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FAST FREE WAKE ANALYSES IN HOVERING AND FORWARD FLIGHT

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Introduction

Vibration control and, later, noise reduction were the problem areas which drove the search for an individual blade treatment of rotor aerodynamics, as opposed to the actuator disc theory which had served so well for performance estimation in the past. The search is ongoing, however the complexity of the problem makes it unlikely that a numerically precise solution will soon be available. The following examples are two among many which could serve to illustrate this complexity.

As a first step a model for the individual spiralling wake generated by each blade was needed. It soon became apparent, from flow visualizations in hover[1] and low speed forward flight[2], that the wake structure was far from being a uniform spiral. Early, and reasonably successful, attempts at computing the distorted wake are shown in Fig.1, taken from Ref.2. However, when these results were first used to compute airloads, agreement with the measured airloads was unsatisfactory until vortex breakdown, occurring prior to encounter with the blade, was introduced. Agreement was then much improved. Vortex bursting had occasionally been observed experimentally and later measurements of the vortex structure appears to bear out that such a phenomenon could occur[3].

In addition to the real fluids effects on the vortex, those on the blade resulting from a close B/V encounter can have a major effect on the resulting loads. For example tests[4] have shown flow separations occurring at fairly low induced angles of attack during a blade vortex encounter. This was attributed to spanwise flows arising from the highly localized spanwise changes in angle of attack, in combination with the effects of viscosity.

Clearly, even if a design tool which adequately covered all such effects were to be developed, the computational complexity would make it of doubtful value to the designer. The time and expense involved would discourage its use in the heuristic approach usual in design optimization, while formal optimization would be even less attractive. These considerations led to the search for a simpler approach to modeling the wake recognizing that the final design optimization will usually require extensive experimentation through to flight testing. Physical insight is therefore frequently of more value than a high degree of numerical precision, with theory offering a guide to such experimentation, hopefully with most of the more sensitive parameters included.

In the two dimensional treatment of the oscillating rotor blade Ref.5 used doubly infinite line vortices to represent the wake. Ref.6 represented the wake where it passed under a blade by doubly infinite vortex sheets. In Ref.7 the results from a model using doubly infinite line vortices at B/V encounters was compared with the results from a complete representation of a rigid spiral wake. The simpler model reduced the required computer time by a factor of about 50 yet gave results almost identical to those from the more complete model leading, as a first step in reducing complexity, to the later development of the fast free wake (FFW) methods discussed in the following sections.

Hovering Flight

In order to test the use of the infinite line vortex approximation on a free wake model, the hovering case was first selected[8] because the spiral wake could be represented more realistically by a system of vortex rings for which closed form solutions exist. Both models were found to give almost identical results and agreed well with experiment (Fig.2). The hovering free wake case is in many ways more difficult to compute than the forward flight case because of the tendency towards instability of helical vortices [9]. In ref.2 it was shown that the hovering case could only be made to converge by using a high degree of relaxation, a problem only slightly relieved in the FFW model of Ref.8 by adding to the near and intermediate wake a far wake represented by a semi-infinite rigid vortex cylinder.

For conditions with higher inflows than in hover, such as vertical climb and autorotation, convergence is more rapid and the solutions more robust. For example in the case of a wind turbine[10] the free wake solution agreed with the test results throughout the operating regimes (Fig.3) and well into stall, if the blade section characteristics at high angles of attack are reasonably well modeled. It is interesting to note that, in the vortex ring/turbulent wake region, the empirical correction suggested by Glauert almost fifty years ago gives results remarkably close to those obtained by the free wake model and test results (Fig.4).

The FFW method considerably facilitates formal optimization which would otherwise be difficult with more computationally intensive codings. Such an optimization of the blade in hover using the conjugate gradient method predicted the expected tapered, twisted plan form[11]. There is however a more global optimization which it would be of interest to attempt for tilt rotors where the twist and taper are optimized simultaneously for both the hover and forward flight regimes. A similar global optimization for the helicopter would also be of interest, though for this case complicated by the transition from axial to cross flow.

The FFW approach is also useful as a means of examining the roll up of the wake as it leaves the blade[12]. The roll up of an isolated near wake in hover (without far wake effects) represented by 20 vortex filaments is shown in Fig.5 after the blade has rotated 180 deg. from the azimuth of the wake's birth. Its characteristics agree well with the experimental results of Ref.1. The wake rolls up from the outer portion of the blade into a tight tip vortex, then separates, reforming as an inboard vortex sheet. There is some evidence of a weak vortex forming near the outboard edge of this sheet but there is no clear experimental indication of its existence.

The FFW technique may also be used to compute wake geometry, with the more direct but computationally demanding CFD methods, such as those based on solutions of the Euler equations[13], used to compute the blade loads. Fig.6 shows results using this technique for the same case as that of Fig.2. The fine grid used (96x20x40) gives improved results compared to the lifting line model of Fig.2. Extending this approach to the computation of the wake structure and roll up schedule at any appreciable distance beyond its azimuth of birth is complicated by the problems associated with numerical diffusion.

Forward Flight

In the forward flight regime one of the most significant findings was that reported by Hooper[14] as a result of his review of all available experimental data on rotor airloads. He noted the existence of a region of negative loading on the advancing blade at the higher advance ratios which resulted in an almost impulsive higher harmonic load on the outer sections of the blade near the 90 deg.

azimuth. Fig.7 shows the experimental results from wind tunnel tests[15], plotted in the Mercator format proposed by Hooper to clarify the temporal and spatial distribution of the airloads. Time (azimuth) is along the x axis, blade span along the y axis and load (in pounds per inch) along the z axis. Both total load and the higher harmonic loads above the second harmonic are plotted. The higher harmonic loads are due almost entirely to wake interference effects and are the primary source of vibratory airloads. The impulsive loading, occurring at about the 90 degree azimuth, is clearly evident.

Having established that the fast free wake approach was an adequate and useful tool for analyzing the aerodynamics of the rotor in axial flow, and challenged by Hooper's demonstration in Ref.14 that no existing rotor analysis technique could predict the vibratory airloads measured in high speed forward flight, a fresh look was taken at an earlier coding. The free wake coding of Ref.2, discussed in the Introduction, modeled the wake by two vortex filaments. The program searched for the peak positive loading and located the origin of the vortices on either side of this peak, using the Betz criterion to determine their spanwise locations. Since the geometries of the vortex spirals were computed throughout their length for at least two turns, this wake model was used in order to reduce the computational time to a reasonable value with the equipment then available. However lower peak loadings, such as the small but intense area of negative loading noted by Hooper, were missed.

Using the FFW method for the forward flight case, initially with a rigid wake[16], and with the fore knowledge of the region of negative loading, an additional vortex was introduced inboard of the tip vortex in that region . Agreement with the experimental data was much improved. These preliminary results were followed by a free wake analysis[17] which gave results in good agreement with the test data but was far more computationally demanding (several minutes vs. several seconds). A "semi-rigid " model was therefore developed in which the vertical location of a vortex at its point of encounter with a following blade was determined by the downwash velocity on the blade generating the vortex at that point. It was found that the semi-rigid wake gave results almost identical to those using the free wake and was as efficient as the rigid wake model.

These conclusions were further substantiated in Ref.18 where it was reported that computations of the wake roll up, similar to those conducted for hovering flight, supported the assumptions inherent in the semi-rigid wake model. However several problems still remained in that the method, while giving reasonable agreement with the test results at the important outer blade sections, indicated more activity over the inboard portions of the blade than was evident from the experimental results of Fig.7.

The most recently published results[19] discussed a more elaborate analysis of the roll up characteristics of the vortex sheet generated by a blade and concluded that there was very little evidence of an appreciable roll up other than from the tip and possibly the root, with the inner trailed wake remaining essentially as a sheet. A model was accordingly developed in which the inner wake was represented by a sheet of vorticity which was assumed not to roll up. This resulted in only a minimal reduction in the inner wake activity. The peak loading at the tip was also somewhat reduced in comparison with both the experimental results and those using a rolled up inner trailed wake. The conclusion was that further investigations were needed to improve the analytical model.

Since the preparation of Ref.19, further analyses have indicated that improved results could be obtained if the far shed wake, as well as the far trailed wake, were represented by a vortex sheet rather than by discreet vortex filaments. In order to clarify the discussion which follows, Fig.8 defines the components of vorticity forming the wake. The trailed wake is generated by the spanwise variations of the bound vorticity along the blade. The shed wake is generated by the temporal variations as the blade rotates. The near wake is that attached to the target blade, the far wake is that generated by all the other blades. In general the effects of the far shed wake had in the past been shown to be small[7]. Consequently, in the interests of computational efficiency, the far shed wake was modeled as discrete vortices of strength equal to the change in bound circulation over two azimuthal segments and located mid way between them. The near shed wake was treated using strip theory and the classical two dimensional lift deficiency function C(k)=F+iG. A straight near wake was assumed, so that the changes in the geometry due to wake curvature as segments were added was neglected. Generally two segments ahead of and behind the blade were used.

The first step was to change the geometry of the wake interference as segments were added. Fig.9 shows the results, which are very similar to those reported in Ref.19 and agree well with the experimental results of Fig.7 over the important outboard sections. The greater activity over the mid sections is still present, though somewhat reduced over that of Ref.19, indicating that modeling of the far shed wake is of some significance. A direct comparison between the theoretical and experimental results for a representative spanwise station near the blade tip is shown in Fig.10.

The next step was to refine the shed wake by doubling the number of line vortices and locating one at the midpoint of each azimuthal segment. The results were unsatisfactory in that the loading over the outer sections showed large peaks which were traced to a very close encounter between the blade and a shed vortex generated by a blade 270 degrees behind the target blade. Evidently modeling the far shed wake by a series of line vortices could result in occasional spurious loadings.

Since there is no obvious justification for assuming a roll up of the shed wake, a model was developed in which the shed wake, as well as the trailed inner wake, was treated as a sheet of vorticity. The results are shown in Figs.11 and 12. The activity over the inboard sections of the blade has been reduced, however the higher harmonic pulse loading near the tip is also somewhat reduced compared to the experimental results.

In all the above results the treatment of the unsteady flow due to the near wake are approximated through the use of strip theory and the classical two dimensional lift deficiency functions C(k). The reduced frequency, k, is based on the local velocity as the blade rotates. Ref.20 has shown that this a reasonable approximation for the case of a time varying forward velocity, at least on the advancing side of the rotor. Useful discussions of methods for the treatment of the unsteady circulatory lift in forward flight, and the pertinent literature, are given in Refs 21 and 22. In particular, treatment in the time domain rather than the frequency domain would appear to be preferable, thus avoiding the use of lift deficiency functions based on the harmonics of the loads. Accordingly, and in view of the highly three dimensional and impulsive character of the blade loadings evident in Fig.7, a three dimensional solution in the time domain, rather than in the frequency domain, was attempted. In this model the rear neutral point (half a chord from the center of lift) was used as the lower limit of integration of the sheet of vorticity shed from the blade since Ref.7 had shown this to be a reasonable approximation for the two dimensional case. The solution was three dimensional in that a time varying trailed near wake was introduced, as well as the time varying near shed wake, and the contributions of each segment of wake to all segments of the blade were included. The results, shown in Figs.13, are similar to those of Fig.11. Fig 14 indicates some improvement over Fig.12 in the magnitude and phase of the higher harmonic pulse loading.

Treating the far trailed and shed wakes as sheets rather than as discrete vortices appreciably increases computational times. The logarithmic singularities involved cause difficulties in finding reliable closed form solutions which cover all possible encounters. Numerical integration, for the same reason, requires a very fine discretization in the vicinity of the B/V encounter. It is therefore of interest to consider a simpler model where both near and far shed wake, and the time dependency of the near trailed wake, are ignored and the far wake is rolled up. Reasonable results are obtained, as shown in Figs.15 and 16. For more approximate analyses, and in the interests of computational efficiency, it may be acceptable to use such a quasi-steady solution, as has often been the case for fixed wing analyses. However, in treating blade aeroelastic stability problems where the relevant reduced frequencies tend to be higher than in the case of blade airloads, such an approximation may not be valid.

Further refinements in the fast free wake methodology would be desirable, for example the incorporation of corrections for the effects of sweep. In forward flight the blade experiences a varying angle of effective sweep as it rotates which the lifting line representation of the blade can not sense. At the important segment of the azimuth, around 90deg, this correction is obviously small, however it could have a more appreciable effect at the 180deg azimuth where the measured and computed total loads are not always in good agreement.

Continued investigations will undoubtedly shed further light on these important problems. Hopefully the fast free wake technique will assist in such investigations, providing a simple means of treating the wake and allowing full computational power to be concentrated on a more elaborate analysis of the wake, and of the aerodynamics of the blade itself, in the immediate vicinity of B/V interactions.

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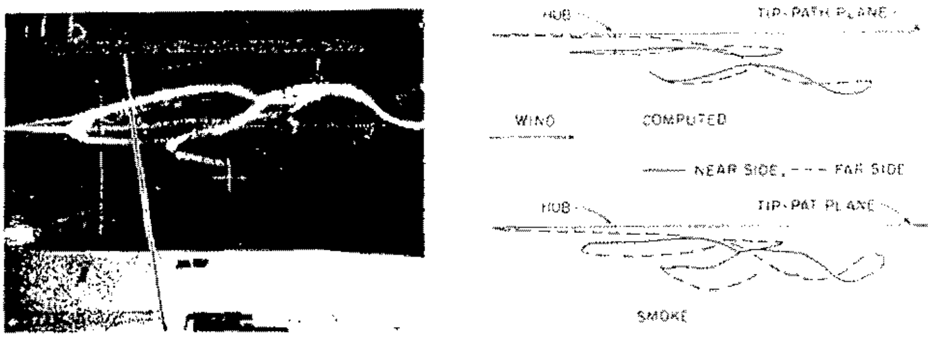

Fig.1 Experimental and predicted free wake geometry. Advance ratio of 0.10.

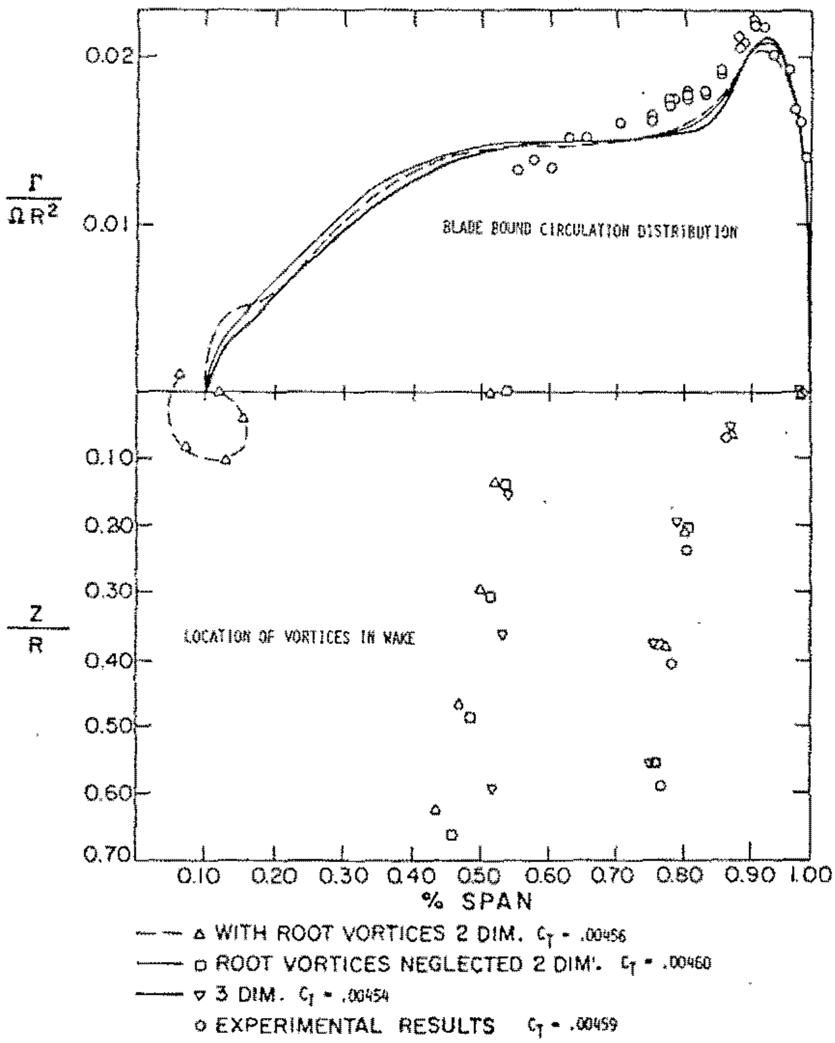

Fig.2 Experimental and predicted blade bound vortex distribution and wake geometry in hover. 2D uses line vortices, 3D uses vortex rings. Exprimental results fro NASA TM 78615, 1979

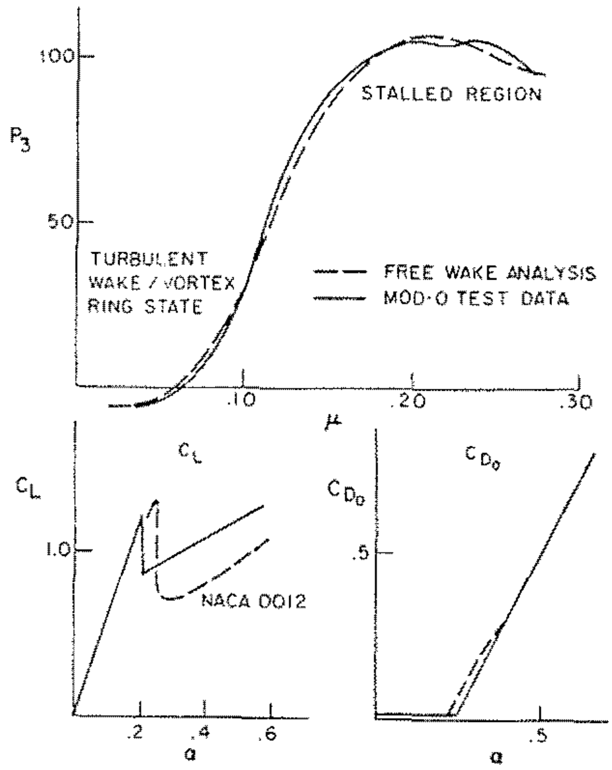

Fig.3 Comparison between measured performance of Mod 0 wind turbine and free wake analysis using lift and drag schedule shown. P_3 in KW.

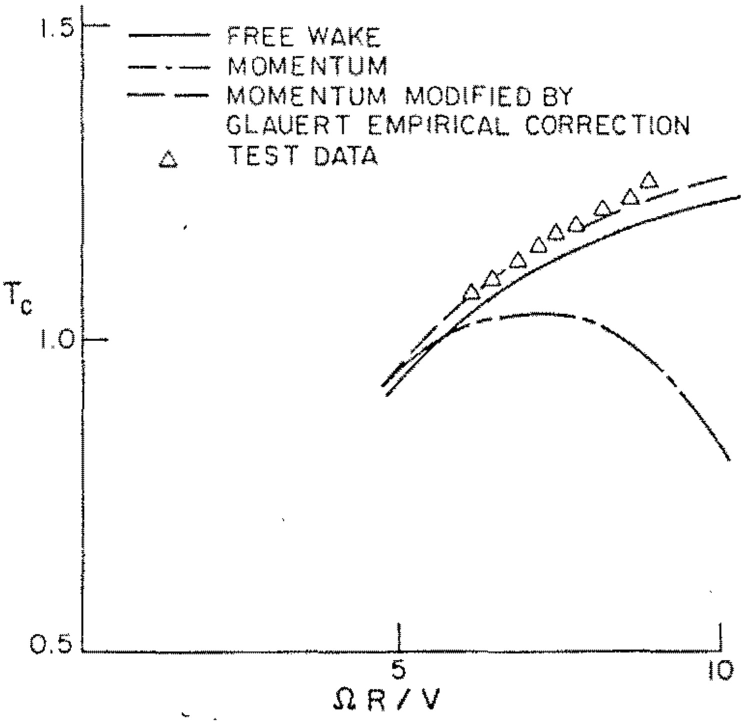

Fig.4 Comparison between predictions of wind turbine thrust coefficients in vortex ring state and wind tunnel tests.

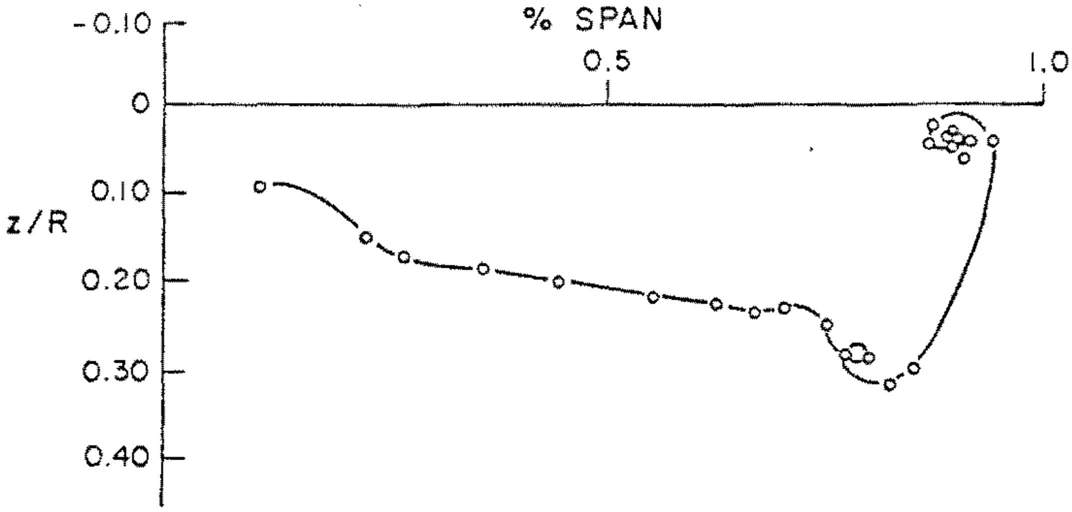

Fig.5 Roll up of complete near wake at 180 deg. azimuth from birth - no far wake effects included.

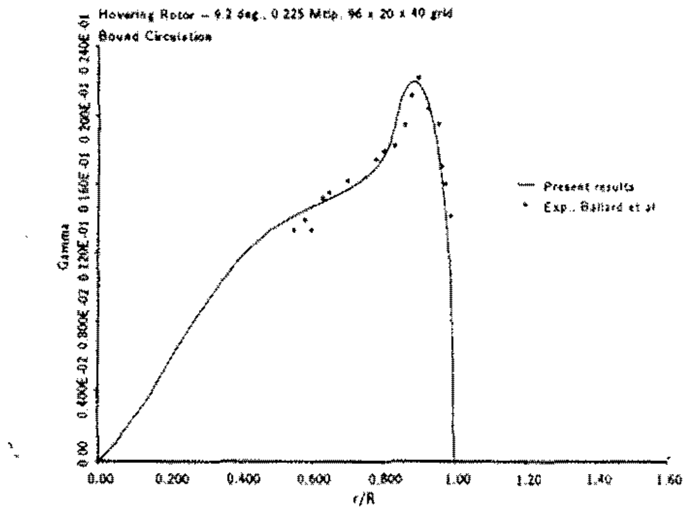

Fig.6 Same as Fig.2 but with bound circulation predicted by Euler solver coupled to FFW geometry .

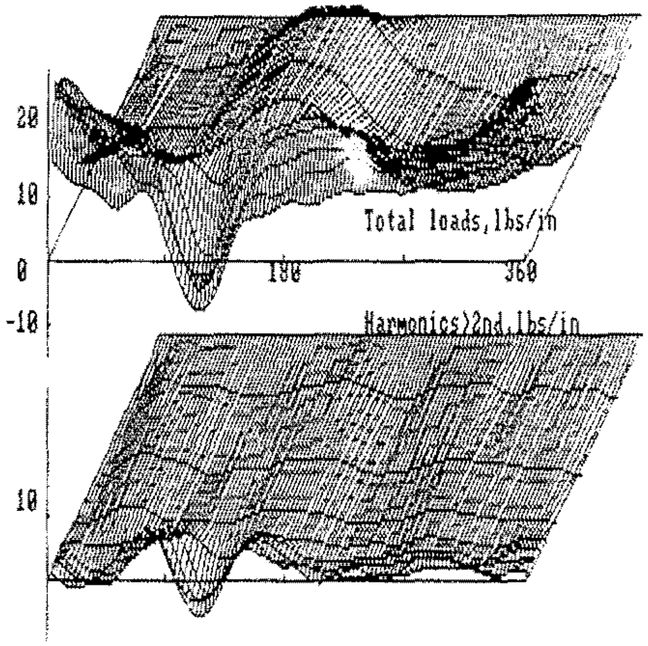

Fig.7 Airloads from full scale wind Tunnel tests. Advance ratio of .39, shaft angle 5 deg. forward.

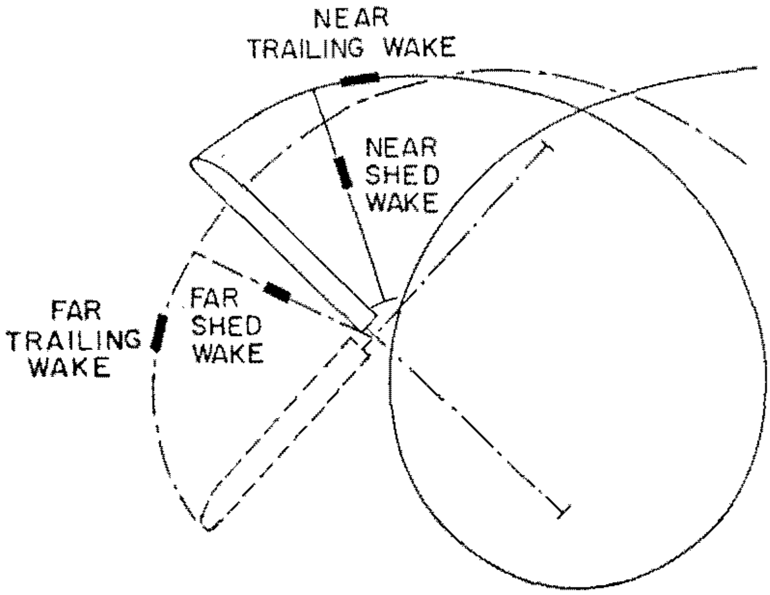

Fig.8 Wake geometry showing near and far trailed and shed wakes.

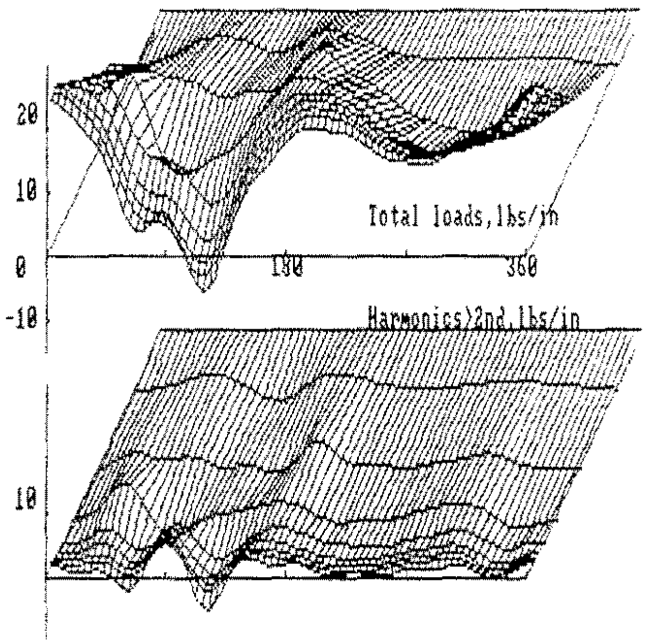

Fig.9 Predicted airloads for same case as Fig.7. Far trailed and shed wakes modeled by rolled up vortex filaments.

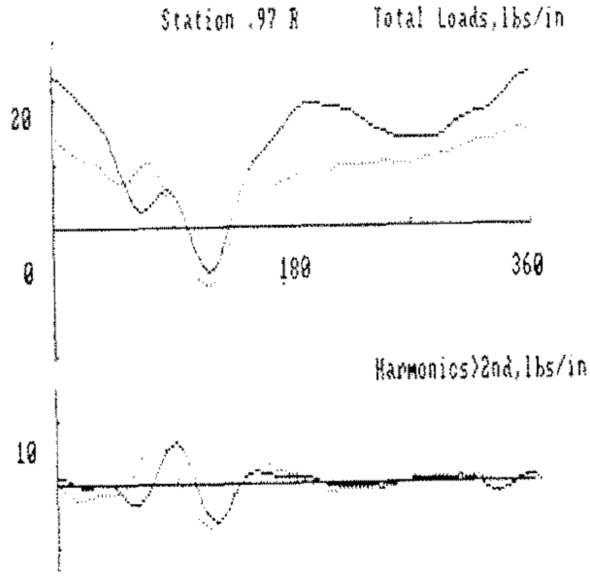

Fig.10 Comparison at 97% span between airloads of Fig.9 with experimental airloads of Fig.7 .
------ theory
...... test.

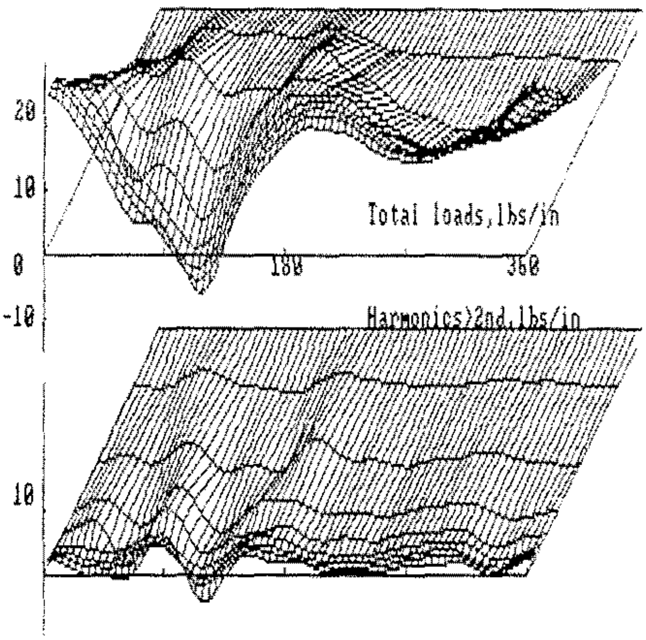

Fig.11 Same as Fig.9 but with far shed wake and mid section of far trailed wake modeled by vortex sheets.

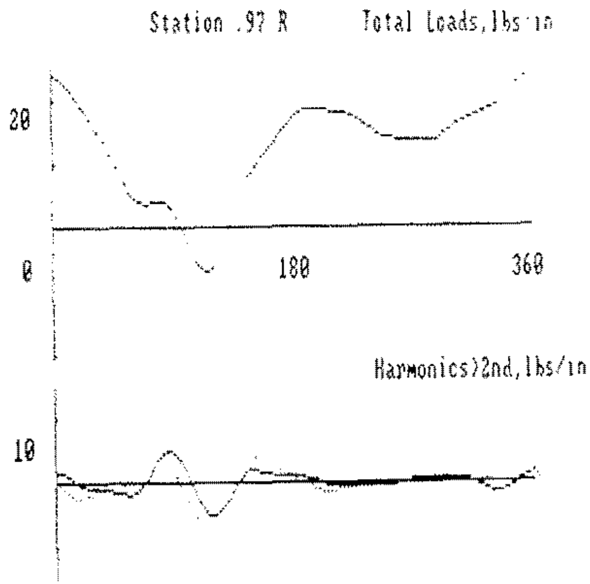

Fig.12 Same as Fig.10 but with wake model of Fig.11.

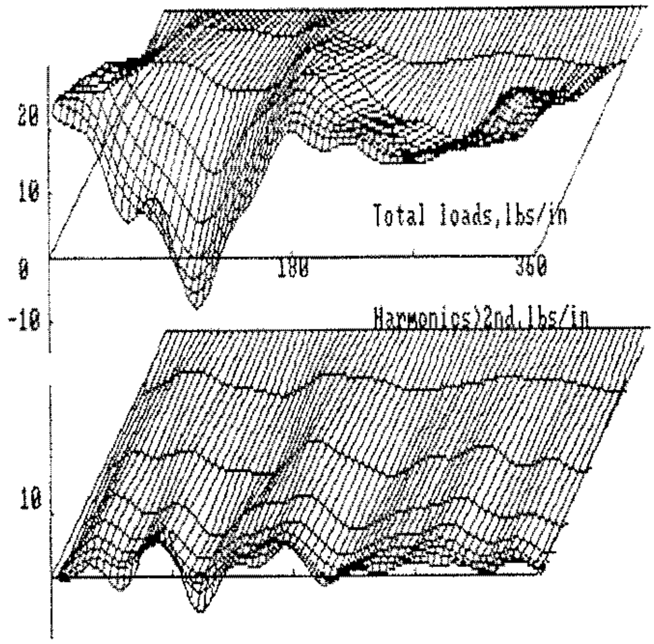

Fig.13 Same as Fig.11 but with near shed sheet and near trailed wakes modeled in time domain.

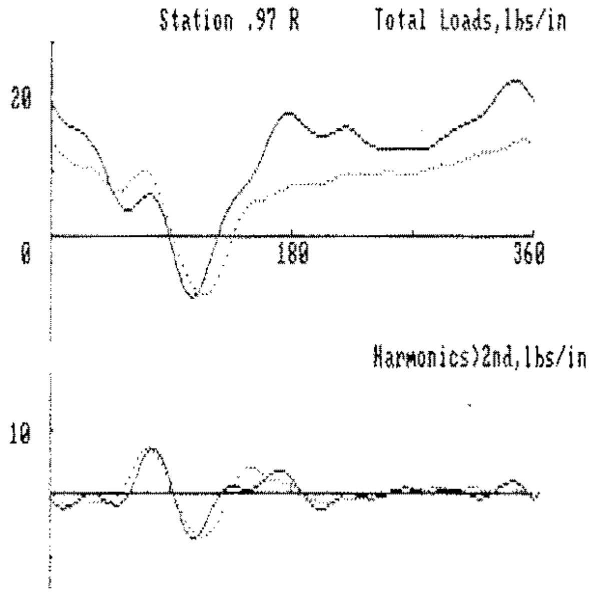

Fig.14 Same as Fig.10 but with wake model of Fig.13.

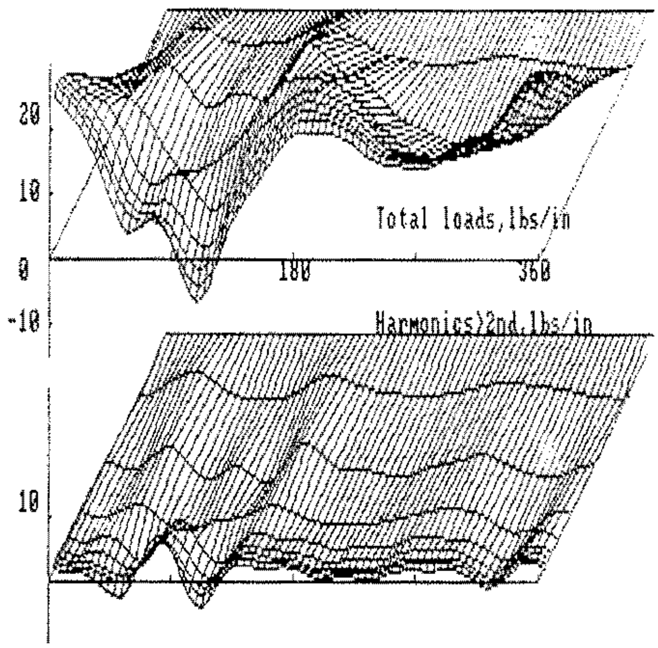

Fig.15 Same as Fig.9 but with near and far shed wakes neglected.

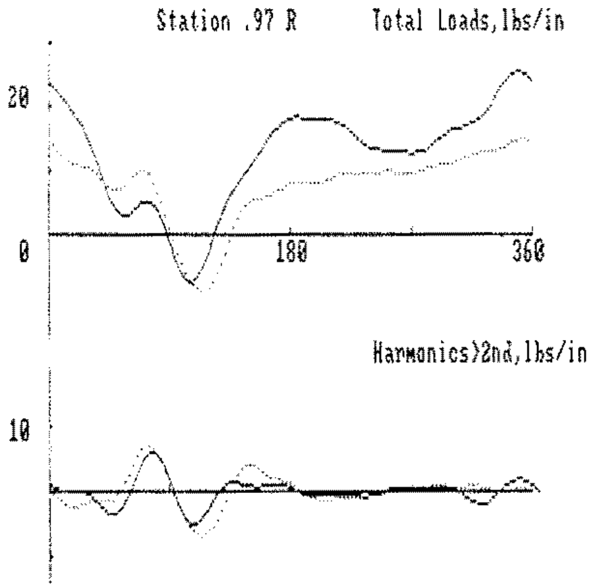

Fig.16 Same as Fig.10 but with wake model of Fig.15.