CORRELATIONS OF ROTOR WAKE / AIRFRAME INTERACTION MEASUREMENTS WITH FLOW VISUALIZATION DATA

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ABSTRACT
Interaction between the aerodynamics of the rotor and the airframe causes large unsteady pressure fluctuations on rotorcraft airframes. A two-bladed rotor and a hemisphere-cylinder airframe model are used to study these pressure fluctuations in a wind tunnel, simulating low-speed forward flight conditions. Controlled displacement of the airframe is used to obtain finely-spaced pressure data. These are correlated with azimuth-resolved, quantitative laser sheet visualization of the dynamics of the tip vortices and the inboard vortex sheets from the rotor, along the top of the airframe. Three prominent periodic interactions are observed on the airframe surface. These are the effects of blade motion, the approach and impingement of the tip vortex, and of the vortex sheet. These interactions determine, to a large degree, the overall pressure distribution on the airframe surface, and hence the airframe unsteady airloads. The pressure signatures from the blade passage and the vortex impingement are quite different, and are explained using 2-dimensional models.

NOMENCLATURE

- $C_p$: Pressure coefficient based on freestream dynamic pressure
- $C_{P\text{mean}}$: $(P_{\text{mean}} - P_\infty)/q_\infty$
- $C_{P\text{inst}}$: $(P_{\text{inst}} - P_\infty)/q_\infty$
- $C_{P\text{steady}}$: $C_p(V_{\infty}/V_{\text{steady}})^2$
- $C_{P\text{unsteady}}$: $P_{\text{unsteady}}/q_\infty$
- $C_T$: Rotor thrust coefficient, $T/(\rho \pi \Omega^2 R^4)$

- $h$: Vertical distance between 2-D vortex core and surface
- $H$: Vertical spacing between rotor hub center and airframe centerline
- $P_{\text{mean}}$: Mean static pressure
- $P_\infty$: Freestream static pressure
- $P_{\text{inst}}$: Instantaneous static pressure
- $P_{\text{unsteady}}$: Unsteady component of static pressure ($P_{\text{inst}} - P_{\text{mean}}$)
- $q_\infty$: Freestream dynamic pressure

- $R$: Rotor radius
- $T$: Rotor Thrust
- $U$: Velocity at surface beneath 2-D vortex

- $V_{\text{blade}}$: Velocity of blade section
- $V_{\text{steady}}$: Far field velocity in a steady reference frame.
- $V_\infty$: Tunnel free-stream speed
- $X$: Streamwise distance from hub center
- $X_L$: Local horizontal coordinate
- $X_N$: X co-ordinate of airframe nose

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It was shown that the longitudinal aerodynamic characteristics of the airframe were significantly affected by the rotor and hub. Wind tunnel tests conducted by Wilson and Mineck also showed that the rotor wake imposed a significant yawing moment on the airframe. Trept conducted wind tunnel tests on a 0.15-scale Bell 222 main rotor and a set of fuselage fairings. Test cases included a range of forward flight conditions from $\mu = 0.10$ to $\mu = 0.30$ as well as some hover tests. Results indicated that the rotor's effect on the fuselage was considerably more important to aircraft performance than the fuselage effect on the main rotor.

Recent analytical efforts have also examined various aspects of rotor-airframe interaction. Lorber and Egolf combined an existing lifting line prescribed wake with a source panel fuselage code to arrive at an unsteady rotor-airframe interaction analysis program. They emphasized the importance of accounting for unsteady terms in the velocity potential when computing fuselage surface pressures. Bound vortices (which represent the rotor blades) along with free vortex filaments (representing the rotor wake tip vortices) were found to be the largest contributors to flow unsteadiness. Ref. 5 presents analytical results from modelling the flowfield of the basic rotor/airframe configuration shown in Fig. 1. Further analytical comparisons with experimental data were made by Mavris who devised a method to modify and couple an existing lifting line free-wake rotor code and a existing vortex surface panel code. He succeeded in modeling the unsteady and steady pressure and velocity fields of the configuration of Fig. 1, except for the effects of vortex-surface interactions. His work was conducted in parallel with the work reported in this paper.

The experiment reported in this paper follows up on the systematic

| $X_B$ | Streamwise distance from nose of airframe |
| $Y$ | Transverse distance from hub center |
| $Z$ | Vertical distance from airframe axis |
| $Z_L$ | Local vertical coordinate |

**Greek Symbols**

- $\mu$: Rotor advance ratio, $V_\infty / (\Omega R)$
- $\rho$: Density of air
- $\Psi$: Rotor azimuth in deg., measured from downstream position
- $\Omega$: Rotor blade angular velocity
- $\Gamma$: Vortex core strength
- $\Delta$: Incremental change in a quantity

**INTRODUCTION**

The helicopter in forward flight represents a unique problem in aerodynamics. The rotor adds significant levels of energy to the flow, producing a non-steady wake dominated by regions of concentrated vorticity. Also, the rotor blade tips have large velocities relative to the airframe components. As a result, the flow over the airframe is highly non-steady. It involves strong interactions arising from the rotor operating in close proximity to the airframe and from the wake impinging on the airframe surface. The main features of rotor/airframe interactions are summarized by Sheridan and Smith. These include flow unsteadiness, redirection, distortions and vortex surface impact.

Several researchers have conducted experimental investigations in which the interactions between a rotor and airframe in forward flight were examined. Betzina and Smith examined the steady state interaction effects between a rotor and a body of revolution. Time-averaged forces and moments were measured independently for both the rotor and airframe for various flight conditions. In addition, mean surface pressures were measured along the body.
progression of work done on this configuration over the years. Ref. (8), presented in 1985, described the facility and showed the first results from it, demonstrating the large magnitude of the unsteady pressure fluctuations near the wake-impingement regions relative to the time-averaged distributions, and the need for prediction techniques that recognized these. No such techniques existed at the time, and no existing code could predict the observed data even with qualitative consistency. Ref. (9) documented the steady and unsteady pressure distributions over the airframe surface, and Ref. (10) presented results from the strobed laser sheet flow visualization technique, showing the vortex trajectory from the rotor plane to the airframe. Distortions of the vortex filaments about the airframe were observed. Results indicated that the tip vortex filament was strongly affected by the presence of the airframe. The vortex filament became distorted and finally disappeared from the flow visualization after interacting with the airframe surface. The filament did not appear to remain in contact down the sides of the airframe. Instead, it was split by the airframe and the ends of the filament began to dissipate as each end was swept past the airframe. Results indicated what happened during the vortex-surface interaction, and to correlate these measurements with the observations from the dynamic flow visualization. This was to provide the first dynamic representation of such a vortex-surface interaction, and is the primary subject of this paper.

Scope and Objectives

This paper aims to present the detailed dynamics, and provide a detailed interpretation, of the pressure variation observed along the top of an airframe due to rotor and wake interactions. The pressure variations are compared with quantitative time-resolved flow visualization data, which are phase-synchronized with the pressure data. The experimental results presented here are an excerpt from ref.14. Previous results had demonstrated the need for closer spacing of measurement locations to interpret vortex phenomena near the surface. An experiment was performed to obtain unsteady pressure measurements with fine spatial resolution along the top of a cylindrical airframe subject to rotor wake interactions in forward flight. These are correlated with flow visualization data. This experiment aims to provide insight into the flow field phenomena that determine the effects of various rotor-wake/airframe interactions. Improved prediction methods can be developed once these phenomena are better understood.

FACILITY DESCRIPTION

The experiments were conducted in the John J. Harper 2.13m x 2.74m (7x9-foot) wind tunnel at the Georgia Institute of Technology. The model configuration and notation used are shown in Fig.1. The airframe model consists of a cylinder (134 mm dia.) with a hemispherical nose. It is sting mounted at zero angle of attack, independent of a 2-bladed teetering rotor which is driven by a shaft projecting down from the tunnel ceiling. A row of 53 static pressure taps is used to measure the mean surface unsteady pressure transducers, (or, as it turned out, by moving the airframe) the details of what happened during the vortex-surface interaction, and to correlate these measurements with the observations from the dynamic flow visualization.
pressure distribution. The symmetric sting mount permitted rotation of the cylinder, so that the single row of pressure taps served to cover the entire surface. Each mean pressure value is the average of 5000 samples, digitized over a period of 5 seconds, corresponding to 175 rotor revolutions. The amplifier gain on the signal conditioner was software-controlled to optimize precision.

The one-piece rotors used in these tests are very stiff so that elastic motions and coning of the blades are negligible. Results presented here are from tests using an untwisted, constant section NACA 0015 rotor with an 86 mm chord and 0.45 m radius. The advance ratio \( \mu \) is 0.075. The rotor thrust is measured by mounting the rotor system on a frame fixed to the wind tunnel external balance, and is accurate to 0.1lb, giving a worst-case error of 0.98%. Absence of collective and cyclic rotor controls minimizes hub effects in the data. A flapping hinge allows rotor blade flapping, and the shaft is inclined 6 deg. The rotor speed is kept at 2100 (\( \pm 1 \)) rpm and the tunnel velocity is varied to achieve the desired advance ratio. The tip path plane orientation is measured using a laser system\(^1\). At \( \mu = 0.075 \), the leading edge of the tip path plane (\( \psi = 180 \)) is 1.89 deg. below the horizontal, and the edge on the retreating side (\( \psi = 270 \)) is 1.76 deg. above the horizontal.

The spacing between the airframe axis and rotor hub center (H/R) is 0.30 for the data presented here, while the airframe nose is positioned directly below the forward edge of the tip path plane (\( X_N/R = -1 \)). These parameters facilitate clear measurements of the dominant interaction effects to aid the development of analytical prediction methods. Obviously, they do not simulate any particular helicopter design. The influence of tunnel walls on the data is negligible\(^14\) for \( \mu > 0.06 \).

### Unsteady Pressure Measurement

Condenser microphones were used to measure instantaneous surface pressure, relative to the mean. Analog signals from the microphones were digitized at 12600 samples per second, with each sample block containing 360 points, synchronized with one cycle of the rotor. The data were sorted into 6-deg. intervals of rotor azimuth \( \psi \) in order to reduce storage requirements. The data within each interval were averaged over 100 rotor revolutions and converted to \( C_{punsteady} \). The instantaneous pressure at any point on the airframe is obtained by summing the mean and unsteady components.

These parameters were determined as follows. The delay times, sampling rate and sample periods for the time-averaging were determined by trial and error, until results were seen to be precise, stable and repeatable. Examination of pressure spectra obtained by random sampling\(^13\) confirmed that signal energy was negligible beyond about 2000 Hz, so that no anti-aliasing filters were necessary. Phase-synchronized measurements with finer resolution (50400 Hz) were performed as required to verify that no details were being lost during vortex passage. The only filters in the circuit were the 0.1Hz high-pass imposed by the condenser microphone's pressure equalization passage around the diaphragm, and the 10KHz low-pass filter setting in the amplifiers (100KHz for the 50400Hz sampling). Constant monitoring of oscilloscope traces by the experimenters provided guidance on the cycle-to-cycle repeatability, and the variation in signature shape at different locations. It must be mentioned that the extrema of the pressure traces may be underestimated because of the finite size of the microphone sensors.

The spatial resolution of unsteady pressure data was limited by the spacing between microphone ports on the
airframe (38.1 mm). Flow visualization suggested the need for finer spacing to capture the details of vortex impingement, especially at low advance ratios. A method was devised to translate the microphones to intermediate locations. The front section of the airframe was translated in the streamwise direction using a computerized traverse (Fig. 2) while the rear portion remained rigidly attached to the sting mount. A plastic sleeve sealed the gap between the airframe segments. Translating the front segment thus moved the microphones to the desired locations in the wake impingement zone.

The major assumption in this technique was that the periodic pressures measured at a fixed point (relative to the rotor hub) do not change appreciably as the airframe nose moves incrementally to a new location. For example, if periodic pressures are measured on the airframe at Xb/R=0.5 and then remeasured at Xb/R=0.55 with the nose moved by ΔXN/R=.05, the two cases should be nearly identical. Discrepancies between the two cases can become greater when the measuring points are close to the nose, since differing nose positions can affect the wake slightly. However, points of vortex impingement on the airframe considered in these tests were at least one airframe diameter downstream of the nose. Also, the nose was moved by a maximum of only 19 mm from the nominal position. Figure 3 illustrates the changes in the unsteady pressure signature measured at a fixed point relative to the rotor hub (X/R=-.425) for two airframe nose positions. The first curve (with square symbols) corresponds to the output from microphone port 6 with the airframe nose translated forward by 19 mm (XN/R=-1.042). The second curve (with circular symbols) represents the measured pressure at the same location relative to the rotor hub (X/R=-0.425), except this time corresponding to the output from microphone port 5, and with the airframe nose translated downstream by 19 mm (XN/R=-0.958).

Although the nose position has been translated a total of 38 mm, the difference in microphone output signals between the two cases is small. The results shown in Fig. 3 are typical and show that the change in microphone output signal due to nose translation is a higher-order effect, negligible to a first approximation. Subsequent testing, with the airframe mounted on the traversing system, was conducted for airframe translation increments equal to the microphone diameter (6.25 mm).

Quantitative Flow Visualization

Flow visualization tests utilized a strobed laser sheet and mineral oil seeding. This technique allowed the blade tip vortex coordinates to be obtained as a function of the blade azimuth angle Ψ. The position of the vortex sheet structure could also be deduced from the flow visualization data. Flow visualization data were obtained over the airframe centerline, on the front half of the airframe, where measurements indicated the most significant pressure fluctuations. This allowed correlations between pressure measurements and flow visualization to be made in a region of high flow field activity.

Flowfield Features

A qualitative view of the flow field structures that cause the interaction effects is depicted in Fig. 4. The wake structure is a region of concentrated free vortex filaments and a trailing vortex sheet. Both the tip vortex and trailing vortex sheet are observed by flow visualization. These structures, along with the passage of the rotor blades themselves, are found to produce major effects on the airframe surface.

The tip vortex core and the vortex sheet are made up of filaments with opposite signs of circulation. The sheet does not appear to roll up into a concentrated core. It moves with the local flow velocity, being seen as a discontinuity in the flow velocity.
component tangential to the sheet surface. The velocity field over the airframe was investigated extensively by Liou\textsuperscript{12}. Details of vortex sheet motion during interaction with the airframe surface are given in Ref.\textsuperscript{13} along with a discussion on the tip vortex behavior.

**RESULTS**

The instantaneous pressure at a point on the airframe surface is made up of a mean and an unsteady component. Changes in this instantaneous pressure can be correlated with rotor and wake details determined from flow visualization by matching the known rotor azimuth angle between the pressure and flow visualization data sets. The unsteady pressure data were added to the mean pressure data using an interpolation scheme, since the spacing between data points was different for the two cases. Flow visualization data were also interpolated, since vortex core positions were required specifically at the 6-degree increments in rotor azimuth angle at which the microphone data were recorded. Results discussed here were obtained over an entire rotor revolution, but only one-half a revolution is used in this presentation since, for a 2-bladed rotor, the data repeat every 180 deg.

Figure 5 contains a sequence of plots showing the measured airframe surface pressures along the top of the airframe from $X_B/R=0$ to $X_B/R=1.0$. The sequence begins with a plot of the mean pressure distribution, followed by plots of the instantaneous pressures measured at 6-deg. intervals of rotor azimuth. The vertical scale in each plot ranges from $C_{P_{\text{mean}}}=-12$ to $C_{P_{\text{mean}}}=18$. The insets represent the top view of an idealized rotor wake, drawn assuming that the vortex filaments move with the freestream speed without mutual interactions. The vortex core positions, shown as black dots in the main plot, are based on flow visualization.

The instantaneous pressure distributions are arranged sequentially and are referred to by the azimuth angle of the reference blade. Beginning at the top of the left column in Fig. 5, the blade is shown aligned with the airframe in the $\Psi=0$ position. The single dominant characteristic at $\Psi=0$ is the effect of blade passage, which causes static pressure differentials as large as 18 times $q_\infty$. This positive pressure pulsation is directly proportional to the blade loading and hence the blade bound circulation\textsuperscript{9}. The blade passage effect diminishes as the rotor-airframe spacing is increased.

At $\Psi=0$ two vortex cores are shown as black dots in the main plot; one at $X_B/R=0$, from the blade at $\Psi=180$, and one at $X_B/R=0.27$ from the reference blade (see inset) at $\Psi=0$. Although more vortex filaments are sketched in the inset, only two vortex cores are actually visible in the vertical plane extending above the airframe centerline. The other filaments in the plane of symmetry are either below the top of the airframe or have disappeared from flow visualization.

At $\Psi=6$ the leading edge of the blade passage pressure field has passed beyond the airframe due to blade rotation. The effect of the tip vortex core near $X_B/R=0.27$ is clearly evident at $\Psi=6$, where it creates a strong suction on the airframe surface below. At this and subsequent blade azimuth angles, the tip vortex is associated with a strong suction peak as it convects streamwise, passing over the airframe. The suction peak on the airframe surface follows the streamwise motion of the tip vortex core and becomes stronger as the vortex core approaches the airframe surface.

The instantaneous pressure distribution at $\Psi=12$ shows a stronger suction peak since the tip vortex is moving closer to the airframe surface. At $\Psi=18$, passage of the blade trailing edge pressure field again results in elevated pressures on the airframe surface. $C_{P_{\text{inst}}}$
near $X_B/R=0.2$ increases from a value of 2.7 (at $\Psi=12$) to a value of 6.0 at $\Psi=18$, thus indicating the trailing edge of the blade passage effect. The peak suction pressure due to the tip vortex is elevated by this blade passage effect, and therefore is greater than at $\Psi=12$, when the vortex was further from the airframe. The vortex suction effect on the airframe actually increases quite consistently as the vortex impinges on the airframe. However, this fact can be obscured by the simultaneous effects of the blade passage.

The diminishing effect of blade passage is noted at subsequent azimuth angles. Fig. 5 shows that the elevated surface pressures due to blade passage become negligible at $\Psi=30$. After $\Psi=30$, changes in the instantaneous surface pressure distribution are due to the effects of the tip vortex and the vortex sheet. The effects of blade passage are not sensed again until $\Psi=156$. At this azimuth angle, the leading edge of the pressure field from the reference blade leads to elevated instantaneous pressure along the top of the airframe. The effects peak at $\Psi=180$, after which the entire sequence repeats. In all, approximately 60 deg. of azimuthal travel are involved in the blade passage effect.

The streamwise motion of the tip vortex is now discussed, beginning at $\Psi=30$. The flow visualization data at consecutive azimuth angles show that the streamwise component of the core’s convective velocity decreases as the core approaches the airframe surface. This is also deduced by observing that the suction peak caused by the vortex appears at almost the same location $X_B/R=0.31$ from $\Psi=30$ until the vortex disappears at $\Psi=48$.

The decelerated streamwise motion of the vortex core is attributed to the vorticity distribution set up on the airframe surface in response to the approaching vortex filament. If the airframe surface is treated as being locally 2-dimensional, then an image vortex can be used to represent the solid surface of the airframe. The image vortex has a circulation which tends to induce an upstream flow component where the tip vortex is located. Thus, as the tip vortex approaches the airframe surface, its convective velocity in the streamwise direction should decrease. Note that vortex filaments generated over the rear of the airframe ($\Psi=0$) would be accelerated streamwise by their image systems.

The vortex effect on the airframe displays a maximum suction peak between $\Psi=36$ and $\Psi=40$, just before the vortex disappears from the light sheet in flow visualization. Flow visualization tests showed that after the vortex disappeared from the light plane, it split down either side of the airframe while diffusing rapidly. This is represented in the figure insets by the filaments being separated into two parts on either side of the airframe. During the diffusion process the vortex effect on the airframe is drastically reduced (from a peak suction of $C_{P_{inst}} = -12$ before the filament disappears, to $C_{P_{inst}} =-3$ just after it disappears from the light sheet). Although the vortex disappears from flow visualization after $\Psi=42$, its effect, although smaller, remains evident and well defined in the surface pressure signature for an extremely long period thereafter. Since a low pressure region remains on the airframe surface after the tip vortex has disappeared (from flow visualization), it appears that some type of vortical region must also remain there.

The surface pressure suction peak attributed to this diffused vortical region moves streamwise at a speed much lower than the free stream. Note that during the 132 deg. of subsequent blade rotation (from when the tip vortex disappeared at $\Psi=48$ to $\Psi=180$), particles in the free
stream will move a distance $\mu \Delta \Psi$. Thus $\Delta X/R$ is 0.177. The diffused vortical region causing the suction peak moves a distance $\Delta X/R < 0.05$ during the same interval. Since the motion of this diffused region is retarded with respect to the free stream, it must have the same circulation sense as the original tip vortex. The effect of the diffused vortical region creates a sharp suction peak between $\Psi = 48$ and $\Psi = 90$. At later azimuth angles the peak becomes less concentrated and diminishes in magnitude.

Fig. 5 also shows the asymmetry of the tip vortex impingement pressure distribution. The airframe surface inside the rotor wake (to the right of the impinging tip vortex) has higher pressures than the surface outside the wake. This distinction is seen most clearly to either side of the tip vortex-induced suction peak, which indicates consistently higher pressures on the downstream side. The time-averaged result of this effect is a sharp rise in mean pressure coefficient signature upon entry into the wake zone.

Another phenomenon observed in the instantaneous pressure signature is the effect of the vortex sheet. The vortex sheet is visible when the seeder is located upstream of the airframe for heavy seeding. Fig. 6 shows particle streaklines above the airframe for $\Psi = 45$. The vortex sheet (shown as a line containing vorticity filaments with circulation opposite to the tip vortex) impinges on the surface shortly after the tip vortex from the previous blade disappears. The effect of vortex sheet impingement is clearly evident (Fig. 5) beginning at $\Psi = 78$ as a second suction peak near $X_B/R = 0.5$. The sheet interaction becomes stronger at later stages of impingement, as seen at values of $\Psi$ greater than 78.

As seen in Fig. 6 the region of vortex sheet impingement is associated with a circulation opposite to that of the tip vortex core. As a result, the movement of the vortex sheet signature in the surface pressure distribution contrasts sharply with that observed for the tip vortex. From the time when the vortex sheet effect is first noted ($\Psi = 78$) to the time when it is last visible ($\Psi = 156$), it moves streamwise by $\Delta X/R = 0.20$. In the same period, the freestream moves a distance corresponding to $\Delta X/R = 0.094$. Thus, the region where the vortex sheet strikes the surface moves downstream at roughly twice the freestream speed.

The reasons for the accelerated motion of the sheet impingement zone are twofold. The first is based on the geometry of the vortex sheet cross-section over the airframe centerline. Referring to Fig. 4, the outboard edges of the sheet are lower (descend faster) than inboard sections of the sheet. Thus, the sheet is inclined to the airframe surface and the outboard edge will be the first to contact the airframe. This would occur even in the absence of a freestream, since it is due to the vertical motion of the inclined sheet and not to the streamwise motion. As the sheet continues to descend, the edge where it hits the airframe would appear to move streamwise, simply due to the sheet's inclination to the airframe (even in hover). The second reason for the faster motion can be seen from an equivalent image vortex system, set up on the surface in response to the circulation in the sheet. The circulation sense of the image is such that it would induce streamwise motion above the surface. This would also cause the sheet structure to move downstream faster than the freestream. Such flow accelerations have been measured and are reported in Ref. 13. The effect of the vortex sheet is fairly weak compared to that of the tip vortex or blade passage. Since the circulation strength is spread over the entire sheet, its effect at the edge where it impinges on the
airframe is never as strong as the effect of the concentrated tip vortex.

Modelling of Unsteady Effects

As already seen, the unsteady portion of the pressure signatures on the airframe surface is of the greatest importance. An attempt was made to explain the observed features. Fig. 5 showed that tip vortex impingement on the airframe was dominated by a low pressure (suction peak). Blade passage was identified by a positive pressure pulsation on the airframe surface. The spine of the airframe represents a geometric plane of symmetry. The tangent to the vortex trajectory is approximately perpendicular to the airframe axis at the spine. The blade span is parallel to the airframe axis as the blade crosses the spine. For these reasons, two-dimensional modeling of these effects at the spine was considered justifiable as a first step. Two cases of 2-D vortex motion over a solid surface are shown in Fig. 7. For both cases, it is assumed that the vortex strength (\( \Gamma \)) is the same, and that all velocities are relative to the stationary surface.

Fig. 7 shows a bound vortex moving with velocity \( V_{\text{blade}} \) in a stream of speed \( V_\infty \) (where \( V_{\text{blade}} > V_\infty \)), and a free vortex (tip vortex filament) located at height (h) above the surface. \( V_\infty \) is the speed of the uniform flow over the surface in the absence of the bound vortex or the free vortex. The free vortex moves streamwise at the local flow velocity, which includes the free stream velocity and a contribution due to the image vortex system which satisfies the solid surface boundary condition. The latter velocity contribution at the vortex center is \( \Gamma/(4\pi h) \). \( V_\infty \) is the reference velocity, assumed to be the same on both sides of Fig. 7. The issue here is the difference in the surface pressure signatures of a bound vortex and a free vortex. In the actual rotor-airframe geometry, the bound vortex is directed parallel to the airframe axis, while the free vortex is directed normal to it. Thus \( V_\infty \) is not to be interpreted as the tunnel freestream speed.

In the reference frame fixed to the surface, both the bound vortex and the free vortex produce identical instantaneous velocity patterns. However, the two cases produce completely different pressure effects on the surface. The moving bound vortex left of Fig. 7 causes increased pressures (higher than \( P_\infty \)) on the surface while the free vortex causes a predominantly decreased pressure on the surface. This apparent discrepancy of having identical velocity fields but opposite pressure effects is resolved in the unsteady nature of the problem. Neither of the situations posed in Fig. 7 are steady problems when examined in the surface fixed reference frames.

Figure 8 shows the steady streamline pattern associated with the bound vortex of Fig. 7, along with a plot of the velocity ratio \( U/V_{\text{steady}} \) and \( C_{P_{\text{steady}}} \) at the surface(s). These are results well-known to students of aerodynamics, and presented here simply to illustrate a point. The bound vortex experiences a force in the +\( Z_L \) direction, with the flow moving from right to left with velocity \( V_{\text{steady}} = V_{\text{blade}} - V_\infty \). In this steady reference frame, velocities alone are sufficient for determining the local static pressure. The net velocity (U) at the surface below the bound vortex has decreased from the far-field value because of the induced velocity of the bound vortex and its image vortex. Consequently, a higher pressure exists on the surface as indicated in the \( C_{P_{\text{steady}}} \) curve.

Fig. 9 shows the streamline patterns for the free vortex of Fig. 7. In this steady reference frame, the far-field velocity \( V_{\text{steady}} \) is equal to \( \Gamma/(4\pi h) \). This is equal but opposite to the velocity induced by the image vortex at the free vortex core. Note that no forces are experienced by the free vortex, since it moves with the local flow velocity.
The free vortex streamline pattern shown in Fig. 9 remains the same regardless of the strength of the vortex. Stagnation conditions occur at two points on the surface at $X_L/h = \pm \sqrt{3}$ as indicated by $C_{P\text{steady}}=1$. A suction peak with $C_{P\text{steady}}=-8$ occurs directly beneath the vortex at $X_L/h=0$. The free vortex system thus leads to both high and low pressures on the surface. However, the low pressure peak of $C_{P\text{steady}}=-8$ dominates the pressure signature. This explains why the instantaneous vortex core velocity profile data reported in Ref. 13 indicate nearly stagnant flow between the vortex and the airframe ($V/V_\infty$ is essentially -1) and yet the surface pressure coefficient is negative.

In the above 2-D approximations the computed pressures are the same regardless of whether the reference frame is steady or unsteady. However, the value of pressure coefficient depends on the reference velocity chosen to normalize the pressure. In order to obtain the usual definition of pressure coefficient normalized by freestream dynamic pressure (i.e., $C_p$), the following transformation is required:

$$C_p = C_{P\text{steady}}(V_{\text{steady}}/V_\infty)^2$$

The quantity $V_{\text{steady}}/V_\infty$ reaches a maximum of $(1/\mu)-1$ for the bound vortex case. Thus $C_p$ can greatly exceed $C_{P\text{steady}}$, as is noted during the blade passage. The large values of $C_p$ correspond to the large values of $C_{P\text{inst}}$ observed during blade passage in Fig. 5.

For the free vortex, the value of $V_{\text{steady}}/V_\infty$ will depend upon the height of the vortex core above the surface. For a viscous core model this ratio will be limited. However, it can easily lead to values of $C_p$ far lower than those computed in the steady reference frame in Fig. 9. This explains why vortex impingement on the airframe surface is dominated by a strong negative pressure coefficient, while the blade passage effect is associated with a positive pressure pulsation.

This illustration serves to explain the observed differences between the effects of the blade passage and the tip vortex interaction. It is the velocity in the appropriate steady reference frame that determines the pressure sensed by the airframe. In the actual 3-dimensional case, however, there is no general reference frame that will permit an equivalent steady analysis. The tip vortex filaments are actually curved, and undergo non-steady motion toward the airframe surface. In order to properly predict the pressures associated with the actual unsteady velocity field, especially on the sides of the airframe, where no symmetry exists, use of the unsteady Bernoulli equation is essential. The unsteady terms in such an analysis will have a major impact on the determination of the time-varying pressure field associated with the vortex systems of rotorcraft.

**CONCLUSIONS**

The flow field between a model rotor and airframe has been investigated through a series of wind tunnel experiments. The pressure variation due to interaction effects of the rotor and its wake on the airframe has been correlated with quantitative flow visualization data, allowing specific interaction effects to be identified with the structure causing the effects. Simple theoretical models for explaining the interaction behavior have been developed. Some conclusions are stated below.

1. Mean static pressure coefficients greater than unity on the airframe surface indicate energy addition to the flow by the lifting rotor. The mean pressure on the airframe cannot be determined from the local flow velocity alone, unlike in fixed-wing problems.

2. The unsteady pressure on the surface is periodic at the blade passage frequency.
3. The unsteady pressure fluctuations due to interaction are much larger than the mean interaction effects experienced by the airframe.

4. A large pressure excursion occurs on the airframe as the blade passes over it. This is related to the blade bound circulation. Instantaneous pressure differentials can be many times the freestream dynamic pressure.

5. The second largest unsteady effect on the airframe surface is caused by interactions with the tip vortex. These are associated with very low pressures on the airframe. The suction peaks as the vortex impinges on the surface. After impingement, the vortex filament suffers strong viscous effects and breaks down into separate filaments which travel independently past the sides of the airframe. A weak low pressure region remains at the impingement location even though the tip vortex is no longer seen by flow visualization.

6. The tip vortex effect is carried a large distance from the blade which originated the vortex. On the contrary, blade passage effect is sharply reduced by increasing the separation distance between the blade and the airframe surface. Thus, in practical rotorcraft configurations, the vortex effect may dominate the instantaneous pressure signature, rather than the blade passage effect.

7. A weaker interaction is that due to the vortex sheet. This is characterized by a low pressure region on the airframe. This effect is minor compared with that of the tip vortex, but is observable in the unsteady pressure signature.

8. The motion of the tip vortex is strongly affected by the airframe. Portions of the filament that lie over the airframe are affected in a manner qualitatively consistent with treating the surface as an image plane. Tip vortices descending on the front of the airframe are decelerated streamwise, while the vortex sheet at nearby locations is accelerated.

9. Simple vortex models for explaining the unsteady interaction effects can be established by finding the appropriate steady reference frame for the particular interaction effect. These models furnish a basis for more complete treatments since they correctly predict the trends observed in the measured unsteady data.

10. Interaction effects determine, to a large degree, the airframe pressure distribution.

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