

The Vortex Flow Field Generated by a Hovering Helicopter

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SUMMARY Important vortex elements in the wake of a hovering helicopter are identified on the basis of well established fixed wing theory. The vortex positions are specified using experimental results. To make the problem mathematically simple, Willmer's rectangularisation principle is introduced. Using this wake model, the calculated velocity field and blade loading are compared with available helicopter flight data. The comparison shows that the present simple method yields satisfactory results.

1 INTRODUCTION

As helicopters become large and sophisticated, the study of the flow field in the vicinity of a helicopter rotor assumes greater importance. A detailed knowledge of the velocity field in the wake of a helicopter rotor is essential in many practical cases, which include vibration analysis, flight simulation studies, estimation of various power losses, stability analysis of supply drops from the helicopter where parachute and attached load travels through the rotor vortex wake, and study of droplet dispersion in agricultural spraying.

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 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 momentum method, to wake modelling procedures. The advent of the high speed electronic 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 wake modelling methods progressed to the sophisticated and computationally demanding free wake analysis (Crimi, 1965), then retreated to the simpler prescribed wake methods (Jenney et al, 1967). In the prescribed wake method, the wake geometry is specified, on the basis of experimental data, as a function of rotor configuration and thrust level through simple analytical expressions. Because of their simplicity, the prescribed wake models are used extensively in helicopter performance calculations. Recently, similar prescribed wake models were used by Rayner (1978) at Cambridge University to study the hovering flight of insects and birds. In the free wake analysis, the mutual interaction of the circulation distribution, velocity field, and blade motion is included. Many theoretical models based on the above free wake concept have been developed. The majority of these models rely exclusively on discrete vortex filament methods. However, because of the extensive numerical computations involved, they offer only limited physical insight, and lack the versatility of simpler methods.

Even when using the most sophisticated models, convergence in the hovering range is very doubtful (Crimi, 1965).

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 the following analysis is to identify important vortex elements in the wake of a hovering helicopter, position these vortex elements in appropriate positions based on experimental and theoretical results, calculate the velocity field and blade loading, and then compare these with available flight data. The method incorporates Willmer's (1963) mathematical simplification to avoid lengthy, complex computations.

The theory is developed for aircraft having a single rotor with any number of blades. The aircraft is assumed to be in steady vertical flight or hover and fuselage interference of the rotor wake is not incorporated. It is also assumed that the fluid is inviscid and incompressible.

2 ROTOR WAKE VORTICITY DISTRIBUTION

Consider the rotor blade in steady flight. Because the circulation generally varies along the span, vortex elements leave the trailing edge and spiral downwards beneath the rotor. In addition, however, the blade experiences oscillatory aerodynamic effects even in steady flight due to wind and other disturbances. This is fundamental for rotary wings, since variations in relative air speed occur at a blade section as the blade traverses the azimuth. Flapping and blade pitching angles are made to vary with azimuth in order to tilt the rotor thrust vector in the desired direction. Hence the blade incidence varies as a function of rotor azimuth creating shed vortices in the wake. In steady hover, however, because variations in the angle of attack are small, the magnitude of the resulting shed vorticity will also be small. Its contribution to the velocity field is neglected therefore. Thus as the blades rotate, a continuous sheet of vorticity streams from each section of the blade. It is well established that the vortex sheet is unstable and tends to roll up somewhat like a sheet of paper as shown in Figure 1 for a typical blade. Similar wake structures exist for other blades, with the aggregate forming the complete wake. This vortex wake system makes the aerodynamic analysis of helicopters much more complicated than that of fixed wing aircraft. For the fixed wing, the wake

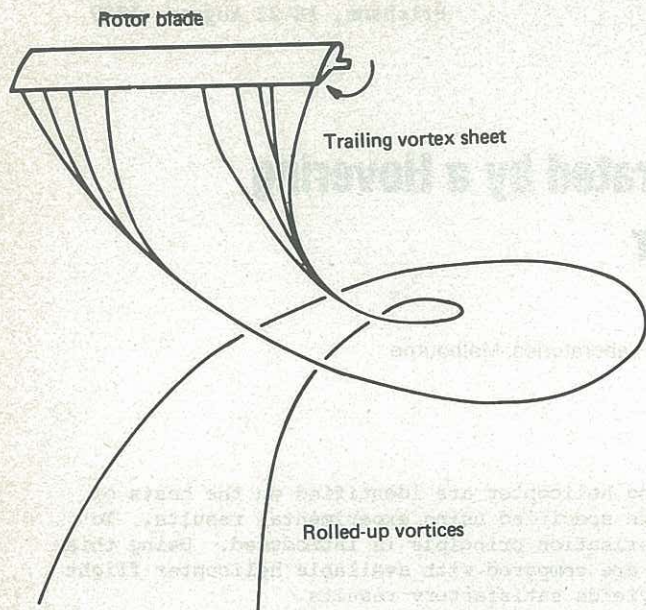


Figure 1 Rotary wing wake geometry

is assumed to lie in the same plane as the wing; while, for the helicopter, the vortex elements return very close to the rotor blade in a spiral form. The very nature of this spiral prevents the development of simple solutions for the velocity field which it induces. The analysis of of hovering flight of insects presents similar problems (Ellington, 1978). Because of this complexity, generalized solutions will probably never be possible. However, numerical solutions for specific cases are possible utilizing high speed digital computers. These solutions are frequently sufficient for engineering applications.

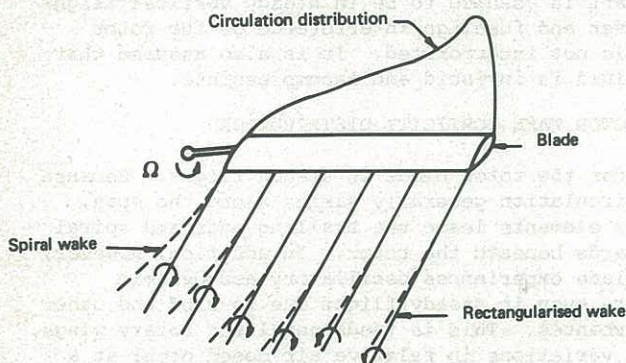


Figure 2 Rectangularization of rotary wing wake

Figure 1 indicates pictorially the complexities of attempting to obtain a complete representation of the rotor wake. To solve this difficult problem numerically, Willmer (1963) made two simplifying assumptions. The first is that conditions change sufficiently slowly to allow a quasi-static approach. The second is that the spiral wake is amenable to rectangularization. Consider the trailing wake from a blade (Figure 2). Willmer (1963) argued that the radius of curvature of the vortex sheet and rolled up vortices is large enough (especially for the important outer parts of the wake) for the wake elements (vortex sheet and rolled up vortices) to be regarded as straight. He also assumed that only those parts of the wake

which are near to the reference blade are important. Consistent with this idea, one may allow the rows of vorticity to extend to infinity in order to achieve mathematical simplification. Thus the wake attached to the reference blade is assumed to be a straight sheet extending back to infinity, while those of other blades are assumed to be doubly infinite rolled-up vortices as shown in Figure 3. The positions of these vortices depend on the mean flow velocity through the rotor disc, and the number and relative positions of the blades that shed them. Once the numbers and positions of the wake elements had been chosen, the velocity at any reference point could be calculated by an extension of Glauert's wing theory. Positioning of these vortices forms one of the important aspects in the rotor wake analysis. The axial distance h between the vortices is calculated using the average induced velocity through the rotor. A method based on the experimental data is used to determine the radial locations. This is discussed in the following section.

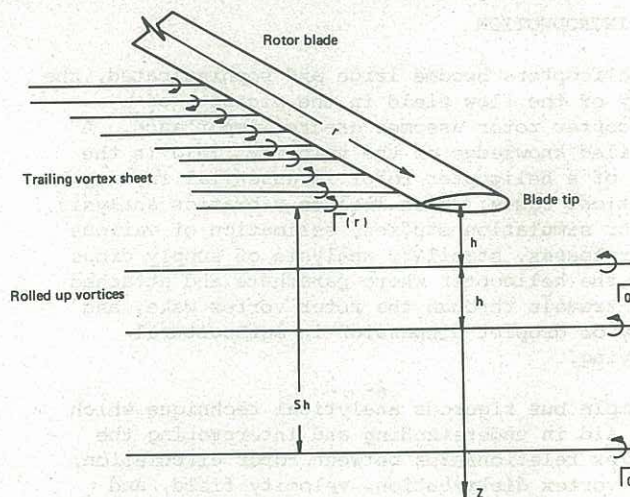


Figure 3 Trailing vortex sheet and rolled-up vortices near blade tip

3 WAKE GEOMETRY

Concurrent with the rotor inflow methods based on a theoretical wake geometry, other methods have been developed based on empirical wake models. Most of these methods are directed toward the rotor hover condition in that this condition is the one most influenced by wake distortion effects. The requirement for a method employing an accurate prescribed wake model obtained from experimental wake data was concluded by Jenney et al (1967). They found that the rapid contraction of the slipstream under a hovering rotor places the vortex system sufficiently close to the rotor blades for it to cause significant changes in the velocity field. In the mid 1950's, Gray (1955) developed a semi-empirical method for the wake of a single bladed rotor based on experimental wake geometry data obtained from smoke visualization tests. More recently, Landgrebe (1972), and Kocurek and Tangler (1976) have conducted a series of smoke tests which confirm Gray's results and give more details of the wake geometry.

The two flow visualization studies revealed that the wake radial contraction occurs in an exponential manner with increasing wake azimuth, ψ . It is characterized by a rate parameter, k , and an effective minimum non-dimensional radius, A . The

generalized wake radial coordinate r is given by

$$r/R_2 = A + (1-A)e^{-k\psi} \quad (1)$$

Where R_2 is the rotor radius. For the stable near-wake region, the radial coordinates may be determined by setting A equal to 0.78 and substituting for k one of the following relations:

$$k = 0.145 + 27 C_T \text{ Landgrebe} \quad (2a)$$

or

$$k = 4(C_T)^{1/2} \text{ Kocurek \& Tangler} \quad (2b)$$

Landgrebe's linear variation of k agrees with the non-linear representation of Kocurek and Tangler in the medium C_T range. However, the contraction rate tends towards zero as the blade is unloaded in the latter case. From (2) it is concluded that, for a given azimuth, the radial coordinates of the wake are proportional to disc loading (or C_T) and decrease with increasing loading. For a fixed disc loading, the radial coordinates are independent of tip speed, number of blades, blade twist, and aspect ratio. Taking a mean C_T value of 0.005 and h/R_2 equal to 0.058, the wake geometry is plotted in Figure 4. The figure shows how rapidly the wake contracts under the

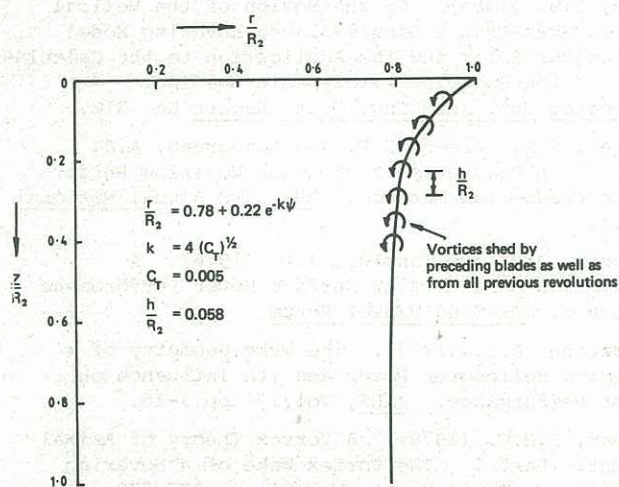
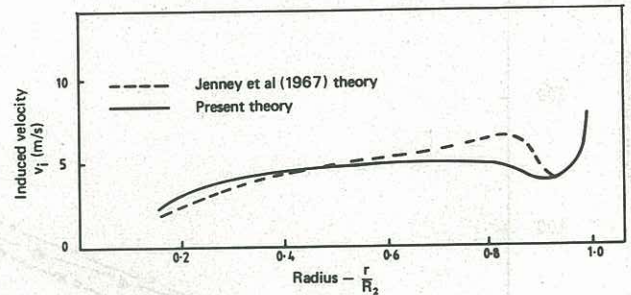


Figure 4 Contraction of rotor wake

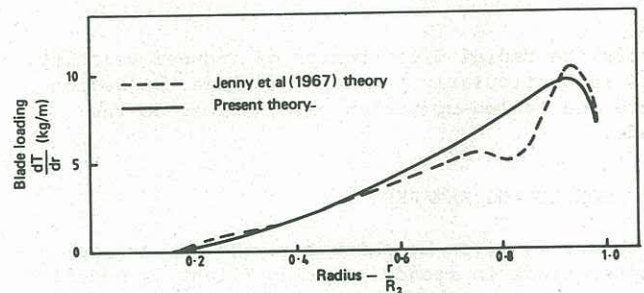
rotor: the contraction is practically complete within a distance of 20 to 30% of the rotor radius. Using the above described wake flow model and the wake contraction rate given by Kocurek and Tangler (1976), a mathematical analysis is developed. Because of space restrictions mathematical details are completely omitted here, but are given in a report (Reddy, 1979).

4 COMPARISON WITH FLIGHT DATA AND WITH OTHER THEORIES

Calculations were performed to determine the induced velocity and blade loading for two helicopter rotor configurations, viz, a model rotor and S.58 helicopter rotor. To test the accuracy of the method, we first compare the calculated velocity field and blade loading with other theoretical results for the case of the model rotor. Then we compare the calculated blade loading with flight data for the S.58 helicopter rotor. Induced velocity is calculated in the plane of the rotor. The calculated velocity and blade loading are



(a) Induced velocity



(b) Blade loading

Figure 5 Comparison of calculated values with Jenney, Olson and Landgrebe's (1967) results for model rotor

plotted as a function of rotor radius. One should be cautious in comparing the present mathematical model with other theories, as all theories necessitate many simplifying assumptions. Therefore any comparison would rest upon the significance of the simplifying assumptions and how they affect the calculated values. Figure 5 shows a comparison with Jenney, Olson and Landgrebe's (1967) sophisticated mathematical model. The results compare well over the greater part of the blade span except near 80% of the blade radius. This could possibly be due to the simplification of the wake representation by planar rather than curved surfaces. Comparison of calculated values with the experimental data is limited by the amount of flight data available. Computed blade loading is compared with measured blade loading (Scheiman, 1964) in Figure 6. The results shown in this figure indicate that the incorporation of wake contraction significantly

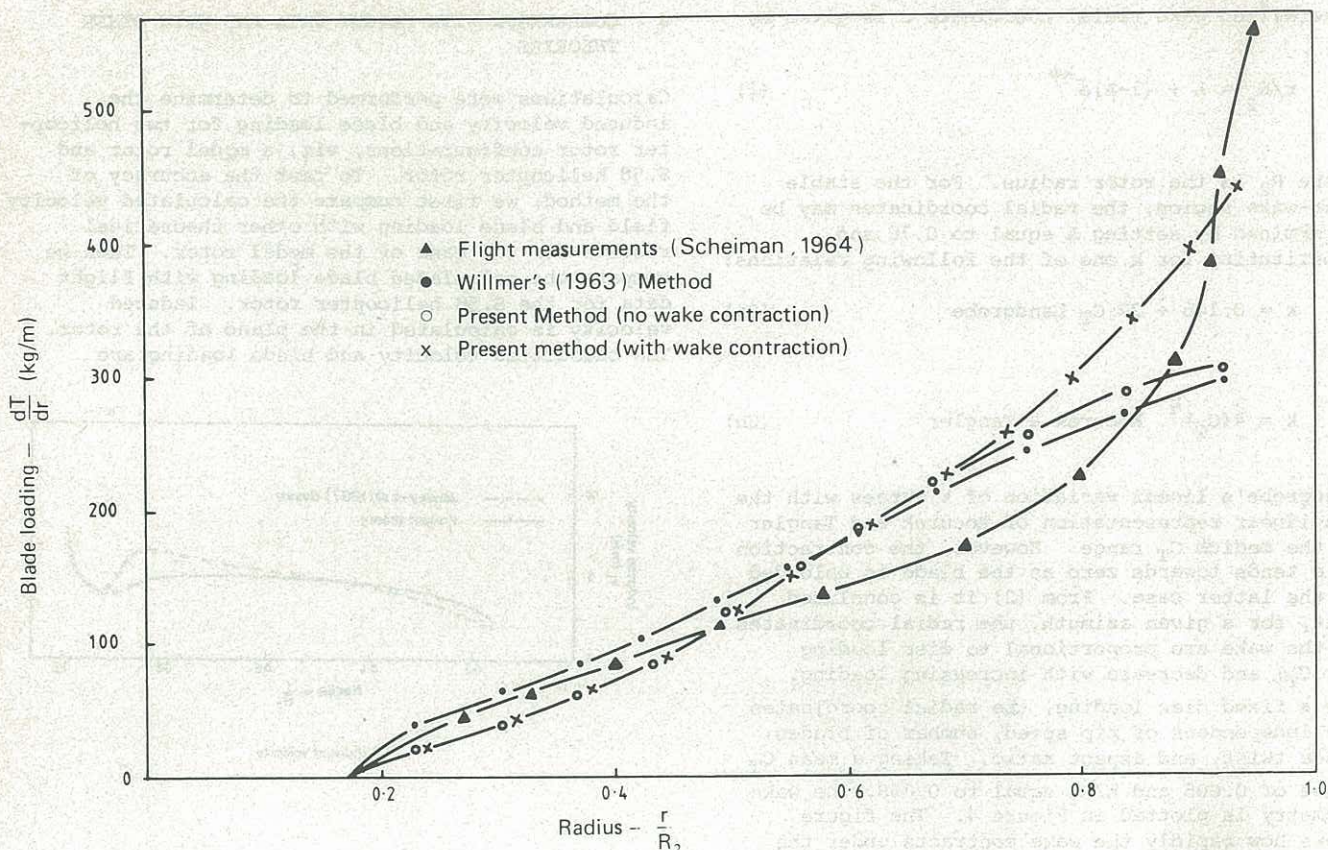


Figure 6 Variation of blade loading with span - S.58 helicopter

alters the radial distribution of induced velocity. This is particularly true in the blade tip region where the rolled-up vortex passes close to the blade.

5 CONCLUDING REMARKS

A theory is given by which the wake of each helicopter blade in steady hovering flight is modelled as a stack of infinite line vortex elements and a semi-infinite vortex sheet. The method provides a rapid, computer-oriented, numerical technique for evaluation of rotor induced velocity and blade loading. Correlation of the computed and measured results is quite good, considering the simple wake geometry used. The theory can be extended to cover the hovering flight of insects and hummingbirds. This work will also help to understand the behaviour of spray droplets emitted into the helicopter vortex wake in aerial spraying of pesticides.

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