

Comprehensive Modeling of the Apache With CAMRAD II

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ABSTRACT

This paper presents a report of a multi year study of the U.S. Army LONGBOW APACHE (AH-64D) aircraft. The goals of this study were to provide the Apache Project Managers Office (PMO) with a broad spectrum of calibrated comprehensive and CFD models of the AH-64D aircraft. The goal of this paper is to present an overview of the comprehensive model which has been developed. The CAMRAD II computer code was chosen to complete this task. The paper first discusses issues that must be addressed when modeling the Apache using CAMRAD. The work required the acquisition of a data base for the aircraft and the development and application of a multidisciplinary computer model. Sample results from various parts of the model are presented. Conclusions with regard to the strengths and weaknesses of simulations based on this model are discussed.

INTRODUCTION

The AH-64A Apache Advanced Attack Helicopter is an aircraft that was designed in the mid-to-late 1970's at a gross weight of approximately 14600 pounds. In the late 1980's and early 1990's, an upgraded version of the aircraft was developed, called the AH-64D Longbow Apache. The principal structural differences between the A-Model and the D Model are an upgraded engine, the extended forward

avionics bays (EFABs), and the mast-mounted assembly (MMA). In addition, a variety of new avionics equipment, pilot displays, and sensors were added, thus necessitating the MMA and EFABs. As a result of these improvements, the primary mission gross weight of the aircraft grew to approximately 17,200 pounds, and was estimated as high as 21,000 pounds in the ferry configuration. The increase in gross weight of between 18% and 44% indicated that it was necessary to look at a redesign of the rotor system, and particularly the rotor blades. An enhanced Apache with an invigorated performance (capable of restoring the original APACHE requirements) can require a wide range of aeromechanical and dynamics system improvements. The selection of the particular improvements to pursue will depend on cost and capability tradeoffs. In order to conduct these tradeoffs, a comprehensive model of the aircraft is required. Prior to the work described herein, two validated models of the Apache were in use. The first and oldest, is a model originally developed by Hughes Helicopter Company, and now maintained by Boeing-Mesa (formerly McDonnell Douglas). This model of the rotor systems is implemented using a proprietary computer program know as DART¹ (Dynamic Analysis Research Tool). The second model was also developed at Boeing-Mesa, and is implemented using CAMRAD/JA² (Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics/Johnson Aeronautics). While the DART models focus mainly on rotor dynamics, the CAMRAD/JA model is similar in scope to the present work. The development of newer analytical models of the Apache can be justified by the need for modeling of the multiple load paths in the rotor system which, in the case of the Apache includes both the main and tail rotors.

A detailed description of the model which has been developed would be beyond the scope of this

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short summary. The work will be presented, therefore, in two parts; the present paper will give an overview of the total model; and a companion paper by Kunz³ will present the details of the main rotor model only. This approach was adopted to provide a balanced introduction to the model. The capabilities of the model will be demonstrated by presenting results for a sampling of the computations. Conclusions with regard to the strengths and weaknesses of the simulation based on the model will be discussed.

COMPREHENSIVE ANALYSIS

The multidisciplinary nature of rotorcraft analysis has long been recognized and has led to the development of a class of computer analyses that attempt to resolve these complex interactions. These codes are generically referred to as comprehensive models. The most successful of these models is the CAMRAD⁴ series of computer codes which began with a government developed code. The CAMRAD code has been successfully developed into two advanced versions, the latest of which is called CAMRAD II⁵. CAMRAD II is an analysis of aeromechanical systems that incorporates a combination of advanced technology, including multibody dynamics, nonlinear finite elements, structural dynamics, and aerodynamics. It can be used for conceptual design, detailed design, and development. CAMRAD II calculates performance, loads, vibration, response, and stability with a consistent, balanced, yet high level of technology in a single computer program applicable to a wide range of problems, and a wide class of configurations. The use of comprehensive models allows for analysis of virtually the entire aircraft for at least a minimum level of detail. This depth and breadth of analysis capability is the reason these types of codes are used.

The development of an effective comprehensive model for a complex configuration such as the Apache is accomplished in three steps.

First, the acquisition of a data base and the translation of that data in to an appropriate format. Second, the refinement of the input data to accommodate shortcomings in the model and/or the extension of the data to "capture" advanced features (e.g. developing a multiple load path model) . The third step is to calibrate the model against experimental data, this includes adjustments in numerical approximations and can also include some modification of the aircraft description .

DATA BASE

Table 1 presents a summary of the data base source documents along with a brief comment on each source. As can be seen from the table, the data was obtained from a wide variety of sources. The primary source data is the ADS10B⁶, an Army document prepared by Boeing-Mesa. The ADS10B is a comprehensive description of the aircraft covering all of its major geometric, aerodynamic and structural features. Aside from the inevitable typographical errors inherent in the production of such a document, there are several more serious issues including the use of main rotor properties taken from previous computer models of the aircraft (e.g. CAMRAD/JA). Use of data from previous modeling efforts has the effect of propagating any errors in those models and of introducing errors caused by the limitations of the assumptions of the previous model. For example, the CAMRAD/JA model integrates blade properties using 51 equally-spaced blade stations independent of property input location. Frequently, the blade properties are averaged at various locations on the blade in order to produce a more accurate integral - hence data in CAMRAD/JA input files are frequently inaccurate in detail while giving accurate integrated properties. In addition, the tail rotor properties seem to be inconsistent: especially the mass properties. The tail rotor airfoil data is also not consistent with the specified airfoil.

Source	Content	Quality	Comment
Longbow Apache ADS-10B2 ⁶	Aircraft Description	Good	Rotor Data Issues
AH-64C/D Weight & Balance Status Report ⁷	Weight & Inertia	Good	
First Article Pre-production Tests of the AH64A Helicopter ⁸	Flight Performance Data	Very Good	High Quality "A" Model Data
NASTRAN Dynamics Model for AH-64D ⁹	Fuselage Structural Description	Fair	Needs Update for New Fuselage & More Modes
NASA TM SX-3543 ¹⁰	Fuselage Aerodynamics	Good	Reynolds Number
NASA TM SX-78763 ¹¹	Fuselage Aerodynamics	Good	Reynolds Number
Longbow Apache 1/7th Scale Model Wind Tunnel Test. ¹²	Fuselage Aerodynamics	Good	Reynolds Number
Structural Flight Demo - 1982 ¹³	Flight Loads Data	Fair	"A" Model Data
Operators Manual AH-64D ¹⁴	Mission Descriptions	Good	Useful Background
System Spec. for AH-64C ¹⁵	System Specification	Good	Useful Background
Longbow Performance & Range Substantiation Report ¹⁶	Range & Performance Data	Good	Useful Background

The other source documents are qualified in the table. Most of the issues relating to their use are due to the age of the document and the status of the aircraft system at the time of the document was produced. The NASTRAN model for instance is based on shake tests of the "A" model fuselage, the flight performance data was taken on the original aircraft, wind-tunnel data were taken on 1/7 scale models and/or isolated components giving rise to Reynolds number and interference effects issues.

Efforts have been made to correct as many of these issues as possible within the current model.

AERODYNAMICS MODEL

An aerodynamic model of the Apache was been generated using the data described above. The model consists of a complete description of the main and tail-rotor aerodynamics to including blade planform, airfoil, and twist characteristics. Rotor inflow modeling progresses from simple unified inflow models through complete enhanced free-wake inflow models. Fuselage Aerodynamics are modeled based on wind-tunnel derived data which describe the lift, drag and moment response of the total fuselage system.

Rotor Aerodynamic Model

Rotor aerodynamics are typically modeled by decomposing the full 3D problem into inner and outer problems which are iterated to obtain convergence. The inner problem is an airfoil at a

specified angle-of-attack and Mach number, and the outer problem is a lifting line bound vortex with a shed wake. Convergence is achieved by relating the bound circulation to the load produced by the airfoils distributed along the span of the rotor. The bound circulation is used to produce an inflow at the disc which defines airfoil angle-of-attack and hence the local load. Additional effects such as unsteady aerodynamics, radial drag, and dynamic stall are included as modification to the steady 2D airfoil response which is typically obtained from table look-ups based on experimental data. Critical to the success of these models are accurate airfoil data and a good method for computing inflow. Table 2 gives a summary of the rotor model features

Feature	Main Rotor	Tail Rotor
Radius	24 , ft.	4.58, ft.
Number of Blades	4	4
Mean Chord	1.75, ft.	.833, ft.
Twist	-9 ⁰	-8.8 ⁰
Aerodynamic Panels	25	6
Airfoil Sections	3	1
Sweep	20 ⁰ @ tip	None

Fuselage Aerodynamic Model

Fuselage aerodynamic modeling within the current model is relatively simple. The aerodynamic load is obtained via table look up or by the use of simple equations which describe the response of the system as a function of angle -of-attack and side-slip angle. Table 3 gives a summary of the current model. The LONGBOW MMA effects are included with the fuselage.

Property	Value	Source
Lift Curve Slope, L_{α}/q	3., ft^2	ADS10
Minimum Drag, D/q	33.51, ft^2	ADS10
Stall Drag, D/q	110., ft^2	ADS10
Induced Drag, D/L^2	.000001, ft^2	ADS10
Slope of Pitching Moment with Alpha, M_{α}/q	17., ft^3	ADS10
Slope of Side Force with Sideslip, Y_{β}/q	3., ft^3	ADS10
Slope of Roll with Sideslip, $N_{\gamma\beta}/q$	2., ft^3	ADS10
Slope of Yaw with Sideslip, $N_{z\beta}/q$	-20., ft^3	ADS10
Horizontal Tail Lift Slope, L_{α}/q	.060, ft^2	ADS10
Horizontal Tail Min. Drag, D/q	.02, ft^2	ADS10
Vertical Tail Lift Slope, L_{α}/q	.051, ft^2	ADS10
Vertical Tail Min Drag, D/q	.163, ft^2	ADS10

STRUCTURES MODEL

A structural dynamics model of the Apache has been generated. The model generated is as comprehensive as possible and consists of a complete description of the main- and tail-rotors to include blade properties (e.g. EI, GJ, mass, inertia, offsets) and hub and control system characteristics (e.g. mass, stiffness, inertia, kinematic couplings, dampers, tension-torsion straps). The effects of the LONGBOW radar mount has been included in the shaft dynamics and inertia modeling. The dynamic

properties of the airframe are represented by linear normal modes. A drive train model is also included.

Rotor Models

In order to make an analytical comparison of any new blade design to the existing design, it necessary to have a robust and reliable structural model of the existing blade. As mentioned above, two models of the Apache blade had been previously developed: one using the McDonnell Douglas (Boeing) proprietary code DART (Dynamic Analysis Research Tool), and the other using CAMRAD/JA (Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics/Johnson Aeronautics). Both models were developed and validated by McDonnell Douglas (Boeing). The objective of the current task was to develop a new model using the expanded capabilities of CAMRAD II. While CAMRAD II provides improvements in all of the modeling capabilities available with CAMRAD/JA, the principal improvement lies with the capability for modeling multiple load paths and the use of finite-element modeling of the structure. Both the main and tail rotor of the Apache have unique multiple load paths.

Main Rotor

The main rotor system is neither fully articulated, nor hingeless, nor bearingless. Instead, it contains features which are common to all three designs. For example, the rotor has a true lag hinge but no flapping hinge. Flapping is obtained through a system of elastic elements known as a strap pack. Pitch is introduced through a pitch housing that twists this same set of flexible members. As a result of the hybrid nature of the this system, accurate modeling of the kinematics is not a trivial task. Details of the main rotor model are presented by Kunz³ in the companion to this paper.

Tail Rotor

The tail rotor of the Apache consists of two teetering hubs of two blades each, a flexible drive fork and the necessary controls. Each pair of blades is of the teetering, semi-rigid, delta-three hinge type. The two hubs are mounted 55 degrees apart in azimuth. The tail rotor is controlled in pitch via pitch-links attached to a pitch bearing, longitudinal and lateral flapping are not controlled.

Traditional comprehensive codes (e.g. CAMRAD/JA), are incapable of modeling such a system. The fundamental assumption made in earlier models is that the blades are identical and equally spaced. Also no allowance is made for spacing

between multiple hubs. Figure 1 depicts the conventional tail rotor model and Figure 2 shows the more accurate dual-hub model.

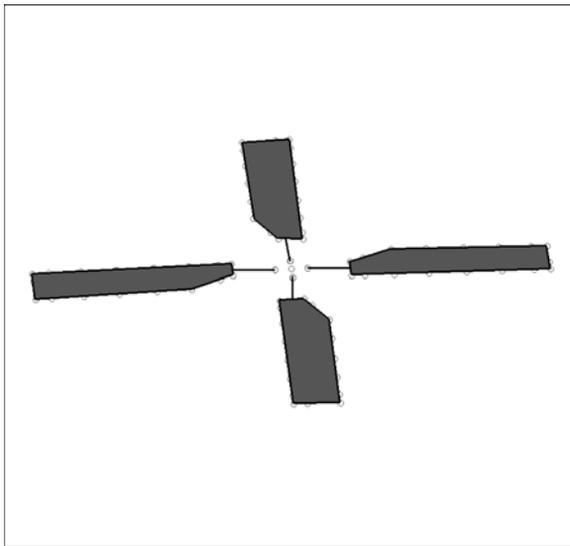


Figure 1. Conventional tail rotor model.

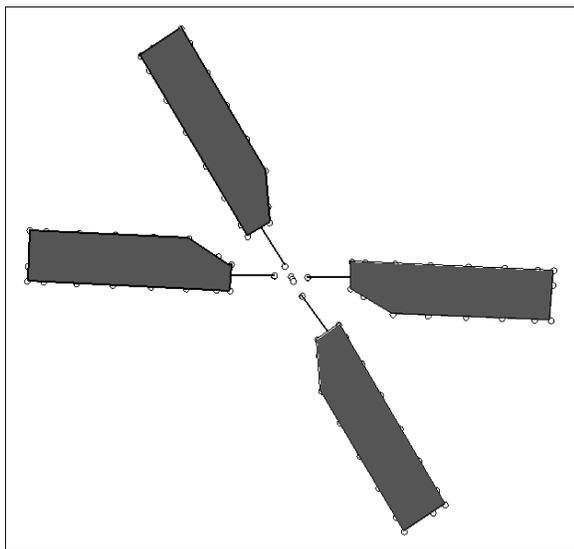


Figure 2. Dual-hub tail rotor model

Fuselage

The current fuselage structural model is composed of a modal model which was derived from a NASTRAN analysis. The modified airframe model includes 9 modes and 40 location the NASTRAN model is the AH-64A preliminary model, full armament configuration, developed by Mostafa Kia (Boeing). The modal analysis uses the Lanczos method. These analytical modes from NASTRAN

correlated fairly well with shake test data acquired from Boeing AH-64A model during the DAMVIBS program. These modes were used as the basis for a modal identification of the AH-64 LONGBOW NASTRAN model and the corresponding LONGBOW NASTRAN modes are used as input for the CAMRAD II model, (note that the modes used in the old CAMRAD/JA model are taken from experimental test data). The experimental values used for the generalized mass and the structural damping in the old model were also used for the modified model. The frequencies are NASTRAN computed values which are very close to the experimental values. Table 4 lists the 9 modes used in the model along with the fuselage response from which they were extracted. Table 5 presents a list of the major node locations. Numerical experimentation using this model indicates that further work is needed. In particular, a larger number of CAMRAD modes needs to be developed in order to capture any significant fuselage vibrations.

CAMRAD Mode	NASTRAN Mode	A/C Location
1	20	tail boom torsion
2	22	first vertical bending
3	28	first lateral bending
4	32	vertical stabilizer long. bending
5	36	longitudinal m/r mast bending
6	37	lateral m/r mast bending
7	38	symmetric wing bending
8	39	anti-symmetric wing bending
9	52	stabilator yaw

Main Rotor	Forward Landing Gear
Main Rotor Shaft	HellFire Racks
TADS	Wing Leading Edge
Chain Gun	Wing Trailing Edge
Pilot	Pylon Lower End
CoPilot	DASE
Pilot Seat	Fuselage
CoPilot Seat	Horizontal Tail
Vertical Tail	MMA

EXAMPLE COMPUTATIONS

The combined structural and aerodynamic models described above provide a detailed description of the flight vehicle. These models may be used to conduct studies of flight vehicle loads and performance. Use of a modern comprehensive analysis such as CAMRAD II involves the selection of dozens of options in the execution of a particular run. The judicious use of such a complex model requires a careful selection of modeling options with the twin goals of minimizing complexity and ensuring an accurate prediction. A common mistake is to make use of the complete model for even the simplest applications. While it is true that modern comprehensive models allow for the study of very detailed aspects of the aircraft response, the successful employment of such detailed options is by no means simple. Rotor loads along the complete load path may be computed - but the price for this is that the complete load path must be modeled. We can, for example, compute the load in the main rotor pitch-link as a function of aircraft speed - but it is not necessary to do this in order to predict aircraft performance. A more practical approach is to select the minimum level of complexity required to perform a particular computation. A complete examination of all the possible permutations of the model at hand would be beyond the scope of this paper; instead, a selection of computations will be presented. Three examples have been chosen: aircraft performance prediction, transient flight loads and tail rotor aerodynamics and loads. Each of these examples is meant to illustrate a feature of the model ranging from simple to complex applications.

Performance Predictions

Basic performance predictions of the Apache have been made using the current model. Figures 3-6 are sample performance computations for the "A" model compared to flight test data. Performance prediction is an example of a relatively simple application of the model. The goal of this computation is to predict the total aircraft power required as a function of aircraft speed. The performance prediction model employed, used simple uniform inflow (except for the hover calculation), rigid blades, and simple controls. Total power is the summation of main rotor and tail rotor power plus a correction for auxiliary power, IR suppression, and

transmission losses. For this simple example, total losses were estimated using a 8% increase in predicted power. Hover performance predictions also includes a 7% download correction.

Figure 3 presents the predicted results for aircraft hover performance along with flight test data. Prediction of performance for rotors in hover is heavily dependent on accurate induced velocity calculation. For this reason, the full free-wake model was used for the hover prediction. The correlation shown is reasonably good.

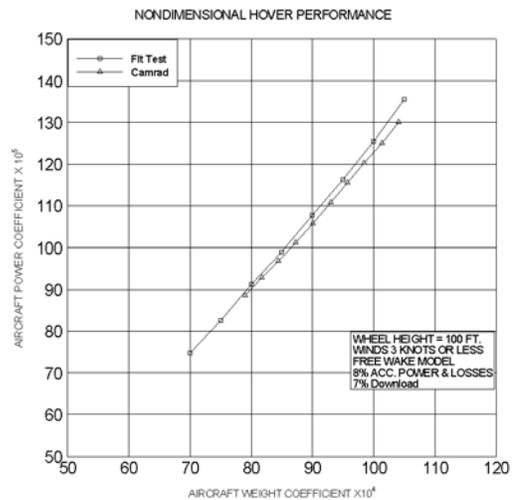


Figure 3. Predicted hover performance compared to flight test.

Figures 4-6 present predicted forward flight results for the aircraft at different gross weights and altitude. The correlation is generally good except at higher speed, indicating possible problems with the aircraft drag model and/or attitude trim. Drag and trim modeling assumptions can always be "adjusted" to force a calibration for a particular configuration/condition. The current modeling choices were deemed to give the best overall results.

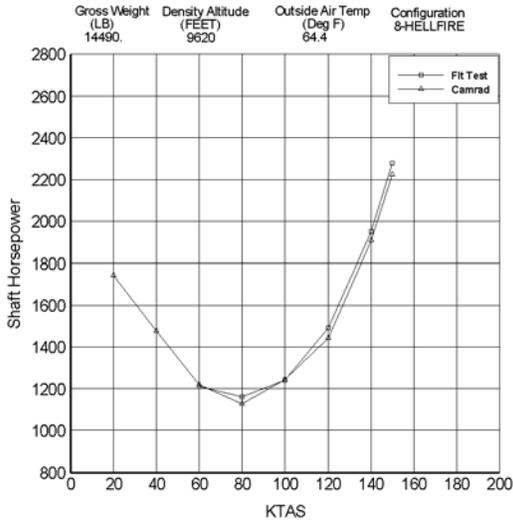


Figure 4. Predicted forward flight power required compared to flight test measurement, (low gross weight).

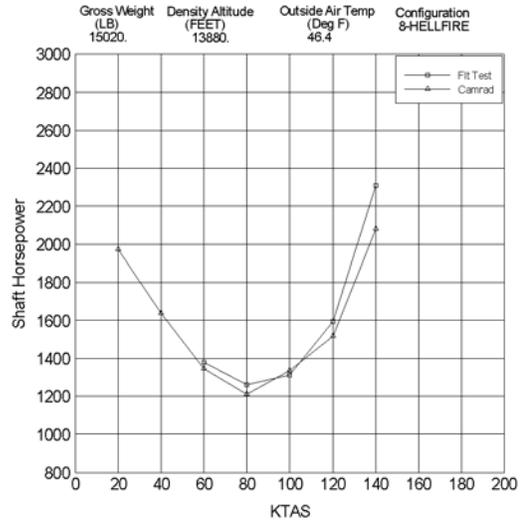


Figure 6. Predicted forward flight power required compared to flight test measurement (high altitude).

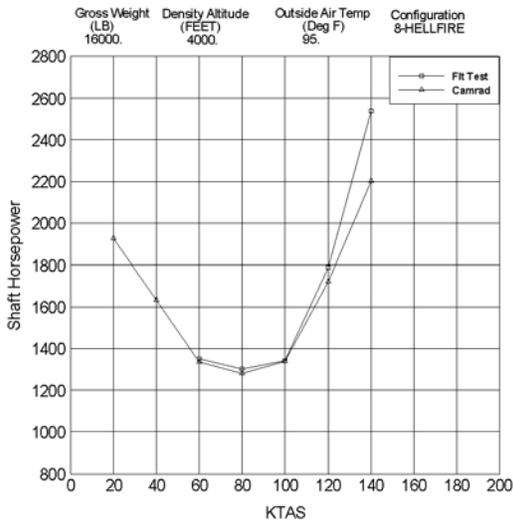


Figure 5. Predicted forward flight power required compared to flight test measurement (high gross weight).

Transient Flight Loads & Response

A maneuver condition was computed using the transient flight option available in the model. It is useful to differentiate between two general categories of maneuvering flight: 1) steady maneuver (e.g., a coordinated turn; and 2) transient maneuvers (e.g., entering or exiting a turn).

Steady maneuvers are closer to the linear, constant velocity flight that is routinely analyzed (e.g. the performance prediction above). To study steady maneuvers, we need to account for the acceleration of the aircraft (due to a change in aircraft velocity or to a change in flight direction) and the change in rotor trim state. A typical example would be a coordinated turn which can easily be modeled in CAMRAD II by specifying a turn rate.

Transient maneuvers are more complex—both the motion and the loading are not periodic. Thus, the fundamental assumption of periodicity, made in the simpler model is invalid. A periodic analysis is appropriate for steady maneuvers but cannot describe transient maneuvers.

For a vehicle in a transient maneuver, the solution algorithm is modified to become a time stepping method. The forces and moments are integrated to obtain the response at each time step due to specified control input. A solution set from a previous trim is used to initiate the problem. For the present application, there are three things to note about this approach. First, since the solution is no longer periodic, it may be necessary to treat each blade as a separate component. Second, the solution requires

that the control settings are specified a priori. Third, the procedure does not routinely include a sub-iteration mechanism to stabilize the numerical integration—a shortcoming that leads to the accumulation of round-off and convergence errors that may eventually destroy a computation which is allowed to run too long. The transient used in the current example problem was chosen to be short in duration (~2 sec) and hence avoided an accumulation of time-integration error.

The maneuver chosen for the current example is a relatively simple event which we call an arrested descent. Put simply, the aircraft is "trimmed" in a 3° decent condition, after which a 6° collective pulse is applied. The configuration is a 16000 lb gross weight, 80 KTAS, 9 elastic beams, simple controls, dynamic inflow wake model.

Figure 7 shows the time history of the pulse, with "time" measured in azimuth displacement. Figure 8 shows the vertical displacement of the aircraft during the 2 seconds of the event.

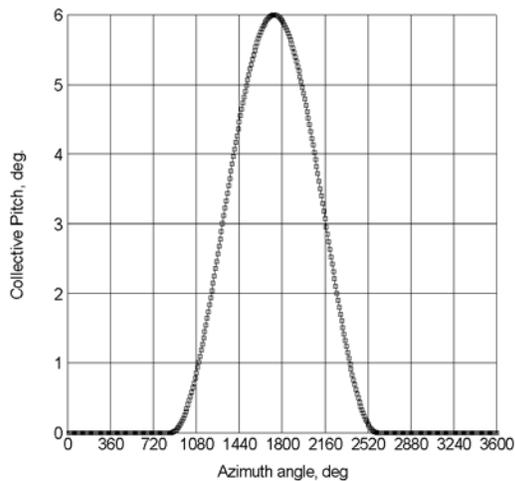


Figure 7. Specified main rotor collective control input vs. time for the arrested descent maneuver.

Figure 9 presents the blade flapping response, while figure 10 gives the blade loading at $r/R = .7625$, both plotted vs. azimuth. Both figures 9 and 10 show the response of each blades to the control input as an individual trace. As can be seen from the figures, each blade has its own unique time-history response to the control input. The transient response example demonstrates a computation which while available in earlier methods, is considerably easier to implement with the enhanced modeling features of

the CAMRAD II code. The ability to track individual blade behavior is particularly useful.

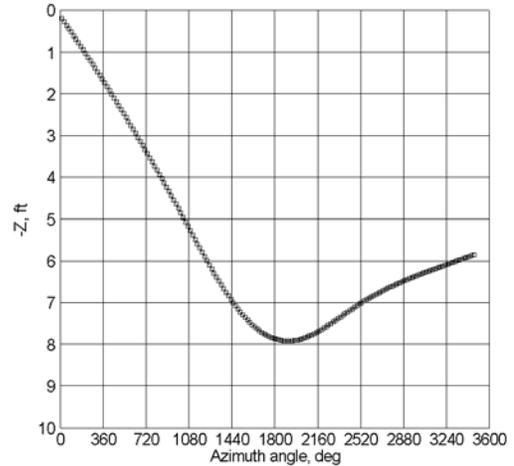


Figure 8. Aircraft vertical location vs. time during transient control input.

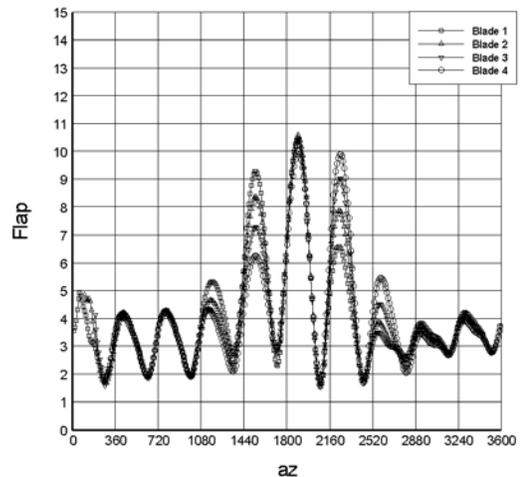


Figure 9. Blade flapping response during an arrested decent maneuver.

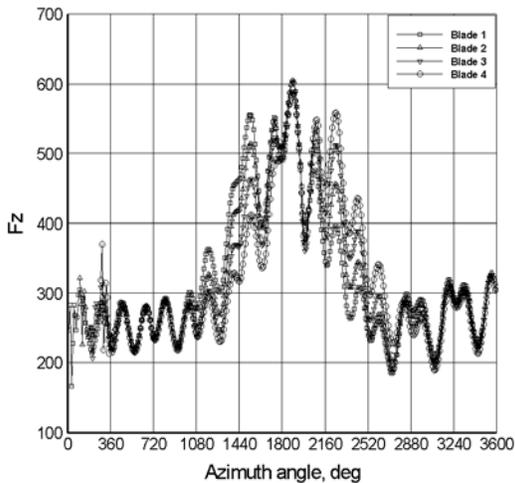


Figure 10. Main rotor normal loads at $r/R = .7625$ during an arrested decent maneuver.

Tail Rotor Response

The final example is a prediction of tail rotor loads and performance. As a point of interest, these computations were made using the two distinct tail rotor models described above. Figures 11 and 12 display results for a typical forward flight speed sweep. The aircraft configuration/condition is the same as that used for the maneuver case discussed above, however, for these computations the free-wake model was used. Figures 13 through 16 show rotor blade average angle-of-attack and root loads vs. azimuth for the 80 knot trim condition.

Figure 11 shows the tail rotor thrust required vs. speed. As might be expected, the tail rotor thrust is essentially the same for both configurations. This is true because tail rotor thrust is driven by main rotor torque and any rotor configuration will be required to deliver the same thrust. Figure 12 shows the power required for each configuration, and a distinct difference between each rotor model. A clue to the difference can be found in figures 13-14. Figure 13 shows average angle-of-attack for the conventional model. As can be seen in the figure, alpha on each blade is identical as a function of azimuth. Figure 14 shows the same results for the dual-hub model. As can be seen from the figure, the predicted alpha is split between two different patterns depending on which hub the individual blades are attached to. Blades 1 & 3 are on the "upper" hub and blades 2 and 4 are on the "lower" hub. The aerodynamic environment for each hub is different. Note also, that

the angle-of-attack for the conventional model is generally higher than for the dual-hub model. Generally speaking, airfoil efficiency is proportional to angle-of-attack (until stall) - hence the conventional rotor model would be expected to have lower power requirements.

Figures 15 and 16 show blade root load for both the models. Once again, the dual-hub model shows a different response pattern for each "hub-set", while the conventional model shows a repetitive load history.

As a final point figure 17 shows the difference in load experienced by blade 1 for each model. Notice the significantly lower loads for the dual hub model. The reduction in load is due to the fact that each hub in the dual hub model has only 2 blades attached (figure 2) while the conventional model has four blades attached to the hub (figure 1) - hence the reduction in load.

These tail rotor response results are a good example of an application which cannot be conducted with anything except a system such as CAMRAD II.

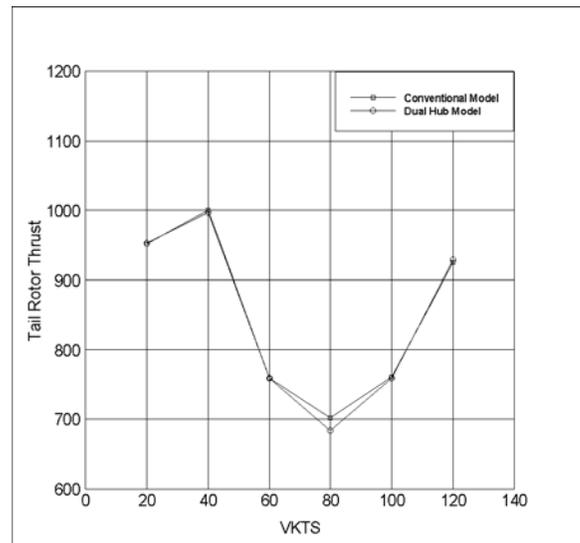


Figure 11. Comparison of tail rotor thrust vs. speed for both conventional and dual-hub model.

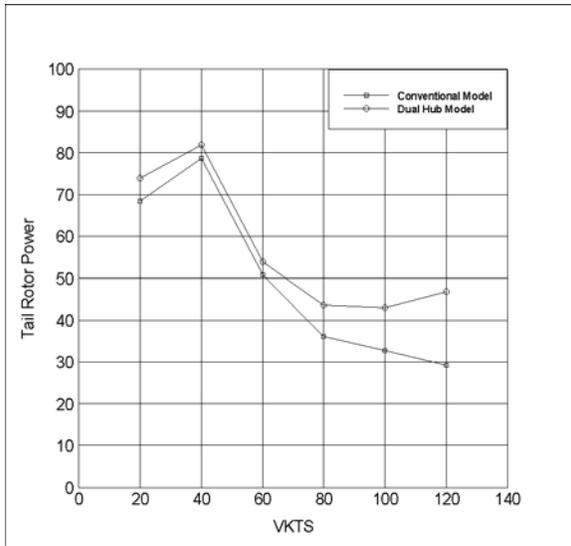


Figure 12. Comparison of tail rotor power vs. speed for conventional and dual-hub model

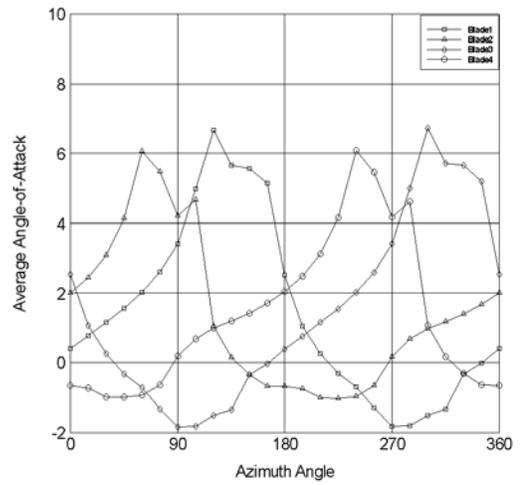


Figure 14. Average blade angle-of-attack vs. azimuth for dual-hub model.

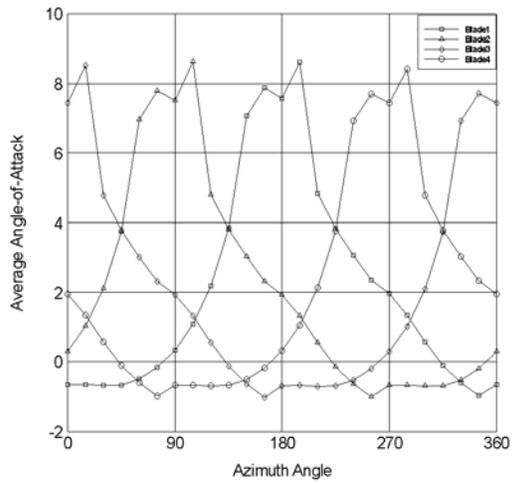


Figure 13. Average blade angle-of-attack vs. azimuth for conventional tail model

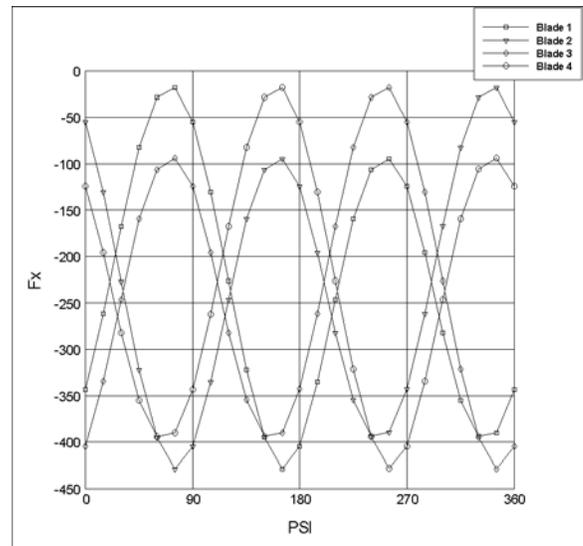


Figure 15. Chord wise root load on conventional tail rotor model for all blades

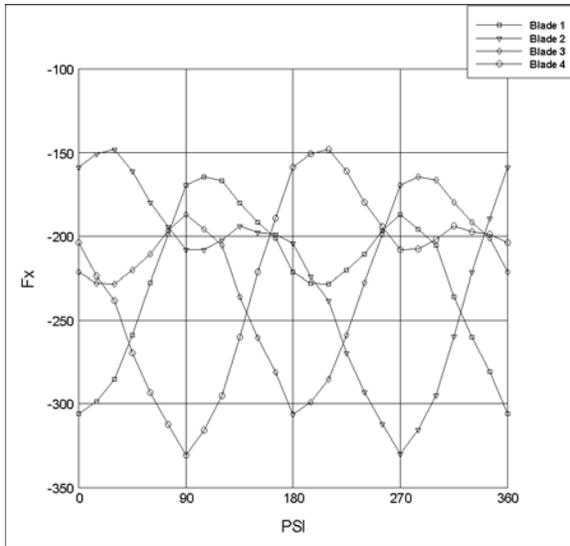


Figure 16. Chord wise root load on dual-hub tail rotor model for all blades

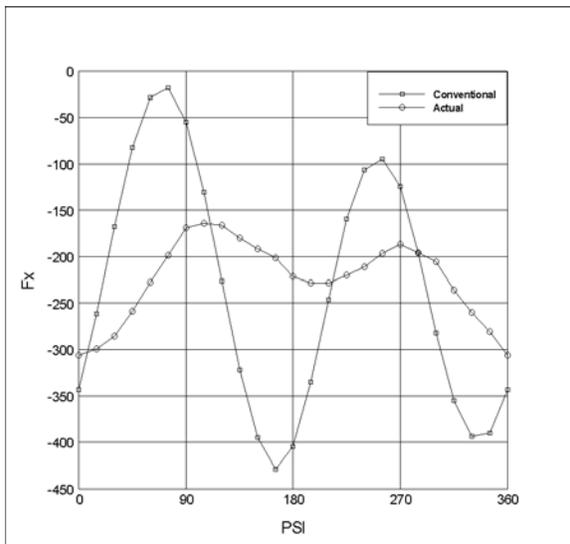


Figure 17. Comparison of predicted chord wise load on blade 1 for conventional and dual-hub models.

CONCLUDING REMARKS

A comprehensive analytical model of the Apache aircraft has been developed using the CAMRAD II computer system. As a part of the development effort, a review of the data base available was completed. Extensive use was made of the capability of CAMRAD II to model multiple load path structures, particularly with regard to the main and tail rotor structural models. Results have been presented for a selection of problems. The following observations can now be made:

1. The data base for the aircraft is extensive and generally good, however, some details need some correction-particularly details of the rotor models.
2. Numerical experimentation using the fuselage structural model indicates that a larger number of CAMRAD modes needs to be developed in order to capture any significant fuselage vibrations.
3. Basic performance predictions compare well with flight test data.
4. The transient flight analysis works well and has proven to be relatively easy to implement.
5. A dual-hub tail rotor model has been developed and has yielded unique results.

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