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PREDICTION OF BLADE AIRLOADS IN HOVERING AND FORWARD FLIGHT USING FREE WAKES

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ABSTRACT

Recent advances in the determination of rotor airloads and performance in hovering and forward flight, including autorotation, are discussed. The ability to predict the spatial and temporal variation of blade airloads in forward flight is particularly important, since the higher harmonic components of these loads are the primary source of helicopter vibration. Flight regimes and rotor configurations are identified that require the use of free-wake analytical techniques, as opposed to those regimes for which the simpler rigid wake or momentum balance techniques are adequate.

1. INTRODUCTION

It is well known that the geometry of the wake generated by a helicopter rotor in hovering flight is uniquely dependent on the velocity field generated by the rotor and its wake, since no other velocity exists in the wake, and that rotor performance and blade loading is critically dependent on this geometry. Analytical models must therefore include a free wake which is allowed to assume the geometry corresponding to the bound circulation distribution, as determined by the rotor blade planform and twist. In forward flight, additional inflow does exist due to the component of forward velocity perpendicular to the tip path plane. In both cases, because of the relatively light loading of the rotor compared to propellers, the wake remains close to the rotor disc, certainly for the first spiral. Rotor/wake interactions, therefore, have a profound influence on rotor performance, vibration and noise, requiring a precise knowledge of the wake geometry for their prediction.

In the case of the more highly-loaded propellers and wind turbines, the problem is less severe and approximate estimates of the wake geometry are adequate for most applications except for certain cases, such as static thrust for the propeller or wind turbines with low inflows operating in the vortex ring and windmill brake conditions.

Free-wake analytical techniques require the computation of induced velocities throughout the modeled wake and are therefore far more demanding computationally than rigid-wake techniques, in which the geometry is prescribed, and induced velocities need be computed only at the rotor blade; or semi-rigid wake techniques, in which the wake is assumed to move with the local velocity existing at the rotor blade when the wake was initially generated.

The wake itself consists of a complex system of vortex filaments and sheets with viscous cores of uncertain stability. A complete analysis of rotor aerodynamics therefore requires that at least the near-wake structure and its stability also be determined, preferably by direct solution of the flow equations, including real fluid effects. [The "near wake" is defined as that portion of the wake attached to the generating blade up to the following blade location. The "far wake" is defined as that generated by all other blades (Fig. 1).] Such analyses are complex and become computationally manageable only if limited to the near wake, with the far-wake geometry computed using less-detailed free- or semi-rigid- wake techniques. It is therefore important to identify those operating regimes for which the simpler rigid or semi-rigid techniques may be used. It is the purpose of this paper to attempt such identification, and to present some recent results involving application of these techniques to rotors in hover and forward flight.

2. FORWARD FLIGHT

Several investigators have examined the problem of computing airloads in forward flight. Reference 1 summarized an extensive review of the limited experimental data available on rotor loads, compared these results with the then-existing free- and rigid- wake theories, and concluded that none of these theories were capable of predicting the loadings accurately, in particular their higher harmonic content. This higher harmonic content is an important and probably dominating source of helicopter vibration.

One of the earliest free-wake studies was that of Ref. 2, in which the wake geometry was determined for several spirals and the wake roll-up, as predicted by the experimental results of Ref. 3, demonstrated analytically.

Reference 4 concentrated on the important problem of blade-vortex interaction, of critical importance in computing the blade airloads which determine rotor vibration and acoustic signature. The analytical results were compared with available experimental results and it was concluded that vortex bursting could have an important effect on blade loads. These results have been discussed further in Ref. 5 and compared with some more-recent experimental evidence of possible vortex bursting.

In an attempt to understand the reasons for the lack of agreement between theory and test demonstrated in Ref. 1, and to clarify the physics of the problem, a simplified approach to computing airloads was developed, as discussed in Ref. 6. This approach identified those factors not fully modeled in the previous investigation, which had to be included in the analysis in order to ensure agreement with the test data. These factors included recognition of the existence of a mid-vortex, in addition to the usually-postulated tip and root vortices, over a portion of the rotor disc, as sketched in Fig. 2. The near and far shed wakes (Fig. 1) also required modeling, since their effects on rotor loads were found to be not negligible.

When the analytical approach was modified to include these effects, reasonable agreement with test data resulted. However, the model used a rigid wake with the location of the center vortex prescribed a priori, which limited the generality of the solution. A free-wake analysis was therefore developed in Ref. 7, again based on the simplified approach of Ref. 6. Reasonable agreement with test data was obtained without the use of a prescribed wake location; however, the complete free-wake program was far more computationally demanding (several minutes vs. several seconds), to the point where much of the advantage of the simplified approach was lost. Much of the additional computation was due to the far shed wake modeling, which analysis showed to make only a small contribution to the overall blade loading. By eliminating the far shed wake from the computation, this approach should still be fast enough to use as the basis for a more elaborate analysis of the near wake in order to identify the roll-up characteristics by CFD techniques involving a direct solution of the Euler equations.

In addition to the difficulty with the location of the center vortex, the three vortex models of Ref. 6 also led to additional computational problems when the center vortex location was not prescribed, particularly on the advancing side. An indication of the type of problems can be seen in Fig. 2. This shows the computed position of each vortex element trailed. A "shark fin" occurs at around 80° as the root vortex position jumps outboard as a result of the blade bound circulation distribution. In an effort to eliminate this problem and to avoid the difficulties mentioned above, a first step toward a free-wake model was the development of an improved model of the trailed wake. The key to this model was to allow a variable number of vortex trailers, depending only on the blade bound circulation at the appropriate azimuthal position. This introduced some computational problems that were eased by starting the computation with a rigid wake with the maximum allowable number of vortices trailed from each azimuth. Once a relatively stable solution was found, it could then be used to find an initial downwash distribution for starting the free-wake solution. This approach also simplified the geometry calculations. Rather than trying to find only the actual blade vortex interactions as the number of vortices changed, a prescribed number of trailers for each blade were always present. In many cases, however, the corresponding strength of the vortex was set to zero as the blade bound circulation distribution became smoother.

A simpler model for the displacement of each trailed vortex element was used for the semi-rigid wake analysis. The displacement of each vortex was calculated using the average of the velocity in the wake at the time the vortex was generated and the velocity in the wake at the blade vortex interaction point. If no interaction occurred, the displacement was calculated using only the initial velocity. For those vortices trailed from the blade 180° ahead, the displacement was calculated using only the initial velocity, the velocity at the point of intersection with the 90° blade and the velocity at the computational blade. The vortex was assumed to roll up instantaneously at the trailing edge of the generating blade. Vortices trailed from the other blades were treated as semi-rigid. Since results indicated that the far shed wake had only minor effects, a semi-rigid model was also used for the shed wake.

The major finding from this work was that most of the changes in blade loading from a rigid wake modeling occurred when the semi-rigid wake model was implemented. The free-wake model did not cause a significant change in blade loading from the semi-rigid modeling. Another finding was that while radial motion of the vortices was minimal, vertical motion was quite significant. One problem area resulting from this vertical motion was the tendency for some vortex elements to rise above the rotor disk. This indicates that there is a need for an accurate modeling of the vortex roll-up in order to determine vertical displacements accurately.

Some results are presented in Figs. 3 and 4. Figure 3 follows the technique of Ref. 1, in which a Mercator-type plot of the airloads is used. This projection is of value in presenting a qualitative view of the entire loading for comparison with the test data. Two projections are shown in Fig. 3, both for the computed loads using a semi-rigid wake and for the experimental results of Ref. 8 as used in Ref. 1. Reasonable agreement is apparent in both total and higher harmonic loadings near the tip, but discrepancies exist towards the inner part of the blade, where more activity is evident in the theoretical than in the experimental results. These discrepancies become clearer from Fig. 4, where the same loads are compared directly with experimental data, station by station as in Ref. 6.

Figure 4 shows the total blade loading and higher harmonic loads for the outer 50% of the blade. These were calculated using the free wake model for the trailing vortices and a semi-rigid shed wake. As mentioned above, the inner stations did not show as good agreement and appeared quite noisy. The tip stations 0.97R and 0.99R are not shown, since the theoretical results do not predict the drop-off in lift evident in the experimental results. This may be due to the lack of a reliable method for predicting tip losses as the tip vortex is formed. Empirical estimates of the tip losses have not been included in the analysis.

From Fig. 4, it can be seen that this model shows reasonable agreement with experimental results with two significant exceptions. The first area is the higher loading predicted by theory over the outboard portion of the retreating blade. This may be due to blade elasticity, as discussed in Ref. 6. The second area where theory differs from the experimental results is in the azimuth range from 40^{o} to 80^{o} at the more outboard stations. For example, at 60^{o} and 0.95R, the computed loads are 3.7 lbs/in, as compared to an experimental load of 14.5 lbs/in. An examination of the contributions from each wake element shows that the major influences at this station and azimuth are the tip vortices from the two preceding blades and the mid vortex from the immediately preceding blade. Based on the free wake results, the induced velocity from each of these elements is directed upward at 0.95R. The two vortices from the immediately preceding blade are the most significant, and result from the circulation distribution shown in Fig. 5. The tip vortex is assumed to contain the vorticity from the tip to the first peak at 0.99R. The mid vortex then contains the vorticity from the negative peak at 0.99R to the next peak at 0.4R. A vortex core size of 0.01R was used in this modeling for both the trailed vortices and the shed wake. One likely explanation for the discrepancies in loading is that the radial positions of the wake vortices are not exactly modelled. Small changes in the radial position can cause large changes in loading in this model. Since the radial velocities are not large enough to cause significant radial motion over the time interval of concern, this may be due to the inability of the model to accurately predict the circulation distribution over the inboard sections of the blade.

Another phenomenon not included in the above analysis is the vertical migration of the curved system of trailing vortices leaving the blade, which may well result in a further displacement of the free wake. This effect arises from the mutually-induced velocities and is quite separate from the effects of the self-induced velocity on the vertical displacements of a curved line-vortex. This phenomenon is discussed in Ref. 3 and a method developed for its computation in the case of hovering flight, where a greater degree of curvature exists but time-dependent effects are absent. Extension of these methods to include the time-dependent effects of the forward-flight case is a necessary further step towards a better definition of the wake geometry.

3. FREE WAKES IN HOVER AND AXIAL FLOW

Free-wake analytical techniques are particularly important for the determination of the hovering performance of rotors with unconventional geometries when no experimental data exists for estimating wake geometries a priori. An example is the highly-twisted and tapered blade of the tilt rotor aircraft. In Ref. 9, the fast free-wake technique of Ref. 10, which uses a simplified wake geometry representation, was applied to the computation of the performance of the tilt rotor described in Ref. 11. Good agreement with the experimentally-determined performance and wake geometries was achieved using this free-wake technique, as shown in Figs. 6 and 7, whereas, as pointed out in Ref. 11, agreement using prescribed-wake techniques was not as good, as might be expected for rotors with geometries radically different from the previously-available experimental data base.

Another application in which free-wake techniques are desirable is in the formal optimization of a hovering rotor. Formal optimization techniques are computationally demanding, since the aerodynamic theory used must allow for a sufficient number of design variables to ensure identification of the true optimum. The fast free-wake technique of Ref. 10 is well suited to such an application, and was used in Ref. 9 to demonstrate the use of an unconstrained quasi-Newton formal optimization algorithm. The results for conventional rotors indicated no need for radical changes in planform or twist, other than moderate taper, but the technique developed may well be of interest for the formal optimization of more radical designs.

In the case of axial flow, an interesting application of the free-wake techniques is to a rotor in vertical descent operating in the autorotative regime in the vortex ring condition, close to minimum rate of descent. Conventional momentum or rigid-wake vortex theories are inapplicable in this regime, which is usually analyzed using the experimentally-determined corrections suggested by Glauert in Ref. 13. However, free-wake techniques may also be used for this application.

It is difficult to obtain precise experimental data for helicopters operating in the vortex ring regime; however, useful data has been obtained on wind turbines operating in this regime in Ref. 13 and in Ref. 14. These exerpimental results indicated that wind turbines operate satisfactorily in this regime of low inflows, whereas helicopter rotors operating under such conditions show a tendency towards erratic and unstable flight. The fast free-wake technique was therefore applied to the case of the full-scale wind turbine of Ref. 13. Figure 8 shows the predicted power output compared with the experimental results. Evidently the fast free-wake theory works well in the vortex ring condition and throughout the operating range, including well into stall, providing that the post-stall airfoil characteristics are modeled. Figure 9 shows the computed wake geometries.

The experimental results of Ref. 13 did not include thrust data; however, thrust measurements were taken in Ref. 14. As shown in Fig. 10, the fast free-wake theory predicted the experimental thrusts where the conventional momentum theories failed. The excellent agreement provided by the classical empirical corrections suggested by Glauert is also evident.

4. CONCLUSIONS

Free-wake techniques are generally necessary in hovering flight, where the only inflow is that induced by the rotor and its wake. Such free-wake analysis need not be computationally demanding if the fast free-wake technique is used. Formal or heuristic search techniques may then be used to optimize rotor performance.

Free-wake techniques are probably not essential for axial-flow conditions in which the inflow is large compared to the induced flow, as is the case for propellers in forward flight or wind turbines under normal operating conditions. However, when the inflow velocities are of the same order as the induced velocities, as in the case of a helicopter in close-to-minimum vertical autorotative descent, or a wind turbine operating in light winds, free-wake techniques are necessary.

In forward flight, semi-rigid wake techniques appear to be adequate, at least in the cruising flight regime, and are computationally more efficient than complete free-wake solutions.

Much remains to be done before a completely-satisfactory and robust method which allows for the true vortex structure and near-wake geometry is available, but the methods discussed in this paper appear to give reasonably-accurate results suitable for design trade-off studies and are computationally sufficiently efficient for rotor optimization studies, either formal or heuristic.

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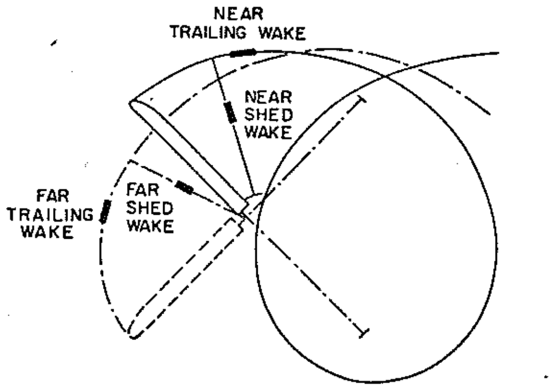

Fig. 1. Wake geometry showing near and far trailed and shed wakes.

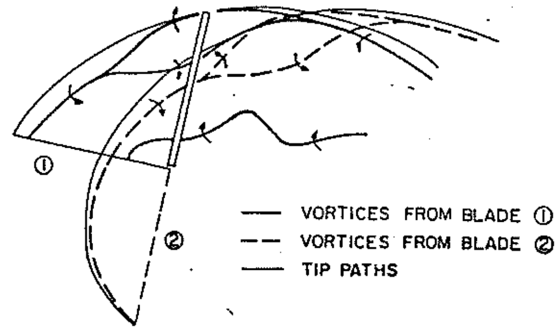

Fig. 2. Sketch of wake geometry at critical intersections using three trailed vortex model.

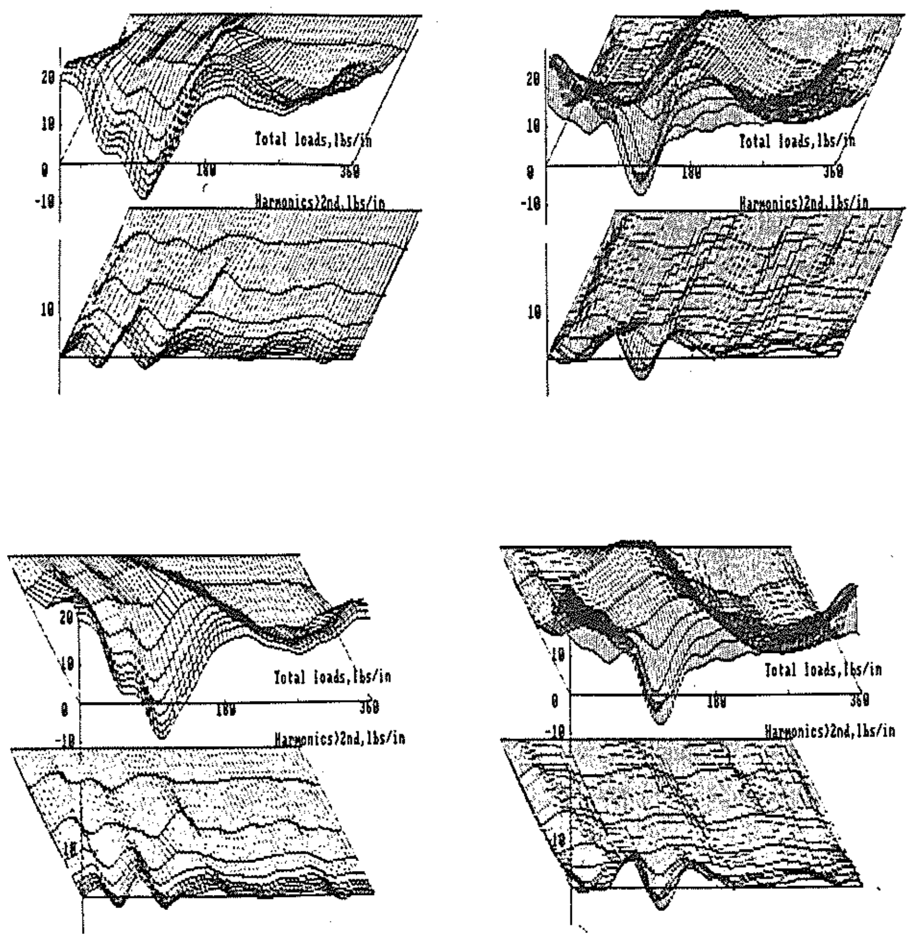

Fig. 3. Perspective plots of airloads (vertical scale) along blade (inclined axis) vs. azimuth (abscissa) for CH 54 helicopter at 150 mph with 5^{o} forward shaft tilt. Column 1: theory. Column 2: experimental data.

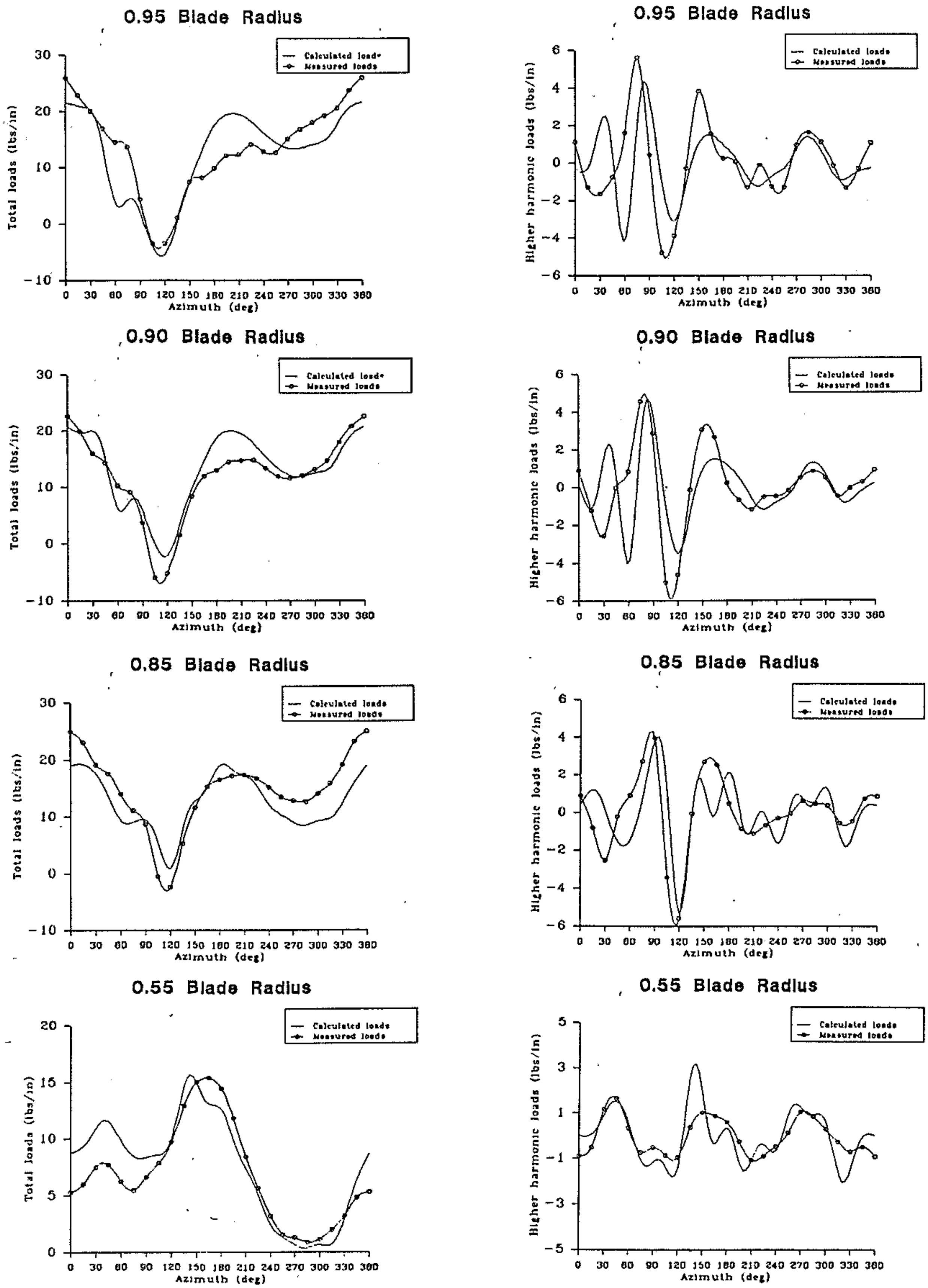

Fig. 4. Computed blade loading as a function of azimuth for same flight condition as Fig. 3. compared with experimental data of Ref. 8. Column 1: total loads, Column 2: harmonic loads above 2nd.

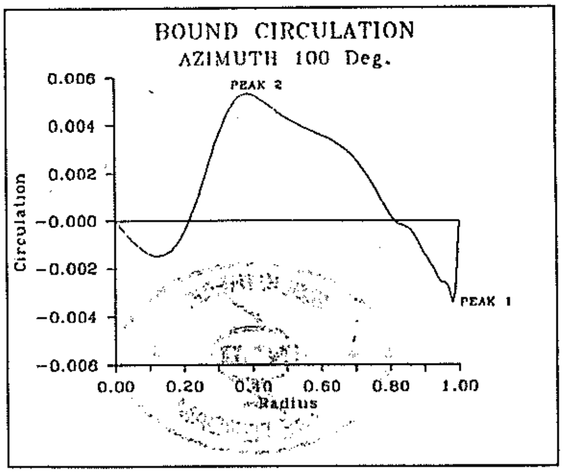

Fig. 5. Blade bound circulation at 100° azimuth.

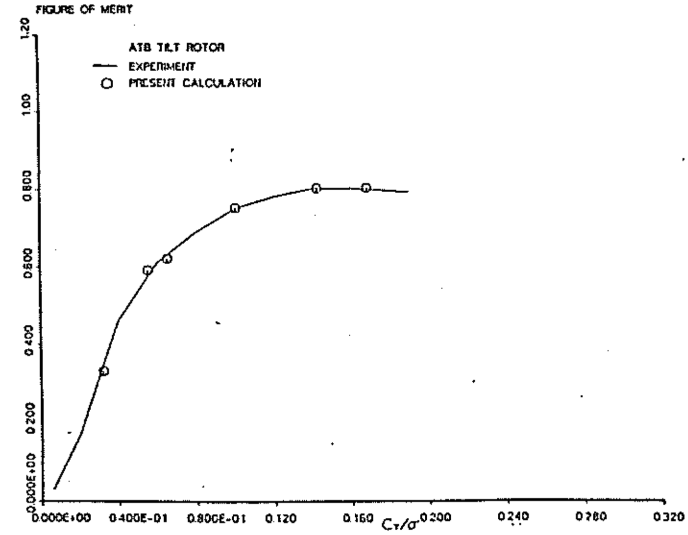

Fig. 6. Comparison of computed figure of merit for tilt rotor on hover compared to experimental data of Ref. 11.

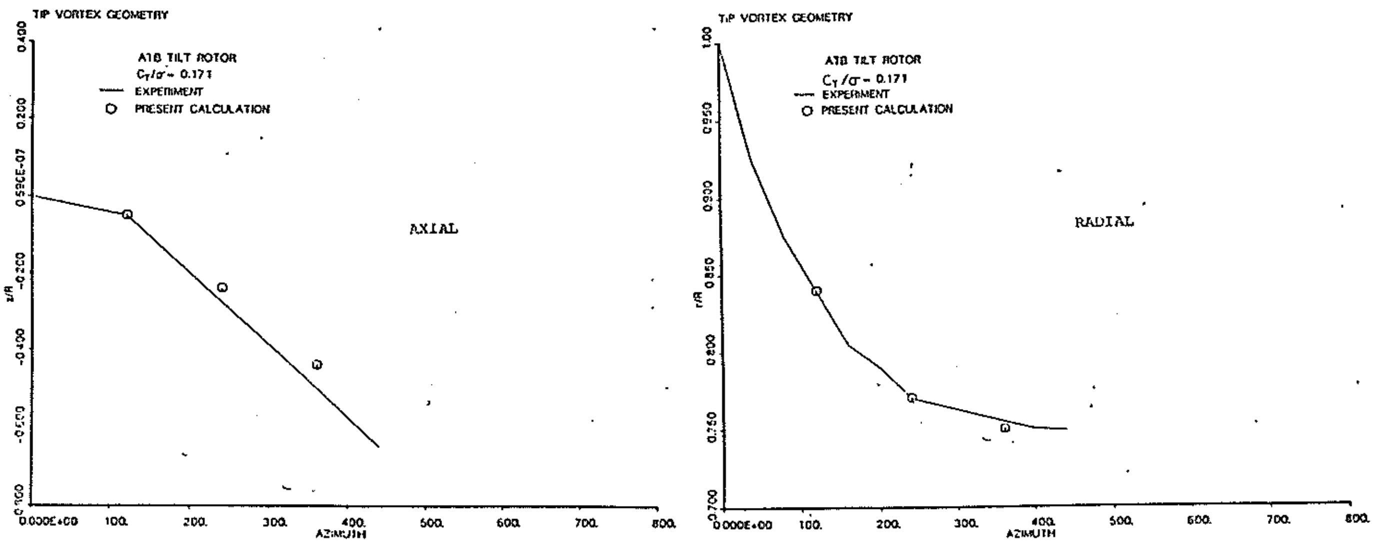

Fig. 7. Experimental and computed wake geometries for rotor of Fig. 6.

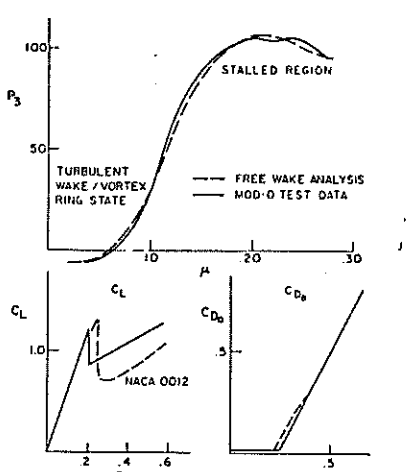

Fig. 8. Comparison between measured performance of Mod-O wind turbine (Ref. 13) and free wake analytical results with lift and drag schedule as shown. P_3 in KW.

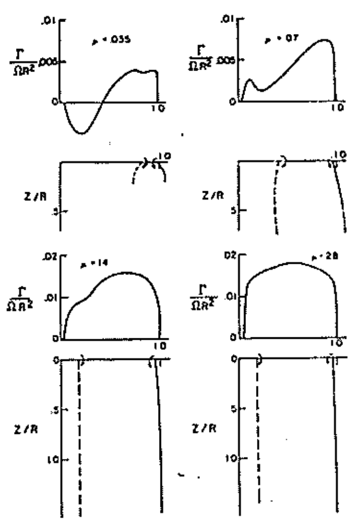

Fig. 9. Selected wake geometries from free wake analysis of Mod-O wind turbine.

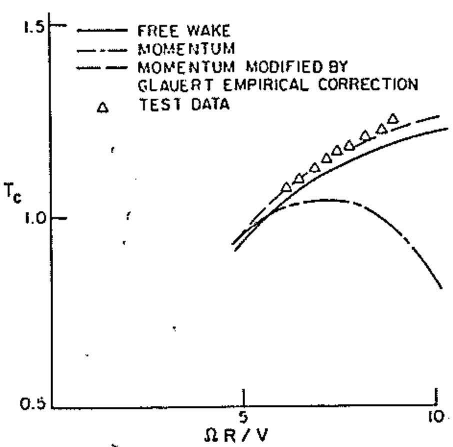

Fig. 10. Wind turbine performance predictions in turbulent wake/vortex ring state and comparison with experimental results of Ref. 14 and with empirical correction of 1926 by Glauert.