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A SUMMARY OF HELICOPTER VORTICITY AND WAKE TURBULENCE PUBLICATIONS WITH AN ANNOTATED BIBLIOGRAPHY

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FINAL REPORT

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16. Abstract

A review of all literature published since 1964 relating to helicopter vortex systems and wake turbulence was made. The results of this review are evaluated and summarized, and conclusions are drawn relative to that review. The documents are grouped in general categories, and this is further supplemented by an annotated bibliography and authors index. Also incorporated in the review is a comparative analysis of rotary-wing versus fixed-wing circulation intensity time-history.

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INTRODUCTION

BACKGROUND.

In 1964, the Federal Aviation Administration (FAA) sponsored a program to develop a mathematical model of the wake velocities produced by both fixed- and rotary-wing aircraft. The program was accomplished by the Boeing Company under contract. The results obtained are contained in the FAA Contractor's Report RD-64-4, dated March 1964 (index No. 248). The objective of that effort was to provide the technical information required to establish minimum safe aircraft separation and parallel runway spacing, upon which criteria might be based.

The time-history of lift-induced vortex system was computed for the following aircraft types, gross weights, flight speeds, and flight conditions:

Aircraft Type	Gross Weight (lbs)	Aircraft Velocity (knots)	Flight Phase
B-707-320B	326,500	174	Takeoff
	210,000	134	Approach
B-707-120	175,000	139	Approach
DC-6B	88,200	108	Approach
V-745	57,500	115	Approach
Gulfstream	35,100	110	Takeoff
	33,600	111	Approach
Jet Star	21,000	126	Approach
F9F-8P	17,980	145	Approach
AC-680F	8,000	85	Approach
S-61L*	18,700	5	Takeoff
	17,700	117	Cruise
	18,700	27	Approach
V-107/11*	17,500	119	Cruise
S-58C*	12,500	85	Cruise

*Rotary-wing (helicopter) aircraft

A followup program was recently undertaken for the purpose of (1) validating the fixed-wing model, (2) updating fixed-wing information to include today's jumbo jets, (3) verifying the rotary-wing model, and (4) updating the rotary-wing information.

The information contained herein is limited to rotary-wing aircraft.

OBJECTIVES.

The specific objectives of this report are to:

1. Survey all available literature relating to helicopter wake turbulence, vortex systems, and safe separation criteria based on vorticity either produced by, or influencing, helicopter operations.

2. Summarize the information available in the literature published since reference 1 (i.e., since 1964) relating to safe air traffic separation criteria as influenced by, or influencing helicopter operations in the terminal area.

3. Summarize the effects of variations in ambient conditions, as reflected by the literature, on the characteristics and dissipation of wake turbulence generated by Federal Aviation Regulations (FAR) 27 and FAR 29 helicopter operations.

4. Update the information contained in index 248 on the intensity, duration, and characteristics of wake turbulence generated by helicopters.

<u>LITERATURE SURVEY</u>.

The annotated bibliography contained in appendix A of this report was based on the following sources:

1. Defense Document Center (DDC), Search Control No. 077412, (reference 1).

2. National Aeronautics and Space Administration (NASA), Literature Search No. 17873 (reference 2).

3. Supplementary search by the Technical Library of the National Aviation Facilities Experimental Center (NAFEC).

4. Acquisition of related documents referenced in those reports obtained by 1 through 3, inclusive.

A review of the 132 documents cited in reference 1 disclosed the following:

1. Fifty-three documents did not pertain to any of the objectives noted.

2. Twenty-three of the documents predated index No. 248.

3. Ten documents were prior to index No. 248 and, further, did not pertain to any of the prior-defined objectives.

Accordingly, 76 of the documents cited in reference 1 have not been included in appendix A.

Reference 2 denotes 79 publications which relate to one or more of the objectives noted. One of these is among those listed in reference 1, and 13 predate index No. 248. Therefore, 14 of the documents noted in reference 2 have not been incorporated in appendix A.

The supplemental search by NAFEC's Technical Library identified 43 publications which were not included in either references 1 or 2 and were published after 1964. These additional documents are included in appendix A.

Finally, the references noted in the 175 documents which were identified through these procedures were perused for relevance. In this manner, an additional 164 pertinent documents were identified and have also been incorporated into the bibliography.

Thus, although 428 documents were reviewed by title and abstract, only 334 of these have been incorporated in the bibliography. Of this number, 116 selected documents were reviewed in their entirety.

The documents in appendix A are listed alphabetically by title and are numbered sequentially. A precis for each has been included where possible, or desirable.

The documents contained in appendix A may be grouped into eight general categories, namely:

I	Vortex Generation
II	Vortex Motion and Decay
III	Vortex Control
IV	Vortex Interaction With Aircraft Blades
V	Vortex Mathematical Models
VI	Rotor Dynamics
VII	Rotor Noise
VIII	Vortex, Vorticity, Vortex Wake, and Wake Turbulence Hazard

Appendix B lists by title and index number the documents of each category. In those cases where a document pertains to more than one of the noted classifications, it has been listed in each applicable category. Neither a multiplicity of listings nor the omission from all categories for any given reference should be interpreted as a reflection of the relative importance of that document.

Appendix C provides the reader an added convenience - a cross index by author according to alphabetical order. The articles, whether authored or coauthored, are identified by index number.

LITERATURE REVIEW RESULTS

I VORTEX GENERATION.

The majority of the documents within this group are concerned with the near-field vortex systems and their influence on a following blade.

The U.S. Army Air Mobility Research and Development Laboratory (USAAMRDL) Contractor's Report 71-24, index No. 29, by Anton J. Landgrebe is a recent, in-depth treatment of relationship of wake geometry to rotor performance. This document evaluated the accuracy of various analytical methods in predicting rotor performance based on wake geometry. The report indicates that the "attempts to develop a theoretical method for predicting contracted wake geometries were only partially successful." It further recommends that additional full-scale correlation studies be made to provide additional information on the adequacy of the generalized wake geometry information contained in the report.

The methods considered in this report were:

1. BLADE ELEMENT - MOMENTUM ANALYSIS. This analysis is described in index No. 219, and is based on the assumption that the lift acting on an annulus of the rotor disc is equal to the change in momentum of the air passing through that annulus. The relationships developed can be shown to be equivalent to those obtained using vortex theory in which the rotor is modeled by an infinite number of blades, and the vorticity deposited in the wake of the rotor forms a continuous cylindrical vortex sheet having a diameter equal to the rotor diameter. This analysis neglects effects due to the finite number of blades and those related to wake contraction.

2. GOLDSTEIN-LOCK ANALYSIS. This analysis is effectively the rotary-wing equivalent of the classical lifting-line analysis used for fixed wings. The analysis is based on the work of Goldstein who obtained a solution for the velocity potential for the flow "about an axially translating, double-infinite, rigid, helicoidal surface." The analysis accounts for the finite number of blades on a rotor but still retains the assumptions that the blades are lifting lines and that the wake is uncontracted.

3. UARL-PRESCRIBED WAKE HOVER PERFORMANCE PROGRAM. The computer program consists of three major subroutines, namely: Wake Geometry, Biot-Savart Law Circulation Matrix, and Performance. The method differs in that the blade inflow distribution is determined by the induced effects of the wake (Biot-Savart Law) as opposed to introducing approximate momentum considerations. The major assumptions of this analysis are:

a. Each blade is represented by a lifting line divided into a finite number of segments each having a different circulation strength.

b. The wake is represented by a finite number of vortex filaments, the circulation strength of which is constant along its length.

c. The blade and wake characteristics are independent of azimuth motion.

d. The airflow at the blades is two-dimensional with radial, induced velocity neglected.

e. Tangential, induced velocity components are neglected.

f. Following the blade circulation and inflow solution, conventional strip theory is applicable to compute rotor performance.

Within this program, the wake geometry is evaluated by:

a. Classical Wake Analysis. The primary differences between this analysis and the Goldstein-Lock analysis are that the helical sheets of vorticity (figure 1) are approximated by a finite number of discrete trailing vortex filaments, and the axial transport velocity of each element is constant with radius and equal to the momentum value. Tangential transport velocities are assumed to be zero. At lower disc loadings, the outer portion of the wake approximates the Goldstein wake.

b. Experimental Wake Analysis. This analysis differs from the classical in that a more realistic, contracted wake geometry based on experimental flow-visualization data is used as input to the main, Prescribed Wake Program. The difference between the classical and experimental wakes is shown in figure 2.

The inputs to the Prescribed Wake Hover Performance Program are wake geometry, blade design, flight condition and airflow data, and the outputs are blade performance, rotor performance, and wake trajectory plots as shown in figure 3.

An example of the solution for blade-section angle of attack versus a dimensionless radial coordinate is shown in figure 4 as it is reflected in index No. 219. Since angle of attack directly influences lift and because the vortex characteristics are a function of lift, the variability between the several analytical models would greatly influence the far-field wake turbulence generated by the rotor.

The full-scale rotor tests reported in index No. 170 indicated reasonably good agreement with the model rotor in most cases, with the exception that the wake of the full-scale rotor appeared to contract to a maximum extent nearer the rotor disc. Since the far-field characteristics of helicopter-produced vorticity is dependent on the explicit near-field flow, the usefulness of analytical models for predicting far-field wake turbulence could be limited by such factors.

Index No. 324, indicates that the far-wake region of a hovering rotor is not stable. This document of May 1972 indicates that a detailed analysis of the flow visualization, figure 5, showed a definite departure from the classical concept of a smoothly contracting wake below the rotor. Whether the tip

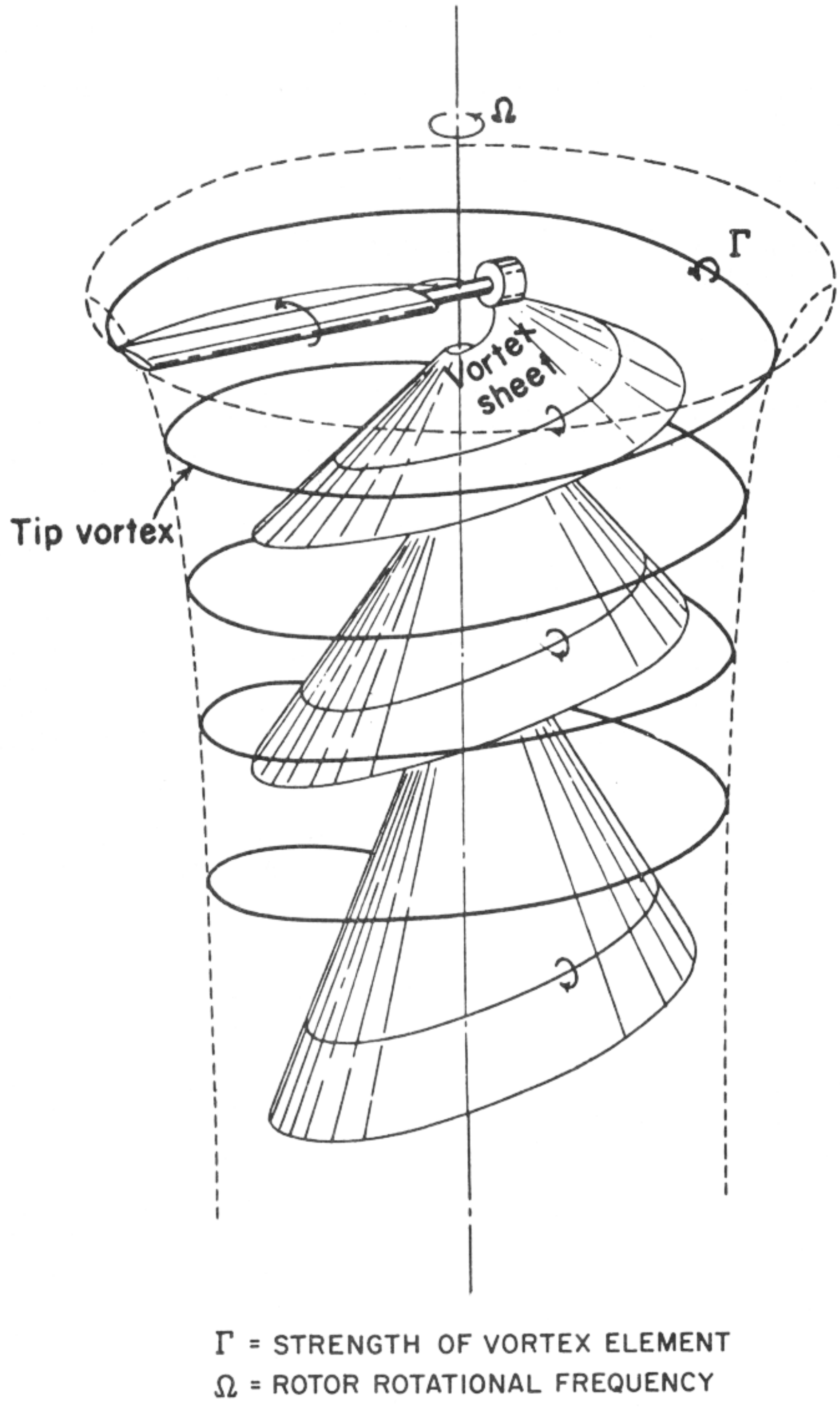


FIGURE 1. HELICAL SHEETS OF VORTICITY (INDEX NO. 219)

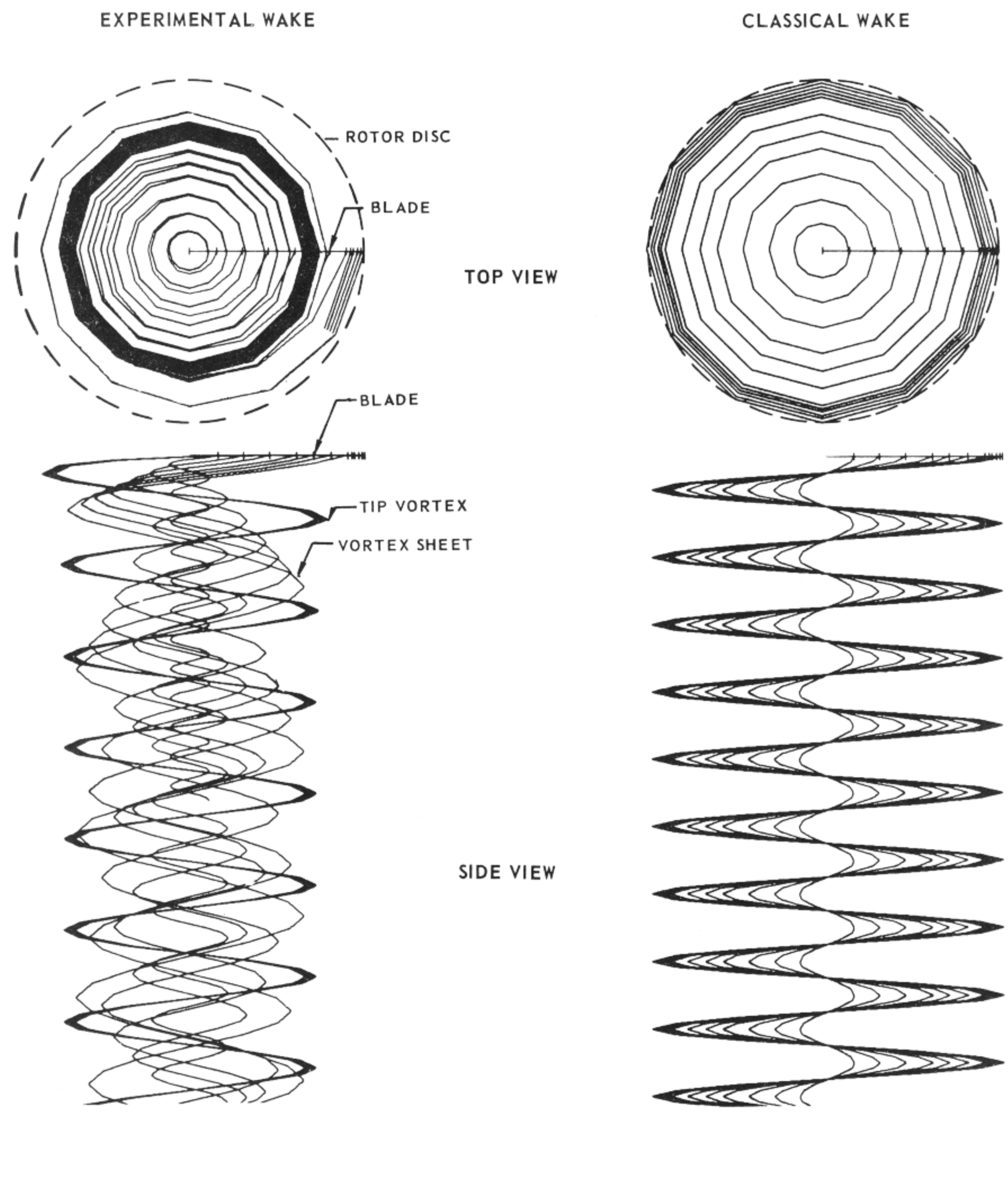


FIGURE 2. COMPUTER WAKE TRAJECTORIES FOR ONE BLADE (INDEX NO. 219)

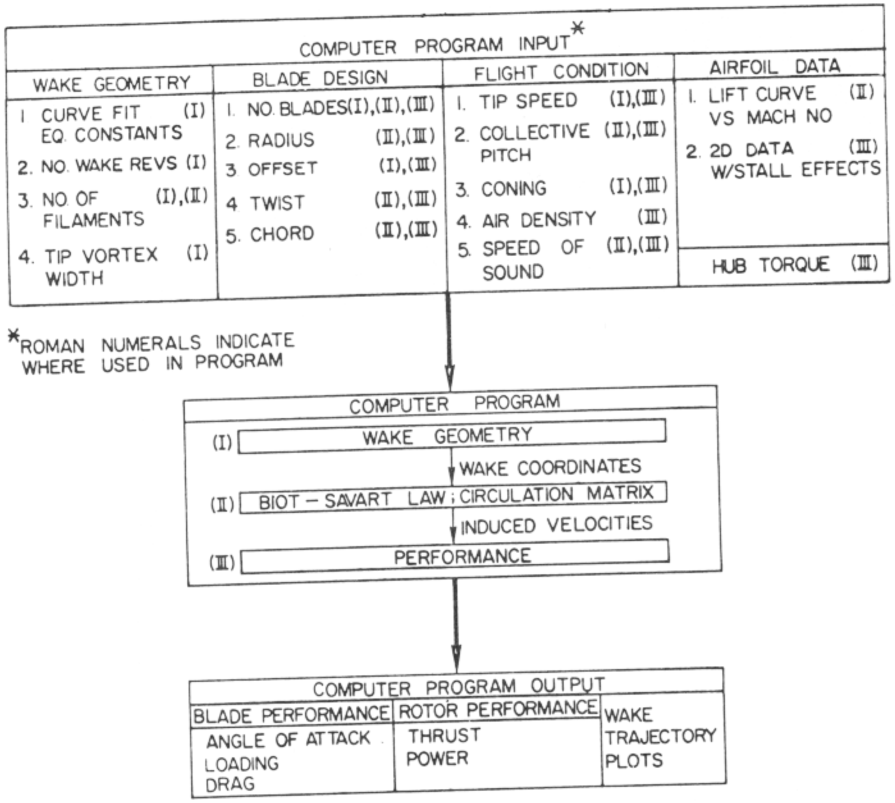


FIGURE 3. UARL PRESCRIBED WAKE HOVER PERFORMANCE PROGRAM (INDEX NO. 220)

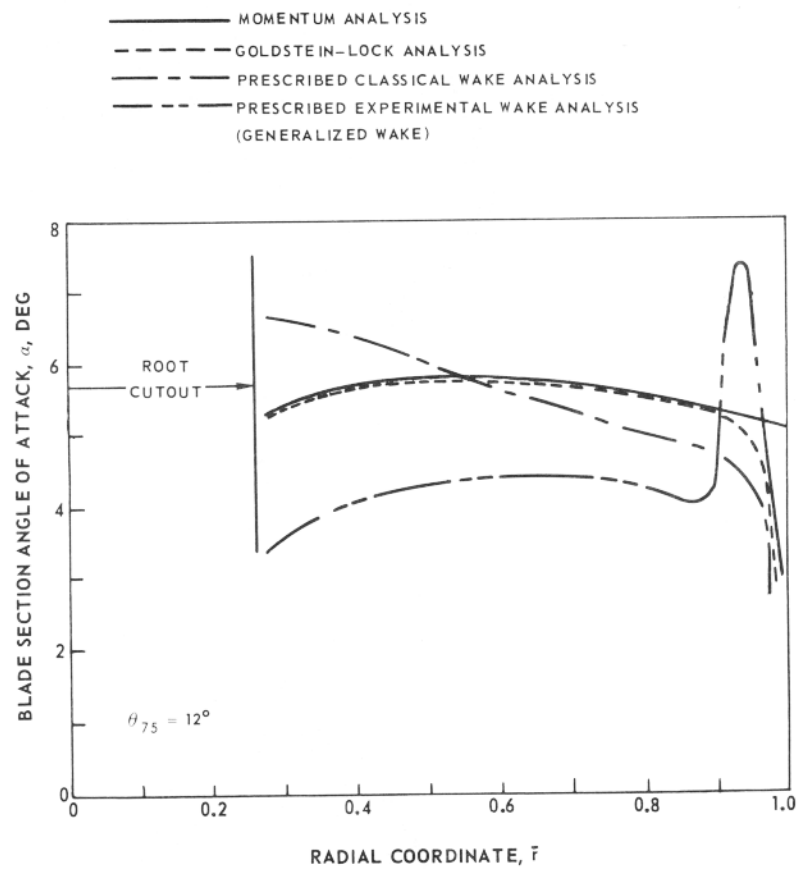
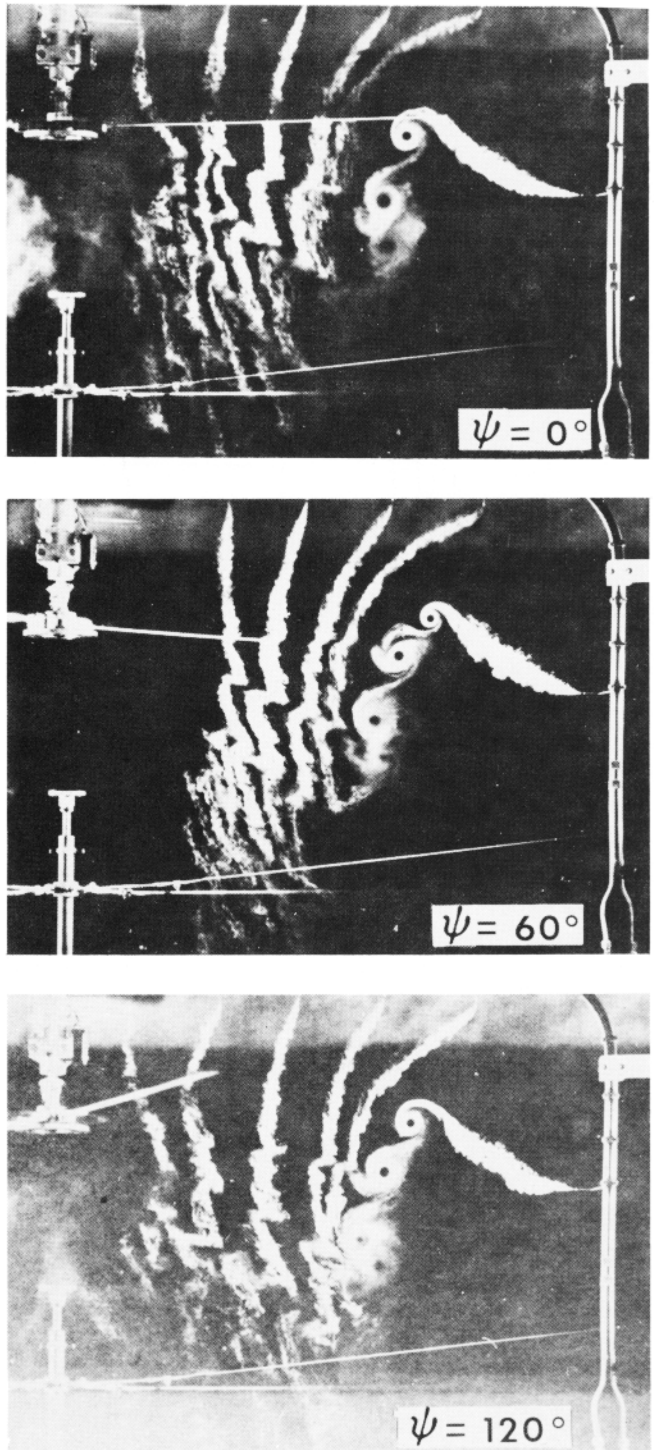


FIGURE 4. COMPARISON OF CH-53A BLADE ANGLE OF ATTACK DISTRIBUTION PREDICTED BY VARIOUS ANALYSES (INDEX NO. 220)

$C_T/\sigma = 0.08$



ψ = BLADE AZIMUTH ANGLE MEASURED FROM X AXIS

C_T = ROTOR THRUST COEFFICIENT

σ = RATIO OF TOTAL BLADE AREA TO DISC AREA

FIGURE 5. FLOW VISUALIZATION OF ROTOR-PRODUCED VORTEX (INDEX NO. 324)

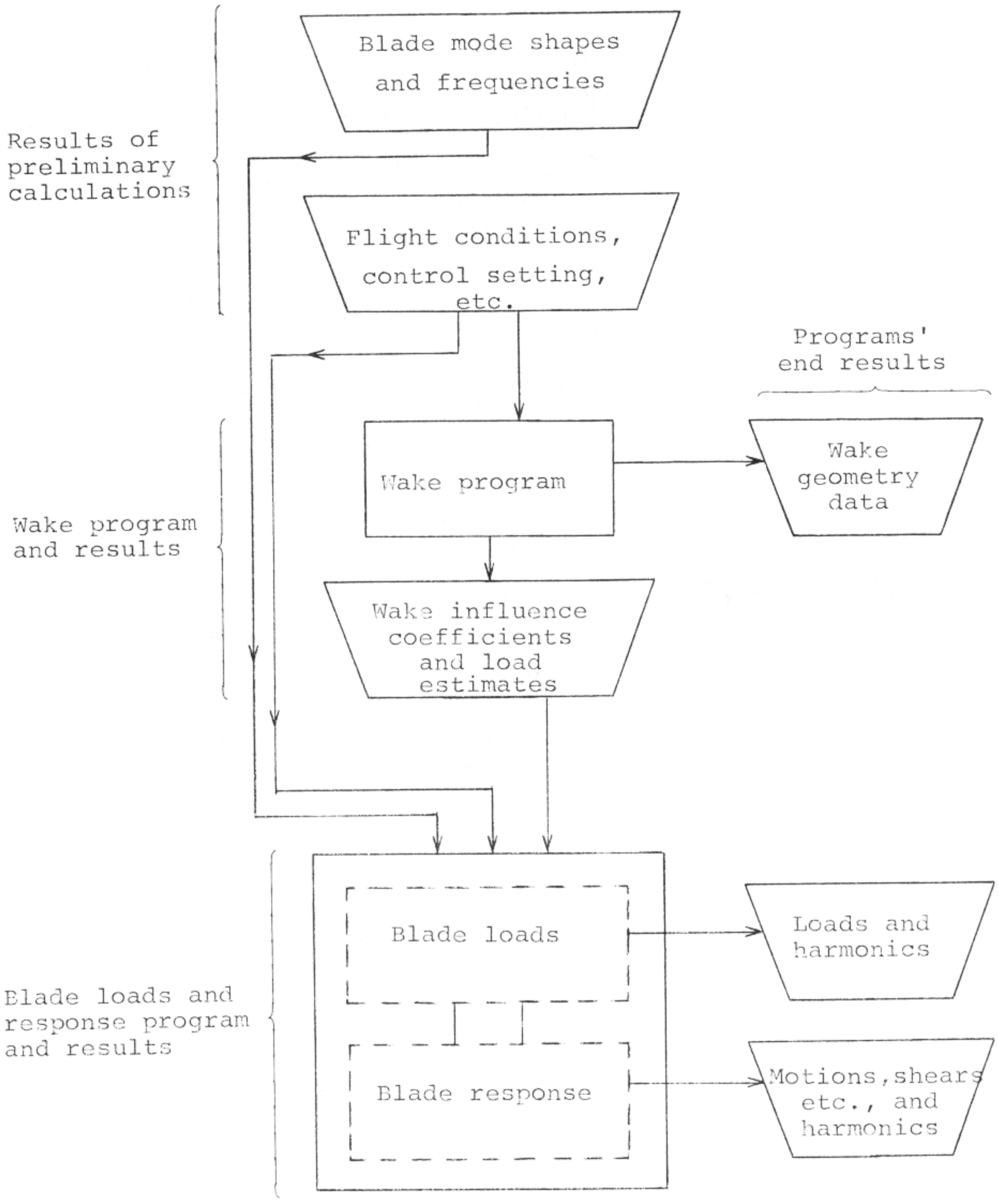


FIGURE 6. PROGRAM USAGE FLOW DIAGRAM (INDEX NO. 71)

vortex undergoes a form of viscous dissipation (decay) or vortex breakdown (bursting) characterizing certain fixed-wingtip vortices was conjecture as of that date.

An independent study of main rotor free-wake geometry in steady maneuvers was sponsored by NASA. The theoretical formulation, analysis, and associated computer program are contained in the two-volume contractor's report, index Nos. 70 and 71. Figure 6 reflects the flow diagram for the computer program.

A program sponsored by the U.S. Army Aberdeen Proving Grounds evaluated the then existing techniques (1965) in predicting the periodic loadings and the resulting response of the rotating structural components of vertical takeoff and landing (VTOL) aircraft. One of the publications relating to this study, index No. 321, includes a line diagram of the fixed-skewed-helical wake configuration, and force-free wake configuration, figure 7. The difference between the configurations is due to the fact that in the latter the wake convects under its own influence. The rolled-up vortex formation can be observed in the free-wake configuration. Further modifications to the wake model would occur due to fuselage and second rotor (tail or compound) flowfield interaction, just to cite a few additional vortex modifiers.

In a summary of the Advisory Group for Aerospace Research and Development (AGARD) meeting on aerodynamics of rotary wings in March 1973, index No. 9, it is stated that "though much ingenious modeling has been done, the fact remains that the position of the all-important first spiral of vorticity cannot be predicted satisfactorily due to an apparent gap in physical understanding."

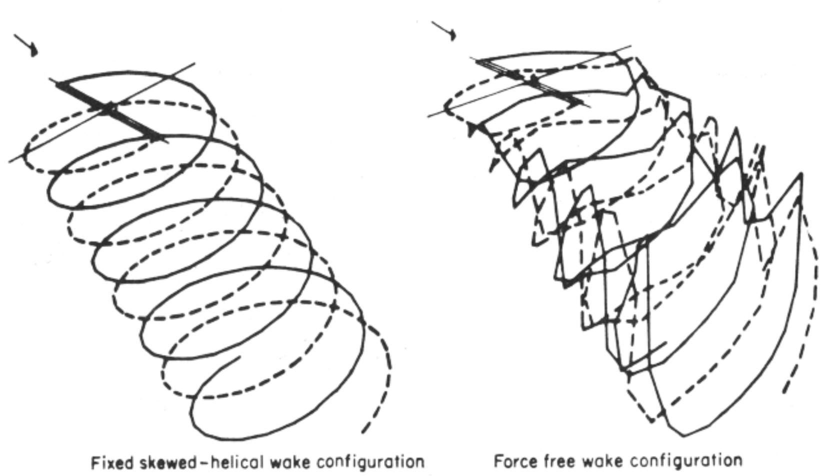


FIGURE 7. COMPARISON OF "FIXED" AND "FREE" WAKE CONFIGURATIONS OF A TWO-BLADED ROTOR (INDEX NO. 321)

II. VORTEX MOTION AND DECAY.

There has been accelerated activity in this general area within the past decade. This increased activity was triggered by the marked increase in terminal area traffic at many airports and the mixing of various categories of aircraft within that environment. Most of the publications dealing with this subject matter are related to fixed-wing aircraft.

The documents cited within this group are limited to vortex motion and decay in relation to helicopter generation.

The U.S. Army-sponsored study undertaken by Mississippi State University, index No. 170, indicated that the decrease in tangential velocity within the core was similar to that of fixed-wing aircraft. Specifically, the measured maximum tangential velocities in the vortex decreased inversely with the square root of the distance behind the aircraft (figure 8), as measured and reported by McCormick, index No. 252, for the fixed-wing aircraft.

The decrease in maximum axial velocity in the vortex trails, figure 9, indicates that the vortices had to expand with increasing distance behind the blades if the momentum losses represented by the axial velocity defects were to remain constant. The axial velocity defect is generally associated with profile drag losses of the vortex generator. The expansion rate of the vortices appeared more closely related to the rate of maximum tangential velocity decline (conservation of total energy). Using the same abscissa, figure 10 shows the vortex growth is apparently linear with respect to the square root of the distance behind the blade. It should be borne in mind that these tests with the OH-13E rotor, as shown in figure 11, were performed at the top of a test tower and do not indicate the total machine-produced flow field (fuselage and other rotor interaction, aircraft motion).

Index No. 154 reports the results of the variation of selected parameters on vortex decay. The effect of varying jet blowing indicated that (1) maximum tangential velocity increases to a maximum and then decreases with continually increasing jet blowing, and (2) at the high values of jet blowing, the vortex was found to decay rapidly downstream. An analysis of the information contained in this document suggests that (1) increasing the jet momentum coefficient up to a certain point may delay the onset of turbulence, (2) beyond that critical value, the turbulence generated due to shear accelerates the expansion of the cross sectional area of the vortex thus decreasing the maximum tangential velocity, and (3) the effect of increasing the rotational surface area in contact with the stationary ambient atmosphere would increase losses in this boundary layer and increase the decay rate downstream.

The results of an Aeronautical-Research-Council-sponsored experiment by the University of Southamption, index No. 14, indicated that, at low tip-speed ratios, trailing vortices close to the leading edge of the disc first pass up through the disc before entering the main field. This sort of distortion to classical flow was demonstrated numerically by Scully, index No. 173.

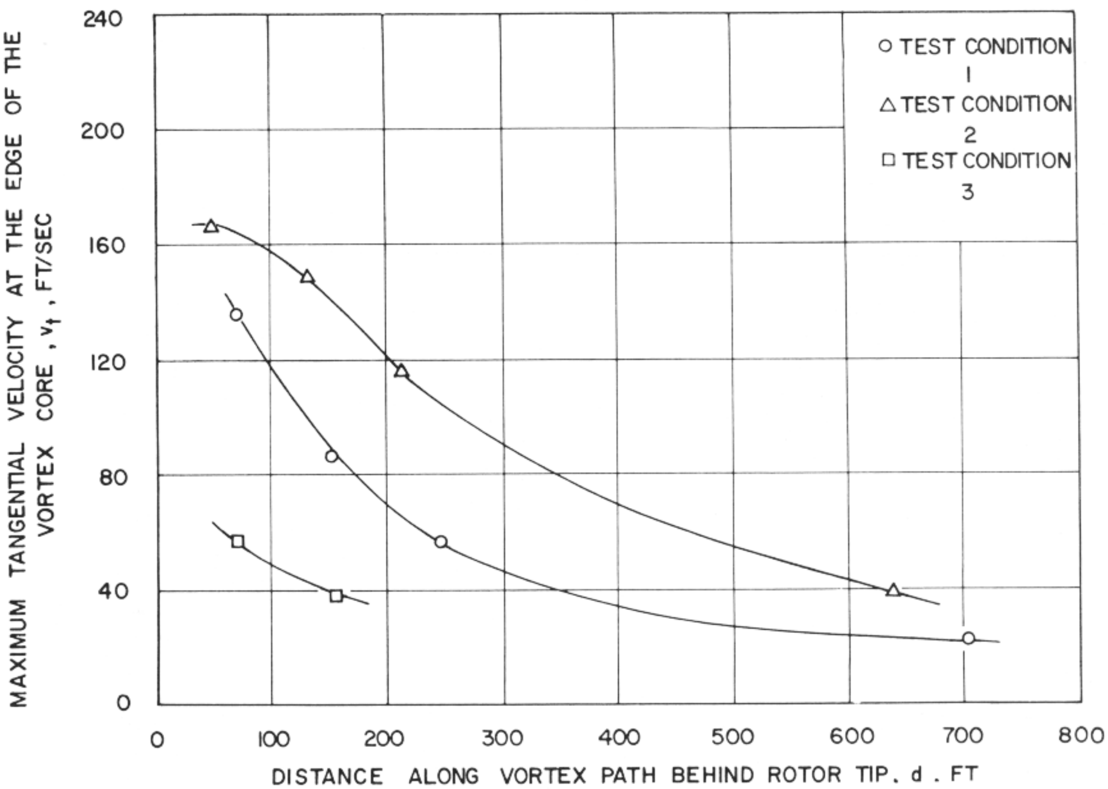


FIGURE 8. DECLINE OF MAXIMUM TANGENTIAL VELOCITY AT THE EDGE OF THE VORTEX CORE WITH DISTANCE BEHIND THE BLADE (INDEX NO. 170)

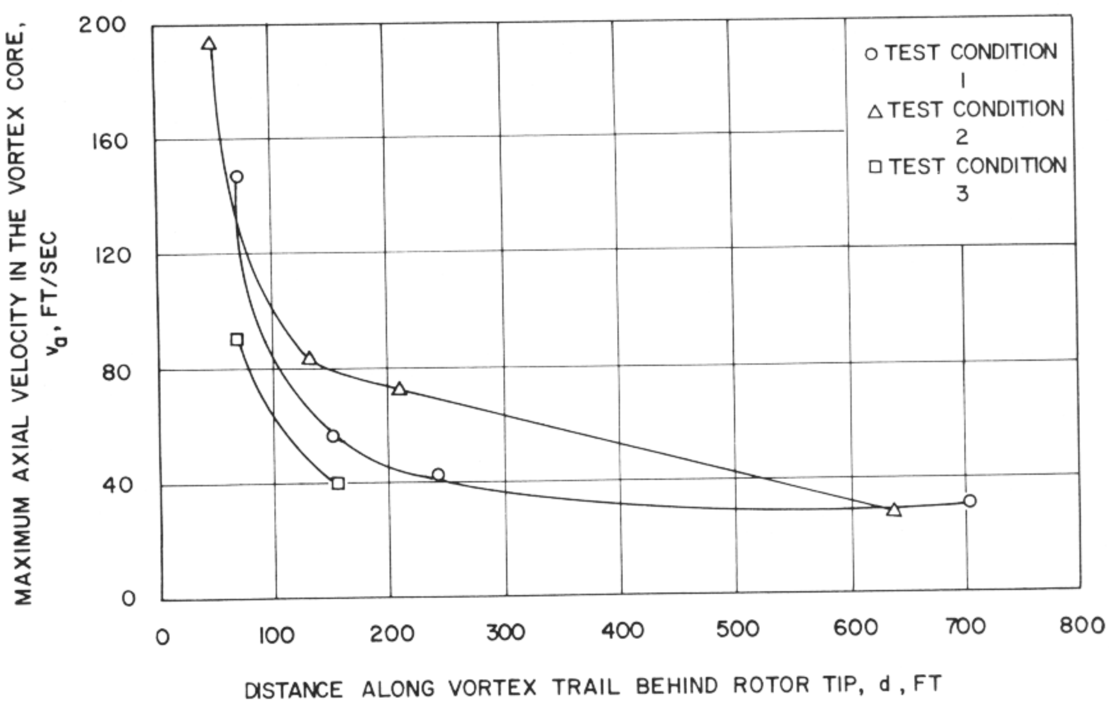


FIGURE 9. DECLINE OF MAXIMUM AXIAL VELOCITY IN THE VORTEX CORE WITH DISTANCE BEHIND THE BLADE (INDEX NO. 170)

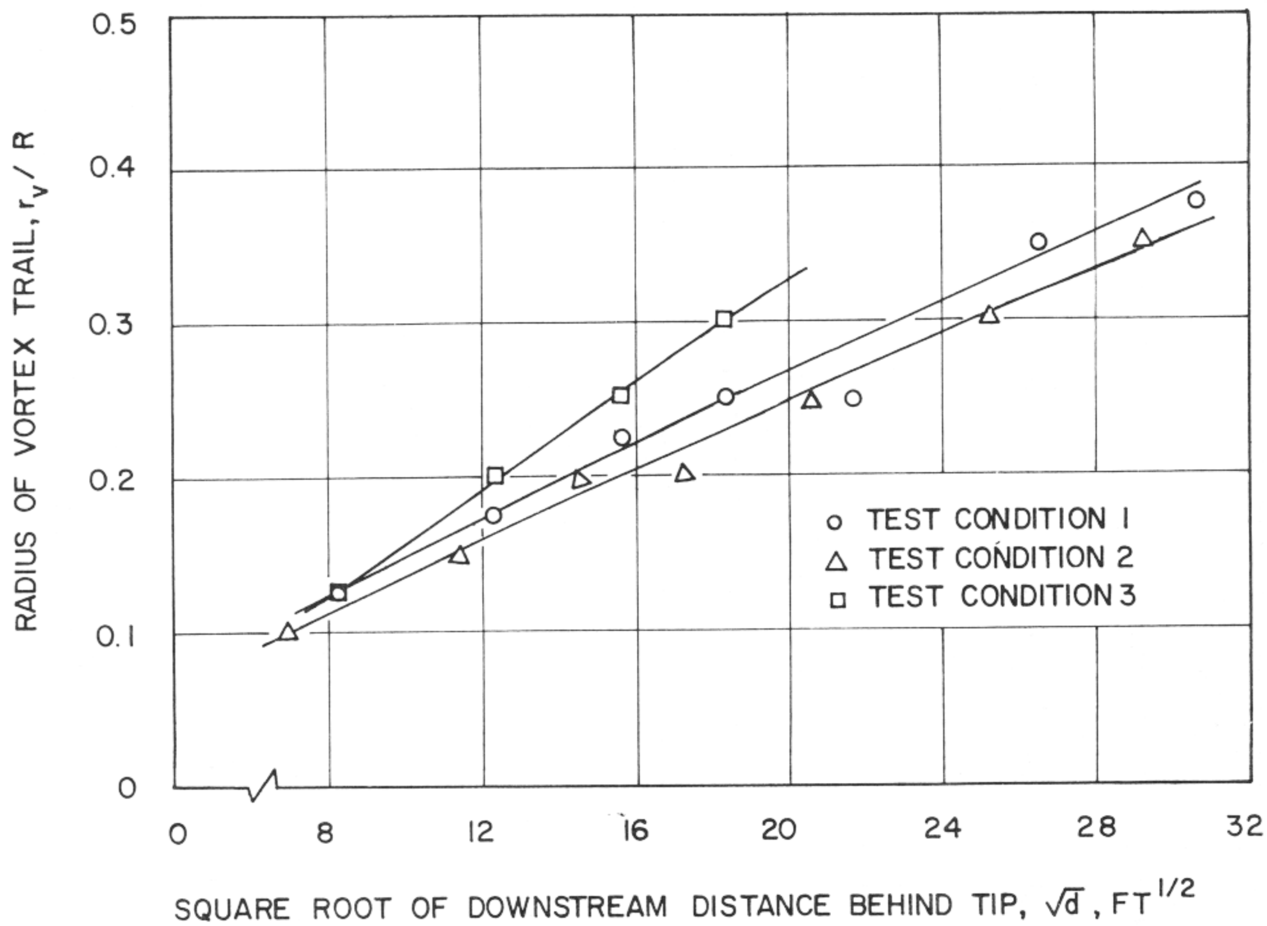


FIGURE 10. GROWTH OF THE TRAILING VORTICES DOWNSTREAM OF THE BLADE TIP (INDEX NO. 170)

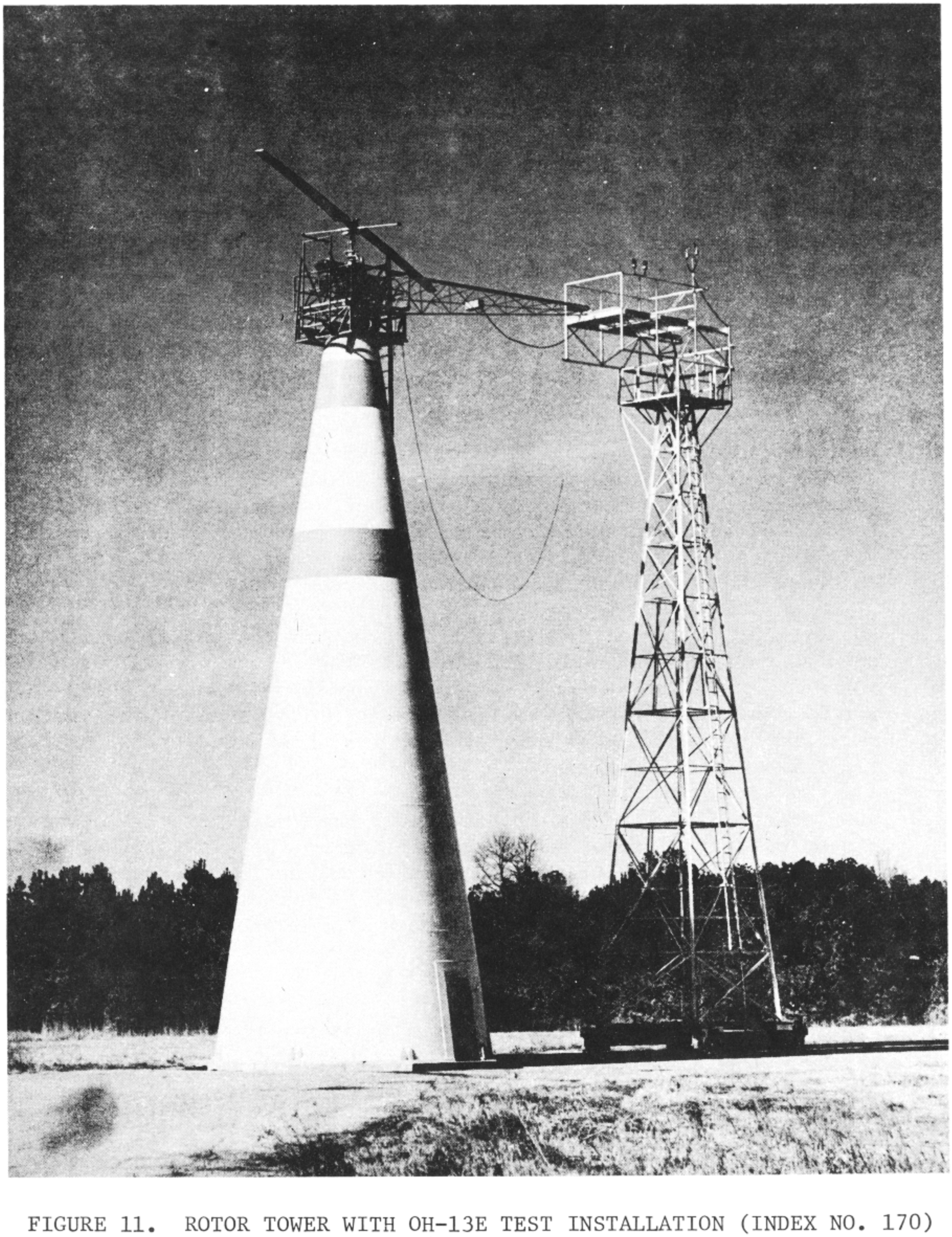


FIGURE 11. ROTOR TOWER WITH OH-13E TEST INSTALLATION (INDEX NO. 170)

These tests indicate that wake distortion due to mutual interference of successive trailing vortices in the rear wake will influence the position in space and the velocity profile of the far-field vortex sheet. This upward motion and interaction is shown in figure 12.

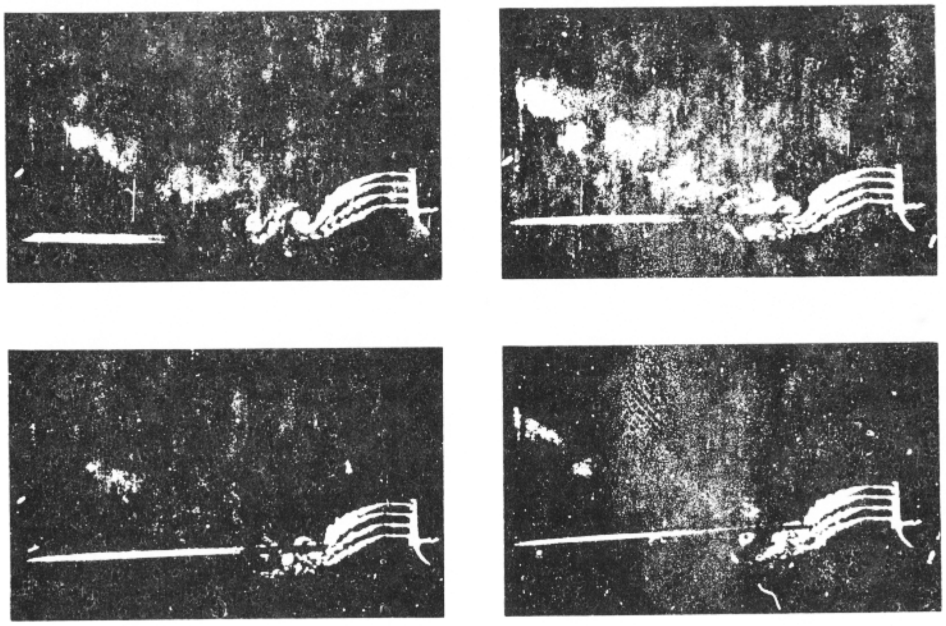


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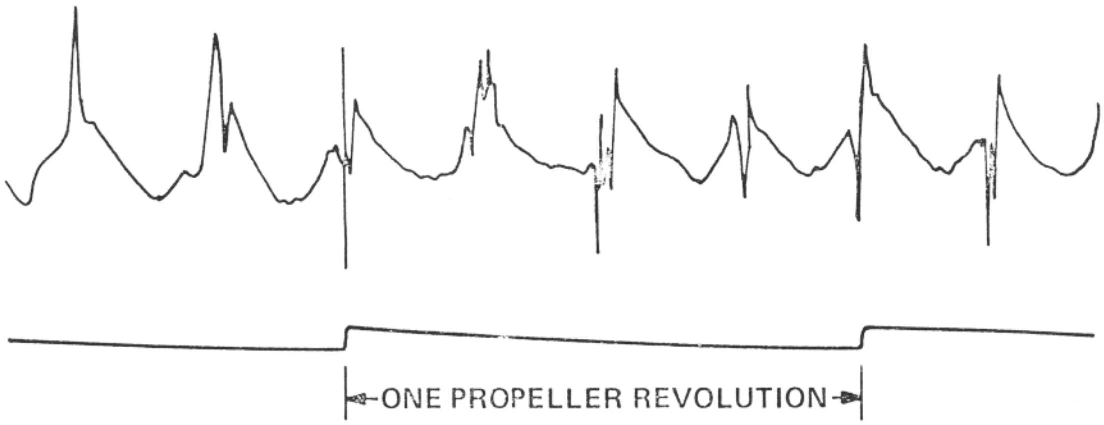
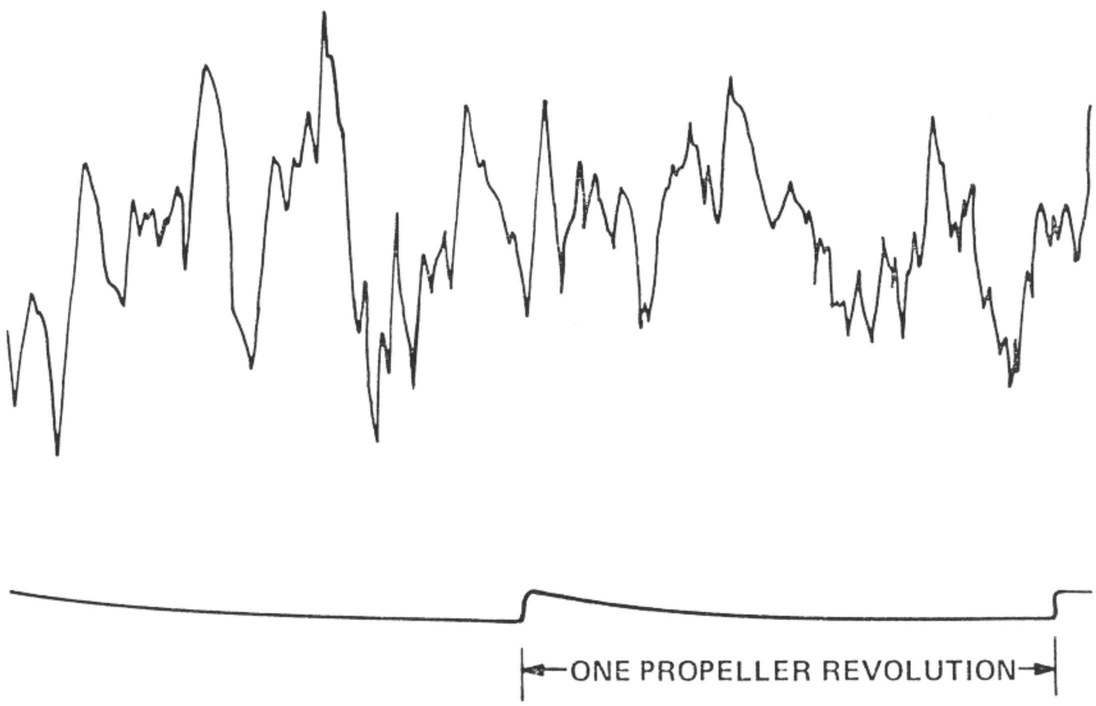
FIGURE 12. MOVEMENT AND GROWTH OF VORTICES AT LEADING EDGE OF DISC (INDEX NO. 14)

Tests were conducted by Cornell Aeronautical Laboratory (CAL), index No. 59, under sponsorship by the U.S. Army. These measurements, obtained during tests using four-blade, 7-foot-diameter propellers, indicated that the flow-field exhibited repeatable characteristics (figure 13a) over the middle part of the blade, and random, nonrepeatable characteristics (figure 13b), both near the hub and near the tip. This is shown diagrammatically in figure 14.

The formation and decay of a rotary-wing, aircraft-produced vortex is analytically defined in index No. 248. The analysis notes the assumptions that the inclination of the aircraft's path remains constant with respect to the ground, and that the aircraft's velocity and transverse wind velocity remain constant. An additional assumption is that the decay of circulation for the shed vortex ring is similar to that for an isolated laminer rectilinear vortex. The analysis includes the determination of the defined vortex characteristics both in and out of ground effect. Index No. 248, includes a correction of the rolled-up vortex system position due to a horizontal wind component of up to 90° with respect to the flight path of the generating vehicle. The report notes that the viscose decay term will



(a) REPEATABLE WITH BLADE PASSAGE



(b) NONREPEATABLE WITH BLADE PASSAGE

FIGURE 13. TYPICAL HOT-WIRE SIGNALS - 65 AF PROPELLER (INDEX NO. 59)

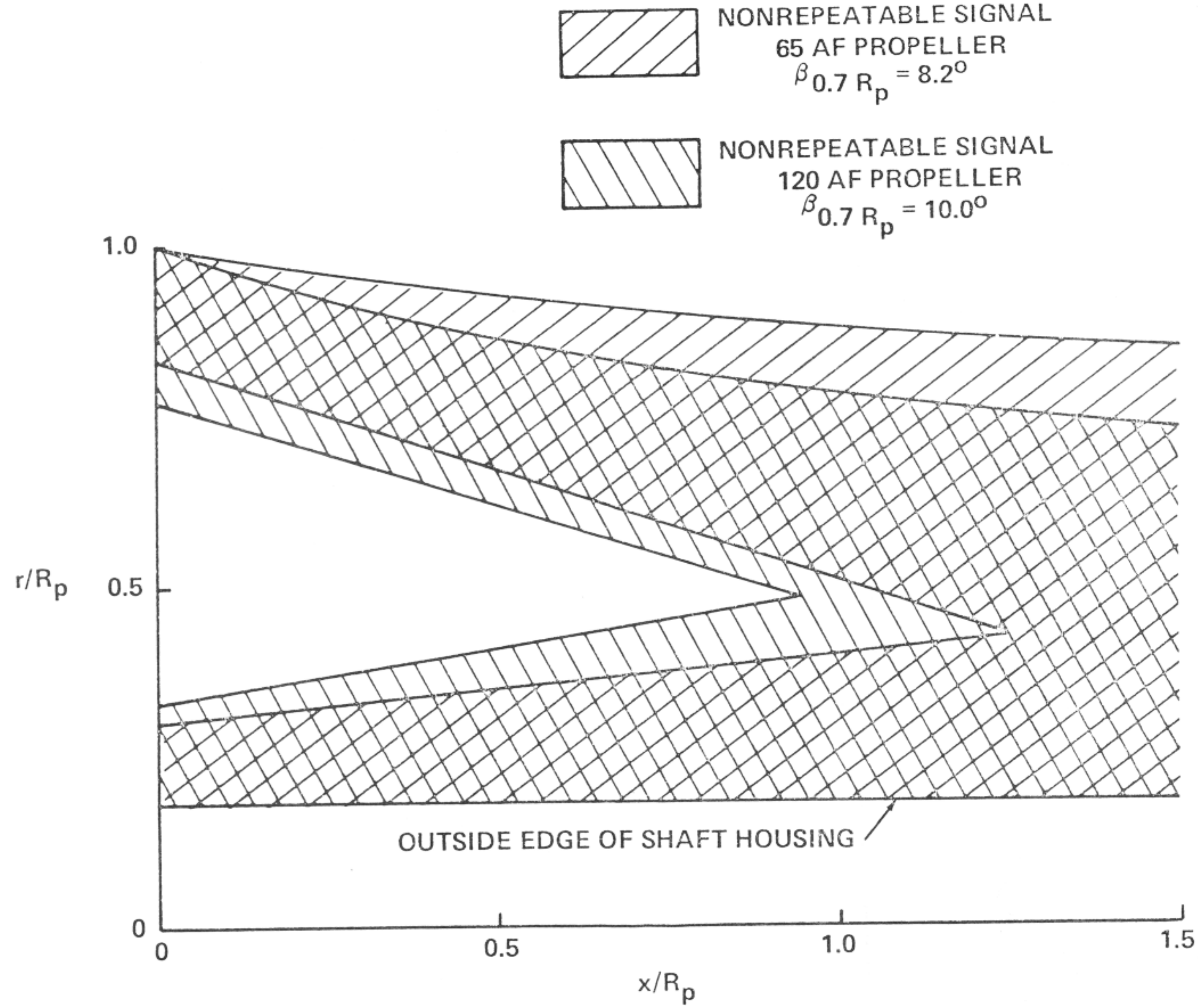


FIGURE 14. EXTENT OF REGIONS OF NONREPEATABLE HOT-WIRE SIGNALS FOR TWO PROPELLERS (INDEX NO. 59)

vary with altitude for any particular atmospheric condition, and further inherent in the analysis is the fact that the rate of decay is directly dependent on atmospheric eddy viscosity; however, these are not incorporated in the mathematical model. A computer program was developed to accomplish the theoretical model developed in the report.

The U. S. Air Force has sponsored a program to develop an independent model for calculating the helicopter's vortex path and wake velocities, index No. 170. The model flow field used in this anlaysis is shown in figure 15. The flow field at high foward speeds is assumed to roll up into two concentrated counter-rotating vortices in a manner much the same as that shed from a fixed-wing aircraft. This roll-up is assumed to be completed before the rotor wake hits the ground. At lower speeds (near hover), the rotor wake is assumed to impinge on the ground. The criterion of decision is when the dynamic pressure exceeds one-fourth of the average total pressure increase within the wake.

This report further notes that previous analyses dealing with the motion of trailing vortices near the ground have assumed two-dimensional motion, such as Z. O. Bleviss, Douglass Report SM-18647, and J. W. Wetmore and J. P. Reeder, NASA TN D-1777. The analysis contained in this report is based on a three-dimensional approach.

The Levinsky/Strand mathematical model also includes a correction of the vortex system position due to ambient wind. However, the effects of the localized wind conditions or other atmospheric factors, such as corrective action due to heating or wind gust on decay or disruption of the vortices, are not considered in either this report or any other document contained in appendix A for rotary-wing aircraft. However, index No. 106, tests involving the fixed-wing Hunter aircraft, states "there was no clear indication as to whether the vortices decayed more rapidly in the presence of the ground and atmospheric turbulence, then would have been expected from earlier measurements away from the ground in calm air."

The viscous decay characteristics described by H. Lamb have been modified to utilize an effective turbulent viscosity term in lieu of the laminar viscosity term, as described by M. G. Hall, index No. 251. The turbulent viscous decay term used is defined as a function of vortex strength.

Tests were conducted by NAFEC, reference 3, in 1963 with an S-58 helicopter to record the time-history of the vorticity generated under crosswind conditions near the ground. The test results of crosswinds (ranging from 0 to 18 miles per hour (mi/h)), helicopter forward speeds (ranging from hover to 60 mi/h), and terrain clearance (varying from 25 to 150 feet) are summarized in this report. The maximum measured airflow produced was reported to be 67 mi/h (113 feet per second) by instrumentation located at 20 feet above the ground with the helicopter in hover 30 feet above the ground. The reported time-history for that test condition is shown in figure 16.

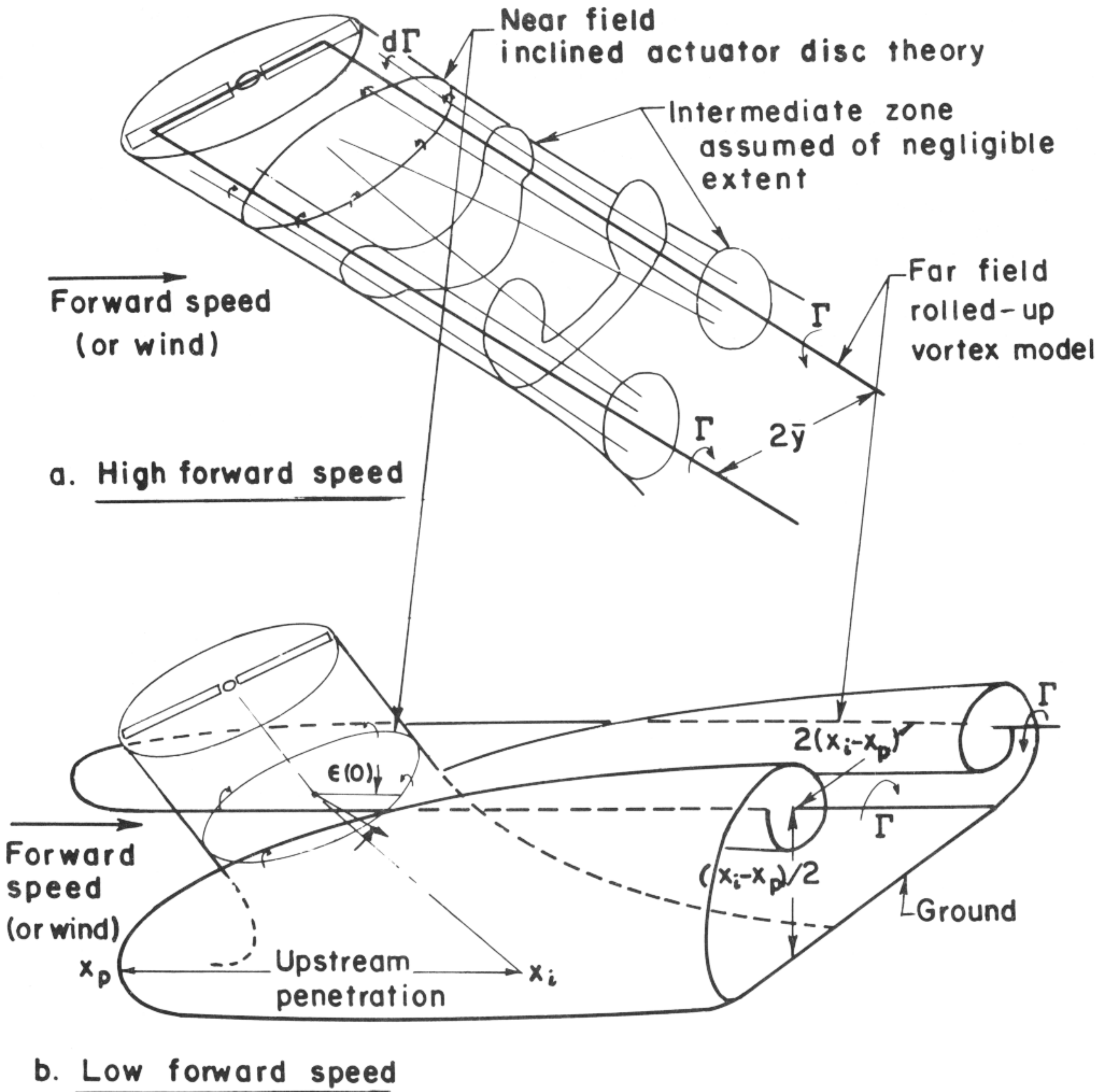
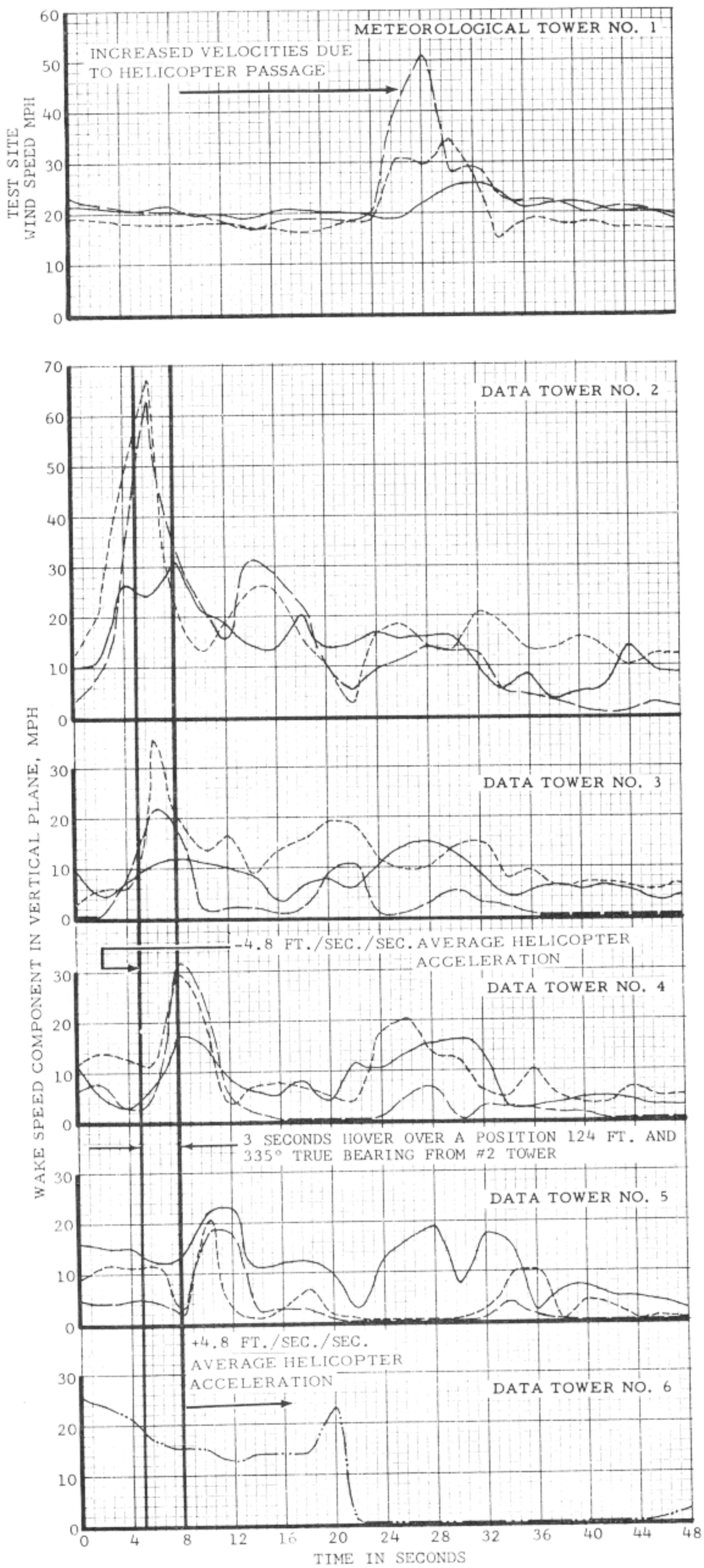


FIGURE 15. SIMPLIFIED ROTOR WAKE MODEL WITH ROLL-UP (INDEX NO. 171)



RUN NUMBER 26

TYPE OF RUN HOVER - 45 KNOT APPROACH

DATE 1-4-63

TIME 1440

HELICOPTER SIKORSKY SH-34J

GROSS WEIGHT 11,950 LBS. APPROX.

ALTITUDE 73' TO ROTOR HUB

I.A.S. 45 TO 0 KNOTS

GROUND SPEED 0 KNOTS

AVERAGE WIND SPEED AT 20' HEIGHT 17 M.P.H.

AVERAGE WIND DIRECTION 360° TRUE

LINE OF TOWERS 329° TRUE, TOWER SPACING 75'

LOCATION OF FLIGHT PATH 75° TO THE LINE OF TOWERS, HOVER 115' UPWIND OF TOWER #2

LEGEND

- ——— 50 FT. LEVEL
- — — — 35 FT. LEVEL
- - - - - 20 FT. LEVEL
- —·· — 6 FT. LEVEL

NOTE:

INSTRUMENTATION MEASURED THAT COMPONENT OF WAKE SPEED IN A VERTICAL PLANE ALIGNED PERPENDICULAR TO THE LINE OF TOWERS, PLUS THAT COMPONENT OF METEOROLOGICAL WIND IN THE SAME PLANE.

FIGURE 16. HELICOPTER WAKE, TIME-HISTORY HOVER RUN NO. 26 (REFERENCE 3)

The mathematical model previously cited in index No. 248 was employed to compute the time-history of the vortex produced by a medium (12,000 lbs) and large (175,000 lbs) helicopter. The results were ratioed to a fixed-wing aircraft of similer gross weight and span loading using the mathematical model described by Bennett in index No. 248. The results obtained are shown in figures 17 through 26 inclusive.

III VORTEX CONTROL.

There are several reports noted in appendix B within this grouping. However, although it is not one of the specified objectives of this literature review, index Nos. 78, 145, and 291, are suggested to the reader interested in this work area. Figures 27 through 29 indicate several tip configurations evaluated as reported in index No. 291. The effects on tangential velocity as a function of vortex radius are shown in figure 30.

IV VORTEX INTERACTION.

Published reports within this grouping may be placed in two general subgroups: those concerned with rotor dynamics and noise; and those concerned with vortex dissipation.

The blade/vortex interaction as it relates to noise is not a specific objective of this report and, as such, will not be covered in any detail. However, index No. 126 does present a theoretical model for the sound radiation induced by the transient lift fluctuations due to such interaction. These calculations show very good agreement to recent experimental results.

Most of the documents relating to vortex dissipation are for fixed-wing aircraft. The assumption reported in the literature is that out of ground effect the helicopter-generated vortex systems rolls up into the fixed-wing form as shown in figure 15.

Index No. 120 presents an analytical precedure for calculating the spread of a trailing vortex behind the generating lifting surface. The method provides a means of determining the distance behind the lifting surface at which the trailing vortices will touch one another. The results of such interaction beyond that point are not delineated to any length.

Index No. 246 indicates that the trailing vortices do not decay by simple diffusion. They usually undergo a symmetrical and nearly sinusoidal instability, eventually forming a train of vortex rings as shown in figure 31. The theory presented relates the induced velocity, due to infraction, to vortex displacement and the growth rate of sinusoidal perturbations.

V MATHEMATICAL MODELS.

A majority of the reports in this category deal with near-field wakes. They were developed to evaluate blade/rotor dynamics and performance. There are 81 reports in this category, most of which must have primary application to

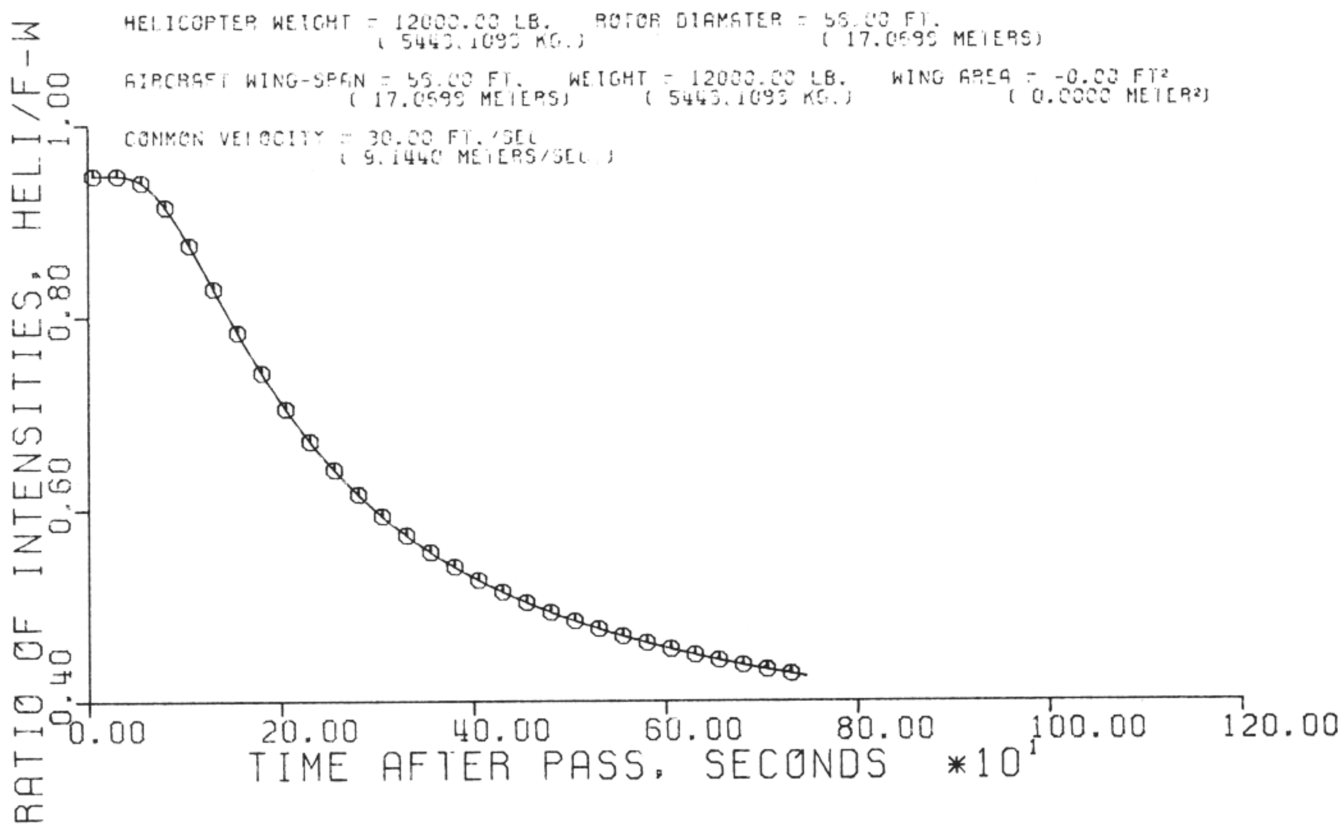


FIGURE 17. RATIO OF VORTEX INTENSITY FOR A 12,000-POUND HELICOPTER, VELOCITY = 30 ft/s

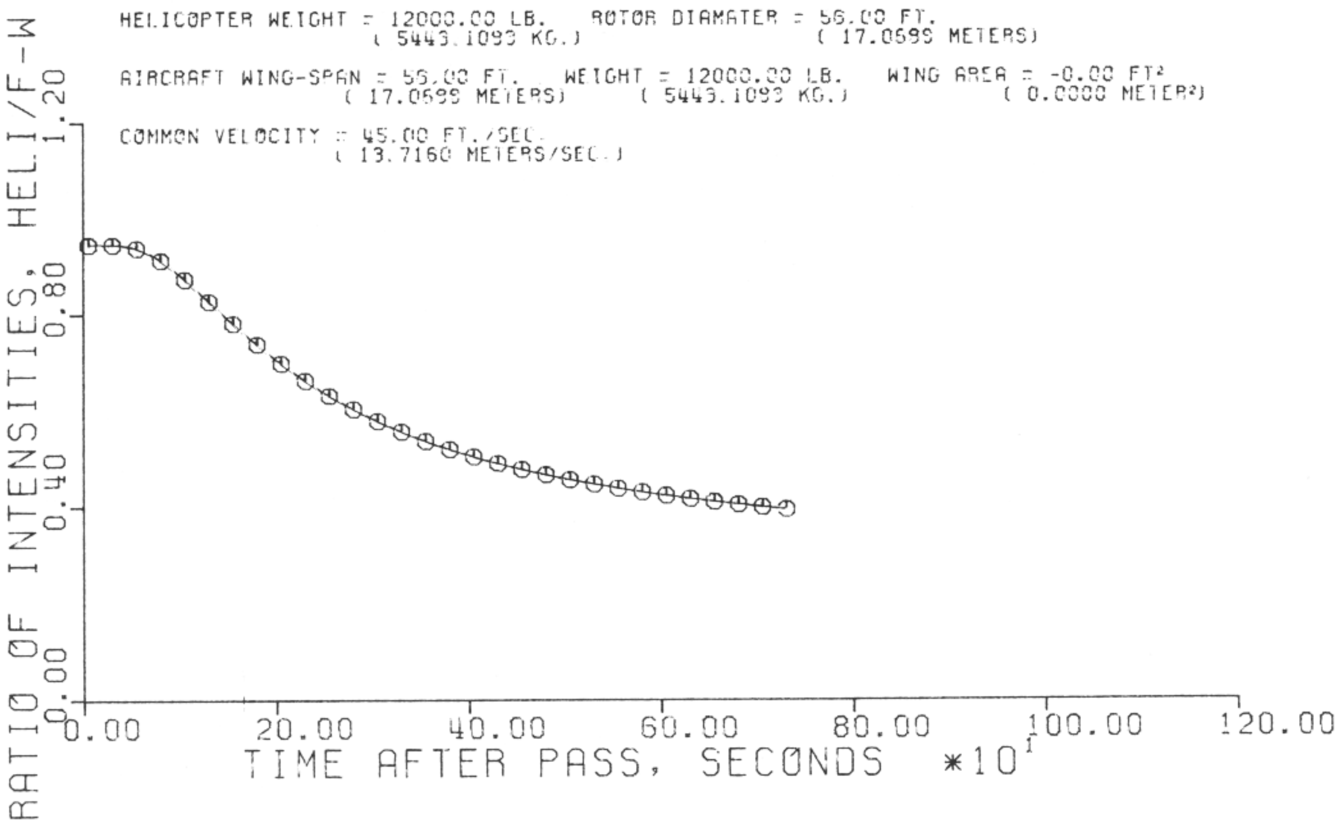


FIGURE 18. RATIO OF VORTEX INTENSITY FOR A 12,000-POUND HELICOPTER, VELOCITY = 45 ft/s

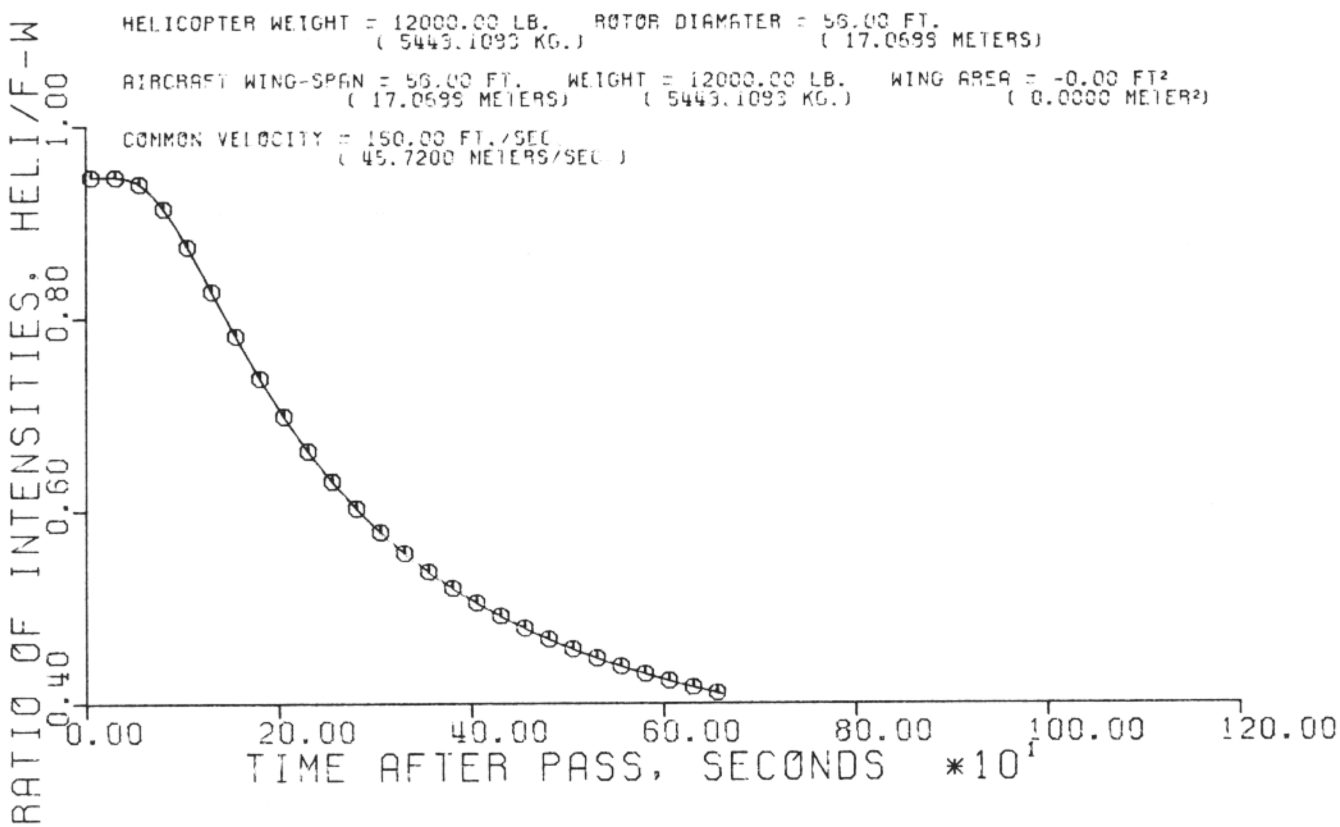


FIGURE 19. RATIO OF VORTEX INTENSITY FOR A 12,000-POUND HELICOPTER, VELOCITY = 150 ft/s

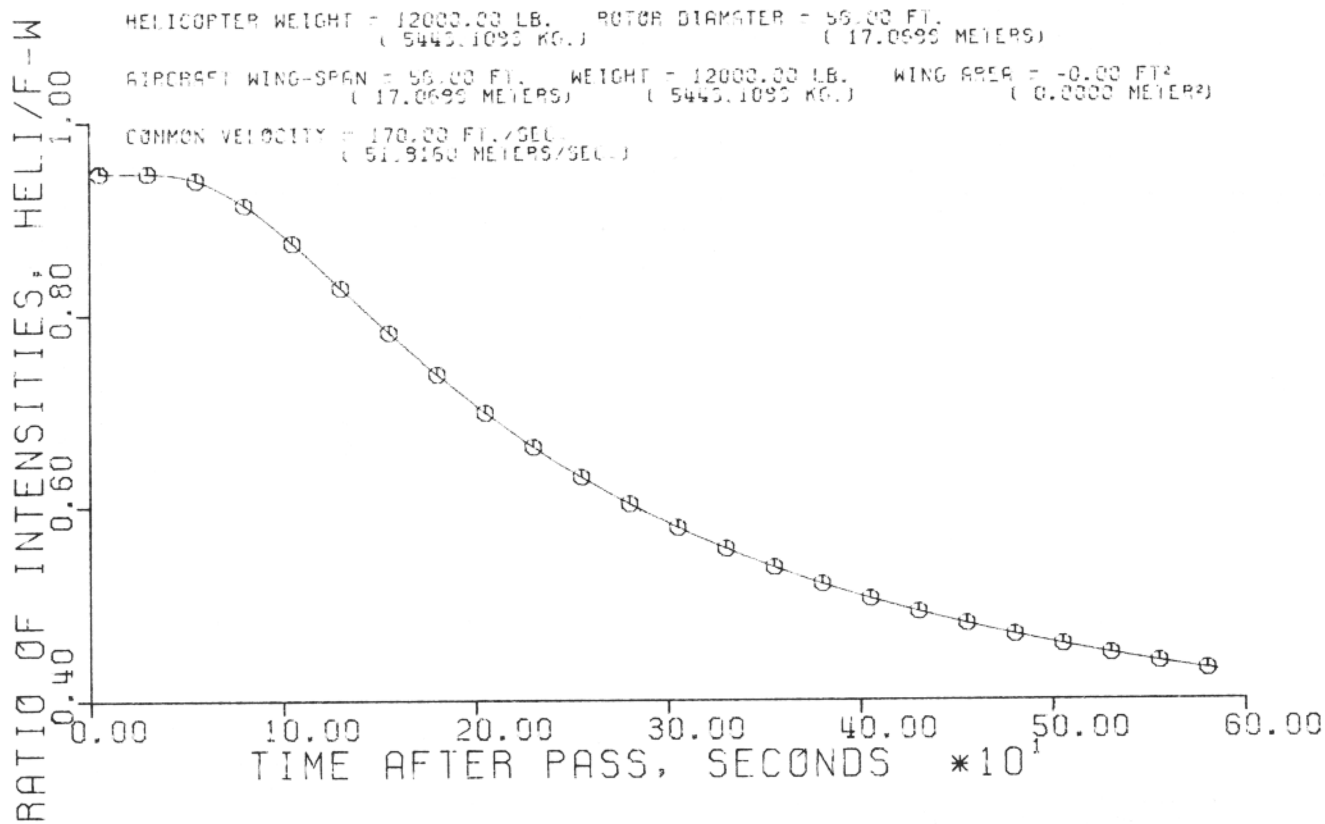


FIGURE 20. RATIO OF VORTEX INTENSITY FOR A 12,000-POUND HELICOPTER, VELOCITY = 170 ft/s

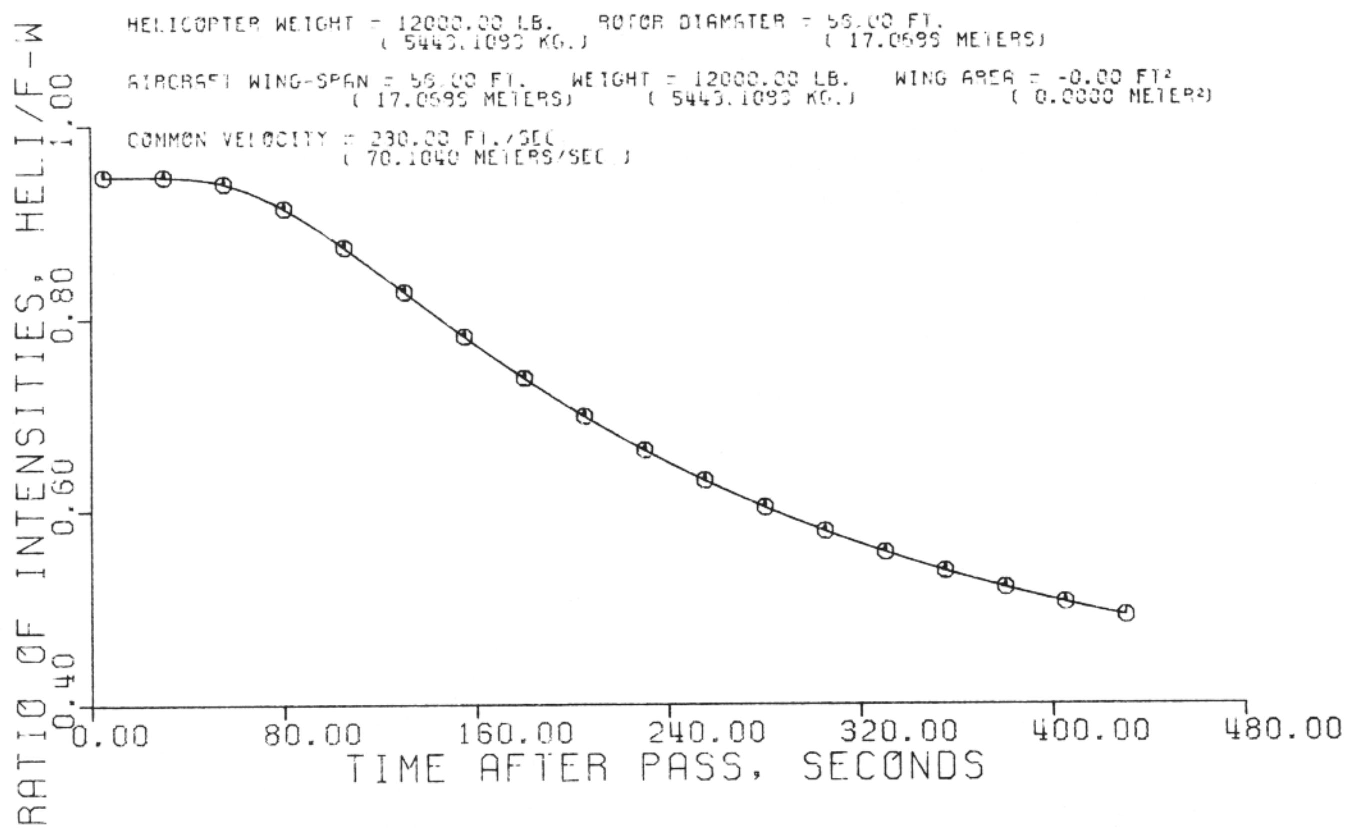


FIGURE 21. RATIO OF VORTEX INTENSITY FOR A 12,000-POUND HELICOPTER, VELOCITY = 230 ft/s

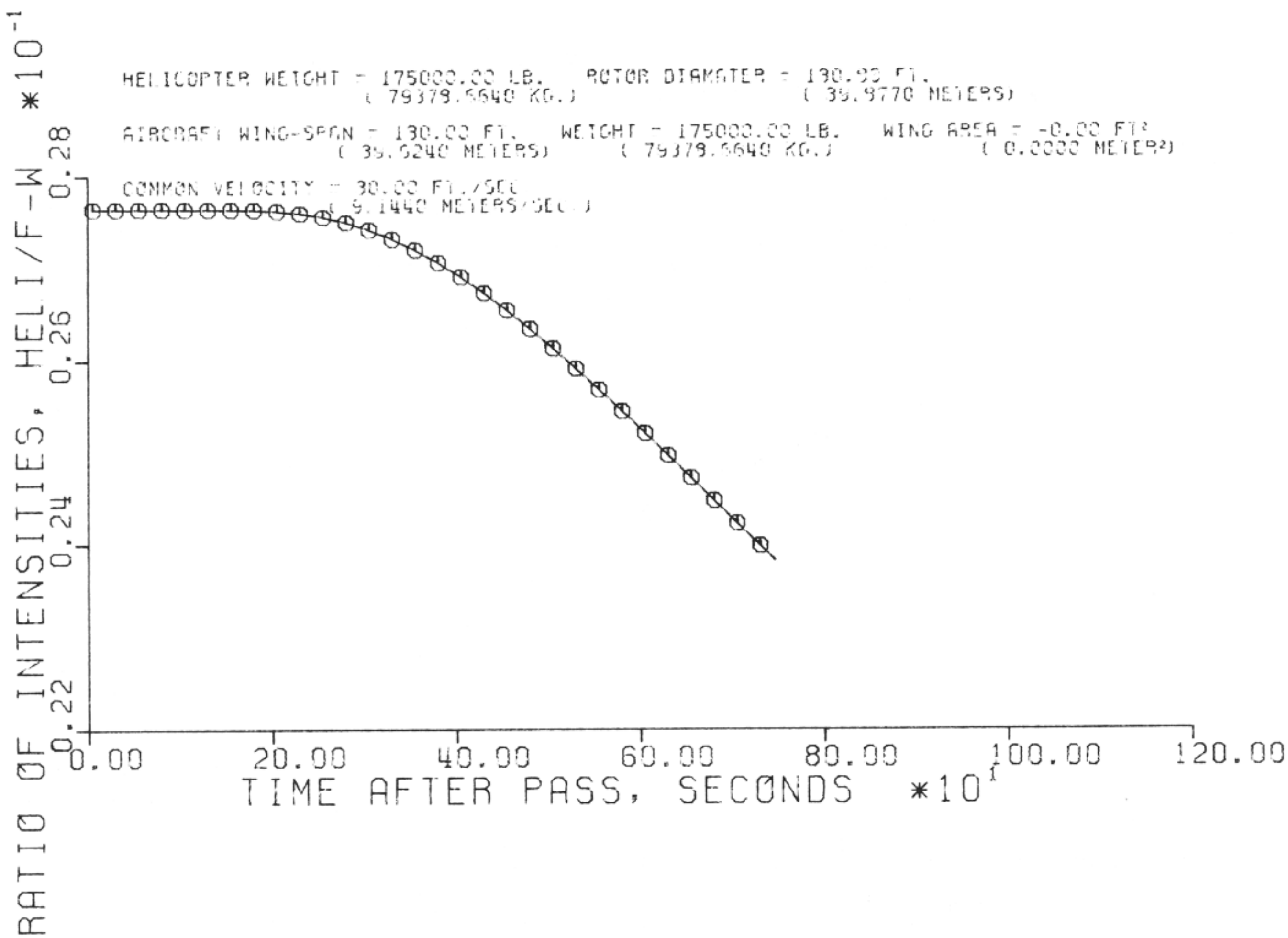


FIGURE 22. RATIO OF VORTEX INTENSITY FOR A 175,000-POUND HELICOPTER, VELOCITY = 30 ft/s

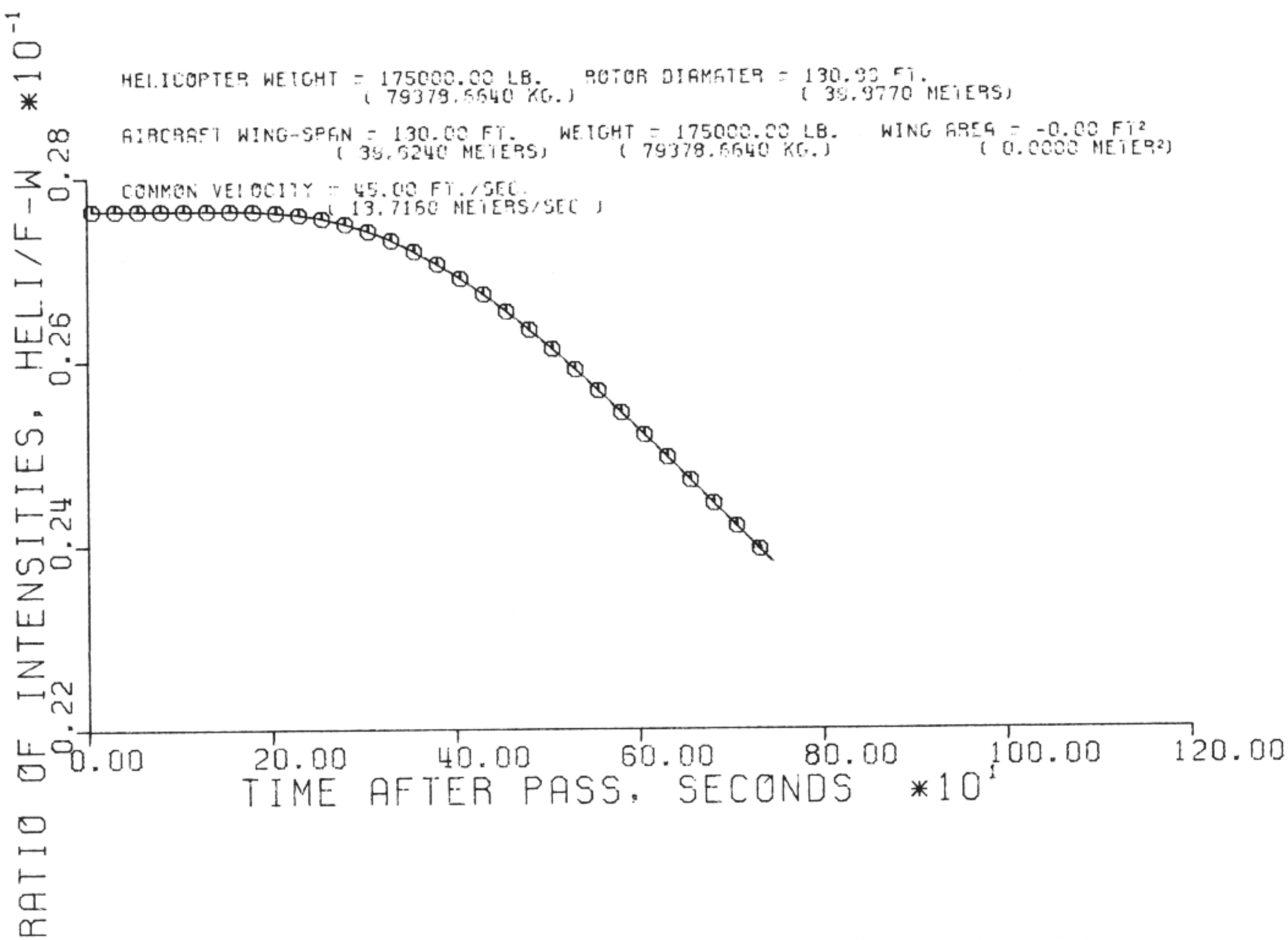


FIGURE 23. RATIO OF VORTEX INTENSITY FOR A 175,000-POUND HELICOPTER, VELOCITY = 45 ft/s

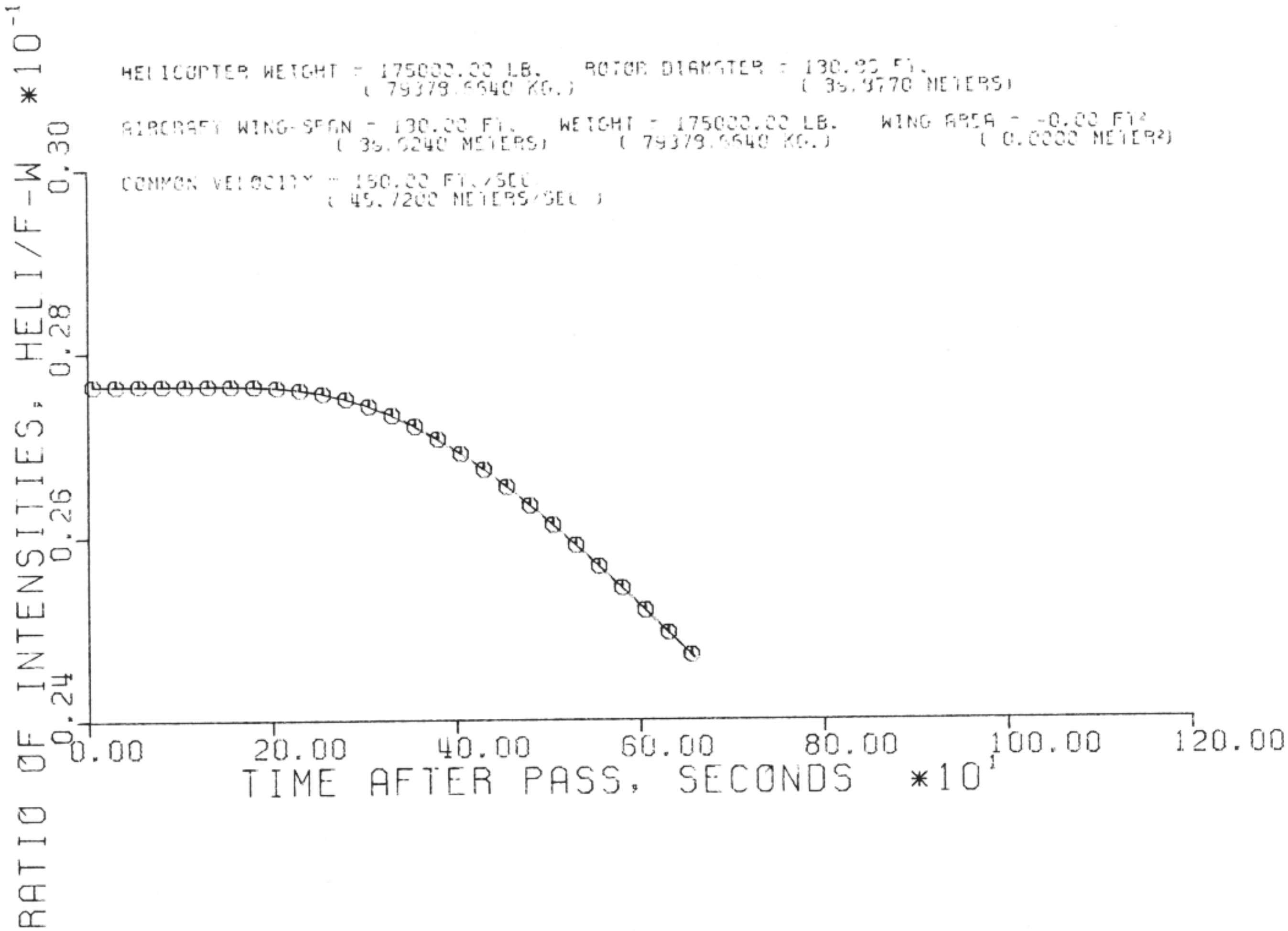


FIGURE 24. RATIO OF VORTEX INTENSITY FOR A 175,000-POUND HELICOPTER, VELOCITY = 150 ft/s

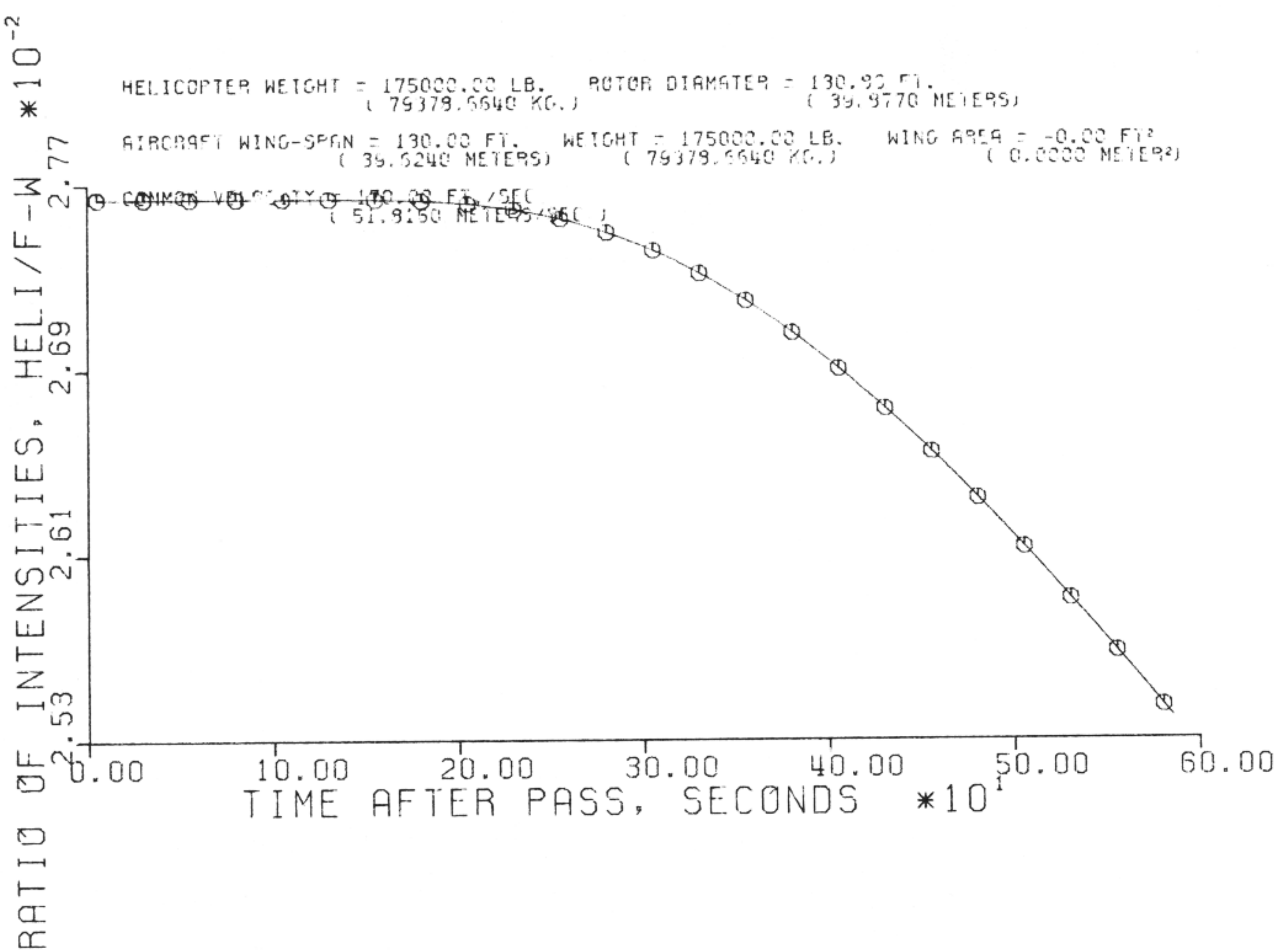


FIGURE 25. RATIO OF VORTEX INTENSITY FOR A 175,000-POUND HELICOPTER, VELOCITY = 170 ft/s

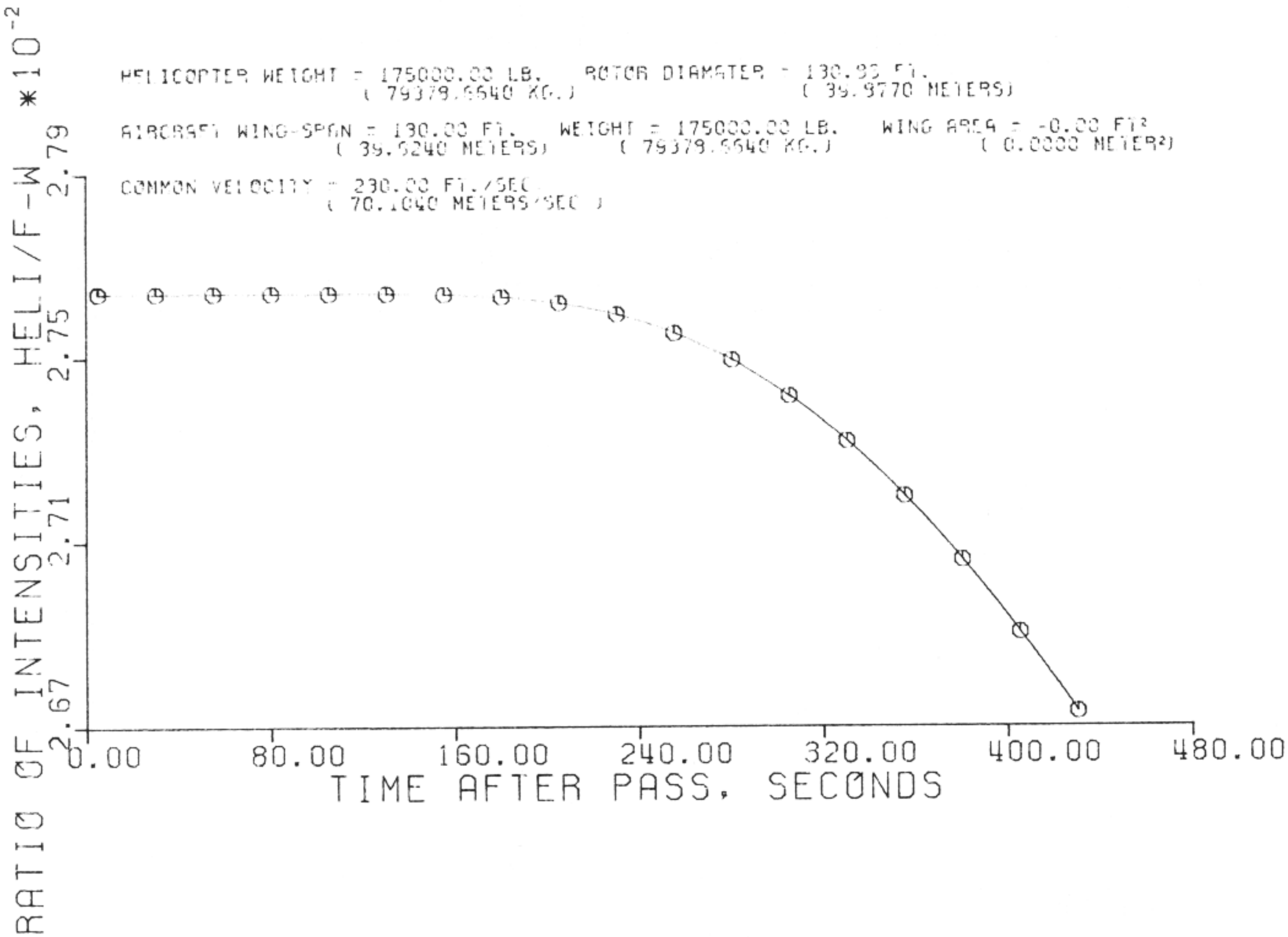
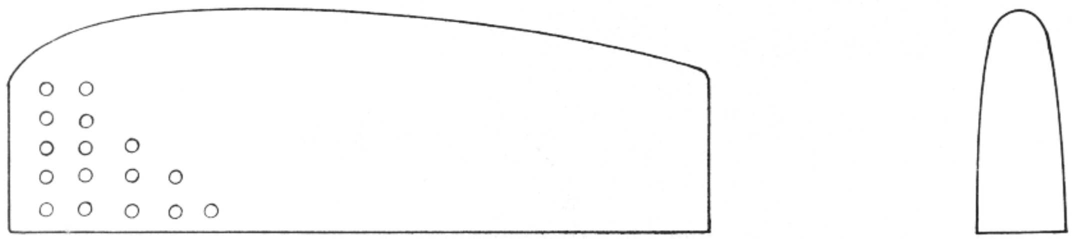
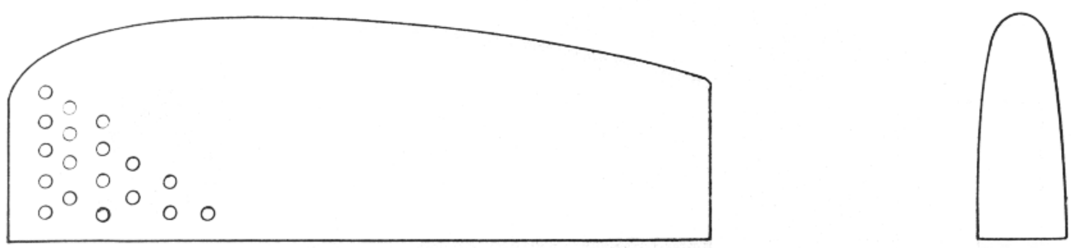


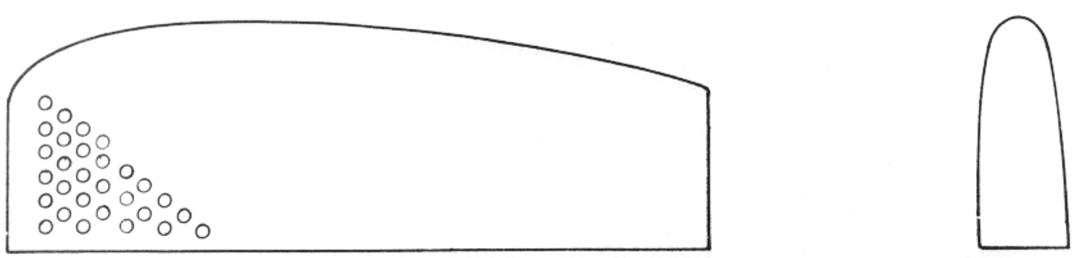
FIGURE 26. RATIO OF VORTEX INTENSITY FOR A 175,000-POUND HELICOPTER, VELOCITY = 230 ft/s



10%-Porous



20%-Porous



40%-Porous

FIGURE 27. VARIATIONS IN WING-TIP POROSITY (INDEX NO. 291)

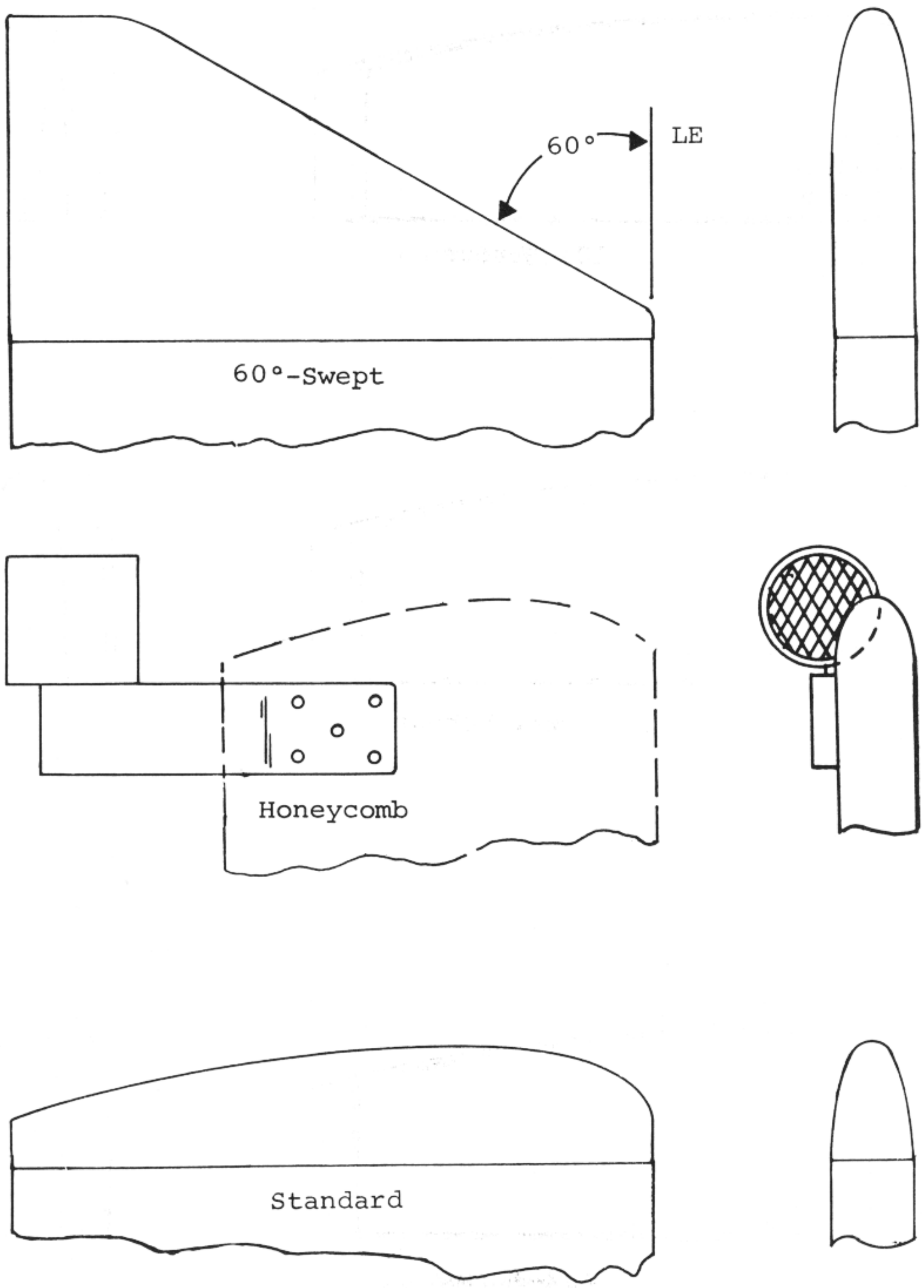


FIGURE 28. VARIATIONS IN WING-TIP GEOMETRY (INDEX NO. 291)

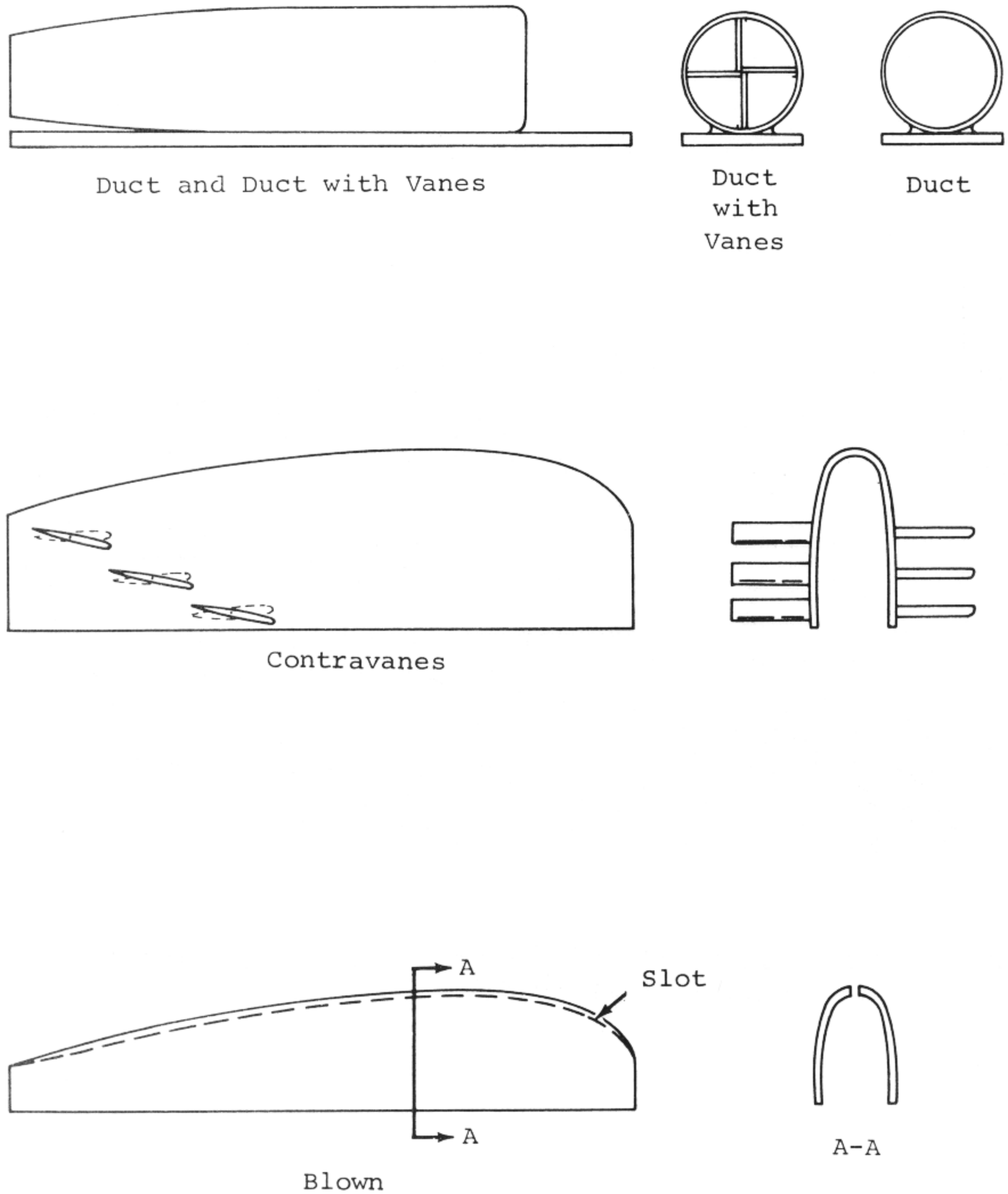


FIGURE 29. VARIATIONS IN WING-TIP FLOW CONTROL (INDEX NO. 291)

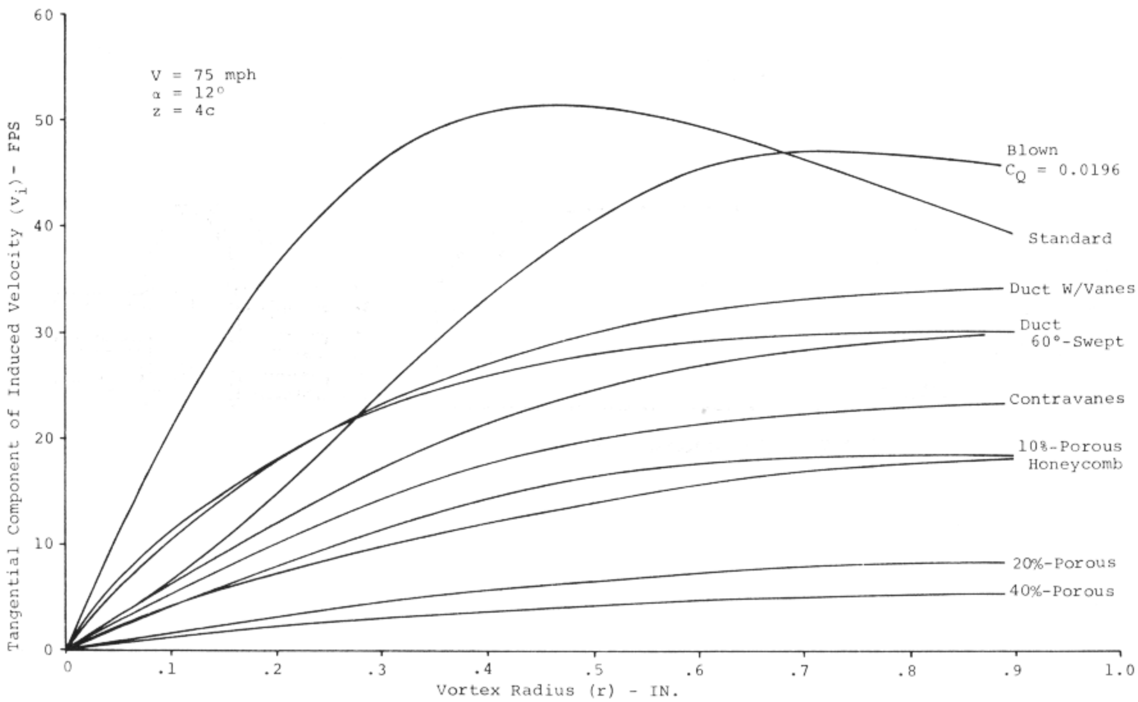


FIGURE 30. TANGENTIAL COMPONENT OF INDUCED VELOCITY VARIATION FOR TEN TIP CONFIGURATIONS (INDEX NO. 291)

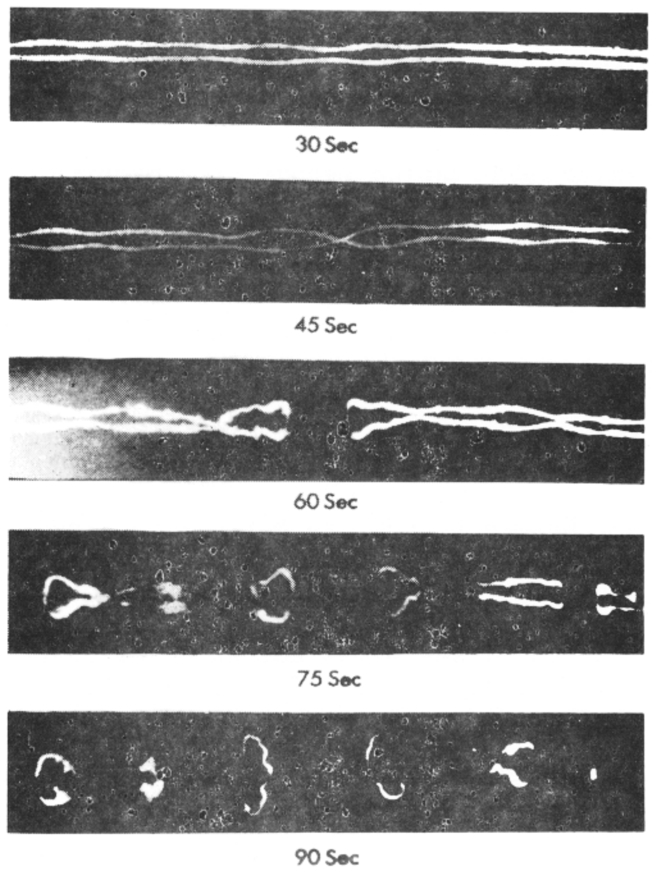


FIGURE 31. VORTEX TRAIL OF A B-47, PHOTOGRAPHED WITH A CAMERA AIMED STRAIGHT UPWARDS. THE TIME ELAPSED SINCE THE PASSAGE OF THE AIRCRAFT APPEARS UNDER EACH PICTURE (INDEX NO. 246)

rotor performances or dynamics. The reports by S. Gene Sadler, index Nos. 71 and 72, and that by Anton J. Landgrebe, index No. 29, are recommended to those primarily interested in this area. The latter report indicated that "the prediction of a tip vortex helix instability at moderate distances from the rotor by the analysis" was "apparently substantiated by available experimental results."

Index No. 32 reports that the analytical predictions of vortex-ring boundaries for helicopters in steep descent "are in good agreement with experiment."

In a recent AGARD technical evaluation report on a meeting of specialists in the field of fluid dynamics, there are included the following cautionary conclusions: "We are not able to describe, in sufficient detail, much less model, the physical processes in the following:

1. The wake of a hovering rotor, in or out of ground effect.
2. The wake of a translating rotor.
3. The formation of a blade tip vortex.
4. The structure of a blade tip vortex.
5. The rolling up of the blade-trailing wake."

This report by Professor Norman D. Ham, in March 1973, index No. 9, further notes that the usefulness of the "ingenious modeling" is compromised by some of the technological gaps.

These deficiencies lay in the areas of establishing aerodynamic efficiency and aerodynamic-induced vibration. The effect on far-field wake and turbulence calculations, though influenced by them, is not as sensitive to these deficiencies.

The document by E. S. Levinsky and T. Stand, index No. 172, was the most applicable to the stated objectives of this report. One of the innovations in this document is the computation and use of an effective turbulent-viscosity term, which is a function of the strength of the rolled-up vortex. A computer program for this analytical model titled "Heliwake" computes the time-history of the vortex system under steady state atmospheric conditions. This program has been prepared for use with either a Control Data Corporation (CDC) 6600 or International Business Machines (IBM) 360 Computer.

The Bennett time-history solution for both fixed- and rotary-wing aircraft, reference 1, has been prepared for use with the IBM 360 Computer.

The computer program developed for this report computes the maximum vortex velocity of aircraft wakes at 5-second intervals after a test aircraft passes a given point. Using the computer velocities of two different aircraft, the program provides a point-for-point comparison of the intervals (with each point representing a velocity computation taken between two 5-second intervals). The comparisons in this report are presented as ratios with "1" indicating equal velocities. Those contained herein are made at 30, 45, 60, 90, and 120 knots. However, other velocities may be substituted for these speeds as necessary.

VORTEX COMPUTER PROGRAM PURPOSE. The program is used to:

1. Compare a Sikorsky S-58 helicopter with a theoretical, fixed-wing aircraft of equal weight and a wingspan equal to the rotor diameter; and

2. Compare a Boeing 707 to a theoretical helicopter of equal size that has a rotor diameter equal to that of the 707's wingspread.

FORMULAE. The formulae used in this report were obtained from reference 1, as developed and implemented by W. J. Bennett, J. W. Wetmore, and J. P. Reeder, respectively.

This program prepared for use with the IBM 360 Computer is diagnosed in appendix D.

VI ROTOR DYNAMICS.

A significant number of the publications listed in appendix A are concerned with rotor dynamics, both mechanical and aeronautical. The purpose of these analytical and experimental programs is primarily to improve rotor performance and reduce mechanical problems related to unsteady rotary-wing loading. This is not a specific objective of this report; however, the FAA is interested in both operational flight safety and mechanical reliability of all types of aircraft. Accordingly, it was decided to provide interested readers with this subgrouping of relevant reports in appendix B.

An analytical treatment of the effects of the near-field wake geometry on rotor-blade loading is presented in index No. 167. One of the conclusions of this theoretical simulation is that the calculated aerodynamic loads are dominated by stall effects where vortex blade infraction occurred. Further, both angle of attack rate and Mach number must be included if aerodynamic representations of the airfoil are to be realistically reflected in computed air loads.

Index No. 140 indicates that the computed rotor blade bending moments showed good agreement with in-flight measurements with the XH-51A compound helicopter rotor. However, this was not true when comparing the computed versus the measured torsional moments.

A summary of the state of the art concerning periodic aerodynamic loadings is contained in index No. 322. The report cites the need for a better understanding of aerodynamic characteristics, both when affected by dynamic stall, and when reverse flow is required. Further, it indicates the need for basic research in the field of vortex/vortex and blade/vortex interaction in the development of the theoretical formulation of wake distortion of single and intermeshing rotor configurations.

VII ROTOR NOISE.

Helicopter or rotor noise generation is of interest to civil rotary-wing operations for several reasons. They include (1) noise abatement, (2) structural vibratory requirements due to blade/vortex interaction of which generated noise is an indication, and (3) stability and control, again generated noise being indicative of fluctuations in aerodynamic lift, hence control.

The reports within this grouping, in appendix B, are principally concerned with noise as it relates to variations in aerodynamic loading, a matter which, as noted above, is of interest to the FAA, although not a specific objective of this report.

The relative importance of the several noise sources such as rotational noise, vortex noise, and blade slap are reviewed in index No. 125. Present analytical procedures for predicting helicopter noise and comparison to experimental full-scale tests are also documented.

An experimental study with a CH-53A helicopter, index No. 92, indicated that, at hover, rotor impulse noise (RIN) is due to blade/vortex wake interaction. As previously noted in the section on "Vortex Interaction," index No. 126 shows very good agreement between experimental and analytical results in this area.

Index No. 217 is a recent comprehensive document on the subject which segregates helicopter noise into four parts: (1) main-rotor rotational noise, (2) tail-rotor rotation noise, (3) main-rotor vortex noise, and (4) gear-box noise. The report addresses itself to all of the aspects noted above.

VIII VORTEX, VORTICITY AND WAKE TURBULENCE HAZARDS.

Most of the published literature in this area is concerned with fixed-wing aircraft.

As noted in several of the preceding sections of this report, analytical approaches to this problem, index No. 171, laboratory tests, index No. 170, and field tests, reference 3, all conclude that the far-field vortex system is similar to that of the fixed-wing aircraft when in forward flight. The principal difference is the quicker transition to turbulent flow due to interaction between the near-field shed vortex and the advancing or retreating blade and, at hover or very low forward speeds, the downwash of the flow field and ground impingement.

Several analytical techniques have been developed to determine the strength and position of the vorticity produced by helicopters. These mathematical models are covered in section V of this report and noted in appendix B.

Studies have been undertaken or sponsored by the military relating to helicopter downwash and the ground environment. An evaluation of prediction techniques to test data, available as of October 1971, index No. 1, concluded that "it remains doubtful that an accurate definition of the AAOE (Army Aircraft Operational Environment) can be derived based upon the questionable prediction methods and verification data that are presently available." Index No. 30 does indicate that "a combined method, however, of proven experimental data and certain analytical approaches have yielded a useful means of predicting the general downwash flow field parameters."

The U. S. Army Material Command (AMC) sponsored a program to measure the downwash of seven different types of helicopters in close proximity to the ground during takeoff, hover, and fly-by operations. The data report containing the results of these tests titled "Helicopter Downwash Data Report" is currently in preparation by the Waterways Experimental Station, Corps of Engineers, Vicksburg, Mississippi. The maximum measured velocities for the helicopters employed are summarized in table 1.

TABLE 1. MAXIMUM MEASURED DOWNWASH VELOCITY

Helicopter Type	Helicopter Height (ft)	Flight Mode	Horizontal Distance from Rotor Hub (ft)	Height of Measurement Point Above Ground (ft)	Maximum Measured Downwash Velocity (ft/sec)
OH-58A	0.5	Lift-Off	30	0.3	68.9
	35.0	Hover	20	0.3	74.8
	2-4	Hover	20	0.3	80.7
	6	Fly-By	30	0.3	71.9
	12	Fly-By	40	1.0	58.7
OH-6A	2-3	Hover	20	0.3	77.7
	26	Hover	20	0.3	68.9
	6	Fly-By	20	0.3	64.5
AH-1G	-	Lift-Off	30	3.0	114.4
	44	Hover	50	1.0	107.1
	8	Fly-By	30	3.0	86.5
	66	Fly-By	50	1.0	108.5
	77	Fly-By	50	1.0	108.5
UH-1H	-	Lift-Off	40	0.3	96.8
	3-8	Fly-By	50	1.0	88.0
UH-1M	-	Lift-Off	20	0.3	110.0
	44	Hover	30	0.3	110.0
	66	Hover	50	1.0	110.0
CH-47	-	Lift-Off	50	5.0	186.3
	30	Hover	50	1.0	164.3
	90	Hover	30	0.3	162.8
CH-54	4	Lift-Off	50	0.3	159.9
	40	Hover	50	0.3	127.6
	80	Hover	50	0.3	108.5
	10	Fly-By	50	0.3	108.5

A recent U. S. Air Force Director of Aerospace Safety Bulletin cited several helicopter-related accidents were reportedly due to encountering the in-flight wake of a helicopter. Unpublished U. S. Army accident investigations have identified at least nine accidents or incidents due to the downwash flow field with related ground impingement and deflections since 1970. The typical downwash of an S-58 helicopter is reported to be about 60 feet per second (ft/s) (35 knots). Measured values reported in reference 3 show that maximum velocities under the S-58 helicopter can reach speeds in excess of 134 ft/s (80 knots). Figures 17 through 26, inclusive, indicate that out-of-ground effect, the vortex intensity of a helicopter, decreases more rapidly with time than a similar weight fixed-wing aircraft. Thus, according to the math models contained in index No. 250, the in-flight turbulence encountered by a following aircraft would be less than that produced by a fixed-wing aircraft using the same time separation criteria. The previous safety bulletin also notes that 1 minute is a good separation criteria between a following landing aircraft and a heavy helicopter. This criteria is similar to that proposed in reference 4 following flight tests with the S-58 helicopter. Figures 17 through 19 reflect that the vortex system would in fact decay to less than 45 percent of its maximum intensity within this time period.

Index No. 46 predates the criteria identified under objective "2" (post 3/64); however, this report is included due to its relationship to helicopter wake hazard. The flight tests reported in this publication "have shown the helicopter wake presents a potential hazard to aircraft operating near the wake."

CONCLUSIONS

Based on a summary of the literature reviewed and the analytical evaluation made, the following conclusions may be drawn:

1. There are several models of the general characteristics of the time-history of the vortex system produced by a rotary-wing aircraft. These models include such definitions, from hover through high-speed flight, for both in- and out-of-ground effect.

2. The models define the position of the vortex system; both the aging characteristics of the vortex and its relative position with respect to a ground reference under various steady-state atmospheric conditions of temperature, pressure, and surface wind conditions.

3. Analytical modeling indicates that the time-history circulation strength characteristics are lower than that of comparable fixed-wing aircraft.

4. The usefulness of the analytical models for near-field definition of the vortex is limited due to some technological gaps.

5. Helicopter flight test results indicate that interaction due to the following blades, fuselage, and other rotor assemblies induce instabilities in the vortex system which are not present in fixed-wing aircraft.

6. The hazards of rotor-wing-produced vortex systems should be less than that of comparable fixed-wing aircraft.

7. Ground- and atmospheric-induced turbulence does not appear to alter the decay rate of vortex systems within the first 20 seconds of generation.

8. Documented flight tests show a reasonable approximation of the calculated far-field characteristics of the helicopter vortex system.

9. The effects of ground impingement of the downwash of a rotary-wing aircraft in low speed or hovered flight could be hazardous to other aircraft or personnel within the downwash.

10. The dynamic loading imposed on a following blade due to interaction between the blade and vortex produced by previous blades may adversely affect blade fatigue life.

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2. Anonymous, NASA Literature Search No. 17873, February 1973.

3. Ahlers, Robert H., and Hiering, William A., Evaluation of the Wake of an S-58 Helicopter, Report No. 417257, July 1963.

4. Conner, Andrew B., and O'Bryan, Thomas C., A Brief Evaluation of Helicopter Wake as a Potential Operational Hazard to Aircraft, NASA Langley Research Center, Langley Air Force Base, Virginia, D-1227, 1962.

APPENDIX A

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The purpose of this report is to evaluate the effectiveness of aircraft/environment interaction prediction methods and to provide guidance for future efforts in the specification of the Army Aircraft Operational Environment (AAOE) design and test criteria. The comparison of several wall-jet prediction methods with existing test data obtained only moderate agreement between theory and test data. It remains doubtful that an accurate definition of the AAOE can be derived based upon the questionable prediction methods and verification data that are presently available.

2. AN ACTUATOR-DISC ANALYSIS OF HELICOPTER WAKE GEOMETRY AND THE CORRESPONDING BLADE RESPONSE, Joglekar, M., and Loewy, R., Rochester University, New York, USAAVLABS TR-69-66, December 1970, AD-881 981.

On the assumption that a helicopter rotor in forward flight can be represented by a flat plate, the authors developed expressions relating the pressure field to the steady aerodynamic thrust and moment and the time-dependent flapping moment. A comparison of results of a modified program with experimental data indicated that the effect of distorted wake is greater at low advance ratios than at high advance ratios.

3. AN ACTUATOR DISC THEORY FOR THE SHED WAKE AT LOW TIP SPEED RATIOS, Jones, J. R., Massachusetts Institute of Tech, Cambridge, Massachusetts, Report No. TR-133-1, 1965, AD-637 744.

A model of the flow through a helicopter rotor, suitable for estimating shed wake effects in hovering and at low tip speed rations, is described. The method leads to the same result for the aerodynamic damping of blade-bending oscillations as more complex theories.

4. AERODYNAMIC CALCULATION FOR HELICOPTER LIFTING ROTORS IN VERTICAL DESCENT (VORTEX RING METHOD), Shaidakov, V. I., Army Foreign Science and Technology Center, Charlottesville, Virginia, Report No. FSTC-HT-23-708-71, October 1971, AD-734 229.

A theoretical study was made of the performance of a lifting helicopter rotor during vertical descent. The vortex ring method was used in aerodynamic calculation of lifting systems.

5. AERODYNAMIC COMPUTATION OF THE MAIN ROTOR OF A HELICOPTER UNDER CONDITIONS OF STEEP DESCENT, BY THE METHOD OF RING VORTICES, Shaidakov, V. I., Russia, 1969.
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7. AERODYNAMIC LOADING OF HIGH SPEED ROTORS, Rabbott, John P., and Paglino, Vincent M., CAL/USAAV LABS Symposium, June 1966.

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9. AERODYNAMICS OF ROTARY WINGS, Ham, N. D., Tech. Evaluation Report on Fluid Dynamics Panel Specialists Meeting, AGARD-AR-61, March 1973.
This report assesses presented papers on the basis of: (1) Contribution to improvements in aerodynamic noise efficiency and vibration /EVE/ of helicopters, and (2) How well they indicate the need for further knowledge in some area.

10. AERODYNAMICS OF ROTARY WING AND V/STOL AIRCRAFT (VOLUME I), CAL/AVLABS, Symposium Proceedings (3rd), Cornell Aeronautical Lab, Inc., Buffalo, New York, June 1969, AD-693 246.
Contents: Continuous vortex sheet representation of deformed wakes of hovering propellers; propeller wake deformation due to instability of a trailing vortex sheet; vortex field, tip vortex, and shock formation on a model propeller; a hover performance analysis combining the strip-momentum and prescribed wake theories; helicopter rotor noise generation; the importance of vortex-shedding effects on helicopter rotor noise with and without blade slap; prediction methods and trends for helicopter rotor noise; and rotor noise measurements in wind tunnels.

11. AERODYNAMICS OF ROTARY WING AND V/STOL AIRCRAFT (VOLUME II), CAL/AVLABS. Symposium Proceedings (3rd), Cornell Aeronautical Lab., Inc., Buffalo, New York, June 1969, AD-693 247.
Contents: model versus full-scale rotor testing; the flow throughout a wind tunnel containing a rotor with a sharply deflected wake; comments on V/STOL wind tunnel data at low forward speeds; problems associated with tunnel tests of high disk-loading systems at low forward speeds; some research on rotor circulation control; the aerodynamics of a circulation-controlled rotor; higher harmonic pitch control; and the controllable twist rotor.

12. AERODYNAMICS OF ROTARY WING AND V/STOL AIRCRAFT (VOLUME III), CAL/AVLABS, Symposium Proceedings (3rd), Cornell Aeronautical Lab, Inc. ,Buffalo, New York, June 1969, AD-693 248.
Contents: notes on rotor aerodynamic research; aerodynamic research related to propeller driven V/STOL aircraft; and some problems in the numerical solution of vortex motion equations.

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16. AIRCRAFT TRAILING VORTICES: A SURVEY OF THE PROBLEM,
El-Ramly, Z., Carleton University, Ottawa, Canada,
Mechanical Engineering Department, Aerothermodynamics
Division, November 1972, 179 pp.
A survey of aircraft trailing vortices problem is presented in this report. Only the work related to vortices shed from high aspect ratio, straight or swept back wings, is considered. The extensive work on leading edge vortices, generated by slender wings, is not presented, except when it is felt that a particular piece of work is directly helpful for the problem at hand.

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Rose, R., Dee, F. W., ARC CP 795, 1965.

18. AIRCRAFT WAKE TURBULENCE, Anon, DOT, FAA,
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and Charak, Mason T., NASA Headquarters,
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The purpose of the program was to measure the airflow velocities existing in the turbulent envelope of a UH-1C helicopter to ascertain the feasibility of installing an airspeed indicator in this envelope.

24. AIR LOADINGS ON A ROTOR BLADE AS CAUSED BY TRANSIENT INPUTS OF COLLECTIVE PITCH, Segel, Leonard, Cornell Aeronautical Lab, Inc., Buffalo, New York, USAAVLA BS, TR-65-65, October 1965, AD-624 860.
Develops a method for predicting the nonperiodic airloads resulting from control inputs applied to a rotary wing in forward flight by making use of a numerical description of the geometry and circulation strength of the vorticity in the wake to compute the time-varying, nonuniform flow field in the plane of the rotor disc. In general, it was concluded that the calculation and prediction of nonperiodic loadings on rotary wings is a feasible task.

25. ANALYSES RELATING TO AIRCRAFT VORTICAL WAKES, Kurylowich, Dr. G, Air Force Flight Dynamics Laboratory, February 1973.
This is a comprehensive review of literature based on analyses relevant to the vortical wake structure behind an aircraft. In general, these analyses fall into two categories, which relate to either the near wake or the far wake. Mathematical models were also formulated.

26. ANALYSIS AND CORRELATION OF HELICOPTER ROTOR BLADE RESPONSE IN A VARIABLE INFLOW ENVIRONMENT, Carlson, R. G. and Hilzinger, K. D., USAAVLABS Technical Report 65-51, 1965.
An investigation to determine the extent to which present analytical methods can be used to evaluate rotor blade air loads and rotor dynamic response was undertaken. Significant improvement was attained by combining CAL variable inflow analysis with Sikorsky blade aeroelastic analysis using test data from the H-34 and HU-1A aircraft.

27. AN ANALYSIS OF THE STALL FLUTTER INSTABILITY OF HELICOPTER ROTOR BLADES, Carta, F. O., AHS Vol. 12, October 1968.

An analytical study was carried out to determine the susceptibility of helicopter rotor blades to a stall flutter instability. This analysis was based on the use of unsteady aerodynamic data previously obtained by the United Aircraft Research Laboratories.

28. ANALYTICAL DETERMINATION OF THE VELOCITY FIELDS IN THE WAKES OF SPECIFIC AIRCRAFT, Bennett, W. J., The Boeing Company, Airplane Division, Renton, Washington, May 1964.

The material presented in this report, together with that in FAA Report RD-64-4, comprises one part of a larger program directed toward determining safe separation times and distances for aircraft operating in the air terminal traffic pattern. A discussion of the assumptions and limitations of the analytical models used is included along with a discussion of possible correlation of the calculated values with test results.

29. AN ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF HELICOPTER ROTOR HOVER PERFORMANCE AND WAKE GEOMETRY CHARACTERISTICS, Landgrebe, Anton J., United Aircraft Research Labs, East Hartford, Connecticut, USAAMRDL TR-71-24, June 1971, AD-728 835.

An analytical and experimental investigation was conducted to acquire data on systematic model rotor performance and wake geometry and to evaluate the accuracy of various analytical methods in predicting the effects on performance of changes in helicopter rotor design and operating parameters, N72-13982. The prediction of a tip vortex helix instability at moderate distances from the rotor by the analysis, apparently substantiated by available experimental results, was of particular interest.

30. AN ANALYTICAL METHOD OF DETERMINING GENERAL DOWNWASH FLOW FIELD PARAMETERS FOR V/STOL AIRCRAFT, Hohler, David J., A.F. Aero Propulsion Laboratory Research and Technology Division, AFSC, TR 66-90, November 1966.

This report presents a method of analytically determining the general downwash flow field parameters of various types of V/STOL aircraft. This downwash can cause damage to nearby aircraft, equipment, or personnel. Past theoretical methods based on incompressible flow theory have been unsuccessful in establishing a means of computing this downwash flow field. A combined method, however, of proven experimental data and certain analytical approaches have yielded a useful means of predicting the general downwash flow field parameters. This report presents these approaches and demonstrates their usefulness.

31. AN ANALYTICAL METHOD FOR PREDICTING ROTOR WAKE GEOMETRY, Landgrebe, Anton J., United Aircraft Corporation, Research Labs, Fluid Dynamics Lab, Rotary Wing Technology Group, East Hartford, Connecticut, AIAA Paper 69-196, February 1969.
An analytical method for predicting the distorted geometry of a helicopter rotor wake is described. Sample comparisons of analytical and experimental wake geometries of a rotor in forward flight are presented and indicate the ability of the analysis to predict the characteristic distortion features of the wake.

32. ANALYTICAL PREDICTION OF VORTEX-RING BOUNDARIES FOR HELICOPTERS IN STEEP DESCENT, Wolkovitch, J., Mechanics Research, Inc., Los Angeles, California, DAAJ02-69-C-0004, July 1972.
A simple method of predicting the combination of rate of descent and angle of descent at which the vortex-ring state occurs is described. Momentum theory and actuator disk concepts are employed. The key assumption of the analysis is that the vortex-ring state will occur when the relative velocity of the vortex cores normal to the disk falls to zero. The parasite drag of the rotor and of other components is considered. The causes of vertical and inclined descent, and the lower boundary of the vortex-ring state are studied. The results are in good agreement with experiment.

33. ANALYTICAL STUDIES OF AIRCRAFT TRAILING VORTICES, Kuhn, G. D., Nielsen, J. N., AIAA Paper 72-42, January 1972.

34. ANGLE-OF-ATTACK DISTRIBUTION OF A HIGH SPEED HELICOPTER ROTOR, Madden, Paul A., Massachusetts Institute of Tech, Cambridge Aeroelastic and Structures Research Lab, Cambridge, Massachusetts, AROD 4846:4, 1967, AD-655 476.
This study presents a numerical solution for the angle-of-attack distribution, downwash, and motion of a high speed helicopter rotor. Comparison is made with experiment for longitudinal flapping of an essentially rigid teetering rotor at Mu = .94. Three separate calculations of the example case were performed. The calculated angle-of-attack contour for the Mu = .94 case is presented.

35. HELICOPTER ROTOR BLADE AIRLOAD BY APPLYING LIFTING SURFACE SOLUTION, Johnson, W., MIT, Cambridge, Massachusetts, May 1971.
Application of a lifting-surface theory to the calculation of helicopter airloads.

36. APPLICATION OF THE RING VORTEX METHOD TO AERODYNAMIC DESIGN OF LIFTING ROTOR SYSTEMS, Shaidakov, V. I, Army Foreign Science and Technology Center, Charlottesville, Virginia, Report No. FSTC-HT-23-709-71, November 1971, AD-735 018.

The ring vortex method is a simplified procedure for accurately determining the aerodynamic characteristics of the lifting rotor. The replacement of the vortex cylinder with a system of discrete vortex rings is equivalent to expanding the vortex cylinder into rings and longitudinal vortices. Ignoring the longitudinal vortices creates no significant error for lightly loaded lifting rotors.

37. AN APPLICATION OF VORTEX THEORY TO PROPELLERS OPERATING AT AERO ADVANCE RATIO, Gartshore, I. S., McGill University, Mechanical Engineering Research Lab., Inc., TN 66-3, June 1966.

38. AN APPRAISAL OF THE DETAILS OF HELICOPTER ROTOR LOADINGS AND METHODS FOR THEIR COMPUTATION, Clarke, A. E., Royal Aircraft Establishment, Farnborough, England, Report No. TN-NAVAL-66, April 1964, AD-460 675L.

A survey is made of the state-of-the-art in estimating the detailed distribution of blade loading on helicopter rotors. Comparisons of various theories with experimental results are discussed.

39. APPROXIMATE SOLUTIONS FOR COMPUTING HELICOPTER HARMONIC AIRLOADS, Scully, Michael P., Massachusetts Institute of Tech., Cambridge Aeroelastic and Structures Research Lab, Cambridge, Massachusetts, Report No. TR-123-2, December 1965, AD-636 928.

Assuming a constant circulation, rigid trailing wake, and using a lift deficiency function to represent the unsteady aerodynamic effects, various methods of calculating the airloads on a helicopter rotor in steady, forward flight were developed. Since most of the solution time is required to calculate the induced velocities due to the trailing wake, various approximate methods of calculating the induced velocities due to a rigid, skewed helix were developed.

40. AN ASSESSMENT OF DOMINANT MECHANISMS IN VORTEX-WAKE DECAY, Macreody, P. B., Jr., Boeing/AFOSR Aircraft Wake Turbulence Symposium, 1970.

41. AVOIDANCE OF TRAILING VORTEX HAZARDS, McGowen, W. A., AGARD Conference, AGARD-CP-76-71.

Results of accident investigations, theoretical exercises, wind-tunnel experiments, and flight tests are used to describe the formation and severity of trailing vortices and the spatial extent of their influence, including factors governing persistence. The procedures provide the potential hazards and how best to avoid the dangerous portions of the wake during flight operations. Schemes to monitor remotely both the trailing vortex location and intensity in the airport area and to prohibit formation of high intensity vortices, through aircraft design, are discussed.

42. BASIC MECHANISMS OF NOISE GENERATION BY HELICOPTERS, V/STOL AIRCRAFT, AND GROUND EFFECT MACHINES, Lowson, M. V., Wyle Labs., Report No. WR65-9, May 1965, Journal of Sound and Vibration Vol. 3, Part 3, pp. 454-466, 1966.

43. BLADE TIP AERODYNAMICS - PROFILE AND PLAN-FORM EFFECTS, Spivly, R. F., 24th National Forum of the American Helicopter Society, May 1968.

44. BOUNDARY LAYER DISCONTINUITY ON A HELICOPTER ROTOR IN HOVERING, Velkoff, H. R., Blaser, D. A., Jones, K. M., AIAA-AHS-VTOL, Research, Design.

An experimental study was conducted using flow-visualization techniques to investigate the nature of the boundary layer on a helicopter rotor in hovering. The study revealed that an unanticipated boundary layer behavior occurred. The traces initially moved chordwise along the surface then abruptly turned outwards. A short distance later, the traces moved inwards and then continued aft along the blade in a somewhat diffuse pattern. Similar traces were found over wide ranges of pitch angles and rotor speeds. It is hypothesized that a standing laminar separation bubble exists on the blade surface aft of the peak pressure position. (Author)

45. THE BOUNDARY LAYER OF THE HOVERING ROTOR, Tanner, W. H. and Buettiker, P., CAL/USAAVLABS Symposium Proceedings, Vol. III, June 1966.

46. A BRIEF EVALUATION OF HELICOPTER WAKE AS A POTENTIAL OPERATIONAL HAZARD TO AIRCRAFT, Conner, A. B., O'Bryon, T. O., NASA TN-D-1227, 1962.

Flight tests were conducted with an airplane and a single-rotor helicopter to determine some characteristics of the helicopter wake and its possible upsetting tendencies on an airplane.
Flight tests with the airplane and helicopter have shown the helicopter wake presents a potential hazard to aircraft operating near the wake.

47. A BRIEF REVIEW OF THE AIRCRAFT TRAILING VORTEX PROBLEM, Donaldson, C. duPont, AFOSR-TR-71-1910, May 1971.

48. CALCULATED NORMAL LOAD FACTORS ON LIGHT AIRPLANES TRAVERSING THE TRAILING VORTICES OF HEAVY TRANSPORT AIRPLANES, McGowan, William A., Langley Research Center, Langley Field, Va., May 1961.
This report presents results of normal-load-factor calculations made for a light normal-category airplane and a light transport-category airplane traversing the trailing vortices generated by each of three heavy transport airplanes.

49. CALCULATION OF TURBULENT SHEAR-FLOWS FOR ATMOSPHERE AND VORTEX MOTIONS, Donaldson, C. duPont, AIAA Paper 71-217, Presented at AIAA 9th Aerospace Sciences Meeting, January 1971.

50. A CATALOGUE OF DEVICES APPLICABLE TO THE MEASUREMENT OF BOUNDARY LAYERS AND WAKES ON FLIGHT VEHICLES, Miley, Stan J., Mississippi State University, State College, Mississippi, Department of Aerophysics and Aerospace Engineering, NASA-CR-116776, January 1972.
A literature search was conducted to assemble a catalog of devices and techniques which have possible application to boundary layer and wake measurements on flight vehicles. The devices contained in the catalogue were restricted to those that provided essentially direct measurement velocities, pressures and shear stresses.

51. COMPARISON BETWEEN EXPERIMENTAL DATA AND HELICOPTER AIRLOADS CALCULATED USING A LIFTING SURFACE THEORY, Johnson, Wayne, Massachusetts Institute of Tech, Aeroelastic and Structures Research Lab, Cambridge, Massachusetts,Report No. ASRL-TR-157-1, July 1970, AD-726 717.
Results of the calculation of helicopter airloads using a lifting surface theory solution are presented and compared with experimental data. The results indicate that a very accurate wake geometry model will be required in order to make full use of the accuracy of the lifting surface theory solution.

52. A COMPARISON BETWEEN EXPERIMENTAL DATA AND A LIFTING SURFACE THEORY CALCULATION OF VORTEX INDUCED LOADS, Johnson, W., Massachusetts Institute of Tech; Aeroelastic and Structures Research Lab, Cambridge, Massachusetts, NASA-CR-112769, August 1970.
This report is a comparison between experimental data and lifting surface theory calculation of vortex induced loads on single-bladed rotary wings.

53. COMPRESSIBILITY EFFECTS ON OSCILLATING ROTOR BLADES IN HOVERING FLIGHT, Jones, W. P., Rao, B. M., Texas A & M University College Station, Department of Aerospace Engineering, College Station, Texas, Report No. AROD T-5: October 1968, AD-678 624.
A theory is developed and used for determining the influence of compressibility on the aerodynamic forces affecting helicopter rotor blades as they oscillate during hovering flight.

54. COMPUTATIONAL STUDY OF ROTATIONAL NOISE, Wright, S. E. and Tanna, H. K., ISVR Technical Report No. 15, 1969.

55. COMPUTATIONS OF THE GENERATION OF TURBULENCE IN THE ATMOSPHERIC BOUNDARY LAYER, Donaldson, C. duPont and Conrad, Peter W., Proceeding Conference Cosponsored by AIAA and CASI A71-29749 14-20, NAS 1-10192, 1971.
Results of an attempt to develop a detailed model of atmospheric shear layer are discussed. Agreement between calculation and experiment was good, using the experimental data of Wyngaard and Cote of the USAF Cambridge Research Laboratories. The role played by the scale of atmospheric turbulence in determining the intensity of turbulence generated by a given shear layer can be investigated by means of the calculations presented.

56. COMPUTER FLIGHT TESTING OF ROTORCRAFT, Duhen, J. M., Harvey, K. W., and Blankenship, B. L., Jour AHS, Vol 10, No 4, October 1965.
This paper describes a recently developed analytical tool for computer 'flight testing' of VTOL designs. Steady state flight, maneuvers, and gust response are evaluated. The basic equations and programming procedures are presented and discussed. Details are given concerning the representation of airframe and rotor parameters, the types of maneuver inputs and the output format available to the engineer.

57. COMPUTER PROGRAMME FOR THE PREDICTION OF ROTATIONAL NOISE DUE TO FLUCTUATING LOADING ON ROTOR BLADES, Tanna, H. K., ISVR Technical Report No. 13, 1968.

58. A COMPUTER STUDY OF A WING IN A SLIPSTREAM, Ellis, N. D., Institute for Aerospace Studies, University of Toronto, TN-101, 1967.
A Fortran IV program for the IBM 7094-II digital computer has been formulated based on a theory of wing-slipstream interference by Ribner which accounts for the slipstream effects by means of a vortex sheath. This sheath together with the wing vorticity lead a pair of simultaneous integral equations for the unknown circulations. A stepwise approximation of the circulations reduces the pair to a system of linear algebraic equations.

59. A CONTINUOUS VORTEX SHEET REPRESENTATION OF DEFORMED WAKES OF HOVERING PROPELLERS, Erickson, J. C., Jr., Cornell Aeronautical Lab, USAAML 3rd Symposium, Buffalo, N. Y., 1969.
This study contains lifting line theory for hovering propellers and deformed wakes based on continuous vortex sheet representation. It emphasizes determining a satisfactory force-free approximation to the effective pitch of the trailing vortex sheets, but with the contraction pattern fixed according to a heavily loaded actuator disc theory. Numerical solutions to the governing equations were found.

60. A CONTRIBUTION TO THE THEORY OF JET-WAKE AND VORTICES IN FREE AND CONFINED SURROUNDINGS, Fragoyannis, George Basil, USAAVLABS, Tech Rep. 66-69, November 1966.
The report presents a study of the flow field of steady, viscous, incompressible jet-wakes and vortices submerged in free and confined surroundings. The general principles of the motion of a free laminar jet have been analyzed and reviewed. From these principles, an understanding of the very complex behavior of a turbulent jet has been obtained.
Using a linearized form of the Navier-Stokes equations of motion, a set of solutions capable of describing the laminar axial, rotational, and radial velocity profiles of a jet was deduced. It was concluded that the laws describing jet-wakes and vortices for laminar and turbulent motion are of the same general nature.

61. CONTROL LOADS AND THEIR EFFECTS ON FUSELAGE VIBRATIONS, Kidd, D. L., Lawrence, K. L., and Spivey, R. F., Bell Aerospace Corporation, Bell Helicopter Company, Fort Worth, Texas, AHS Paper 133, May 1967.
Effect of rotor control feedback loads of two-bladed rotor system on helicopter fuselage vibrations.

62. CORRELATION OF THE VORTEX LATTICE METHOD ON ROTOR/WING CONFIGURATIONS, Liu, D. T., and Rodden, W. P., Hughes Tool Company, Aircraft Division, Stability and Control Section, Culver City,, California, August 1969.
Vortex lattice method correlation on rotor wing configurations for aerodynamic characteristics are discussed noting triangular and circular hub and blades.

63. A CORRELATION OF VORTEX NOISE DATA FROM HELICOPTER MAIN ROTORS, Widnall, Sheila E., Massachusetts Institute of Tech., Cambridge, Massachusetts, AROD 6495:2-E, February 1969, AD-695 142.
The document presents a correlation of existing data on main rotor vortex noise which is, at the present state of the art, an irreducible effect of operating the main rotor.

64. A CRITICAL REVIEW OF VORTEX BURSTING, Rogge, T. and Lee, D., RN AFFDL 04-72-1, 1971.

65. DECAY OF AN ISOLATED VORTEX, Donaldson, C. duP. and Sullivan, R. D., Proceedings of a Symposium on Aircraft Wake Turbulence, September 13, 1970.

66. DECAY OF TRAILING VORTICES, Sherrieb, H. E., M.S. Thesis, Penn State Univ., 1967.

67. THE DECAY OF A TURBULENT TRAILING VORTEX, Owen, P. T., Aeronautical Quarterly, Vol XXI, February 1970.
The decay of a trailing vortex containing a turbulent core is examined according to the argument that the turbulence is partly sustained by, and interacts with, the irrotational flow through viscous diffusion of eddies across the core boundary.
The principal conclusion of practical interest is that the maximum circumferential velocity in a trailing vortex generated by an aeroplane in flight is,
$U_{,1} = 0.065(\Gamma/\nu)^{3/4} (\nu/t)^{1/3}$,
where is the circulation about large circuits enclosing the vortex, is the kinematic viscosity of the air, and t is the (sufficiently great) age of the vortex.

68. DESIGN OF AIRFOILS FOR ROTORS, Wortmann, F. X., Dr. Professor, Drees, J. M., University of Stuttgard, Germany, and Consultant to Bell Helicopter Company, Paper presented at the CAL/AVLABS Symposium on Aerodynamics of Rotor Wing and VTOL Aircraft, 1969.
Summary of airfoil design methods which have recently become available and permit the analytical optimization of performance at selected operating conditions with one airfoil. Analytical design techniques for rotor airfoils are discussed. Methods for minimizing profile drag in hover and when the advancing tip operates at high Mach numbers are evaluated.

69. DEVELOPMENT OF A METHOD FOR PREDICTING THE PERFORMANCE AND STRESSES OF VTOL-TYPE PROPELLERS, USAAVLABS, TR 66-26, 1966. No author given.
The report presents a theoretical method which allows the prediction of performance and stress characteristics of a single VTOL-type of propeller-wing-nacelle combination operating in various flight conditions. The method includes all the effects of a distorted wake, i.e., the effects of contraction and radial and axial velocity variations: (2) the effects of hovering close to the ground: (3) the interference effects from a nacalle and wing buried in the propeller slipstream. Because of the insufficient accuracy of the experimental data collected no definite evaluation of the model is made.

70. DEVELOPMENT AND APPLICATION OF A METHOD FOR PREDICTING ROTOR FREE WAKE POSITIONS AND RESULTING ROTOR BLADE AIR LOADS. VOLUME 1: MODEL AND RESULTS, Sadler, S. Gene, Rochester Applied Science Associates, Inc., New York, Report NASA-CR-1911, December 1971.
Rotor wake geometries are predicted by a process similar to the startup of a rotor in a free stream. Blade loads computations include the effects of non-uniform inflow due to a free wake, nonlinear airfoil characteristics, and response of flexible blades to the applied loads. Computed wake flows and blade loads are compared with experimentally measured data. The effects of advance ratio, vertical separation of rotors, different blade radius ratios, and different azimuthal spacing of the blades of one rotor with respect to the other are investigated.

71. DEVELOPMENT AND APPLICATION OF A METHOD FOR PREDICTING ROTOR FREE WAKE POSITIONS AND RESULTING ROTOR BLADE AIR LOADS. VOLUME 2: PROGRAM LISTINGS, Sadler, S. Gene, Rochester Applied Science Associates, Inc., New York, Report NASA-CR-1912, December 1971.
Computer program listings for calculations discussed in Volume 1 are presented.

72. THE DYNAMIC RESPONSE OF A FLEXIBLE ROTOR BLADE TO A TIP-VORTEX-INDUCED MOVING FORCE, Ward, John F. and Snyder, William J., NASA, Langley Research Center, Hampton, Virginia, (AIAA/AHS, VTOL Meeting, Georgia Institute of Technology, Atlanta, Georgia, AIAA Paper 69-203, February 1969.

Approximate analytical solution of the dynamic response of a flexible rotor blade to a radially moving force. The results are interpreted specifically in terms of helicopter rotor blade vibration characteristics associated with tip vortex impingement.

73. DYNAMICS OF A FULLY ARTICULATED ROTOR BLADE, Harrison, J. M., Westland Aircraft Limited Technical Report, Aero/Research/z 1965.

74. DYNAMIC STALL OF AIRFOIL SECTIONS FOR HIGH-SPEED ROTORS, Livia, J. and Davenport, F. J., AHS, 24th Nat. Forum, May 1968.

The dynamic stall characteristics of symmetrical and cambered 11-percent and 6-percent thickness ratio helicopter rotor blade airfoils were determined in a two-dimensional wind tunnel. Several devices designed to improve the aerodynamic characteristics of the cambered 11-percent thickness ratio airfoil were also tested and are discussed in this paper. A mathematical description of lift behavior during dynamic stall, depending only on instantaneous values of angle of attack and pitch rate, was formulated.

75. EFFECT OF GROUND WIND SHEAR ON AIRCRAFT TRAILING VORTICES, Burnham, D. C., AIAA J., Vol 10, No 8, p 1114-15, August 1972.

76. EFFECT OF ROOT CUTOUT ON HOVER PERFORMANCE Cassarino, Sebastian J., United Aircraft Corporation, Sikorsky Aircraft Division, Stratford, Connecticut, AFFDL-TR-70-70, June 1970, AD-711 396.

Tests were conducted to determine the effect of blade root cutout on the hovering performance of a helicopter rotor. The test data revealed a loss in hovering efficiency of 5 to 7 percent for the 50-percent cutout rotor at a typical design thrust coefficient. This result is in agreement with previous calculations made using blade element-momentum theory. The loss in hovering efficiency was highly nonlinear with increasing root cutout, a behavior not predicted by blade element-momentum theory or a prescribed wake hover performance analysis using a standard wake pattern. The flow visualization phase of the investigation showed that the increase in root cutout decreases the radial contraction of the tip vortex. When this result was included in the prescribed wake analysis, the correlation accuracy was improved.

77. THE EFFECT OF WING GEOMETRY AND LOWER SURFACE BOUNDARY LAYER ON THE ROLLED-UP VORTEX, Grow, T. L., M. S. Thesis, Penn. State Univ. 1967.

78. EFFECT OF WING TIP CONFIGURATION OF THE STRENGTH AND POSITION OF A ROLLED-UP VORTEX, Padakannaya, R., Pennsylvania State University, University Park, Pennsylvania (Department of Aerospace Engineering), NASA-CR-66916, NGR-39-009-111, March 1970.
The effect of wing tip configuration on strength and position of rolled-up vortex is discussed.

79. EFFECTS OF DOWNWASH UPON MAN, Schane, William P., Army Aeromedical Research University, Fort Rucker, Alabama, USAARU-68-3, November 1967, AD-662 208.
The threats imposed upon man by helicopter and VTOL downwash are explored. Information is derived from (1) reference material, (2) mathematical calculation, (3) individual data collection, and (4) personal experience. Eight types of threat are explored in some detail, and conclusions are drawn concerning needs for protection.

80. EFFECTS OF MODIFYING A ROTOR TIP VORTEX BY INJECTION ON DOWNWASH VELOCITIES, NOISE AND AIRLOADS, Rinehart, Stephen A., AHS, Vol 16, No 4, October 1971.
The present analytical investigation shows that it should be possible to significantly alter the characteristics of the trailing tip vortex for almost all flight conditions in a beneficial manner by injecting an airstream directly into the forming tip vortex. Analytical expressions were developed for the initial and final states of the vortex in order to evaluate the effects of mass flow injection on the vortex strength, swirl velocity distribution, vortex core pressure, and vortex core size.

81. THE EFFECTS OF NONUNIFORM SWASH-PLATE STIFFNESS ON COUPLED BLADE-CONTROL SYSTEM DYNAMICS AND STABILITY, Piarulli, Vincent J., NASA CR-1817, 1971, Rochester Applied Science Assoc., Inc., New York, Report 70-70.
The results are presented of a study investigating the effects of an anisotropically mounted, flexible swash-plate including blade out-of-track, on the vibratory and mechanical stability characteristics of helicopter rotor systems.

82. AN EMPIRICAL STUDY OF HOVERCRAFT PROPELLER NOISE, Trillo, R. L., Journal of Sound Vibration 6, Vol. 3, No. 3, pp. 476-509, 1966.

83. AN ENGINEERING APPROXIMATION FOR THE AERO-DYNAMIC LOADING OF HELICOPTER ROTOR BLADES, Young, M. I., Boeing Company, Vertol Division, Morton, Pennsylvania, November 1966.
Periodic aerodynamic loading of helicopter rotor blades approximated by principles of potential flow aerodynamics.

84. AN EVALUATION OF METHODS FOR PREDICTING THE PERFORMANCE OF PROPELLERS OPERATING AT ZERO ADVANCE RATIO, Gilmore, David C., McGill University, Mech. Engr. Research Lab., Technical Note 67-2, April 1967, Quebec, Montreal.
Several methods by which the performance of a propeller operating with zero forward speed can be evaluated are reviewed.

85. EXPERIMENTAL BOUNDARY LAYER STUDY ON HOVERING ROTORS, Tanner, W. H. and Yaggy, P. F., 22nd National Forum of the American Helicopter Society, May 1966.

86. EXPERIMENTAL DETERMINATION OF HELICOPTER TIP VORTEX GEOMETRY USING SMOKE, Stoddard, F. S. and Scully, M. P., Massachusetts Institute of Tech, Cambridge Aeroelastic and Structures Research Lab, Cambridge, Massachusetts, Report No. ASRL-TR-142-1, December 1969, AD-699 415.
Experimental techniques were developed and proven to be successful as a means of providing correlation with the analytical treatment required to predict the actual tip vortex geometry of a helicopter rotor.

87. EXPERIMENTAL INVESTIGATION OF EFFECTS OF BLADE SECTION CAMBER AND PLANFORM TAPER ON ROTOR HOVER PERFORMANCE, Bellinger, E. Dean, United Aircraft Corp., East Hartford, Conn., USAAMRDL-TR-4, October 1970/1971, AD-743 232.
An experimental and analytical investigation was conducted to determine the effects of blade section camber and blade planform taper on helicopter rotor hover performance and to assess the accuracy of several theoretical methods in predicting such performance.

88. AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF ROTOR HEAD CONFIGURATION AND FUSELAGE YAW ON THE WAKE CHARACTERISTICS AND ROTOR PERFORMANCE OF A 1/8TH SCALE HELICOPTER, Linville, James C., United Aircraft Corporation, Stratford, Connecticut (Sikorsky Aircraft), USAAVLABS TR-69-94, February 1970, AD-869 390.

The report presents the results of an experimental investigation of the effects of rotor head configuration and fuselage yaw on the wake characteristics and rotor performance of a generalized 1/8th scale helicopter model. Several rotor head configurations were tested with and without rotor blades at various operating conditions. Wake survey data were obtained with and without rotor blades; however, the data obtained with blades were not consistent.

89. AN EXPERIMENTAL INVESTIGATION OF AN OSCILLATING TWO-DIMENSIONAL AIRFOIL IN REVERSE FLOW, Child, Richard F., Vertol Div., The Boeing Company.

90. EXPERIMENTAL INVESTIGATION OF SEVERAL NEUTRALLY-BUOYANT GENERATORS FOR AERODYNAMIC FLOW VISUALIZATION, Hale, R. W., Tan, P., and Ordway, D. E., Sage Action, Inc., Ithaca, New York, June 1971.

A new technique for flow visualization is described, involving the implantation of small bubbles, about 1/8 inch in diameter, in an airflow, and photographing their motion. The technique was used to investigate the problem of the 'tip vortex' from an aircraft wing or helicopter rotor blade.

91. AN EXPERIMENTAL STUDY OF BLADE TIP VORTICES, Piziali, Raymond and Trenka, Andrew, Cornell Aeronautical Lab, January 1970.

An initial experimental investigation was conducted to determine the influence of tip shape on the tip vortex formation and the aerodynamic performance of lifting surfaces representative of typical helicopter rotor blades. The objective was to assess the potential for beneficially altering the generation of the tip-trailing vorticity by proper design of the tip. Some of the results of both visualization techniques are presented and discussed for each tip configuration. An additional sequence of smoke flow photographs which clearly show the details of the tip vortex formation on a square tip is also presented.

92. AN EXPERIMENTAL STUDY OF HELICOPTER ROTOR IMPULSIVE NOISE, Bausch, William E., Munch, Charles L., and Schlegel, Ronald G., United Aircraft Corporation, Sikorsky Aircraft Division, Stratford, Connecticut, Contract USAAVLABS TR-70-72, June 1971, AD-730 359.

Results of a study of helicopter Rotor Impulsive Noise (RIN) are presented. Rotor noise, together with rotor blade dynamic and pressure data, was measured during hover and cruise of a CH-53A helicopter for use in a correlation study of calculated and measured noise. Hover RIN is shown to be due to vortex interference (blade/wake interaction RIN). While cruise RIN is shown to be due to the combination of acoustic effects of a high subsonic tip Mach number on wave propagation and blade drag, and is referred to as advancing blade RIN.

93. AN EXPERIMENTAL STUDY OF ROTOR BLADE VORTEX INTERACTION, Surendraiah, Makam, M. S. Thesis, Dept. of Aerospace Engineering, Penn State University, December 1969, University Park, Pa., NASA-CR-1573.

Results of an experimental investigation of the instantaneous blade airloads and their time derivatives are presented for a rotor blade intersecting a completely rolled-up trailing vortex. Parameters such as the rotor r/min, vortex strength, and intersection angle were examined. Sample photographic records are presented in order to show the influence of the tip vortex on the blade loading.

94. EXPERIMENTAL STUDY OF ROTOR UNSTEADY AIRLOADS DUE TO BLADE VORTEX INTERACTION, Padakannapa, Raghuveera, NASA, CR-1909, November 1971.

Additional measurements of uunsteady, rotor blade airloads and their time derivatives are presented for a rotor blade intersecting a completely rolled-up vortex. Incremental values in section lift coefficient generally decrease with increasing radius.

95. AN EXPERIMENTAL STUDY OF TIP VORTEX MODIFICATION BY MASS FLOW INJECTION, Rinehart, Stephen A., Balcerak, John C., and White, Richard P., Jr., Rochester Applied Science Associates, Inc., New York, Report No. RASA-71-01, January 1971, AD-726 736.

An experimental program was conducted to investigate the modifications of a tip vortex which could be obtained by injecting the core of a tip vortex with a stream of air. Wind tunnel tests of an airfoil model were conducted.

96. EXPERIMENTAL STUDY ON THE UNSTEADY AERODYNAMICS OF A MODEL HELICOPTER ROTOR OPERATING IN THE VORTEX RING STATE, Azuma, A., Koo, J., Oka, T., Washizu, K., Tokyo University, Department of Aeronautics, Tokyo, Japan, 1965.
Unsteady aerodynamic characteristics of model helicopter rotor operating in vortex ring state, are discussed considering thrust and torque fluctuation.

97. EXPERIMENTAL STUDY ON THE UNSTEADY AERODYNAMICS OF A TANDEM ROTOR OPERATING IN THE VORTEX RING STATE, Azuma, A., Koo, J., Oka, T., and Washizu, K., Tokyo University, Department of Aeronautics, Tokyo, Japan 1966.
Unsteady aerodynamics of tandem rotor operating in vortex ring state are described.

98. EXPERIMENTS ON A MODEL HELICOPTER ROTOR OPERATING IN THE VORTEX RING STATE, Azuma, A., Koo, J., Oka, T., and Washizu, K., Tokyo University, Department of Aeronautics, Tokyo, Japan, Jour. of Aircraft Vol 3, No 3, pp. 225-230, June 1966.
See Index No. 96.

99. EXPERIMENTS ON ROTOR WAKE CONTRACTION, Nook, M. and Jones, J. P., University of Southampton, Proceedings 3rd CAL/AVLABS Symposium, Vol III, 18-20 June 1969.

100. EXPLORATORY INVESTIGATION OF FACTORS AFFECTING THE WING TIP VORTEX, Scheiman, J., Shivers, J. P., and Megrail, J. L., NASA, TM X-2516, April 1972.
An investigation was conducted in the Langley full-scale tunnel to study some factors affecting the tip vortex of a wing. It was found that there was a pronounced effect of Reynolds number on the tip vortex core size. An attempt was made to determine what aerodynamic parameters - such as lift, drag, or induced drag - influence the size of the vortex core, but no particular function of the parameters was found to be superior to all others.

101. EXPLORATORY INVESTIGATION OF THE STRUCTURE OF THE TIP VORTEX OF A SEMISPAN WING FOR SEVERAL WING-TIP MODIFICATIONS, Scheiman, James and Shivers, James, P., NASA, TN D-6101, 1971.
Wind tunnel tests were performed on a semispan wing with rather radical wing tip modifications. These modifications were chosen in an attempt to deform, displace, or modify the cross-sectional characteristics of the trailing tip vortex.

102. AN EXTENDED LIFTING LINE THEORY FOR THE LOADS ON A ROTOR BLADE IN THE VICINITY OF A VORTEX, Jones, J. P., Massachusetts Institute of Technology, Cambridge, Mass., TR-123-3, December 1965, AD-636 929.

An extension of the lifting line theory is described based upon the argument that in the vicinity of the vortex the flow pattern will be more like that on a low aspect ratio wing, while still retaining the characteristics of high aspect ratio well away from the vortex. The results of lifting line and modified lifting theory are compared, and it is found that, except when the vortex is very close to the blade, there is little to choose between the results.

103. EXTERNAL NOISE AND DOWNWASH MEASUREMENTS ON THE VOUGHT XC-142A, Hancock, R. N., LTV Aerospace Corporation, Dallas, Texas, 04-02, November 16-18 1970, American Helicopter Society, American Institute of Aero and Astro Joint Conference.

Noise and downwash measurements were made underneath and to one side of the vehicles for a number of hover heights up to an altitude of 200 feet above ground level. Data gathered for both wooded and clear test sites are summarized in this paper. A few of the problems encountered with microphone wind noise and other instrumentation difficulties are briefly discussed.

104. THE FARFIELD STRUCTURE OF AIRCRAFT WAKE TURBULENCE, Mason, W. H. and Marchman, J. F., AIAA, Paper No 72-40, January 1972.

105. FLIGHT MEASUREMENTS OF THE STABILITY AND CONTROL OF A WESTLAND WHIRLWIND HELICOPTER IN VERTICAL DESCENT, Brotherhood, P., Royal Aircraft Establishment, Farnborough, England, Report No. RAE-TR-68021, January 1968, AD-846 511.

Tests have shown that during vertical descent, the response to cyclic and collective pitch differs somewhat from that measured during hovering flight. It is considered that much of the difficulty in control experienced by pilots at medium rates of descent was consistent with flight in a high degree of turbulence which in the vortex ring state of operation is self-induced and due to the unsteady flow at and around the rotor.

106. FLIGHT MEASUREMENTS OF WING-TIP VORTEX MOTION NEAR THE GROUND, Nicholas, O. P. and Dee, F. W., ARC-CP-1065, 1969.

Tests have been made to measure the movement of the wing tip vortices from a Hunter Aircraft flying at 170 knots approximately 35 feet above a runway, in a variety of wind conditions. Measurements were limited to a maximum time of 20 seconds after vortex generation. There was no clear indication as to whether the vortices decayed more rapidly in the presence of the ground and atmospheric turbulence, than would have been expected from earlier measurements away from the ground in calm air.

107. FLIGHT SCIENCES LABORATORY REVIEW, JULY - DECEMBER 1965, Boeing Scientific Research Labs, Seattle, Washington, 1965.

Flight sciences research in areas such as jet impingement, boundary layer control, and hot-wire anemometers.

108. FLIGHT TEST NOISE MEASUREMENTS OF A UH-1B HELICOPTER, Evans, Timothy D. and Nettles, William E., U.S. Army, Aviation Materiel Laboratories, Fort Eustis, Virginia, 1970, (AHS/AIAA and University of Texas, Joint Symposium on Environmental Effects on VTOL Designs, Arlington, Texas, November 1970 Proceedings).

Discussion of some results of a noise measurement test of a UH-1B helicopter conducted with the objective of studing the noise characteristics of this helicopter, with special emphasis on gaining some insight into the various forms in which reduced data can be represented. Several types of data reduction and analysis were investigated. A subjective analysis of the recordings was also performed in an attempt to gain a better understanding of the frequency and sound pressure analyses. In addition, several other problems of common character are discussed and some solutions are suggested.

109. FLIGHT TEST STUDIES OF THE FORMATION OF TRAILING VORTICES AND A METHOD TO ACCELERATE VORTEX DISSIPATION, Chevalier, H., Texas A & M University, College Station, Texas, September 1972.

110. FLOW FIELD MEASUREMENTS FOR A HOVERING ROTOR NEAR THE GROUND, Fradenburgh, E. A., A.H.S., 5th Annual Forum, September 1968.

111. THE FLOW THROUGHOUT A WIND TUNNEL CONTAINING A ROTOR WITH A SHARPLY DEFLECTED WAKE, Heyson, Harry H., NASA, Langley Research Center, Hampton, Virginia, 1969, Cornell Aeronautical Lab. and U.S. Army Aviation Materiel Laboratories, Symposium, 3rd, Buffalo, N.Y., June 1969 Proceedings, Volume 2.

Examination of the flow field throughout a wind tunnel of a rotor with sharply deflected blades, using modified NASA TR R-124 and TR R-302 computer programs. The general nature of the computed flow field is verified by flow studies.

112. FLUID DYNAMICS OF ROTOR AND FAN SUPPORTED AIRCRAFT AT SUBSONIC SPEEDS, Advisory Group for Aerospace Research and Development, Paris, France, Report No. AGARD-CP-22, September 1967, AD-669 226.

The collection of papers emphasizes the following areas: Rotors and fans in hover and transition; interference with the airframe and the ground; ground effects on rotors and fans; and noise problems and testing techniques. The topics are based on low-disc-loading devices.

113. FLUIDIC VORTEX ANGULAR RATE SENSOR CONCEPT INVESTIGATION FOR HELICOPTERS AND V/STOL AIRCRAFT, Wachtell, G. P., Franklin Institute Research Labs, Philadelphia, Pennsylvania, USAAVLABS TR-70-25, April 1970, AD-874 029.

An experimental investigation was undertaken to establish the feasibility of sensor concepts for application in helicopter and V/STOL aircraft stability augmentation systems.

114. FLUIDIC VORTEX VALVE SERVOACTUATOR DEVELOPMENT, Honda, T. S. and Ralbovsky, F. S., General Electric Company, Schenectady, New York, USAAVLABS-TR-69-23, May 1969, AD-859 804.

A fluidic vortex valve servoactuator for UH-1B helicopter stability augmentation system is discussed.

115. THE FLUTTER OF A HELICOPTER ROTOR BLADE IN FORWARD FLIGHT, Stammers, C. W., Ph.D. (Westland Helicopters Ltd., Yeovil) October 1968.

The nature of flapping torsion flutter of a helicopter blade in forward flight is discussed. Two different instability mechanisms can be distinguished and are related to the two energy sources in the system, namely the rotation of the rotor and the forward speed of the helicopter. It is found that forward flight can have a significant stabilizing influence on flutter and that, as the tip speed ratio increases, flutter occurs predominantly at half-integer frequencies. The results are confirmed by the use of a numerical method.

116. FOG FORMATION AND DISPERSAL BY VELOCITY FIELD INDUCED BY HELICOPTER TRAILING VORTICES, Baronti, P. and Elzweig, S., Advanced Technology Labs, Inc., Jericho, New York 1971.

A presenting Dynamic Model With Droplet Depletion, Evaporation and Condensation, fog formation and dispersal by trailing vortices is presented.

117. THE FREE WAKE ANALYSIS - A METHOD FOR THE PREDICTION OF HELICOPTER ROTOR HOVERING PERFORMANCE, Clark, David R. and Leiper, Albert C., United Aircraft Corporation, Sikorsky Aircraft Division, Stratford, Connecticut, AHS Paper 321, May 1969.

Improved method for calculating helicopter hovering performance where the most important step is the calculation of the wake geometry below the rotor using an involved iterative technique. The improved ability to calculate performance using the new technique is demonstrated. The significance of blade wake interference and the influence of blade number is discussed.

118. THE FREE WAKE ANALYSIS - A METHOD FOR THE PREDICTION OF HELICOPTER ROTOR PERFORMANCE, Clark, D. R. and Leiper, A. C., Journal of American Helicopter Society, Paper 15, January 1970.

119. FULL-SCALE HELICOPTER ROTOR NOISE MEASUREMENTS IN AMES 40-by-80-FT. WIND TUNNEL, Cox, C. R., Report 576-099-052, July 1967.

120. THE GROWTH OF A VORTEX IN TURBULENT FLOW,
Squire, H. B., Aeronautical Quarterly,
August 1965.

The growth of a line vortex with time and the spread of a trailing vortex behind a wing due to turbulence are considered. It is shown that the eddy viscosity for this type of motion may be taken to be proportional to the circulation round the vortex and the solution is then similar to the solution for the growth of a vortex in laminar flow. The method is applied to calculate the distance behind a wing at which the trailing vortices will touch one another.

121. HELICOPTER BLADE SLAP, Taylor, F. Webb and
Leverton, John W., Southampton University,
England, June 1966. AD-634 644.

The paper considers a possible mechanism for the generation of blade slap. A simplified theory for this is presented. In particular, it shows that the noise is dependent on the fourth power of the velocity and the square of the gust size (vortex strength). Because of this, highly loaded rotor blades, which produce a strong tip vortex, have a greater penchant toward loud blade slap.

122. HELICOPTER BLADE SLAP,
Leverton, J. W. and Taylor, F. W.,
Journal of Sound Vibration, Vol 4,
No 3 pp 345-357, 1966.

Blade slap appears to be caused by a blade passing through the tip vortex shed by another blade in its proximity. This has been simulated on a rotor whirl stand under controlled conditions, and the effect of various parameters investigated. A theory has been developed to predict the noise generated during a blade slap condition.
There is good correlation between the flight tests, model tests and theory. The paper discusses all aspects of the investigation.

123. HELICOPTER ENGINES AND ROTORS (VOLUME I),
Defense Documentation Center, Alexandria,
Virginia, Report No. DDC-TAS-68-57,
November 1968, AD680 200.

The annotated bibliography is a selection of unclassified and unlimited distribution references on helicopter engines and rotors. Rotor abstracts include descriptions of reports on hubs, blades, materials, hovering, transitional flight, wake characteristics, flight tests, wind tunnel tests, environmental tests, and rotor noise. Tandem rotors, heavy-lift rotors, hot-cycle rotors, rigid rotors, jet-flap rotors shrouded rotors, and tail rotors are represented.

124. HELICOPTER NOISE, Davidson, I. M. and Hargest, T. H., Journal Royal Aeronautics Society, Vol 69, May 1965.

125. HELICOPTER NOISE, Leverton, J. W., Southampton University, Southampton, England, NASA-CR-66335, February 1967.
Tandem-rotor rig, test facilities, and analysis equipment for study of helicopter noise is discussed.

125. HELICOPTER NOISE, Leverton, John W., Southampton University, AGARD CP No. 31 June 1968
The relative importance of several noise sources is discussed with particular reference to the external noise generation of a helicopter.
Rotational noise, vortex noise, and blade slap are reviewed in the light of recent experimental and theoretical investigations.

126. HELICOPTER NOISE DUE TO BLADE-VORTEX INTERACTION, Widnall, Sheila, MIT, Cambridge, Massachusetts, July 1971.
The generation of impulsive sound, or blade slap due to blade-vortex interaction for helicopter rotors is discussed. The unsteady lift on the blades is calculated using linear unsteady aerodynamic theory for an oblique gust model of the blade-vortex interaction. A theoretical model for the radiated sound due to the transient lift fluctuations is presented. Expressions for the directivity, frequency spectrum, transient signal, and the total power of the acoustic signal are derived. Typical results are presented and discussed. Calculations of the transient signal are presented in comparison with recent experimental results. The agreement is very good.

127. HELICOPTER ROTOR NOISE ANALYSIS, Schaeffer, E. G., Boeing Company, Vertol Division, Morton, Pa., Report No. D8-0596, December 1966, AD-684 036.
A preliminary analytical method for predicting whether rotor blade slap will occur is described and correlated with data from tandem rotor helicopters. The operating limits which will cause a single rotor to slap are discussed.

128. HELICOPTER ROTOR NOISE GENERATION, Wright, S. E. and Leverton, J. W., Institute of Sound and Vibration Research University of Southampton, Southampton, Hampshire, England, June 1969.
This paper outlines the recent advances made in the understanding of helicopter rotor noise generation. Full details concerning the investigation are reported in I.S.V.R. Technical Reports No. 5, 13, 14, 15.

129. HELICOPTER ROTOR NOISE GENERATION AND PROPAGATION, Schlegel, Ronald, King, Robert, and Mull, Harold, United Aircraft Corporation, Sikorsky Aircraft Division, Stratford, Connecticut, USAAVLABS TR-66-4, October 1966, AD-645 884.

An improved method is presented for calculating rotor system overall vortex noise and frequency spectra for stalled and unstalled rotors. A new procedure is also derived for calculating near and far field rotor rotational noise with nonuniform inflow. The study was performed for single rotor systems only, and in its present form is not directly applicable to systems with multiple rotors in juxtaposition.

130. HELICOPTER ROTOR NOISE PART 1: THEORETICAL INVESTIGATION OF ROTATIONAL NOISE, Tanna, H. K., Southampton Univ. (England) Inst. of Sound and Vibration Research, March 1969 32 p refs, NASA-CR-66870:

Existing rotational noise theories are surveyed and evaluated by their usefulness in rotor blade design considerations. The presence of fluctuating forces on rotor blades due to nonuniform overflow was found to be the critical factor in rotational noise generation.

131. HELICOPTER ROTOR PERIODIC DIFFERENTIAL PRESSURES AND STRUCTURAL RESPONSE MEASURED IN TRANSIENT AND STEADY-STATE MANEUVERS, Ward, John F., Journal of the American Helicopter Society, Vol. 16, No. 1, January 1971.

This paper summarizes a detailed review and analysis of recorded rotor blade differential pressure and structural load data for five maneuver flight conditions. The paper describes the test aircraft, instrumentation, data reduction technique, and presents a sample of the significant data in time-history form.

132. HELICOPTER ROTOR WASH EFFECTS, Flinn, E. H., Air Force Flight Dynamics Lab., FDCC TM-67-2, 1967.

133. HIGH-SPEED HELICOPTERS AND COMPONENTS IN MANEUVERS AND GUSTS, Drees, J. M. and McGuigan, M. J., Proceeding of the 21st Annual National Helicopter Forum of the American Helicopter Society, May 12-14, 1965.

134. A HOVER PERFORMANCE ANALYSIS COMBINING THE STRIP MOMENTUM AND PRESCRIBED WAKE THEORIES, Rorke, J. B. and Wells C. D., CAL/AAVLABS Symposium, June 1969.

135. THE IMPINGEMENT OF A CIRCULAR JET NORMAL TO A FLAT SURFACE WITH & WITHOUT CROSS FLOW, Colin, P. E. and Olivari, D., Von Kreman Inst. for Fluid Dynamics Technical Report, 1969.
The flow field resulting from a circular jet impinging on a flat surface in a main cross-flowing stream was investigated. The results presented bring out some of the typical characteristics of the flow field investigated. An analysis is proposed to explain and predict some of these characteristics.

136. THE IMPORTANCE OF VORTEX SHEDDING EFFECTS ON HELICOPTER ROTOR NOISE WITH AND WITHOUT BLADE SLAP, Loewy, R. G. and Sadler, S. G., Rochester Applied Science Associates, Inc., Rochester, New York, NASI-7618, June 1969.
Vortex-shedding effects on helicopter rotor noise with and without blade slap, is discussed noting far and near field noise.

137. INDUCED FLOW THROUGH A HELICOPTER ROTOR IN FORWARD FLIGHT, Cook, C. V., Westland Helicopter Ltd Yeovil, Research Paper 374, January 1970.

138. INDUCED FLOW VARIATION OF THE HELICOPTER ROTOR OPERATING IN THE VORTEX RING STATE, Azuma, A. and Obata, A., Journal of Aircraft 5, July - August 1968.
By using small, quickly responsive, and very sensitive windmills we can measure the inflow variation of the model-helcopter rotor operating in the vortex ring state. The wind-tunnel tests show that (1) as the rotor starts to descend vertically, the periodic-induced-flow variation is observed at the rotor tip without any notable thrust change; (2) when the rate of descent approaches the induced velocity generated at hovering state, a thrust reduction appears, this being closely correlated with the increment of the downwash component near the rotor tip induced by a strong vortex ring; (3) as the rate of descent increases beyond the aforementioned induced velocity, the downwash variation becomes predominant near the center of the rotor, and the thrust variation tends to decrease; (4) torque variation is not observable for low collective pitch operation, but for high pitch the torque fluctuates with thrust variation. The preceding final result is explained by the blade element theory with measured inflow.

139. THE INDUCED VELOCITY DISTRIBUTION IN THE LIFTING ROTOR DISK PLANE, Wang, S. C., Northwestern Institute of Technology, Hsien-Yang, Communist China, September 1964.
Induced velocity distribution of helicopter lifting rotor plane is discussed noting dependence on azimuth.

140. IN-FLIGHT MEASUREMENT AND CORRELATION WITH THEORY OF BLADE AIRLOADS AND RESPONSES ON THE XH-51A COMPOUND HELICOPTER ROTOR, (VOLUME III), Sweers, J. E., Lockheed-California Company, Burbank, California, USAAVLABS TR-68-22C, May 1968, AD-674 195.
In most of the conditions analyzed, the computed bending moments were found to be in good agreement with the measured moments. The agreement between computed and measured torsion moments, however, was poor, indicating that improvements are required in the mathematical model as far as the torsional properties are concerned.

141. INFLUENCE OF DIFFERENT PARAMETERS (LIKE JET CONTRACTION, VORTEX CORE DIAMETER) UPON ROTOR DOWNWASH CALCULATION. APPLICATION TO THE CASE OF AN AUXILLIARY WING, Fuhr, J. W., Stuttgart, West Germany, June 1971.
Rotor downwash variation by changing vortice diameter, flapping, rotor speed, and radius and placing infinite span wing in flow field is discussed.

142. THE INFLUENCE OF NEAR-WAKE ASSUMPTIONS ON THE LIFTING CHARACTERISTICS OF A ROTOR BLADE, Woodley, J. G., Royal Aircraft Establishment Technical Report 71046, March 1971.
A study of the interrelation between a simplified wake model and the loading on a rotor blade has been made. For this model the wake is treated as an infinite vortex sheet of simplified shape in quasisteady flow, and an iterative scheme is used to solve the downwash equation of the blade derived from lifting surface theory. Using this model as a basis a comparison has been made of the influence of some nearwake assumptions on the lifting characteristics of a rotor blade.

143. INFLUENCE OF THE TIP VORTEX ON HELICOPTER ROTOR NOISE, Sternfeld, H., Jr., Boeing Company, Vertol Division, Morton, Pennsylvania, 1966.
The differences between slapping and nonslapping signatures and the conditions which result in blade vortex intersections are discussed. Correlation between acoustical signature and the analytical prediciton of vortex interaction is shown. Experimental investigations utilizing smoke visualization techniques are reported and illustrated with photographic sequences, showing the formation of the vortex core structure on a rotor test tower, and the intersection of rotor blades and tip vortices on a tandem rotor helicopter.

144. INFLUENCE OF THE WAKE GEOMETRY ON THE VELOCITY AND LOAD DISTRIBUTION OF VTOL PROPELLERS, Schultheiss, G., Vereinigte Flugtechnische Werke-Fokker G.m.b.H., Munich, West Germany, June 1971.

To determine the velocity and load distribution of VTOL propellers, a method was employed with discrete slipstream vortex stress. Induced angle of incidence, circulation distribution, thrust distribution, and the distribution of the ratios of thrust and power coefficients are compared with the results obtained from the Goldstein method.

145. INVESTIGATION OF THE DISSIPATION OF THE TIP VORTEX OF A ROTOR BLADE BY MASS FLOW INJECTION, White, R. P., Jr. and Balcerak, J. C., RASA Report No. 72-03, 1972.

146. INVESTIGATION OF THE ENVIRONMENT GENERATED BY V/STOL AIRCRAFT OPERATING IN GROUND EFFECT, George, M. and Kieslowski, E., USAAVLABS, TR-68-52, July 1968.

Analytical methods are developed for determining the downwash environment generated by multirotor/propeller V/STOL aircraft configurations operating in ground proximity.

The theoretically predicted results are generally in good agreement with the limited test data. Additional full-scale test data are required to verify further the assumptions inherent in the theory.

147. INVESTIGATION OF HELICOPTER CONTROL LOADS INDUCED BY STALL FLUTTER, Arcidacono, P. J., Carte, F. O., Cosellini, L. M., and Elmon, H. L., USAAVLABS, Tech. Rpt. 70-2, AD. 869823 March 1970.

An analytical study was conducted to determine if available unsteady aerodynamic test data could be used with existing helicopter rotor aeroelastic and variable inflow analyses to predict the stall flutter response of a helicopter rotor blade. In addition, scaling procedures were developed in an attempt to account for the effects of compressibility. A need for further development is indicated.

148. AN INVESTIGATION OF THE MIXING OF LINEAR AND SWIRLING FLOWS, White, R. P., Jr. Balcerak, J. C., RASA Report 72-04, 1972.

A research program was conducted to study in detail the importance of various aerodynamic and geometric parameters on the dissipation of a concentrated trailed vortex in which the dissipation is greatly enhanced by the continuous injection of a mass of air into its core. The efficiency of the optimum system was shown to be almost an order of magnitude better than had been demonstrated previously.

149. AN INVESTIGATION OF NOISE GENERATION ON A HOVERING ROTOR, Sternfeld, H., Spencer, R. H., and Schairer, J. O., Boeing Company, Vertol Division, Philadelphia, Pennsylvania, Report No. AROD 8704:E, January 1971, AD-721 312.
This report presents the results of a program of helicopter rotor noise measurement, using a 60-foot diameter CH-47B three-bladed rotor on the Boeing-Vertol engineering rotor whirl tower.

150. INVESTIGATION AND PREDICTION OF HELICOPTER ROTOR NOISE, Stucky, T. J. and Goddard, J. O., Journal of Sound and Vibration, Vol. 5 No. 1, January 1967.
This report includes noise measurements taken from a three-bladed Wessex rotor of 56 ft diameter, mounted on a rotor whirl tower. The broad-band or "vortex" noise has been found to obey a reasonable relationship with the sixth power of the blade tip velocity and also to be dependent upon $C_L^{1.66}$ (tip-referred lift coefficient).

151. AN INVESTIGATION OF THE QUANTITATIVE APPLICABILITY OF MODEL HELICOPTER ROTOR WAKE PATTERNS OBTAINED FROM A WATER TUNNEL, Landgrebe, Anton J. and Bellinger, Elton D., United Aircraft Corporation, East Hartford, Connecticut, USAAMRDL-TR-71-69, December 1971, AD-739 946.
An analytical investigation was conducted to evaluate quantitative applications of available model rotor tip vortex patterns from a water tunnel. The study included an examination of the sensitivity of water tunnel wake geometry to the water tunnel test parameters which did not duplicate full-scale rotor values and the applicability of a water tunnel wake geometry to determine the airloads of a full-scale rotor. Finally, the possibility of developing simplified wake documentation and generalization procedures and improved water tunnel test techniques was assessed.

152. INVESTIGATION OF ROTOR BLADE TIP-VORTEX AERODYNAMICS, Lewellen, W. S., Massachusetts Institute of Technology, Aeroelastic and Structures Research Lab, Cambridge, Massachusetts, NASA-CR-112009, September 1971.
Aerodynamics of helicopter rotor blade tip vortices are discussed.

153. INVESTIGATION OF THIN AIRFOILS OSCILLATING NEAR STALL, Livia, J., Gray, L., and Davenport, F. J., Boeing Document D8-0925, January 1969.

154. AN INVESTIGATION OF THE TRAILING VORTEX SYSTEM GENERATED BY A JET-FLAPPED WING OPERATING AT HIGH WING LIFT COEFFICIENTS, Schumacher, William J., AHS SW-70-12, November 1970.

Parameters varied during testing included the jet flap angle, angle of attack, aspect ratio, and jet momentum coefficient. Vortex measurements were obtained using a vortex meter which measured the rotational speed of the fluid within the vortex. Values obtained were numerically integrated to yield the tangential velocity and circulation distribution through the vortex. Experimental results indicate that the maximum tangential velocity increases to a maximum and then decreases with continually increasing jet blowing. At high values of jet blowing, the vortex was found to decay rapidly downstream.

155. INVESTIGATION OF THE VORTEX NOISE PRODUCED BY A HELICOPTER ROTOR, Johnson, H. Kevin and Katz, Walter M., Rochester Applied Science Associates Inc., New York, USAAMRDL-TR-72-2, February 1972, AD-741-778.

Karman-street-type vortex shedding from a lifting surface was analyzed as a source of noise from a helicopter rotor in hover and forward flight. The results of the investigation indicated that a vortex noise is the major source of acoustic radiation from a helicopter rotor in hover or low-speed flight and that it is concentrated in the frequency range of 200 to 500 Hz.

156. INVESTIGATION OF THE VORTEX SYSTEM OF A HELICOPTER ROTOR, Kolkov, V. G., Russia, 1970.

A smoke visualization technique is applied to a study of the vortex system of a rotor and the induced velocity field over a wide range of positive and negative angles of attack, flight conditions, and unit loads. Expressions describing the dependence of the configuration of the vortex system on the velocity of the oncoming flow and on the unit load at the rotor are proposed. Vortex system configurations are determined for various modes of rotor operation. The range of applicability of existing vortex models is established.

157. INVESTIGATIONS ON VORTEX FLOWS, Achorya, Y. V. G. and Krishnamurthy, K., National Aeronautical Laboratory (India), TN AS-28-65, September 1965.

A tunnel was designed and fabricated, the salient features of the tunnel being a vertical duct fabricated from perspex for flow visualization, and a cascade of entrance vanes with a mechanical device which can be operated so that all the vanes rotate simultaneously to effect a required incidence. One can obtain a purely axial flow or a helical flow in the tunnel. The report describes the results of flow investigations in the vortex tunnel at 15° vane angle. The investigations in the JHU tunnel are also reported in this note. The results obtained in both tunnels have been compared and the agreement is satisfactory.

158. INVISCID-INCOMPRESSIBLE-FLOW THEORY OF NORMAL AND SLIGHTLY OBLIQUE IMPINGEMENT OF A STATIC ROUND JET ON THE GROUND, Strand, T., Journal of Aircraft, Vol. 4, September-October 1967.

An inviscid-incompressible-flow theory of normal and slightly oblique impingement of a static round jet on the ground is developed and compared with the results of a bench test. The velocity distribution along the ground and across the jet exit, the location of the free stream tube boundary, and thrust ratios at constant power and constant total head are presented as functions of the height of the jet exit above the ground and of the angle of tilt. The agreement between theory and experiment is satisfactory, except at very low height/diameter ratios.

159. INVISCID FLOW FIELD INDUCED BY A ROTOR IN GROUND EFFECT, Greenberg, M. D. and Kaskel, A. L., National Aeronautics and Space Administration CR-1027, May 1968, Therm Advanced Research, Inc., Ithaca, N.Y.

The inviscid flow field induced by a rotor in ground effect is calculated based upon an actuator disk model of the rotor, for the case of a constant circulation distribution over the blade radius. The governing nonlinear integral equations are solved by a systematic iterative scheme which is similar to the Newton-Raphson method for the solution of nonlinear algebraic equation. Numerical results are presented for both the ground-effect case and the out-of-ground effect limit.

160. INVISCID AND VISCOUS MODELS OF THE VORTEX BREAKDOWN PHENOMENON, Bossel, H. K., University of Calif. Berkeley, Report No. AS-67-14. August 1967.

161. IUTAN SYMPOSIUM ON VORTEX MOTION, Kuchemann, D., Journal of Fluid Mechanics, Vol. 21, 1965.

A brief survey of the matters was presented at the symposium on concentrated vortex motions in fluids, involving inertia, pressure, and viscous forces and sometimes buoyancy. The various sections deal with the following: (1) the formation of coherent vortex sheets, as a result of flow separation from solid bodies and their rolling-up, with a discussion of the structure of the rolled-up cores, and of the various possible deviations from smooth cores; (2) the occurrence of columnar vortices in rotating fluid systems, especially in the atmosphere, where the mechanism by which vorticity is generated and concentrated presents major problems; and (3) discussion of vortex wakes behind bodies, where the classical subject of the flow past circular cylinders and Karman vortex sheets plays a prominent part.

162. LEADING EDGE PRESSURE MEASUREMENTS OF
AIRFOIL VORTEX INTERACTION, Walsh, R. G.,
MIT., ASLR, TR 153-1,

Experimental pressure-differential measurements made at 10-percent chord of an airfoil-vortex interaction are presented. Maximum pressure differences were observed to occur in phase across the blade, even with yaw, and were directly proportional to the square of the free stream velocity. The maximum dynamic pressure coefficients obtained were as high as 1.0 when vortex bursting occurred.

163. LIFTING SURFACE THEORY AND TAIL DOWNWASH
CALCULATIONS FOR V/STOL AIRCRAFT IN TRANSITION AND CRUISE, Levinsky, E. S., USAAVLABS,
TR 68-67, October 1968.

A large-tilt-angle lifting-surface theory is developed for tilt-wing and tilt-propeller/rotor V/STOL aircraft. The method is based upon an inclined actuator disc analysis in which closed-form solutions are obtained for the velocity potential at large distances behind the actuator surface. Agreement between theory and experiment is shown to be satisfactory for small slipstream inclination angles. However, insufficient data are available for making a general evaluation of the theory at large angles.

164. LIFTING-SURFACE THEORY FOR V/STOL AIRCRAFT IN
TRANSITION AND CRUISE, PART 1, Levinsky, E. S. and
Thommen, H. U., Journal of Aircraft, November-
December 1969; Part 1, January-February 1970.

This is the first part of a two-part paper in which a large-tilt-angle lifting-surface theory is developed for tilt-wing and tilt-propeller (or rotor) type V/STOL aircraft. Part 1 deals with the development of an inclined actuator disk analysis which forms the basis of the method. Closed form solutions are obtained for the velocity potential at large distances behind the actuator surface.

165. LIFTING-SURFACE THEORY FOR V/STOL AIRCRAFT
INTRANSITION AND CRUISE PART II, Levinsky, E. S.,
Thommen, H. U., Yager, P. M., and Holland, C. H., Air
Vehicle Corporation, California, received December
2, 1968; Revision Received June 4, 1969.

This is the second part of a two-part paper dealing with a large-tilt-angle lifting-surface theory for tilt-wing and tilt-propeller (or rotor) type V/STOL aircraft. Agreement between theory and experiment is shown to be satisfactory for small slipstream inclination angles. Insufficient downwash angle data are currently available for making a general evaluation of the theory at large slipstream angles.

166. LIVING WITH VORTICES, Vickers, Tirey K., The Controller, Vol. 4, pp. 6-13, January 1965.
The purpose of this article is to summarize the most important facts which have been learned about the generation and behavior of trailing vortices.

167. MAIN ROTOR FREE WAKE GEOMETRY EFFECTS ON BLADE AIR LOADS AND RESPONSE FOR HELICOPTERS IN STEADY MANEUVERS. VOLUME 1 - THEORETICAL FORMULATION AND ANALYSIS OF RESULTS, Sadler, S. Gene, Rochester Applied Science Associates, Inc., Rochester, New York, NASA-CR-2110, September 1972.
A mathematical model and computer program was implemented to study the main rotor free wake geometry effects on helicopter rotor blade air loads and response in steady maneuvers. Volume I contains the theoretical formulation and analysis of results. Volume II (NASA-CR-2111) contains the computer program listing.

168. MEAN FLOW STREAMLINES OF A FINITE-BLADED PROPELLER, Hough, G. R. and Ordway, D. E., Journal of Aircraft, Vol. 4, No. 6, November-December 1967.
The purpose of this note is to present the results of calculations of the mean flow streamlines for two distributions of propeller bound-blade circulation. One is a constant, corresponding to the conventional actuator disk model; the other is a simple analytic form, chosen to approximate closely the familiar Goldstein optimum. The calculations are based upon earlier studies of the propeller-induced velocity field.

169. MEASUREMENTS OF THE INSTANTANEOUS VELOCITIES IN THE WAKE OF TWO PROPELLERS OPERATING AT ZERO ADVANCE RATIO, Gilmore, D. C. and Gartshore, I. S., McGill University, Dept. of Engineering, January 1967.

170. MEASUREMENTS OF VELOCITY COMPONENTS IN THE WAKE OF A FULL-SCALE HELICOPTER ROTOR IN HOVER, Boatwright, Donald W., U.S. AAMRDL, TR 72033,
This report presents three-component wake velocity measurements made with a split-film total vector anemometer. The measurements were made in the wake of a full-scale OH-13E helicopter rotor. The results indicated that maximum values of induced velocity in the mean wake exceeded twice the magnitude of momentum values, and that instantaneous values of the vertical velocity component in the vicinity of the vortex trails could be as large as ten

times the momentum value of induced velocity at high thrust coefficients. Velocity distributions across the tip vortices revealed longitudinal components of velocity of the same order of magnitude as the rotational components. Also, tip vortex structure and dissipation characteristics were found to be similar to the vortices shed from fixed-wing aircraft.

171. A METHOD FOR CALCULATING HELICOPTER VORTEX PATHS AND WAKE VELOCITIES, Levinsky, E. S. and Strand, T., Air Vehicle Corporation, San Diego, Calif., AFFDL TR-69-113, July 1970, AD-710 694.

A simple method is developed for calculating the time-averaged velocity field induced at large distances from the rotor by a helicopter in steady horizontal motion. The influence of the ground plane and of horizontal winds on the rotor wake and velocity field is included.

172. METHOD OF CALCULATION OF STREAMLINED ROTORS USED AT NORD-AVIATION, Hirsch, R., Association Technique Maritime Et Aeronautique, Paris, France, 1968.

Streamlined rotors calculation are discussed, interpreting compatibility conditions between streamlining and airscrew stressed.

173. A METHOD OF COMPUTING HELICOPTER VORTEX WAKE DISTORTION, Scully, Michael P., Massachusetts Institute of Tech, Cambridge Aeroelastic and Structures Research Lab, Cambridge, Massachusetts, Report No. ASRL-TR-138-1, June 1967, AD-693 234.

A method for computing the geometry of the tip vortex of a helicopter rotor in steady, forward flight, including the distortion due to the velocities induced by the vortex wake, was developed. The relative importance of various parameters and approximations used by this method was evaluated for one test case, including comparison with experimental results obtained from a flow visualization study.

174. A METHOD FOR PREDICTING THE AERODYNAMIC LOADS AND DYNAMIC RESPONSE OF ROTOR BLADES, Piziali, R. A., USAAVLABS Technical Report 65-74, U.S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, January 1966.

A method for predicting the aerodynamic loads and the flapwise bending moments experienced by the blades of a rotor in steady translational flight has been developed. The lift loadings and bending moments were computed for two flight conditions of the H-34 and the HU-1A rotors. Comparisons of these results with measured results are presented as time-histories and radial distributions of the harmonic components.

175. A METHOD FOR PREDICTING THE AERODYNAMIC LOADS AND DYNAMIC RESPONSE OF THE ROTOR BLADES OF A TANDEM-ROTOR HELICOPTER, Balcerak, John C., Cornell Aeronautical Lab, Inc., Buffalo, New York, USAAVLABS TR-67-38, June 1967, AD-656 755.
The blades of each rotor are represented by segmented lifting lines located at the quarterchord positions of the blades, and the vortex strength is assumed to be constant over each segment of the blade at each of an arbitrary number of azimuth positions. The wake is represented by a mesh of shed and trailing vortex filaments up to an arbitrary finite distance behind each blade, and beyond this point, the wake is represented by a segmented, tip-trailing vortex or by segmented, tip- and root-trailing vortices.

176. A METHOD FOR PREDICTING HELICOPTER WAKE GEOMETRY WAKE-INDUCED FLOW AND WAKE EFFECTS ON BLADE AIRLOADS, Sadler, S. G., Rochester Applied Science Associates, Inc., Rochester, New York, NASI-8448, May 1971.
Wake model and computer program to compute geometries, flows and velocity influence coefficients for helicopter blade load calculations are discussed.

177. A METHOD FOR PREDICTING THE TRIM CONSTANTS AND THE ROTOR-BLADE LOADINGS AND RESPONSES OF A SINGLE-ROTOR HELICOPTER, Chang, T. T., Cornell Aero Labs, USAAVLABS Tech. Report 67-71, November 1967, AD-666 802.
The present effort was undertaken to extend the previously developed method by (1) including the blade inplane and torsional motions, and (2) treating the four trim constants (namely, the blade pitch-control settings and the rotor-shaft tilt angle) as unknowns. The equilibrium conditions are called the trim equations and are derived in this report, taking into account the inertial forces of the blades due to elastic deformations. Lagrange's equations for the blade motions are given.

178. METHOD FOR SOLUTION OF THE AEROELASTIC RESPONSE PROBLEM FOR ROTATING WINGS, Piziali, R. A., Proceedings of the Symposium on the Noise and Loading Actions on Helicopters, V/STOL Aircraft and Ground Effect Machines, University of Southampton, England, September 1965.
This report presents a numerical method for solving the aeroelastic response problem of rotating wings in steady-state flight (hovering or translating), employing high-speed digital computation. The report includes equations of motion for the blade flapping and flapwise bending degrees of freedom. Results of computations to investigate the sensitivity of the computed airloads and bending moments to variations in some of the wake configuration parameters are also presented and discussed.

179. MODEL AND FULL SCALE COMPOUND HELICOPTER RESEARCH, Fradenburgh, E. A., and Segel, R. M., Paper presented before the American Helicopter Society 21st Annual National Forum, May 1965.

180. MODEL STUDIES OF HELICOPTER ROTOR FLOW PATTERNS, Lehman, August F., Oceanics, Inc., Plainview, New York, Report No. USAAVLABS TR-68-17, April 1968, AD-671-670.
The report discusses an experimental program undertaken in a water tunnel wherein the tip vortex patterns were made visible through air bubble injection at the rotor tips. Discrete tip vortex patterns are created for forward flight regimes in the general ranges of hover to 10 knots, 10 to 50 knots, and above 50 knots.

181. MODEL STUDIES OF HELICOPTER ROTOR FLOW PATTERNS IN A WATER TUNNEL, Lehman, August F., Oceanics Inc., Head-Water Tunnel Division, Plainview, New York, AHS, Annual National Forum, 24th, Paper 207. Washington, D.C., May 1968.
Description of an experimental program undertaken in a water tunnel to observe and document the tip-vortex patterns created by a model helicopter rotor in an initial effort to clarify at least part of the physical characteristics of the rotor-wake geometry. The tip-vortex patterns were made visible by emitting air bubbles from the rotor tips. Different aspects of the tip-vortex patterns were visible from 2 to 6 rotor diameters downstream. Very good lift-value-coefficient agreement between the model and the full-scale vehicle was obtained.

182. MODEL STUDIES OF HELICOPTER TAIL ROTOR FLOW PATTERNS IN AND OUT OF GROUND EFFECT, Lehman, August F., Oceanics Inc., Plainview, New York, Report No. 70-79, USAAVLABS TR-71-12, April 1971, AD-725 591.
Water tunnel studies of a model helicopter which entailed a visualization of the main and tail rotor wakes, the inflow patterns, and their subsequent interactions as the wind velocity and wind reading were changed are presented. Of significant interest was the impingement of the main rotor wake with a ground plane.

183. MOTION AND DECAY OF A VORTEX RING, Tung, C. and Ting, L., Physics of Fluids, Vol. 10, No. 5 pp. 901-910, May 1967.

In classical inviscid theory of the vortex ring, the velocity at a point near the vortex ring becomes singular due to terms of r^{-1} and logarithm r, where r is the shortest distance from the point to the vortex ring; by means of systematic matching, singularities of r^{-1} and logarithm r in classical inviscid theory are removed; from the analysis, the effective radius of the cross section of the vortex ring is found.

184. THE MOVEMENT, STRUCTURE AND BREAKDOWN OF TRAILING VORTICES FROM A ROTOR BLADE, Simons, I. A., Pacifico, R. E., and Jones, J. P., Aeronautical Research Council, London, England, Report No. ARC28993, April 1967, AD-687 168.

The results of some flow visualization experiments on the trailing vortices from a model rotor blade are presented. It is found that, at low tip-speed ratios, trailing vortices close to the leading edge of the disc first pass up through the disc before entering the main flow field. At the rear of the disc, the vortices maintain a regular pattern relative to each other. The vortices are fully rolled-up in about 60° of azimuth movement of the blade. Measurements with a hot-wire anemometer show that the vortex core is about one-tenth of a blade chord in diameter, which is consistent with a laminar core state. Outside the core, the velocity field is irrotational.

185. THE MOVEMENT, STRUCTURE AND BREAKDOWN OF TRAILING VORTICES FROM A ROTOR BLADE, Simons, I. A., Pacifico, R. E., and Jones, J. R., Proceedings, CAL/USAAVLABS Symposium on Aerodynamic Problems Associated with V/STOL Aircraft, Vol. I, Technical Session 2, Cornell Aeronautical Laboratory, Inc., Buffalo New York, June 1966.

186. NASA AIRCRAFT TRAILING VORTEX RESEARCH, McGowan, William A., Federal Aviation Administration, Symposium on Turbulence, Washington, D.C., March 1971.

Wind tunnel experiments are used to develop the detailed processes of wing tip vortex formation and explore different means to either prevent trailing vortices from forming or induce early break up.

187. THE NATURE OF LIMITATIONS IMPOSED ON THE PERFORMANCE OF A HELICOPTER ROTOR, Harrison, J. M. and Ollerhead, J. B., Journal of Sound Vibration, Vol. 3(3), 1966.

A systematic theoretical approach to the investigation of helicopter rotor performance limitations is outlined. The essence of the method is a digital computer programme devised to solve the equations of motion of a typical articulated blade, part of a rotor system in a state of steady flight. The main programme and the next in order of importance, computing downwash in the rotor disc plane from a knowledge of blade loading and wake geometry, are described in some detail along with their mathematical models. Detailed discussion is restricted to downwash distribution and its effects, first upon blade-bending stresses. An interpretation of the mechanism modifying power requirements follows, and is combined with further description of an attempt to reconcile blade loading and downwash distribution in a consistent blade motion solution. It is shown how, by linking four programmes in a closed loop, rapid progress is made towards convergence.

188. THE NEMESIS OF THE TRAILED TIP VORTEX - IS IT NOW CONQUERED, White, R. P., Jr., and Balcerak, J. C., Rochester Applied Science Associated, Inc., Rochester, New York, May 1972.

A recent experimental research program was conducted in which the outer section of an UH-1D helicopter blade was modified to incorporate a system for injecting the tip vortex produced by the blade with a mass of linearly-directed air. The effects of nozzle geometry, the velocity of injection, the turbulence wavelength, and the angle of injection on the resulting strength of the trailed tip vortex are presented in terms of quantitative measurements of the circulation strength as a function of the injected mass of air. Data obtained from flow-visualization studies in which illuminated helium bubbles, smoke, and tuft grids were used are also presented.

189. NOISE SURVEY: A TURBOSHAFT POWER PLANT COUPLED TO A MOBILE TEST BED, Stong, R. A., Defense Research Establishment, Toronto, Downsview, Ontario, Report No. DRET-TM-788, March 1971, AD-887 957.

Measurements were made of the overall sound pressure levels and spectra of the noise generated by a turboshaft powerplant coupled to a mobile engine test trailer and operated outdoors.

190. A NOTE ON THE MEAN VALUE OF INDUCED VELOCITY FOR A HELICOPTER ROTOR, Heyson, H. H., NASA TN-D-240, 1966.
A theoretical study shows the exact equivalence of momentum and vortex theory in the determination of the induced velocity at the rotor regardless of whether terms involving the sine of the azimuth angle are included in the blade circulation. It is shown that erroneous results may be incurred by failure to utilize a consistent set of assumptions in formulating the vortex-theory analysis. In particular, if the lateral dissymmetry on the rotor is represented by blade circulation which varies as the sine of the azimuth angle, it is necessary to include the effect of the axial wake vorticity.

191. A NOTE ON A PHENOMENON AFFECTING HELICOPTER DIRECTIONAL CONTROL IN REARWARD FLIGHT, Huston, R. J. and Morris, C. E., NASA, Langley Research Center Hampton, Virginia, October 1970.
Main rotor wake adverse effects on tail rotor directional control in low velocity wing are discussed.

192. A NOTE ON THE USE OF DIGITAL COMPUTERS IN ROTOR PERFORMANCE AND VIBRATION CALCULATION, Jones, J. P., Westland Helicopter Ltd. Veovil, ARC 31210 Comp(FM) 179, 1969.

193. A NUMERICAL METHOD FOR SOLVING THE EQUATIONS FOR A VORTEX CORE, Hall, M. G., Aeronautical Research Center, R & M No. 3467, TR 65106, May 1965.
A method is presented for calculating steady, axially symmetric, spiralling motions of an incompressible fluid at large Reynolds numbers. By making approximations of the boundary-layer type the Navier-Stokes equations are reduced essentially to a pair of nonlinear parabolic equations. The calculation is by a marching technique which proceeds step-by-step in the axial direction. A programme is developed for a digital computer of moderate size and examples of the application of the method are given.

194. A NUMERICAL SOLUTION OF THE UNSTEADY AIRFOIL WITH APPLICATION TO THE VORTEX INTERACTION PROBLEM, Rudhman, Wylie E., M. S. Thesis, Department of Aerospace Engineering, Penn State University, NASA-CR-111843, December 1970.
A numerical method to predict the aerodynamic forces acting on a thin airfoil operating in an unsteady potential flow is developed. The time dependent solution including wake generation is obtained starting with the system at rest. A rigid wake assumption is used where the wake vortices lie in the direction of the chord line and move with the free stream velocity. The

results of the numerical solution are shown to agree with results using the classic theories of Theodorsen for the oscillating airfoil and of Wagner for the impulsively started airfoil. Using the numerical method, a parametric study is conducted to determine the time history of the loads on an airfoil produced by a vortex passing in proximity to the airfoil. Results of the study are compared to an experimental investigation of the rotor blade-vortex interaction problem.

195. A NUMERICAL STUDY OF THE FLUCTUATING FLOW FIELD OF A UNIFORMLY LOADED PROPELLER, Hough, G. R., Journal of Aircraft, Vol. 4 No. 1, January - February 1967.

A simple method has been developed for calculating the flow-field of a finite-bladed propeller in the forward flight regime. This method is based upon classical propeller vortex theory and the Fourier analysis of the resulting induced velocities. The total inflow at the propeller blades has also been calculated and correlated with the known analytical results for the steady inflow at the propeller plane.

196. OBSERVATION OF A MECHANISM, CAUSING A TRAILING CONTRAIL VORTEX TO BREAK UP, Harvey, J. K., and Fackrell, J. E., Imperial College, London, Aero Report 70-08, 1970.

Simple flow visualization experiments have been performed to identify a new form of vortex breakdown which is characterized by the disturbance appearing somewhere near the edge of the core and not on the vortex center line. There is a marked similarity between the disc observed and those seen in condensation trails.

197. OBSERVATIONS OF THREE-DIMENSIONAL FLOW PATTERNS OBTAINED DURING STALL DEVELOPMENT ON AEROFOILS, AND ON THE PROBLEM OF MEASURING TWO-DIMENSIONAL CHARACTERISTICS, Gregory, N., Quincey, V. G., O'Reilly, C. L., and Hall, D. J., Aeronautical Research Council, London, England, Report No. ARC-CP-1146, January 1970, AD-887 323.

Surface oil-flow patterns were used at low speeds on both thick and thin aerofoils to show the onset of three-dimensionality separation or reattachment when there is an appreciable extent of the separated flow that accompanies the development of the stall. Observations on a thick aerofoil in compressible flow showed a similar trend in the reattachment behind a shock-induced separation.

198. ON THE COMPUTATION OF HELICOPTER ROTOR WAKE GEOMETRY, Scully, M. P., Massachusetts Institute of Tech., Cambridge Aeroelastic and Structures Research Lab, Cambridge, Massachusetts, Report No. ASRL-TR-145-2, December 1968, AD-702 768.

A new technique is described whereby the rotor tip vortex geometry may be calculated.

199. ON THE COMPUTATION OF HELICOPTER ROTOR WAKE GEOMETRY, Scully, M. P., Massachusetts Institute of Tech., Cambridge Aeroelastic and Structures Research Lab, Cambridge, Massachusetts, Report No. ASRL-TR-150-2, December 1968, AD-702 774.

The tip vortex, because of its concentration, is best represented by a vortex line, with a finite vortex core where viscous effects dominate, and is responsible for the sharp peaks in the rotor airloads distribution. Thus, accurate geometry is much more important for the tip vortex than for the rest of the wake and effort has been concentrated on the accurate and efficient computation of the tip vortex geometry.

200. ON THE DYNAMIC STABILITY OF CONVECTIVE ATMOSPHERIC VORTICES, Bergman, Kenneth Harris, (Ph.D. Thesis), Washington University, Department of Atmospheric Sciences, Seattle, Washington, February 1970, AD-705 667.

Some characteristics of convective atmospheric vortices, with special reference to dust devils, are first discussed, and the presence of certain phenomena indicating dynamic instability is indicated. Theoretical models of steady vortex flow are then reviewed, and observational evidence for a two-cell structure with reversed axial flow in convective atmospheric vortices is presented. Solutions, obtained by numerical methods, of the dynamic stability problem formulated are presented and discussed. The theoretical results are compared with available visual observations, and a discussion of possible implications of dynamic instability and dissipation is given.

201. ON THE FEASIBILITY OF REPLACING A HELICOPTER TAIL ROTOR, Sowyrda, A., Cornell Aeronautical Lab, Inc., Buffalo, New York, Report No. CAL-BB-2584-S-1, July 1968, AD-677 642.

The feasibility of replacing the tail rotor of a simple helicopter by using fixed aerodynamic surfaces immersed in the rotor wake is examined analytically. The major requirements surfaces would be to balance the main rotor drive torque, as well as furnishing control moments.

202. PARAMETERS GOVERNING THE GENERATION OF FREE VORTICES, Dergarobedion, Paul, and Fendell, Frances, "The Physics of Fluids", Vol 10, No 11, November 1967.
An asymptotic expansion of the Navier-Stokes equations is proposed which provides a new basis for previously stated free-vortex equations. Two main parameters emerge from the description of vortex generation. One is a conventional Ekman number, and the other indicates that unless the product of the area of the updraft and the average vertical gradient of the vertical velocity greatly exceeds the kinematic viscosity coefficient, no localized vortical flow develops. It is proposed that the analysis (although laminar) may suggest the counterforces basic to the generation concentrated geophysical vortices: a vertical updraft induces a radial inflow, which may concentrate ambient angular momentum into a vortex unless turbulent viscous forces counteract the intersification.

203. PARAMETRIC STUDIES OF ROTOR DOWNWASH CALCULATION. INFLUENCE ON FIXED WING FLOW, Bergmann, H.. and Fuhr, J. W., Stuttgart, West Germany, DLR-FB-70-62, December 1970.
Rotary wing downwash influence on fixed wing flow using magnetic induction vortex model is discussed.

204. THE PERFORMANCE OF PROPELLERS OPERATING AT ZERO ADVANCED RATIO, Gilmore, David, C. (M.S. Thesis) September 1967.
The thesis is concerned with methods of predicting the performance of air propellers operating at zero advance ratio. Measurements from two such propellers, often called static thrust propellers, are used as a basis for evaluating the following performance prediction methods: the modified Lock-Goldstein method and the Gartshore-Gray method.

205. PERIODIC AERODYNAMIC LOADINGS, THE PROBLEMS - WHAT IS BEING DONE AND WHAT NEEDS TO BE DONE, White, R. P., Proceedings - Symposium on Noise and Loading Action on Helicopter V/STOL Altitude Ground Effect Machines, University of Southampton England, September 1965.

206. PHENOMENON OF VORTEX FORMATION ASSOCIATED WITH THE OBLIQUE FLOW PAST A ROTOR, Larin, A. V., Russia, 1970.
The structure and shape of the vortex wake behind ,a multiblade-hinged rotor in oblique flow is studied by the cavitation method for various flight loads and various flow conditions at the rotor. The results are analyzed and are illustrated by photographs and sketches. A new effect is observed which consists in the transformation of the outer cycloidal segments of trailing vortices into vortex filaments consisting of several helical loops.

207. PLANNING OF ARMY AVIATION FACILITIES,
Dept. of the Army Tech. Manual, Headquarters,
Dept. of the Army TM 5-803-4, March 1970.

This manual presents the general provisions, criteria and policy for guidance in planning, designing and construction programming of permanent U.S. Army airfields, heliports and related aviation facilities.

208. PREDICTION OF FAR FLOW FIELD IN TRAILING VORTICES, Baldwin, B. S., Chigier, N. A., NASA Ames Research Center, Moffett Field, California, and Sheaffer, Y. S., Sheffield University, Sheffield, England, September 1972.

A finite-difference machine code is brought to bear on the wake vortex problem in the quasi-cylindrical boundary-layer approximation. A turbulent-energy model containing new features is developed. Parameters of the model are evaluated by comparison of calculated velocities and turbulent intensities with measurements in an axisymmetric wake. Comparisons are made with a previous calculation of the decay of an isolated vortex and with wind tunnel and flight measurements in trailing vortices.

209. PREDICTION METHODS AND TRENDS FOR HELICOPTER ROTOR NOISE, King, Robert, J. and Schlegel, Ronald G., Sikorsky Aircraft, Div. of United Aircraft Corporation, 1969.

Rotational noise and vortex noise are treated separately in this paper. Vortex noise, and its relationship to rotational noise is discussed briefly and current emperical prediction methods are presented. Theoretically derived and empirically substantiated trend studies are presented for both rotational and vortex noise in terms of the basic parameters of tip speed, thrust, blade area, diameter and number of blades. Finally, some examples of rotor noise trending application to both detection and annoyance situations are discussed.

210. PREDICTION OF THE PERFORMANCE AND STRESS CHARACTERISTICS OF VTOL PROPELLERS, Trenka, A. R., CAL/USAAVLABS Symposium Proceedings, Vol. I, June 1966.

211. PREDICTION OF ROTOR INSTABILITY AT HIGH FORWARD SPEEDS, VOL. I, STEADY FLIGHT DIFFERENTIAL EQUATIONS OF MOTION FOR A FLEXIBLE HELICOPTER BLADE WITH CHORDWISE MASS UNBALANCE, Arcidiacond, P. J., USAAVLABS, TR 68-18A, February 1969.

The differential equations of motion for a linearly twisted rotor blade having chordwise mass unbalance and operating under steady flight conditions are derived. The differential equations of motion are expanded in terms of the uncoupled vibratory modes of the blade in order to facilitate their numerical solution on a digital computer.

212. PREDICTION OF ROTOR WAKE FLOWS, Crimi, P., Proceedings, CAL/USAAVLABS Symposium on Aerodynamic Problems Associated with V/STOL Aircraft, Vol. I, Technical Session 2, Cornell Aeronautical Laboratory, Inc., Buffalo, New York, June 1966.

213. A PRELIMINARY EXPERIMENTAL INVESTIGATION OF THE STRUCTURE OF A TURBULENT TRAILING VORTEX, Poppleton, E. D., TN 71-1 Mech. Engineering Research Laboratory, March 1971.
Measurements have been made of the distribution of the Reynolds stresses and of the mean velocity in a turbulent trailing vortex. The pressure distribution was also measured. The effect of injecting air into the vortex core has also been investigated and it was found that the decay of the vortex can be accelerated considerably by this means.

214. PRELIMINARY FLIGHT TEST DATA UH-1B HIGH PERFORMANCE HELICOPTER, Army Transportation Research Command, Fort Eustis, Virginia, November 1964, AD-627 133.
This report presents the results of flight investigations conducted in association with the primary flight test investigation of the high-performance UH-1 helicopter. Results reported include main rotor blades with inboard trailing edge flaps, a two-bladed flex beam rotor, and tapered tip main rotor blades.

215. THE PRESCRIBED WAKE-MOMENTUM ANALYSIS, A HOVER PERFORMANCE ANALYSIS COMBINING THE STRIP-MOMENTUM AND PRESCRIBED WAKE THEORIES, Rorke, James B. and Wells, Clifford D., Sikorsky Aircraft, Division of United Aircraft Corporation, June 1969. Cornell Aeronautical Lab. and U.S. Army Aviation Materiel Laboratories, Symposium, 3rd, Buffalo, N.Y., Proceedings, Volume 1, June 1969.
The Sikorsky Prescribed Wake Momentum Analysis was developed as a practical, rapid method of rotor static performance calculation which includes the effects of the near wake's interference on the rotor inflow distribution. The method involves a simple extension of conventional strip-momentum theory to include the effects of the near wake vortex system. The wake structure prescribed in the analysis was determined empirically from detailed analysis of model rotor smoke studies and full-scale vapor trails, and analytically from the Sikorsky Free Wake Analysis.

216. A PRESENTATION OF MEASURED AND CALCULATED FULL-SCALE ROTOR BLADE AERODYNAMIC AND STRUCTURAL LOADS, Rabbott, J. P., Lizak, A. A., and Paglino, V. M., USAAVLABS Tech. Report 66-31, July 1966.

A test of a set of Sikorsky CH-34 rotor blades was conducted in the NASA/Ames full-scale wind tunnel at speeds of 110 to 175 knots. The test results are presented, two- and three-dimensional pressure distributions are compared, and a correlation of airloads and blade stresses is made with a flexible blade aeroelastic theory, including both uniform and variable inflow assumptions. The results were generally good. However, the need for a more precise wake treatment is indicated.

A comparison of some of the wind tunnel data with flight test results shows good agreement.

217. PROBLEMS OF HELICOPTER NOISE ESTIMATION AND REDUCTION, Lawson, M. V. and Ollerhead, J. B., AIAA paper 69-195, February 1969.

The general problem of helicopter rotor noise generation, propagation, and reception is reviewed in the light of recent theoretical work. Prediction methods are described, and in several comparisons of theoretical and experimental results good agreement is found. These methods have been programmed for computer solution, and a parameter study is presented which demonstrates the effects of the significant variables on the aural detection of rotor noise.

218. PROPELLER WAKE DEFORMATION DUE TO INSTABILITY OF A TRAILING VORTEX SHEET, Cummings, D. E. and Kerwin, J. E., Dept. of Naval Architecture and Marine Engineering.

1. This report demonstrates nature and effect of propeller vortex sheet deformation for wide-blade propellers at finite advance speeds; 2. Develops a method for determining the geometry of deformed trailing vortex sheets including a finite-core representation of the tip vortex; 3. Investigates the effect of wake deformation and computed blade section pitch and camber; and 4. Comparative effect of several wake approximations an blade section geometry is shown for a specific example.

219. A REASSESSMENT OF ROTOR HOVERING PERFORMANCE PREDICTION METHODS, Jenney, David S., Olson, John R., and Landgrebe, Anton J., Journal of the American Helicopter Society, Vol. 13, No. 2, April 1968.

In this paper the predictions of several methods are compared with representative full scale test data. A method for considering the effects of flow contraction on hovering performance is presented. It is shown that including this effect promises to provide improved accuracy in the prediction of hover performance.

220. RECENT EXPERIMENTS ON WAVE VORTEX BEHAVIOR OF A HOVERING HELICOPTER ROTOR, Child, R. Boeing/AFOSR Symposium on Aircraft Wake Turbulence, September 1970.

221. RECIRCULATORY FLOW VISUALIZATION IN HELICOPTER FLIGHT MODES, Nelson, Arthur William, III, Naval Postgraduate School, Monterey, California, September 1971, AD-734 873.
The classical working states of the airscrew were studied employing the three-dimensional flow visualization tunnel at the Naval Postgraduate School, Monterey, California. Using a feasible distribution ascertained from the flow visualization, the induced velocity distribution was calculated for several points in the vortex ring state.

222. REMOTE DETECTION OF TURBULENCE IN CLEAR AIR, McGowan, William A., AIAA Air Transportation Conference, June 1971.
Various concepts were reviewed for remote detection of turbulance in clear air. The conclusion was that there is no technique now available for operational use.

223. REPRESENTATION OF PROPELLER WAKES BY SYSTEMS OF FINITE CORE VORTICES, Brady, W. G. and Crimi, P., Cornell Aero Lab, Inc., CAL Report BB-1665-S-2, February 1965, AD-612 007.
This report discusses the development of a propeller wake model and computational procedure aimed at the determination of the spatial distribution of wake vorticity and the associated induced velocity distribution. In a model proposed for the wake flow of a rotor in steady forward flight, the tip vortices are represented by continuous finite-core vortices. For purposes of numerical calculation, the continuous vortex is approximated by short straight-line segments.

224. RESULTS OF TRAILING VORTEX STUDIES IN A TOWING TANK, Olsen, John H., Document DI - 82-4004, Boeing Scientific Research Labs, September 1970.
Flow visualization studies were performed in a towing tank using an electrochemically activated dye. Type types of instability were observed in the tank: an instability associated with the axial flow within the core was observed to destroy the flow in the neighborhood of the core without destroying the motion far from the core; a second instability involving the mutual interaction of the two vortices was observed but somewhat masked by the first instability.

225. REVIEW OF THE VORTEX WAKE ROLL UP PROBLEM, McMahon, T. A., MIT, ASRL-TR-145-1, June 1967.

226. ROTOR BLADE BOUNDARY LAYER CALCULATION PROGRAMS, Clark, David R. and Arnoldi, Douglas R., United Aircraft Corporation, Sikorsky Aircraft Division, Stratford, Connecticut, USAAVLABS TR-71-1, March 1971, AD-723 989.

The development of the turbulent compressible boundary layer on two typical helicopter rotors, for a range of hover conditions, has been calculated using two different analytical methods: The differential method, which uses the differential form of the boundary layer momentum equations and solves for the local velocity gradients, and the integral method, which uses the integrated form of the momentum equations and solves for the development of the characteristic boundary layer thickness parameters and skew angle.

227. ROTOR FLOW AND FLIGHT MECHANICS OF HINGELESS ROTORS, Deutsch Gesellschaft Fuer Luft - Und Raumfahrt, Stuttgart, West Germany, DLR-MITT-71-12, June 1971.

Rotor and propeller wake calculation, recovery rotors and rotor feedback control are discussed.

228. ROTOR INDUCED FLOW FIELDS IN GROUND EFFECT IN THE VICINITY OF A VERTICAL STEP, Migliore, Paul G., West Virginia University, Department of Aerospace Engineering, Morgantown, West Virginia, Report No. TR-12, January 1969, AD-683 792.

This analysis devises means of theoretically predicting the flow fields induced by hovering rotors in ground effect and influenced by the proximity of a vertical step. A two-dimensional investigation is performed. Results appear to be qualitatively accurate within the confines of the wake cylinder and in areas very close to the wake boundaries.

229. ROTOR INDUCED VELOCITIES IN FORWARD FLIGHT BY MOMENTUM THEORY, Wood, E. R. and Hermes, M. E., AIAA/AHS STOL Meeting, AIAA Paper 69-224, Georgia Inst. of Tech., Atlanta, Ga. February 1969.

A method is developed based upon momentum theory for obtaining the induced flow field of a helicopter rotor in forward flight. The method has been programmed for the UNIVAC 1108 computer. The combined blade element-momentum theory is modified to include cyclic pitch and tilt of the rotor. Induced

velocity values are determined for a reference coordinate system which defines the cycloidal path of the rotor blade in forward flight. The total induced velocities are then obtained by superposition of values for individual blades following an exponential time relationship.

230. ROTOR NOISE MEASUREMENTS IN WIND TUNNELS, paper to be presented at Third CAL/AVLABS Symposium, "Aerodynamics of Rotary Wing and V/STOL Aircraft", Cox, C. R., Bell Helicopter Company, June 1969.

231. ROTOR PERFORMANCE IN HOVER, Cook, C. V., Westland Helicopter Ltd., Yeovil Research Paper 357, November 1968.

232. ROTARY WING BOUNDARY LAYER AND RELATED RESEARCHES, Tanner, W. H., Bell Helicopter Company, Fort Worth, Texas, September 1967.
Boundary layer, forming tip vortex, and stall of hovering rotors are discussed.

233. A ROUTINE METHOD FOR THE CALCULATION OF AERODYNAMIC LOADS ON A WING IN THE VICINITY OF INFINITE VORTICES, Kfoury, D. J., M.I.T. Aeroelastic and Structure, Laboratory Report, TR 133-2, May 1966.
The vortex lattice method for the calculation of loads on a wing advancing in a uniform stream was extended to the case of a wing in the vicinity of infinite vortices. The results in the report were limited to checking their convergence with respect to the three parameters involved and investigating what conditions them.

234. A SOLUTION TO THE VORTEX BREAKDOWN PHENOMENON IN A TRAILING LINE VORTEX, Logan, A. H., M. S. Thesis, Dept of Aerospace Engeneering, Penn State University, December 1966.

235. SOME ASPECTS OF BLADE/VORTEX INTERACTION ON HELICOPTER ROTORS IN FORWARD FLIGHT, Simons, I. A., Southampton University, Institute of Sound and Vibration Research, Southampton, England, November 1966.
Vortex-rotor disk interaction effect on helicopter rotor performance in forward flight is discussed.

236. SOME CONSIDERATIONS ON THE EFFECT OF THE SLIPSTREAM OF VTOL AIRCRAFT, Stickle, George W., Tactical Air Command, Langley Air Force Base, Virginia Office of Operations Analysis, Report No. TAC-OA-WP-133, March 1967, AD-842 236L

237. SOME DEVELOPMENTS IN THE THEORY OF VORTEX BREAKDOWN, Benjamin, T. B., Journal of Fluid Mech., Vol 28 p.65-84, 1967.

238. SOME EFFECTS OF INTERFERENCE OF THREE-DIMENSIONAL BODIES ON THE WAKE GEOMETRY OF A HOVERING ROTOR, Boatwright, Donald W., Lovette, George H. and Clingan, Jerry, Mississippi State University, State College, Mississippi, AIAA Paper 69-228, February 1969.
Results of a flow visualization study of wake deformation due to the presence of vertical and horizontal cylinders in the wake of a hovering rotor are given. Tests were conducted with the rotor hovering both in and out of ground effect and above cylinders which were positioned at various distances below the rotor plane. Lateral and vertical wake deformations caused by interference of the cylinders are presented. Rotor inflow characteristics and flow phenomena related to the wake bodies are discussed in addition to the effects of rotor angular velocity, collective pitch, and orientation of the wake cylinders. The experimental wake data obtained are discussed relative to mathematical models used in theoretical prediction, methods for rotor wake velocities and hovering performance.

239. SOME OBSERVATIONS OF VORTEX CORE STRUCTURE, Adams, G. N. and Gilmore, D. C., Canadair, Ltd., Montreal, Canada, June 1972.
During observation of propeller tip vortex locations by means of smoke and stroboscopic lighting, a fortuitous atmospheric condition resulted in the formation of visible condensation in the vortex cores. Photographs were taken, and a selection of these is presented here, for the inspiration of fluid dynamicists and the edification of others.

240. SOME PROBLEMS IN THE NUMERICAL SOLUTION OF VORTEX MOTION EQUATIONS, Jones, J. P. and Noak, M., Southampton University, Department of Aeronautics and Astronautics, Southampton, England, 1969, A69-41376

This study presents results of some flow visualization experiments on the trailing vortices from a model helicopter rotor. It was found that the wake contraction was a cyclic phenomenon dependent on the number of blades. An investigation was conducted into some of the problems encountered when attempting to solve numerically the equations governing vortex motion. The accuracies of the fourth order Runge-Kutta method and the Euler method were compared at the theoretical solution when solving the equations of motion of two infinitely long line vortices. These two numerical integration methods were then used in computing the motion of two ring vortices in close proximity.

241. SOME WORK AT THE RAE ON THE BEHAVIOUR OF VORTEX WAKES, Bisgood, P. L., Maltby, R. L., and Dee, F. W., "Aircraft Wake Turbulence and Its Detection" (Ed. J.H. Olsen, et.al), Plenum Press, 171-206, Also RAE Tech. Memo, Aero 1244, 1971.

242. THE SOUND FIELD FOR SINGULARITIES IN MOTION, Lowson, M. V., Proceedings of the Royal Society of London A, Vol. 286 pp 559-572, August 1965.

243. SOUND RADIATION FROM A LIFTING ROTOR GENERATED BY ASYMMETRIC DISC LOADING, Wright, S. E., Southampton University, Institute of Sound and Vibration Research, England, April 1968, AD-854 432.

Contents: Theoretical concept; application to helicopter spectrum; general theory.

244. SPAN LOADING AND FORMATION OF WAKE, from "Aircraft Wake Turbulance and Its Detection. Olsen, J., et.al., September 1970.

245. THE STABILITY OF A VORTEX PAIR IN THE PRESENCE OF A GROUND PLANE, Rotta, N. R., Oceanics Inc., Report No 71-81A, June 1971.

246. STABILITY THEORY FOR A PAIR OF TRAILING VORTICES, Crow, S. C., Boeing Scientific Research Lab Document D1-82-0918, September 1969, AIAA J, Vol 8, No 12, December 1970.
This paper develops an eigenvalve problem through on equation relating induced velocity to vortex displacement. It presents an argument that d/b=0.063 for the vortices trailing from an elliptically loaded wing, where d = cutoff distance, and b = vortex separation.

247. A STALL FLUTTER OF HELICOPTER ROTOR BLADES: A SPECIAL CASE OF THE DYNAMIC STALL PHENOMENON, Ham, Norman D., Massachusetts Institute of Tech, Cambridge, Massachusetts, Contract AROD 4846:3, May 1967, AD-655 003.
Several conclusions were drawn with respect to stall flutter and airload prediction of high speed and/or highly loaded helicopter rotor blades.

248. STATE-OF-THE-ART SURVEY FOR MINIMUM APPROACH, LANDING, AND TAKEOFF INTERVALS AS DICTATED BY WAKES, VORTICES, AND WEATHER PHENOMENA, Bennett, W. J., Phase I Final Report, The Boeing Company, Airplane Division, Renton, Washington, FAA Report No. RD-64-4, January 1964.
This report is a study of the generation and decay of the wake behind an aircraft, both in free air and ground effect, and its effect on following aircraft. An analysis is presented for both fixed- and rotary-wing aircraft which defines the wake movement with time and the wake-induced velocities. The wake due to the propulsion system is analyzed both for normal operation and reversed thrust, as well as for pure propulsion lift. The influence of atmospheric parameters such as wind, temperature, and turbulence is discussed as it applies to the generation and decay of the wake.

249. STEADY THREE-DIMENSIONAL VORTEX FLOW, Granger, Robert, Journal of Fluid Mechanics, Vol. 25, Part 3, pp. 557-576, 1966.
A theory is developed for an incompressible fluid in a steady three-dimensional rotational flow. Solutions are obtained subject to the restriction of small perturbations and are determinant provided that the vorticity distribution along the axis of rotation is known. Effects of viscosity are included. Closed-form expressions for the zeroth-order circulation and stream function and first-order circulation are given, with other higher-order expressions requiring high-speed computers.

250. THE STEADY VELOCITY FIELD OF A PROPELLER
WITH CONSTANT CIRCULATION DISTRIBUTION,
Hough, G. R. and Ordway, D. E., Journal
AHS, Vol. 4, No.2, April 1965.

251. THE STRUCTURE OF CONCENTRATED VORTEX CORE,
Hall, M. G., Progress in Aero Science, Vol.
7, 1966.
A review is given here of recent work on the structure of such vortex cores. It discusses the equations of motion and the appropriate boundary conditions, and describes in general terms the character of the flow, the effects of compressibility and turbulence and the phenomenon of energy separation. Finally, a discussion is given of the phenomena of stagnation in the axial flow, spiral instability and finite transition.

252. STRUCTURE OF TRAILING VORTICES,
McCormick, B. W., Tangler, J. L., and
Sherrieb, H. E., Journal of Aircraft,
Vol. 5, No. 3, May-June 1968.
A study of aircraft trailing vortex systems involving actual flight testing as well as model testing and analytical considerations, has resulted in a method for predicting the vortex geometry and velocity field downstream of an aircraft.

253. STUDIES OF HELICOPTER ROTOR NOISE,
Lowson, M. V. and Ollerhead, J. B., U.S. Army Aviation
Materiel Laboratories, Fort Eustis, Virginia,
USAAVLABS Technical Report 68-60, January 1969,
AD-684 394.
A comprehensive study of the problem of helicopter noise radiation is presented. After a review of the basic features of the noise, the limited experimental data are reviewed in some detail, and empirical laws are proposed. An exact theoretical expression for the noise is derived. This expression has been used as the basis for the development of a comprehensive computer program to calculate helicopter noise at any field point, including all effects of fluctuating airloads and all possible rigid and flexible blade motions. Design charts are presented which enable routine calculation to be made of noise radiated from any helicopter in hover or forward flight.

254. STUDY OF THE EFFECT OF THE MARGINAL VORTEX
FROM A HELICOPTER BLADE ON THE AERODYNAMIC
FLOW AROUND THE FOLLOWING BLADE, Monnerie, B.
and Tognet, A., ONERA, Chatillonsous-Bagneux,
Hauts-de-Seine, France, November 1970.
The basic characteristics of marginal vortices from wings with limited span are investigated, and the effect which these vortices can have on the aerodynamics of lifting surfaces in their neighborhood is explored. The effects

of the presence of a vortex in the flow upstream of a blade are discussed, and effects of the blade form are considered. A method for calculating the effect of a vortex on a wing is presented. The noise spectrum for a rectangular blade tip and for a trapezoidal blade tip is shown.

255. STUDY OF MODIFICATION OF ROTOR TIP VORTEX BY AERODYNAMIC MEANS, Rinehart, Stephen A. Rochester Applied Science Associates, Inc., New York, Report No. RASA-70-02, January 1970, AD-704 804.
The analytical investigation shows that it should be possible to significantly alter the characteristics of the trailing tip vortex for all flight conditions in a beneficial manner by injecting an airstream directly into the forming tip vortex. Analytical expressions were developed for the initial and final states of the vortex in order to evaluate the effects of mass flow injection on the vortex strength, swirl velocity distribution, vortex core pressure, vortex core size and the induced drag on the blade.

256. A STUDY OF NOISE PRODUCED BY A HELICOPTER ROTOR-TIP VORTEX INTERACTION, Shepard, W. S. and Wolfe, J. R., Mississippi State University, State College, Mississippi, 1970.
Helicopter wake impulsive noise calculation based on rotor tip vortex interaction are discussed

257. STUDY OF ROTOR BLADE TIP VORTEX GEOMETRY FOR NOISE AND AIRFOIL APPLICATIONS, Sternfeld, Harry, Jr. and Schairer, John O. Boeing Company, Philadelphia, Pennsylvania (Vertol Division), Report No.D8-2464-1A, December 1969, AD-863 600L
The application of a technique for making helicopter tip vortices visible in order to study the effect of the separation between the vortex and a rotor blade on the noise generated by the rotor system was the primary purpose of this program. A secondary objective was to evaluate analytical prediction of the vortex path. Mathematical analyses were developed to obtain blade-vortex separation from the motion picture films taken during the tests.

258. A STUDY OF ROTOR BLADE-VORTEX INTERACTION, McCormick, Barnes W. Jr., Pennsylvania State University, University Park, Pa. and Surendraiah, Maham AHS/Annual National Forum, 26th, Washington, D.C., June 1970, Grant No. NGR-39-009-111, November 1968.
An experimental and analytical study of the rotor blade-vortex interaction problem was conducted. Time-dependent surface pressures were measured on

a model rotor blade as it passed through a vortex generated by a fixed wing, mounted upstream of the rotor. The pressures were integrated to obtain the time-wise variation of the rotor section lift coefficients. The geometry of the test setup was varied in order to study the effect of such parameters as the distance of the vortex axis from the rotor plane, the angle at which the rotor blade intersects the vortex, the vortex size and strength, and the rotor rpm. Results of an approximate quasi-steady and unsteady two-dimensional analysis are compared with the measured section lift-coefficients.

259. STUDY OF ROTOR CONFIGURATIONS FOR MINIMUM POWER AND ROTOR-WAKE PRESSURE DISTRIBUTIONS
Tung, C. and Brady, W. G., Cornell Aeronautical Lab, Inc., Buffalo, New York, Report No. CAL-BB-2293-S-2, September 1967, AD-664 689.
Two independent tasks are included as follows: Task I - Develop a method analytically determining rotor planform and twist distribution to minimize the power required by a hovering or slowly advancing rotor; and Task II - Predict the time-varying pressure distribution on a smooth surface due to a hovering rotor. Under Task I, the mathematical developments required were completed and are discussed. Digital computer calculations of the unsteady static pressures on a smooth ground plane directly beneath a hovering rotor were performed for two separate rotor configurations.

260. A STUDY OF THE VORTEX SHEET IMMEDIATELY BEHIND AN AIRCRAFT WING, Tangler, J. L, M. S. Thesis, Penn. State University, 1965.

261. SUPPRESSION OF TRANSMITTED HARMONIC ROTOR LOADS BY BLADE PITCH CONTROL,
Daughaday, Hamilton, Cornell Aeronautical Lab, Inc., Buffalo, New York, Report No. USAAVLABS TR-67-14, November 1967, AD-665 430.
A method is developed for computing the pitch angle inputs required to eliminate the transmission of harmonic vertical forces from a helicopter rotor to its driving shaft. In finding the aerodynamic loads, a realistic model is used which represents the wake vorticity by a mesh of segmented vortex filaments. Results of computations for three flight conditions are presented.

262. SUPPRESSION OF TRANSMITTED HARMONIC VERTICAL AND INPLANE ROTOR LOADS BY BLADE PITCH CONTROL, Balcerak, John C. and Erickson, John C., Jr., Cornell Aeronautical Lab, Inc., Buffalo, New York, Report No. USAAVLABS TR-69-39, July 1969, AD-860 352

A method was developed to study the possibility of using higher harmonic pitch-angle inputs to eliminate the transmission of oscillatory vertical and in-plane forces from a helicopter rotor to its driving shaft. The aerodynamic loads are computed by using a realistic model which represents the rotor blades by bound vorticity distributions and the wake by a mesh of segmented vortex filaments. Computed results are presented.

263. SURVEY OF AVAILABLE MATERIAL ON VTOL DOWNWASH PREDICTION, Spooner, Stanley C., U.S.A. AVLABS, Reliability and Maintainability Division, February 1971.

It was determined that, to satisfy reliability needs, effort in downwash prediction should be expanded with the goal of developing a semi-empirical computer model which will predict flow fields of aircraft in the hover condition. After completion of semi-empirical equations that describe the downwash flow field, the computer program would be written and tested.

264. SURVEY OF DIFFERENT MODELS FOR COMPUTING THE FLOW OF A LIFTING ROTOR, Kussmann, A., Stuttgart, West Germany, DLR-MITT-70-19, December 1970.

Mathematical models are given for lifting rotor aerodynamic calculations, noting wake configurations.

265. SURVEY OF DIFFERENT MODELS FOR COMPUTING THE FLOW OF A LIFTING ROTOR, Kussmann, A Deutsche Forschungs, Stuttgart, West Germany, June 1971.

Lifting rotor flow is discussed noting wake models.

266. SURVEY OF EXPERIMENTAL VELOCITY DISTRIBUTIONS IN VORTEX FLOW WITH BIBLIOGRAPHY Timm, G. K., Boeing Scientific Research Labs, Report 126, November 1967.

Experimental data on circumferential velocities in real vortices was determined mostly for vortex flows generated by straight wings and delta wings. A literature search was conducted to collect pertinent data and to present a unified picture of present experimental knowledge. Circumferential velocity distributions in wing vortices determined in four investigations are set forth. A bibliography on vortex flows is also prescribed.

267. SYMPOSIUM ON AIRCRAFT WAKE TURBULENCE, Boeing Scientific Research Lab., Document D1-82-0993, September 1970.

278. TABLES OF AERODYNAMIC DERIVATIVES OF OSCILLATING ROTOR BLADES IN HOVERING FLIGHT, Rao, B. M. and Jones, W. P., Texas, A & M University College Station, Department of Aerospace Engineers, College Station, Texas, Report No. AROD T-5:3-E, June 1969, AD-697 177.

A theory was developed for determining the influence of compressibility on the aerodynamic forces acting on helicopter rotor blades when oscillating in hovering flight, using the usual 2-dimensional mathematical model of the flow. The same theory is used to compute the aerodynamic derivative coefficients referred to the quarter-chord point on the airfoil.

269. TAIL ROTOR DESIGN, PART 1, Lynn, R. R., Robinson, F. D., Batra, N. N., and Duhon, J. M., Bell Aerospace Corporation, Bell Helicopter Co., Fort Worth, Texas, Aerodynamics 25th Annual National Forum of the American Helicopter Society, May 1969.

This report is a discussion of the major aerodynamic aspects of tail rotor design. The principal tail rotor design criteria are defined. Critical ambient conditions, maximum thrust, and the effects of precession are discussed. The effect of fin interference on the tail rotor performance and the effect of fin-tail rotor separation is considered. Various rotor parameters and their effect on performance and rotor noise are discussed.

270. TECHNICAL EVALUATION REPORT ON FLUID DYNAMICS, PANEL SPECIALISTS MEETING ON AERODYNAMICS OF ROTARY WINGS, Ham, Norman D., AGARD-AR-61, March 1973.

271. TEST SECTION SIZE INFLUENCE ON MODEL HELICOPTER ROTOR PERFORMANCE, Lehman, August F. and Besold, Jeffrey A., Oceanics, Inc., Plainview, New York, USAAVLABS TR-71-6, March 1971, AD-724 191.

The study indicates that the successful testing of model helicopter rotors in tunnels when in the hover and transitional flight regimes requires not only Reynolds number scaling, but also a scaling of a characteristic defined here as the wake energy dissipation pattern. These conflicting factors have led to the requirements of relatively large models and correspondingly large transitional flight modes are of interest.

272. THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE INSTANTANEOUS INDUCED VELOCITY FIELD IN THE WAKE OF A LIFTING ROTOR, Miller, N. and Tang, J. C., Dynasciences Corporation, Blue Bell, Pennsylvania, Report No. USAAVLABS TR-67-68, January 1968, AD-667 384.

Measurements have been made of the instantaneous and time-averaged values of the induced velocities in the wake of a full-scale helicopter in actual steady flight conditions. Simple, analytical methods are formulated to predict the instantaneous and time-averaged, induced velocities in the rotor wake. Calculated values of the induced velocities are compared with the experimental data, and agreement is obtained for the hovering flight condition.

273. THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF A PROPELLER WORKING AT STATIC CONDITION, Iwasaki, M., Sasaki, R., Shiki, T., and Himori, A., Report of Research Institute for Applied Mechanics, Vol. 16, No. 52, pp 33-67, 1968.

Formulas to calculate static performance of propellers are derived assuming infinite number of blades. Distributions of section left coefficient, thrust coefficient grading, and power coefficient grading along radius of four-bladed propellar are obtained. The effect of section drag coefficient and tangential induced velocity is discussed. It is found that drag affects power coefficient grading and that tangential induced velocity has considerable effect on blade element characteristics of inner radius. Experimental results for model propeller having same principal.

274. THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF V/STOL PROPELLER OPERATION IN A STATIC CONDITION, Erickson, John C., Jr., USAAVLABS, TR 69-55, October 1969.

A general theory for performance prediction has been formulated based on continuous vortex representation along the lines of a classical lifting-line model. Numerical techniques and computer programs have been developed to calculate inflow to the propeller and velocity induced along arbitrarily described deformed trailing vortex sheets. Theoretical calculations could not be iterated successfully in cases, so significant theoretical and experimental comparisons could not be made. Detailed observations have been made on the character of the numerical computations, and certain generalizations have been made which lead to computational simplifications.

275. THEORETICAL AND EXPERIMENTAL STUDY OF THE DECAY OF ISOLATED VORTICES, Donaldson C. duPont, A.R.A.P. Tech. Memo 71-2, February 1971.

276. A THEORETICAL METHOD FOR ROTOR BLADE FLUTTER IN FORWARD FLIGHT, Wood, E. R. and Shipman, K. W., Georgia Institute of Technology, Atlanta, Ga., AHS/ Annual National Forum, 26th, June 1970.

Presented is a theoretical method for determining rotor blade flutter in forward flight. The theory accounts for the unsteady aerodynamic contribution of the wake below the rotor. In particular, it is assumed at the onset of flutter that oscillations begin to build up prior to the blade reaching a critical azimuth position, then decay as the blade moves beyond this point. Based upon this, a wake model is postulated and the theory developed. The theory is applied to bending-torsion flutter for the tip segment of a rotor blade. Here, beyond a certain value of advance ratio, the influence of advance ratio on flutter speed is found to be essentially constant.

277. THEORETICAL PREDICTION OF THE FLOW IN THE WAKE OF A HELICOPTER ROTOR (Part 1), Crimi, Peter, Cornell Aeronautical Lab, Inc., Buffalo, New York, Report No. CAL-BB-1994-S-1, September 1965, AD-629 782.

A study was performed with the objective of predicting the time-varying flow in the vicinity of a helicopter in hovering or forward flight. An analytical model was formulated which represents the rotor, its wake and the fuselage of the aircraft. The wake vortices are assumed to be free to convect under the influence of the blades, the fuselage and the wake itself. A digital computer program was written which implements the model developed. It has been concluded that the model developed provides a valid representation of the unsteady flow in the vicinity of a helicopter.

279. THEORETICAL PREDICTION OF THE FLOW IN THE WAKE OF A HELICOPTER ROTOR (PART 2), Crimi, Peter, Cornell Aeronautical Lab, Inc., Buffalo, New York, Report CAL-BB-1994-S-2, September 1965, AD-629 783.

Two digital computer programs were prepared which direct the calculation of the time-varying flow in the vicinity of a helicopter rotor in forward or hovering flight. Fuselage interference effects are taken into account. For applicability of these programs to specific problems and procedures for their use is discussed. First, the assumptions made in constructing the mathematical model and the relationship of the model to the physical flow are outlined. Finally, the procedures for implementation of the programs are given. The relationship of input quantities to aircraft flight parameters, program accuracy and computer running time are specified. A sample calculation, including both inputs and outputs, is presented.

279. THEORETICAL PREDICTION OF THE FLOW IN THE WAKE OF A HELICOPTER ROTOR (ADDENDUM-EFFECTS DUE TO A FUSELAGE IN A CONSTANT, NONUNIFORM FLOW), Crimi, Peter and Trenka, Andrew R., Cornell Aeronautical Lab, Inc., Buffalo, New York, Report No. CAL-BB-1944-D-3, August 1966, AD-637 872.

The addendum reports the results of an extension to the study to determine the time varying flow in the vicinity of a helicopter rotor in hovering and forward flight and having a fuselage immersed in the rotor wake. The purpose of the extension was to compare two models representing the fuselage, one based upon the assumption that the fuselage was immersed in a constant and uniform flow; the second upon the assumption that the fuselage was immersed in a constant but nonuniform flow. Comparisons between the two models are presented.

280. THEORETICAL STUDY OF CONDITIONS LIMITING V/STOL TESTING IN WIND TUNNELS WITH SOLID FLOOR, Heyson, Harry H., National Aeronautics and Space Administration, Langley Research Center, Langley Station, Virginia, NASA-TN-D-5819:L-7042, June 1970.

Under sufficiently large wake deflections, the forward portion of the wake is found to flow forward along the floor leading to a vortex pattern which results in Rae's limits. Although wind-tunnel data cannot normally be corrected successfully beyond these limits, it may be possible to obtain ground effect data for conditions more severe than those implied by Rae.

281. THEORETICAL STUDY OF HIGH FREQUENCY HELICOPTER ROTOR ROTATIONAL NOISE, Tanna, H. K., Southampton Univ. (England), Institute of Sound and Vibration, AD-721661, Avail: NTIS CSCL 20/1, September 1970.

The investigation deals with the radiation of rotational noise due to fluctuating forces on the rotor blades of a helicopter with particular emphasis on studying the effects of chordwise and spanwise differential-pressure profiles. The variation of profiles with azimuth was studied as a possible source of higher harmonic rotational noise. Previous theories were modified to include the chordwise and spanwise differential pressure profiles. Computer programs were written to compute the r.m.s. value of mth harmonic of sound pressure at any observer position using rotor geometry and operating conditions, field point position relative to the rotor center, and motor blade differential-pressures at several chordwise and spanwise stations. A detailed study of the available measured aerodyamic loading data was carried out.

283. THEORETICAL STUDY OF ROTATIONAL NOISE, Wright, S. E., ISVR Technical Report No. 14, 1969.

The theory first considers in detail the properties of steady and fluctuating force radiation for point rotating forces. The effect of distributive loading typical of a rotor, both chord and span is then considered. The onset of the near field for steady and fluctuating lift radiation is established and the radiation properties within the near field discussed. A composite blade loading radiation equation is developed to predict the general radiation from a rotor.

283. A THEORY OF THE AERODYNAMIC INTERFERENCE BETWEEN A HELICOPTER ROTOR BLADE AND A FUSELAGE AND WING IN HOVERING AND FORWARD FLIGHT, Bramwell, A. R. S., Royal Aircraft Establishment, Farnborough, England, Report No. TR-65127, June 1965, AD-485 099.

The report presents a theory of the aerodynamic interference between a helicopter rotor blade and a fuselage or wing. A two-dimensional analysis is made to which a correction factor is applied to convert the two-dimensional calculations to the appropriate three-dimensional case. The pressures and forces on circular and square-sectioned fuselages and on wings are calculated for hovering flight and also the corresponding changes of lift on the blade. The analysis is extended to cover the case of interference between a blade and a lifting wing or tail fin in forward flight.

284. THEORY AND COMPUTER STUDY OF A WING IN A SLIPSTREAM, Ribner, H. S. and Ellis, N. D., AIAA Paper 66-466, 1966.

285. A THEORY FOR PREDICTING THE ROTATIONAL NOISE OF LIFTING ROTORS IN FORWARD FLIGHT, INCLUDING A COMPARISON WITH EXPERIMENT, Loewy, R. G. and Sutton, L. R., Rochester University, Department of Mechanical and Aerospace Sciences, Rochester, New York, Report 65-82 January 1966, AD-629 377.

Lifting rotor-propeller noise prediction for military helicopters and V/STOL aircraft in forward flight are discussed.
The lifting rotor is considered as a swept surface, area segments of which are subjected to oscillating pressures, expressed as a Fourier series in time. The theory is extended to include up-plane components of forward speed and azimuthal asymmetry. The sound pressure at any field point is then bound by a straightforward numerical integration. Radiation patterns were, in fact, investigated for the $H-_{34}$ and HU-1A helicopters both around the azimuth

and in the shaft direction, for several forward speeds. Sound spectra were compared with measurements for the first 20 harmonics for selected cases. The influence of chord, number of blades, rotor r/min, and other changes on rotor noise were also investigated.

286. A THEORY FOR PREDICTING THE ROTATIONAL AND VORTEX NOISE OF LIFTING ROTORS IN HOVER AND FORWARD FLIGHT, Loewy, R. G. and Sadler, S. G., Rochester Applied Science Associates, Inc., New York, NASA-CR-1333, May 1969.
A theory is presented for predicting rotational and vortex noise of lifting rotors in hovering and forward flight.

287. A THEORY FOR STATIC PROPELLER PERFORMANCE, Erickson, J. C. and Ordway, D. E., CAL/AAVLABS Symposium Proceedings, I, June 1966.

288. THEORY OF STATIC PROPELLERS AND HELICOPTER ROTORS, Theodorsen, T., American Helicopter Society, New York, AHS Paper 326, May 1969.
Helicopter rotors and static propellers theory based on Prandtl-Betz Theorem, calculating ideal performance are presented.

289. A THEORY FOR VTOL PROPELLER OPERATION IN A STATIC CONDITION, Erickson, J. C., Jr., Ladden, R. M., Borst, H. V. and Ordway, D. E., USAAVLABS, TR 65-69, October 1965.
A general theory for calculation of propeller performance at the static condition has been formulated based on a continuous vortex representation along the lines of the classical lifting-line model. A computer program has been developed to calculate both the inflow at the propeller and the induced velocity at any field point for an arbitrary description of the trailing vortex sheets. The wake hypothesis used provides a reasonable representation of the "pitch" of the elements of the deformed trailing vortex sheets as well as the envelope of their trajectories.

290. THREE-DIMENSIONAL POTENTIAL FLOW PAST THE SURFACE OF A ROTOR BLADE, Sopher, Robert, United Aircraft Corp-Sikorsky Aircraft Division, Stratford, Connecticut. Proceedings of the 25th Annual National Forum of the American Helicopter Society, Paper No. 324, May 1969.
The flow past the surface of a rotor blade was obtained by means of a linearized potential flow method which accounts for both the effect of compressibility

and the three-dimensional character of the flow. The results are viewed with particular emphasis on the limitations of the blade-element theory and the dependence of the three-dimensional flow on compressibility.

291. TIP VORTEX CORE THICKENING FOR APPLICATION TO HELICOPTER ROTOR NOISE REDUCTION, Spencer, R. H., Sternfeld, H., Boeing Company, Vertol Division, Morton, Pennsylvania, McCormick, B. W., Report No. USAAVLABS TR-66-1, September 1966, AD-644-317.
The study deals with modification of the induced velocity structure of the vortex from both an analytical and an experimental standpoint. Ten tip configurations were evaluated in a wind tunnel to determine the magnitude of velocity reduction achievable. Drag data measured on the model wing for each blade tip indicates that most configurations adversely affect performance.

292. TIP VORTEX CORE THICKENING FOR APPLICATION TO HELICOPTER ROTOR NOISE REACTIONS, Spencer, R. H., Sternfeld, H., Jr., and McCormick, B. W., USAAVLABS, TR 65-82, September 1966.

293. TIP VORTEX EFFECTS ON OSCILLATING ROTOR BLADES IN HOVERING FLIGHT, Jones, W. P. and Rao, B. M., Texas A & M University, College Station, Texas, AROD T-5:4-E, May 1970, AD-724 853.
The present paper examines the validity of using the 2-dimensional strip theory as the method of approach and gives results which reveal to what extent the assumptions made are acceptable. From the general theory developed, it is concluded that up to tip Mach numbers of about 0.8, the use of two-dimensional strip theory would not lead to serious error, provided the blades oscillate at several cycles per rotation. In this more accurate theory, the two-dimensional mathematical model of the flow normally adopted is replaced by a modified version in which the trailing vortices are fully represented.

294. TIP VORTICES - VELOCITY DISTRIBUTIONS Corsiglia, Victor, R. and Jacobsen, Robert, A., Symposium on Aircraft Wake Turbulence, Boeing Seattle, September 1970.
Detailed measurements of velocity distributions have been made in vortices generated at the tip of a square-tip, 18-inch chord, 48-inch semispan blade. Time-mean-average velocity components were measured. With the blade at an angle of attack of 12° traverses were made through the vortex centers at six axial stations. The dimensions of the vortex increase with distance downstream

over the blade surface. Axial velocity in excess of free-stream velocity was measured in the vortex core with maximum axial velocity of 140 percent of free-stream velocity at x/c equal to 0.25.

295. TRAILING VORTEX HAZARD, McGowan, W. A., SAE 680220, April 1968.
Envelopes of vortex system velocities, duration, and movement for various wind conditions have been determined. Specific operational procedures for the takeoff landing and enroute phases of flight are suggested to enable the light aircraft pilot to avoid the wake turbulence of heavy aircraft.

296. A TRAILING VORTEX MODEL AND ITS EFFECT ON A PENETRATING AIRCRAFT, Funston, Neil L. and Koob, Stephen J., NAECON 1971, Record, pp. 23-27.
The trailing vortex system produced by an aircraft in flight, and the penetration of the system by a second aircraft are modeled mathematically.

297. TRAILING VORTEX WAKE SYSTEMS A PREVIEW OF THE WAKE TURBULANCE PROBLEM, Williams, G. M., Lockheed - California Co. Report, ZR 24275, Part III, January 31, 1971

298. TRAILING VORTICES FLIGHT MEASURMENTS OF THE VORTEX WAKE BEHIND A CONVAIR 880, ICAO Circular 92-AN/76, 1969.
The conference favors the adoption of a more positive approach towards making adequate allowances for turbulent wake effect in determining separation between aircraft in the approach and landing phases of flight.

299. TRANSPORT AND STABILITY OF A VORTEX WAKE, Tombach, I. H., Air Force Office of Scientific Research, MRI 72 FR-1010, April 17, 1972.
The influence of the atmospheric environment on the transport and decay of a trailing vortex wake has been studied analytically and experimentally. An analytical model describing the descending motion of an entraining wake in a stably stratified atmosphere has been developed. A flight test program was carried out in which the smoke-marked vortices behind a light plane were observed in an atmosphere of measured turbulence and stratification. The wake was observed to decay from both sinuous and bursting type instabilities, and the lifetime of the wake was correlated with the level of atmospheric turbulence and the degree of atmospheric stability. Turbulence was found to have a strong effect on wake life, regardless of the mode of decay, with the atmospheric stratification having a weaker influence.

300. TRIM REQUIREMENTS AND STATIC-STABILITY DERIVATIVES FROM A WIND TUNNEL INVESTIGATION OF A LIFTING ROTOR IN TRANSITION, Jenkins, J. L., Jr., NASA TN D-2655, 1965.

A wind-tunnel investigation of a 15-feet-diameter rotor was made to determine the trim requirements and static stability derivatives for rotor operation at transition speeds. In addition, photographs of a vertical tuff grid in the longitudinal plane below the rotor were taken to indicate the influence of the rotor downwash on an aircraft fuselage.

301. TURBULENT AND LAMINAR JET PROPAGATION IN ROTATING SYSTEMS AND ITS APPLICATION TO JET MIXING IN THE WAKE OF REACTION DRIVEN ROTORS, Schmidt, R. and Heynatz, J. T., Dornier-Werke G.m.b.H., Friedrichshafen, West Germany, April 1971.

Using typical mixing laws, this report compares rectilinear jet laminar and turbulent jets. The transferability of the theoretical statements on jet propagation from one reference system to another is discussed. The principles of jet propagation in rotating systems are treated in a system of correlated coordinates. In addition, the characteristic properties of jet propagation are experimentally investigated using smoke photographs.

302. TURBULENT VORTEX WAKES AND JETS, Fernandez, F. L. and Lubard, S. C., AIAA Paper No. 71-615, presented at the AIAA 4th Fluid and Plasma Dynamics Conference, June 1971.

The turbulent viscous core of a potential vortex with axial velocity excess or defect is considered in this paper. An integral method is used with quasi-cylindrical flow approximations to describe the flow in the core of the vortex. Models are postulated for both axial and swirl mixing. The resulting equations are shown to possess both regular wake-like and jet-like solutions which become singular indicating vortex breakdown. The analysis is compared with available wind tunnel and flight test data, and the disagreement in the observed mixing rates is discussed.

303. TWO-DIMENSIONAL LOW-SPEED TUNNEL TESTS ON THE N.A.C.A. 0012 SECTION INCLUDING MEASUREMENTS MADE DURING PITCHING OSCILLATIONS AT THE STALL, Moss, G. F. and Murdin, P. M., Aeronautical Research Council, London, England, Report No. ARC-CP-1145, May 1968, AD-887 309.

Lift measurements were made on a 10-percent thick N.A.C.A. 0012 section under static conditions and during pitching oscillations in an attempt to provide sectional data for use in calculations on helicopter rotors. Strong three-dimensional effects were found at the stall, which seemed to be inherent in the aerodynamics of the stall itself. Also, the cyclic variation of lift during the pitching oscillations was found to be intermittent between two distinct types.

304. TWO-DIMENSIONAL TESTS OF AIRFOILS OSCILLATING NEAR STALL, VOL. I SUMMARY AND EVALUATION OF RESULTS, Livia, J., Davenport, F. J., Gray, L. and Walton, I. C., USAAVLABS, TR 68-13A, April 1968.

An experimental investigation into rotor blade dynamic stall was conducted. Two typical airfoils, the NACA 0012 (modified) and the Vertol 23010-1.58, were tested over a range of angles of attack covering the stall regime. There were two main objectives: (1) to determine the influence of stall on the aerodynamic pitching moment of an airfoil executing pitching motions corresponding, to the elastic torsional oscillations of a rotor blade; to determine the extent to which time-varing angle of attack could affect the maximum aerodynamic lift that a rotor blade can develop.

305. UNSTEADY AERODYNAMIC AND STALL EFFECTS ON HELICOPTER ROTOR BLADE AIRFOIL SECTIONS, Livia, J., Paper No. 68-58, Presented at the 6th Aerospace Sciences Meeting of the American Institute of Aeronautics of Astronautics, January 1968.

306. VARIABLE GEOMETRY ROTOR SYSTEM, Ward, J. F., National Aeronautics and Space Administration, Langley Research Center, Langley Station, Virginia, NASA-CASE-LAR-10557, July 1971.

Variable geometry rotor system for direct control over wake vortex is presented.

307. VELOCITY MEASUREMENT IN VORTEX FLOWS, Chigier, N. A., Paper presented at ASME Fluids Engineering Division Conference, May 11, 1971.

308. VORTEX BREAKDOWN FLOWFIELD, Bossel, H. H., Phy. Fl., vol. 12, No. 3, pp. 498-507, March 1969.

309. VORTEX DECAY ABOVE A STATIONARY BOUNDARY, Barcilon, Albert I., J. Fluid Mech, Vol. 27, Part I. pp. 155-175, 1967.

An attempt to understand the decay of a free vortex normal to a stationary, infinite boundary is made. For rapidly swirling flows in fluids of small viscosity, thin boundary layers develop along the rigid boundary and along the axis; the axial boundary layer being strongly influenced by the behavior of the plate boundary. An overall picture of the flow is sought, with only moderate success in the region far from the origin. Near the origin, the eruption of the plate boundary layer into the axial boundary layer is studied.

310. VORTEX FIELD, TIP VORTEX, AND SHOCK FORMATION ON A MODEL PROPELLER, Tanner, W. H. and Wohlfeld, R. M., Bell Aerospace Corp., Bell Helicopter Co., Fort Worth, Texas, Cornell Aeronautical Lab. and U.S. Army Aviation Materiel Laboratories, Symposium, 3rd, Buffalo, N Y., June 1969 Proceedings. Vol. 1

Description of the use of a schlieren system for photographing the flowfield of a rotating static thrust propeller or hovering rotor. The presently operating pilot system uses rotors or propellers up to 14-inch in diameter and has a maximum tip speed of Mach. 85. Among the results presented are details on the contraction of the stream tube of a model propeller. Results for a number of blades are presented. Another topic discussed is the formation of the tip vortex. Photographs of the airflow around the blade tip are presented, along with a discussion of the basic mechanisms of the tip loss. Briefly discussed is the formation of shock waves on a propeller.

311. VORTEX FLOW OVER HELICOPTER ROTOR TIPS, Hoffman, John D. and Velkoff, Henry R., Ohio State University, Columbus, Ohio, September 1971.

Study of the flow over square tips, using a flow visualization technique whereby ammonia vapor was expelled for a short time from a network of orifices in the tip and carried by the boundary layer flow over a diazonium salt solution which was sprayed over the tip.

312. VORTEX INTERACTIONS IN A PROPELLER WAKE, Cummings, D. E., Mass. Inst. of Tech., Report No. 68-12, June 1968.

This report concerns the kinematics of the motion of trailing vortex sheets in the wake of a propeller and the dynamics of the tip vortex. The problem is solved numerically for a lifting line wing model and the results applied to propeller theory. Special consideration is given to the subjects of tip vortex cavitation (changes in loading on a blade due to rollups of the trailing vortex angle) and the trajectory of the tip vortex. Experimental confirmation was obtained for the pressure at which cavitation appeared and the motion of the vortex sheet through testing a hydrofoil in a propeller tunnel.

313. A VORTEX MODEL DEALING WITH THE AIRSTREAM AT THE ROTOR BLADE OF A HELICOPTER, Isay, W. H., Techtran Corporation, Glen Burnie, Maryland, NASN-TT-F-14228, Report 272, July 1971.

An approximate method is given for calculating the buoyancy distribution at rotor blades in forward flight. The theory presented takes into consideration, with reference to vortex geometry, a nonuniform (especially trapezoidal) flow through the plane of the rotor, as well as the unrolling process and the contraction of the free transverse vortex. Formulas for computing acoustic pressure fields radiated from a rotor (compressible treatment) are included.

314. VORTEX SHEDDING NOISE OF AN ISOLATED AIRFOIL, Paterson, Robert W., Vogt, Paul G, Fink, Martin R., and Munich, C. Lee, United Aircraft Research Labs, East Hartford, Connecticut, AD-734-433, AIAA Paper 72-656, June 1972.

The purpose of the study was to determine the vortex shedding noise characteristics of isolated airfoils in a Reynolds Number range applicable to full-scale helicopter rotors. Measurements of far field noise, airfoil surface pressure fluctuations, and correlation coefficients were obtained for three airfoils. The presence of a laminar boundary layer on the pressure surface of the airfoils was found to be critical to the presence of the presence of vortex shedding noise.

315. VORTEX THEORY FOR A PROPELLER OF CONSTANT AERODYNAMIC PITCH AND STUDY OF THE WAKE CONFIGURATION WITH THE AID OF THE SMOKE TRAIL METHOD, Pelissier, R., Aix-Marseille Universite, Marseille, France, June 1971.

Approximate analytical expressions are expressions are derived for the pitch of vortex streets in the rotational plane of a propeller as a function of the propeller's mode of operation and its geometrical characteristics. Smoke-trail visualization of the pitch of vortex streets in the wake is also described.

316. VORTEX VELOCITY DISTRIBUTIONS AT LARGE DOWNSTREAM DISTANCES, Logan, A. H., Journal of Aircraft, Vol. 8, No. 11, page 930-32, November 1971.

It is the purpose of this paper to extend the available data on the velocity structure within a trailing vortex to large distances downstream of the generating wing. Data are presented to show the variation of both axial and tangential velocity with tunnel speed and trailing vortex strength.

317. THE VORTEX WAKE AND AERODYNAMIC LOAD DISTRIBUTION OF SLENDER RECTANGULAR WINGS, Wickens, R. H., Canadian Aeronautics and Space Journal, Vol. 13, No. 6, pp. 247-260, June 1967.
An experimental investigation has been made of the aerodynamic characteristics of two slender rectangular plates. One of the plates was flat, the other had a midchord deflection of 20°.

318. VORTEX WAKE DEVELOPMENT AND AIRCRAFT DYNAMICS, Hackett, J. F. and Theisen, J. G., Aircraft Wake Turbulence and its Detection, (Ed. Olsen, J. H., et al.) Plenum Press, pp. 243-263

319. VORTEX WAKES AND THEIR INFLUENCE ON AIRCRAFT TERMINAL AREA SEPARATION REQUIREMENTS, Reeder, John P., Zalovcik, John A., and Dunham Earl R., Jr., NASA Report to DOT Advisery Commission on ATC Group I, January 1970.

320. V/STOL DOWNWASH IMPINGEMENT STUDY, VELOCITY ESTIMATE, Watts, A., MAA-284-001, January 1969.
This memo describes a short method to estimate downwash velocities along the ground for V/STOL aircraft of various gross weights, disc loadings and number of propellers, operating at various heights and speeds, the latter resulting in different angles of downwash impingement on the ground. It is to be noted that there exists large discrepancies in the test data analysed, because in many cases small jets and ducted fans and small diameter rotors of low disc loading were used to simulate full scale aircraft downwash flow.

321. VTOL PERIODIC AERODYNAMIC LOADINGS, White, R. P., Jr., Proceedings of the Symposium on the Noise and Loading Actions on Helicopters, V/STOL Aircraft and Ground Effect Machines, University of Southampton, England, September 1965.

322. VTOL PERIODIC AERODYNAMIC LOADINGS: THE PROBLEMS, WHAT IS BEING DONE AND WHAT NEEDS TO BE DONE, White, R. P., Journal of Sound and Vibration, Vol. 4, No.3, pp. 305-344, November 1966.

323. WAKE AND BOUNDARY LAYER EFFECTS IN HELICOPTER ROTOR AERODYNAMICS, Clark, David R. and Landgrebe, Anton J., United Aircraft Corp., Sikorsky Div. Stratford, Conn., United Aircraft Research Labs, East Hartford, Conn., AIAA Paper 71-581, NASI-8350, June 1971.

Theoretical methods recently developed are discussed in light of the new understanding they give to the aerodynamics of the helicopter rotor. Results of wake geometry prediction methods, supported by experimental data, emphasize the importance of wake effects on rotor performance and behavior. The influence of viscosity has been studied with particular emphasis on the development of the blade boundary layer.

324. THE WAKE GEOMETRY OF A HOVERING HELICOPTER ROTOR AND ITS INFLUENCE ON ROTOR PERFORMANCE, Landgrebe, Anton J., Presented at the 28th Annual National Forum of the AMS, May 1972.

Analysis of wake data resulted in (1) the development of a simple, generalized representation of the near wake which facilitates the rapid estimation of realistic wake geometries for a wide range of rotor designs and operating conditions, and (2) the discovery of a reduction in wake stability with increasing distance from the rotor. The results of a theoretical method for predicting the wake geometry are also presented, as are the initial results of advanced experimental techniques for determining rotor wake characteristics.

325. WAKES AND LIFTING PROPELLERS (ROTORS) IN GROUND EFFECT, Duwaldt, F. A., Cornell Aeronautical Lab, Inc., Buffalo, New York, Report No. CAL-BB-1665-S-3, November 1966, AD-643 159.

The report presents the development of a wake model for a lifting propeller (rotor) in ground effect and the computation procedure used to determine the spacial distribution of wake vorticity and the induced velocity field accompanying that vorticity distribution. Sample calculations for a two-bladed rotor were carried out. Locations of wake vortical elements and the associated induced velocities at selected field points are presented for various advance ratios for a H/R ratio of rotor height above ground to rotor radius of 1.0. Also, a few results for a hovering case with H/R = 0.5 are presented. A calculated root-mean-square velocity map is compared with measured hovering data and good agreement is obtained in the outer half of the slipstream.

326. WAKE TURBULENCE, Anon., FAA Advisory Circular 90-23A, 1965.

327. WAKE VORTEX SENSING, Kodis, R. D.,
U.S. Department of Transportation,
Transportation Systems Center,
Cambridge, Massachusetts, A72-42676
22-14, 1972.

Experimental studies and test are reported on two wake vortex sensing techniques designed to sense the presence and track the motions of low altitude aircraft wake vortices endangering operations around terminal areas. The techniques studied are based on acoustic pulse deflection and velocity field measurements.

328. A WIND-TUNNEL INVESTIGATION OF THE AERODYNAMIC ENVIRONMENT OF A FULL-SCALE HELICOPTER ROTOR IN FORWARD FLIGHT,
Bowden, Thomas H. and Shockey, Gerald A.,
Bell Helicopter Co., Fort Worth, Texas,
USAAVLABS, TR-7035, July 1970, AD-875-744.

Aerodynamic data were measured at one blade radius station as the initial phase of a program designed to define the aerodynamic environment over the entire rotor disc. These data were then used to determine angle of attack, effective airfoil profile, section normal force, chord force, and pitching moment, and stall and unsteady aerodynamics effects. The test data were compared with two-dimensional empirical data and theory.

329. WIND TUNNEL SIMULATION OF FULL SCALE VORTICES, Rorke, James B. and Moffitt, Robert C., Sikorsky Aircraft Division for NASA CR-2180, March 1973.

An experimental investigation has been conducted to determine the important scaling parameters for the flow in the core region of a vortex generated by a rectangular wing tip. The effect of an unconventional planform, the ogee tip on the tip vortex is also determined.

330. WIND TUNNEL STUDIES OF TRAILING VORTICES WITH DISSIPATION, Jacobsen, R. A., Corsiglia, V. R., and Chigier, N. A., Proceedings of Aircraft Wake Turbulance Symposium, Seattle, September 1-3, 1970.

331. WIND TUNNEL TEST DATA FOR WING TRAILING VORTEX FLOW SURVEY, Chigier, N. A., and Corsiglia, N. A., NASA TM X.62, 148, May 1972.

332. WIND TUNNEL TESTS OF THIN AIRFOILS OSCILLATING NEAR STALL Vol. 1: Summary and Evaluation of Results, Gray, Lewis, Livia, Jaan, and Davenport, Franklyn, J., USAAVLABS TR-68-89A, January 1969.

The report presents the results of an experimental investigation of rotor blade dynamic stall. Forces and moments in two-dimensional flow were determined for two thin airfoil sections (NACA 0006 and Vertol 13006-.7) usually considered in advanced helicopter rotor concepts by measuring differential pressure during oscillatory pitch motions. The Mach number, Reynolds number, and angle of attack prevailing in the retreating blade stall region were investigated up to typical first-torsion mode natural frequencies.

333. WIND TUNNEL TESTS OF THIN AIRFOILS OSCILLATING NEAR STALL, VOL. 2, Gray, Lewis and Livia, Jaan, USAAVLABS-TR-68-89B, January 1969.

The report presents the actual computer data that resulted from the two-dimensional tests of thin airfoils oscillating near stall. An introduction provides a general background, and a set of table forms an index to specific data. More than 200 pages of computer data are included.

334. WING TIP VORTEX DECAY: AN EXPERIMENTAL INVESTIGATION, Whthycombe, E., II, Thesis, S. B., MIT, August 1970.

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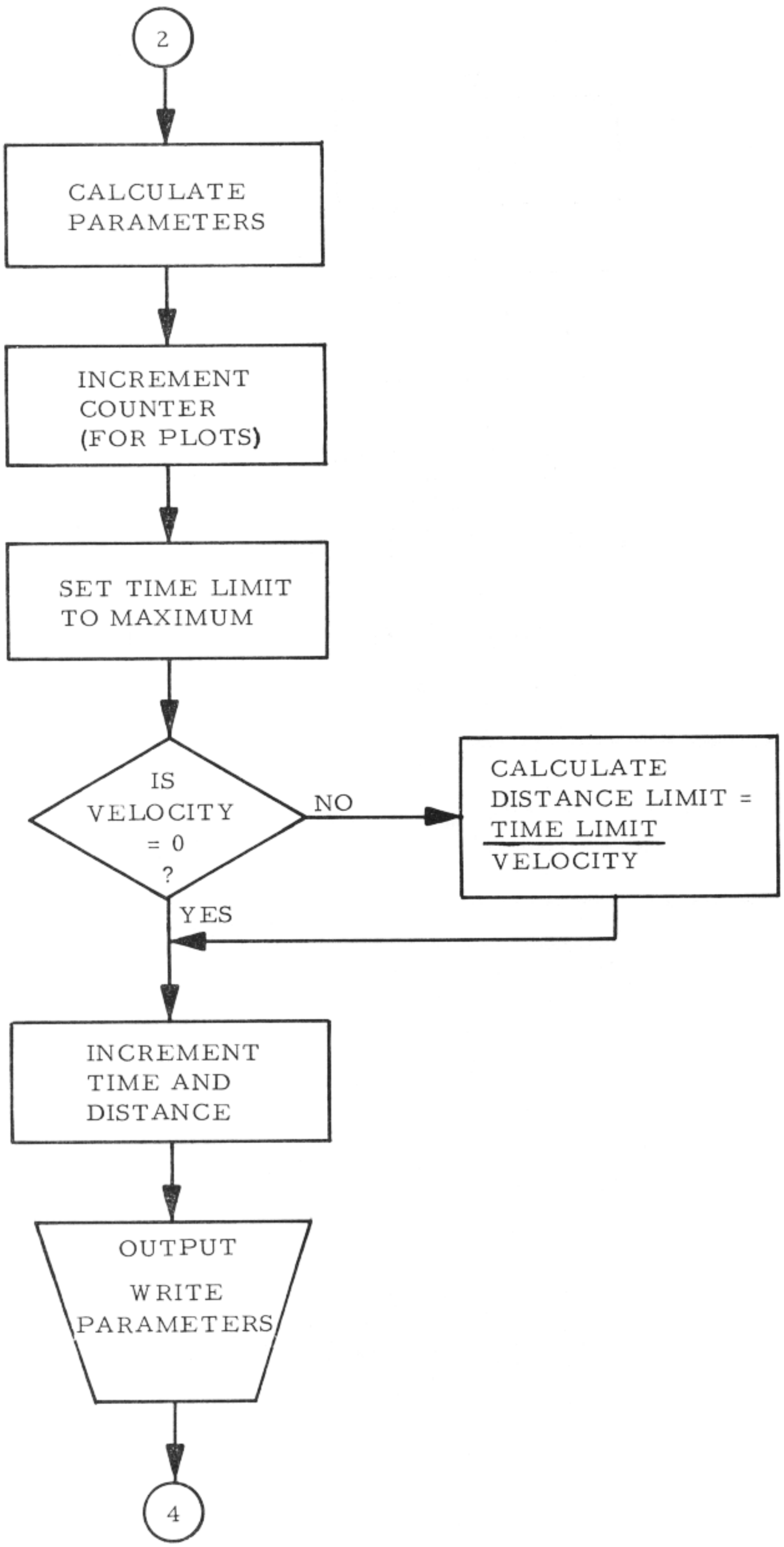
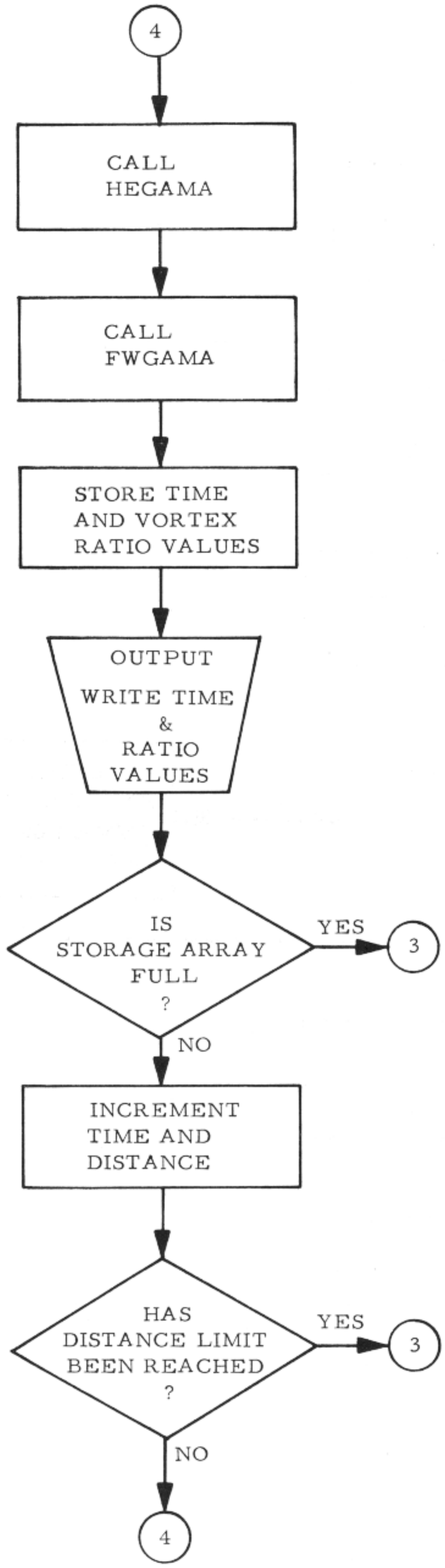
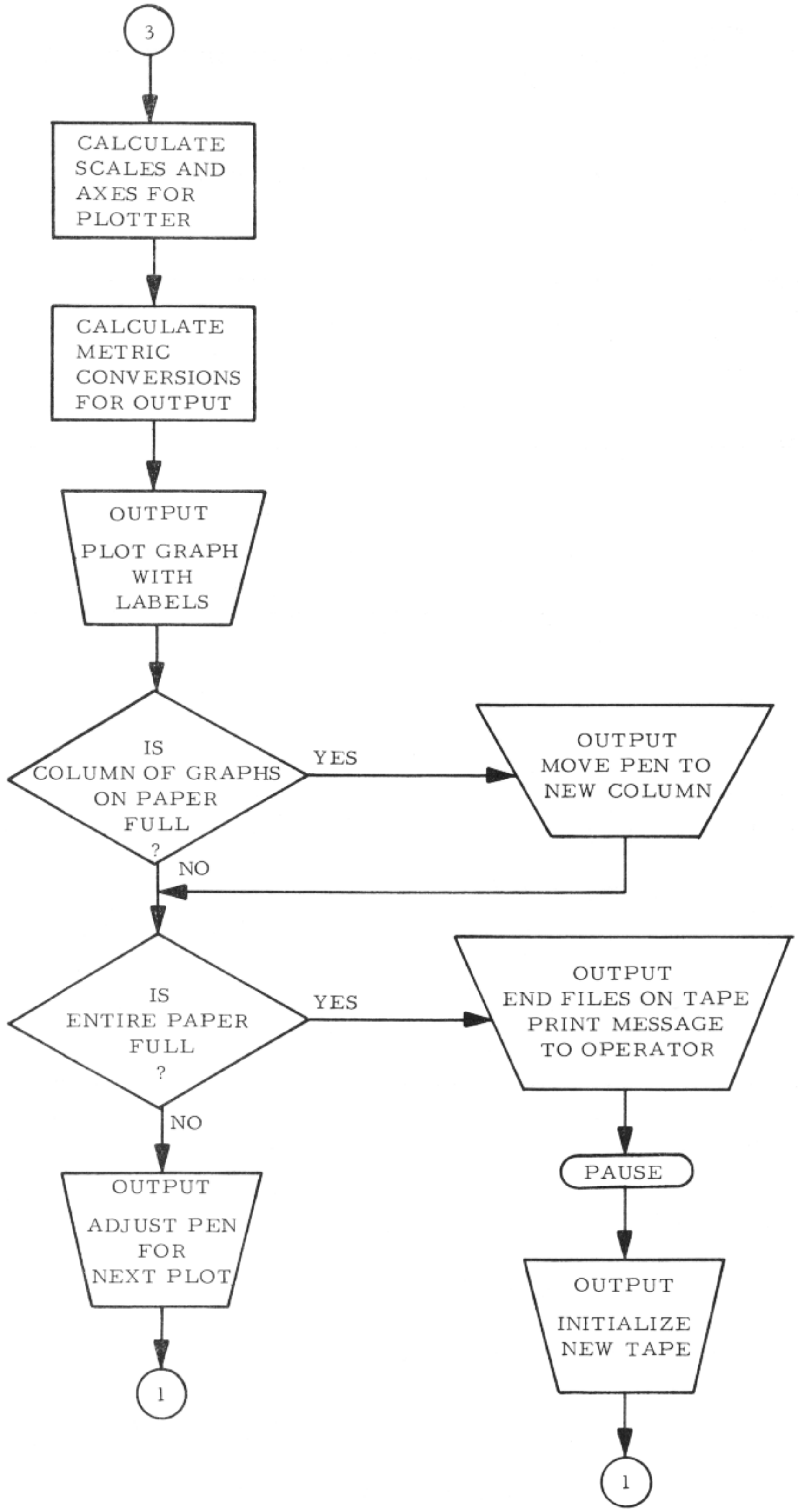

2
CALCULATE PARAMETERS
INCREMENT COUNTER (FOR PLOTS)
SET TIME LIMIT TO MAXIMUM
IS VELOCITY = 0 ?
NO
CALCULATE DISTANCE LIMIT = TIME LIMIT / VELOCITY
YES
INCREMENT TIME AND DISTANCE
OUTPUT
WRITE PARAMETERS
4


4
CALL
HEGAMA
CALL
FWGAMA
STORE TIME
AND VORTEX
RATIO VALUES
OUTPUT
WRITE TIME
&
RATIO
VALUES
IS
STORAGE ARRAY
FULL
?
YES
3
NO
INCREMENT
TIME AND
DISTANCE
HAS
DISTANCE LIMIT
BEEN REACHED
?
YES
3
NO
4


3
CALCULATE SCALES AND AXES FOR PLOTTER
CALCULATE METRIC CONVERSIONS FOR OUTPUT
OUTPUT
PLOT GRAPH WITH LABELS
IS COLUMN OF GRAPHS ON PAPER FULL ?
YES
OUTPUT
MOVE PEN TO NEW COLUMN
NO
IS ENTIRE PAPER FULL ?
YES
OUTPUT
END FILES ON TAPE
PRINT MESSAGE TO OPERATOR
NO
PAUSE
OUTPUT
ADJUST PEN FOR NEXT PLOT
OUTPUT
INITIALIZE NEW TAPE
1
1

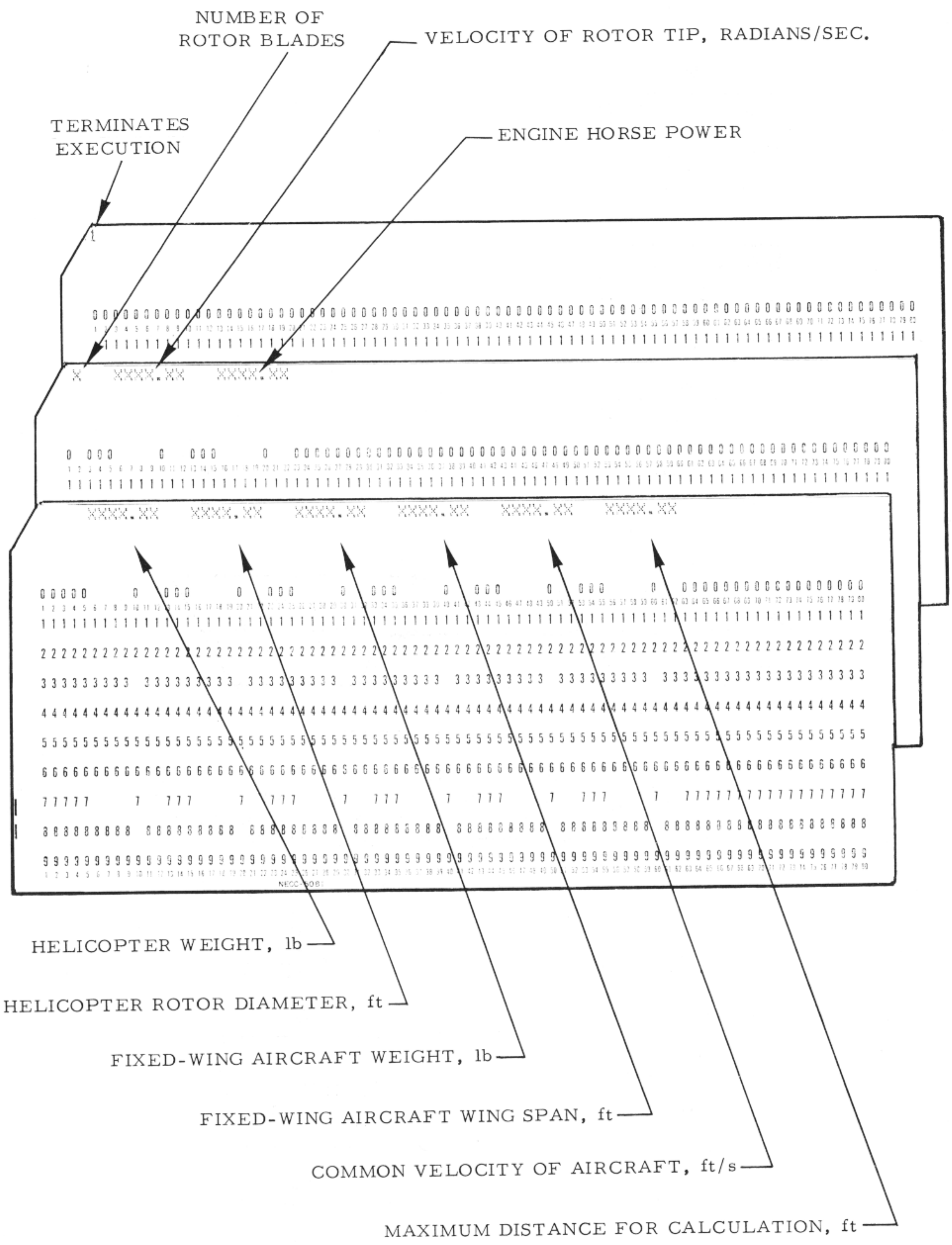


FIGURE D-2. INPUT CARDS FOR VORTEX WAKE COMPUTER PROGRAM

VORTEX INTENSITY AT HELICOPTER ROTOR TIP.

$$\Gamma_H = \frac{12 \quad T}{\eta \; \rho \; \Omega \; D_\rho^{2}}$$

T	=	Helicopter rotor thrust, pounds
η	=	Number of helicopter rotor blades
ρ	=	Air density, - 0.002378 slug/cubic foot
Ω	=	Velocity of helicopter rotor tip, radians/second
$D\rho$	-	Rotor Diameter, feet
Γ_H	=	Initial vortex intensity at rotor tip, square feet/second

DECAY OF FIXED-WING AIRCRAFT VORTEX.

$$\Gamma_{EFF} = \Gamma_A \left(1 - C \frac{-Rv^2}{4 \; \nu \; t}\right)$$

Rv	=	Vortex radius, feet
ν	=	Air viscosity, - 0.2001 square feet/second
t	=	Time since vortex generation, seconds
Γ_A	=	Initial vortex intensity, square feet/second
Γ_{EFF}	=	Present vortex intensity, square feet/second

DECAY OF HELICOPTER VORTEX.

$$\Gamma_{EFF} = \Gamma_H \left(1 - C - \left(\frac{\delta 1 + \delta 2}{2}\right)^2 \cdot \frac{Rv}{4 \varepsilon t^1}\right)$$

$$\delta_1 = \sqrt{\beta^2 + (\alpha-1)^2}$$

$$\delta_2 = \sqrt{\beta^2 + (\alpha+1)^2}$$

$$t^1 = \frac{t \eta \Omega}{2 \pi}$$

$$\alpha = \frac{D\rho}{Rv}$$

$$\beta = \frac{Z_{AP}}{Rv}$$

Rv = Vortex radius, feet

TT = 3.1415927

ε = Eddy viscosity of air, = 0.200 square feet/second

t = Time after pass of helicopter, seconds

η = Number of helicopter rotor blades

Ω = Velocity of rotor blade tip, radians/second

$D\rho$ = Rotor diameter, feet

Z_{AP} = Distance above vortex plane at which intensity is calculated, = 1 foot

Γ_H = Initial vortex intensity, square feet/second

Γ_{EFF} = Present vortex intensity, square feet/second