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Correlations of Rotor/Wake - Airframe Interactions with Flow Visualization Data.

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ABSTRACT

Wind tunnel tests were conducted on an idealized rotor-airframe configuration in forward flight. High resolution unsteady surface pressure measurements were obtained along the top of the airframe in order to examine the interaction effects of the rotor and wake on the airframe. In conjunction with these pressure measurements, flow visualization tests were conducted in order to identify flow field features which cause the interaction effects. Results indicate that there are three prominent interactions with the airframe. In order of significance these are: blade passage effect, tip vortex effect and vortex sheet effect. These interactions determine, to a large degree, the overall pressure distribution on the airframe surface, and hence the airframe unsteady airloads. It is crucial that future aerodynamic interaction codes have the ability to correctly predict these effects, especially when high disk loadings and small rotor-airframe spacings are being considered in a rotorcraft design.

NOMENCLATURE

C_p	Pressure coefficient based on freestream dynamic pressure
C_{Pmean}	$(P_{mean} - P_\infty)/q_\infty$
C_{Pinst}	$(P_{inst} - P_\infty)/q_\infty$
$C_{Psteady}$	$C_P(V_{steady}/V_\infty)^2$
$C_{Punsteady}$	$P_{unsteady}/q_\infty$
C_T	Rotor thrust coefficient, $T/(\rho\pi\Omega^2R^4)$
h	Vertical distance between 2-D vortex core and surface
H	Vertical spacing between rotor hub center and airframe centerline
P_{mean}	Mean static pressure
P_{inst}	Instantaneous static pressure
$P_{unsteady}$	Unsteady component of static pressure
q_∞	Freestream dynamic pressure
R	Rotor radius
T	Rotor Thrust
U	Velocity at surface beneath 2-D vortex
V_{blade}	Velocity of blade section
V_{steady}	Velocity in a steady reference frame. $V_{steady}=V_{blade}-V_\infty$
V_∞	Tunnel free-stream speed
X	Streamwise distance from hub center
X_L	Local horizontal coordinate
X_N	X co-ordinate of airframe nose
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

μ	Rotor advance ratio, $V_\infty/(\Omega R)$
ρ	Density of air
Ψ	Rotor azimuth, measured from downstream position
Ω	Rotor blade angular velocity
Γ	Vortex core strength
Δ	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 that is dominated by regions of concentrated vorticity. Also, the rotor blade tips have large velocities relative to the airframe components. As a result, the aerodynamics of the airframe are highly non-steady and involve strong interactions that arise from the rotor operating in close proximity to the airframe and from the wake impinging upon the airframe surface. The main features resulting from rotor/airframe interactions are summarized by Sheridan and Smith[1]. These include flow unsteadiness, flow redirection, flow 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[2] examined the steady state interaction effects between a rotor and a body of revolution. Steady state 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. 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[3] also showed that the rotor wake imposed a significant yawing moment on the associated airframe.

Trept[4] 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 μ =0.10 to μ = 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[5] 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. Reference 5 contains some analytical results (from modelling the present experimental case) which may be used for comparing with the experimental results presented here. Further analytical comparisons with experimental data were made by Mavris [6,7] who devised a method to modify and couple an existing lifting line free-wake rotor code and a existing vortex surface panel code. Comparisons with preliminary results from the present expermental study were used to validate the computed results at specific points on the airframe surface.

Results presented in this paper have their origins in experimental tests reported in Ref. (8) through (10). In Ref. 9, large excursions in the mean airframe surface pressure distribution were observed where the wake boundary impinged on the airframe. Large unsteady fluctuations about the mean were also reported. Distortions of the vortex filaments about the airframe are discussed in Ref. 8. 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. Ref. 12 offers an interpretation and discussion of the different stages of vortex filament interaction with a cylindrical surface.

Scope and Objectives

This paper aims to provide a detailed interpretation of the pressure variation observed on the top of the airframe by comparison with quantitative time-resolved flow visualization data. The experimental results presented here are an excerpt from ref.13. Previous results had demonstrated the need for fine spatial resolution 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 experimental results described here were obtained from tests conducted in the John J. Harper 2.13m x 2.74m (7x9-foot) low speed wind tunnel at the Georgia Institute of Technology. The rotorcraft test configuration consisted of an idealized cylindrical airframe (134mm in diameter) with a hemispherical nose. It was supported on a sting mount, independent of a 2-bladed teetering rotor which was driven by a shaft projecting down from the wind tunnel ceiling. The airframe was fitted with a row of 53 static pressure taps starting at the nose and terminating at the model base. The static pressure taps were used to measure the mean surface pressure, by averaging 5000 digitized samples from a pressure transducer from each tap over a period of 5 seconds, corresponding to 175 rotor revolutions. The symmetric sting mount permitted rotation of the cylinder, so that the single row of pressure taps served to cover the entire surface. The airframe was mounted at zero angle of attack with respect to the tunnel freestream.

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 86mm chord and 0.45m radius. Data were obtained for advance ratios between 0.075 and 0.20, but only the μ=0.075 case is presented here. The rotor thrust at μ=0.075 was measured by mounting the rotor system on a frame fixed to the wind tunnel strain gage balance, and corresponds to a thrust coefficient C_T of 0.008425. The thrust measurement is accurate to within 0.1lb, giving a worst-case error of 0.98%.

The 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. During tests, the rotor speed is kept at 2100 ($\pm$1) rpm and the test section velocity is varied to achieve the desired advance ratio. The tip path plane orientation is measured using the tunnel laser system[14].

The spacing between the airframe axis and rotor hub center (H/R) was 0.30 for the data presented here, while the airframe nose was 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 model configuration and notation used are shown in Fig.1.

The influence of wind tunnel walls on the pressure measurements was shown to be negligible[14] for μ >0.075. More details are given in Ref.13 along with data from a similar rotor with a 3:1 taper ratio.

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 ψ in order to reduce storage requirements. The data within each interval were averaged over 100 rotor revolutions and converted to $C_{p_{unsteady}}$. The instantaneous pressure at any point on the airframe was 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. The amplifier gain on the signal conditioner was software-controlled to optimize precision. Examination of pressure spectra obtained by random sampling 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 passages. 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 measurement locations.

The spatial resolution of unsteady pressure data was limited by the physical spacing between microphone ports on the airframe (38.1mm). Flow visualization suggested that a finer spacing was needed to capture the details of vortex impingement, especially at lower advance ratios. A method was devised to translate the existing microphones to intermediate locations. Since it was not possible to translate the microphones relative to the airframe, the front section of the airframe was translated in the streamwise direction using a computerized traverse (Fig. 2) while the rear portion of the airframe remained rigidly attached to the sting mount. A plastic sleeve sealed the gap between the airframe segments. The rotor was mounted independently of the airframe through the wind tunnel ceiling. Translating the airframe segment thus moved the microphones to the desired locations in the wake impingement zone.

The major assumption in applying 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 $X_B/R=0.5$ and are then remeasured at $X_B/R=0.55$ with the nose moved by $\Delta X_N/R=-.05$, 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. This, combined with moving the nose by only a small distance (9mm maximum from nominal position), resulted in only minor changes in the measured surface pressures at the same spatial location (relative to the rotor hub) for different nose positions.

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 marker symbols) corresponds to the output from microphone port 6 with the airframe nose translated forward by 19mm ($X_N/R=-1.042$). The second curve (with circular marker 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 19mm (X_N/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 (6.25mm). The total distance translated was 19mm from the nominal position; thus, only small errors in the measured pressure are expected when the airframe nose is moved to various intermediate locations.

Quantitative Flow Visualization

Flow visualization tests utilized a strobed laser sheet and mineral oil flow seeding. The visualization technique, described in Ref. 15, allowed the rotor blade tip vortex coordinates to be obtained as a function of the blade azimuth angle Ψ. In addition, the position of the vortex sheet structure could be deduced from the flow visualization data. Measurements indicated that the most significant pressure fluctuations occurred over the top-front of the airframe. Accordingly, flow visualization data were obtained over the airframe centerline, on the front half of the airframe. This allowed correlations between pressure measurements and flow visualization to be made in a region of concentrated flow field activity.

Flowfield Features

Before presenting results from pressure measurements, it is useful to become acquainted with the flow field structures that cause the interaction effects. The main features in the flow field are depicted schematically in Fig. 4. The wake structure can be described as a region of concentrated free vortex filaments and a trailing vortex sheet. Both the tip vortex and trailing vortex sheet were observed during the course of the investigation by flow visualization. These structures, along with the rotor blades themselves, were 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, manifesting itself as a discontinuity in the flow velocity component tangential to the sheet surface. Details of the velocity field in the region depicted in Fig. 4 were investigated extensively by Liou[14]. Details of vortex sheet motion during interaction with the airframe surface are given in Ref.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 x-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-degree intervals of rotor azimuth. The vertical scale in the mean pressure plot varies from $C_{P_{mean}}$ =-12 to

C_{Pmean} =18 to show the instantaneous pressures on the same scale. The insets represent the top view of an idealized rotor wake. The tip vortex filaments of the insets are drawn such that the filaments move with the freestream speed only and do not interact with each other. The vortex core positions, shown as black dots in the main plot, are based on flow visualization. The filament geometry and the blade position in the insets should be used as a guide to interpreting the main plot.

The instantaneous pressure distributions are arranged sequentially and are referred to by the respective blade azimuth angle. Beginning at the top of the left column in Fig. 5, the blade is shown aligned with the airframe in the Ψ=0position. The single dominant characteristic at Ψ=0 is the effect of blade passage, which causes static pressure differentials approximately 18 times q_∞. This positive pressure pulsation is directly proportional to the blade loading and hence the blade bound circulation[13]. Since it is not primarily a thickness effect, a rotating lifting line is probably sufficient for capturing many of the blade effects experienced by the airframe.

At Ψ=0 two vortex cores are shown as black dots in the main plot; one at X_B/R=0, from the blade at Ψ=180, and one at X_B/R=0.27 from the reference blade (see inset) at Ψ=0. Although more vortex filaments are sketched in the inset, only two vortex cores were 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 due to seed particle entrainment.

At Ψ=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 Ψ=6, where it creates a strong suction on the airframe surface below. At this and subsequent blade azimuth angles, it is seen that 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 Ψ=12 shows a stronger suction peak since the tip vortex is moving closer to the airframe surface. At Ψ=18, passage of the blade trailing edge pressure field again results in elevated pressures on the airframe surface. Note that C_{Pinst} near X_B/R=0.2 increases from a value of 2.7 (at Ψ=12) to a value of 6.0 at Ψ=18, thus indicating the trailing edge of the blade passage effect. Note also that the peak suction pressure due to the tip vortex is elevated by this blade passage effect, and therefore is greater than at Ψ=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 presence of the blade passage effect.

The diminishing effect of blade passage is noted at subsequent azimuth angles. Fig. 5 shows that the elevated surface pressures due to blade passage effect become negligible at Ψ=30. After Ψ=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 Ψ=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 Ψ=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 Ψ=30. Close inspection of the flow visualization data at consecutive azimuth angles shows 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 Ψ=30 until the vortex disappears at Ψ=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 (Ψ=0) would be accelerated streamwise by their image systems[12].

The vortex effect on the airframe displays a maximum suction peak between Ψ=36 and Ψ=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 airfame. 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 Ψ=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.

It is observed that 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 Ψ=48 to Ψ=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 Ψ=48 and Ψ=90. At larger azimuth angles the peak becomes less concentrated and diminishes in magnitude.

A further observation from Fig. 5 concerns the asymmetry of the tip vortex impingement pressure distribution. It is noted that 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 observed 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 creates the sudden rise in mean pressure coefficient observed in the mean pressure signature upon entry into the wake zone.

Another phenomenon observed in the instantaneous pressure signature regards the effects induced by the vortex sheet. The vortex sheet was visible during upstream seeding of the flow field, thus allowing these correlations to be made. Fig. 6, excerpted from Ref.13 depicts a streakline above the airframe for Ψ=45 or 225. The vortex sheet (shown as a line containing vorticity filaments with circulation opposite to the tip vortex) was observed to impinge on the airframe surface shortly after the tip vortex from the previous blade disappeared. The effect of vortex sheet impingement on the airframe surface is clearly evident (Fig. 5) beginning at Ψ=78 by virtue of a second suction peak appearing near $X_B/R=0.5$. The sheet interaction effect becomes stronger at later stages of vortex sheet impingement, as seen at consecutive values of $\Psi>78$.

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 (Ψ=78) to the time when it is last visible (Ψ=156), it moves streamwise by $\Delta X/R=0.20$. In the same time period, particles in the freestream move a distance corresponding to $\Delta XR=0.094$. 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 vortex 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 accelerated motion is attributed to an equivalent image vortex system, which is set up on the airframe in response to the circulation in the sheet being near a solid boundary. The circulation sense of the vortex sheet is such that its image would induce streamwise motion above the airframe surface. This in turn would also cause the sheet structure to move downstream faster than the freestream speed. Such flow accelerations have been measured and are reported in Ref. 14. The effect of the vortex sheet is fairly weak in comparison to that of the tip vortex or blade passage effects. This is expected, 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

It was seen in Fig. 5 that tip vortex impingement on the airframe was dominated by a low pressure (suction peak). Blade passage was indentified by a positive pressure pulsation on the airframe surface. These two effects are examined next by constructing a 2-dimensional model of the interaction. 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 (Γ) is the same, and that all velocities are relative to the stationary surface.

On the left of Fig. 7 is a representation of a lifting line moving with velocity V_{blade} in a flow with free stream speed V_∞ (where $V_{blade}>V_\infty$). The right side of Fig. 7 represents a tip vortex located at height (h) above the surface. Since the tip vortex is a free vortex, it moves streamwise at the local flow velocity. The local velocity is the sum of the free stream velocity and a contribution due to the image vortex system which satisfies the solid surface boundary condition. The velocity contribution at the tip vortex center due to the image vortex is $-\Gamma/(4\pi h)$. Thus, the net convective velocity of the free vortex is $V_\infty - \Gamma/(4\pi h)$. V_∞ is the reference velocity, assumed to be the same on both sides of Fig. 7.

In the reference frame with the surface at rest, both the bound vortex and the free vortex produce identical instantaneous velocity patterns - both at the surface and in the surrounding flow field. A velocity measuring instrument will see no difference between the instantaneous flows in these two situations. However, the two cases produce completely different pressure effects on the surface. The surface on the left of Fig. 7 (which represents a surface beneath a rotor blade) experiences increased pressures (higher than P_∞), while the surface on the right (beneath a tip vortex) experiences a predominantly decreased pressure due to the vortex. This apparent discrepancy of having identical velocity fields but opposite pressure effects is resolved in the unsteady nature of the problem. Note that neither of the situations posed in Fig.7 are steady problems when examined in the surface fixed reference frames.

By examining the two situations in Fig. 7 in their respective steady reference frames, the differences between the two cases become apparent. 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_{steady} and $C_{Psteady}$ at the surface (s). The bound vortex experiences a force in the $+Z_L$ direction, with the flow moving from right to left with velocity $V_{steady}=V_{blade}-V_\infty$. 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 $C_{Psteady}$ curve.

The steady reference frame for the tip vortex modelled on the right of Fig. 7 is given in Fig. 9. This figure shows the streamlines corresponding to a free vortex over a solid surface. In this steady reference frame, the far-field velocity V_{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 $C_{Psteady}=1$. A suction peak with $C_{Psteady}=-8$ 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 $C_{Psteady}=-8$ dominates the pressure signature. This explains why the instantaneous vortex core velocity profile data reported in Ref.8 indicate nearly stagnant flow between the vortex and the airframe (V/V_∞ 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 freestram dynamic pressure (i.e., C_P), the following transformation is required:

$$C_P = C_{Psteady}(V_{steady}/V_\infty)^2$$

The quantity V_{steady}/V_∞ reaches a maximum value of $(1/\mu)-1$ for the bound vortex case. Thus C_P can greatly exceed $C_{Psteady}$. The large values of C_P correspond to the large values of C_{Pinst} observed during blade passage in Fig. 5. For the free vortex, the value of V_{steady}/V_∞ 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 Cp far lower than those computed in the steady reference frame in Fig. 9. This explains why vortex impingement with 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 in the effects of the blade and the tip vortex. 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 to take place. The vortex filaments, in addition to introducing effects due to their curvature, are also undergoing non-steady motion toward the airframe surface. In order to properly predict the pressures associated with the actual unsteady velocity field, 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 pressure field associated with the unsteady 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. 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 through the action of the lifting rotor. Thus, the mean static pressures 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 interaction effects are much larger than the mean interaction effects experienced by the airframe.
4. A large positive pressure pulsation occurs on the airframe as the blade passes over it. This is related to the blade bound circulation. Instantaneous pressure differentials reach 18 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 filament is strongly affected by the presence of the airframe. Portions of the filament that lie over the airframe are affected in a manner consistent with treating the surface (locally) as an image plane. Tip vortices descending on the front of the airframe are decelerated streamwise, while portions of the vortex sheet at nearby locations are 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.

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REFERENCES

1. Sheridan, P.F., Smith R.P., "Interactional Aerodynamics - A New Challenge to Helicopter Technology," Proc. 35th An. Forum of the A.H.S., Wash., D.C., May 1979.
2. Betzina, M.D, Smith C.A and Shinoda, P., "Rotor/Body Aerodynamic Interactions", NASA TM-85844, Oct 1983.

3. Wilson, J.C. and Mineck, R.E., "Wind Tunnel Investigation of Helicopter-Rotor Wake Effects on Three Helicopter Fuselage Models," NASA TMX3185, 1975.
4. Trept T., "A 0.15-Scale Study of Configuration Effects on the Aerodynamic Interaction Between Main Rotor and Fuselage," NASA CR NAS2-11268, Sep. 1986.
5. Lorber P.F., Egolf T.A.,"An Unsteady Helicopter Rotor- Fuselage Interaction Analysis," NASA CR4178, 1988.
6. Mavris D.N., "An Analytical Method for the Prediction of Unsteady Rotor/Airframe Interactions in Forward Flight," Ph.D. Thesis, Georgia Instt. of Tech., Dec. 1988.
7. Mavris D.N., Komerath N.M., McMahon H.M., "Prediction of Unsteady Aerodynamic Rotor-Airframe Interactions," AIAA Paper 88-4420, August 1988.
8. Brand A.G., Komerath N.M., McMahon H.M., "Results From Laser Sheet Visualization of a Periodic Rotor Wake," Journal of Aircraft, Vol. 26, No.5, pp. 438-443, May 1989.
9. Brand A.G., McMahon H.M. and Komerath N.M., "Surface Pressure Measurements on a Body Subject to Vortex Wake Interaction," AIAA J., Vol 27, No.5, p.569-574, May 1989.
10. Komerath, N.M., McMahon, H.M., and Hubbartt, J.E., "Aerodynamic Interactions Between a Rotor and Airframe in Forward Flight," AIAA-85-1606, July 1985.
11. McMahon, H.M., Komerath, N.M., and Hubbartt, J.E., "Studies of Rotor-Airframe Aerodynamic Interactions in Forward Flight," AIAA Paper 85-5015, October 1985.
12. Quackenbush T.R., "Free Wake Calculation of Rotor Flow Fields for Interactional Aerodynamics," Proceedings of the 44th Annual Forum of the American Helicopter Society, Washington D.C., June 1988.
13.Brand A.G., "An Experimental Investigation of the Interaction Between a Model Rotor and Airframe in Forward Flight," Ph.D. Thesis, Georgia Instt. of Tech., March 1989.
14. Liou S.G., "Velocity Measurements on a Lifting Rotor /Airframe Configuration in Low Speed Forward Flight," Ph.D. Thesis, Georgia Institute of Technology, Dec. 1988.
15. Brand A.G., Komerath N.M. McMahon H.M., "A Laser Sheet Technique for Visualizing a Periodic Rotor Wake," Journal of Aircraft, Vol.25, No.7, July 1988,pp. 667-668.