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VORTICITY IN THE WAKE OF A HELICOPTER ROTOR IN FORWARD FLIGHT

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SUMMARY: In this paper, important vortex elements in the wake of a helicopter rotor are first identified. Various simplifying assumptions are then introduced in order to reduce the computational time to acceptable levels. Using a blade tip vortex model, a number of wake geometries have been investigated. The results show that a simple skewed helical vortex wake model provides acceptable results for helicopter flight simulation and performance studies.

1 INTRODUCTION

A clear understanding of the rotor vortex wake structure of a helicopter has been recognised as very important in improving fuel economy, safety, and ride quality as well as in reducing vibration and noise. Knowledge of the vorticity distribution beneath a helicopter is also important for the farmer wishing to spray his crop with fertiliser or insecticide. The helicopter rotor wake is extremely complex because of the presence of multiple blade vortices. The interaction of these vortices results in a highly distorted wake structure. A simple but rigorous analytical technique which will aid in understanding and interpreting the complex relationships between rotor circulation, wake vortex distribution, velocity field, and blade/wing motion will be of great value in the flight analysis of helicopters, insects, and birds. This problem has been the subject of considerable work over many years. The calculation techniques have evolved from simple momentum theory based on actuator disc theory, through the classical blade element theory, to wake modelling procedures. The advent of the high speed digital computer has made possible the straight forward approach of tracing the vortex filaments trailed by each blade, and integrating the Biot-Savart relation to obtain the velocity field.

The true distribution of vorticity in the wake of helicopters, birds, and insects is highly complex, and for an effective investigation, simplifications must be made carefully. The aim of this paper is to identify important vortex elements in the wake of a helicopter, position these vortex elements in appropriate positions based on experimental and theoretical results, calculate the velocity field in the plane of the rotor, and then compare with other theoretical results. It is assumed that the helicopter has a single rotor and that the fluid is inviscid and incompressible.

2 THE VORTEX WAKE MODEL FOR FORWARD FLIGHT

As the helicopter blade rotates, a continuous sheet of shed and trailing vorticity streams from each section of the blade as shown in Figure 1. Similar wake structures exist for other blades, with the aggregate forming the complete wake. This vortex wake system is the one which makes the helicopter aerodynamic analysis so much more complicated than the fixed wing aerodynamic problem. Whereas for the fixed wing the wake is assumed to lie in the same plane as the wing, the helicopter wake is forced below the plane of the rotor. The exact configuration of the vortex wake depends on the local velocity, which is the sum of the induced velocity and the main flow due to helicopter motion. Since the resultant local velocity is determined in part by the spatial distribution of the wake vorticity, a closed form analytic solution for both the downwash and wake vorticity is virtually impossible. Hence numerical methods must be used to solve the problem.

A detailed wake model for calculating the induced velocity 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 these vortex sheets due to their own induced velocities and those of the lifting surfaces. As the vortex sheets roll up into line vortices, viscous effects would become important in the vortex core (Van Holten, 1977). Because the above model would require an excessive amount of computer time, a simplified model must be constructed. For mathematical analysis, the rotor blades are represented by lifting lines (bound vortices), and the vortex wake (shown in Fig. 1) is idealized by a set of trailing and shed line vortices. These vortex filaments are free to convect at the local velocity, which is the sum of the free stream velocity and the velocity induced by the trailing, shed, and bound vortices. This form of rotor wake representation is one of the most complex. The computer requirements and cost to run such a wake model are normally prohibitive. It is known from experiments that the strength of the shed vorticity is small in comparison to the trailing vorticity. Hence the influence of the shed vorticity on the wake distortions is neglected.

A further simplication of the rotor wake geometry is valid if certain approximations based on experimental results are introduced. It is known that the vorticity trailed by a rotor blade tends to be concentrated towards the blade tip and rolls up into a core of rotating air. Most of the contribution to induced velocity and blade loading comes from this tip vortex. Representation of the real wake by a tip vortex alone is a fairly good approximation. This wake model is shown in Figure 2. Crimi (1965), Scully (1967), and Sadler

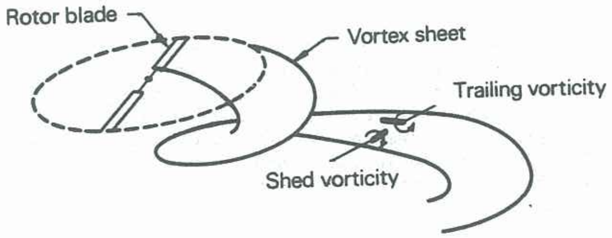

Figure 1 Vorticity in the wake a helicopter blade

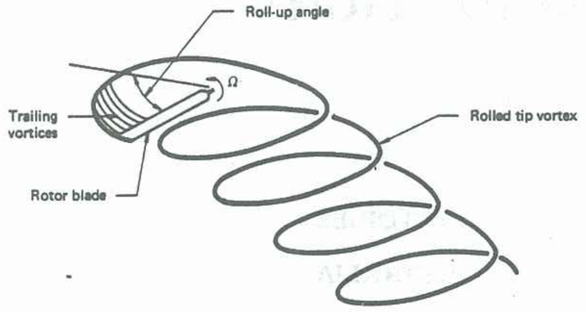

Figure 2 Roll-up of trailing vortices

(1971) used similar idealized wake models. In Figure 2, it is indicated that the vorticity which rolls up into the tip vortex must clearly be shed as a sheet; however, little is known about the roll-up process. Flow visualization pictures suggest that roll-up occurs close to the blade. In this paper it is assumed that the roll-up takes place immediately behind the blade trailing edge, that is, it is assumed that the vortex sheet roll-up angle (see Fig. 2) is zero.

3 COMPUTATIONAL PROCEDURE TO CALCULATE THE INDUCED VELOCITY DUE TO VORTEX ELEMENTS

In the previous section, a simplified model was evolved for the vortex wake of a rotor blade. The next task is to determine the geometrical distribution of the vorticity in the flow field. The wake geometry is calculated by an iteractive numerical process. As a part of the computational procedure, the tip vortex behind each blade is broken into convenient straight line segments as shown in Figure 3. These segments were chosen to be sufficiently small so that for purposes of computation of the wake-induced velocities they may be considered as rectilinear vortices having constant circulation along their length. The wake configuration at any instant is then defined by the location of these line segments. Each vortex filament has length L_{ij}, core radius a_{ij}, and vortex strength Γ_{ij}. The length of each vortex element depends on how finely the tip vortex is divided. The wake and bound vortices are assumed to have finite-sized cores of rotational fluid. Various sources (Crimi, 1965; Scully, 1967) estimate the vortex core radius and give a range of values. However, for the case of a rotor in forward flight, the results turn out to be insensitive to vortex core size. After extensive calculations, Crimi (1965) assigns a representative value of 0.05 to the ratio of core radius to the rotor radius. The vortex strength Γ_{ij} of the filament is taken as the value of the bound vorticity when it was generated. Once formed, the strength of the vortex elements are assumed to remain unchanged as the wake develops. Knowing the vortex filament length, core radius, and strength, the Biot-Savart relation can be used to calculate the induced velocity at any point.

4 FREE WAKE METHOD

In the free wake method, the computations are initiated by specifying the initial wake configuration. The velocity contributions of all vortex elements are calculated at each reference point (end points of vortex filaments). Then these points are allowed to propagate with the computed velocity generating a new vortex geometry. This process is repeated until the solution converges.

As an example, the rotor wake for a four-bladed Wessex rotor is shown in Figure 4. The important parameters for the rotor are:

Advance ratio	0.215
Rotor forward tilt	3.5 deg
Rotor speed	22.2 rad/s
Weight	53 400 N
Rotor radius	3.5 m

The iterative vortex wake solution converges for this case. It takes 36 minutes CPU time on the DEC System-10. For clarity, the tip vortex of only one of the blades is presented in Figure 4. The wake elements become distorted as a result of interactions with other elements in the wake. The large displacements of the wake elements two to three rotor radii downstream must be viewed with caution, considering stability and viscous dissipation problems involved in that region and beyond.

Using the converged wake, the induced velocity can be calculated at any reference point, again applying the Biot-Savart relation. Time averaged induced velocities at various points in the rotor plane were calculated for this case as shown in Figure 5.

Even using modern, fast computers, the time required in the free wake analysis restricts its application. For example, depending on the advance ratio, 4 to 10 iterations may be needed in the rotor wake geometry calculation. This means 30 to 50 minutes CPU time on the DEC System-10. The lower the advance ratio, the more time is required for wake vortex interaction. Thus in rotor downwash calculations, the major portion of the computer time goes into the determination of the wake geometry.

5 RIGID WAKE METHOD

If the wake geometry can be prescribed, based on previous theoretical calculations and experimental results, much time and labour can be saved. This is particularly necessary where induced downwash calculations form a part of the overall problem of helicopter flight simulation studies. For flight simulation, the overall mathematical model is divided into simple realistic sections (e.g. rotor aerodynamics, fuselage aerodynamics, helicopter control system, dynamics of slung bodies) so that the problem can be accommodated on a medium-sized computer and results expected in a reasonable time. With this application in view, the various simple prescribed wake methods described here are studied and the accuracy of their results determined by comparing with the results of the free wake model.

The concept of the prescribed wake method is simple. In the rotor wake, the vortex filaments are distributed in some complex form as shown in Figure 4. This has to be arranged into a simple logical form so that it closely approximates the actual rotor wake. Willmer (1959) used infinite line vortices to represent the

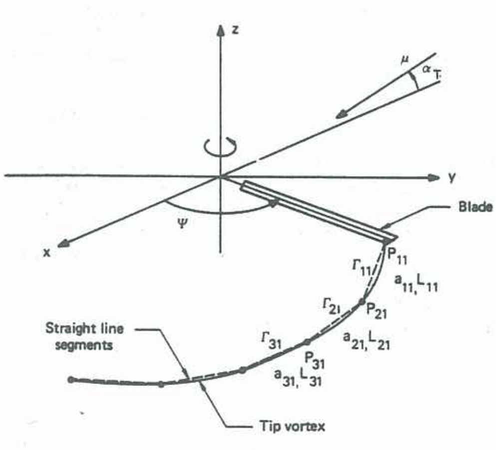

Figure 3 Approximation of blade tip vortex by linear vortex elements

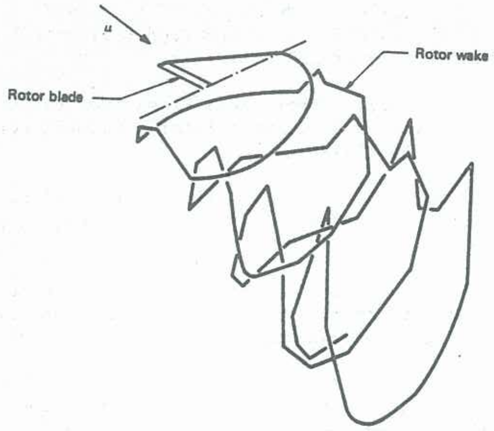

Figure 4 Distribution of vorticity in the rotor wake after convergence of the free wake solution

prescribed wake. Piziali (1968) used a method in which the vortex filaments, both shed and trailing, are broken into a number of straight elements, so that the wake has the appearance of a twisted spider's web. Cook (1970) used circular vortex rings and ring segments to represent the vortex wake in forward flight downwash calculations. Recently, Rayner (1979) used circular rings to study the hovering flight of birds and insects, and elliptical rings to generate the wake of the forward flight of animals. The interesting work could be classified as a semi-rigid wake model.

Although the geometric differences between the distorted and undistorted wakes are significant, it has been found (Landgrebe et al, 1972) that the differences are generally unimportant when it comes to the determination of rotor downwash for conventional forward flight conditions. This cannot be generalized, however, to include flight conditions which place portions of the wake in the plane of the rotor, for example during manoeuvres.

The hovering rotor generates approximately a quarter to a third of its lift over the outer 10% of the blades. The passage of a tip vortex close to the blade in this tip region has been shown to influence significantly the blade tip loading. In forward flight with forward tilt of the rotor disc, the blades are moving away from the wake, and therefore are less influenced by it. The vortices do not pass continuously under the blades in the predominant loading regions. In fact, for rotors with a small number of blades flying at high advance ratios, there are no blade-vortex interactions over a large range of the blade azimuth travel. This makes the rigid wake model a fair proposition in forward flight simulation.

As stated earlier, the main aim of the work reported here is to develop a rotor wake model so that downwash calculations can be made in a few minutes of computer time. If interest is limited to calculating the velocity field in the rotor plane, a simple vortex wake geometry, in the form of a skewed helix, can be used in combination with the Biot-Savart relation to produce a satisfactory, simple model. The results from this model are compared with those of Cook (1970) and free wake calculations to assess their accuracy. The skewed helix closely resembles the free wake near the rotor but it differes increasingly from the free wake with distance below the rotor plane. However, this divergence is not important since the vortex elements far away from the rotor contribute very little to the induced velocity. The reason for this is that the induced velocity calculated at a point by the Biot-Savart

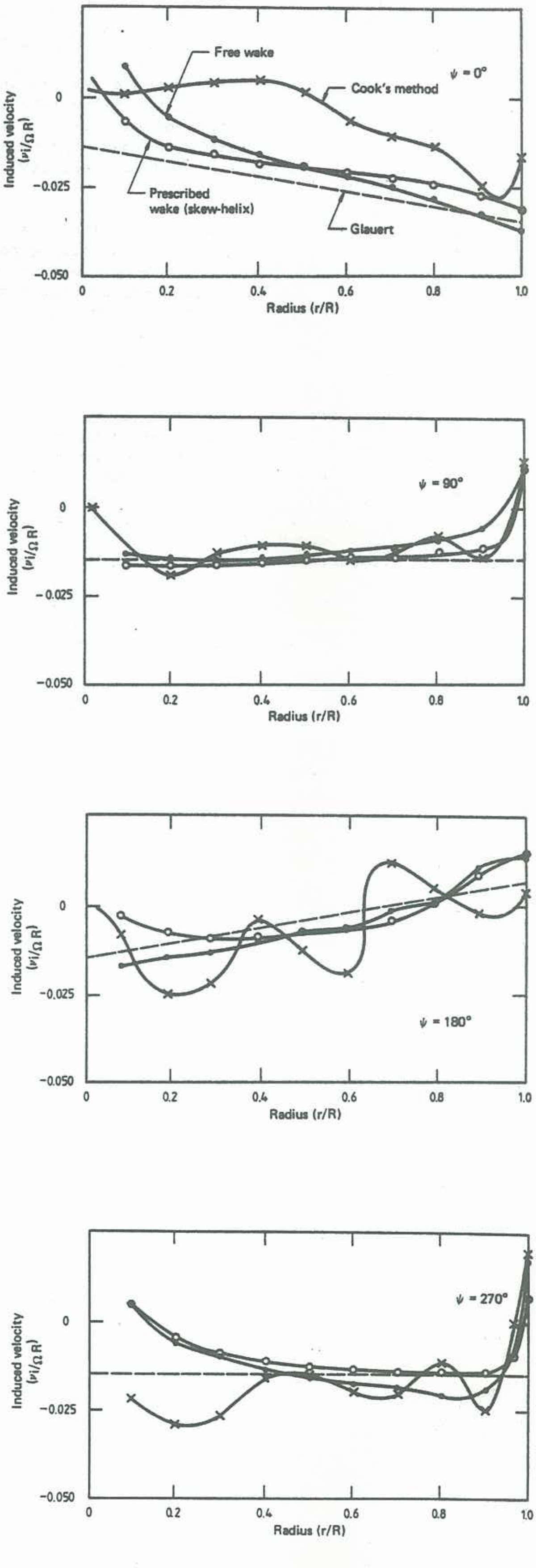

Figure 5 Variation of induced velocity with blade radius in the plane of the rotor (ψ is the blade azimuth angle).

relation is inversely proportional to its distance from the vortex element.

Figure 5 shows the time-averaged induced velocities in the rotor plane calculated using free vortex and prescribed helical wake models, along with Cook's circular ring vortex model. Glauert's classical trapezoidal downwash distribution is also presented in the figure. Induced velocity as a function of blade span is shown at four azimuth stations. The graphs illustrate the magnitude of the difference between various approaches and show that the basic agreement between the free vortex and prescribed helical wake induced velocity results is fair.

With Cook's vortex ring model, over the front half of the rotor disc, the amplitude of the induced velocity fluctuates along the blade span. These fluctuations are, however, not observed in the results calculated here using the free vortex and prescribed helical wake models.

6 CONCLUDING REMARKS

A number of mathematical models for calculation of rotor downwash in forward flight have been investigated. It has been found that even the tip vortex model in free wake analysis requires about 50 minutes CPU time on a DEC system-10 for the Wessex helicopter. For flight simulation studies, this amount of computer time is unacceptable. Various ways to reduce the time are being investigated. The most useful approach for practical applications seems to be an empirical one based on a prescribed wake type of approximation. The development of a satisfactory method requires knowledge about the kind of wake geometries that occur under various flight conditions. This in turn can only be acquired by the extensive analysis of rotor wake experimental data, theoretical results, and physical reasoning. Preliminary results carried out using a simple skewed helix model are very encouraging.

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