Aerodynamic Interactions Between Bodies In Relative Motion
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Abstract

Aerodynamic interaction problems of rotorcraft are as yet too complex to be computed using the full Navier Stokes equations, but the dominant features of such interactions can be captured using using ideal fluid flow concepts. A formulation allowing unsteady interactions between bodies in relative motion is used here to compute the aerodynamic interactions between a rotor and an airframe in low-speed forward flight. The computational scheme is time dependent and designed to handle several bodies moving with respect to each other. It is not specialized in its treatment of lifting versus nonlifting bodies or their motion characteristics. The wakes of the bodies are modeled by vortex particles. Results for a two-bladed rotor above a hemisphere/cylinder airframe are compared to detailed experimental data on the vortex trajectories, surface pressure variations, and velocity field. A good level of success is demonstrated in predicting the dominant steady and unsteady features of the interaction problem.

INTRODUCTION

Rotorcraft in low-speed flight must operate in the complex, three-dimensional, unsteady wakes generated by their rotors. The interaction of the rotor flow field with the airframe, and vice versa, cause significant effects. It is important to the success of future rotorcraft designs to be able to predict these interaction effects early in the design process. This paper describes the results obtained with a prediction method that is aimed at efficient computation of these interaction effects.
The requirements for a full Navier-Stokes computation of the rotor-airframe interaction problem are as yet daunting. However, it has been demonstrated\cite{1,2} that many of the dominant features of the interaction problem can be captured using codes which use an ideal fluid formulation. This finding raises the possibility of being able to determine unsteady rotor loads and airframe loads with a moderate commitment of computational resources. It is also important to attempt to improve the performance of potential-based methods in predicting the flowfield, so that the true limits of potential flow modeling can be identified. These are the sources of motivation of this work.

**Previous Work**

The rapidly growing literature in the field of rotorcraft interactional aerodynamics has been studied in Refs. 3 and 4. A few recent developments will be addressed here. Egolf and Lorber\cite{2} showed that many features of the time-varying surface pressure distribution on an airframe due to rotor wake effects could be modeled with good accuracy using a potential-flow formulation for the airframe, coupled to a generalized rotor wake computation. They also showed the importance of including an unsteady potential term in their formulation. Brand et al\cite{3} identified the dominant unsteady effects of rotor blade passage, tip vortex interaction, and vortex sheet effects in the periodic pressure variation along the top of an airframe. Mavris et al\cite{1,5} used the insights gained from an extensive set of experiments at the present authors' laboratory to develop a phenomenological prediction method for rotor/airframe interactions. They were able to accurately model the blade passage effect, as well as the energy addition by the rotor, and to accurately compute the periodic and time-averaged pressure distribution along the top of a cylindrical airframe model. They also computed the periodic velocity field of the cylinder with excellent accuracy, except for the effects and consequences of the interaction of the tip vortices with the airframe surface.

The major simplifying assumption in Mavris' formulation was that the flowfield was purely periodic. Also, wake distortion over the airframe was difficult to model, due to
the requirement that the different elements of the wake remain attached together. The effects of blade passage were added on as a post-processing step at desired locations, in order to reduce computational requirements. The unsteady effects of the wake at the sides of the airframe were difficult to predict, since the behavior of the vortex system on the sides of the airframe were unknown. A new formulation was thus investigated, where these restrictions could be partially avoided. This led to the choice of the present method.

The present method is partially based on the work of Rehbach\textsuperscript{6}, and Cantaloube et al.\textsuperscript{7,8,9}. They have used a velocity-based vortex lattice body and a vortex particle free wake model where the vortex particles play the role of the vortex lattice without the inconvenience of the lattice connectivity. The vortex point concept was chosen here because of the long-term possibility of investigating the behavior of the vortex system as it reached the airframe, without the complications posed by methods which use connected sheets and segments.

**Present Scope and Objectives**

The objective of the present effort is to study unsteady aerodynamic interactions between rigid bodies (lifting/non lifting) in prescribed relative motion in an incompressible, inviscid flow. The approach selected is to develop a Lagrangian vortex-point technique and to use it in computing rotor-airframe interaction effects. The mathematical formulation of the present computational technique has been detailed in Refs. 10 and 11. Initial validation of the technique was performed by comparison with analytical results, and with experimental data for a fixed wing and then a single-bladed rotor in hover\textsuperscript{4}. This paper presents results for a rotor-airframe configuration, and comparison with experimental results, excerpted from Ref. 11. The formulation is restricted to incompressible flow, and viscous effects are not modeled except as wakes shed from the rotor and the airframe. It is assumed that flow separation is absent.

The rotor/airframe interaction problem is summarized in Fig. 1. The main feature of the flowfield is the wake produced by the rotor. Its presence causes the unsteady problem
to become non linear. Each wake is a set of surfaces of velocity discontinuities shed from the immersed bodies in their motion through the fluid. As the kinematic conditions of the flowfield change along time, so does the wake shed from the bodies. The surfaces making up the wake distort and the velocity discontinuities that they carry change on their own and under the influence of the flowfield. However, they carry information about the flowfield kinematics at the time they were shed. Therefore, the wake records the history of the kinematics of the flow field. For fixed wing problems, the wake assumes a self-similar or steady shape and geometry as one moves downstream from the the aircraft. As a result, its influence on the flow field seen by the aircraft is a linear function of the aircraft motion and geometry. For rotorcraft problems, where several bodies move relative to each other, the wake produced by the lifting surfaces (i.e. the rotor blades) strongly affects the rotor and the other nearby components. Its development and effects are in consequence completely unsteady if not aperiodic or chaotic.

**Problem statement**

The problem consists in solving for loads around rigid bodies in mutual unsteady prescribed motion in the framework of an ideal fluid flow model (incompressible, inviscid fluid flow). It is therefore an initial value problem in time of a boundary value problem in space. The time dependent solving of the problem is implemented through a series of time steps sufficiently small to capture the unsteadiness of the flow. At each time step, four operations are carried out. As shown in Fig. 2, the first iteration is started with several bodies in relative motion. At the initial instant, no wake is present. Subsequent iterations then generate the wake. The spatial boundary value problem is first solved to obtain the velocity field satisfying boundary conditions around the rotor and airframe in relative motion in the presence of a wake. Wakes are then created from body surfaces along trailing edges and/or detachment lines along with changes in the bound vorticity. Next, the rotor and airframe are are displaced in time as prescribed by their relative motion schedules. The wakes are finally relaxed in time under their own influence and those of the nearby
immersed bodies. Under the new bound circulation, body positioning, body and wake induced velocities, a new boundary value problem is solved by returning to the first operation. The computation of loads can be performed at any time step. It is decoupled from the preceding four operations. There is no dynamic model present in this work so the loads do not affect the prescribed motions of the bodies.

RESULTS

Description of the geometry

A set of laser sheet vortex trajectory\textsuperscript{12}, flow velocity\textsuperscript{13,14} and surface pressure measurement\textsuperscript{3,15} data are available for a simple rotor-fuselage configuration. The 2-bladed rotor has NACA0015 rectangular blades of aspect ratio 5.31, at 10 deg. collective pitch. The rotor axis is at 6 deg. of tilt with respect to flight path and is positioned 1.595 blade chords above the axis of a cylindrical body at one radius from its hemispherical nose. The cylinder, aligned with the flight path has a radius of 0.779 blade chords and a length of 15.77 blade chords. The experimental configuration is described in Ref. 3. In this analysis, 180 panelas are used per blade. The tips are paneled by rotating the tip section about the chord to generate a body of revolution. The paneling of the hemisphere-cylinder is clustered at the forward nose and includes 384 elements. The advance ratio $V/(\Omega R)$ is 0.1 where $V$ is the flight path velocity. Vortex core size data\textsuperscript{12} suggest values up to one fourth of blade chord after one revolution, starting from a one tenth chord size. The particle core sizes, however were assigned a value of half a blade chord to avoid instability in their relaxation, and was increased continuously from one half chord by a fixed multiplicative factor at each time step. Fig. 3 shows the configuration with a developed wake.

Comparison with laser sheet vortex trajectory data

The trajectory of the tip vortices is correlated in three projections at different instantaneous positions. A planform view of the vortex structure for various rotor azimuth positions for which laser sheet visualization data is available\textsuperscript{12} is plotted for comparison. Fig. 4 shows the tip vortex line for 333 deg. rotor azimuth. The tip vortex lines are defined
as the clustered emission lines on the figures. They correspond to the particles shed from the tip of the blade. In the computer algorithms, they remain distinct. Their clustering emulates the rollup of a real tip vortex line. The location of the experimentally visualized tip vortex line on the advancing side of the fuselage (side where the blade is advancing against the freestream) is always further downstream than the computed tip vortex line for the first four plots. The modeling of the real tip vortex line is not perfect. In one case, one has a continuous vortex filament, and in the other, one has a collection of vortex particles trailed at successive time steps. The location on the retreating side of the fuselage is however well predicted. Fig. 5, with the rotor at 450 deg., exhibits the real as well as predicted tendency of the tip vortex line to slow down as it approaches the fuselage. This is a non viscous effect and can be described through the use of the image vortex filament analogy. The presence of the fuselage boundary can be accounted for with an image vortex filament which will slow down the original filament with respect to the freestream. The effect would be reversed for a change in circulation direction of the tip vortex filament. A cross section of the vortex line for various rotor azimuth positions is compared with laser sheet visualization data on Fig. 6. On this figure, the rotor is shown at the 360 deg. azimuth position where it is aligned with the fuselage. Cross sections of the vortex line are plotted for rotor positions of 252, 306, 360, 405 and 423 deg. The comparison shows that the location of the experimentally visualized tip vortex line is well predicted. A front view of the vortex line for 333 deg. and 387 deg. is plotted in Fig. 7 and 8, respectively. The tip vortex lines are again defined as the clustered emission lines on the figures. The comparison shows a good agreement of tip vortex line direction with the location of the experimentally visualized tip vortex line on the advancing-rotor side of the fuselage. In general, agreement is obtained as to the lower position of the tip vortex line on the advancing side than on the retreating side.

Comparison with Velocity data
A side view of the computed outflow velocity field in a tip path plane parallel to the rotor disc, positioned .1476 chords below it, is shown in Fig. 9. The rotor is at 270 deg., and the velocity is normalized by freestream velocity. Fig. 10, shows laser velocimeter data for the same conditions. In both figures, upward arrows indicate positive outflow which translates into downward velocities. Good qualitative agreement is seen in several respects. Upwash is seen over the nose of the fuselage. The upwash induced by the foremost tip vortex line at the leading edge of the velocity survey plane is captured, as is the downwash induced inboard of the foremost tip vortex line. Downwash velocities of the same order as the freestream speed are observed at 90 and 270 deg. The downwash in the rear quadrant of the rotor disk reaches twice the freestream speed. Fig. 11 shows the centerline downwash velocities, plotted positive downward. The influence of the tip vortex of age 90 deg. can be seen as well as the upwash upstream over the fuselage nose.

At the leading edge of the rotor disk, the flow is influenced by the tip vortex line shed by the blade which has already passed the measuring location, the vortex line shed by the blade which is in the process of passing over the measuring location, and the bound circulation of the blade. These influences are depicted in Fig. 12. Depending on the location of the measuring location with respect to the moving blade and the convected tip vortex lines, a downwash or an upwash will result. Fig. 13 shows the variation of outflow over one period of rotor revolution, at several radial locations at the 187.5 deg. position under the rotor disk. Downward flow (outflow) is positive and normalized by flight velocity. At r/R = 1.0, before the next blade passage, i.e. between 90 and 180 deg., the measuring location is outboard of the tip vortex from the previous blade. The velocities induced by this line are upward (negative). The growing upwash induced by the bound circulation of the approaching blade compensates for the diminishing upwash due to the previous tip vortex. The tip vortex effect diminishes because of the diffusion of the vortex core and especially because it is convected downstream. At 180 deg., the blade overflies the measuring location and the influence of bound circulation changes to downwash. This is
indicated by the positive peak. The difference between experiment and computation peak intensity is expected. In the computation scheme, the bound circulation is modeled by a line near the leading edge of the blade. For the physical blade, the circulation is spread over the surface of the blade in the form of a sheet of vorticity. As a result, the induced velocity from the computational model will be a narrower peak than the measured velocity. The computed downwash peak is also sensitive to sampling blade positions.

The downwash induced by the blade bound circulation is soon canceled out after blade passage. At this radial position the upwash of the tip vortex line soon replaces the bound circulation effect. The measuring station is outboard of this tip vortex line and therefore, velocity values on the plot return to the negative side. The experimental data for these rotor azimuth positions show zero velocity because seed particles are absent inside the vortex core, so that no velocity could be measured\(^1\). The velocity remains negative until 270 deg. where the cycle repeats for the second blade.

At \(r/R = 0.944\), between 90 and 180 deg., the measuring location is still outboard of the previous blade trailed tip vortex line. However, this line is closer and induces a stronger upwash. The growing upwash of the approaching blade shows a more intense effect. At 180 deg., blade passage causes downwash, which diminishes after blade passage. However, it is not canceled as rapidly by the tip vortex of the passing blade. The measuring station goes outboard of this tip vortex line later than for the previous radial station. Thereafter, velocity values on the plot revert to being negative. The experimental data for rotor azimuth greater than 190 deg. show velocities induced by structures not modeled in the computational scheme. Ref. 13 attributes the secondary peaks and drops in outflow to the rolling up of the trailing sheet into the tip vortex line. The computational scheme does not model the wake as sheets but as vortex points. The velocity values remain negative until 270 deg. where the cycle begins to repeat.

At \(r/R = 0.833\), the experimental data show a sharper vortex line effect than accounted for by the computations. Indeed, the vortex line passage across the measuring
location is accompanied by a peak of downwash at 270 deg. followed by a shift to upwash velocities for 100 deg. The difference is due both to the large core sizes used for the vortex particles and to the modeling of the uninterrupted vortex line by a collection of isolated particles. The smoothness of the velocity signature of the vortex particles suggests that the value of particle vortex core size compensates for the spatial dispersal of those particles compared to the continuity of a real vortex filament. It was indeed expected that a collection of unconnected particles may give an irregular velocity field in their vicinity and the particle vortex core was necessary to smooth out the irregularities. Therefore, a scarcity in the number of particles may be compensated by smearing of the vortex cores which in turn costs resolution in terms of flow details.

At \( r/R = 0.667 \), before the passage of the blade up until 150 deg., induced downwash increases due to the previous blade trailed tip vortex line arc getting closer to the measuring location which it encloses in its curvature. Experimental data show a peak of downwash just before the previous blade trailing vortex line leaves the measuring location outboard of its curvature. This event coincides with the blade leading edge passage which explains why the difference between measured and computed trends is so marked at 180 deg. Indeed, the computation scheme lets the effect of bound circulation dominate (upwash negative velocity peak) whereas experimentally, vortex line induced downwash predominates until blade passage. Measured velocities, are not available with good reliability between 180 and 220 deg. due to scarcity of seeding particles, possibly because of blade passage. After blade passage, the downwash stays approximately constant until 270 deg. This value is somewhat smaller than for the previous radial position because the previous blade trailing vortex line induces an upwash outside of its curvature which compensates the downwash induced by the current blade and its trailing tip vortex. At \( r/R = 0.500 \), induced downwash assumes lower average values than at more outboard radial stations. This can be attributed to lower bound circulation values at the span station where blade passage occurs and also because the measuring location is more distant from the tip
vortex line shed by the previous blade between 90 and 180 deg. and from the tip vortex line shed by the present blade between 180 and 270 deg. Vortex passage occurs at 250 deg. as measured by the downwash peak by experiments.

**Comparison with pressure data**

**Blade passage effect**

The blade carries a circulation which causes higher pressures on its lower surface. Upon blade passage above the fuselage surface, this high pressure zone is felt in the form of a pulse, causing high values of pressure coefficient on the surface. Fig. 14 shows the blade passage effect at rotor azimuth angles of 174 and 180 deg. The pressure coefficient is related to the freestream dynamic pressure, and the experimental data are from Ref.(15).

**Vortex line passage effect**

The tip vortex line shed by the blade over the forward portion of the airframe is perpendicular to the airframe axis. The circulation induces flow deceleration underneath the vortex and acceleration above it. Fig. 15 shows two vortex passage effects being captured by the computations between 243 and 261 deg. The pressure coefficients are formed with respect to freestream velocity. The first instance occurs close to the airframe nose and the pressure coefficient assumes lower values than if the airframe was isolated in the freestream. Minimum values of -1.5 are obtained. In the second instance, the effects simulated by the computations are less pronounced because the vortex cores of the particles have grown. Therefore, induced velocities are not as high and the pressure coefficient achieves a minimum value of -1. The results are sensitive to the relative locations of the vortex line and the paneling control points. The maximum influence of vortex passage would be captured if a panel control point is directly underneath a vortex line. Fig. 16 illustrates the narrowness of the measured vortex effects as well as their greater intensity between 252 and 270 deg.. The pressure coefficients are formed with respect to freestream velocity. Stagnation flow pressure coefficients are present in the measured data. The discrepancy between measured and experimental data can be attributed to paneling
density as well as vortex core modeling. Fig. 17 shows the vortex passage effect on the retreating-blade side of the fuselage. The pressure coefficients are plotted for a location along the side of the body at 315 deg. around the circumference of the fuselage, clockwise looking upstream. The pressure coefficients are formed with respect to freestream velocity. This figure is to be compared with Fig. 16 which is relative to the body top centerline. Between 252 and 270 deg., as the vortex line effect decreases on the top centerline, it increases on the fuselage side as the vortex line descends along the side of the body. The experimental data are from Ref.(56). Here, the computations capture the effect of the vortex line on the side of the fuselage through a pressure coefficient drop of -2. versus -5. for the measured values. The lower pressures obtained by the computations show a difference also obtained on the downwash values at the same location. Fig. 18 shows an azimuthal plot of downwash at 0.147 blade chords above the fuselage surface in a radial direction. The measurement points are located at XB/R of 0.409 and 0.450 along a line situated at 60 deg. measured around the body axis, looking upstream. In the figures, downward flow is positive (outflow) and normalized by flight velocity. The abscissa denotes the position of the rotor from a downstream reference position. The computations show a stronger downwash than experiments; hence the lower pressure coefficients obtained in Fig. 17. The discrepancy in downwash may be caused by vortex interaction effects not simulated by the computations: these were also observed in Ref. 5. The flow around the fuselage is indeed left attached and no vorticity is shed from it. The rise in downwash on the figure at 180 deg. for the XB/R = 0.409 location and at 200 deg. for the XB/R = 0.450 location is due to the blade bound circulation upon its passage. The shift in phase between measured and experimental data is due to the modeling of the support of the bound circulation. For the computational scheme, the blade bound circulation is supported by a line located near the leading edge of the blade. The real blade bound circulation is supported by vorticity sheet across the whole chord. As a result, the computed downwash happens sooner than the real one.
DISCUSSION

This method started out with a fully-unsteady, fully-coupled free wake formulation of the rotor/airframe interaction problem. We have now succeeded in demonstrating agreement, without assuming periodicity, of the dominant features with the experimental results for a strong-interaction test case. Several areas of disagreement do remain. Considerations of computational efficiency have forced choice of a rather large vortex core size, which has resulted in the predicted vortex effects being much milder than the observed results. The coarse paneling and single-line modeling of bound circulation have prevented exact matching of the details of the blade passage effect, although, for the first time, the fully unsteady blade passage effect has been simulated. The observed high stagnation pressures during the impact of the tip vortex on the airframe have not been observed in the computation. This is attributed to the lack of detail in the model of the vortex core. On the sides of the airframe, even though the vortex particles are free to move on their own, and a fully unsteady formulation is seen, the disagreement in downwash velocity that was observed by Mavris et al\(^1\) is seen again. This confirms the conclusions reached by Mavris et al\(^5\) that these effects are not calculable without accurate modeling of the vortex-surface interaction.

Despite these difficulties, several new milestones have been achieved. The present method demonstrates capture of the dominant features of the rotor-airframe interaction with very moderate computer resources. The formulation and code are eminently adaptable to massively parallel algorithms, and we have used no devices that required special knowledge of the features of the particular configuration. Refinements in accuracy of modeling of the rotor blade and the vortex structure are necessary, and will cost more computer resources; however, the present research results show that these improvements should produce an effective tool for the routine computation of aerodynamic interaction between bodies in relative motion. In addition, the time step of the computation must be shortened, and the surface panel density increased, during the close vortex-surface
encounters, and blade-vortex encounters, to improve resolution of these phenomena. These again are improvements to be deferred to a "production" version of this code.

CONCLUSIONS

An ideal fluid flow formulation, allowing complex unsteady interactions between arbitrary-shaped bodies, has been implemented. A computationally efficient wake (vortex point method) is implemented in the code. A new method for computing velocities at body surface from neighboring singularity strengths is also introduced. The results obtained with this method have been compared in detail to experimental results for a two-bladed rotor whose flowfield interacts strongly with that of a hemisphere-cylinder airframe in low-speed forward flight. Specific conclusions are as follows:

a) The trajectory of the tip vortices shows good correlations with measured values in all three projections at different instantaneous positions of the rotor.

b) The computed outflow field in a plane parallel to the tip path plane showed good qualitative agreement with experimental data. Upwash over the nose of the cylinder was observed as well as the upwash/downwash separation line due to the foremost tip vortex line at the leading edge of the velocity survey plane. Strong downwash velocities in the rear quadrant of the rotor disk are present in both computed and measured data.

c) Predicted rotor outflow velocities show the correct influence of bound circulation and the tip vortex lines. The modeling of the bound circulation as a single line caused narrower influence in downwash than measured effects.

d) The code successfully predicts the strong blade passage pulse along the top centerline of the airframe; however, the detailed effects of the blade circulation are not captured.

e) Pressure deficits due to the proximity of vortex lines are predicted with lower intensity and definition than the measured values.

f) The lower predicted pressures on the side of the fuselage correspond to the stronger predicted downwash values at the same location.

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c) .889 radial station
d) .833 radial station
e) .778 radial station
f) .722 radial station
g) .667 radial station
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g) .556 radial station
h) .500 radial station

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