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Computation of Velocity Field in the Vicinity of a Helicopter

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ABSTRACT

A mathematical model of the helicopter rotor wake in the vicinity of a rotorcraft fuselage is formulated. It is assumed that the vortex sheet behind each rotor blade rolls up into blade tip and root vortices, and that the fuselage can be represented by constant source potential flow panels. The velocity field given by the combined rotor wake and fuselage model is presented for the case of a Sea King helicopter in forward flight.

1. INTRODUCTION

The velocity field close to a helicopter is influenced by several components, which include the main rotor, tail rotor, fuselage, landing gear, and fairings. In the early days of development of helicopters, the engineering effort was mainly concentrated on the mechanics of flight and the development of the rotors, controls, and power-plant. Little attention was paid to the aerodynamics of non-rotating parts and the effect of their interference on rotating components. Designers are now trying to reduce fuel consumption, operating costs, noise, and vibration, and to improve safety, performance, and ride quality.

The importance of fuel economy and reduction in operating costs needs no elaboration. The high noise and vibration levels of the present-day helicopter reduce its usefulness and operational effectiveness. Potential gains to be made in reducing these levels include increased passenger and crew comfort, reduced detection for military helicopters, and greater acceptance by the community for civil helicopters. The importance of a knowledge of the helicopter aerodynamic environment in the analysis of vibration and noise is unquestionable.

Knowledge of the velocity field is required in the calculation of load distribution, forces, moments, and the trajectory characteristics of a store released from a helicopter. Since a free-flight projectile such as a rocket, when fired from a helicopter, initially travels at a speed which is the same order of magnitude as the flow velocities, the flow field induced by the rotor wake system can have a significant effect on the rocket trajectory. This can necessitate some form of aiming compensation or special firing techniques (Landgrebe et. al, 1981).

The ability of the helicopter to hover, and therefore to take off and land in confined areas, has proven to be of significant value in aerial spraying of insecticides. The helicopter rotor wake has a significant effect on spray dispersal. The flow field close to a helicopter is highly non-uniform. Therefore, an understanding of the flow field in the vicinity of a helicopter could be used in the design and positioning of the spray nozzles in order to achieve a more uniform distribution of insecticides (Parkin, 1980).

Because of the large number of helicopter components influencing the flow field, its accurate determination is extremely difficult. Mutual interaction of the vortex elements generated by the separate components will deform the vortices, which, because of viscosity, will eventually dissipate. To solve this complex interactive flow problem, various simplifying assumptions are necessary. In particular, these include the number and geometry of aerodynamic elements, and the flow field generated by each element. In this paper, only the main rotor and fuselage, which are two of the most important aerodynamic elements, are considered.

Reasonably simple analytical models of the flow beneath the isolated rotor, both in hover and forward flight, are now available (Landgrebe, 1969; Piziali, 1966; Scully, 1967). Similarly, simple panel methods which mathematically model the fuselage are beginning to be used routinely on fixed wing aircraft and are being used on rotary wing aircraft design and analysis (Sheridan & Smith, 1980). Combining both of these analyses into a truly representative model of the flow field is a task which would tax even the largest computer in use (Chapman, 1979). However, the problem can be approached progressively by gradually increasing the complexity of the model.

As an initial step towards investigating the rotor and fuselage interaction problem, an iterative approach is adopted. The effect of the rotor on the fuselage is first calculated, with the fuselage considered to be immersed in the flow field below an isolated rotor. Then the effect of the fuselage on the rotor is determined where the components of flow generated by the fuselage exposed to the freestream (time and spatial average of rotor flow) are added to the self-induced inflow of the rotor. A brief description of this approach is presented in the following sections. Detailed analysis is presented by Reddy (1983).

In developing the theory, consideration has been limited to aircraft having a single rotor. The aircraft has been assumed to be in steady forward flight. The spatial and time average of the rotor induced flow is used to calculate the fuselage on-set flow. It is assumed that the fluid is inviscid and incompressible. It is also assumed that the flow about the fuselage is not separated, so the calculation of flow field must be limited to regions where separation effects are negligible.

2. ROTOR WAKE MODEL

Consider the motion of a blade when the helicopter is in steady forward flight. Because the blade circulation is a function of radius and azimuth, as the blade rotates, a continuous sheet of vorticity streams from each section of the blade. This vortex sheet rolls up into blade root and tip vortices as shown in figure 1. Similar wake structures exist for other blades, with the aggregate forming the complete wake. If the vortex distribution in the wake is known, then the velocity field at any point can be calculated.

The main task is to determine the geometrical distribution of vorticity in the rotor wake. A detailed wake model would represent the rotor blades by lifting surfaces and the rotor wake by vortex sheets. The calculation of wake geometry would involve the computation of the distortion and roll up of vortex sheets due to their own induced velocities and those of other aerodynamic elements. This would require an excessive amount of computer time. As a first approximation to this very complex flow problem, a simple rotor wake model is used. It is known that the vorticity trailed by a rotor blade tends to be concentrated towards the blade tip and rolls up into a strong tip vortex. Most of the contribution to induced velocity and blade loading comes from this tip vortex. In the present analysis, rotor blades are represented by lifting lines and the vortex wake is idealized as a set of trailing tip vortices as shown in figure 2; root vortices are neglected. However,if the velocity field very close to the centre of the rotor were to be required, then blade root vortices would have to be included. As a part of the computational procedure, the tip vortex

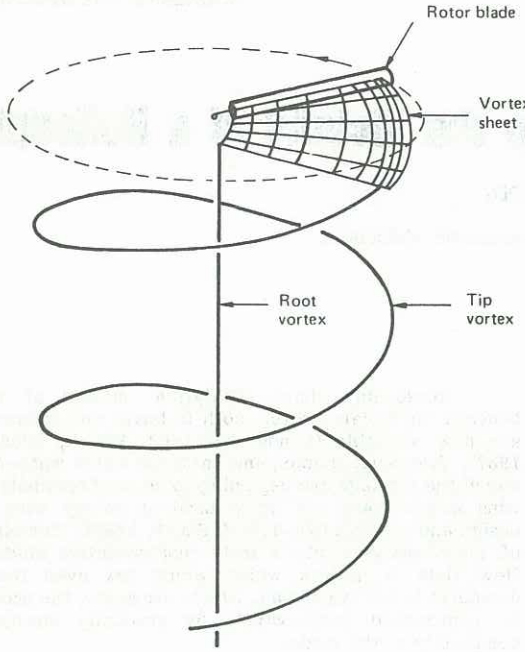


Fig 1: Helicopter rotor vortex wake structure

behind each blade is broken into convenient straight line segments (Reddy 1983). The wake configuration at any instant is defined by the location of these vortex segments. Each vortex filament has length L_{ij}, core radius a_{ij}, and vortex strength Γ_{ij}. Induced velocities due to these vortex filaments are calculated using the well known Biot-Savart relation.

3. POTENTIAL FLOW ABOUT THE FUSELAGE USING A PANEL METHOD

The aerodynamic flow around a fuselage is modelled using the 'panel' method, sometimes known as the 'boundary integral' or 'surface singularity' method. Such methods are currently in production use by most of the fixed wing aircraft manufacturers (Hess & Smith, 1966; Rubbert & Saaris, 1972). These panel models are now appearing in rotary wing aircraft design and analysis (Sheehy, 1975; Clark & McVeigh, 1985). Panel methods have the useful property that a grid need not be constructed for the whole flow field. Instead, it is possible to formulate the problem in such a way that the unknown quanitites (source strength) are positioned only on the surface of the configuration (see figure 3). Once these unknown quantities have been determined, the flow solution may be readily obtained at any point. The practical advantages offered by this simplification are that the number of unknowns in the problem are reduced by an order of magnitude and that the geometric data are easily prepared. However, it is interesting to note, as evidenced by recent literature (Williams, 1980), that the finite element method is proving a suitable tool for certain classes of aerodynamic problems not amenable to panel methods. In this paper, the panel method is used to model the helicopter fuselage.

The problem considered is that of a steady flow of a perfect fluid about a three-dimensional body. Hess and Smith (1960), and Rubbert and Saaris (1972) provide a comprehensive report on this subject as well as discussions of the computational aspects of the panel method. Constant source panels are used as basic building blocks which are arranged in networks on the boundary surfaces as shown in figure 3. One boundary condition per panel is used. The boundary condition at the body surface is that, at each control point, the resultant normal component of velocity from all of the superimposed flows vanishes.

Using the above method, the basic integral equation is decomposed into a set of linear algebraic equations. The panel source strengths are determined by solving these equations. Once the source strengths have been obtained, the velocity field can be computed at the surface control points and at any arbitrary point located off the surface.

Computer time requirements vary with the number of the panels. Numerical accuracy depends on the panel layout and the panel density. The source panel density should be increased in regions of high curvature and the entire panel model must be selected with a view toward minimizing the differences in source strengths between adjacent panels.

4. COMPUTATIONAL PROCEDURE AND RESULTS

Once the isolated fuselage source panel and vortex rotor wake computational models have been developed, the next task is to determine the source strength of each panel representing the fuselage and the geometrical distribution of the vorticity that constitutes the wake model. This is carried out by an iterative numerical process. The computations are initiated by specifying the initial wake configuration. Using this wake geometry, the induced velocity in the rotor plane is calculated. The spatial and time average of this induced velocity is added to the rotorcraft flight velocity to obtain the fuselage on-set flow, V_∞. For this on-set flow, the source strength of each fuselage surface panel is calculated. Then the velocity at each wake reference point P_{ij} (see figure 2) is calculated by summing the velocity contributions of all vortex and source elements in the flow field. Then these points are allowed to propagate with the computed velocity over a small increment in time, generating a new wake geometry. The above process is repeated until convergence. The computer time and rate of convergence of the numerical procedure will depend on the total number of wake vortices taken into account, the magnitude of the time interval, the number of source panels used to represent the fuselage, and the advance ratio of the rotorcraft.

A 5-bladed Sea King rotor of diameter 18.9 m was used in the calculations. The rotor hub is fully articulated and the rotor blades have a twist of -8 deg and are untapered. The details of the operating conditions for which the results are calculated are given below.

Advance ratio($V/\Omega R$)	$\mu = 0.10$
Rotor forward tilt	$\alpha = 0.6583$ deg
Rotor speed	$\Omega = 21.89$ rad/s
Rotorcraft mass	$W = 7200$ kg

The panelling scheme used for modelling the Sea King helicopter fuselage is shown in figure 3. It is assumed that the fuselage is symmetric with respect to the x-z plane. Half of the fuselage, for which y is positive, is divided into

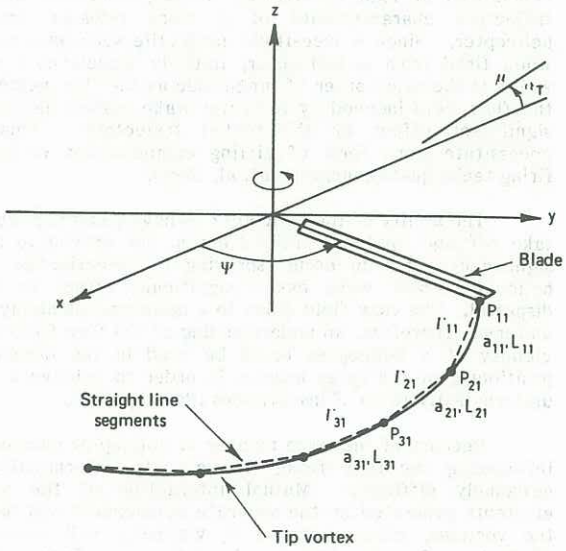


Fig.2: Straight line approximation of rotor blade tip vortex

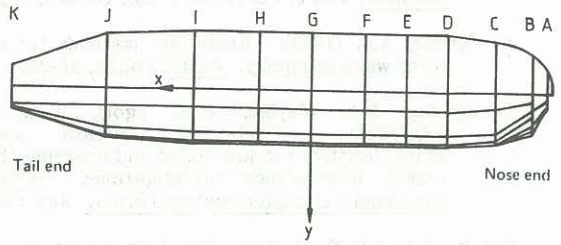


FIG. 3a: PANEL REPRESENTATION OF A SEA KING FUSELAGE

Plan view

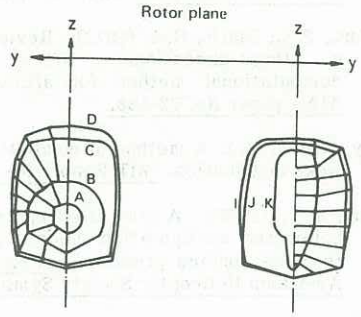


FIG. 3b: PANEL REPRESENTATION OF A SEA KING FUSELAGE

End views

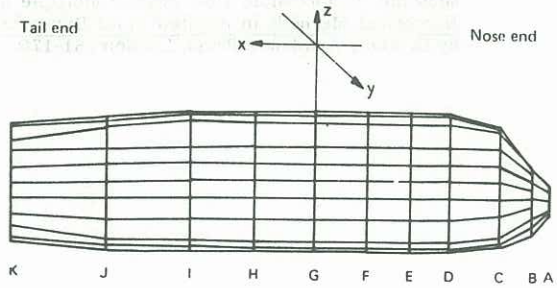
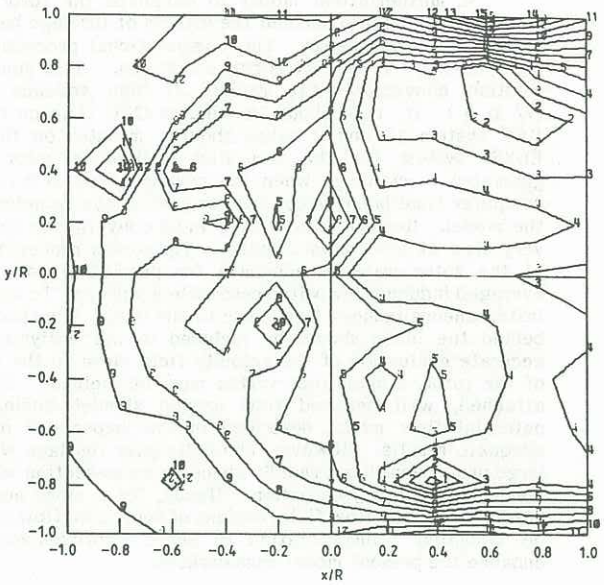


FIG. 3c: PANEL REPRESENTATION OF A SEA KING FUSELAGE

Side view

quadrilateral elements. Those portions of the surface having large curvature (nose end) are divided into smaller elements. The thin tail end of the fuselage is not included in the calculations.

The velocity field calculated using the iterative numerical method is presented in the form of contour plots. As an example, the z-component of the velocity in the rotor plane, required in blade load calculations and rotor performance estimation, is shown in figure 4; additional results are given by Reddy (1983). All quantities are in non-dimensional form, with lengths scaled by the rotor radius R, and velocities by the rotor tip speed ΩR. Plotted results correspond to the rotor configuration where one of the blades aligns with the tail end of the fuselage ($\psi = 0$). The non-uniform nature of the inflow velocity at the rotor disk is evident from figure 4. It is also clear that there is a substantial difference in inflow levels for the fore and aft portions of the rotor in forward flight. The characteristic upwash at the front of the rotor disc is well defined. The contribution of the fuselage to the total flow in the rotor plane is small. Some of the results are presented in figure 5, where the downwash distribution in the plane of the rotor is shown, both with and without the effect of the fuselage included.



Contour Number	Nondimensionalized velocity ($V_z/\Omega R$)
1	−0.09206
2	−0.07966
3	−0.06726
4	−0.05486
5	−0.04246
6	−0.03006
7	−0.01766
8	−0.00526
9	0.00714
10	0.01954
11	0.03194
12	0.04435
13	0.05675
14	0.06915
15	0.08155

Fig.4: Contours of z-component of velocity in the plane of the rotor for forward flight ($z/R=0.0$, $\mu=0.1$)

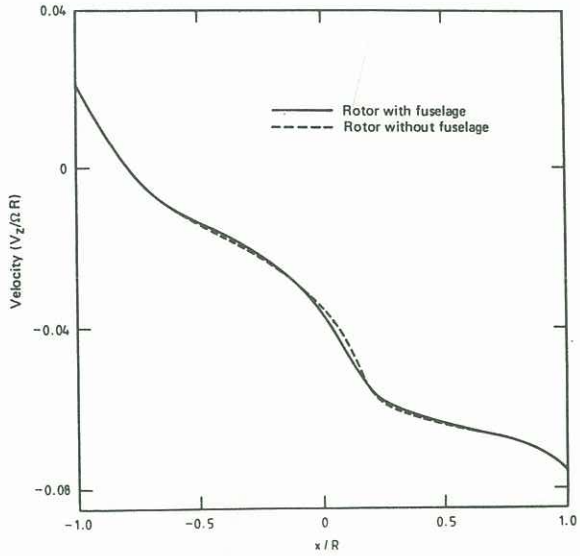


Fig.5: Effect of the fuselage on downwash distribution in the plane of the rotor ($y/R=0.0, z/R=0.0$, $\mu=0.1$)

5. CONCLUDING REMARKS

A mathematical model to calculate the rotor wake geometry taking into account the effects of fuselage has been presented in this paper. The computational procedure has been tested for various flight conditions. The numerical solution converges quite rapidly at high advance ratios ($V/\Omega R$). It took about 70 minutes CPU time on the old DEC system 10 and it takes about 4 minutes on the new ELXSI system for the Sea King helicopter rotor wake geometry to converge when the advance ratio is 0.1. This computer time is not excessive considering the complexity of the model. However, the vortex wake convergence becomes very slow at low forward speeds. Tip vortex representation of the rotor wake is adequate for predicting rotor time averaged induced flow with reasonable accuracy. To evaluate instantaneous induced flow close to the blade, a vortex sheet behind the blade should be included in the analysis. For accurate evaluation of the velocity field close to the centre of the rotor, a blade root vortex must be included. For the attached, well behaved flow around slender bodies, the potential flow model described in this paper can provide adequate results. However, the helicopter fuselage with its large protrusions has a rapidly changing cross-section which is conducive to flow separation. Hence, for a more accurate prediction of the flow field, regions of separated flow have to be modelled. Incorporation of these improvements will enhance the present model considerably.

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