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Rotor and Control System Loads Analysis of the XV-15 With the Advanced Technology Blades

Joseph J. Totah and John F. Madden, III

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ROTOR AND CONTROL SYSTEM LOADS ANALYSIS OF THE XV-15 WITH THE ADVANCED TECHNOLOGY BLADES

Joseph J. Totah and John F. Madden, III
NASA Ames Research Center
Moffett Field, California 94035

ABSTRACT

An analysis of the rotor and control system loads of the XV-15 with the Advanced Technology Blades (XV-15/ATB) was conducted to investigate the effects of modifications designed to alleviate high collective actuator loads encountered during initial flight tests. Rotor loads predictions were correlated with flight data to establish accuracies of the methodology used in the analysis. Control system loads predictions were then examined and were also correlated with flight data. The results showed a significant reduction in 3/rev collective actuator loads of the XV-15/ATB when the control system stiffness was increased and the rotor blade chord balance and tip twist were modified.

INTRODUCTION

Development of the XV-15 Tiltrotor Research Aircraft began in 1973 and by 1979 two XV-15 aircraft had been built. The XV-15 aircraft shown in Figure 1 had steel rotor blades designed for a flight envelope that extended out to approximately 300 knots in airplane mode at 16000 feet. The primary objective of the XV-15 program was the proof-of-concept flight demonstration of the tiltrotor aircraft. This was to be accomplished by addressing deficiencies discovered during the Army/Air Force/NASA XV-3 Aircraft Program (1951-1966), which included power and drag limitations, rotor and rotor/nacelle/wing instabilities, and stability and control.

In the early 80's an interest in greater hover performance and improved stall margins became the focus of a program to develop new rotor blades for the XV-15. These blades were designed and fabricated by Boeing Vertol using composite material technologies to achieve highly complex blade contours and structure without sacrificing strength. They are referred to as the Advanced Technology Blades (ATBs), a schematic of which is depicted in Figure 2. The primary design objectives of the ATBs were to improve hover performance as well as expand the flight envelope. The ATBs have provisions for a limited chordwise balance adjustment within the tip weight fitting and the tip shell aerodynamic contour can be changed, as well.

Initial flight tests (1988) of the XV-15/ATB in helicopter mode forward flight at speeds of up to 60 knots revealed high control system loads with a large 3/rev content. The high loads were determined to be caused by a control system 3/rev structural resonance which was excited by the large blade feathering inertia. The feathering inertia of the ATB was 0.42 slug-ft^2, more than double that of the steel blades. The collective actuator was the "weak link" in the control system and was experiencing over three times the experimentally

*Presented at the American Helicopter Society National Technical Specialists' Meeting on Innovations in Rotorcraft Test Technologies for the 90's, Scottsdale, Arizona, October 1990.

determined endurance limit at a helicopter mode forward speed of 60 knots.

In the ensuing months a variety of activities took place, the most important of which were a series of static and dynamic hanger tests to measure the control system stiffnesses, dynamic characteristics, and cross-coupling effects. The measurements revealed a collective/cyclic cross-coupling due to deformations of the inner gimbal ring which is used for lateral flapping alleviation. Aluminum shims were subsequently placed between the inner gimbal ring and the lateral flapping stops during these tests and the results showed a 50% increase in control system stiffness. These shims have been flown on an experimental basis and have allowed additional loads reduction tests to be undertaken, such as chord balance and tip twist modifications of the ATBs. The primary analysis used to generate rotor and control system loads predictions was the Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics, Johnson Aeronautics Version (CAMRAD/JA)[1].

This report documents the findings of an analysis of the XV-15/ATB aircraft flown in 1988 that initially experienced resonance and resulting high loads, as well as the XV-15/ATB subsequently flown with the shims and rotor blade chord balance and tip twist modifications. Flight data show significant loads reductions of the XV-15/ATB collective actuator with the control system shims and rotor blade chord balance and tip twist modifications at helicopter mode forward flight speeds of up to 80 knots, as predicted by CAMRAD/JA.

CONFIGURATIONS

Three XV-15/ATB configurations were examined in this report, and they are labelled as follows: 1) the Baseline Configuration; 2) the Shimmed Configuration; and 3) the Shimmed T Configuration.

The Baseline Configuration is simply the XV-15 with the ATBs installed as originally flown in 1988. The blades were installed with 1^{o} of sweep and the blade twist varied from 27.5^{o} at 17%R to -8.8^{o} at 100%R.

The Shimmed Configuration is a modified version of the Baseline Configuration in which aluminum shims were installed to reduce the control system coupling caused by flexing of the inner gimbal ring, as depicted in Figure 3. These shims were placed between the "soft" inner gimbal ring and lateral cyclic stops on the transmission resulting in a load path bypass of the inner gimbal. The effect was a 50% increase in the control system stiffness.

The Shimmed T Configuration is a modified version of the Shimmed Configuration in which 20 track and balance weights were used to move the chordwise balance forward at the blade tip and in which the rotor blade tip used in 1988 was replaced with a cover that had constant twist between 86.5% R and 100% R. The track and balance weights and modified tip twist essentially changed the blade mass, polar radius of gyration about the elastic axis, CG offset, and twist distribution of the ATBs, as depicted in Figure 4.

Rotor and control system loads predictions were generated for each of these configurations and correlated with flight data. Helicopter mode, steady state forward flight conditions were the only conditions considered in this study for all three configurations.

CAMRAD/JA MODEL

CAMRAD/JA was the primary analysis used to predict rotor and control system loads of the XV-15/ATB for all three configurations. CAMRAD/JA is an extended version of CAMRAD[2] and was released in 1989. CAMRAD/JA was modified to model collective, longitudinal cyclic, and lateral cyclic coupling due to control system structural flexibility. The control system model used in the modified version of CAMRAD/JA was based on experimentally determined control system stiffnesses and cross-coupling of the inner gimbal ring measured during hangar tests in 1988. The relationships which define the inputs to the model are as follows:

Baseline Configuration:

$$\begin{bmatrix}\Theta_0\\ \Theta_{1C}\\ \Theta_{1S}\end{bmatrix} = \frac{\begin{bmatrix}6.5890 & -1.0937 & -1.0937\\ -1.9627 & 6.8167 - \Theta_{75}/20 & 0\\ -1.9627 & 0 & 7.0518 - \Theta_{75}/20\end{bmatrix}}{1.1\mathrm{x}10^5 \cos(\Theta_{75}-19.6)^2 \text{ ft-lb/rad}} \begin{bmatrix}M_0\\ M_{1C}\\ M_{1S}\end{bmatrix}$$

Shimmed and Shimmed T Configurations:

$$\begin{bmatrix}\Theta_0\\ \Theta_{1C}\\ \Theta_{1S}\end{bmatrix} = \frac{\begin{bmatrix}4.4710 & -0.1126 & -0.1126\\ 0 & 5.7208 - \Theta_{75}/20 & 0\\ 0 & 0 & 5.9560 - \Theta_{75}/20\end{bmatrix}}{1.1\mathrm{x}10^5 \cos(\Theta_{75}-19.6)^2 \text{ ft-lb/rad}} \begin{bmatrix}M_0\\ M_{1C}\\ M_{1S}\end{bmatrix}$$

where: Θ_0 collective pitch angle, rad

Θ_{1C} lateral cyclic pitch angle, rad

Θ_{1S} longitudinal cyclic pitch angle, rad

Θ_{75} rotor blade twist at 75%R, deg

M_0 moment associated with Θ_0, ft lb

M_{1C} moment associated with Θ_{1C}, ft lb

M_{1S} moment associated with Θ_{1S}, ft lb

There are three levels of complexity available in CAMRAD/JA, as follows: 1) Uniform Inflow Analysis; 2) Prescribed Wake Analysis; and 3) Free Wake Analysis. The uniform inflow analysis exposes the rotor blade to an aerodynamic environment based on momentum theory and is used primarily for axial flow applications. The prescribed wake analysis models a rigid wake geometry used primarily in hover and high helicopter mode forward speeds for advance ratios in excess of 0.25. The free wake analysis models a wake geometry that is distorted by the encounter of the rotors and the environment in which it is exposed and is used in helicopter mode forward flight for advance ratios between 0.05 and 0.25. There are several tasks that CAMRAD/JA can perform, such as flutter, flight dynamics/stability, transients, and loads. However, only the trim and loads tasks were utilized.

There are several new and improved features in CAMRAD/JA relative to its predecessor, the most noteworthy of which are the dual circulation peak and three-quarter chord collocation point options that search for negative aerodynamic loading and adjust the sense and strength of the tip vortex appropriately. These options are important when modelling highly twisted blades such as the ATBs in a prescribed or free wake environment since negative loading on a portion of the disk may be present anywhere in the flight envelope. One important CAMRAD/JA input option for the prescribed or free wake analyses is tip vortex core size. This parameter was varied within recommended bounds and will be discussed later. Additionally, two types of loads analysis options are available and they are identified in CAMRAD/JA as the Integrated Forces Method and the Curvature Method for calculating rotor blade bending moments. Both methods were compared for the Baseline Configuration, the results of which will be discussed later, as well.

CAMRAD/JA also allows the researcher flexibility in adjusting simulation specific parameters for efficiency and accuracy. These parameters include trim, motion, and circulation tolerances, the number of rotor, engine, and airframe degrees-of-freedom, the number of rotor harmonics, and the number of bending and torsion mode collocation functions. These parameters were varied (e.g. the tolerances were decreased and the number of degrees-of-freedom, harmonics, and collocation functions were increased) until the results did not vary when trimmed using slightly different initial conditions. This was, in effect, equivalent to desensitizing the analysis to simulation specific parameters. As a result, accuracy was increased with an acceptable decrease in efficiency. However, recursive updating of the trim derivative matrix and extremely low relaxation factors (on the order of 0.05) for introducing lags in thrust and bound circulation used to calculate induced velocity were necessary to achieve convergence.

TEST MATRIX

The test matrix used for this study was limited to helicopter mode forward flight for all three configurations. The analysis of the rotor consisted of a comparison of blade normal and edgewise bending moment predictions with flight data at four radial locations: 6%R, 20%R, 69%R, and 84%R. The control system analysis consisted of a comparison of half-peak-to-peak pitch link loads and 3/rev collective actuator loads predictions with flight data. The flight data and analysis test points are given in Table 1.

Table 1. Flight Data and Analysis Test Points

Configuration	35 kts	40 kts	60 kts	80 kts
Flight Data:				
Baseline	X		X	
Shimmed	X			
Shimmed T		X	X	X
Analysis:*				
Baseline	X		X	X
Shimmed	X		X	X
Shimmed T		X	X	X

*All predictions were generated at 571 RPM

The analysis of the Baseline Configuration and the Shimmed Configuration extend out to 80 knots even though no flight data were gathered at those speeds. This is so comparisons of predictions with the Shimmed T Configuration could be illustrated.

RESULTS

The Baseline Configuration was used to assess the effect of various modelling options under consideration. The first modelling options of interest were the analysis levels. A comparison of the uniform inflow analysis, prescribed wake analysis, and free wake analysis for normal bending moment is depicted in Figure 5. It can be seen that the free wake analysis correlates better than either the prescribed wake analysis or the uniform inflow analysis.

Other modelling options considered were the loads calculation methods. A comparison of the integrated forces method and the curvature method for calculating rotor blade edgewise bending moments is depicted in Figure 6 using the free wake analysis. It can be seen that the integrated forces method correlates better than the curvature method. This may suggest large aerodynamic loads relative to blade inertial loads, since the integrated forces method tends not to work well when there is a more equal balance of the two, as suggested by Johnson[3].

The last modelling options considered were the tip vortex core sizes. A comparison of large and small tip vortex core sizes is depicted in Figure 7 using the free wake analysis and the integrated forces method. Differences can be noted but do not appear to be significant. However, convergence of the CAMRAD/JA circulation iteration when trimming was more easily attainable when using large tip vortex core sizes.

Based on these results, the modelling options chosen to analyze each configuration were as follows: 1) free wake analysis; 2) integrated forces method for calculating blade bending moments; and 3) large tip vortex core sizes.

Comparisons of blade normal bending moment predictions with flight data are depicted in Figure 8 as a function of blade radial location and azimuth for the Baseline Configuration at a forward speed of 60 knots (the highest speed at which flight data is available for that configuration). Correlation at 6%R has a steady offset and phase difference of approximately 2000 ft-lb and 15°, respectively. Flight data is shifted ahead of the prediction for that condition as is more easily seen with the mean values removed. Correlation at 20%R is poor. Flight data also suggests the largest normal bending moment is at 20%R whereas CAMRAD/JA shows it to be at 6%R. Normal bending moment correlations at 69%R and 84%R are significantly better with no apparent offsets and the same 15 degree phase shift noted previously. Edgewise bending moment correlations are depicted in Figure 9. Closest agreement is at 20%R and the flight data suggests the smallest edgewise bending moment is at 84%R whereas CAMRAD/JA shows it to be at 69%R. Normal and edgewise bending moment half peak-to-peak amplitudes appear to be lower than flight data in all instances except for normal bending at 6%R.

Normal and edgewise bending moment correlations are depicted in Figure 10 and Figure 11, respectively, for the Shimmed Configuration at a forward speed of 35 knots (the highest speed at which flight data is available for that configuration). The results are much the same as the Baseline Configuration with the exception that the normal bending moment prediction at 84%R shows a lower half peak-to-peak amplitude than flight data suggests.

Normal and edgewise bending moment correlations are depicted in Figure 12 and Figure 13, respectively, for the Shimmed T Configuration at a forward speed of 80 knots (the highest speed at which flight data is available for that configuration). The results are much the same as the Shimmed Configuration with the exception that flight data now suggests the largest normal bending moment to be at 6%R and that appears to correlate well with CAMRAD/JA predictions.

There are many possible explanations for the conditions in Figures 8 through 13 in which predictions and flight data do not compare well. Some explanations focus on the methodology used in the calculation of blade bending moments and others focus on modelling complex flowfield and aerodynamic phenomena, such as stall[4,5]. The former is discussed in more detail by Maier[6], however, the latter is subject only to speculation because of the absence of airloads data on this particular rotor system. Johnson[7] recognized the need for accurate and reliable airloads data for high speed flight in his attempts to validate advanced aerodynamic theories with existing airloads data sets for helicopters. The same can be said for complex, highly twisted rotors subjected to high disk-loading environments.

A comparison of CAMRAD/JA analysis levels in predicting half-peak-to-peak pitch link loads for the Baseline Configuration is depicted in Figure 14. The free wake analysis predicts pitch link loads better than the prescribed wake analysis and uniform inflow analysis. Figure 15 shows a comparison of free wake analysis predictions and flight data of half-peak-to-peak pitch link loads for all three configurations. Flight data for the Baseline Configuration show pitch link loads increasing slightly with airspeed from roughly 300 lb at 35 knots to nearly 400 lb at 60 knots. Predictions are roughly 50% below flight data for this configuration but reflect a similar increase in pitch link loads as a function of airspeed. Flight data for the Shimmed Configuration show pitch link loads between 200 lb and 250 lb at 35 knots and predictions are roughly 30% below flight data at that speed. Pitch link loads predictions remain relatively constant at 145 lb as a function of airspeed for this configuration. Flight data for the Shimmed T Configuration show pitch link loads lower than the Shimmed Configuration but increasing with airspeed from roughly 200 lb at 40 knots to 300 lb at 80 knots. Predictions are well below flight data for this configuration, yet reflect a similar increase in pitch link loads as a function of airspeed.

A comparison of the CAMRAD/JA analysis levels in predicting 3/rev collective actuator loads for the Baseline Configuration is depicted in Figure 16. The free wake analysis predicts pitch link loads better than the prescribed wake analysis and uniform inflow analysis. The apparent trend as load varies with airspeed is also well captured by the free wake analysis. Figure 17 depicts a comparison of free wake analysis predictions and flight data of 3/rev collective actuator loads for all three configurations. Flight data for the Baseline Configuration show these loads increasing with airspeed from roughly 900 lb at 35 knots to 1100 lb at 60 knots. Predictions improve with airspeed from 33% below flight data at 35 knots to roughly 10% below flight data at 60 knots for this configuration. Flight data for the Shimmed Configuration show the 3/rev collective actuator loads between 350 lb and 400 lb at 35 knots and predictions are roughly 10% above flight data at that speed. Predictions increase from 400 lb at 35 knots to roughly 600 lb at 80 knots. Flight data for the Shimmed T Configuration show these loads slightly lower than the Shimmed Configuration and remaining relatively constant with airspeed near the experimentally determined endurance limit of the collective actuator (317 lb). Predictions are roughly 25% below flight data for this configuration. Figure 18 depicts the relative magnitudes of the 3/rev collective actuator loads for each configuration at low forward speeds (35 knots for the Baseline and Shimmed Configurations and 40 knots for the Shimmed T Configuration). This was the only condition at which flight data was available for all three configurations.

CONCLUDING REMARKS

An extensive analytical investigation of rotor and control system loads of three different XV-15/ATB configurations was conducted using a modified version of CAMRAD/JA and the results were compared with flight data at helicopter mode forward speeds of up to 80 knots. The modification to CAMRAD/JA consisted of the introduction of collective/cyclic coupling due to control system flexibility. CAMRAD/JA predictions for all three XV-15/ATB configurations were generated using the free wake, dual circulation peak, three-quarter chord collocation point options with large tip vortex core sizes and the integrated forces method to calculate blade bending moments. These options established improved accuracies of the methodology used in this investigation.

The results of this study showed the following:

1. Rotor blade normal bending moments were generally well predicted at the tip but reflected a steady offset at the root for the Baseline and Shimmed Configurations. Discrepancies existed in the prediction of the location of the largest normal bending moment for those configurations and the smallest edgewise bending moment for all configurations. The half peak-to-peak amplitude of the blade normal and edgewise bending moments for all configurations are generally underpredicted by CAMRAD/JA except for normal bending at the root.

2. The predicted half peak-to-peak pitch link loads trends compared favorably with flight data when varied with airspeed and aircraft configuration, however, the levels were underpredicted. Results showed increasing pitch link loads with airspeed and respectively decreasing loads for the Baseline, Shimmed, and the Shimmed T Configurations.

3. The 3/rev collective actuator loads for the Shimmed Configuration were significantly reduced from levels experienced by the Baseline Configuration and further reduced to levels at the targeted endurance limit for the Shimmed T Configuration. CAMRAD/JA adequately predicted the magnitude of the 3/rev collective actuator loads for all three configurations as well as the trends of the loads with airspeed and aircraft configuration.

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[2]Johnson, W., "A Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics; Part I," NASA TM 81182, June 1980.

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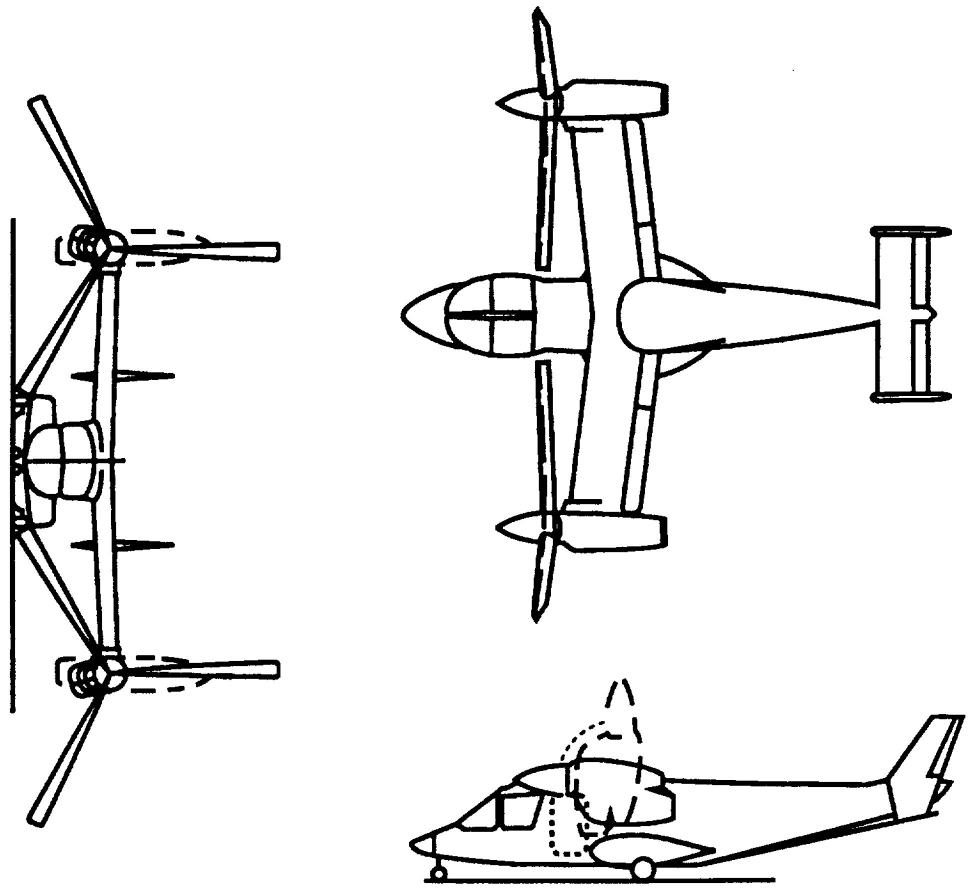

Figure 1. XV-15 Tiltrotor research aircraft.

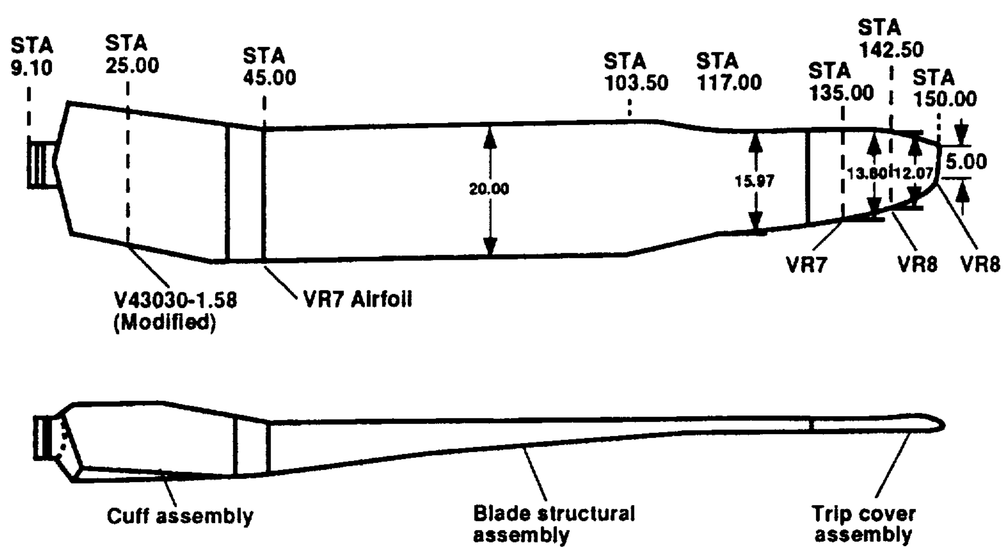

Figure 2. Advanced technology blade.

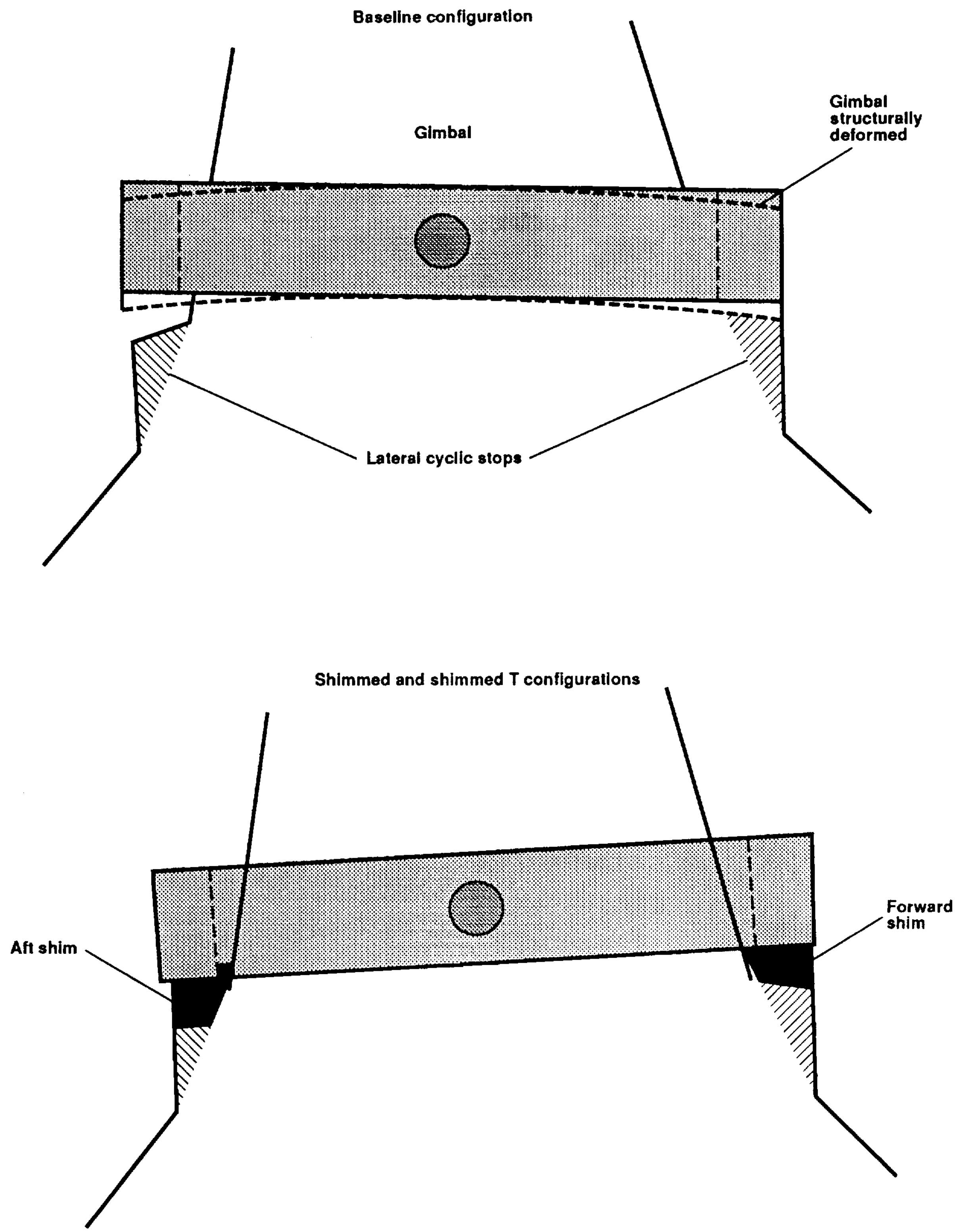

Figure 3. Control system configurations.

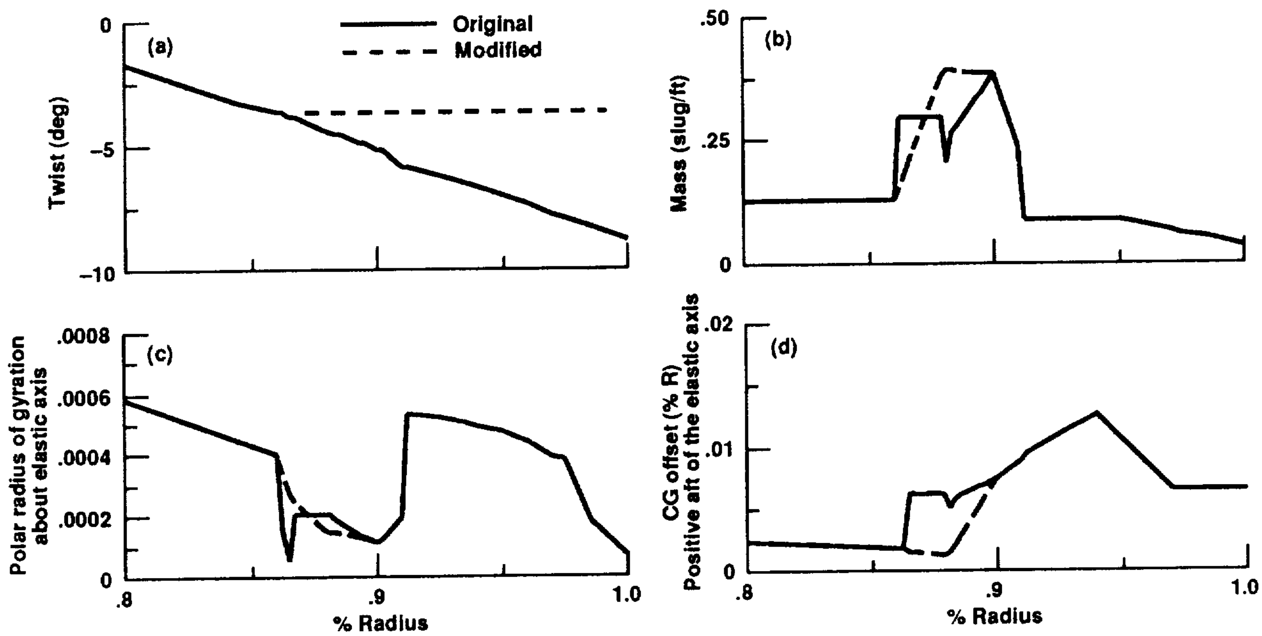

Figure 4. Modified ATB characteristics for the shimmed T configuration.

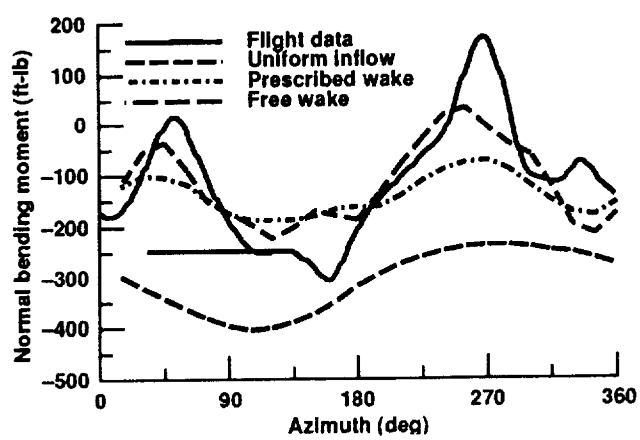

Figure 5. Comparison of CAMRAD/JA analysis levels using a large tip vortex core size and integrated forces method, baseline configuration, 35 knots, 84% radius.

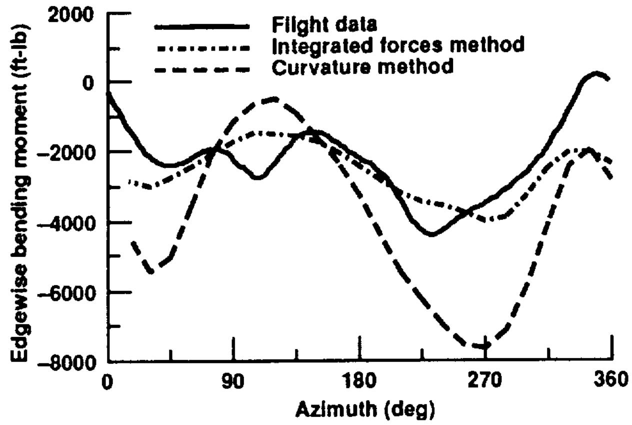

Figure 6. Comparison of CAMRAD/JA loads calculation methods using a large tip vortex core size and free wake analysis, baseline configuration, 60 knots, 20% radius.

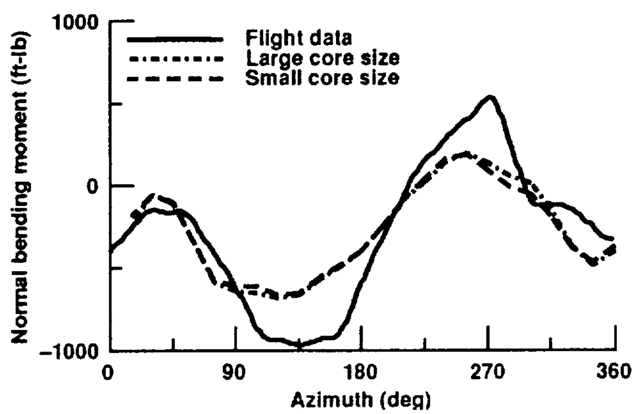

Figure 7. Comparison of CAMRAD/JA tip vortex core sizes using a free wake analysis and integrated forces method, baseline configuration, 60 knots, 20% radius.

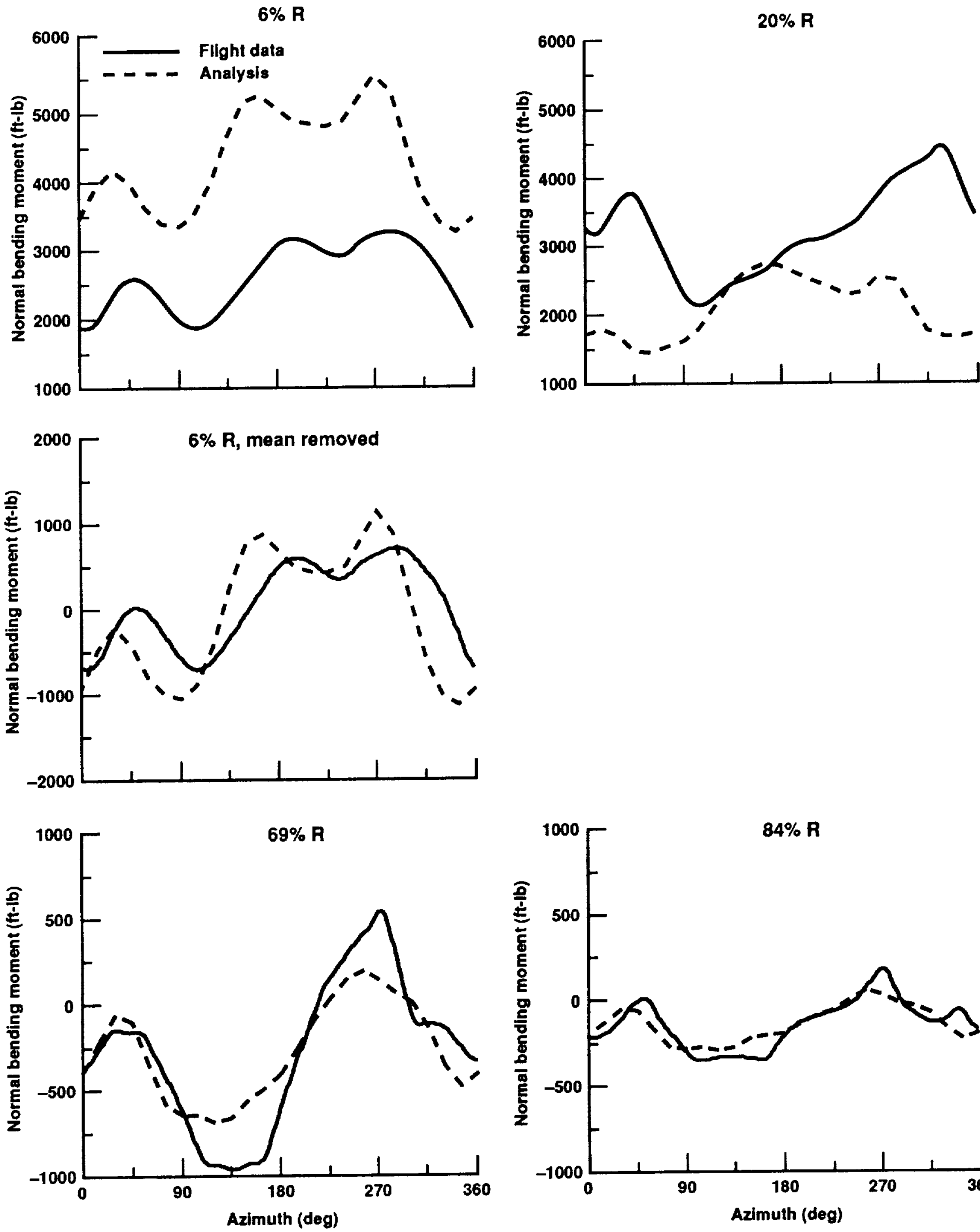

Figure 8. Comparison of CAMRAD/JA blade normal bending moment analysis with flight data for the baseline configuration.

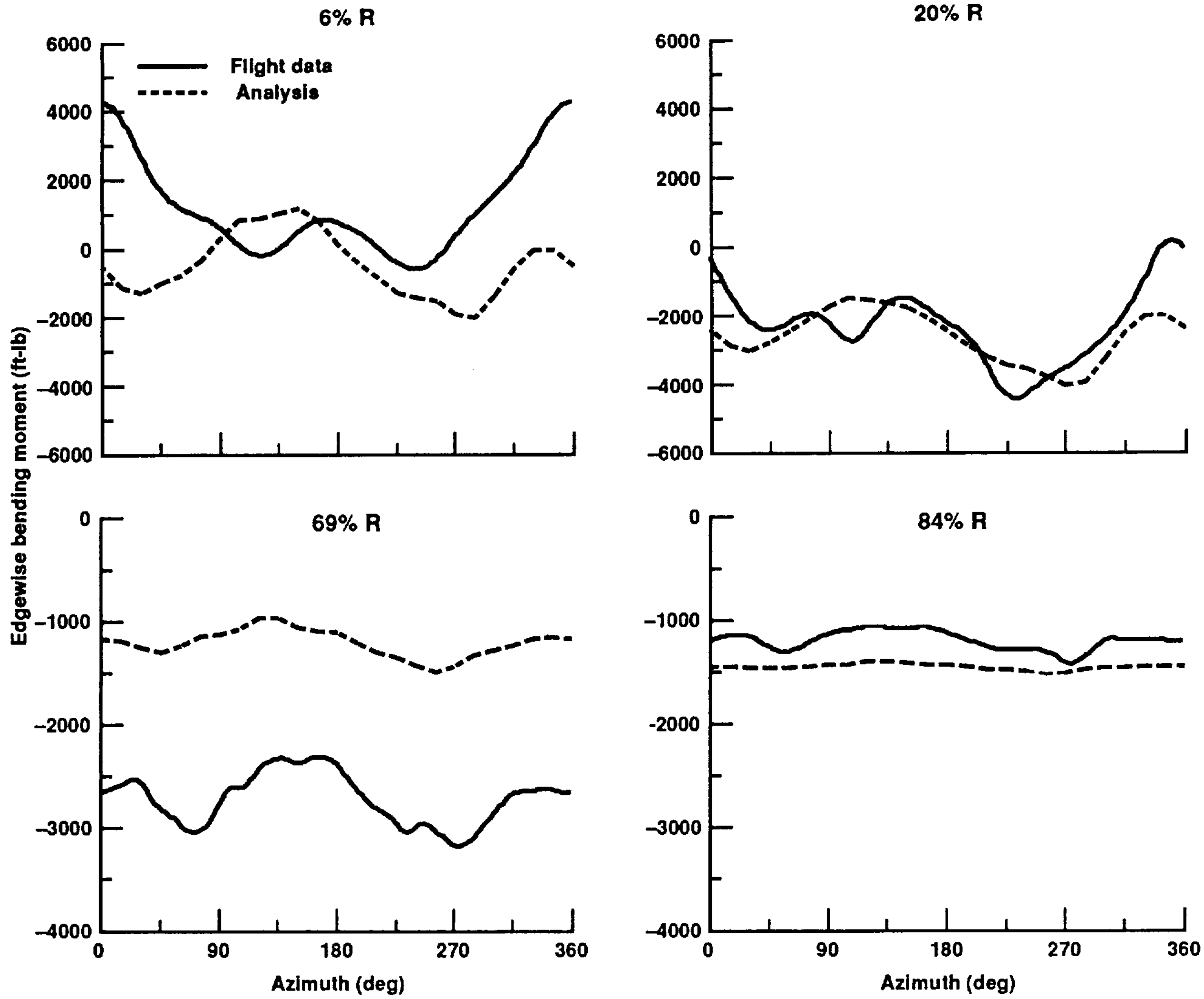

Figure 9. Comparison of CAMRAD/JA blade edgewise bending moment analysis with flight data for the baseline configuration.

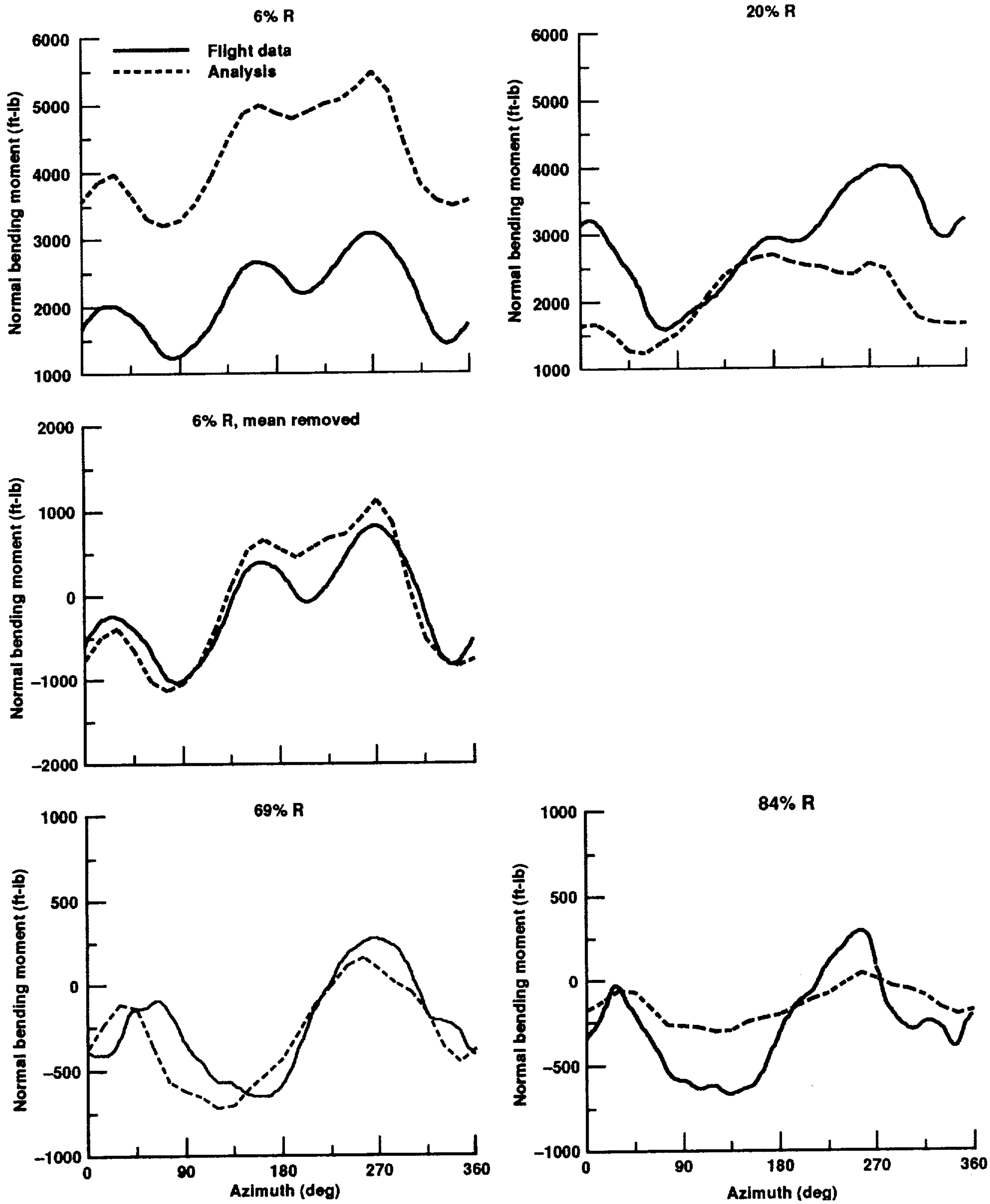

Figure 10. Comparison of CAMRAD/JA blade normal bending moment analysis with flight data for the shimmed configuration.

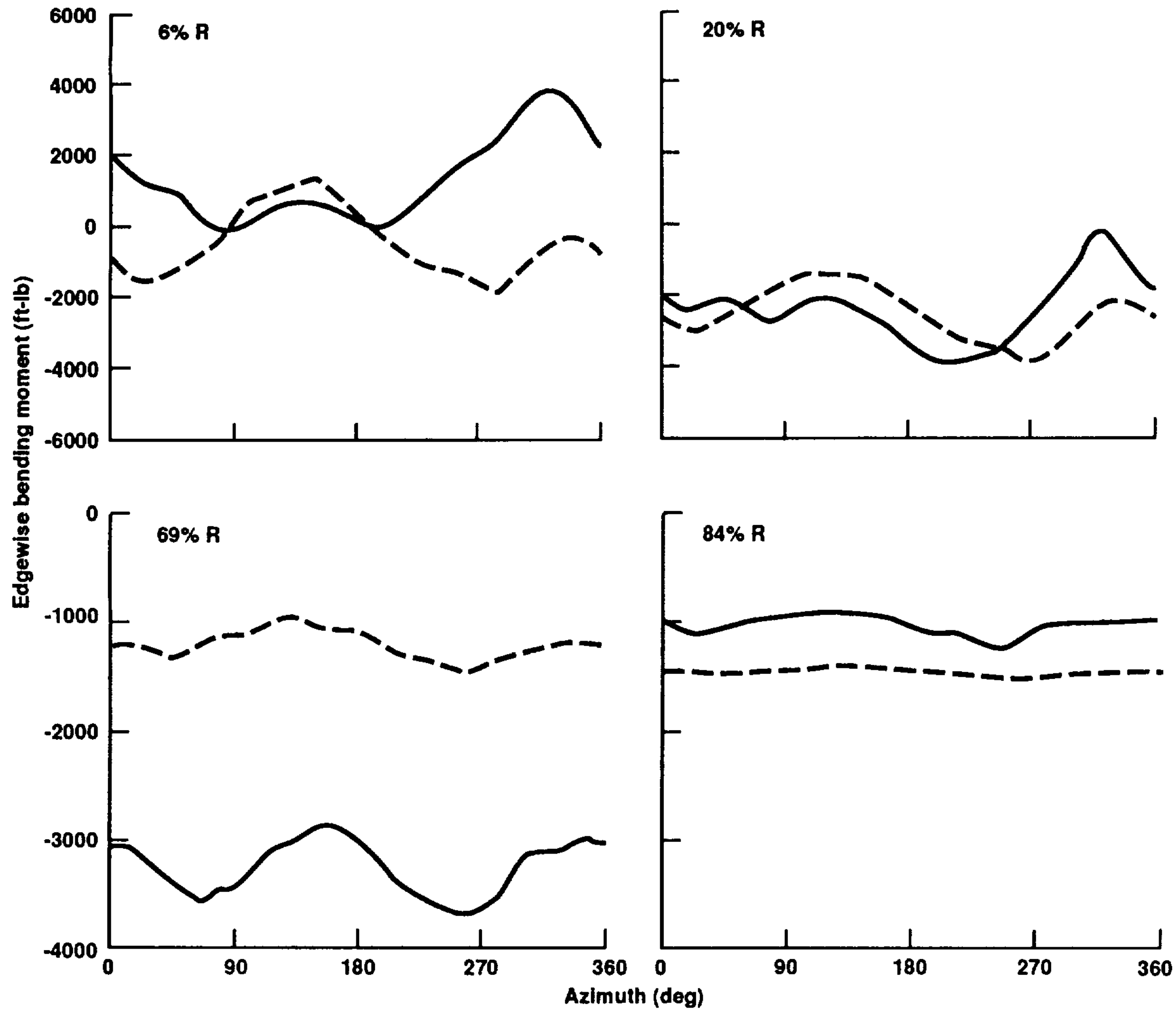

Figure 11. Comparison of CAMRAD/JA blade edgewise bending moment analysis with flight data for the shimmed configuration.

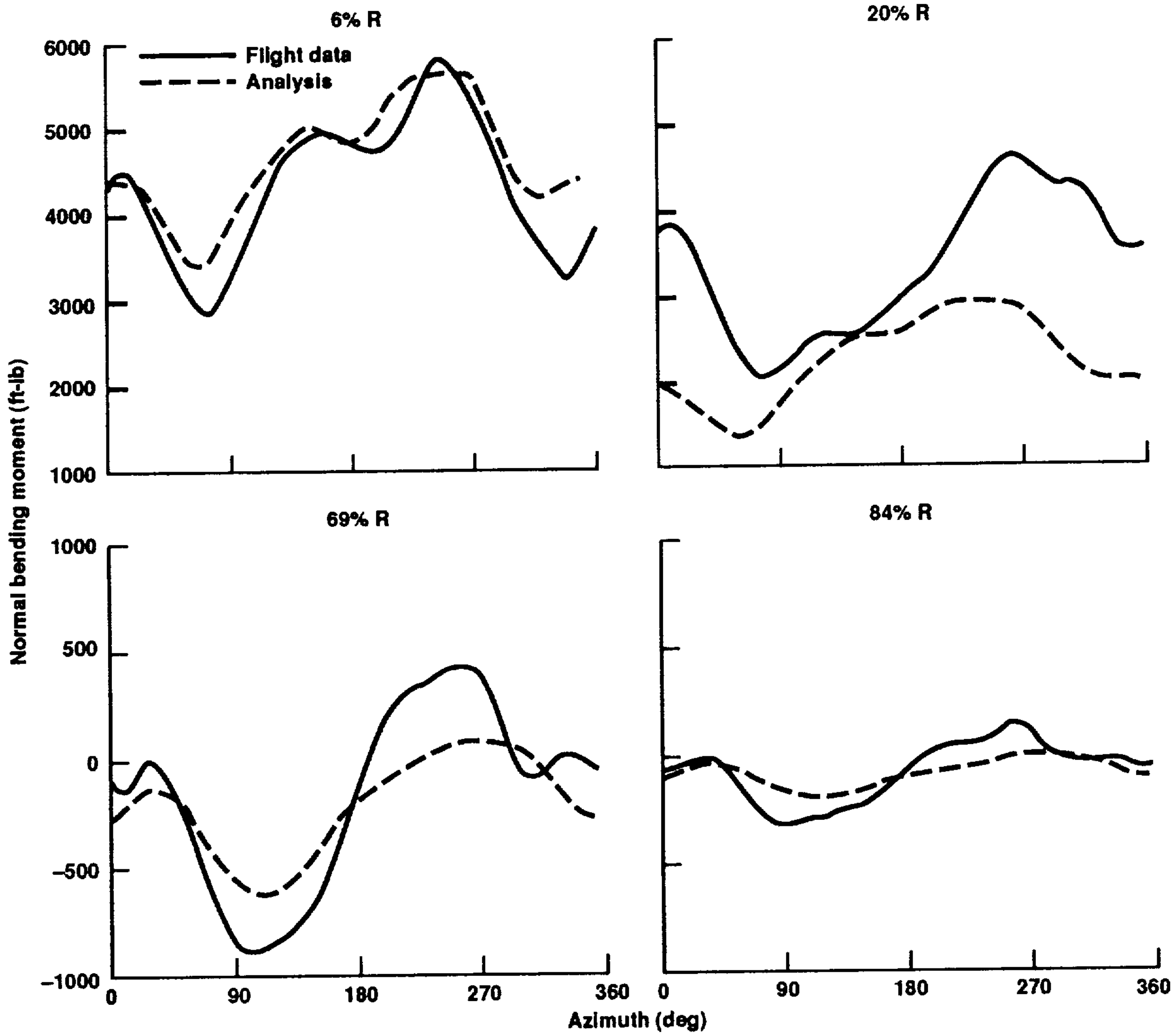

Figure 12. Comparison of CAMRAD/JA blade normal bending moment analysis with flight data for the shimmed T configuration.

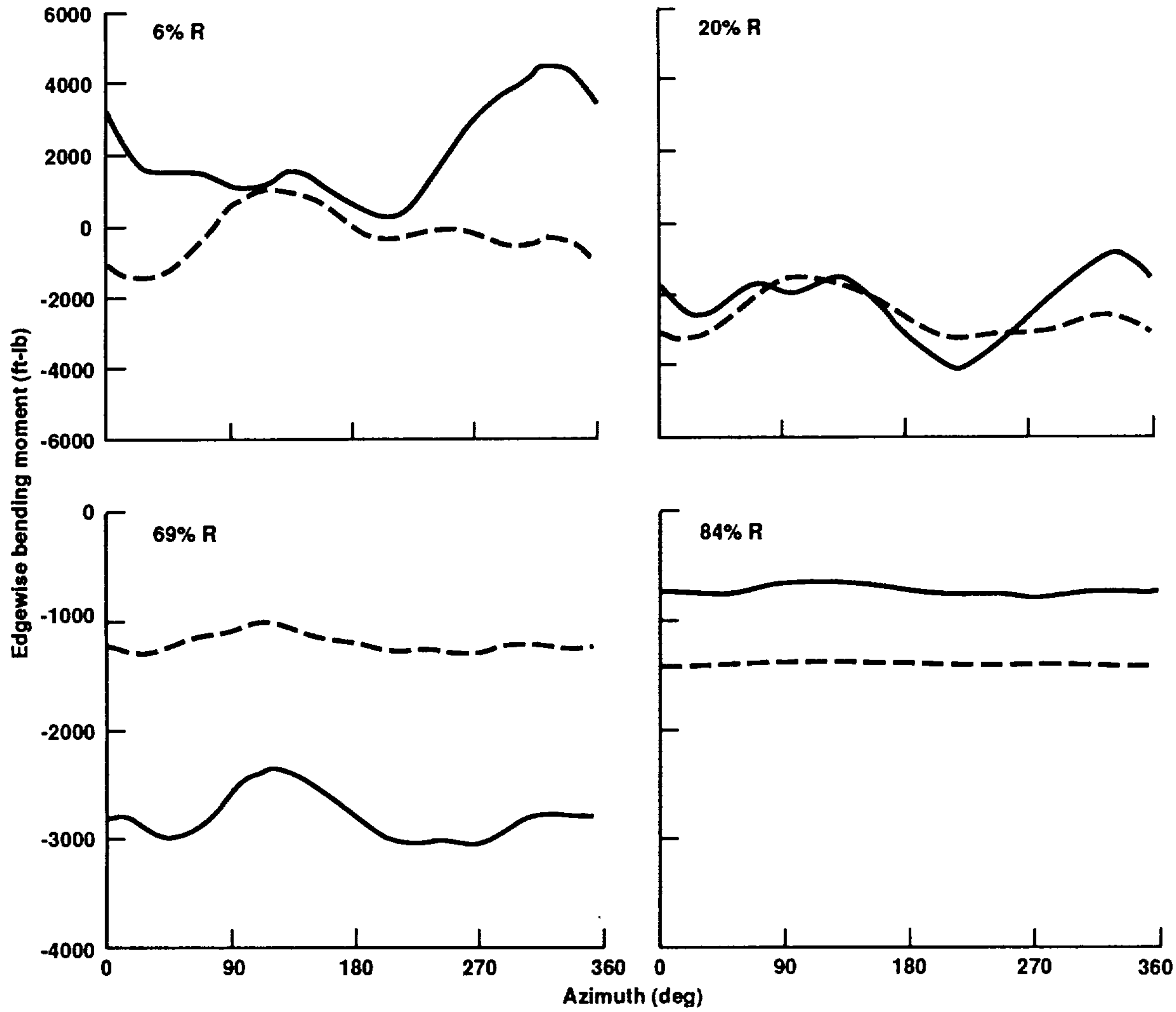

Figure 13. Comparison of CAMRAD/JA blade edgewise bending moment analyses with flight data for the shimmed T configuration.

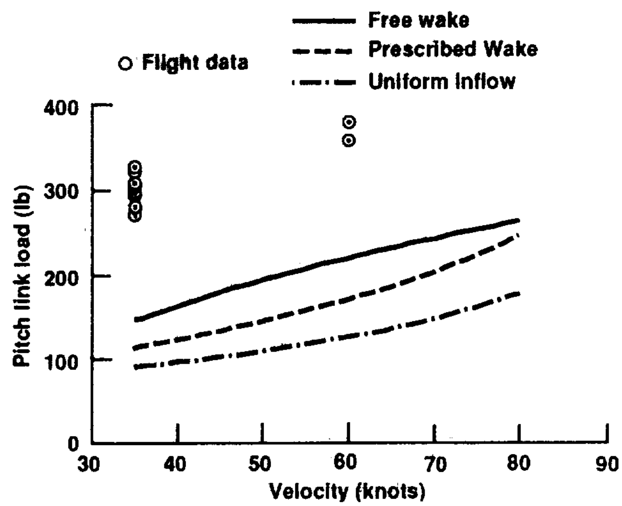

Figure 14. Comparison of CAMRAD/JA analysis levels in predicting half peak-to-peak pitch link loads for the baseline configuration.

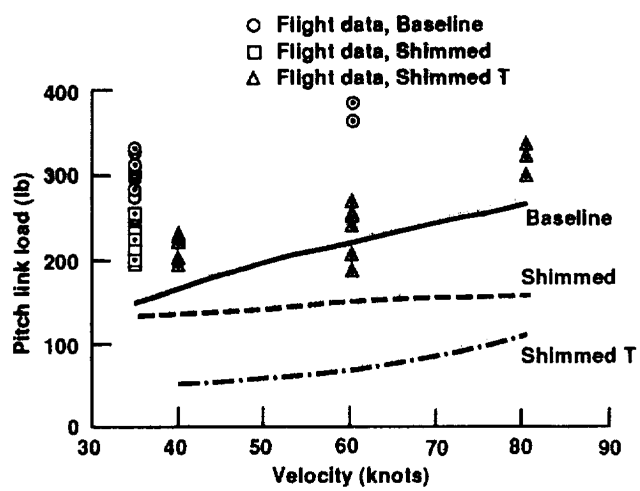

Figure 15. Comparison of CAMRAD/JA free wake predictions of half peak-to-peak pitch link loads with flight data.

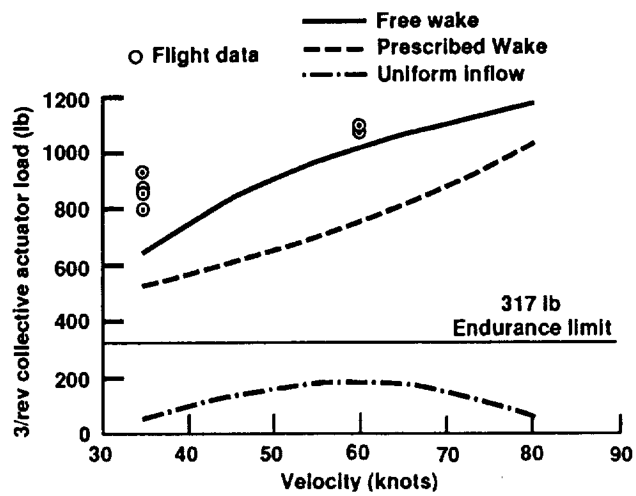

Figure 16. Comparison of CAMRAD/JA analysis levels in predicting 3/rev collective actuator loads for the baseline configuration.

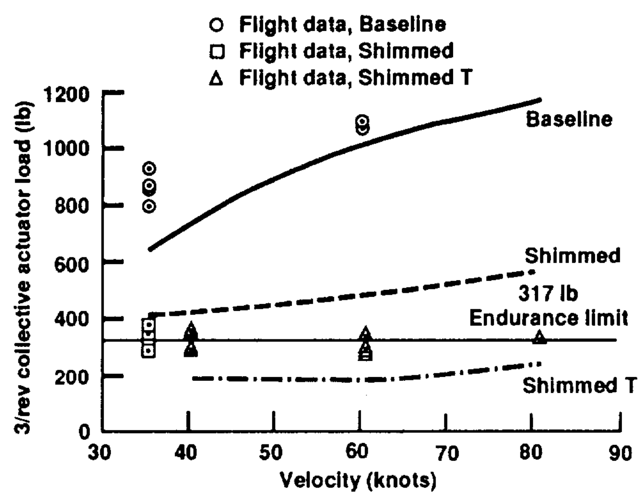

Figure 17. Comparison of CAMRAD/JA free wake predictions of 3/rev collective actuator loads with flight data.

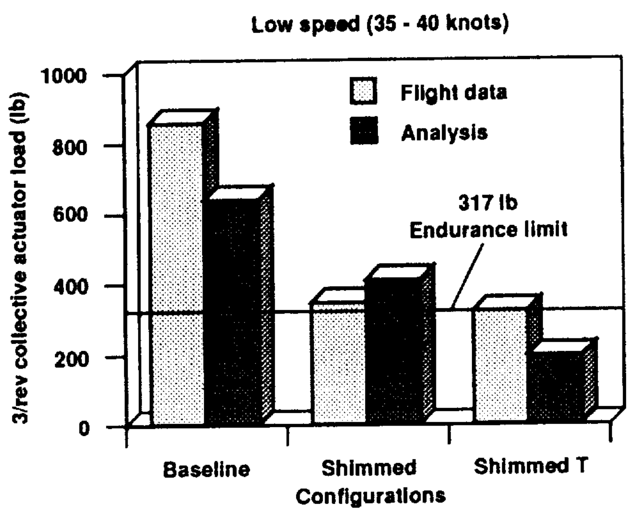

Figure 18. Comparison of collective actuator loads of each configuration at low speeds.

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15. Supplementary Notes

Point of Contact: Joseph J. Totah, Ames Research Center, MS 237-5, Moffett Field, CA 94035-1000
(415) 604-4126 or FTS 464-4126

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16. Abstract

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