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Interaction Between a Vortex Dominated Wake and a Separated Flowfield

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ABSTRACT

The interaction between a rotor wake and the separated flow downstream of an axisymmetric back-step is considered, as a basic representation of higher-order aerodynamic interactions around rotorcraft. The velocity and surface pressure fields are related to previous flow visualization results. The major visualized features are confirmed by azimuth-resolved velocity data and vorticity contours which are phase-linked to the rotor. Vortex interaction features are also seen clearly in the azimuth-resolved surface pressure. A secondary, counter-rotating vortical structure appears downstream of the tip vortex. While the blade frequency is the primary temporal descriptor of the problem, multiple time scales do occur, with pressure spectra showing peaks at the shear layer natural frequencies, the rotor frequency, and their harmonics. Instability of the tip vortex trajectories causes a large spectral peak at the rotor frequency. Vortex interaction with the boundary layer generates local unsteadiness, as seen from histograms of velocity taken during 0.5-degree azimuth intervals.

NOMENCLATURE

C_p	$(P - P_\infty)/ q_\infty$
$C_{P_{unsteady}}$	$(P_{unsteady} - P_{mean})/ q_\infty$
P_{mean}	Mean static pressure
P_∞	Freestream static pressure
P_{inst}	Instantaneous static pressure
$P_{unsteady}$	Unsteady static pressure $(P_{inst} - P_{mean})$
R	Rotor radius
U	Velocity along X direction
W	Velocity along Z direction
U_∞	Tunnel free-stream speed
Xs	Step-heights downstream from the step
Z	Step-heights above step edge.
μ	Rotor advance ratio, $U_\infty/(\Omega R)$
Ψ	Rotor azimuth in degrees, measured from downstream position
Ω	Rotor blade angular velocity
φ	Azimuthal location around airframe.

INTRODUCTION

The prediction of the flowfield around a rotorcraft in forward flight is an ambitious undertaking, yet, after many years of sustained effort, it is beginning to become feasible. Many of the dominant features of the unsteady, three-dimensional aerodynamic interactions between the rotor and the fixed surfaces can be computed from first principles. There are still major unresolved problems. Prime among these is the issue of massively-separated flows over curved surfaces, with unsteady, three-dimensional onset flow, dominated by strong vortices.

Initial efforts to predict rotorcraft aerodynamic interactions used steady rotor wake models, and steady airframe flow calculations. Learning from these efforts, better success has been achieved recently by using the fact that the flowfield is dominated by two phenomena: a) the strong tip vortices and b) the strong pressure pulses caused by motion of the potential field of the rotor blades[1]. Both of these can be described using a single frequency: that of the blade passage, which occurs with perfect phase stability. Thus, what appears to be a hopelessly complex flow problem can be attacked using simple potential-flow concepts in a periodic co-ordinate system. Lorber and Egolf[2], and our group[3,4] used such approaches; the former using a generalized rotor wake model, and the latter using a free wake. These efforts were taken to the limits of potential-flow modeling: they had to circumvent the effects of vortices impinging on solid surfaces. Confirmation of the success of such approaches came when modeling test cases where massive flow separation was known not to occur.

Recently, success has been shown in situations with strong viscous effects in the aerodynamic interaction problem. Conlisk et al[5] have succeeded in modeling the primary features of the close interaction of strong vortices on curved surfaces; Blisset al[6] are including vortex-surface interaction effects in rotorcraft calculations. In anticipation of advancement in computational techniques, we are studying a case with massive flow separation. This paper follows our initial exploration of the problem[7] which used flow visualization and initial pressure measurements. We now investigate the periodic velocity field, and study the surface pressure in more detail.

EXPERIMENTAL CONFIGURATION

The experimental configuration is the same as that described in Ref. 7, and is shown in Fig. 1. The 2.13 m x 2.74 m tunnel test section permits measurements at $\mu > 0.06$ without significant wall effects. The step height on the airframe is 39mm, and the boom radius is 30mm. The boom has a sliding key which carries four 6.35mm microphones and is driven by a stepper motor and worm gear. The 2-bladed, NACA 0015, untwisted teetering rotor has seen extensive prior use[8-11]. The rotor speed was held at 1050 rpm. Tunnel freestream speed was varied to adjust advance ratio. The vertical spacing between the rotor hub and the airframe axis was 0.4R. This is larger than the 0.3R used for the majority of the previous measurements[1, 8-11], since the airframe now extends further forward, and catastrophic blade-surface encounters were feared. At 5 m/s, the Reynolds number of the boundary layer at the step, based on the length from the nose stagnation point is 225,000. Previous measurements of surface pressure on the cylinder surface[10] have shown broad-band turbulence spectra.

The laser Doppler velocimeter (LDV) at the John J. Harper Wind Tunnel has been described in detail in Ref. (9); it is used in the one-component, backscatter mode with frequency shifting. A lens with 1500mm focal length was used. Two downstream seeders enabled uniform test section seeding with mineral oil droplets of about 1 to 4 microns, satisfactory in most of the flowfield, but too large for accurate data inside the rotational core of the tip vortex.

The configuration was selected to enable clear measurements and to facilitate modeling in computational codes. The features of the flowfield without separation have been discussed in Refs (1) and (10), among others. The sharp backstep specifies the separation point, an important simplification in an unsteady flowfield with large spatial and temporal gradients. The axisymmetric boom geometry enables efficient use of a minimal number of pressure transducers. We do not claim to use parameter values that are representative of any existing helicopter: the priorities are to understand the flowfield and facilitate analysis.

VISUALIZATION

In Ref.(7), we examined the flow over the backstep in the absence of the rotor, and observed the typical shear layer and recirculation zone. Surface pressure spectra within the recirculation zone showed sharp peaks obeying Strouhal scaling as U_∞ was varied. The Strouhal number was .054 based on step height or 0.244 based on the reattachment length of 4.52 step heights. Strobed laser sheets showed the periodic phenomena during the descent and interaction of the rotor tip vortex. These results are shown again in Fig.2, and the associated description is repeated from Ref. 7.

In Fig. 2(a), the reference blade is at Ψ = 240 deg. A tip vortex is above the cylinder surface, upstream of the step. The shear layer from the step appears to stay quite straight and then dip down into the reattachment region. Some coherent structures can be seen in the shear layer, and the left-hand upper corner of the recirculation zone shows a clear indication of upflow under the initial portion of the shear layer. In Fig. 2(b), at $\Psi = 270$, the vortex has moved downstream and lower. The shear layer has been pushed down, and is concave. The velocity induced by the tip vortex at the shear layer is now negative, and hence the shear must be reduced greatly. Reattachment still appears in the right hand quarter of the figure. This is a transient situation. Fig. 2(c) shows the tip vortex interacting with the corner of the step at about 300 deg. The shear layer now appears to be pushed far down, and the reattachment point appears to be much closer to the step.

In Fig. 2(d), at 330 deg., the tip vortex has gone under the shear layer, and appears to have merged with the recirculation zone. The reattachment point has moved upstream. The vortex core is still distinctly identifiable, though no longer circular in cross-section, after the interaction with the edge of the step. The vortex core moves downstream , and the shear layer becomes convex, in Fig. 2(e), shown at about 350 deg. This process continues in Fig. 2(f), about 10 deg. later, when the rotor blades are parallel to the axis of the airframe.

Fig. 2(g), 30 deg. later, shows the tip vortex interacting with the surface boundary layer. The bottom half of the vortex has disappeared, and yet the top half retains its structure. In Fig. 2(h), at 60 deg. azimuth, the tip vortex has disappeared, and the reattachment point is now upstream of the vortex impingement zone. At this stage, the next tip vortex filament is seen above the cylinder surface at the top left. Fig. 2(i) at 90 deg. azimuth completes the cycle, with the shear layer having straightened out again.

VELOCITY FIELD RESULTS

In this paper, we examine the velocity field during the interaction. The measuring volume of the LDV was moved in succession to each point of a predetermined grid in the vertical plane above the airframe axis. At each location, 50,000 data values were acquired, in 5 blocks of 10,000 each. The time of arrival of each value was recorded, and related to the phase of the rotor using a once-per-revolution pulse produced by an optical encoder. The data were sorted into bins representing 6-deg. intervals of rotor azimuth. A pre-selected 18-deg. "zoom" interval was further divided into 0.5-deg. bins. After 50,000 points were collected, the data in each bin were averaged. After all the measuring locations in the grid were completed, the LDV beams were re-oriented to measure the other velocity component, and the procedure was repeated. The velocity vectors over the entire grid were then obtained for each azimuth interval, and thus gave a snapshot of the periodic velocity field for that interval. The two components of the velocity data were then used to generate contours of the y-component of the vorticity field. These will be used to examine the flowfield.

Fig. 3 shows the vorticity contours, in units of sec^{-1}, at 5 different rotor azimuth values, chosen to correspond approximately to some of the images in Fig.2. Fig. 3(a) is at 210 deg., and is shown only for comparison with the situation at 30 deg. in Fig. 3(e). Fig. 3(b) is at 270 deg., similar to Fig. 2(b). The strong vorticity corresponding to the tip vortex is seen where expected. The vorticity of the shear layer and the recirculation zone are also seen. Elsewhere in the flowfield, there is no significant vorticity.

Fig. 3(c) is at 330 deg., similar to Fig. 2(d). The tip vortex now dominates the shear layer, and additional vorticity is observed near the boom surface. A curious "secondary" vortical structure develops downstream of the tip vortex, but slightly above it. Fig. 3(d) is at 6 deg. Here, the tip vortex is inside the recirculation zone, and is about to impinge on the surface. The shear layer is beginning to form again at the edge of the step. The secondary structure is clearly visible. Fig. 3(e) is at 30 deg., corresponding to the Fig. 2(g). The vortex is interacting with the airframe surface. The shear layer has lengthened. The secondary structure is about to disappear from the observed flowfield.

A curious feature is the large difference between the surface impingement locations of the vortices from the two blades. The obliqueness of the trajectories amplifies the small initial difference. Thus, there is a large difference in vortex locations between Fig. 3(e) and Fig. 3(a). The difference in location of the secondary structure is not as large, but is still noticeable.

The Secondary Vortical Structure

We are unable at present to give conclusive proof of the origin of the secondary structure. Flow visualization has previously indicated that there is a secondary structure originating in the roll-up of the edge of the inboard vortex sheet from the rotor blades. The sense of vorticity is opposite to that of the tip vortex. The circulation integrated around the periphery of the secondary structure in the current data yields values which are about 1/2 that of the tip vortex; the peak value is only a fifth of that inside the tip vortex. Samples of the velocity vector data, from which the vorticity contours are derived, are shown in Fig. 4. From the vector plot in Fig. 4(b), the presence of the secondary vorticity contours is apparent in the concave curvature of the flow downstream of the reattachment. However, the question remains about the origin of the vorticity located so far above the surface. Further experiments are needed to determine the source of this vortical structure. Previous observations of secondary vortical structures originating downstream of reattachment have been made by Nezu and Nakagawa[12], and related to "boils" observed on river surfaces downstream of backsteps.

AZIMUTH-RESOLVED SURFACE PRESSURE

In Fig. 5, the azimuth-resolved surface pressure is mapped along the top of the boom ($\varphi = 0$ deg.). The vertical axis gives the unsteady pressure coefficient, based on freestream dynamic pressure. The other axes represent rotor azimuth and downstream distance in step-heights. The effect of blade passage appears at 0 and 180 deg. rotor azimuth. The vortex interaction trace is also seen, as the oblique valleys in the pressure map.

Fig. 6 shows the azimuth-resolved surface pressure field around the boom. Data taken at stations downstream of Xs = 3.0 around the boom had to be discarded because of an error in the free-stream velocity setting. Fig. 6(a) is at $\varphi = 45$ deg. A deep, oblique valley appears in the pressure map, corresponding to vortex interaction. The amplitude of pressure fluctuation becomes highest at about 2 step-heights downstream, and diminishes thereafter . The vortex impingement station moves downstream as we move around the boom, as seen from Fig 6(b). At $\varphi = 90$ deg., interaction occurs almost at the edge of the mapped region. It is surprising to note that even directly below the boom, at $\varphi = 180$ deg. and 225 deg., some influence of the vortex is felt. Going back up the other side, we again note that at $\varphi = 315$ deg., there is a significant effect. This is the first indication of vortex "wrap-around" in the rotorcraft aerodynamic interaction problem. The interaction of the vortex with the airframe is apparently more complex than just a cutting interaction.

SURFACE PRESSURE SPECTRA

Fig. 7 shows surface pressure spectra, measured at stations going around the boom. At the top ($\varphi = 0$) and at the side ($\varphi = 270$), the primary peaks are at the rotor blade passage frequency (35 Hz), its subharmonic (17.5Hz) and higher harmonics. The higher harmonics are to be expected, based on the sharp nature of the vortex interaction trace. The subharmonic is due to the difference in trajectories of the vortex systems from the two blades. The blade passage frequency is not dominant at the measuring station considered here, since this is under the inboard part of the rotor disk, where the blade potential field is not strong.

At $\varphi = 180$ deg., along the underside of the boom, the rotor frequency and its harmonics are still seen, but their amplitude is substantially reduced. Now the low-frequency peak typical of the recirculation zone (5.9 Hz) appears as a prominent feature. Re-examination of the Figs. 7(a) and 7(b) shows that this peak is present, essentially unmodified, at the top and side too.

The root-mean-square pressure fluctuation along the top of the boom is summarized in Fig. 8. We now see that the rotor-induced pressure fluctuations are indeed much higher than those occurring without the rotor. The two prominent peaks in the rms profile are seen to correspond to the impingement regions of the two tip vortices. Again, it is noted that the measurement stations are all under the inboard region of the rotor disk, so that the effects of the motion of the blade potential field are not significant.

HISTOGRAMS DURING VORTEX IMPACT

So far, attention has been concentrated on periodic events. To begin considering the deviations from periodicity, we examined histograms of velocity, taken within 0.5-degree intervals. Fig. 9(a) shows histograms of the U-component of velocity, at different heights above the surface, at the approximate station of vortex impingement. All of the data were taken during the interval between 5.5 and 6.0 deg. of rotor azimuth, when the vortex impinges on the surface. At Z= 1, the histogram is sharp-peaked, and the range of variance in velocity is moderate. The range spreads as the measuring point is moved downwards. At Z= -0.17, bimodality begins to appear. At Z= -0.33, several peaks of approximately equal amplitude appear, and this persists down to Z= -0.83. Thus, across the shear layer and into the region of boundary layer interaction, unsteadiness is very substantial. The histogram of w shows a single peak, and continuous scatter, as shown in Fig. 9(b). This suggests that the scatter is due to actual unsteadiness as the vortex interacts with the surface, not due to a cycle-to-cycle changes in vortex position. The latter would have caused multiple, separate peaks in the histograms of both components.

CONCLUSIONS

Obviously, we have only gained a preliminary picture of this interaction problem, and many phenomena remain to be resolved in detail. From this first round of quantitative measurements, we can conclude the following:

1. Data on the periodic velocity field confirm the flow field pictures obtained previously by flow visualization.
2. Vorticity contours show periodic destruction of the step edge shear layer by tip vortex interaction.
3. A large secondary vortical structure, downstream of the tip vortex, has a total circulation of about 50% of that of the tip vortex, an opposite sense of rotation, and a peak strength which is only a fifth of that of the tip vortex. This is also manifested as concavity of the instantaneous velocity field downstream of reattachment.
4. There is a substantial difference in vortex impingement locations for the vortices from the two rotor blades.
5. Pressure spectra exhibit multiple harmonics of the blade frequency, and the undisturbed backstep flow frequency.
6. Vortex interaction effects are seen around the boom, including at the bottom, and 45 degrees below the axis, showing that "vortex cutting" is not a complete description.
7. A strong subharmonic of the blade frequency is due to the difference in vortex trajectories between the two blades.
8. The rms fluctuation peaks in the vortex impact regions.
9. Histograms of velocity during vortex interaction show substantial unsteadiness of the u-component near the boom surface, but relative steadiness of the vertical component, in the periodic frame of reference.
10. The unsteadiness is concluded to be a feature occurring during each vortex interaction event, rather than an uncertainty in vortex trajectories.

At this stage, we see that this problem has several time scales. There is dominant periodicity at the blade frequency, but as a first step, the undisturbed backstep frequency can be assumed to persist through the interaction. Secondary phenomena such as local unsteadiness during vortex-boundary layer interaction also occur.

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Figure 1: Details of the rotor-airframe configuration with the backward-facing step and instrumented boom, with a front view of the installation in the 7' x 9' Wind Tunnel.

Figure 2: Sequence of digitized images of the periodic flow over the backstep, from strobed laser sheet visualization.

Figure 3: Contours of the y-component of vorticity, generated from laser velocimeter data at five different rotor azimuths, for comparison with Fig. 2.

Figure 4: Examples of velocity vector plots compiled from azimuth-resolved measurements of the u- and w- components of velocity.

Figure 5: Map of the unsteady pressure coefficient along the top of the boom, as a function of rotor azimuth.

Figure 6: Maps of unsteady surface pressure coefficient at 45-deg. intervals around the boom, as a function of rotor azimuth

Figure 7: Spectra of surface pressure at three stations around the boom.

Figure 8: Variation of the root-mean-square surface pressure fluctuation along the tip of the boom.

Figure 9: Histograms of the u- and w- components of velocity, using data acquired within 0.5-degree azimuth intervals during vortex-surface interaction.