A "FORCE-FREE" ROTOR WAKE MODEL FOR ADVANCED RESEARCH APPLICATIONS

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Abstract

A "force-free" rotor wake model has been developed to complement the advanced prediction capabilities of the rotor analysis code CRFM (Coupled Rotor-Fuselage Model). CRFM code is being developed by the Defence Evaluation and Research Agency (DERA) and GKN-WHL for various helicopter performance and research studies. The wake model is primarily intended for accurate predictions of the rotor loads at the lower range of forward speeds, but the model is also essential to any research discipline which require accurate prediction of the rotor wake shape and structure. The rotor wake geometry is built through a "force-free" time motion of discrete vortex filaments, which represent the trailing sheets of vorticity from the rotor blades. The filaments are formed of curved vortex elements to increase accuracy and to reduce computation time. The continuity of the wake structure is assured by using a prescribed "far-wake" that follows the "free-wake" distortion with time variation. The interface between the wake model and the rotor analysis code CRFM centres around the iterative exchange of induced velocity and circulation along the rotor blades. The iterative procedure is described with discussion of the problems associated with calculating the induced velocities on the blade. The combined free-wake/CRFM loads prediction of a fully trimmed rotor is compared against similar prediction from a prescribed-wake model and the corresponding flight test data.

Introduction

Recent rapid development in computation power has encouraged both industrial and research institutions to develop aeroelastic rotor codes far more advanced than ever before (Ref. 1,2,3,4). The growth in model sophistication is expected to yield better predictions and to enable problems to be tackled which were not readily addressed before. The success of any aeroelastic code depends on the accurate representation of key rotor components and airflow elements. One of the most influential elements is the rotor wake, which plays an integral part in deciding the performance of the main rotor in particular, and the whole vehicle in general.

Not all flight conditions or calculation requirements demand great accuracy in modelling the rotor wake. Various sophistication levels of rotor wake models or induced velocity calculations can be employed in a rotor analysis model, and each level can then be accessed to suit a particular application. For simple applications, early simple induced velocity formulae (Ref. 5) can be accurate enough, but most rotor analysis codes will include a prescribed wake model to calculate more accurate values of the velocity induced on the main rotor blades. Prescribed wakes (e.g. Ref. 6,7) can be very efficient when exact information about the distorted geometry of the rotor wake is not essential. However, in applications like BVI or tail rotor noise at low forward speeds, the exact geometry of the wake is needed and a free wake model becomes necessary (Ref. 8,9). The higher accuracy in estimating the wake strength and geometry, which the free wake provides, is also essential when calculating the higher harmonic contents of the blade loading at both high and low forward speeds (Ref. 10). Also, rotor wake influence on close-by objects, e.g. when landing on ships or confined areas, can be estimated more accurately if the free wake model is employed.

The free-wake model presented in this paper is being developed at DERA to extend the capabilities of the existing rotor analysis program CRFM (Ref. 1,2) into those areas where a simple prescribed wake model is no longer accurate enough or is unable to fulfil specific requirements. The model is based on representing the vorticity of the wake by discrete vortex filaments trailing from each blade along the span. Each filament is formed of a series of curved vortex elements trailing from the blade as it moves around the azimuth following the Lagrangian motion in simple time-marching steps. The principle of using curved rather than straight vortex elements was originally proposed in Ref. 11.

The rotor wake model can be used as a "stand-alone" module to calculate the wake parameters and the induced velocities if the blade load distribution is known, e.g. from test measurements. However, the more familiar use of the model is to be interfaced with a rotor analysis code, which will require the integration of the module within the solution of the rotor's equations of motion. Since the solution is iterative, a fully integrated rotor/wake code will be computationally expensive. The problem is avoided by coupling the wake code with the CRFM code through an outer iteration loop. The vehicle is fully trimmed only when both inner and outer iteration loops have converged. The combined prediction of the two codes has been analysed and compared against flight test data for a Puma helicopter.

Free Wake Development

Curved vortex elements

Modelling the distorted shape of the rotor blade vortices requires accurate simulation of curvature and orientation. By dividing the vortex filament into elements joined at collocation points, the free wake models can solve the orientation problem. This is because the collocation points are allowed to move freely in the flow field, so that their instantaneous positions are accurate representations of the filament orientation at a specific time. However, researchers have been forced to compromise on vortex curvature by using straight line vortex elements to join the collocation points. This is mainly to simplify the Biot-Savart integral which is used to calculate the velocity induced by a vortex element. The only way to refine the accuracy when using straight elements is to shorten the element length by reducing the time steps, with the obvious penalty of more computation time. The use of straight elements also leads to unreliable velocity calculations at points very close to the element.

Reference 11 tackled this problem by introducing the concept of parabolic shaped elements into the free wake calculations. The concept is based on the fact that the Biot-Savart Integration can be performed analytically, over the parabolic shaped vortex, with approximations of acceptable accuracy. A description of the mathematical basis of calculating the velocities induced by the element is included in Ref. 11, with detailed comparisons between curved and straight vortex elements. The curved elements have two main advantages over straight elements; they allow longer time steps to be used for the time-marching procedure, and improve the accuracy of calculation at points close to the element. However, the first advantage is partially offset by the longer computation time needed to evaluate the Biot-Savart integral, as compared with a straight element joining the same two collocation points. It was found at early stages that substantial savings in computation time could be achieved simply by switching to straight line elements if the element shape had little influence on the accuracy. Therefore, the DERA model employs a mechanism which switches the element to a straight shape whenever the distance between the vortex element and the point where velocity is evaluated exceeds a specified value; typically 1.5 times the element span.

Although the concept of evaluating the Biot-Savart integral analytically has been preserved in the DERA wake model, it has also been necessary to use numerical integration schemes at cases when singularity problems arise. Such cases are rare, but have enough influence on the motion of collocation points to justify the use of a numerical integration scheme. Some other features which Ref. 11 used are preserved in the DERA model; for instance the method used to produce smooth connections between vortex elements, and the circular arc model used to evaluate the self-induced velocity at the end points of a vortex element.

Wake structure

The initial wake is formed from a number of vortex filaments trailing from the span of each of the rotor blades. Each filament has an initial undistorted skewed helical shape, with a skew angle proportional with the forward speed of the rotor. The filament consists of a specified number of free wake turns and a specified number of vortex elements per filament turn. The wake is completed by adding a prescribed portion to the end of the free part, which has a geometry based on the last two free wake turns. The presence of the rotor blades is modelled by the bound circulation line of vorticity along the blade span. The span-wise and time-wise variation of bound vorticity are supplied to the model as input. In order to calculate the exact positions of the blades and the wake filaments in global co-ordinates, the model also requires values of the fuselage and shaft tilt angles, and the time history of blade flapping.

Free wake The final distorted geometry of the wake is achieved through a time-marching process, during which the rotor blades sweep the azimuth in specified time steps. At the end of each step, the blades move to new positions and all collocation point, along the filaments, are also moved to new positions. During this time step, a new element is created on each filament between the current and the previous blade azimuths, while the last element of this free wake filament is discarded to preserve the total number of collocation points per filament. The far wake extension is then adjusted and reconnected to the last existing collocation point. The motion of each collocation point is the result of summing up all the velocities induced at this point; these include velocities induced by:

- All elements of the free wake
- Prescribed far wake
- Bound circulation on the blades
- Relative air velocity due to the motion of rotor.

After the new wake shape has been calculated at the end of this time step, new induced velocities are calculated at all collocation points and a new time step starts. The marching process continues until the wake converges into a geometry which is repeated in two successive rotor turns, within reasonable limits of tolerance.

Far wake The far wake is a continuation of the free part, which practically has to be limited to a finite number of turns. The number of free wake turns differs according to the application within which the free wake model is used. For example, if the purpose of using the free wake is to calculate the induced velocity on the main rotor blades at very low advance ratio, then a relatively large number of free wake turns may be needed. If the advance ratio is high enough to carry the wake away from the rotor influence, then the wake will be more stable, and less free wake turns will be needed. In some cases, it may be necessary to use more free turns at higher speeds to examine the interaction of the wake with other parts of the helicopter or with objects close by.

The far wake used in the DERA model consists of vortex filaments joined to the ends of the free wake filaments. Each filament still consists of vortex elements connecting collocation points, but unlike the free wake, the position of each collocation point is not decided by free motion. The far wake points actually follow the motion of the free wake points. The average distances, along the three global axes, between the last two free wake turns are calculated and used to add stacks of far wake vortex elements. Elements of the far wake are simply positioned at equal distances, similar to those calculated from the last two free wake turns, and each element is given a vortex strength similar to that generated on the previous turn. Note that although the far wake is not generated by "free motion", its shape and position are not rigid and are always updated to follow the free motion of the preceding part.

Figure 1 shows the distorted shape of a tip vortex trailing from the first blade at zero azimuth. The vortex has been extracted from a converged wake within the CRFM code prediction for two Puma flight test cases. Two advance ratios are shown to compare the rapid change in wake structure when speed changes. Only three far wake turns are shown in each case, to demonstrate the characteristics of the wake. Advance ratio 0.15 is a representation of the higher speeds with typical wake characteristics. These include the overlap of the wake turns at the sides leading to a concentration of vorticity which resembles the fixed wing pair of tip vortices. It also includes the collapse of the wake at the middle as a result of the high vorticity on the sides, and the rapid sweep of the wake turns into the free stream resulting in a nearly flattened wake.

At the lower advance ratio of 0.1, the wake turns are not swept as quickly, and the turns remain in close proximity which cause the wake to be pushed downwards. The overlap of turns on the sides still exists, but not with the same concentration as was apparent at the higher speed. The distortion in vortex shapes at the sides happens because the vortices are now stronger and very close. Figure 2 shows in more details how the tip vortex develops over the first three turns. The apperent squeeze of vortices at the sides starts to happen slightly at the second turn, but becomes more evident at the third turn and remains strong. When the vortex moves to the back or the aft positions, there is reasonable separation from other vortices, and distortion is minimal as seen in both figures. The large contrast between what happens at the middle and the sides of the wake is also a result of the large difference in blade loading and bound circulation between the sides and the fore and aft parts of the rotor.

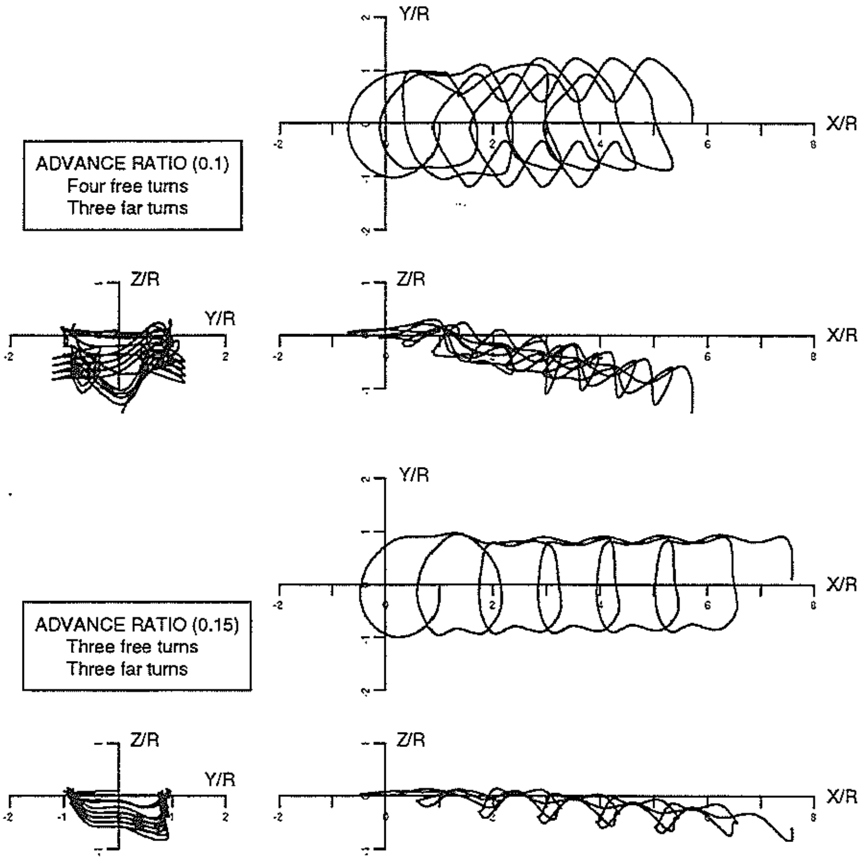
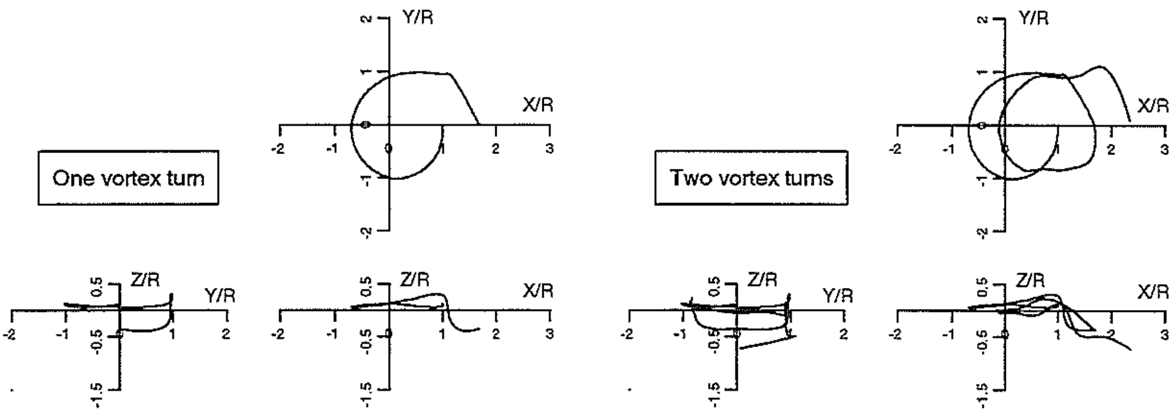


Figure (1) : Three views of the tip vortex trailing from a Puma blade at zero azimuth, other tip and inboard vortices are not shown.



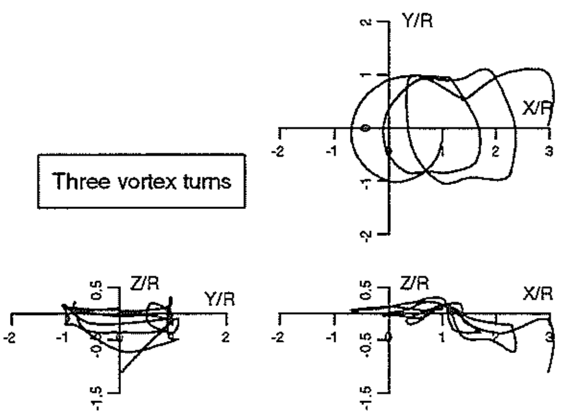


Figure (2)

Development of the tip vortex at Advance Ratio 0.1

Free wake/CRFM Interface

Interface mechanism

The CRFM is a combined rotor/fuselage analysis code designed for steady and manoeuvring flights. The accurate calculation of the velocity induced by the wake on the rotor blades is a critical feature of its calculations. The code was originally developed with various options for calculating the induced velocities, although one prescribed wake has become the preferred option for most applications. This prescribed wake model is a combination of tip vortices formed of half rings, and an interactive near wake (Ref. 6); it is called "vortex rings model". When the free wake option was added to CRFM, a different approach from that used for the prescribed wake was needed. In the case of a prescribed wake, it is assumed that the shape of the wake does not change; only the strength of vortices vary when the trim iterations are performed by the CRFM code. This does not apply to the free wake which changes both geometry and filament strength with any change in circulation distribution over the rotor disc.

Inclusion of the free wake calculations within the iteration procedure of the CRFM code would lead to an unacceptably high computation level. The alternative approach shown in the flow diagram at fig. 3 has therefore been adopted, with the free wake calculations done within an outside iteration loop. CRFM starts by supplying azimuthal variation of the bound circulation, based on the vortex ring model. The free wake code is run separately until the geometry of the wake settles to a converged solution. The wake code then supplies CRFM with azimuthal distribution of the blade's induced velocities, which CRFM uses for a new set of calculations. The new distribution of bound circulation is then fed back to the wake code and the cycle is repeated. Final solution is achieved when the control angles calculated by CRFM do not change from one outer iteration to the next.

This mechanism has proved very efficient. For the inner iteration within the wake code, only one or two marching turns are typically needed, plus one extra turn to calculate the induced velocities. For the outer iteration, only two loops are typically needed at high speeds, although an extra loop may be needed for more accuracy at the lower range of speeds. Larger numbers of wake turns may be needed for cases where the time steps are relatively small, but no accuracy evidence was found to justify the high computation cost of using smaller time steps.

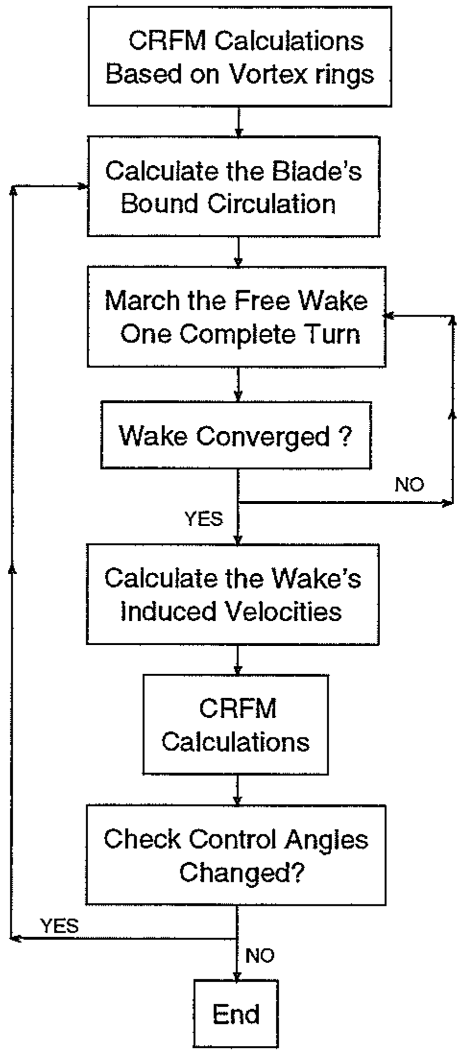


Fig.(3): Flow diagram for the Integrated Wake/CRFM code.

Interfacing problems

The azimuthal distributions of two main parameters are crucial to the success of iteration between the wake code and CRFM, namely the bound circulation on the blade which is supplied by CRFM to the wake, and the induced velocities supplied by the wake to CRFM. Both parameters should be passed from one code to the other, at specified radial positions and azimuth intervals. This restriction is imposed on the wake code by CRFM which supplies and requires the information at pre-determined points on the rotor disc area. The problems created by this restriction are explained below, with a brief description of how it was solved.

Radial calculations The first job for the wake model is to decide the spanwise positions of the trailing vortex filaments, based on the bound circulation it receives from CRFM. At each time step, the point of release of a vortex differs according to the bound circulation profile at that particular time. On the other hand, the code aims to calculate the induced velocities at the same points where the bound circulation was supplied, which may conflict with placing a vortex too close to a point of calculation. This problem has been solved by using the curve fitting technique, with the following procedure:

- Discrete values of circulation supplied by CRFM are fitted to polynomials at all azimuths.
- Each curve is used to decide the vortex release points along the blade span at this azimuth.
- Points where the wake code calculates induced velocities are chosen between the release points.
- When the induced velocities are calculated, their values are again fitted to polynomials.
- The velocity curve is used to calculate discrete values at the stations required by CRFM.

Azimuthal calculations The azimuthal problem was much more complicated, since both codes imposed restrictions. The aerodynamic calculations in CRFM demand smaller azimuth sweeping steps (3° to 5°), while the wake code needs much larger azimuth steps (15° to 30°). Since the wake code can calculate the velocities only at the end of each time step, then any CRFM azimuths between the beginning and the end of this step will be missed. As an extreme example, with a CRFM step of 3° and a wake step of 30°, 90% of the azimuths demanded by CRFM will be missed. A curve fitting solution was tried but failed to yield satisfactory results, mainly because of the possibility of missing important wake features occurring between the beginning and the end of a large time step. The marching time step in the wake program cannot be set as low as that for CRFM calculations because of both computation cost and stability problems. The wake code was modified to solve this problem as explained below:

- The wake model first uses a time step which is suitable for the marching process.

- When the wake converges and induced velocity calculations start, a new marching turn starts but with the initial time step reduced by a value equivalent to the CRFM time step.
- During this second stage, the azimuths where the steps stop are phase shifted and more azimuths are now covered.
- If the marching mechanism detects a repetition of azimuths, then it makes another phase shift by starting from a new azimuth.
- The process stops when all azimuths required by CRFM are covered and induced velocities are calculated at all those positions.

Results

The DERA free wake model has been developed primarily to aid the CRFM code in predicting blade forces and loads more accurately. The emphasis is on its ability to predict the higher harmonic loads, particularly at the lower range of advance ratios. This section includes comparisons between flight test data for the Puma rotor (Ref. 12) and the prediction by CRFM using two different wake options, namely the "Vortex rings" model and the "Free wake" model. The test data are shown in the form of the time variation in the flatwise bending and torsion moments on the blade, at various radial stations. The two advance ratios of 0.15 and 0.1 have been selected to demonstrate the value of using free wake analysis at low advance ratios.

Figure 4 shows the comparisons at 0.15 advance ratio at which, as explained earlier, a more stable wake structure exists. It is therefore possible for the prescribed wake model to yield reasonable results at this speed, as the figure shows. It is noted however that it is quantitatively inaccurate in some parts of the rotor disc, e.g. at the front, and fails to predict the curve trend at a few other parts. The free wake prediction has managed to capture the trend of the curves for most of the azimuth range and radial stations. The free wake model over-predicts the moments at some places in the second quarter, which may be related to the accuracy of the vortex core modelling. On balance, performance of the free wake at this advance ratio is equivalent to, if not better than, the "vortex rings" model which was originally fine tuned for optimum predictions.

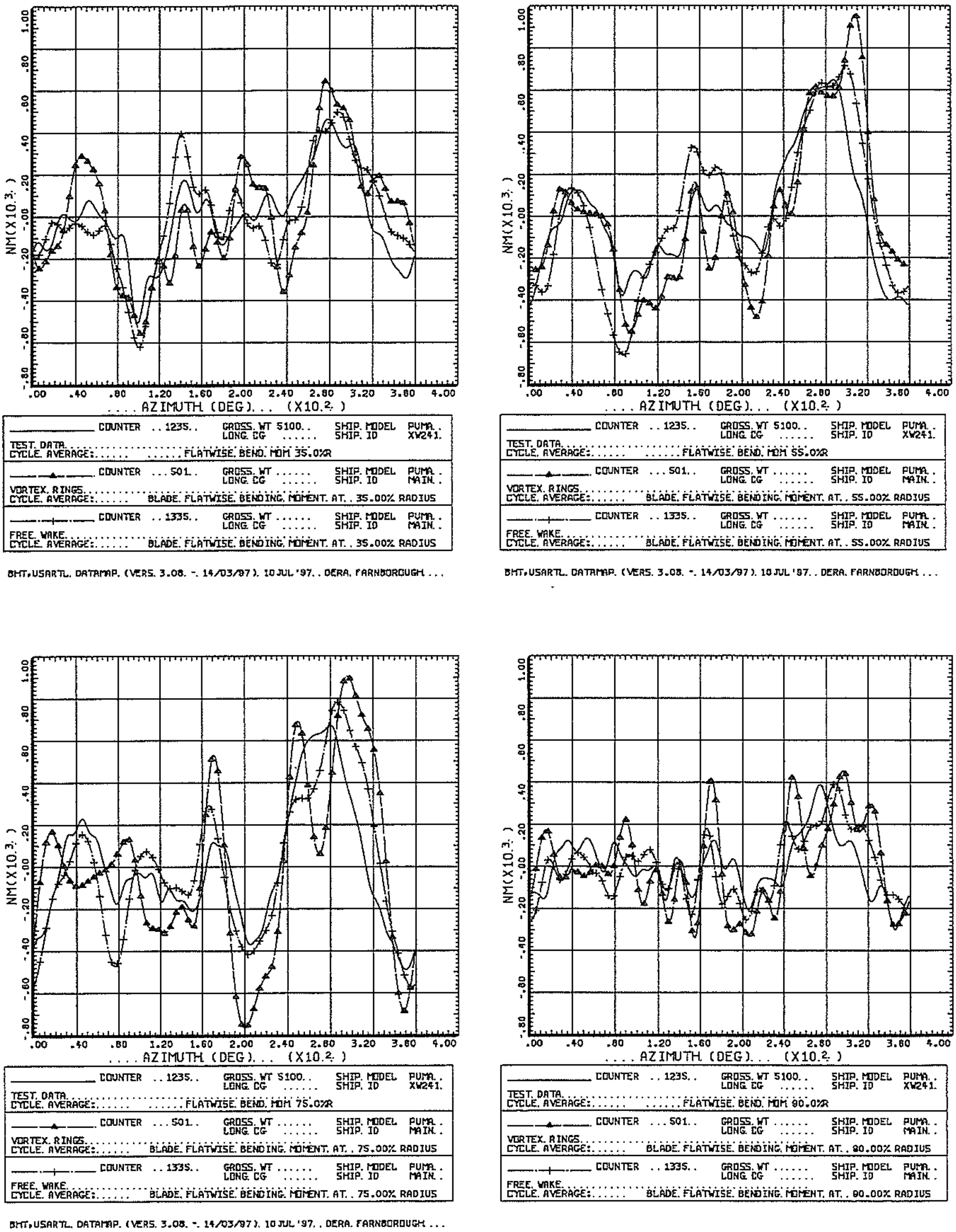


Fig. 4 : Flatwise bending moments at four radial positions; A comparison between the Puma flight test data and CRFM predictions using "Vortex ring model (Δ)" and "Free wake model (+)".
Advance Ratio = 0.15

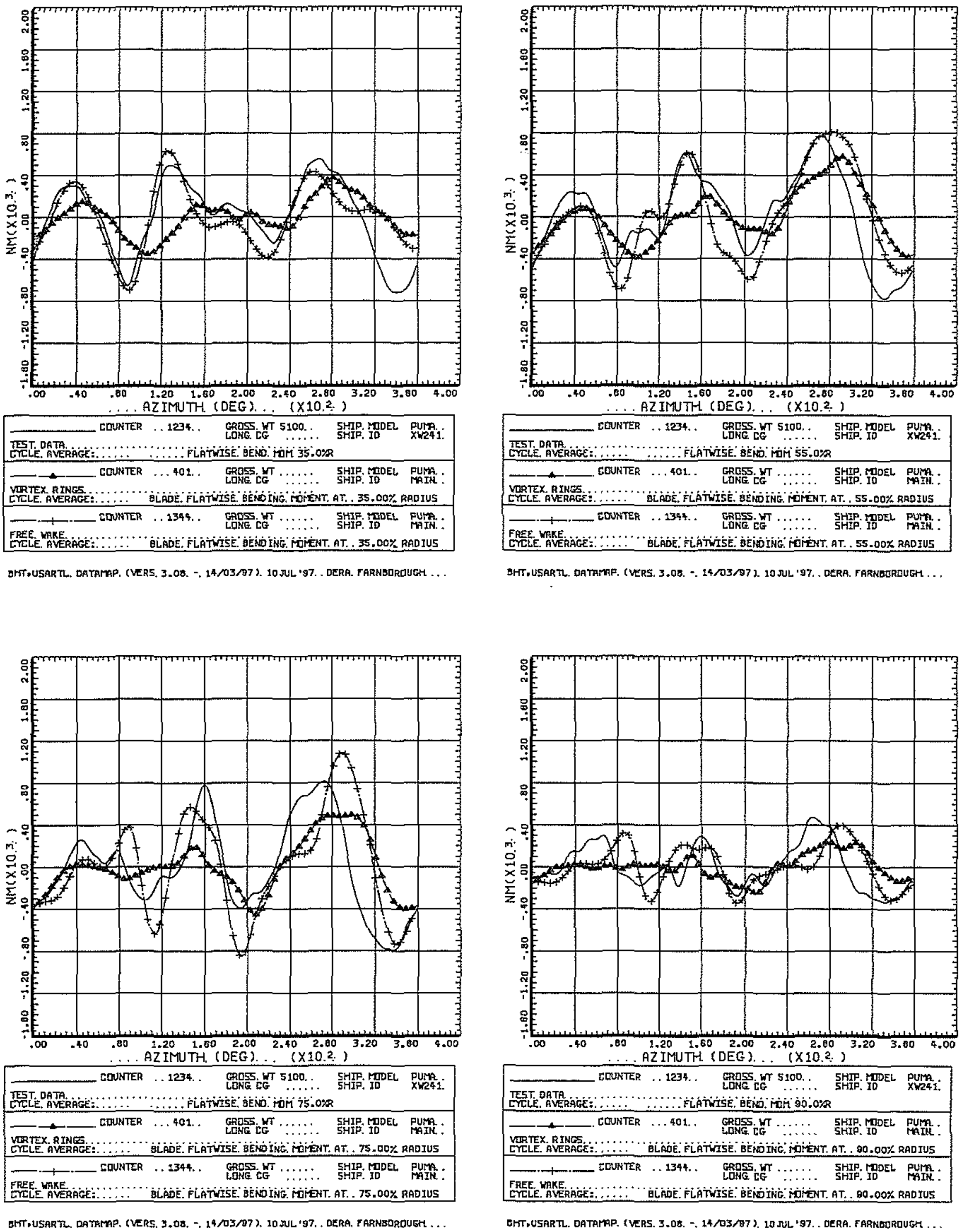


Fig. 5 : Flatwise bending moments at four radial positions; A comparison between the Puma flight test data and CRFM predictions using "Vortex ring model (Δ)" and "Free wake model (+)". Advance Ratio = 0.1

At the lower advance ratio of 0.1 (figure 5), the value of using the free wake model is much more evident. The prescribed wake has failed in most cases to predict the magnitude of bending moments at this low speed. The reason is simply because the wake geometry is too complicated for the simple vortex rings to model accurately. The free wake, however, has made a much more accurate representation of the wake geometry, and has therefore improved the prediction considerably. One interesting feature noted for some parts of the rotor disc is that the model's prediction has a slight phase shift when compared with test data. This observation may also be related to the influence of the vortex core modelling on the motion of vortex filaments near the blades.

A different comparison, for the torsion moment at a single radial station, is shown in Figure 6. Once again, the free wake has improved the prediction over a large part of the azimuth, but a phase shift problem, somewhat greater than that for bending moments, is apperent at the retreating side. It is hoped that by improving the vortex core modelling, this will improve the accuracy in predicting the path of filaments. If the model predicts more accurate filament path near the blades, an even better agreement with flight test data will be expected.

Conclusions

- A rotor wake model has been developed at DERA to predict the accurate geometry of the wake as it follows the motion of the rotor blades.
- The prediction is based on a "force-free" motion of the wake components, and the accuracy of motion is improved by using the curved vortex element techniques.
- The wake model has been successfully interfaced with the DERA's aeroelastic code, with various interfacing problems tackled and solved.
- The free wake prediction has been tested against a prescribed wake. The test cases showed significant benefits in using the free wake modelling when the accurate prediction of the wake geometry was crucial.
- The current studies have shown the need for further investigation into a better modelling of the "vortex-core", a feature which seems to play an important role in the accuracy of rotor loads predictions.
- The free wake model is now ready for a wider range of advanced rotor applications. The emphasis will be on the lower range of advance ratios, and on special applications such as BVI, tail rotor noise and rotor's vibration.

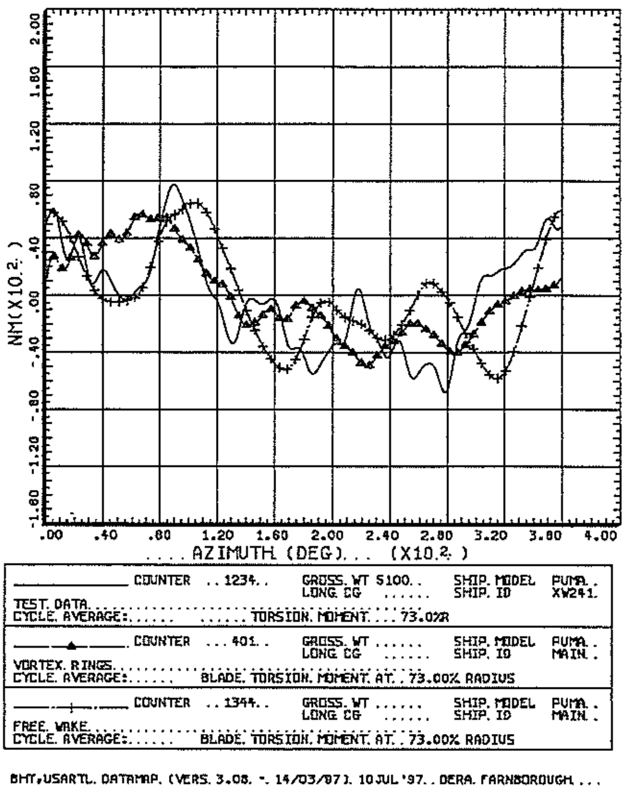


Fig. 6 : Torsion moments of the Puma blade at 73% radius and 0.1 advance ratio.

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