model to undergo heaving, pitching, and rolling motions without hitting the sides of the opening. The model was supported actually by rods extending from the pitch and heave mechanism (located beneath the test section) through the tunnel test section bottom and into the model mounting block. Roll actuation is controlled by a separate push-pull mechanism. Figure 4 is a sketch of the basic model-plate-actuation installation, whereas Fig. 5 is a sketch of the over-

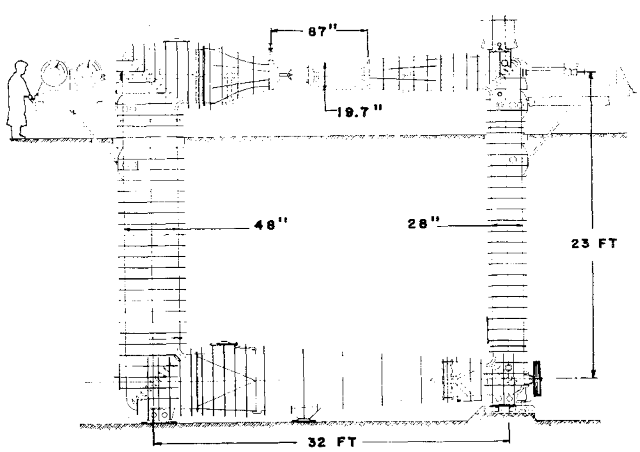

Fig. 3. Sketch of tunnel.

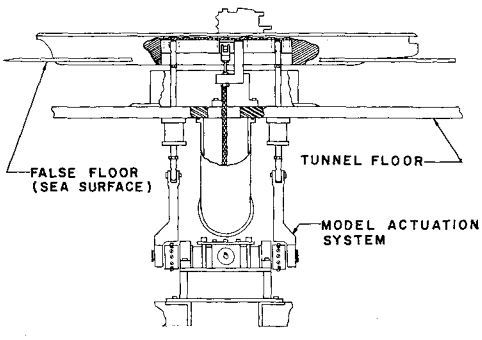

Fig. 4 Model-plate-actuation installations.

all test arrangement, in this case showing the installation of instrumentation for measuring dynamic velocity fluctuations.

Flow Visualization Studies

This portion of the investigation involved visual observation and high speed movies of the carrier model while undergoing pitching, heaving, and rolling motions. The actuation mechanism, in conjunction with the tunnel velocity, was set at speeds that would introduce the proper (scaled) time periods of pitching, heaving, and rolling of the full scale vessel. The tunnel static pressure then was reduced slowly until portions of the disturbed flow about the carrier became visible via the phenomenon of cavitation. These disturbed flow patterns were observed with the carrier in different fixed orientations and with varying rates of pitch, heave, and roll. The disturbed flow patterns made visible by cavitation were examined with normal illumination and the aid of a strobotac. Using the strobotac, attempts were made to "stop" the individual disturbed flow formations.

These observations permitted a good general understanding of the causes of the flow disturbances and the nature of the flowfield downstream of the carrier model. The marked differences in the disturbed flow formations when the model was stationary and when undergoing dynamic motions were noted. Both air and dye were emitted from various openings in the carrier deck and island to see how the flow associated with a particular area behaved when an observation technique other than cavitation was used. Air and dye were also exhausted from the smoke stack to note the behavior of the stack gases and its mingling with the downstream flow pattern.

The flowfield then was examined with the use of high speed movies with the carrier undergoing pitch, heave, and roll motions again scaled to the actual carrier motions. Because the cyclic rate of the model was quite high in order to maintain the proper scaling parameter,‡ film speeds to 4000 frames/sec were employed.

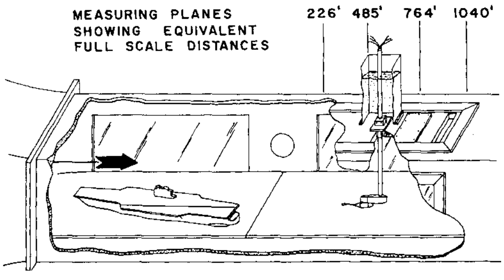

Fig. 5 Over-all test arrangement.

‡ The Strouhal number was employed in scaling; i.e. $(\omega L/V)$ full scale $= (\omega L/V)$ model. Here ω is the cyclic frequency, L is a characteristic length, and V is the wind-over-deck velocity. In this case, for a full scale wind-over-deck velocity of 35 knots and a pitch period of 10 sec, the model cyclic rate was 9.6 cps with a tunnel velocity of 15 fps.

The analysis of the movies was most enlightening and a 16mm sound movie has been composed using some of the high speed film exposed during the studies. (Copies of this movie may be obtained from the Office of Naval Research, Washington, D. C. 20360, Attention: Code 461.) With a body as nonstreamlined as the carrier model, the cavitation technique affords an excellent three-dimensional visualization of the causes of the disturbed flow pattern and the downstream flow pattern itself. The more important conclusions drawn from a study[4] of the high speed movies are:

1) The form and nature of the originating disturbances and the downstream wake field are markedly different in cases in which carrier is fixed in orientation and the model is undergoing pitching and heaving motions.

2) Pitching and/or heaving motions not only introduce a pronounced periodicity in the shedding action, but also in the downstream wake. Each pitch or heave motion produces one mass or grouping of disturbed flow and the motion appears to increase significantly the violence of the downstream disturbances, in addition to introducing the periodicity. Each mass has a general clockwise motion (resulting from the tip vortices) when standing aft and looking in the direction of ship travel.

3) It is not believed that stack gases by themselves influence the flight characteristics of an aircraft. The stack gases mingle with the disturbed flowfield originating from the island, with this disturbance later combining with the disturbed flowfield from the entire carrier. Thus, the gases make the existing flow disturbances visible and add the psychological effect of interfering with the pilot's process of visual orientation.

4) Disturbances originate from the island, the deck, and the hull, but the complete elimination of the island only reduced the downstream disturbed flow pattern to a minor degree.

5) It is believed that the canted deck is the major contributor to the downstream disturbances. This results from the extreme overhang of the deck in relation to the hull.

6) The orientation of the carrier, with respect to the existing natural wind, has an important influence on the path of the disturbed flowfield after it leaves the near vicinity of the carrier, as the disturbances then become a part of the general atmospheric flowfield.

Steady-State Flowfield Measurements

The magnitude and direction of the steady-state velocities existing in and about the glide path were determined with a directional pitot tube in planes perpendicular to the average flow direction at five distances aft of the model corresponding to full scale dimensions of 226, 485, 764, 1030, and 1310 ft aft of the touchdown point on the carrier. Measurements were made up to a maximum of 160 points per plane of investigation. These measurements were made for several carrier pitch orientations and wind directions. Understandably,

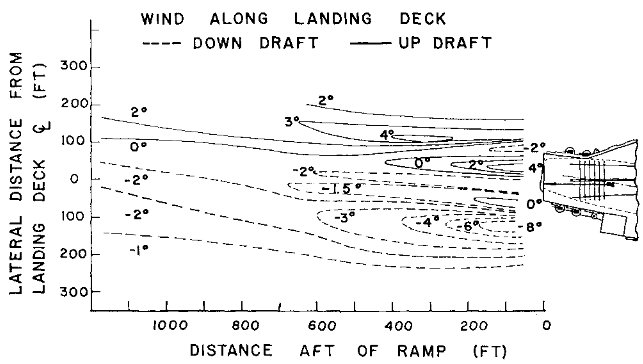

Fig. 6 Plot of steady-state wind directions along a 4° glide path.

these studies[4] produced a mass of data; this information was employed by Systems Technology, Inc., in establishing inputs for systems analysis computer studies undertaken on the carrier landing problem. Figure 6 shows one of the plots developed by Systems Technology, Inc. from the steady-state data obtained. This plot shows clearly the mass rotation of the flowfield as well as the areas in the wake that have specific downwash or upwash magnitudes.

Dynamic Velocity Measurements

Perhaps the most challenging portion of the investigation was that of measuring the dynamic horizontal and vertical velocity fluctuations. To do this it was necessary to develop a dynamic velocity sensing probe having a satisfactory response over the range of frequencies to be investigated. Although a number of dynamic velocity sensing devices have been developed for use in water, here an extremely rugged instrument was wanted which could hold its calibration for several weeks and show no temperamental characteristics when subjected to the environment of a typical water tunnel. An instrument approaching the reliability and simplicity of a Prandtl-type pitot tube was sought.

A significant advantage existed in that the desired frequency response range is exceptionally low when compared with the response range desired by typical turbulence detection devices. For example, the maximum full scale ω range with pitch motion was in the neighborhood of unity; thus in model scale the maximum frequency was about 10 cps. For power spectra, the desired maximum full scale ω value was of the order of three, corresponding to a model scale frequency of the order of 30 cps.

Because of the low frequency requirements, it was believed that a probe utilizing small commercially available pressure transducers (Consolidated Electrodynamics Corporation, type 4-312-002) could be used. Basically, the concept involved a Prandtl-type pitot tube extending from a streamlined pod, which would contain the pressure transducers. A sketch of the probe is shown in Fig. 7. Note that the total head pressure is fed to one transducer, with the static head pressure fed to the other. The electrical output from the transducers is subtracted, one from the other, leaving a signal that is some measure of the velocity head. The calibration technique was rather involved, but essentially it was accomplished by impinging, upon the tip of the submerged probe, jets of water traveling at known velocities and known frequencies. Using this technique the instrument had a satisfactory response up to 40 cps.

In order to prevent cross flows (flows from directions other than that in which a measurement of the velocity fluctuations were desired) from affecting the sensed velocity fluctuations, the tip of the probe was shielded. A 90° shield was used to measure the vertical velocity fluctuations. A photograph of the probe is shown in Fig. 8. On the probe proper is the head employed for measuring vertical velocity perturbations, whereas above this is the head used for measuring axial perturbations. The shield used during axial measurements is above the basic axial unit.

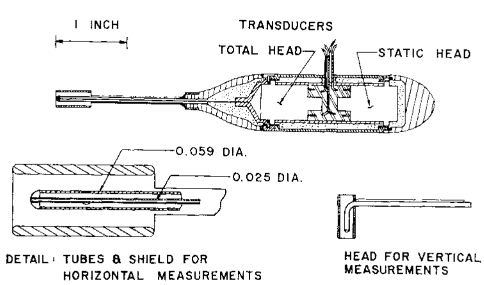

Fig. 7 Sketch of probe.

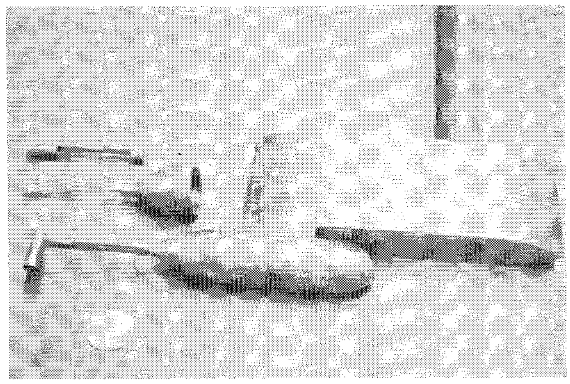

Fig. 8 Final probe showing heads and shields.

For dynamic measurements the probe was positioned at glide path angles of 3°, 4°, and 5°, with measurements taken along the centerline of the glide path and at distances equivalent to 47 ft (full scale) port and starboard of the glide path centerline. Thus a matrix of nine measuring points was formed at each downstream measuring station. These measuring stations were the same as those employed for the steady-state velocity measurements.

The output from the probe was passed through an appropriate filter and that output fed to a strip chart recorder. Simultaneously, a signal was fed to the recorder showing the pitch orientation of the model. In this way, phase relationships between the signal and the carrier position could be established. The data obtained at each point in space for various model pitch frequencies and wind directions were then converted into transfer function amplitudes and phases, for the horizontal and vertical velocity fluctuations relative to the ship pitch angle. Power spectra obtained with no carrier motions (at the same positions) for vertical and horizontal velocity fluctuation measurements were also evaluated.

An indication of the nature of the data obtained during the investigations is presented in Figs. 9 and 10. Figure 9 illustrates the vertical pitch amplitude and phase transfer functions for the position 990 ft aft of the carrier along the centerline of the 3°, 4°, and 5° glide paths. In this figure, w is the vertical velocity perturbation value, V is the free stream wind

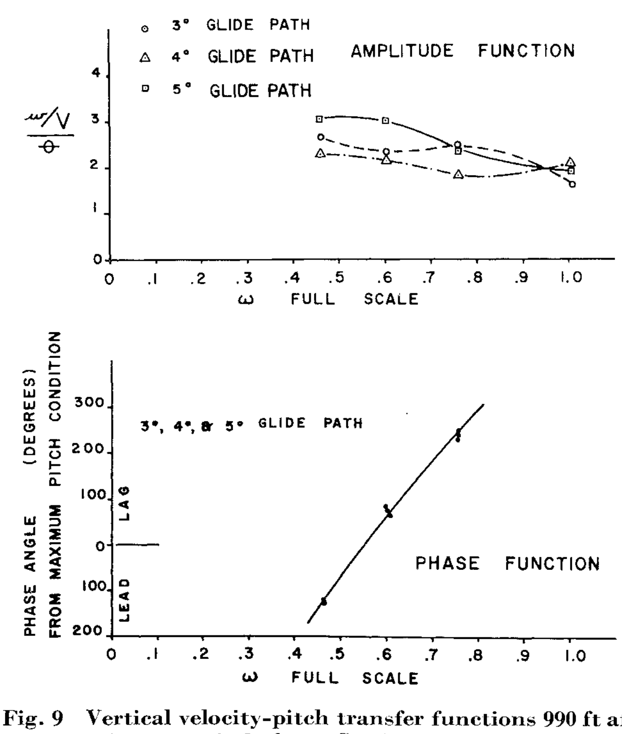

Fig. 9 Vertical velocity-pitch transfer functions 990 ft aft of ramp, wind along C_L of landing deck.

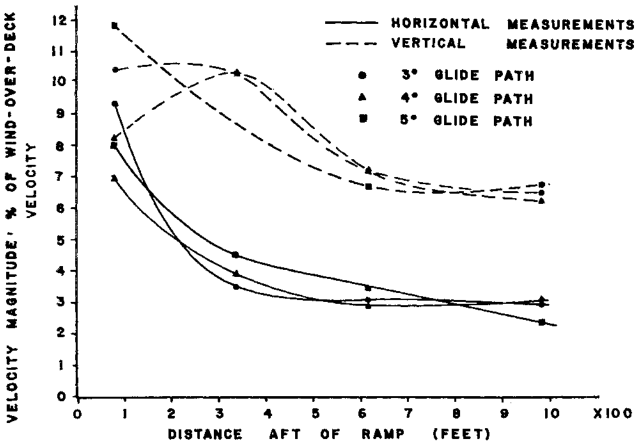

Fig. 10 Velocity fluctuations; 10-sec pitch period wind along C_L of landing deck.

velocity, θ is the pitch angle (radians), and ω is the pitch frequency in radians per second. There is some difference in the amplitude function with glide path angle but the phase function shows little change with the glide path variations investigated. Figure 10 presents the actual magnitude of the horizontal and vertical velocity fluctuations as a percentage of the oncoming flow encountered along the 3°, 4°, or 5° glide path for a specific test condition.

The dynamic velocity measurements[5] tended to reinforce the general conclusions deduced from the flow visualization and steady-state flow studies.[4] The major conclusions were: 1) vertical velocity fluctuations are larger considerably than horizontal velocity flucutations; 2) the magnitude of the velocity flucutations for the horizontal and vertical measurements tended to increase as the position in space moved from starboard to port of the glide path center line; 3) the magnitude of the horizontal and vertical velocity fluctuating values decreased as one proceeds downstream from the carrier; and 4) the magnitude of the velocity fluctuations decreases as the relative wind orientation changes from the center line of the landing deck toward the center line of the ship.

Summary

This investigation proved the practicability of studying both the steady-state and dynamic air wake conditions existing aft of a carrier model in a water tunnel. The use of the water tunnel afforded an excellent means of visualizing the dynamic disturbed flowfield through the phenomenon of cavitation. The use of existing instrumentation coupled with that specially designed for dynamic measurements permitted the determination of both the steady-state flowfield characteristics and the dynamic horizontal and vertical velocity fluctuations existing in and about the glide path area used by aircraft approaching a carrier for landing. The significance of this series of investigations was that a better physical understanding of the air wake now exists and, in addition, actual disturbance values now are available for use in simulator studies or other dynamic analyses.

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