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FACTORS INFLUENCING ROTOR AERODYNAMICS IN HOVER AND FORWARD FLIGHT

R.H. Miller
Massachusetts Institute of Technology
Cambridge, Massachusetts U.S.A.

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Abstract

The aerodynamic characteristics of rotors are heavily influenced by blade vortex interactions, both in hover and in forward flight. In addition to geometrical considerations, the nature of the vortex, including its roll up characteristics, must be specified for reasonably accurate aerodynamic analyses. This paper discusses techniques recently developed for treating these problems. Analytically derived blade loads at forward speeds are examined and compared with test results.

The problem of rotor aerodynamics in all flight regimes is well known to involve highly complex flow characteristics, only some of which are adequately described by ideal fluid models. For this reason, geometrically simplified models are of value for clarifying the physics of the problem and allowing a more detailed treatment of the flow in the vicinity of the blade.

Introduction

A recent paper (Ref. 1) has shown that the experimentally determined airloads on helicopter rotors operating at advance ratios typical of high speed cruise flight have large higher harmonic components (above the second) which existing analytical techniques do not appear to predict. Over the outer portion of the blade these higher harmonic airloads approach at times the steady state lift and may therefore be expected to contribute appreciably to helicopter vibration in forward flight.

These loads are the direct result of a blade passing through a vortex system trailed and shed by the preceding blades. This vortex system in turn is influenced by the spanwise and timewise variations in lift on a blade as it encounters the vortex systems generated by passage of the preceding blades. Thus both the spatial and temporal variations of lift on the blade are of importance and non stationary flow effects must be carefully modelled.

In order to clarify the discussion, the following definitions will be used (see Fig. 1).

1) The near trailed wake is that attached to the blade and resulting from the spanwise variations in bound circulation. This wake is trailed from the blade in the direction of the relative velocity at the blade.

2) The near shed wake is that shed by the blade due to time variations in the blade's bound circulation. This wake leaves the blade essentially parallel to the trailing edge and is convected downstream relative to the blade by the resultant forward velocity of blade and rotor.

3) The far trailed wake is that trailed by all other blades.

4) The far shed wake is that shed by all other blades.

The near shed wake may be treated using the classical methods of non stationary airfoil theory.

The importance of the far shed wake for the case of the helicopter in hovering flight was demonstrated in Ref. 2, 3 and 4 where it was shown that the lift deficiency function, C(k), normally of the order of .8 at values of reduced frequency, k, typical for rotor blades, could approach zero at values of k corresponding to integer frequencies of the rotor speed.

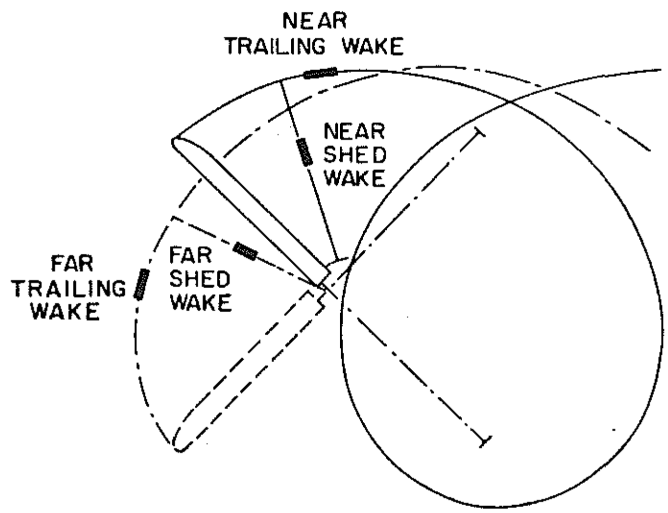

Fig. 1 Wake geometry showing near and far trailed and shed wakes

Aerodynamic Characteristics of the Wake in Forward Flight

The importance of the aerodynamic characteristics discussed above will be evident from an examination of Fig. 2 which shows the total time varying loading at 90% of the span (Fig. 2a), the loading with harmonics up to the second removed, (Fig. 2b) and the spanwise loading at $\psi = 100^\circ$ and $\psi = 120^\circ$ (Fig. 2c). These values of ψ were selected because at $\psi = 80^\circ$ (where the peak positive higher harmonic loading occurs in Fig. 2b), a blade will encounter the vortex from the preceding blade trailed and shed at an angle ϕ

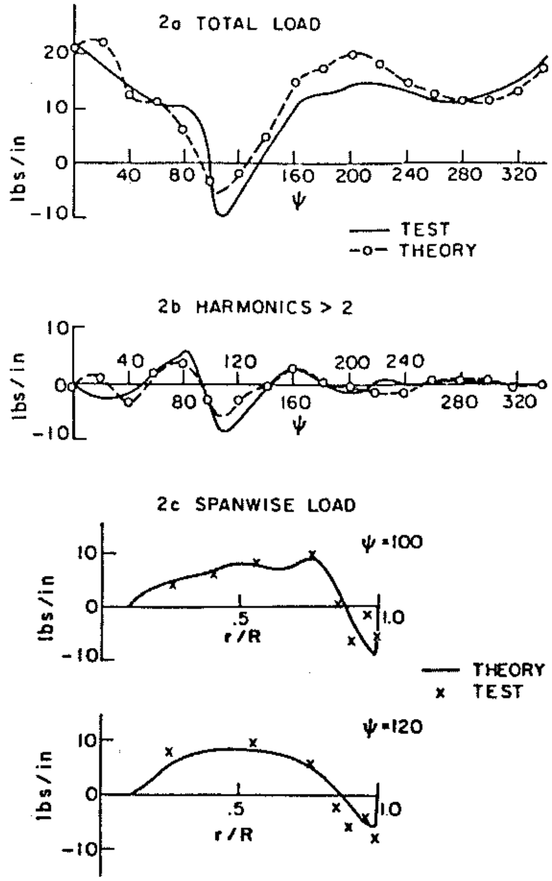

Fig. 2 Blade airloads at 90% span, μ = .39. Experimental data from Ref. 5

between 100° and 120°. Fig.3 shows a typical intersection geometry. In Fig. 2 both the experimental results from Ref. 5 and the analytical results using the modelling described in this paper are shown.

The important effects to be noted are the rapid spanwise variation in lift over the outer

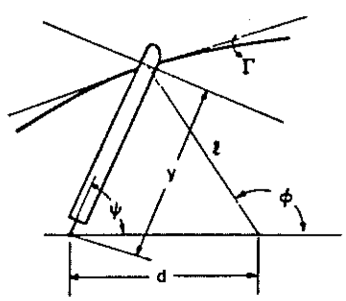

Fig. 3 Geometry of blade vortex intersection

portion of the blade, starting from a negative peak near the tip as shown in Fig. 2c. The trailing wake may be expected to roll up into two vortices of opposite sign, one from the tip, causing an up flow on the following blade and one further inboard of greater strength, also causing up flow on that portion of the blade outboard of the spanwise position of vortex encounter. Together this system of trailing vortices accounts for about 75% of the maximum positive higher harmonic loading (Table I).

The remaining contributions come from the shed wakes generated by the rapid timewise variations in lift from about ψ = 80° to ψ = 100° and again from ψ = 100° to 140°, as shown in Fig. 2a. Two vortex systems of opposite signs will be shed, both producing positive lift on the blade as it reaches a point about mid point between the two vortex systems. This will occur when the following blade is at $\psi \cong 80°$, again close to the point of peak higher harmonic loading.

Fig. 4 shows the experimental and analytical results for additional spanwise stations.

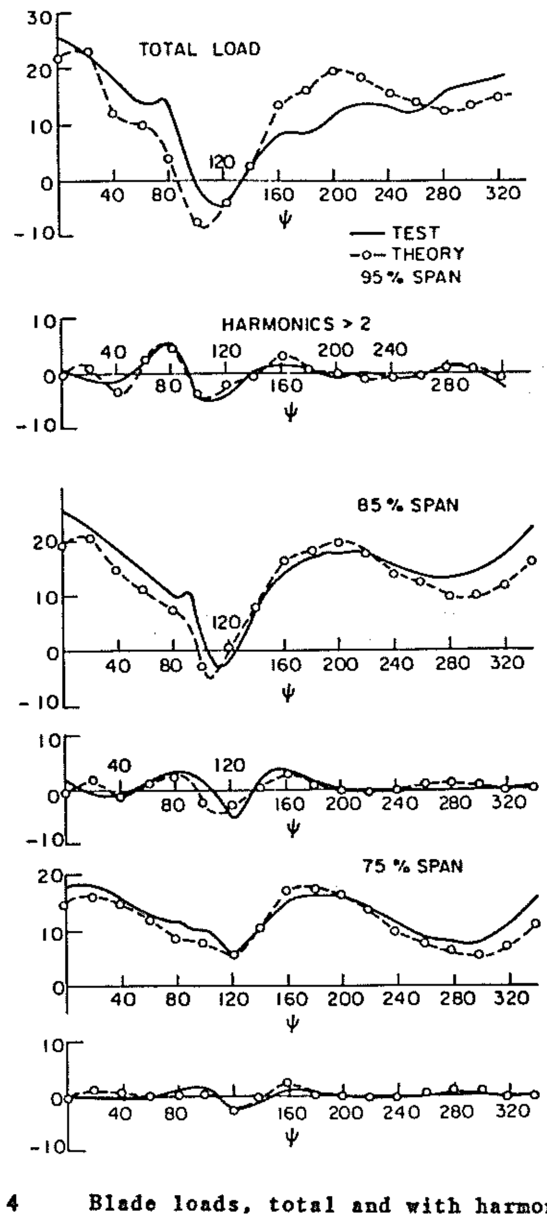

Fig. 4 Blade loads, total and with harmonics below 3rd removed, at various spanwise locations

Modelling the Wake

The mathematical details of wake modelling and the computer codings used in the analyses are discussed in detail in Ref. 6 and will only be briefly summarized here. The method used is based on that of Ref. 7 and on the simplified approach suggested in Ref. 8 in which, after the points of encounter of a blade with the vortex system trailed by preceding blades are computed, the spiral wake at this encounter is replaced by a doubly infinite line vortex (see Ref. 8, Section 7 -- note errata: in equation for δ, η should be ℓ).

It has long been recognized in the treatment of rotor (and fixed wing) aerodynamics that the important elements of a vortex wake are those in the immediate vicinity of the lifting surface in question. The remainder of the wake need only be approximately modelled. A technique frequently used for rotors involves replacing the spiral wake by vortex rings and cylinders (for example References 9 and 10). In Ref. 11 (summarized in Ref. 12) such models have been extended to the free wake analysis of the hovering rotor and compared with an even simpler model using doubly infinite line vortices and sheets, referred to as a two-dimensional model (2D). Fig. 5 compares the results obtained from this 2D model with a free wake model using vortex rings (referred to as a 3D model) and with the experimental results analyzed in Ref. 13. Evidently both models agree well with each other and with the test data. Previously, Ref. 8 had shown that the straight line representation of the wake gave good agreement in forward flight both with test data and with a more elaborate analysis based on complete modelling of the spiral wake. Certain limitations of the straight line approximation for the hovering case, which, however, do not apply to the forward flight case, will be discussed in a later section.

With the increasing availability of high speed computing facilities, the need for approximate geometric modelling may not always be apparent. It is now possible to envision direct solution of the complete flow equations. Ref. 14 is an example of such a solution for the hovering case. However our experience has been that when complete flow modelling is used based, for example, on direct solutions of the Euler equations, simplified approaches assist in providing the physical insight to aid in the formulation of the problem. They may also be readily expanded to include a more detailed treatment of the flow in the vicinity of the blade and could serve as a valuable engineering design tool for rotor optimization, either formal or heuristic.

Wake Roll Up

In addition to modelling wake geometry in order to locate the blade vortex interactions, it is necessary to have some understanding of the manner in which the wake rolls up into concentrated vortex filaments. A logical extension of wake modelling using line vortices or vortex rings for determining blade/vortex interaction is to apply

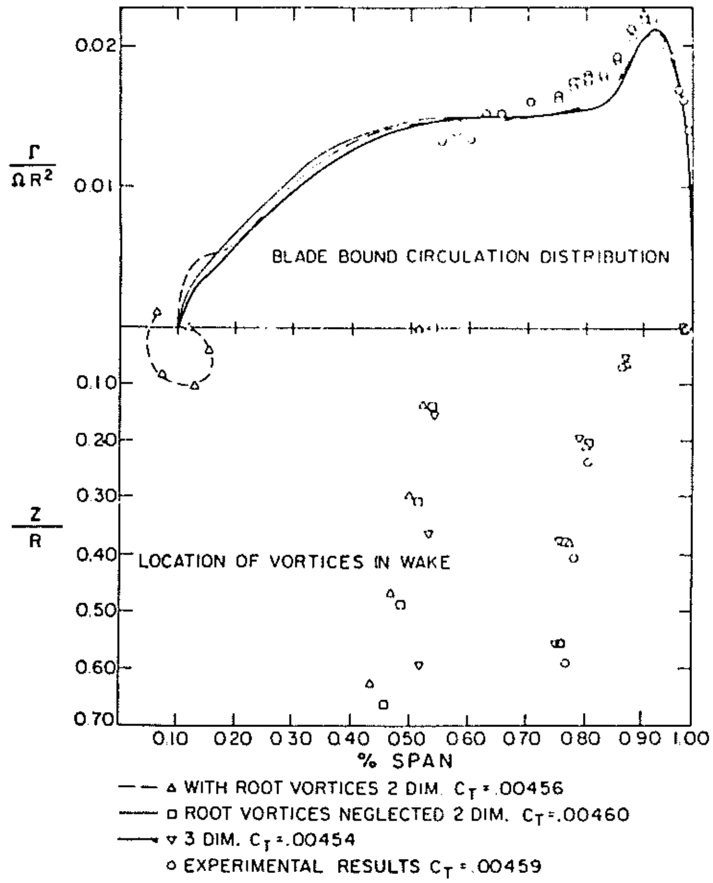

Fig. 5 Blade bound vortex distribution and wake geometry in hover.

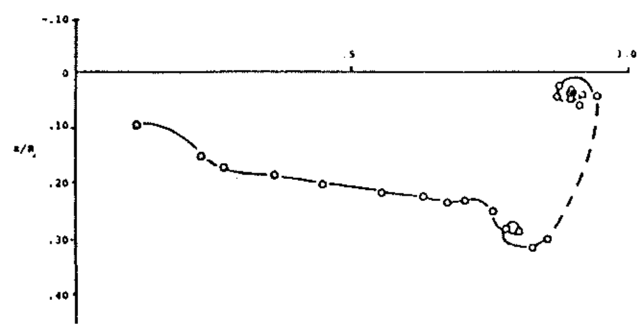

Fig. 6 Roll up of wake from hovering rotor at ψ = 180°

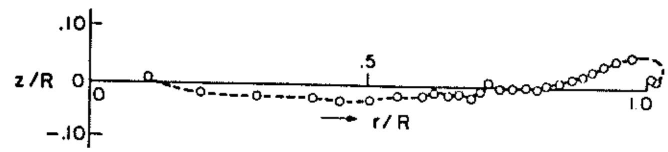

Fig. 7 Roll up of near wake after $\Delta\psi$ of 90° in forward flight (μ = .39)

the same technique for vortex/vortex interaction in order to predict wake roll up. Results using this technique, presented in Ref. 15 for the hovering case, are shown in Fig. 6. The wake for this case was represented by a series of vortex rings. Evidently the familiar pattern of the wake clearly shown by the studies of Ref. 16 are well reproduced.

The outer wake rolls up into a strong tip vortex. The inner wake remains as a sheet terminating in a small rolled up vortex separated from the tip vortex by what is apparently a quiescent region. The technique used for this analysis is discussed in greater detail in Ref. 17 and 18, where it is shown that one characteristic of the roll up of a series of curved vortex filaments is a tendency towards downward migration, which is lost if the sheet is modelled with straight lines. This migration, which is important for free wake modelling of the hovering rotor, is distinct from the familiar movement of a single vortex ring due to self induced effects (Ref. 19).

In order to provide some guidance in modelling the wake roll up, the techniques of Ref. 17 were applied to the trailing wake generated from the blade loading shown in Fig. 2c at $\psi = 100^{o}$. Obviously such a quasi static approximation to the rapidly varying flow conditions can only be justified on the basis of the greater importance of those elements of vorticity closest to each other. It is used here only as a guide for further modelling of the wake. Fig. 7 shows the wakes so modelled at a time period of about one quarter rotor revolution after its initial generation. Of interest is the resultant upward migration of the vortex system over the outer portion of the blade, despite the self and mutually induced tendencies of the curved vortex filaments to descend, as discussed above. Interactions between the rolled up vortices from the preceding two blades may also be expected to have an important effect on the wake geometry at the crucial first encounter with a following blade.

Method of Computation for Forward Flight Analysis

The following computational steps were used for the forward flight case.

1) The rotor geometry, including collective and cyclic pitch, flapping coefficients and inflow were the initial inputs to the program leading to a first estimate of the blade bound circulation. This bound circulation was used to generate a fine near wake containing sixteen semi-infinite straight trailers, as in Ref. 7. A converged solution was obtained at each azimuth, ψ. A $\Delta\psi$ of 20^{o} was used. A lifting line approximation was used with trailer core sizes of .01 of the rotor radius.

2) The near wake thus computed was assumed to roll up into a tip vortex, a mid vortex and a root vortex. The tip vortex contained all the circulation from the tip to the first point of maximum circulation, whether positive or negative, and was located according to the Betz criterion at the centroid of the trailed vorticity. The mid vortex contained all the vorticity from the first to the next inboard maximum bound circulation. Best results were obtained when this vortex was located at approximately 75% of the span, when it existed. If no second maximum of bound circulation occurred, then the mid vortex had zero strength and was merged with the tip vortex. The remaining circulation was assumed to roll up into a root vortex, again located at the centroid of trailed vorticity. The far shed wake resulting from the time variation in airload was then computed at each azimuth.

3) Solution of the transcendental equation for the angle ϕ of Fig. 3, (the azimuth angle at which the vortex of interest was generated) was effected either by searching for all possible intersections or by considering, as in Ref. 8, only the first spiral. Both methods gave similar results but the latter was far less costly in CPU time and was the method used for the results shown here. Knowing ϕ for all intersections, the velocity induced by the far wake was determined, a harmonic analysis of the loading performed and new trim values re-computed for the rotor until convergence. The effects of the near shed wake were introduced using the approximation suggested in Ref. 8. The airloads were modified by a lift deficiency function, F, and phase shift, $\tan^{-1} G/F$ with, for the reduced frequencies of interest here, $F \cong 1/(1 + k\pi/2)$ with a minimum of .5, and $G \cong 4k$ for $k < .05$ and .2 thereafter.

Solutions for Forward Flight

In order to test the possible effects of the wake distortion shown in Fig. 7, the vertical displacement of the wake below the blade at first encounter was reduced by 70%. Fig. 8 shows the effects on the airloads at 90% of the span.

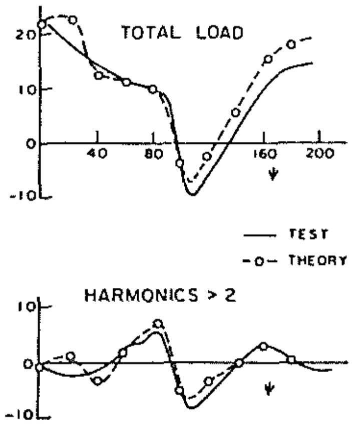

Fig. 8 Effects of wake distortion on airloads at 90% span

The effects of the wake become more evident when the airloads produced by wake interactions only are plotted, as in Fig. 9. It is evident that the blade could be subjected to an almost impulsive type load of the order of the steady state lift component, a loading which is somewhat masked by

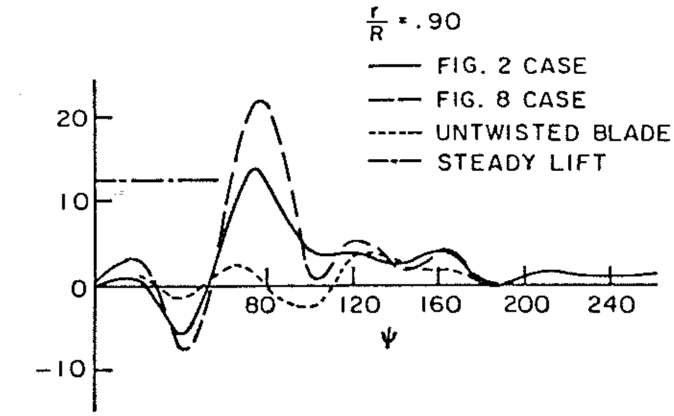

Fig. 9 Airloads due to wake interactions only vs. azimuth
Total Thrust for blade of Ref. 5 (8^{o} twist) = 8441 lbs
Total Thrust for hypotetical untwisted blade = 8424 lbs

including all higher harmonic loads, regardless of their origin, as in in Fig. 2 and 8. Of interest is the apparent reduction of this loading when blade twist is removed and the collective pitch adjusted for approximately equivalent thrust. Until a true free wake methodology has been developed, it may be premature to draw any firm conclusions from such results.

Examination of Figs. 2 and 4 shows an appreciable discrepancy between the experimental and analytical results for the total loads over the retreating portion of the disc, at the outer portions of the blade. The difference disappears when the lower harmonics (up to the third) are removed, which suggests the possibility of effects due to harmonics of flapping above the first, or of blade flexibility. In order to explore such effects, harmonics of flapping up to the third were introduced as well as a first elastic mode using

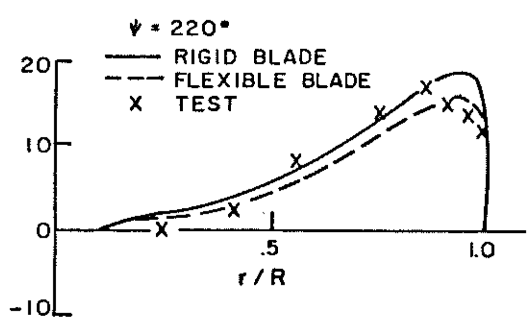

Fig. 10 Effect of higher harmonics of flapping and blade flexibility

generalized coordinates corresponding to the approximate mode shape suggested in Ref. 20 and the known blade frequencies from Ref. 5. Results are shown in Fig. 10. Some improvement is apparent in the outer portion only of the blade. As expected the higher harmonic content of the airloads, which are of primary interest here, remained essentially unchanged.

Solutions for Hovering Flight

As mentioned above, representing the wake at the point of encounter with the blade by a doubly infinite vortex filament results in a simple and computationally efficient method of computing free wake effects in hovering flight, which agrees well with the airloads predicted by the more elaborate vortex ring model (Fig. 5). Far wake modelling is critical in hover if an accurate prediction of the rotor figure of merit is required. Of particular interest is the figure of merit with induced losses only included, a sensitive measure of rotor efficiency which, however, cannot be determined experimentally but can only be inferred. Certainly its value should be less than unity and, for a twisted blade, probably of the order of .9 to .95. The effect of the number of vortex rings in the intermediate wake on this "ideal" figure of merit is shown in Fig. 11, including the effects of wake rotation. The model using line vortices for the intermediate wake tends to give values for the ideal figure of merit of the order of one. Evidently the intermediate and far wakes must be carefully modelled when considering the hovering case. However in the forward flight case, only the first spiral and only the first two preceding blades appear to have any appreciable influence on the loads, as is evident from the results shown in Table I.

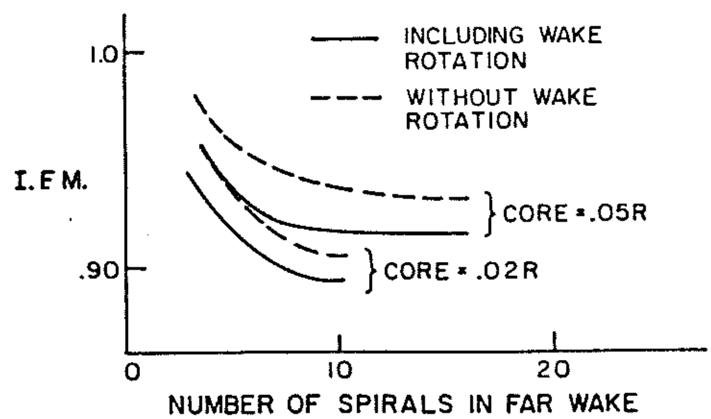

Fig. 11 Ideal figure of merit (IFM) in hover as a function of far wake modelling — 2 bladed rotor of Ref. 11

Another phenomenon of interest in hovering and near hovering flight is the tendency of the wake to migrate above the blade in a slight cross wind. This effect is shown in Fig. 12 where the instantaneous wake position has been computed using the free wake hovering analysis in a cross flow corresponding to a μ of .05. The associated large increase in blade load could cause instantaneous stall, although blade flapping accommodation to this load increase (not included in the analysis) would probably result in a rapid relief of the load. The results shown in Fig. 7 indicate that there is also a possibility of vortex migration over the following blade at higher forward flight speeds.

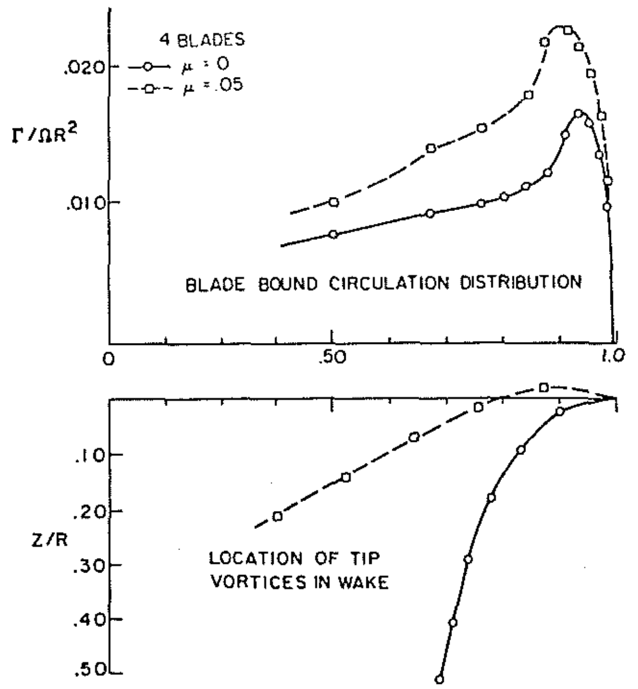

Fig. 12 Effect of cross flow on wake geometry at μ = .05 for a 4 bladed rotor

Concluding Remarks

The analytical results presented in this paper demonstrate, in a preliminary fashion, some of the important parameters which must be considered when attempting to predict higher harmonic blade airloads in forward flight. The simplified model used gives results in reasonable agreement with the test data. The analysis is essentially a rigid wake, lifting line, analysis. Mutually induced wake effects are not included, except for isolated estimates of the wake roll up characteristics and positions. Additional refinements are necessary to improve on the treatment of the near shed and trailing wakes (see, for example, Ref. 21) by using modified lifting line or lifting surface theory. However by far the most important refinement is believed to be the introduction of the true wake geometry. The development of a free wake analysis for high speed forward flight, similar to that developed for the lower cruise speeds in Ref. 22, is a logical next step. The upward migration of the trailed wake shown in Fig. 7, the expected far wake interactions and possible interactions with the bound circulation discussed in Ref. 17, all indicate the importance of using a free wake, thus avoiding the need for arbitrary determination of its position. The actual wake is a geometrically complex and time dependent mesh of more or less orthogonal trailed and shed vortex systems which will roll up and migrate in an as yet unknown fashion, but probably along the lines inferred from the analytical results reported here.

The availability of a geometrically simplified free wake analytical techniques for both forward flight and hover should facilitate the optimization of the rotor for minimum vibratory airloads in forward flight and for maximum performance in hover. The preliminary results shown in Fig. 9 indicate that the vibratory airloads may be adversely affected by blade twist, whereas free wake hover analysis indicates that twist (and taper) improve hover performance. By extending the simplified geometrical modelling used here to include a free wake in the forward flight case, and using Ref. 11 for the hovering case, it may be possible to consider the use of formal optimization techniques, or a heuristic search, to arrive at a best compromise between hover performance and vibration levels in cruising flight. Ref. 23 is an example of the use of formal optimization techniques, in this case applied to wind turbine load alleviation in the presence of tower shadow.

Table 1

Contribution to maximum positive higher harmonic loading from far wakes at 90% span

	Blade 1		Blade 2		Blade 3	
Vortex	Trailed	Shed	Trailed	Shed	Trailed	Shed
Tip	.94	2.41	1.00	2.80	.12	-.00
Mid	6.03	-1.18	2.08	-.61	.21	.00
Root	-.75	- .04	-.06	.00	-.09	.00

Contribution from trailed wakes = .74 of total
Contribution from shed wakes = .26 of total

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