SEVENTEENTH EUROPEAN ROTORCRAFT FORUM

Paper No. 91 - 35

CURRENT EUROPEAN RESEARCH ACTIVITIES IN HELICOPTER INTERACTIONAL AERODYNAMICS

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SEPTEMBER 24 - 26, 1991

Berlin, Germany

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Abstract

An European collaborative programme for Interactional Aerodynamics study on helicopter configuration was started in 1990 in the BRITE/EURAM activities under the name SCIA (Study and Computation of Interactional Aerodynamics).

The involved Partners are :

Industries	Research Centers	Universities
Agusta	Alfapi	Bristol Univ.
Aerospatiale	CIRA	TU-Braunschweig
MBB	DLR	TU-Denmark
Westland	NLR	UNIBW Munchen
	ONERA	Rome Univ.

In this paper, the development and the current results of this research are presented.

The major goal of the participants in the SCIA project is to improve existing methodologies for individual helicopter components (rotor, fuselage) and to develop algorithms for predicting the complex rotor/fuselage interaction problem. The efforts in this project are directed toward code/technology development for an industrial environment rather than pure research purposes.

What follows is an overview of the activities performed by the collaborative group in the computational area and also in the experimental field, the latter included in the program because a sound data base is an essential requirement for any programme involving the development and improvement of theoretical algorithms; the partners agreed on setting up of experimental activities to obtain basic information on rotor/fuselage flow fields, not yet available or specific to the planned activities.

1. Introduction

The flow around individual helicopter components such as main rotor, fuselage, tail rotor etc. is complex. Some of the basic flow phenomena are described in [1]. In aerodynamic isolation, each component exhibits an unique flow field and characteristics. In an integrated system the resultant flow is the sum of the interacting individual flow fields. A number of changes - both favorable and unfavorable - may develop in the characteristics of the individual components and consequently alter the behavior of the system as a whole.

The relative motion between rotating and non-rotating components of the helicopter induces primarily low frequency unsteadiness in the flow. Mid frequency unsteadiness is produced, for example, during interaction of each main rotor blade with the wake of preceding blades. High frequency unsteadiness is generated by blade/tip vortex encounters.

Considering the role of the fuselage, its displacement effect distorts the onset flow resulting in a non-uniform angle of attack distribution in the rotor disk. The rotor wake is deformed due to the presence of the fuselage which in turn alters the unsteady interaction process between rotor blades and their wake. The fuselage can induce high vertical velocities into the forward area of the rotor disc, particularly if the rotor plane is relatively close to the fuselage. This upwash affects local airfoil loading and, in cases where the blade is near stall, can induce local blade stalling with consequent undesirable vibratory effects and increase of rotor power required. Another effect of this localized upwash is to move the tip vortex path upwards.

This can further aggravate the localized aerofoil problem (as the forward blade intersects the vortex path gradually) and can significantly affect the blade/vortex interaction phenomenon where the blade intersects the vortex abruptly causing acoustic problems.

The fuselage is immersed in the main rotor downwash whose near wake region induces unsteady airloads at a frequency equal to and higher than the number of blade passages per revolution.

With transition from hover to cruise flight, the primary interaction area of rotor wake shifts from the fuselage to the tail rotor and the empennage. An indirect rotor/fuselage interaction develops due to distortion of rotor hub wake and powerplant exhaust plume by rotor downwash with ensuing changes in fuselage flow field.

In the rear fuselage region, the main rotor and the hub wakes are merged with the tail rotor wake: this leads to an extremely complex unsteady flow field affecting tail rotor and empennage.

For many years, the various flow phenomena associated with helicopters have been addressed with a mixture of simplified linear aerodynamic theories, wind tunnel data, and design charts. But recently, analytical and experimental investigations have been conducted, in which the interactions between a rotor and airframe were examined.

Sheridan and Smith [2] offered a review of interactional aerodynamics and presented the results obtained testing different rotor/airframe models. Wilby et al. [3] proposed an investigation of the fuselage effects on rotor performance, by using prediction methods and flight test experiments. Rand and Gessow [4] calculated the fuselage effects on main rotor. Freeman [5] applied a coupling methodology in order to predict the rotor/fuselage flow field. McMahon et al. [6] and Leishman et al. [7] used potential flow methods for calculating the unsteady pressure on a simplified fuselage. Dedicated experimental activities have been also conducted in this field: isolated rotor in ground effect, Light [8], simplified interactional models (Komerath et al. [9]), scaled powered models(Leishman et al. [7, 10, 11], Hoad et al. [12]), full scaled models (Norman and Yamauchi [13]).

Starting with the state of the art provided by the published material and considering the different levels of contribution and capabilities among the partners, a program was agreed with sharing of activities and responsibilities; the coordination of the program is in charge to Agusta.

The general scope of the program is the improvement of methodologies and prediction methods for interactional aerodynamics, in order to provide benefits in the helicopter design phase, in particular for:
- prediction of rotor performance and loads
- reduction in power consumption
- reduction of pitch-link loads
- prediction of rotor wake development for blade vortex - interaction and noise analysis
- prediction of fuselage aerodynamic loads
- reduction of vibration level

2. Experimental activities

Information is provided on the isolated rotor, in hover and forward flight, and on the powered models including flow visualization, using a laser cut technique, and measurements, using Hot Wire and three component LDV.

These data bases are designed to provide the following :
- Aerodynamic rotor forces
- Aerodynamic fuselage forces
- Fuselage pressure distributions
- Inflow velocity distribution near rotor

- Isolated rotor tests in hover has been conducted at the Agusta low speed facility. The rotor model is Mach scaled, fully articulated with four rectangular blades and with a diameter of 1.5 m (Figure 1a). The basic tests provide a survey of the external flow field at different thrust and RPM: Hot Wire measurements of the induced velocity (Figure 1b), flow visualization by means of Laser cut technique, this in order to assess the hover numerical methods.

- Tests on a Dauphin powered model (scaled 1/7.7) have been performed in the ONERA S2 Chalais-Meudon wind tunnel. Unsteady velocity field measurements around the fuselage and the rotor in two different transversal planes (perpendicular to the fuselage axis), using a three-dimensional Laser Doppler Velocimeter, have been done.

The fuselage length is about 1.5 m, the rotor diameter is 1.5 m and the rotating tip speed is 100 m/s. A view of the model inside the S2Ch wind tunnel is presented in **Figure 2a.** The configuration studied corresponds to a simulated mass of 4000 Kg, at an advance ratio of 0.2.

The measurements are performed every 4° in azimuth; this means 90 different slots to describe one rotor revolution, each slot has a width of 1° in azimuth and for each slot the measurements are averaged over 100 samples.

The instantaneous vertical velocities for different points located slightly above the rotor disk show that outside the rotor disc ($y/R > 1$) the velocity fluctuations are very small and the mean value positive (upwash) whilst inside the rotor disk ($y/R < 1$, **Figure 2b**) the fluctuations due to the blades passage are important and the mean value negative (downwash).

- Force and pressure measurements for isolated fuselage at different onset velocities and incidence and yaw angles have been also performed on a BO105 scale model in the low speed wind tunnel of DLR at Braunschweig.

With the rotor on configuration, powered model, the time averaged pressure distribution on fuselage surface (450 points) was measured for different thrust ratios and incidence: the **Figure** 3 shows clearly the effect of the rotor downwash on the fuselage.

All these measurements (velocities, pressures and forces) constitute a good data base for code validation in the BRITE/EURAM group working on the helicopter interactional aerodynamics.

3. Theoretical work

Theoretical work has been divided into three broad categories.

4.1 Isolated and uncoupled rotor

In this task different methods are investigated in order to assess their capabilities and to introduce some significant improvements in the case of both isolated rotor (without fuselage effects modelled) and rotor with fuselage induced velocity field modelled.

Isolated rotor

An isolated rotor code, based on the lifting surface approach, [14], has been applied in order to calculate (**Figure** 4) and to compare the induced velocities below the rotor disc of the isolated rotor model in hover O.G.E. at different planes and azimuth. The prescribed wake models (Landgrebe, Kocurek) and the successive relaxations have been investigated.

Especially for the case of axial flight, a higher order modified lifting surface method is applied in order to improve the efficiency of the rotor flow field and airloads calculations.

A comparison of the calculated flow field for the isolated Dauphin rotor model with ONERA wind tunnel measurements is shown in **Figure 5**: although the experimental results are influenced by the fuselage of the powered model, the agreement seems to be satisfactory. The rotor flow has been also calculated using an unsteady vortex lattice method with free wake formulation [19]. Rotor and wake are represented by a distribution of vortex-doublet elements with stepwise constant strength.

Moving the rotor blade (rotation), the vortex activity at blade's trailing edge sheds into the wake during each time step.

Boundary conditions at blade control points must be satisfied by doublet strength of the lifting surfaces. Other collocation points, like wake points, are moving free under the influence of free stream and all existing singularities. In that way, geometrical wake updates require a special procedure, including a near field method for the Biot-Savart law, to achieve a real wake behavior. **Figure 6** presents a panelized 4-bladed rotor with a free vortex lattice wake after one of the blades. The self-induced outer wake roll up, traced by the blade tip, is clearly visible.

A Boundary Element Method (BEM) has been developed for the aerodynamic analysis of an isolated rotor in forward flight for incompressible and subsonic compressible flow regimes. The method solves an integral equation for the velocity potential that is obtained by applying the generalized Green's function method to the linearized governing equation for the velocity potential [20, 21].

This kind of approach requires an explicit treatment of the wake that therefore must be modelled. Presently prescribed-wake geometry traced out by the path of the blade trailing edge during its motion is used; a doublet layer, fully equivalent to a vortex layer, is distributed on this prescribed surface. The blades are represented by a source and doublet distribution. Both blades and wake are discretized by zeroth-order panels.

A first kind of validation of the method has been performed by the calculation of the vertical component of the induced velocity on a plane parallel to the tip path plane (**Figure 7**) for the NASA test case of SCIA common exercise [12].

The results have been compared both with the experimental data and with the numerical results of other partners: a good agreement was find out in both cases.

The BEM methodology has been further developed [22, 23] and numerical investigations have been performed for isolated rotor in hover and forward flight in compressible flows. Free-wake results, **Figure 8**, for subsonic flows, using five-spiral wakes and a 12x12 element discretization over the blades, are compared with the experimental data by Caradonna and Tung [24] in hover (Mtip=0.727). Then, numerical results for forward flight rotors in subsonic flows (Mtip=0.54,μ=0.17), using 12 time step per revolution, 2 spiral wake and a 4x9 element discretization over the blade, are compared, **Figure 9**, with those of Tai and Runyan [25].

Isolated rotor with fuselage effects

A computational efficient model has been then developed, in order to predict the effects of the fuselage on the rotor inflow and hence on rotor performance. The mathematical rotor model [15] is based on 2-D strip aerodynamics and steady state rotor blade dynamics using only out-of-plane bending mode shape, suitable for various types of rotor articulation.

Originally the rotor induced velocity was calculated according to the theory of Mangler and Squire, expressing downwash as a Fourier series; the code has been modified in such a way that an external flow field (e.g. fuselage induced) can be superimposed.

In **Figure 10**, contour plots of the calculated inflow ratio for the Mangler-Squire model with (right) and without (left) the influence of the fuselage are compared (test case [12]). These results show that fuselage upwash disturbs the induced velocity field mainly along the longitudinal axis near the rotor hub, and the velocity distributions correlate well with regard to experimental data trend.

A comparative analysis of the computational results shows that the disturbed flow field, for the configuration under study, influences rotor blade flapping and rotor loads. Rotor torque coefficient predictions and comparison with experimental results, at the same operating conditions, show a better agreement compared to results of the original code without fuselage inflow.

Another approach used for isolated rotor is a lifting line method where the rotor wake is discretized by a lattice linear vortex segments [16] whose intensity is related to the variation in circulation span and azimuth wise. Once the marginal vortex has rolled up (Betz theory), this lattice is reduced to a tip and root vortex forming the far wake. The wake geometry is prescribed with the conventional cycloidal trajectories (empirical formulae inspired from Egolf and Landgrebe work); the induced velocity at each control point on the blade is computed by the Biot and Savart law and the lift is obtained trough 2D airfoil tables.

Blade motion is calculated simultaneously by considering rigid blades and hinged in flap only: this aerodynamics/dynamics problem is solved iteratively with a relaxation method where induced velocities are the unknowns.

The next step is the adding to this isolated model the effect of the fuselage inflow obtained by a low order panel method [17], with constant source and doublet distribution. The computed results obtained for: a) the isolated rotor and b) for the same with the effect of the velocity field computed for an isolated fuselage, are compared with experimental results [12]: a better agreement can be noticed when the fuselage effect is taken into account, in particular on the inboard part of the blade (**Figure 11**).

The effect of fuselage on rotor is usually calculated by panel methods, but in parallel, a computationally efficient method for determining fuselage displacement flow effects on a main rotor has been developed. The necessity for computationally efficiency is because fuselage effects form only a small element in the computation of rotor performance within a comprehensive rotor analysis, which must recognize all significant physical phenomena to a consistent degree of approximation within the overall calculations.

The model for the fuselage displacement flow effects is being developed primarily by correlation with a panel method representation of the fuselage.

The work to date has concentrated on two aspects:

a) the development of a distributed source/sink model for approximating the displacement flow of a fuselage,

b) the development of a simple method for modelling cross-flow effects on a fuselage.

Initial correlations of the distributed source/sink representation for the SCIA test case [12] showed that the simple model can adequately reproduce the inflow perturbation at the rotor plane predicted by panel method. The simple model facilitates the calculation of wake element vertical displacements due to the fuselage flow field, which can be important when calculating the local incidence due to vortices in the flow field, **Figure 12**.

A cross-flow model for the fuselage is currently under development (to be validated by comparison with the panel method), again with the primary aim of developing a simplified model which can be used within complex flow fields with high computational efficiency.

3.2 Isolated and uncoupled fuselage

In this task computational activities are performed in applying and improving uncoupled-approach methods for the calculations of the flow field in the case of both isolated fuselage and fuselage in presence of prescribed rotor downwash.

Isolated fuselage

A panel method [18] has been applied to the SCIA reference fuselage test case [5], in order to analyze the effects of flow separations on surface pressure distribution and in order to handle the fuselage wake models.

The potential no-wake solution shows the presence of an unrealistic stagnation point on the rear side of the pylon, **Figure 13**. By applying a two-dimensional boundary layer analysis on the calculated streamlines, a viscous/inviscid coupling highlights a separation area on the rear of the pylon: a wake has been then modelled and attached at the calculated separation line (doublet panels with prescribed vorticity gradient), and the solution was improved.

The pylon wake has been also numerically simulated by a set of interacting vortex filaments, **Figure 14**, then, a three dimensional boundary layer code computing laminar, transition and turbulent state has been also applied to that configuration in order to improve the separation line prediction.

Isolated fuselage with prescribed rotor downwash

An important part of the research into rotor/fuselage interactions is to develop methods for predicting the pressure over the fuselage in the presence of rotor downwash. This again uses panel methods to represent the fuselage, but now the rotor and its wake are modelled by a vortex system that modifies the flow at the fuselage.

A typical result for the pressure distribution over the upper fuselage center line for low advance ratio is shown in the **Figure 15**. The dotted curve shows the pressure distribution predicted using a constant total head for the flow (consistent with the increased induced velocities induced by the rotor vortex system).

This is seen to markedly under-estimate the pressure loads on the upper fuselage when compared with experimental data. This is because the rotor vortex model, although correctly modelling the velocity field induced by the rotor, does not represent the increment in total head induced by rotor system.

The solid curve shows the result of including an empirical correction to the total head. This is the weakest part of the theoretical method, especially at low advance ratios, and required further development. In particular it is necessary to identify a means of incorporating increments in total head in the rotor model, and then tracking the regions of flow that contain these increments.

3.3 Coupled rotor/fuselage calculations

In this task methodologies are being developed to obtain a rotor/fuselage computational method by the combination of the distinct rotor and fuselage flowfield prediction algorithms applied in the previous tasks and by using global aerodynamic approaches.

A computational method is under development by coupling the isolated fuselage and the isolated rotor methods. The coupling technique is through a time marching approach: a each azimuth step a fuselage calculation is performed with the velocity perturbation due to the rotor, and then the velocities due to the fuselage are computed at the level of the rotor and rotor wake to be taken into account at next time step.

Furthermore a preliminary work for the development and the application of global interactional aerodynamic models will be undertaken. The approach described in [18], VSAERO, is being also applied to a powered model in order to predict the induced inflow 1-chord above the tip path plane of the rotor disc [12]. Using a blade element model of the rotor, the program calculates the radial and azimuth variation of blade loads and converts these in order to calculate the normal velocity boundary condition at the doublet rotor disc in the panel scheme: then the complete helicopter configuration is calculated by solving the doublet strengths on the fuselage and on the rotor.

4. Conclusions and future work

The studies in progress in Europe in the helicopter aerodynamic interactions have been described. In particular, a survey of the activities in the experimental and computational field, both in the isolated and in the complete configuration, were presented.

This research and collaborative work is improving the phenomena understanding and is leading to a development of a dedicated prediction tools.

The activities described here need to be extended in order to analyze other important and complex aerodynamic interactional phenomena, that occur in the helicopter flight envelope such as main rotor/tail rotor wakes, tail rotor wake/empennage, wake development in ground effect.

Future works will include links with more sophisticated C.F.D. solvers (Full-Potential, Euler, Navier-Stokes) to simulate the complex flows around a helicopter, including viscous effects, and to provide more detailed aerodynamic forces for performance and load analysis.

5. Acknowledgement

This work was carried out with funding from **European Economic Community** under the BRITE/EURAM Contract No. AERO-0011-C (A) "Helicopter Rotor/Fuselage Interactional Aerodynamics", acronym SCIA.

The authors would like to acknowledge the contributions of their colleagues in the Steering Committee of the programme: F.T.Wilson, S.Fiddes, D. Papanikas, A. Desopper, F. Toulmay, G. Polz, P. Renzoni, S. Wagner, S.R. Ahmed, F.W. Meyer, J.N. Sorensen, C. Hermans.

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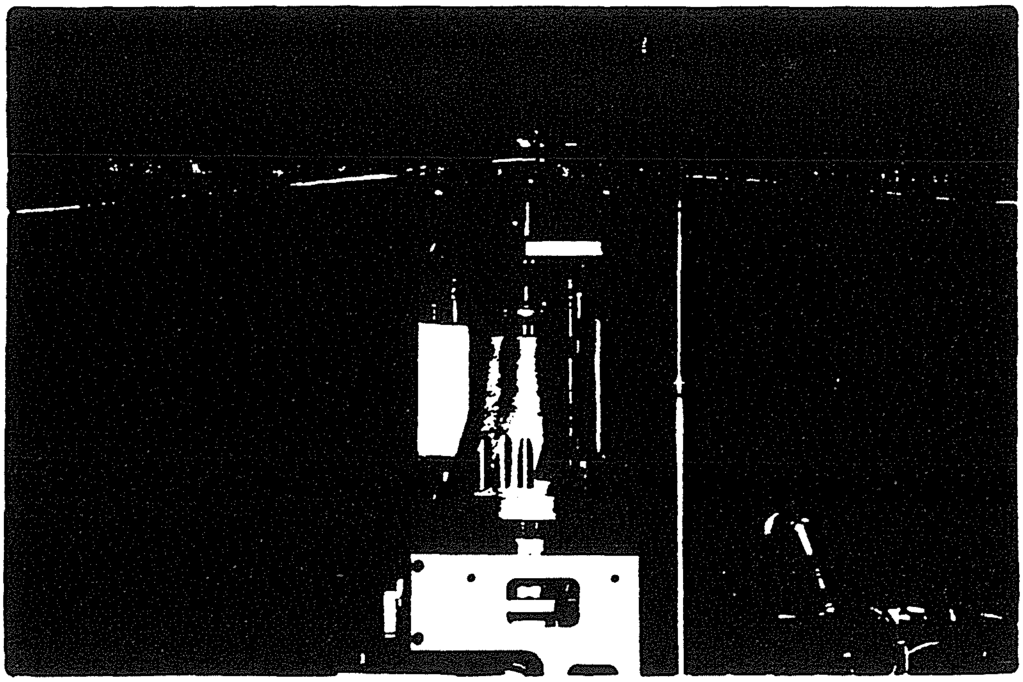

Figure 1a - Isolated rotor model

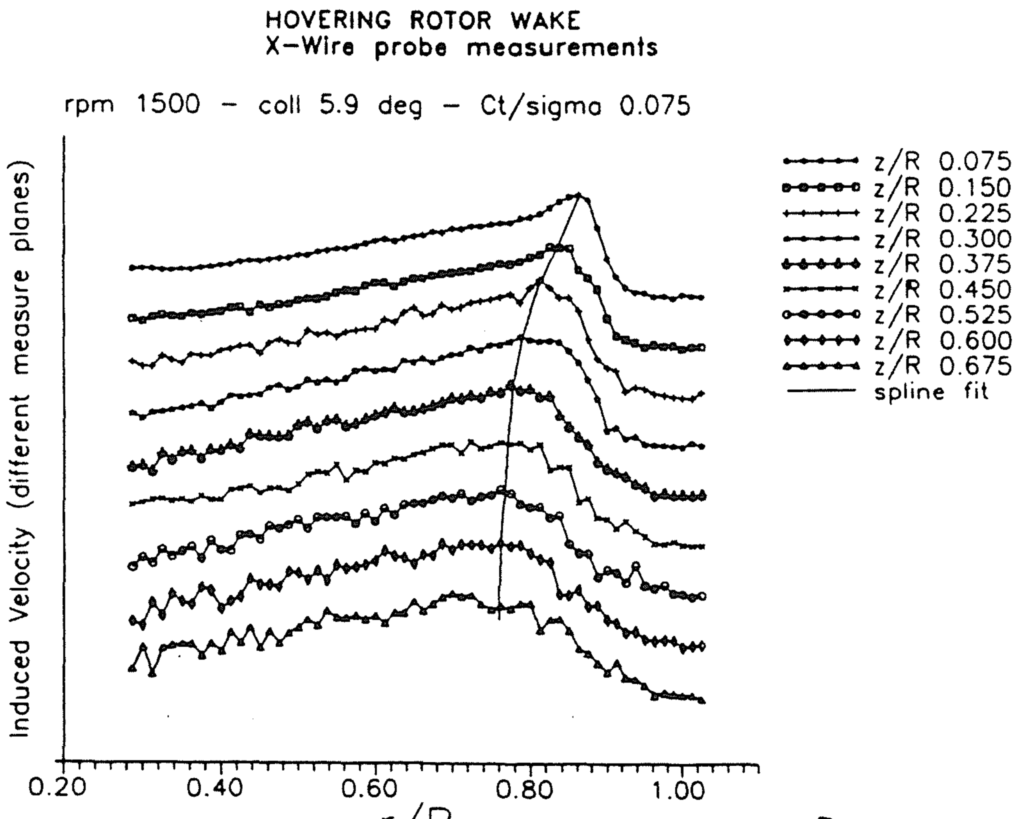

Figure 1b - Hot Wire measurements below isolated rotor

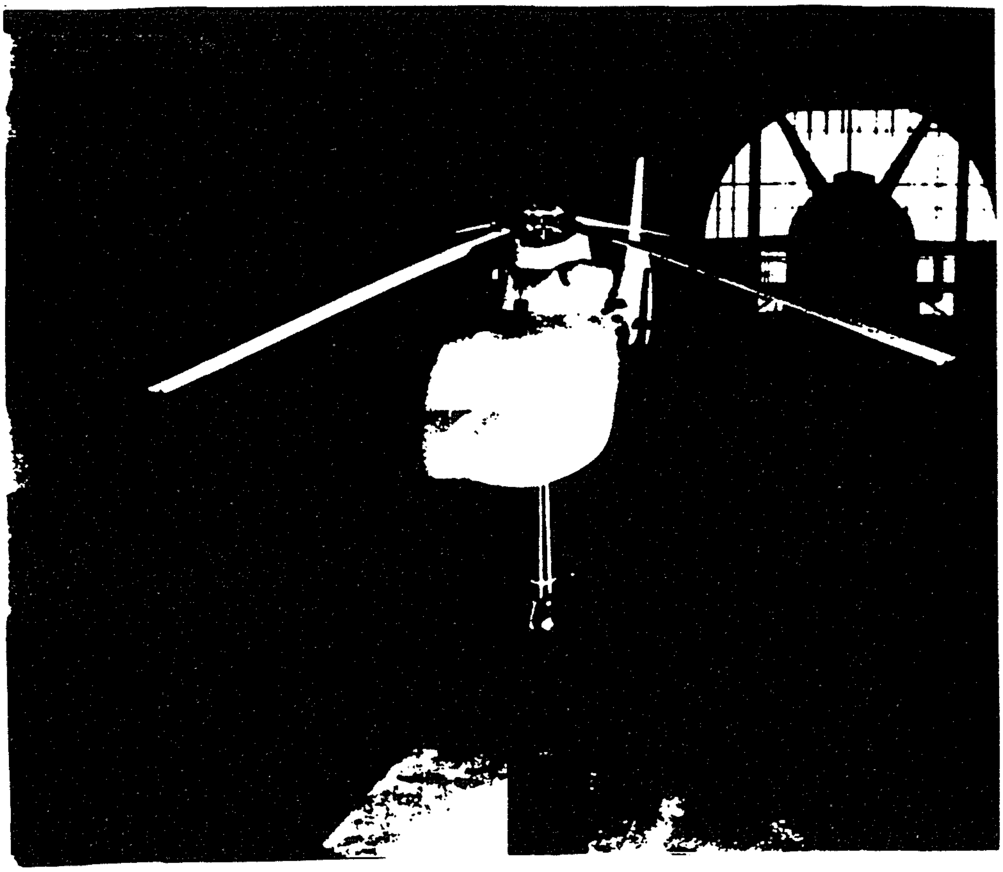

Figure 2a - Dauphin powered model.

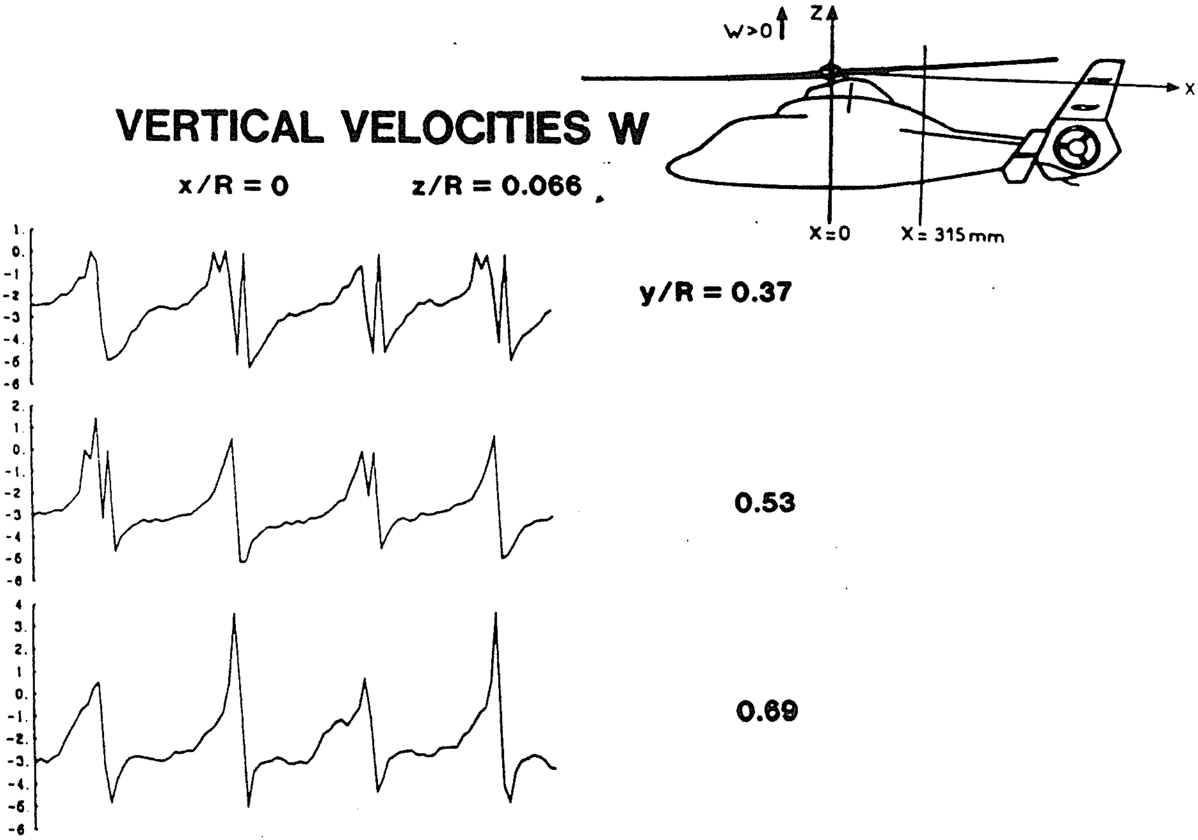

Figure 2b - L.D.V. measurements on a Dauphin powered model.

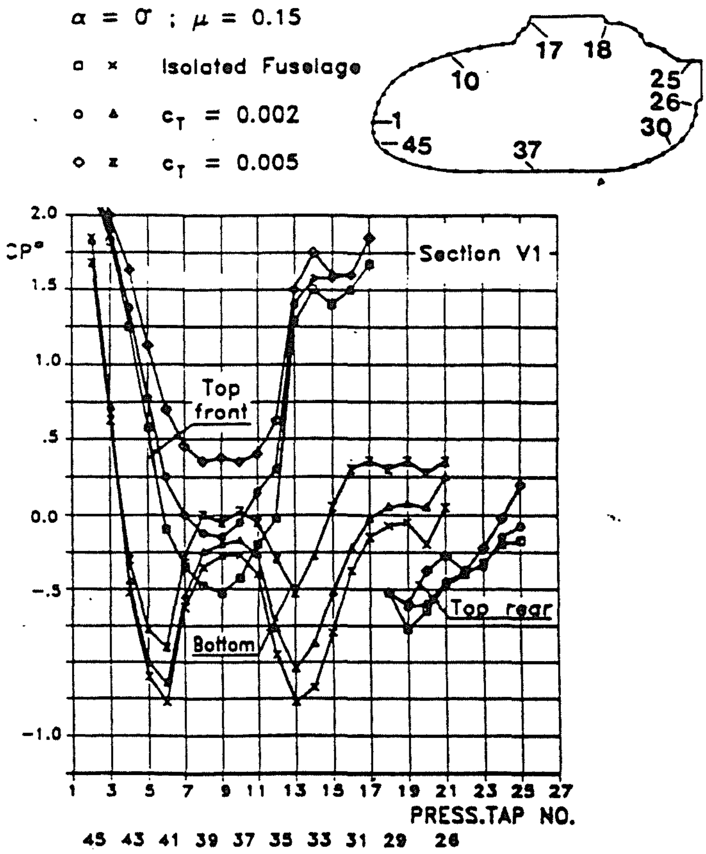

Figure 3 - Influence of rotor thrust on the fuselage Cp.

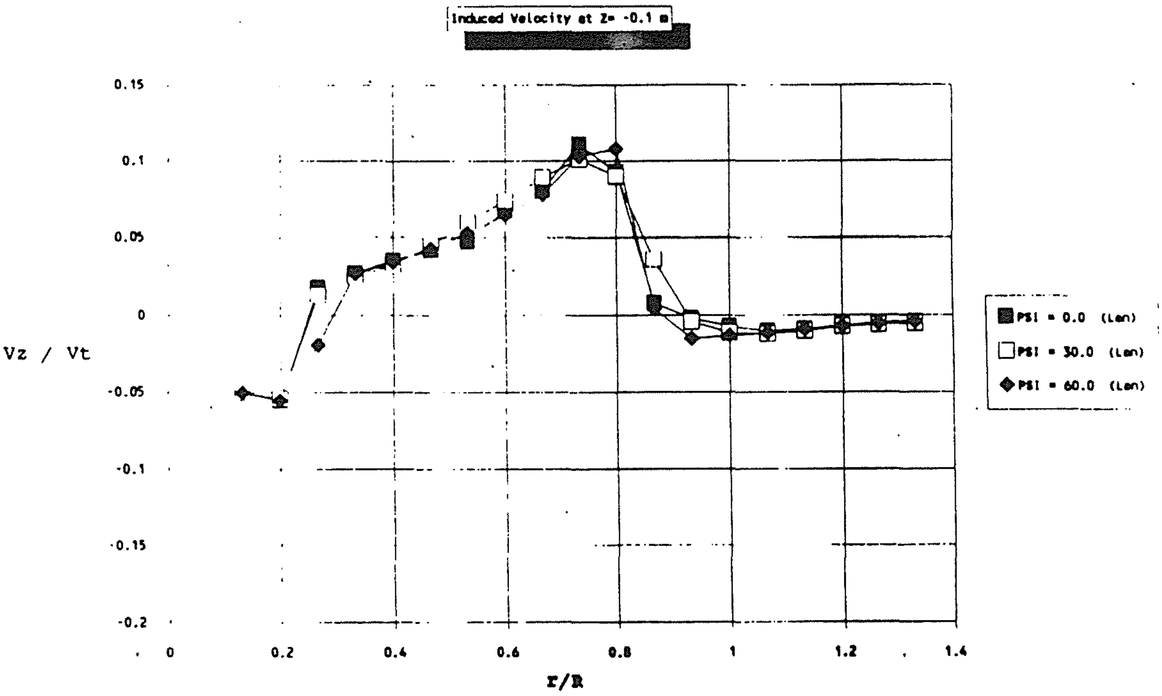

Figure 4 - Calculated induced velocity below an isolated rotor in hover at different blade azimuth.

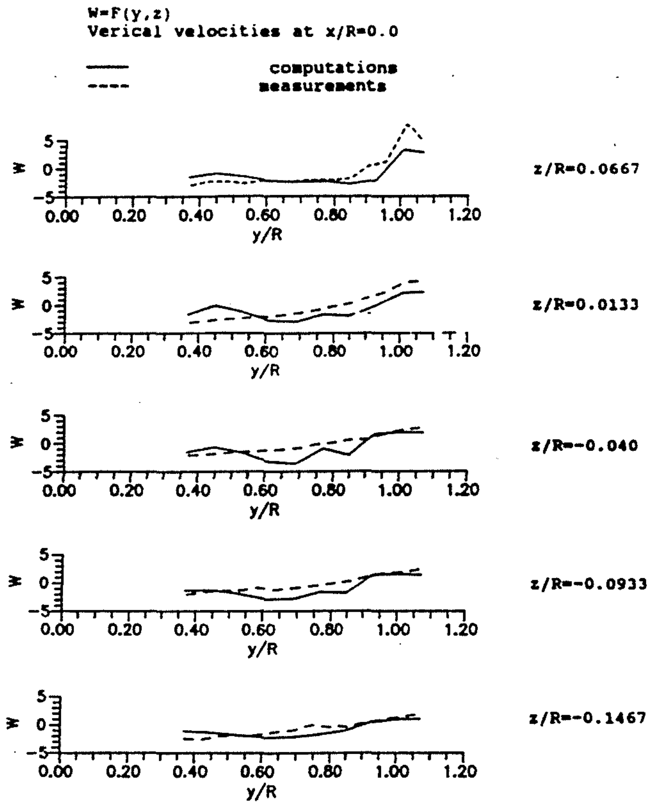

Figure 5 - Calculated vertical velocity on an isolated rotor in forward flight. Comparison with experiments.

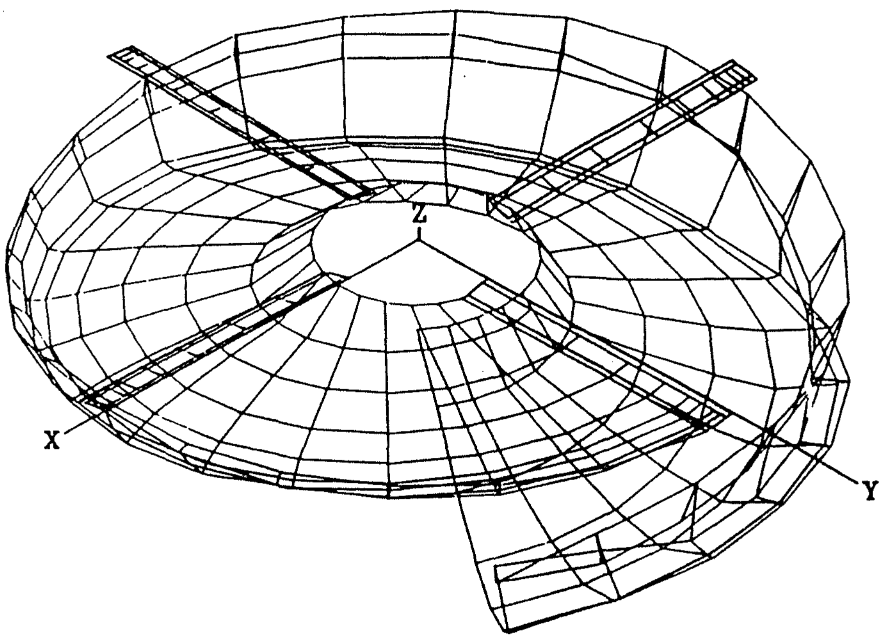

Figure 6 - Vortex lattice wake of one blade at starting process.

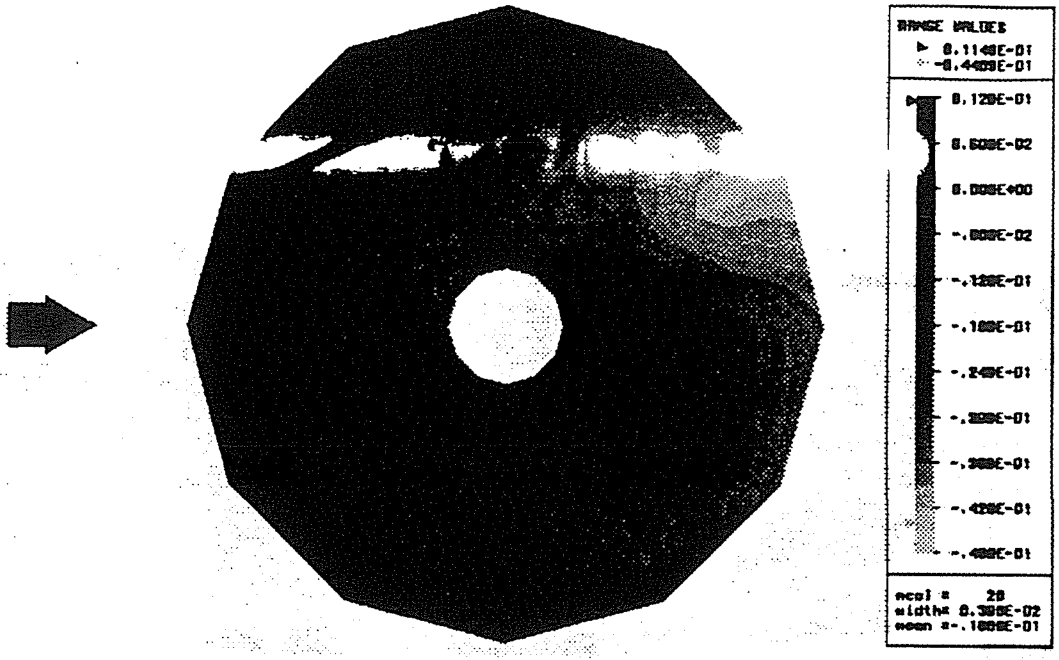

Figure 7 - Calculated induced velocity above TPP of an isolated rotor in forward flight.

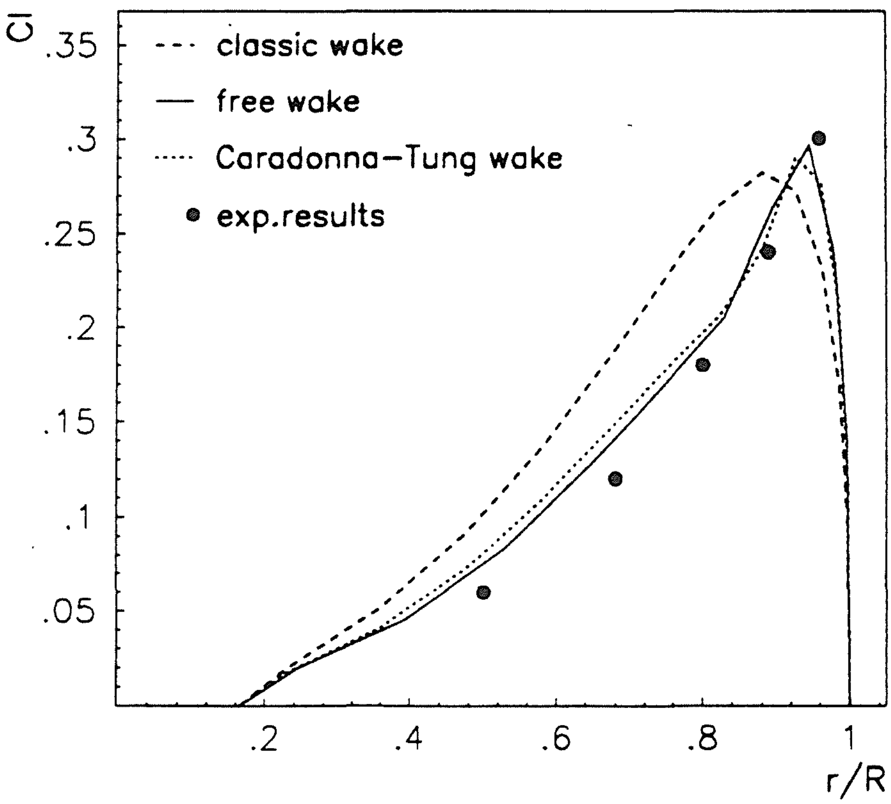

Figure 8 - B.E.M. method: free wake results in hover.

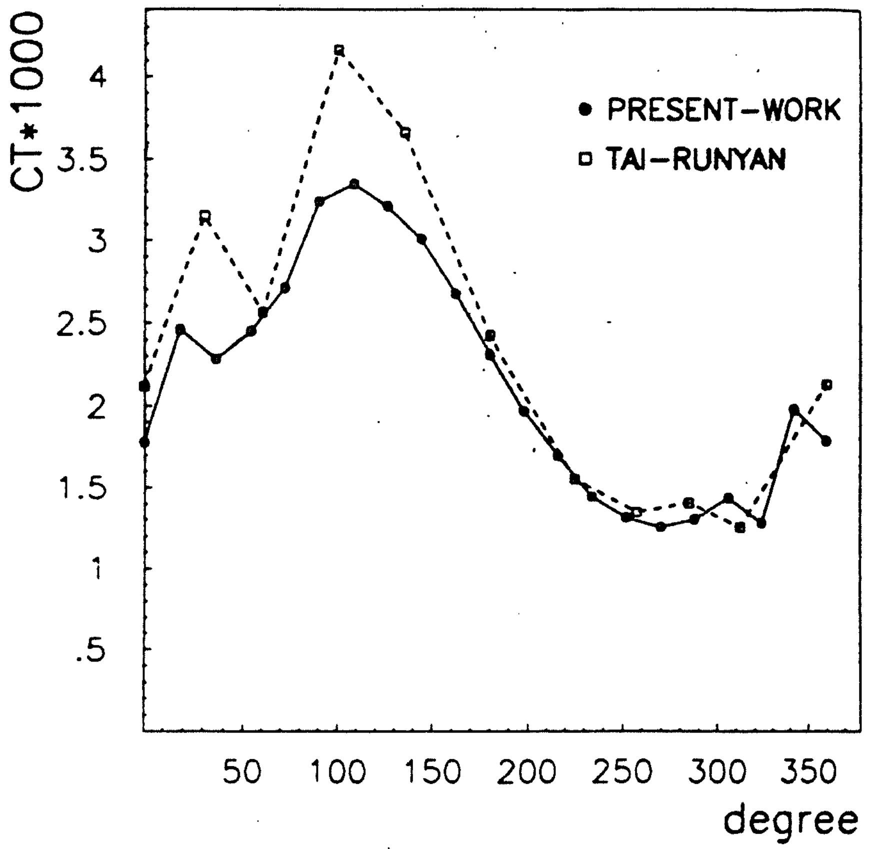

Figure 9 - B.E.M method: results in forward flight.

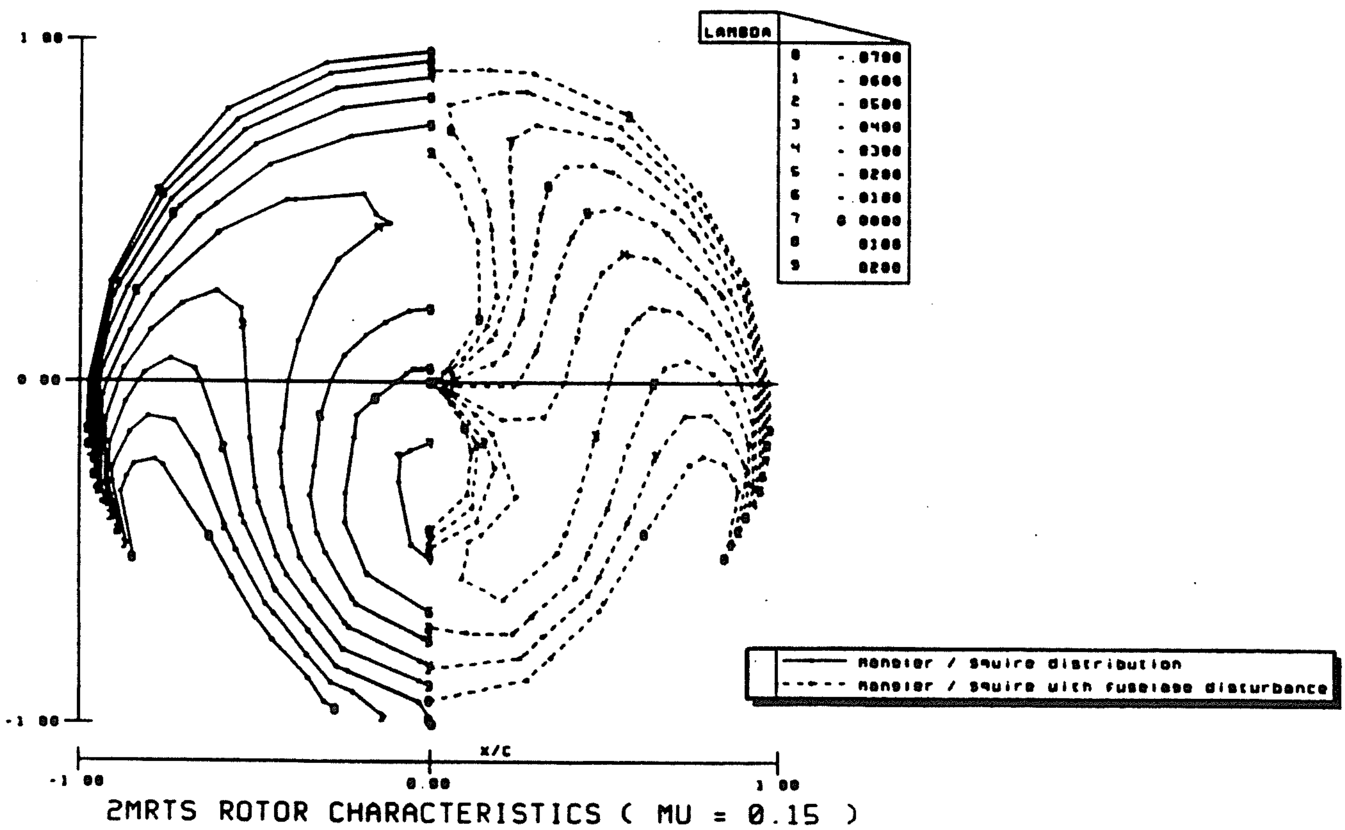

Figure 10 - Calculated effect of fuselage on the rotor flow field.

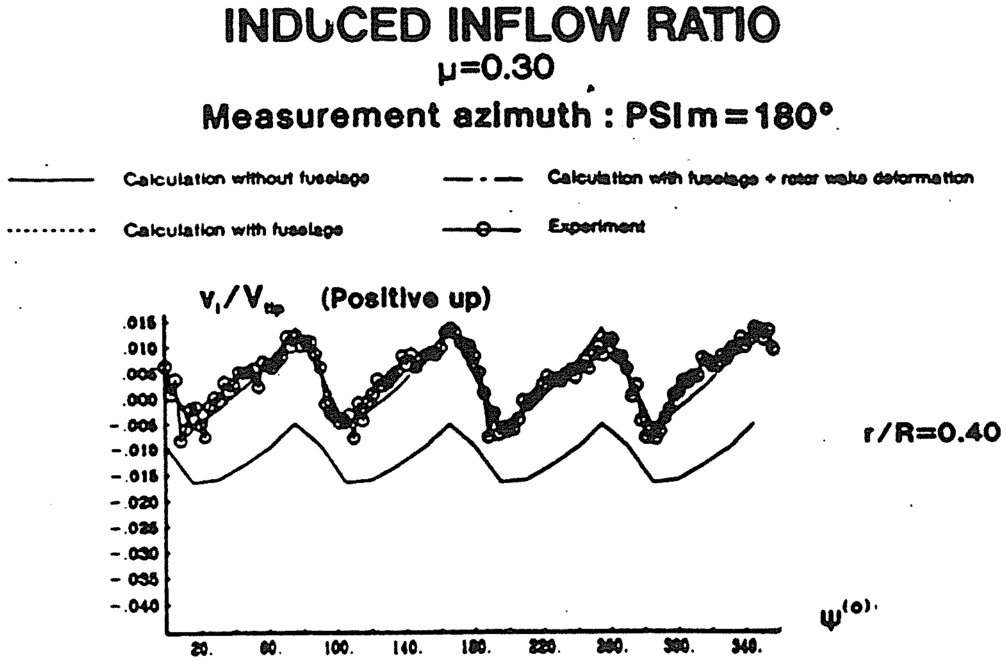

Figure 11 - Calculated effect of fuselage on the rotor flow field: comparison with experimental data.

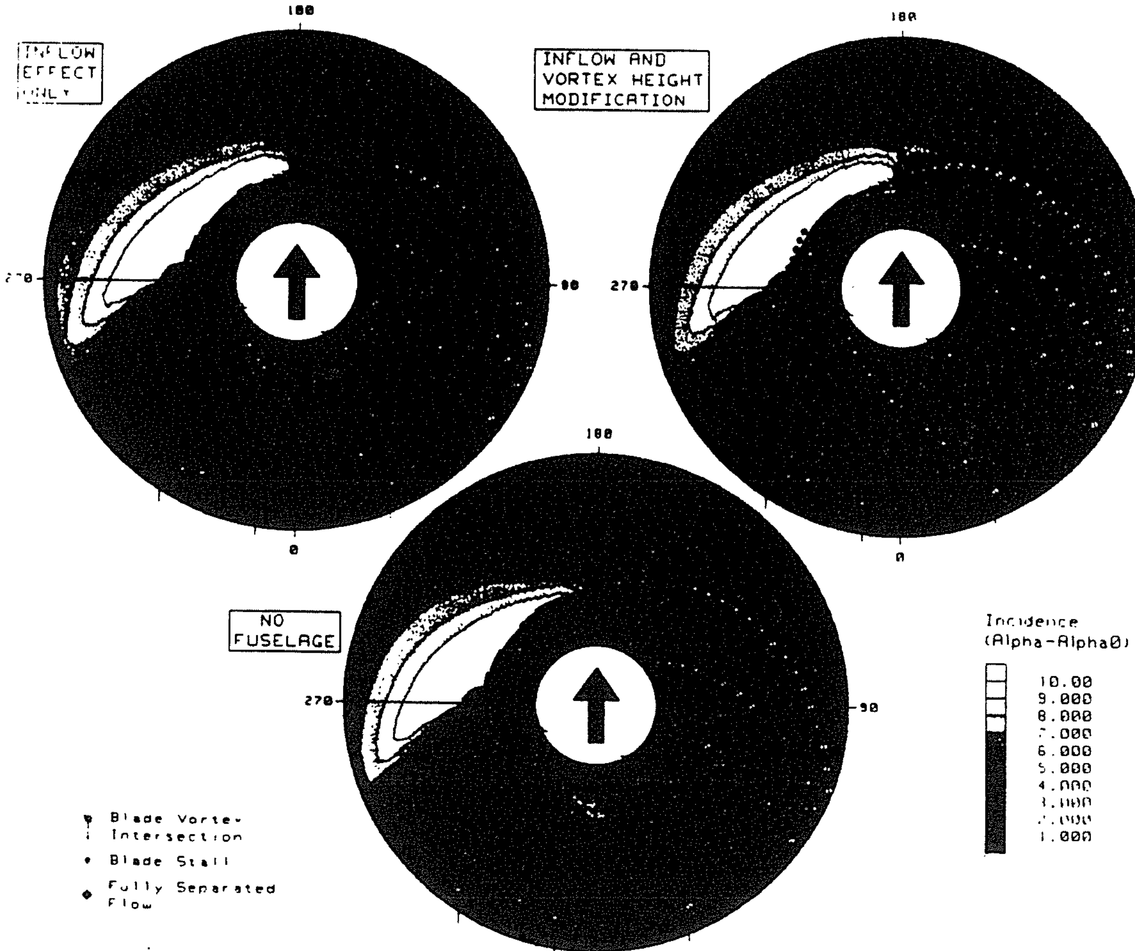

Figure 12 - Calculated effect of fuselage on blade incidence.

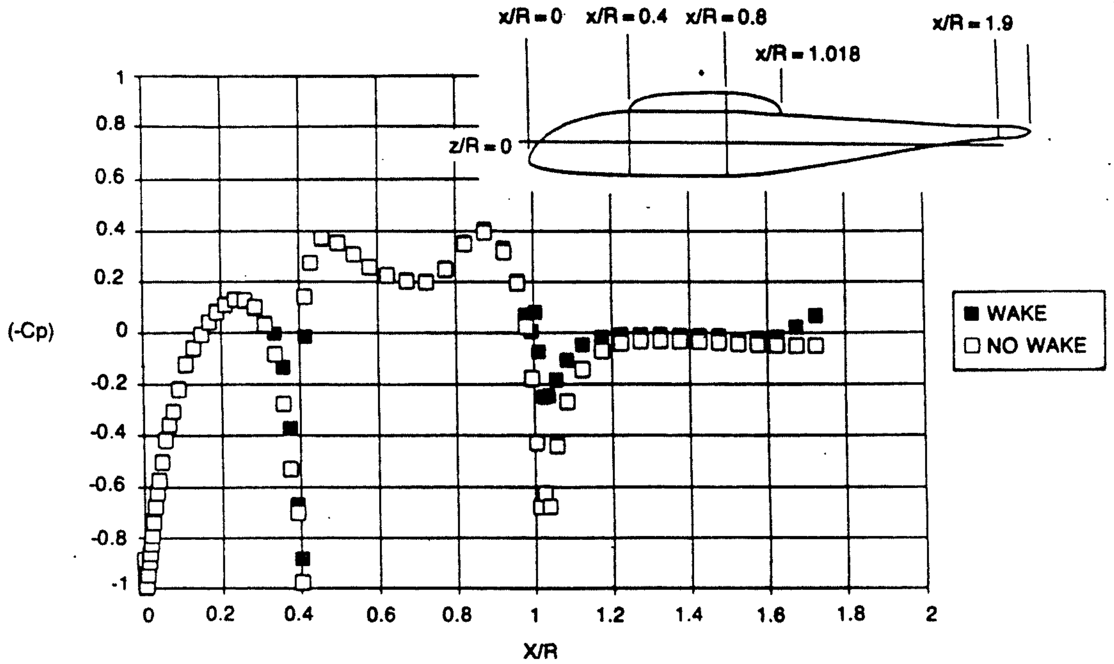

Figure 13 - Wake effect on the top midline fuselage pressure distribution.

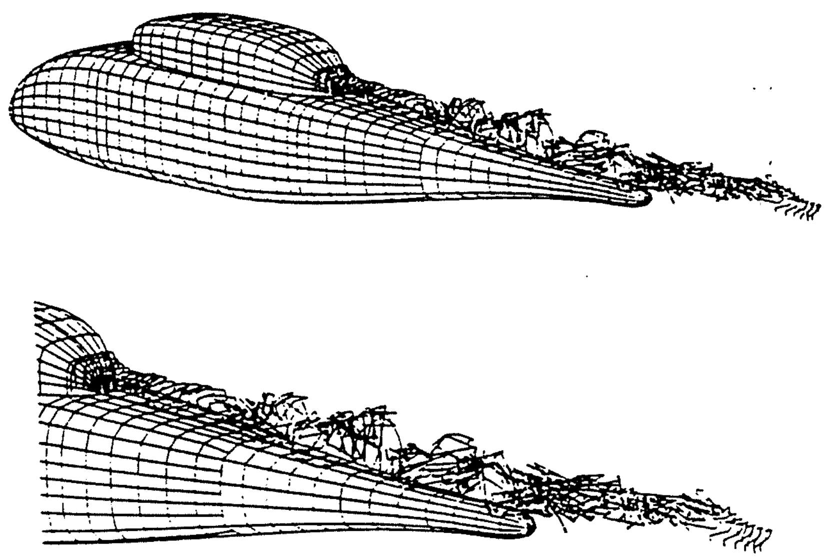

Figure 14 - Simulation of the wake by interacting vortex filaments.

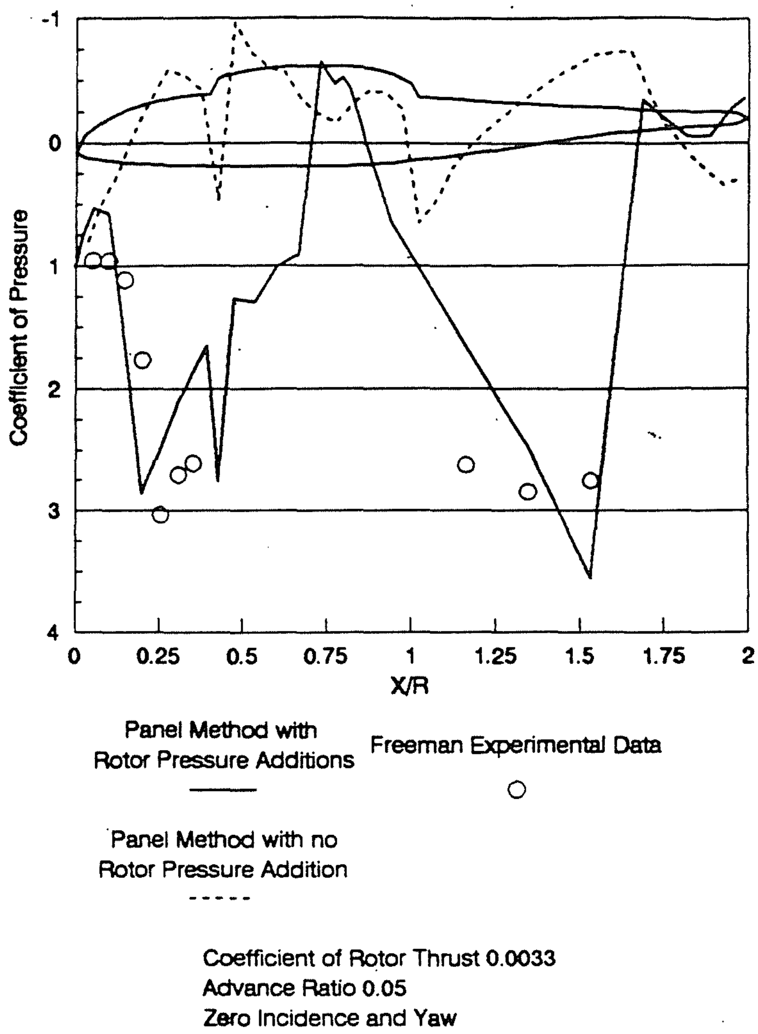

Figure 15 - Calculated pressure distribution with rotor downwash on the top fuselage surface (midline).