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**Prediction and Measurement of the Aerodynamic Interactions Between a Rotor and Airframe**

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**ABSTRACT**

Results of a detailed study of aerodynamic interactions are summarized. The test case is a two-bladed, rigid teetering rotor above a hemisphere-cylinder airframe in low-speed forward flight. A multi-faceted set of measurements, including surface pressures, thrust, flow velocity, and vortex trajectories has been acquired and used to develop and validate a potential-flow method to predict such interactions. The salient features of the measurements and the prediction method are summarized. The test case shows strong interaction effects. The interaction problem is seen to be dominated by unsteady, but mostly periodic, effects. The potential flow method is seen to be capable of predicting the dominant features of the interaction, in an azimuth-resolved fashion, under these conditions. However, it is inadequate to explain the details of the interaction of the strong vortices from the rotor with the airframe surface.

**NOTATION**

$a_1$	Longitudinal flapping angle of the rotor tip path plane. Positive when the trailing edge of tip path plane is higher than the leading edge.
$b_1$	Lateral flapping angle of the rotor tip path plane. Positive when the retreating side of rotor tip path plane is higher than the advancing side.
$C_p$	Pressure coefficient based on freestream dynamic pressure
$C_{p_u}$	Fluctuation in pressure coefficient about the mean.
$C_T$	Rotor thrust coefficient
$H$	Vertical distance from the airframe axis to the rotor blade quarter-chord line.
$q$	Free-stream dynamic pressure
$R$	Rotor radius
$U$	Flow velocity component along the tunnel freestream direction.
$V$	Flow velocity component along the vertical direction, positive downward.
$w$	Velocity component normal to the rotor tip path plane, positive in the outflow direction.
$X_B$	Distance along the airframe axis, measured from the nose.
$X_N$	Distance along the airframe axis from the rotor shaft centerline to the nose of the airframe.
$Y$	Spanwise co-ordinate, origin at the vertical plane through the airframe axis
$Z$	Height above airframe axis
$\mu$	Advance ratio, the ratio of tunnel freestream speed to rotor tip speed
$\theta$	Azimuthal location of measuring point in planes parallel to the tip path plane.
$\phi$	Azimuthal location on airframe surface in degrees. The top is 0 degrees.
$\psi$	Rotor azimuth in degrees. The front is 180 degrees.

**Subscripts**

$\infty$  tunnel freestream conditions.

## INTRODUCTION

The flow environment of a rotorcraft is unique in that the vehicle must operate inside the vortical wake generated by its rotors while hovering or flying at low speeds. The resulting interactions between components makes the prediction of the aerodynamics of a complete rotorcraft quite complicated. Interaction effects can make crucial differences to the performance of rotorcraft. For example, it is easily seen that small errors in the calculated net thrust in hover can translate to large changes in the maximum payload that can be lifted vertically. The periodic wake of the rotor can excite critical frequencies of other structural components. The asymmetry of the wake in forward flight can change side loads, control surface response, and handling qualities. Flow interactions with the ground surface can change the stability of the craft in low-level flight. The interaction can also have large effects on total drag. With better engines, higher disk loading, higher forward speeds, and low-altitude mission requirements, interaction effects have become even more crucial. Agility and compactness requirements demand close spacing between the rotor and the airframe. Elimination of the tail rotor demands better utilization of the asymmetry of the flow around the airframe. Thus, interaction phenomena are growing in significance.

The prediction of such interactions for a full-scale rotorcraft is a major undertaking. Rotor aerodynamic modeling requires large computational resources, and is still a research issue at the leading edge of supercomputer development. Modeling of three-dimensional, viscous, unsteady flow over complex shapes at high Reynolds number still poses major challenges. As such, computation of the time-resolved interactions between two such flows with a fully accurate physical representation is beyond current resources. Simplifying approximations are required, and codes based on such approximations must be carefully validated. Unfortunately, acquisition of complete data sets for such configurations is an equally daunting task. This paper describes the results to-date of an effort to make some headway against the interaction problem.

### Scope and Objectives

Sheridan and Smith (Ref. 1) defined the emerging research area of Interactional Aerodynamics and pointed out the various problem areas. There have since been several efforts in this field, on different aspects of the problem. Detailed references to these can be found in Refs ( 2,3,4 ), and will not be repeated here. The objective of the present paper is to summarize the efforts carried out at this laboratory over the past six years to study a limited subset of the interaction problem. Simultaneous efforts were conducted to compute the aerodynamic environment of a simple rotor/airframe configuration numerically, as well as to measure it in detail.

As in any large research problem, the first step was to limit the scope. Here this is performed by the following:

1. Compressibility effects are avoided. The maximum tip Mach number of the advancing blade is only 0.35.
2. The problem studied is the interaction between a rotor wake and a stationary solid body. Many other aspects of interactional aerodynamics are important, but are avoided at this stage.
3. The airframe model is kept geometrically simple, being a circular cylinder with a hemispherical nose. The definition of this geometry in a computational code is as inexpensive as possible, since body-of-revolution options can be used, and high panel density is required for geometric accuracy, if at all, only at the nose. The other, and perhaps more decisive, advantage of the axisymmetric shape is the resultant economy of instrumentation.

4. Separation effects are avoided. Typical rotorcraft shapes are rarely optimized for minimum drag; utility and volumetric efficiency require the use of bulky shapes with sharp corners and protruberances. These features cause flow separation, and the formation of vortices. Such effects are avoided in the present study. Somewhat fortuitously, the results also show that there is no significant separation of the mean flow even under the airframe.
5. The two-bladed rotor is made of two blades rigidly attached to each other, so that blade deflections, and the rotor coning angle, are demonstrably negligible.

The resulting configuration, though geometrically simple, allowed detailed experimental measurement of interaction phenomena using advanced diagnostic techniques, and the systematic examination of contributing factors. In close interaction with this effort, methods of modeling and computing these phenomena were sought, and a prediction scheme was synthesized and validated. The data base, and the results of the prediction method, are summarized here.

The features studied are briefly indicated in Fig. 1, which shows the flowfield of a single rotor blade interacting with that of a hemisphere/cylinder airframe. The strong tip vortex and the inboard vortex sheet are convected onto the airframe surface, causing distortion and interruption of the vortex system. The bound vorticity distribution of the rotor moves rapidly across and over the airframe. Energy is added by the rotor to the flow, forcing it over and around the airframe.

### **FACILITY DESCRIPTION**

Figure 2 shows the rotor-airframe configuration mounted in the 2.74 x 2.31m test section of the John J. Harper Low Speed Wind Tunnel. The airframe model is a sting-mounted circular cylinder 134 mm in diameter with a hemispherical nose. Eighty-seven surface pressure taps and eighteen microphone ports along the length of the cylinder provide for measurement of the mean surface pressure distribution as well as of temporal fluctuations about the mean at different locations on the surface. The cylinder can be moved axially and vertically. It can also be rotated (manually) about its axis, so that the single line of pressure taps can be used to measure the mean pressure distribution anywhere along the airframe surface (varying  $\phi$ ). The rotor is supported independently of the airframe on a drive shaft projecting downward from the tunnel ceiling. This arrangement allows variation of the spacing between the rotor hub and the airframe as well as ensuring that the only coupling between the rotor and the airframe is through the flow field. Provisions are available to mount the airframe on the tunnel force balance system; however, this was not done in this program since the airframe forces were calculated by integration of the surface pressure field and found to be quite small. The rigid installation and heavy metallic construction ensured that airframe vibrations were minimal in the range of frequencies studied, and did not contaminate surface pressure measurements. Towards the end of the work reported here, the rotor system was mounted on a structure attached to the force balance. This enabled the direct measurement of rotor thrust.

Two rotors with equal radii and planform areas have been used in these tests. The rotors have a solidity of 0.12. An unsuccessful attempt was made, using available rotor design codes, to design the pitch setting of both to produce the same thrust coefficient at the same advance ratio. The blades differ in that one has a rectangular planform and the outer portion of the other is tapered 3:1 (Fig. 3). The tapered blade serves to generate a test case with more uniform spanwise blade loading. Both rotors are very stiff, and are fixed to one another, so that coning is negligible. The blades are mounted in a simple teetering hub. The straight-bladed rotor is set at a fixed collective pitch of  $10^\circ$ , and the tapered one at  $11^\circ$ . The rotor speed is kept constant at 2100 rpm and the advance ratio is varied by changing the

tunnel dynamic pressure. The simulation of forward flight is completed by a 6-degree forward tilt of the rotor shaft as shown in Fig. 2.

### **Instrumentation**

Mean pressure distributions were measured using pressure switches and transducers which allowed sequential scanning of the static pressure ports. The pressure fluctuations were sensed by 6.25mm condenser microphones. These data channels were sampled simultaneously and digitized using a 16-bit A-D system, and the data acquisition and processing were completed by an HP1000 A700 computer. Data acquisition procedures are detailed in Refs. 5 and 6. All of the time-varying data were referenced to a pulse which occurred once every shaft revolution when one rotor blade was at a specified azimuthal position. Data were sorted into 6-degree (or shorter) azimuth intervals, and the contents of each interval were ensemble-averaged at the end.

Flow velocity was measured using a laser Doppler velocimeter (LDV) powered by a 5-watt Argon ion laser. The LDV and its 3-axis optical traverse system were mounted on a platform beside the test section, and were operated remotely from the control room. Lenses of focal lengths 1500 and 2100 mm are used to cover the region of interest. The LDV was operated in back-scatter. The flow was seeded using a pair of mineral-oil atomizer nozzles located downstream of the test section so that the seed particles traversed the entire tunnel circuit before entering the test section. This enabled uniform seeding of the test section flow field with particles whose sizes were in the 5-micron range. Steady data rates exceeding 1000 per second were easily obtained. As with the pressure data, the velocity data were also sorted according to the azimuth of the reference blade at the instant of collection, and ensemble-averaged at the end.

The 5-watt laser was also used to illuminate specified planes of the flow field with strobed light sheets, typically less than 4 mm thick. The uniformly seeded flow field scattered the light in the sheet, and the resulting image was recorded using a video system. Vortex core cross-sections appear in the otherwise uniform images as dark spots devoid of light-scattering particles. This enables observation and quantification of vortex dynamics, as detailed in Ref. 7. Some tests were also conducted with the seeder located upstream, so that densely seeded streams were drawn across the vortices. These tests served to capture the motion of the inboard vortex sheet.

Pitot tubes, Kiel probes, and hot-film anemometer sensors are moved about in the test section using a 3-axis computerized probe traverse. These are used for benchmark tests to validate the LDV measurements, to measure turbulence levels, and to identify the boundaries of the rotor wake.

### **Test Cases**

For all of the experiments conducted, except for some tests with the tapered blade which are discussed separately, the rotor shaft speed was held at 2100 rpm. This speed was quite stable, and only rarely drifted by as much as 1 rpm. Unless otherwise specified, the separation between the rotor and airframe was kept at  $H/R = 0.3$ , the closest spacing where the rotor blades were not in danger of hitting the airframe surface during starting and stopping. Likewise, the preferred streamwise position of the nose of the airframe was 1 rotor diameter upstream of the center of the hub, as shown in Fig. 2. These two parameters were varied, and pressure distributions obtained, to a limited extent. The cases tested are summarized in Table 1. They cover a range of advance ratios from 0.075 to 0.2. Due to the usual constraints faced by experimenters, all the possible measurements could not be conducted for all the test cases. The case of  $\mu = 0.1$  with the straight rotor was the most extensively studied. The flapping angles of the straight rotor are listed in Table 2 for

the different advance ratios. These were measured with an uncertainty of .02 degrees using the laser system.

As discussed in Ref. 3, tunnel confinement effects on the measured pressures and velocities were estimated, and found to be negligible for advance ratios below 0.06. Beyond an advance ratio of 0.2, the measured pressure distributions did not show any sharp features. Also, the lack of cyclic pitch variation was a cause for concern at higher advance ratios. These considerations determined the range of advance ratios used.

### **Prediction method**

Initially, several attempts were made to predict the observed test cases using available versions of existing interaction codes. These had very limited success under the strong-interaction conditions used here. Based on this experience, a new code was put together by taking the successful portions of existing codes, making new models for the missing phenomena, and devising appropriate feedback mechanisms.

A prediction code has been synthesized using potential-flow methods. The code follows the flow-chart shown in Fig.4. The influence of the airframe model on the flowfield at the rotor plane is calculated using the airframe panel code VSAERO, developed by Clark and Maskew (Ref. 8). This perturbation is accounted for in computing the inflow to the rotor plane using the Scully Free Wake code (Ref. 9). The rotor airloads are then determined for a given azimuthal orientation of the rotor, and the wake geometry is iteratively distorted to a force-free condition. The instantaneous velocity at the airframe surface is computed, and is used to generate a new potential flow solution (surface singularity distribution) including the unsteady potential due to rotor motion. The airframe effect on the velocity field at the rotor plane is recomputed, and the interaction loop is completed. This procedure is repeated until the values converge, and then for all other azimuthal orientations of the rotor. The surface pressures are then computed.

Since the rotor is simulated by a lifting line, one effect that is missed is that of the chordwise circulation distribution of the blade as it moves over the surface. This effect is added on at the desired surface points, by simulating the rotor blade section immediately above by a 2-D airfoil at the appropriate angle of attack.

## **Summary of Results**

### **a. Vortex Trajectories**

Fig. 5 shows the trajectories of the vortex system of the rotor, viewed from upstream (Fig. 5a) and from above (Fig. 5b). These results, repeated from Ref.7, were obtained using strobed laser sheet videography. They show that the tip vortex from each blade gets convected downwards and downstream, as expected. When it reaches the airframe, the portion closest to the surface is retarded, so that the trajectory distorts. Close to the surface, the vortices are no longer identifiable from flow visualization. Below the airframe, no vortex cores were identified using the laser sheet. The forward edge of the wake, as defined by vortex core positions, was computed with satisfactory accuracy by the prediction method.

### **b. Periodicity of the Flowfield**

The freestream turbulence intensity in the tunnel was found using hot-wire anemometry to be under 0.5%. The laser sheet visualization served to document what was clearly visible from all the other techniques as well: the vortex core locations and trajectories, as well as all other observed effects, with two exceptions, repeated precisely from cycle to cycle. The two exceptions were the following: Cases of *blade-to-blade* differences were observed during vortex-surface interactions, where very small deviations

in vortex trajectories could produce large deviations in the observed extrema of the pressure signatures. Again, this difference was quite consistent from one cycle to the next. Also, at an advance ratio of 0 (documented merely out of curiosity), the entire flowfield was seen to be quite unsteady. This latter effect is of no present consequence: any data below an advance ratio of 0.06 is considered to be influenced by tunnel confinement effects.

### **c. Velocity Field**

The velocity measurements performed are summarized in Table 3. Initially, the velocity variation in a plane parallel to and 12.7mm below the rotor tip path plane was extensively measured, with and without the airframe present. These measurements showed that the effects of the airframe were (a) to increase upflow (or decrease downflow) along a narrow region downstream of the hub, along the top of the airframe, (b) displace vortex trajectories so that the induced velocities near the blades at the front of the rotor disc were drastically modified, (c) to make blade-vortex interactions more likely by retarding the downward motion of vortices, and (d) to break up the vortices as they reached the airframe. These results are summarized in Fig. 6, which shows the difference in the time-averaged (velocity component normal to the rotor disk, measured under the disk, between the cases where the airframe was present and absent. The time-averaged data were obtained by averaging the azimuth-resolved data obtained at each measuring location, with a blade azimuth resolution of 6 degrees. The time-averaged velocities along rotor radii located at different azimuths were compared with predicted values. Fig. 7 shows a typical comparison, that at an azimuth of 217.5 deg. The agreement could no doubt be improved using newer, specialized rotor aerodynamics codes with more sophisticated rotor and wake models; however, such agreement was considered quite adequate for the present purpose of demonstrating rotor-airframe interaction prediction, in view of the success in predicting rotor wake effects at the airframe surface. The only hindrance to the use of more sophisticated rotor modeling in this problem would be the increased computer cost and the turn-around time, both of which were considered unnecessary for the present purposes.

Figures 8 and 9 show the comparison between measured and predicted values of the time-averaged velocity, along a line 12.7mm above the top waterline of the airframe. The error near the front part of the wake is substantial in Fig. 8; this is where the vortex-airframe interaction is strongest. Agreement elsewhere is good. This indicates that the velocity field calculated from the vortex trajectories and the unsteady potential is quite accurate after the interaction loop has been completed. Vortex distortions above the airframe must have been fairly well represented by the potential flow calculation for this to have occurred. The mismatch in the x-component of velocity (U) near the location of vortex-surface interaction is to be expected, since the details of this event are beyond potential-flow interpretations, as investigated in Ref. 10.

A far more stringent test of prediction capability comes when the periodic variations in velocity at specific locations are compared with measured data. Fig. 10 shows such a comparison at  $XB/R = 0.12$ , which is upstream of the wake. Here, excellent agreement is achieved. Further inboard, phase differences appear in the comparison as the effects of modeling the behavior of the strong vortex structures in the wake become apparent. Fig. 11 shows the comparison of the measured and predicted downward velocity at  $XB/R = 0.37$ . The downward velocity agrees well; it is the axial component, which is substantially modified by vortex-surface interactions, that shows serious problems, as seen in Fig. 12.

### **d. Unsteady Pressures**

This flow problem is inherently unsteady. Hence, it is more logical to consider the temporal variation of quantities before any attempt is made to interpret time-averages. The peaks of the unsteady pressure variation are much larger than any time-averaged difference in static pressure from free-stream conditions. It was found that the complicated shapes and

amplitude variations seen in the fluctuating pressure signature could be attributed mostly to just two major contributors: the blade passage effect and vortex interaction.

### **The blade passage effect**

At stations along the top of the airframe, the passage of each rotor blade is felt as a pressure pulse with a distinct waveform. This waveform can be calculated, over as much as 60-deg. azimuth intervals, by considering the blade passage to be the passage of a 2-d airfoil at angle of attack over the location in question. The angle of attack is easily obtained from the rotor code. Thus, the amplitude of the pulse increases from hub to tip. It is also felt outside the wake. As shown in Fig. 13, the shape and amplitude of the measured peak can be accurately computed using the above model. It may be stated with confidence that this is an effect caused by the lift distribution on the rotor blade. This effect is thus a purely aerodynamic excitation which can potentially cause structural vibrations, especially since it is felt in phase along the top of the airframe.

### **The vortex interaction effect**

Vortex interaction also causes sharp changes in surface pressure. As the tip vortex reaches the surface, the flow stagnates ahead of it. This leads to separation of the upstream boundary layer. What happens next is still open to question after several efforts to capture the details of the vortex interaction (Refs. 10,4). One view (Ref. 10) is that the separated boundary layer causes formation of a secondary vortex structure whose sense of vorticity is opposite to that of the primary vortex. This is illustrated by the measured velocity vector plots in Fig. 14, which shows the primary vortex profile disappearing into the surface, as a secondary vortex forms above it, grows, breaks away, and moves rapidly downstream. Another view is that this secondary structure (which is observed) is the effect of the inboard vortex sheet (Ref. 4). This is shown in Fig. 15. The other observed feature is the large pressure variation on the surface, with two distinct features, one corresponding to the tip vortex, and the other to the secondary structure. Surface interaction accelerates the secondary structure as it moves downstream, and retards the tip vortex until it dissipates into the surface boundary layer. Both models successfully explain the observation of vortex structures of opposite senses of rotation, as well as their subsequent behavior.

The details of the pressure variation during vortex interaction, however, are not yet predicted well, as seen in Fig. 16. In view of the apparent role of the boundary layer, it remains unlikely that the potential flow code can be extended to capture such details. It should be noted that this is the interaction between a curved, helical vortex with a curved surface, in the presence of substantial spatial and temporal velocity and pressure variations. The interaction occurs within the first 500 degrees of blade rotation after the vortex leaves the rotor tip. The shape of the viscous vortex core must influence the interaction. The vortex contains a substantial velocity component inside the core, directed along the vortex axis towards the vortex origin. This last fact was confirmed using laser velocimetry using a mirror to turn the optical axis to be perpendicular to the vortex axis. The results proved the existence of a large, rapidly varying axial velocity field. In view of these difficulties, full modeling of this interaction will remain a challenging problem for some time to come.

### **d. Time-averaged pressures**

The time-averaged surface pressure distribution is the easiest of the measurements to make, but its prediction requires proper modeling of a wide variety of time-varying phenomena. As discussed before, there is a large unsteady potential term to be taken into account in the formulation of the prediction code. Its effect can be partially seen in the stagnation pressure distribution across the wake. The wake from the rotor carries with it a large variation in stagnation pressure, as seen in Fig. 17. The stagnation pressure distribution in this figure was measured by traversing a Kiel-type probe. The simplest way to model this effect is by considering the rotor disc to be made up of a quilt of "actuator

panels", each panel being a segment of finite azimuthal and radial resolution. The stagnation pressure increase of the flow through each segment can then be calculated by a combination of momentum and blade element analyses. The results of such a computation are also plotted in Fig. 17. This procedure can in fact be performed after the the interaction loop has been computed, and the effect can be added on at the end to give the time-averaged surface-pressure distribution, as illustrated in Fig. 18. Here, the magnitudes of the different effects that go into the mean surface pressure are illustrated for comparison.

The prediction code has been improved to where this is not necessary. Instead, as suggested by Lorber and Egolf (Ref 11), an unsteady potential term has been added on in the interaction code. This, when combined with the blade passage effect computation, allows the accurate computation of the periodic pressure distribution, and the somewhat less accurate computation of the off-body velocity field as discussed before. A typical comparison of measured and computed surface pressure distributions are shown in Fig. 19. At the sides of the airframe, severe difficulties remain in calculating the pressure: the calculations conform to simple expectations on what should happen around a cylinder at angle of attack; the measurements do not. This is at present blamed on the vortex-surface interaction for lack of a better explanation. Surprisingly, excellent comparisons are obtained even on the sides when the cruder actuator-panel superposition model is used. Detailed pressure measurements are presented in Refs. (5) and (12), and the predictions are described in Ref. (2).

### **UNRESOLVED ISSUES**

Of course, several unresolved issues remain, even in the environment of the simple configuration studied here. It has been seen that the effects of the rotor hub and shaft are quite significant, and must be included in future modeling. The behavior of the vortex system after interaction with the airframe is largely unknown. So far, no vortex has been visible in the flow visualization studies below the airframe. Vortex interaction phenomena on the sides of the airframe are also yet to be studied.

Going to more complex configurations, one must expect the separated flows around the mast, fuselage, etc. to interact with the rotor flow and with each other. In particular, the presence of separated flow might destroy the near-perfect periodicity of the present experimental results. The behavior of lifting control surfaces in such a time-varying rotor wake is another subject of current study. Yet another step to be taken is to include a ground plane in close proximity to the test configuration.

### **SUMMARY**

An extensive study has been made on the prediction and measurement of the interactive aerodynamics of a simple rotor/airframe configuration. The test case selected has proved to be one where the interaction effects are quite large and significant. In fact, geometric scaling would indicate that the interactions seen here are much stronger than what would be influenced on a typical full-scale vehicle. The following conclusions may be drawn:

1. The rotor/airframe aerodynamic environment is basically unsteady. Approaches based on small perturbations to a steady flowfield will have great difficulty predicting the observed effects.
2. The current test case is almost purely periodic at the blade passage frequency. This may be due to the absence of grossly separated flows.
3. The airframe affects the outflow from the rotor by distorting and displacing vortex trajectories and by reducing the downflow from the rotor at stations directly above the airframe. These effects may also cause blade-vortex interactions.
4. The motion of the bound circulation distribution of each rotor blade over the airframe surface causes a large unsteady pressure signal at the surface. The amplitude and shape of

this pulse can be modeled using a moving 2-D airfoil at angle of attack. Being felt everywhere under the blade, this pressure fluctuation might provide in-phase excitation which could lead to structural vibrations. One implication is that this effect remains at high advance ratios, even when the wake itself may be swept back so that it does not flow over the airframe.

5. When the tip vortex from each rotor blade reaches the airframe, it disappears into the airframe boundary layer. Simultaneously, a secondary structure is observed above the primary vortex, with sense of rotation opposite to that of the tip vortex. This structure grows, and is convected rapidly downstream and dissipated. This interaction also causes significant pressure fluctuations.

6. Energy addition to the flow by the rotor can be included in a prediction code using either an actuator panel model, or using an unsteady potential term. These models predict stagnation pressure increases which are borne out by measurements. Including this effect is vital to the successful prediction of the time-averaged pressure distribution on the airframe surface.

7. Using a simple potential flow -based airframe prediction code and a vortex-wake / lifting line rotor code, it has proved possible to compute most of the observed periodic and time-averaged phenomena observed in this test case.

8. Vortex-airframe interaction phenomena remain outside the realm of the effects successfully predicted by this code.

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### LIST OF FIGURES

- Figure 1: Simplified representation of the phenomena encountered.
- Figure 2: Rotor-airframe configuration installed in the John J. Harper Wind Tunnel.
- Figure 3: Rotor blade geometry
- Figure 4: Flow-chart of the computational scheme
- Figure 5a: Composite view of vortex trajectories from upstream.  
b: Composite view of vortex trajectories from above.
- Figure 6: Difference between the normal velocity below the rotor disk between cases with the airframe present and absent.
- Figure 7: Predicted and measured time-averaged velocity 12.7mm below the rotor disk along the radius at an azimuth of 217.5 deg.
- Figure 8: Predicted and measured time-averaged axial velocity along the top waterline of the airframe, 12.7mm above the surface.
- Figure 9: Predicted and measured time-averaged downward velocity along the top waterline of the airframe, 12.7mm above the surface.
- Figure 10: Predicted and measured periodic variation of the axial velocity upstream of wake impingement.
- Figure 11: Predicted and measured periodic variation of the downward velocity inside the leading edge of the wake.
- Figure 12: Predicted and measured periodic variation of the axial velocity inside the leading edge of the wake.
- Figure 13: Comparison of 2-d airfoil model of the blade passage effect with measured data.
- Figure 14: Velocity profiles above the airframe surface, measured during the interaction of a vortex with the surface. From Ref. 10.
- Figure 15: Interpretation of the measured and visualized vortex interaction phenomena. From Ref. 4.
- Figure 16: Comparison of the measured and predicted surface pressure variation at a station where vortex interaction occurs. Both the primary tip vortex and the secondary vortex affect the pressure at this station. From Ref. 2.
- Figure 17: Kiel-probe data on the stagnation pressure variation across the wake, compared to predictions using an actuator-panel model.
- Figure 18: Terms contributing to the mean surface pressure.
- Figure 19: Comparison of the computed pressure variation along the top surface of the airframe with measured values.
- Table 1: Thrust coefficient for rectangular and tapered-blade rotors with airframe present and removed.
- Table 2: Flapping angles of the straight-bladed rotor.
- Table 3: Summary of velocity measurement test cases.

