2GCHAS Prediction of HART Blade-Vortex Interaction Loading

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Abstract

Analytical predictions of blade vortex interaction (BVI) loading are presented for the 40 percent, Mach-scaled model of the hingeless BO-105 main rotor (HART). The main analytical tool used was the 2GCHAS software, but CAMRAD/JA and full potential rotor (FPR) code predictions are also presented. Correlation includes blade frequencies, blade tip deflections, BVI airloads and tip vortex geometries. The 2GCHAS free wake analysis results include the Scully wake and the Maryland Free Wake (MFW) models. The Maryland Free Wake model was successfully coupled in 2GCHAS and showed a similar level of accuracy in BVI predictions compared with the 2GCHAS Scully wake. Overall, the 2GCHAS BVI loads predictions using the Scully wake and the Maryland Free Wake (MFW) models were slightly better than CAMRAD/JA. Modeling the secondary vortex wake in the MFW model improved the BVI loads prediction. The 2GCHAS Scully wake model captured the high frequency BVI loading, while the 2GCHAS Maryland Free Wake model did not. The use of the MFW model (version 2) in 2GCHAS increases the CPU time by 23-56 times compared with the 2GCHAS Scully wake model. Having two free wake models in 2GCHAS will, however, permit the users to conduct rotorcraft analysis tasks more rigorously. There is a need for further investigation including an estimate of the uncertainty and accuracy of the measured tip deflection data. Acquisition of more data on the tip vortex geometries and vortex strengths may be necessary to better aid understanding of the meaning of the miss distance in the vortex geometry prediction and the resultant effect on blade loading.

Introduction

Recently, the Higher harmonic control Aeroacoustic Rotor Test (HART) [1-2] was conducted at the German-Dutch DNW wind tunnel to obtain detailed technical data on blade-vortex interaction (BVI) airloads. The data included blade surface pressure distributions, blade deformation, acoustic signatures, and tip vortex wake geometry and vortex strength. Since the wake geometry and vortex strength significantly influence BVI airloads, the availability of these data has great potential to aid validation of new analytical prediction methods. A comparison of analytical predictions by US Army AFDD, NASA Langley, German DLR, and French ONERA researchers concluded that the wake geometry prediction was significantly improved by prescribing the blade motion using the measured data [3]. It was noted that further improvement was needed in wake modeling for better loads prediction. Further work concluded that the use of wind tunnel and fuselage flow angle correction and a multicore vortex wake model improved the prediction [4].

In this study, HART data is analyzed using the Second Generation Comprehensive Helicopter Analysis System (2GCHAS) [5-7]. The 2GCHAS code is an interdisciplinary software system that has been developed to integrate rotorcraft analysis functionalities to provide accurate analytical capabilities for researchers, designers, and evaluators across a spectrum of major rotorcraft technical disciplines. It is multi-disciplinary. Its structural analysis capability is based on an element library which includes nonlinear beam, linear beam, and rigid body mass elements. The 2GCHAS user can build a complete structural model by selecting various elements from the element library. Numerous aerodynamic options are available such as linear, nonlinear (table look-up) and unsteady aerodynamics models, prescribed and free wakes, a

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generalized dynamic wake, and various aerodynamic interference options. The interface between structural and aerodynamic models is a user input option. This feature allows the user to easily access various functionalities.

The free wake models in the present 2GCHAS analysis include the Scully wake [5, 8] and Maryland Free Wake (version 2) [9-10]. The Scully wake has been widely used in the rotorcraft industry. It discretizes the convected wake structure into a near wake, a roll-up wake and a far wake region. It models the roll-up and far wake regions by a few wake panels in space. The tip vortex initiates from the roll-up state and fully progresses downstream in the far wake. This tip vortex is allowed to be free, while the inboard trailers are prescribed. The model is computationally efficient but may experience numerical instability or poor convergence.

The Maryland Free Wake (MFW) is based on a pseudo-implicit predictor corrector (PIPC) relaxation algorithm with a five point central difference scheme [9-11]. The wake structure is more robust and fully discretized along the trailed vortex filament. The shed wake effect is not included in the MFW model. The inboard trailers are prescribed and extend to the far wake region, and a pair of free vortices (tip vortex and secondary vortex) are allowed in the model. The free vortex geometry is obtained by solving a partial differential equation using the PIPC algorithm. The free wake geometry calculation includes higher order accuracy, but this process appears computationally very expensive. Further progress on the MFW model was made for computational efficiency [11]. Introduction of numerical acceleration algorithms including an adaptive grid sequencing and velocity field interpolation were found to reduce the computation time up to one order of magnitude.

The purpose of this paper is to present the 2GCHAS predictions of HART blade-vortex interaction loading accompanied with CAMRAD/JA predictions. It will demonstrate the current status of 2GCHAS prediction and address the influence of different free wake models on the HART rotor BVI loadings. Note that predictions from CAMRAD/JA and predictions from CAMRAD/JA coupled with the FPR code were available from earlier work [3] and used for comparison in this paper.

2GCHAS Modeling

The HART rotor was a 40 percent, Mach-scaled model of the hingeless BO-105 main rotor with a radius of 2 m and a root cutout of 0.35 m, operating at a nominal speed at 1040 RPM. The rotor blade has a standard rectangular tip with a solidity of 0.077. It has a NACA 23012 airfoil with a constant chord length of 0.121 m and -8 deg of linear twist.

The blade was discretized into 10 nonlinear beam elements in the 2GCHAS model. To capture BVI loading more accurately, a refined aerodynamic model was employed using 16 aerosegments (Fig. 1). Nonlinear aerodynamics (table look-up) was used with the Theodorsen linear unsteady aerodynamics effect. The induced velocity was calculated separately from both the Scully wake and the Maryland Free Wake (MFW). The Scully wake model was implemented by a tight coupling in the solution algorithm, which performed the induced velocity calculation at every Newton-Raphson iteration in the time step. The MFW model was, however, loosely coupled for computational efficiency and so the induced velocities were calculated once per each rotor revolution via Biot-Savart law using the vortex filaments locations and strengths from the previous period.

The Maryland Free Wake (MFW) solves the vorticity transport equation for the free vortex wake geometry. Unlike the Scully wake model, the prescribed inboard trailers are extended throughout the far wake region without a spatial simplification of the inboard vortex wake panels. The inboard trailers outboard of the maximum bound circulation (Γ_{max}) are replaced by a free tip vortex filament, so that the tip vortex has a strength of Γ_{max}. As a result, the prescribed inboard trailers are convected only inboard of the maximum bound circulation. The tip vortex is released from a user specified radial location near the tip (see Fig. 2) like the Scully wake model. For a dual-peak loading condition, a free secondary vortex is initiated and trailed downstream. With the existence of the secondary vortex, the outboard tip vortex strength is set to be Γ_{min} and the inboard secondary vortex is released with a strength of ($\Gamma_{max} - \Gamma_{min}$) from the radial location where the bound circulation strength has a sign change. This algorithm allows the free tip and secondary vortices to have a combined strength of Γ_{max} which appears practical.

The multicore vortex model [4, 9] in the Maryland Free Wake (MFW) decomposes a free vortex (tip or secondary vortex) into a multiple of concentric, inner sub-vortices, and correspondingly the strengths of the inner sub-vortices are specified by the user with a constraint that the sum of the sub-vortex strengths must be same as the single core vortex strength. Each inner sub-vortex can have a different core size which is supplied by the user. Different core sizes for inner sub-vortices in the multicore vortex model were, however, not attempted in this study due to uncertainty in specifying the inner sub-vortex core sizes and strengths. Note that if the user specifies the inner vortex core sizes to be same as the core size of the single core vortex model, one should generate the same results as the single core vortex model.

Results and Discussion

The correlation study was attempted for the baseline case without the higher harmonic control (Run 140). The thrust coefficient was 0.0044 with an advance ratio of 0.15 and the tip Mach number of 0.641. This baseline case (Run 140) simulated descent flight with a shaft angle of 4.24 deg aft (5.32 deg aft when adjusted due to wind tunnel corrections).

Blade Frequency Prediction

The HART rotor blades are made of glass-fiber reinforced plastic and have mass and stiffness distributions similar to the full-scale BO-105 hingeless rotor blade. Dynamic scaling requires matching of the blade natural frequencies to the full-scale blade. A comparison of the rotating frequencies (Hz) of the first flap, lead-lag and torsion modes in air is shown blade in Table 1 for the scaled HART rotor, operating at a nominal speed of 1040 RPM.

Table 1. Prediction of the HART rotating frequencies [Hz] in air from 2GCHAS and CAMRAD/JA (Nominal Operating Speed = 17.33 Hz)

Modes	Test	2GCHAS	CAMRAD/JA
Flap	19.52	17.91	18.38
Lead-Lag	13.52	13.92	14.55
Torsion	70.20	67.43	71.98

The flap mode rotating frequencies using 2GCHAS and CAMRAD/JA show 8.3% and 5.8% errors, respectively. The lead-lag mode rotating frequencies show 3.0% error for 2GCHAS and 7.6% for CAMRAD/JA. For the torsional mode, 2GCHAS and CAMRAD/JA give reasonable prediction; 3.6% and 2.5% errors, respectively. It may be concluded that the blade rotating frequencies are reasonably predicted by 2GCHAS and CAMRAD/JA.

Blade Deflections

Figure 3 shows comparisons of the tip deflection predictions for the HART rotor (Run 140, baseline). The flap deflection of the test data exhibits 2 per rev and 3 per rev responses. The 2GCHAS results using the Scully wake predict the harmonic shape but the peak-to-peak magnitude is half of the test data. The 2GCHAS results with the Maryland Free Wake (MFW) using either a free tip vortex wake (TVX) or both a free tip and secondary vortex wake (SVX) model predict the flap response reasonably well but show a strong one per rev response. The CAMRAD/JA prediction is almost flat. For the lead-lag mode, the analytical predictions appear similar to one another but are shifted roughly by a quarter chord length (i.e., a chord length = 0.121 m) toward the leading edge compared with the test data. However, one might expect that the rotor requires a minimal torque since the test condition was in descent flight, and accordingly the mean lead-lag response might be trivial (unlike the test data). Similarly, the predictions for the torsional mode exhibit the difference of about 1.5 deg for the mean elastic torsion compared with the test data.

Figure 4 depicts the radial distribution of the elastic torsion at an azimuth of 60 deg. Again, all the predictions appear similar to one another and are poorly calculated by missing about 1.5 deg outboard, while the predictions inboard near the blade root are almost identical to the test data. Although the frequency predictions are reasonable in Table 1, the blade deflections show poor prediction, especially for lead-lag and torsion. This discrepancy may originate from the forcing terms in the equations of motion, which are partially due to the wake. This needs further investigation including an estimate of the uncertainty and accuracy of the test data.

BVI Airloads and Tip Vortex Geometry

The lift time history was compared with the test data (Run 140) using 2GCHAS and CAMRAD/JA. The 2GCHAS results again include predictions with the Scully wake and the Maryland Free Wake (MFW) models. The MFW model in 2GCHAS has the option to use either TVX or SVX model, always accompanied with the prescribed inboard trailers. The 2GCHAS analysis employed an azimuthal time step of 5 deg for both the Scully wake and MFW models. The CAMRAD/JA results include the prediction with the Johnson wake (CJA) [8] and the prediction of CAMRAD/JA loosely coupled with a full potential rotor (FPR) code (CJA/FPR). The CJA/FPR coupling was done by first trimming CAMRAD/JA and then inputting its partial inflow angle into the FPR code. The FPR analysis was performed with a time step of 0.25 deg. Note that the CAMRAD/JA free wake analysis was performed with an azimuthal time step of 15 deg.

Figure 5 shows predictions of the time history of the nondimensional lift using the 2GCHAS Scully wake, the CAMRAD/JA and the coupled CAMRAD/JA - FPR code. The test data exhibits large amplitude 2 per rev and/or 3 per rev harmonics and the magnitudes become larger outboard. All the analytical predictions, however, failed to reasonably capture the harmonics at the 75% and 87% radial locations, yet the predictions were significantly improved at the 97% radial location. The 2GCHAS prediction using the Scully wake is improved compared with the CAMRAD/JA results. The test data shows the blade-vortex interaction (BVI) in the first and fourth quadrants. Interestingly, the 2GCHAS prediction using the Scully wake and the CAMRAD/JA prediction with the FPR code (CJA/FPR) capture the high frequency loading of the BVI loads (although they are overpredicted). This loads capturing is believed due to the high resolution solution algorithm (an azimuth of 5 deg or less). This indicates that the use of computationally expensive CFD codes may not be needed for BVI loads prediction.

The prediction for the same case as in Fig. 5 but using the 2GCHAS with the MFW model, is given in Fig. 6. The MFW models (TVX and SVX) also poorly predict the lift at the 75% radial location. They begin to show improvement of the prediction at the 87% radial location, and make a significant improvement at the 97% radial location like the Scully wake model (Fig. 5). The sharp spikes of high frequency loading which are induced from strong blade-vortex interaction are, however, missed in the MFW prediction, This might be related to the MFW algorithm but the cause of this discrepancy is not presently understood.

When using the MFW SVX model, the secondary vortex wake is initiated on the blade and convected downstream when the negative loading condition (dual-peak) occurs. As shown in Fig. 6, an inclusion of the secondary vortex wake in addition to the tip vortex wake (SVX) in the MFW model slightly improved the BVI loads prediction in the forward and aft locations of the rotor disc, where the secondary vortices were released, when compared with the MFW tip vortex wake model (TVX). Initial release locations of the secondary vortex wake are shown in Fig. 7. Due to the low flight speed (advance ratio of 0.15), a large negative loading condition was not expected, and a small effect of the secondary vortex wake was anticipated. As expected, the initial release points of the secondary vortex on the blade were found outboard of the 97% radial location around the azimuths of 30 and 150 deg, where the 2GCHAS MFW prediction using the SVX model made an improvement compared with the MFW TVX model.

Tip vortex geometry predictions are compared with the experimental data in Fig. 8 at azimuths of 35 and 295 deg where the strong BVI loading are exhibited. The experimental data were obtained from the Laser Light Sheet (LLS) flow visualization technique [12]. The vortex positions are the points from the hub center in the hub coordinate system; the x-axis is positive toward the tailboom (aft) along the precone angle of 2.5 deg, the y-axis is positive right, and the positive z-axis is up. The tip vortex geometries were measured but limited at the two azimuthal locations. For an azimuth of 35 deg, the tip vortex prediction lagged from the experimental data roughly by two chord lengths (top view, Fig. 8a), and all the predictions appear similar. The predicted tip vortex vertical positions are poor and tend to move up earlier (side view, Fig. 8b). For an azimuth of 295 deg, the predictions in the top view (Fig. 8c) are significantly improved but the predictions of the vertical positions are again very poor (side view, Fig. 8d). The trends contradict the BVI airloads predictions which were relatively good at the azimuths of 35 and 295 deg as shown in Figs. 5 and 6. The effects of poor predictions for the tip vortex vertical positions are not clearly understood. Acquisition of more data on the tip vortex geometries and vortex strengths may be necessary to better aid understanding of the significance of the miss distance in the vortex geometry prediction and the resultant effect on blade loading. It is noted that the 2GCHAS geometry predictions using the MFW model are quite similar to the Scully wake predictions in the top view, but predictions in the side view appear quite different.

Computation Time

The Maryland Free Wake model (version 2) version has been successfully integrated in 2GCHAS. It requires a fairly large computation time compared with the Scully wake model. The large CPU time requirement can prevent more complex rotorcraft applications or evaluations of more cases. To improve this situation, numerical acceleration schemes were recently adopted [11] in the version 3, including an adaptive grid sequencing scheme, a velocity field interpolation scheme and the pseudo-impliciteness of the MFW model. This upgrade was found to reduce the CPU time up to one order of magnitude. No results using version 3 are presented in this paper.

Figure 9 shows a comparison of the CPU time required by the 2GCHAS using the Scully wake and the version 2 MFW models including multicore vortices in the periodic solution. The core sizes for the inner sub-vortices were set same as the core size of a single core vortex model for convenience. The computation time is normalized by the 2GCHAS CPU time using the Scully wake. Using the Maryland Free Wake TVX model with a single core vortex needed 23 times more computation time than using the Scully wake. Using the Maryland Free Wake SVX model with a single core vortex (c1) required 39 times more CPU time. Using the multicore vortex model required additional computation time for each case. A three inner core vortex model (c3) increased the CPU time roughly by 45 percent from the single core model (c1) for both TVX and SVX models. Using the secondary vortex wake model (SVX) with a three core vortex (c3) increased the CPU time roughly by 56 times from the Scully wake model.

Conclusions

Correlations of 2GCHAS and CAMRAD/JA with experimental results were conducted for the HART rotor baseline case (Run 140). The Maryland Free Wake (MFW) model was successfully coupled in 2GCHAS and showed a similar level of accuracy in BVI predictions compared with the 2GCHAS Scully wake. Overall, the 2GCHAS BVI loads predictions using the Scully wake and the Maryland Free Wake models were slightly better than CAMRAD/JA. Having two free wake models in 2GCHAS will permit the users to conduct rotorcraft research analysis tasks more rigorously.

In summary, the following key were made:

1. The blade rotating frequencies are reasonably predicted by 2GCHAS and CAMRAD/JA.

2. The 2GCHAS Scully wake and MFW models predicted the flap deflection at the tip reasonably, while the CAMRAD/JA prediction was almost flat.

3. For the lead-lag and torsional deflections, all the analytical predictions appeared poor and missed the mean response by relatively large magnitudes. This discrepancy might originate from the forcing terms in the equations of motion, which are partially due to the wake model. This needs further investigation including an estimate of the uncertainty and accuracy of the test data.

4. The 2GCHAS Scully wake and MFW models failed to capture the harmonics of the lift inboard, yet the predictions were improved outboard. The 2GCHAS prediction appeared slightly better than the CAMRAD/JA prediction.

5. The 2GCHAS Scully wake model captured the high frequency BVI loading in the first and fourth quadrants, and the use of computationally expensive CFD codes may not be required in order to predict the BVI loads.

6. The 2GCHAS MFW models missed the high frequency BVI loading. The cause of this discrepancy is not clearly understood.

7. An inclusion of the secondary vortex wake in the MFW model slightly improved the BVI loads prediction in the forward and aft location of the rotor.

8. The tip vortex geometry predictions were reasonable in the top view, but very poor in the side view. Acquisition of more data on the tip vortex geometries and vortex strengths may be necessary to better aid understanding of the meaning of the miss distance in the vortex geometry prediction.

9. The use of the MFW model (version 2) in 2GCHAS increases the CPU time by 23-56 times compared with the 2GCHAS Scully wake model.

Acknowledgment

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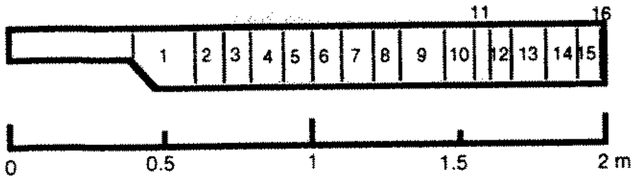
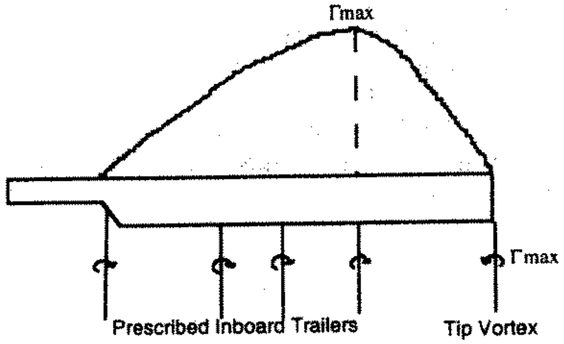
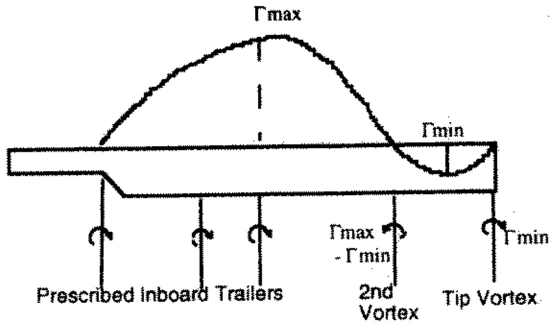


Figure 1. 2GCHAS aerodynamic model for the HART rotor blade consisting of 16 aerosegments with a blade radius of 2 meters



(a) Single Peak Loading



(b) Dual Peak Loading

Figure 2. 2GCHAS Maryland Free Wake (MFW) trailed vortex model with the tip and secondary vortices

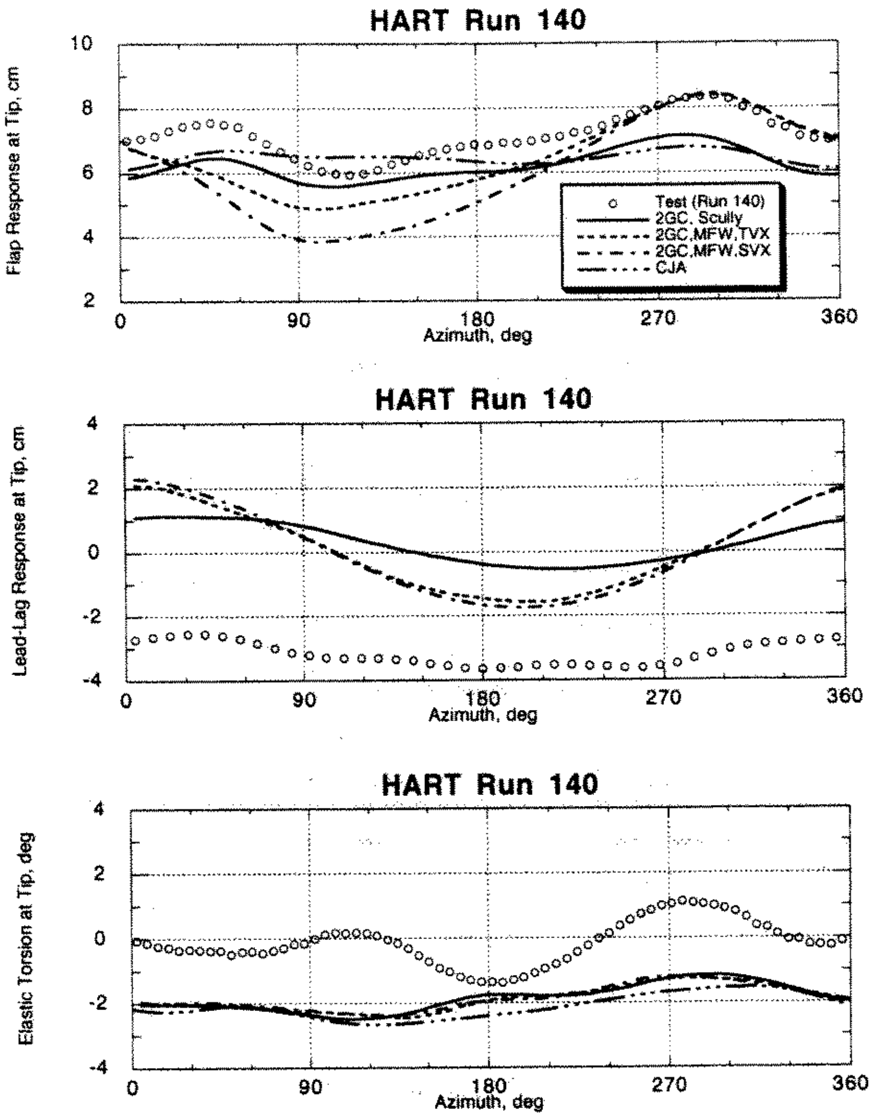


Figure 3. A comparison of the blade tip deflections for the HART rotor using 2GCHAS and CAMRAD/JA free wake analyses at an advance ratio of 0.15

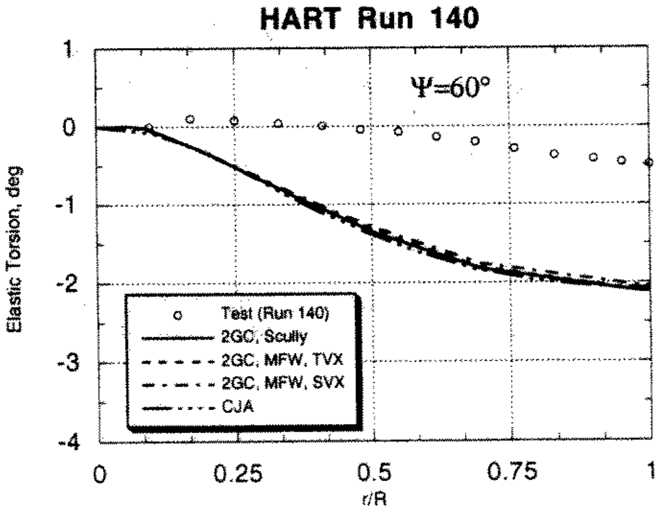


Figure 4. Comparison of the radial distribution of the elastic torsion at an azimuth of 60 degrees using 2GCHAS and CAMRAD/JA

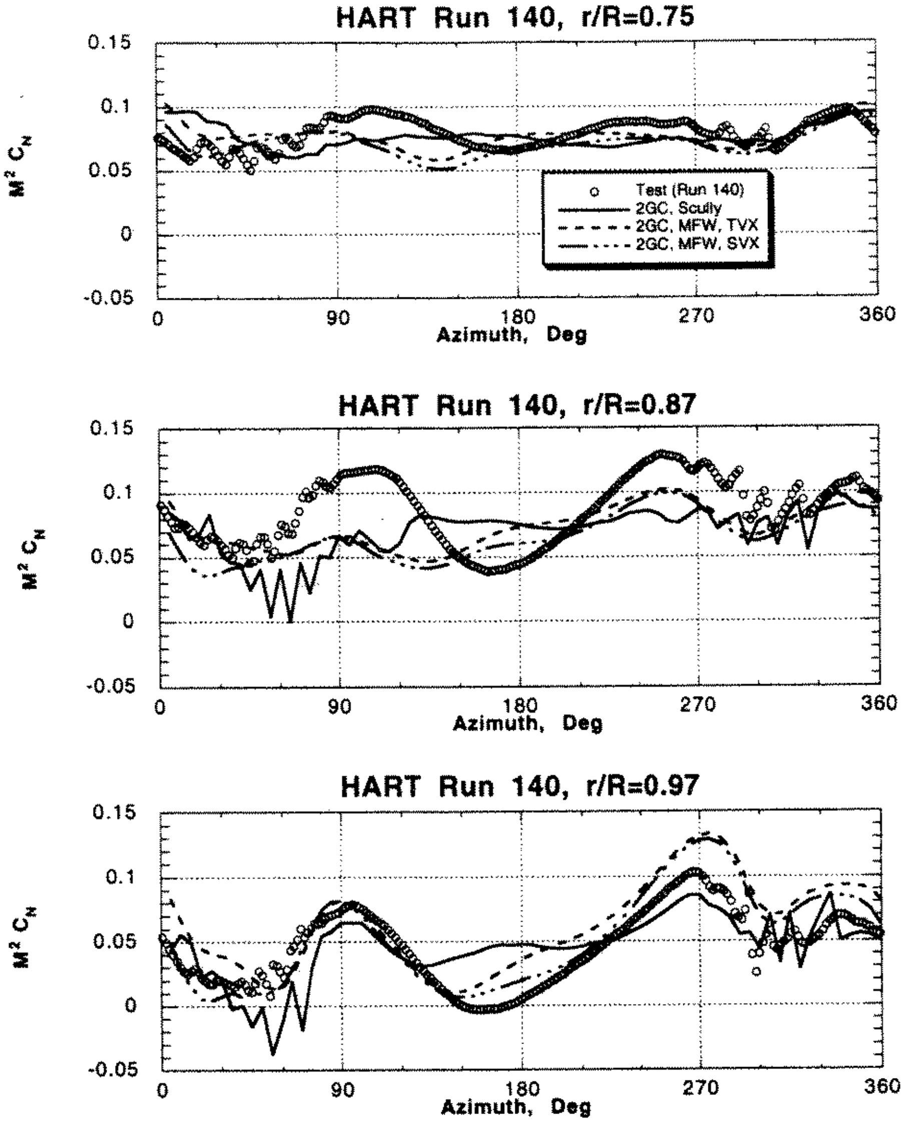


Figure 6. Predictions of the nondimensional lift using the 2GCHAS Scully wake and Maryland Free Wake models at an advance ratio of 0.15

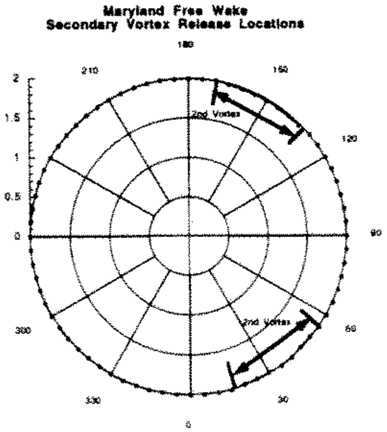
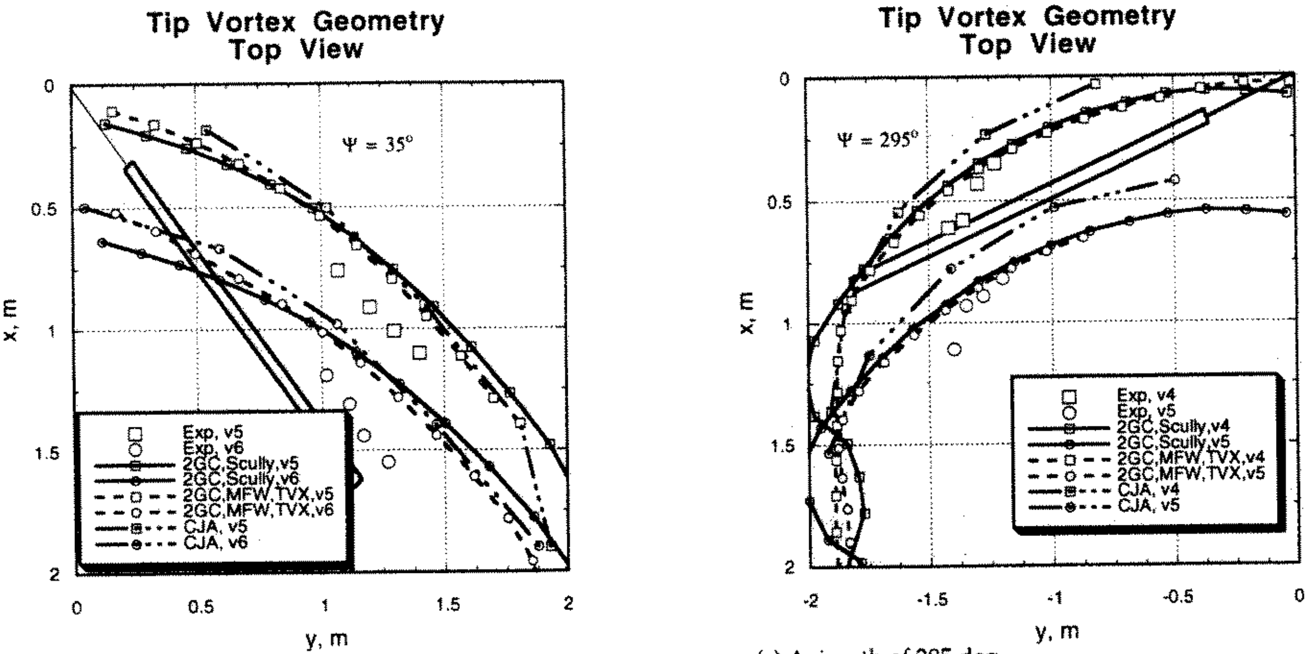
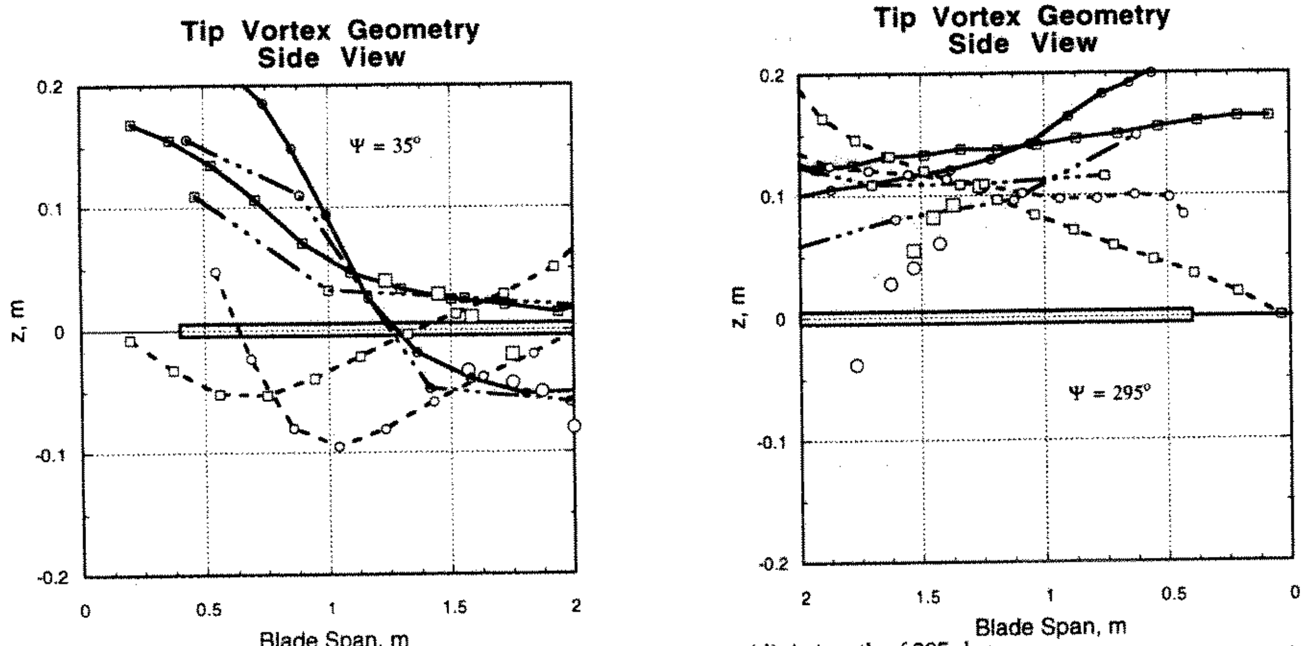


Figure 7. Secondary vortex release locations of the Maryland Free Wake (MFW) model for the HART rotor, Run 140



(a) Azimuth of 35 deg

(c) Azimuth of 295 deg



(b) Azimuth of 35 deg

(d) Azimuth of 295 deg

Figure 8. Comparisons of the measured and predicted tip vortex filament locations at azimuths of 35 and 295 degrees for the HART rotor at an advance ratio of 0.15

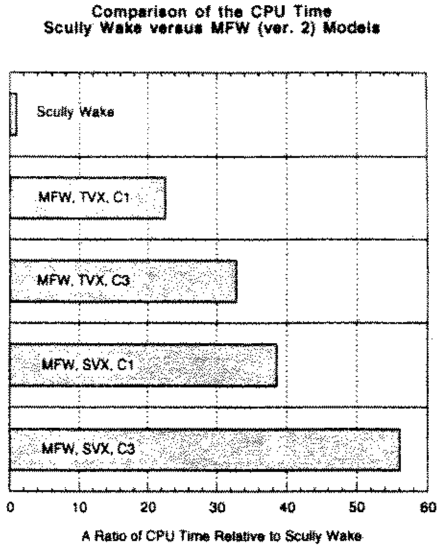


Figure 9. A comparison of the CPU time for the 2GCHAS Scully wake model and the Maryland Free Wake (MFW) with multicore votex model in the HART rotor loads prediction