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THE NASA / INDUSTRY DESIGN ANALYSIS METHODS FOR VIBRATION (DAMVIBS) PROGRAM - BELL HELICOPTER TEXTRON ACCOMPLISHMENTS

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Abstract

Accurate vibration prediction for helicopter airframes is needed to "fly from the drawing board" without costly development testing to solve vibration problems. The principal analytical tool for vibration prediction within the U.S. helicopter industry is the NASTRAN finite element analysis. Under the NASA DAMVIBS research program, Bell conducted NASTRAN modeling, ground vibration testing, and correlations of both metallic (AH-1G) and composite (ACAP) airframes. The objectives of the program were to assess NASTRAN airframe vibration correlations, to investigate contributors to poor agreement, and to improve modeling techniques. In the past, there has been low confidence in higher frequency vibration prediction for helicopters that have multibladed rotors (three or more blades) with predominant excitation frequencies typically above 15 Hz. Bell's findings under the DAMVIBS program, discussed in this paper, included the following: (1) accuracy of finite element models (FEM) for composite and metallic airframes generally were found to be comparable; (2) more detail is needed in the FEM to improve higher frequency prediction; (3) secondary structure not normally included in the FEM can provide significant stiffening; (4) damping can significantly affect phase response at higher frequencies; and (5) future work is needed in the areas of determination of rotor-induced vibratory loads and optimization.

Introduction

Accurate and reliable vibration prediction during the design of new rotorcraft increases the possibility of minimizing vibration and achieving the goal of "flying from the drawing board" with minimal fine tuning during development flight testing. However, there are many problems with accurate airframe vibration prediction, as illustrated in Fig. 1. Accurate vibration prediction requires a systematic approach and any weak links within the analysis degrade the vibration prediction accuracy. The following elements must be accurately represented in the analytical model:

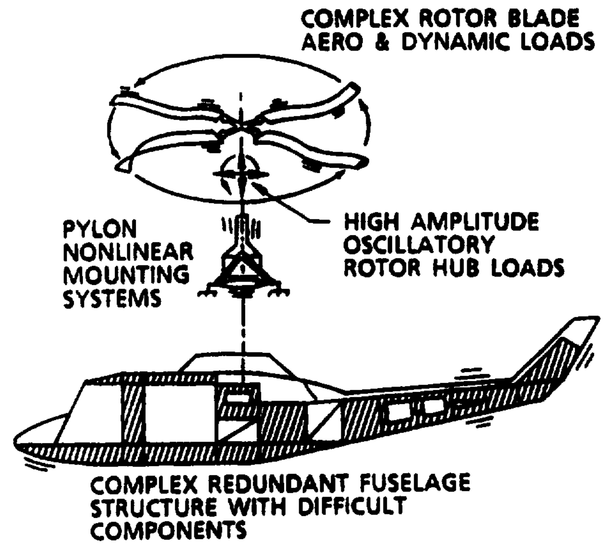

Fig. 1. Problems with vibration prediction.

1. Complex fuselage structure of metallic or composite construction with cutouts and redundancies.

2. "Difficult" (difficult-to-model) components, such as secondary structure, cowlings, fairings, doors, windows, gearboxes, accessories, black boxes, equipment, occupants, fuel, weapons, stores, and landing gear.

3. Main rotor pylon (transmission and mast) and isolation mounting.

4. Main rotor vibratory excitation at the hub and downwash impingement on the fuselage.

Within the U.S. helicopter industry, the NASTRAN finite element analysis[1] has become the accepted design tool for airframe vibration prediction. The early application of NASTRAN at Bell was on airframes with two-bladed main rotor systems having predominantly 2/rev excitation frequency (twice per main rotor revolution). Bell was able to effectively utilize NASTRAN to successfully support the design and development of two-bladed rotorcraft airframe structures.[2] Since the high 2/rev vibratory hub loads required effective pylon isolation systems and fuselage tuning to control

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vibrations, accurate vibration prediction was imperative. In these early modeling efforts, the lower frequency 2/rev vibration responses were more accurately represented than were the higher frequency responses above 3/rev, as shown in Fig. 2.[3] In addition, calculated rotor hub excitations, using Bell's coupled rotor-airframe analysis programs such as C81[4] were considered adequate at 2/rev; but there was lower confidence in the higher frequency range, which requires greater sophistication in the aerodynamic representation.

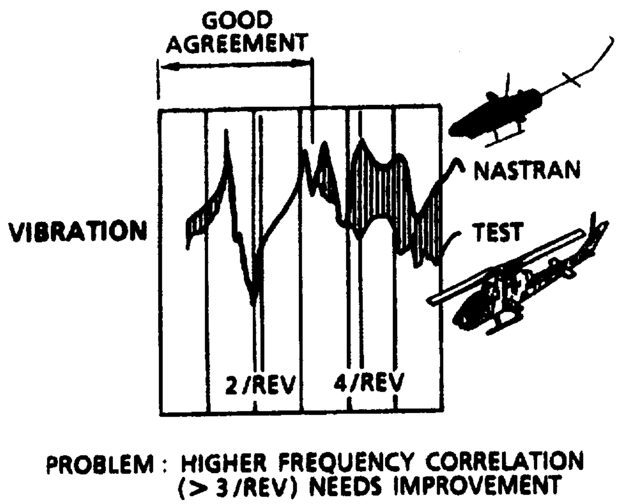


Fig. 2. AH-1G NASTRAN vibrations model frequency response comparison with test.

Bell now has four-bladed main rotor systems on its helicopters with predominant excitation frequencies above 20 Hz. Thus, finite element predictive capability needs to be extended up through 25 - to 30-Hz to encompass the primary excitation of four-bladed rotors in the current or planned helicopter fleet. In addition, vibration prediction for airframes constructed from metallic or composite materials needs to be addressed.

This paper focuses on the R&D efforts and accomplishments made at Bell under the NASA/ Industry DAMVIBS program to improve the higher frequency vibration prediction for metallic and composite airframes.

DAMVIBS Program

The NASA DAMVIBS research program was established with the goal of improving reliability of airframe vibrations analysis using NASTRAN. Under the NASA DAMVIBS program, NASTRAN modeling exercises were conducted by the major U.S. helicopter manufacturers (Bell, Boeing, McDonnell-Douglas, and Sikorsky). As shown in Fig. 3, Bell's exercises included modeling, testing, and correlations of both metallic (AH-1G) and composite (ACAP) airframes. Bell's findings and accomplishments under the DAMVIBS program are summarized in the following paragraphs.

AH-1G Correlations

An existing AH-1G NASTRAN finite element model (FEM) that was developed under NASA/Army funding[5] was used for correlations with flight vibration measurements and ground vibration testing to investigate the effects of difficult components. The existing original AH-1G FEM is shown in Fig. 4. This model was used directly in the coupled rotor/airframe analysis to correlate with flight vibration data and was then improved during the difficult components investigation. The AH-1G, with a two-bladed main rotor, provided a good basis for comparison of the quality of analytical models considered adequate for vibration predictions in the 2/rev frequency range; the same standard of correlation was then extended to analytical models dealing with higher frequencies.

Coupled Rotor/Airframe Analysis and Flight Vibration Correlations[6]

Bell's current methodology for airframe vibration prediction is illustrated in Fig. 5. A Myklestad rotating beam analysis[7] is used to calculate the rotating elastic blade modal properties. A NASTRAN FEM is used to calculate the airframe modal properties. COPTER, a comprehensive rotor analysis program that is a replacement of the C81 first generation computer program, is then used to couple the modal properties of the airframe and rotor and include the aerodynamics to calculate the rotor harmonic hub loads. Finally, the airframe vibrations at specific locations are determined using the hub loads calculated by COPTER to excite the full NASTRAN airframe model.

To perform the flight vibration correlations, the COPTER coupled rotor/airframe analysis was used to develop main rotor hub shears that were applied to the NASTRAN FEM of the AH-1G airframe. In addition to the hub shear excitations calculated by COPTER, measured control actuator loads and fin lateral downwash effects were applied to the FEM. Comparisons of the resultant airframe vibration calculations with measured flight vibrations from an AH-1G operational load survey[8] were then determined for 2/rev and 4/rev main rotor harmonics in the lateral and vertical directions for six airspeeds from 67 and 142 knots.

The analysis was systematically planned and documented, and the correlation results reviewed by

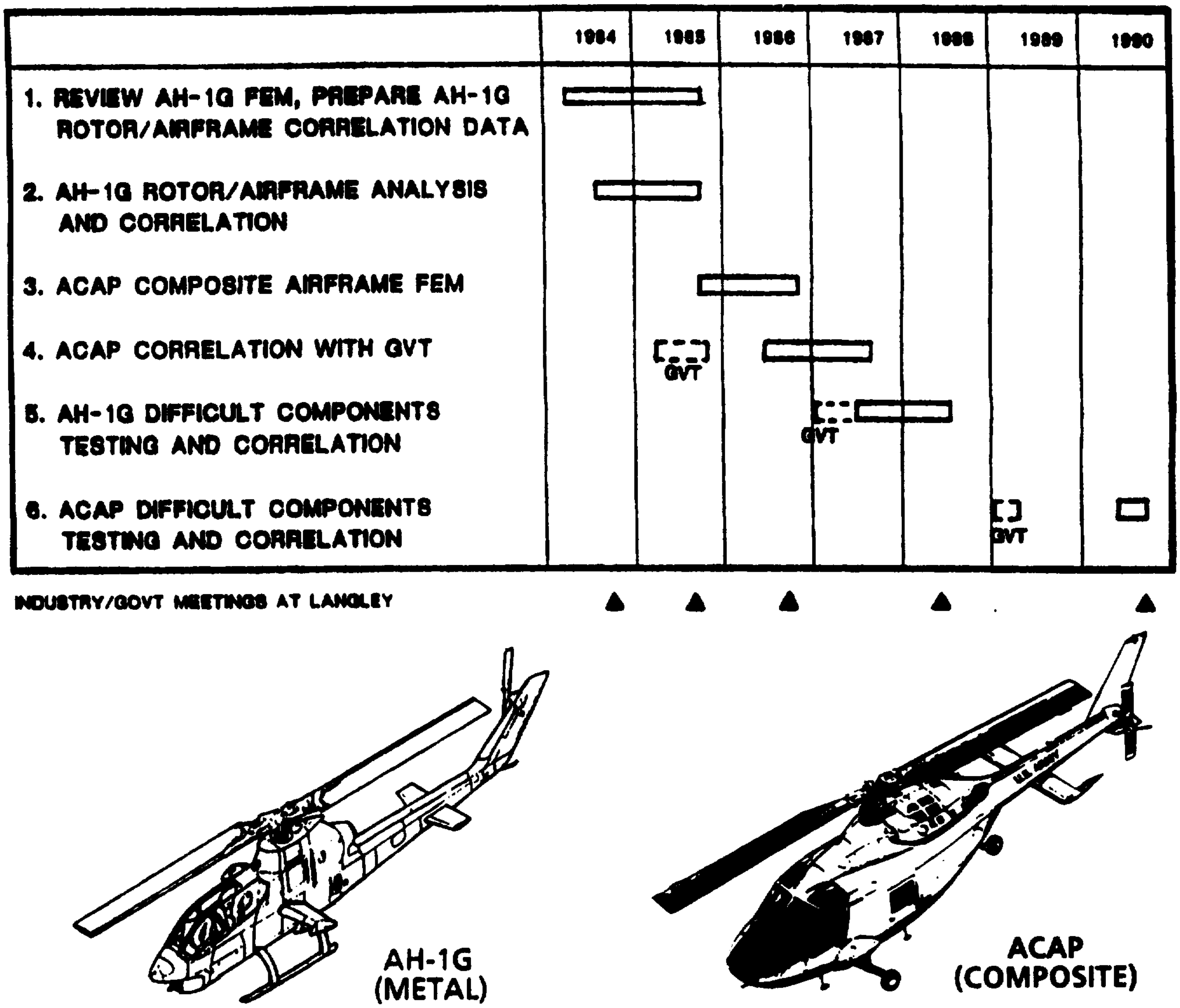


Fig. 3. Bell tests under NASA DAMVIBS research program.

NASA and industry experts in order to ensure scientific control of the analysis and correlation exercise. Thus, the results provide a sound basis for assessing the adequacy of state-of-the-art FEM techniques and rotor/airframe coupling methods for predicting flight vibrations.

The results of the flight vibration correlations are summarized as follows:

1. The rotor loads predicted by the dynamically coupled rotor/airframe analysis showed generally good agreement between calculated blade loads and test, as described by Dompka and Corrigan.[6]

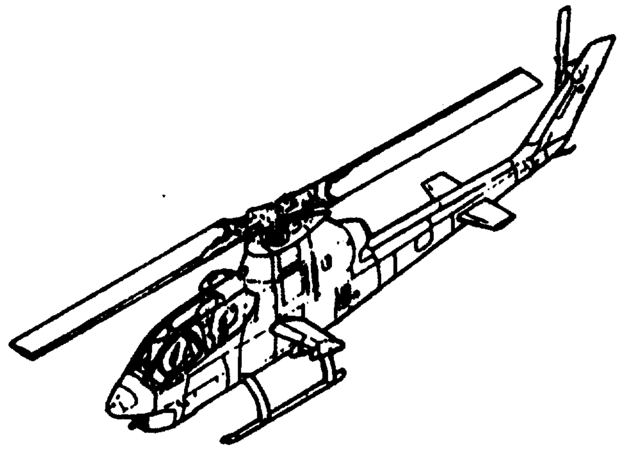
2. As shown in Fig. 6, there was fairly good agreement between calculated and measured vertical 2/rev (10.8 Hz) vibration. The 2/rev frequency is the predominant excitation frequency of the AH-1G two-bladed rotor, producing the most significant flight vibration levels.

3. Lateral 2/rev vibration predictions by NASTRAN when using only calculated 2/rev hub shears were much lower than test measurements. However, the inclusion of the effects of lateral rotor downwash on the tail fin showed significant improvement in the calculated vibrations and warrants further investigation.

4. Calculated and measured 4/rev vibration responses deviated significantly from measured results.

AH-1G Difficult Components Investigation

Under an extensive vibration analysis and testing task conducted on the Army AH-1G metallic airframe, the effects on higher frequency vibration correlations of difficult components (such as cowlings, fairings, doors, windows, secondary structures, engines, fuel, black boxes, transmissions, and shafting) were investigated.[9] The correlations were



DEGREES OF FREEDOM		ELEMENTS	
K_{gg}	2940	BAR	197
K_{nn}	2699	ROD	2012
K_{ff}	1714	SHEAR	340
K_{aa}	241	QDMEM	160
K_{ll}	235	TRMEM	243
		ELAS2	13

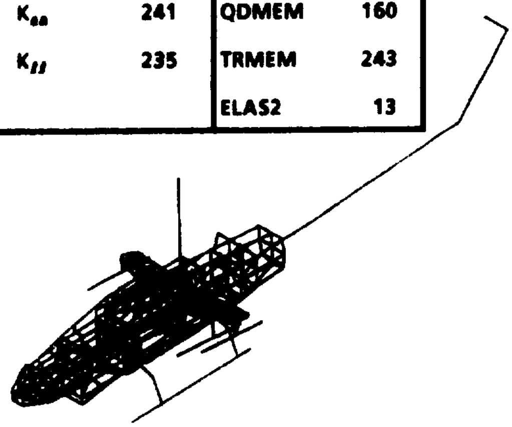


Fig. 4. Original AH-1G NASTRAN FEM.

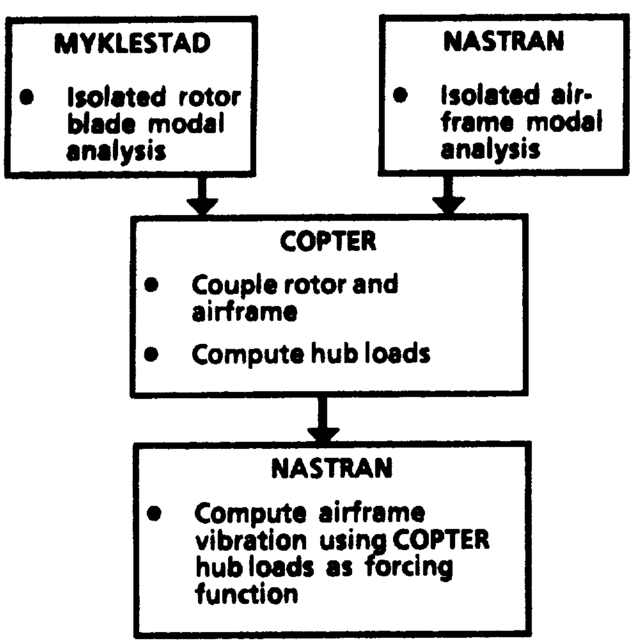
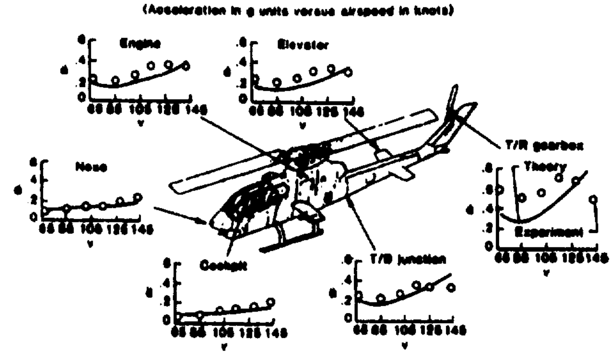
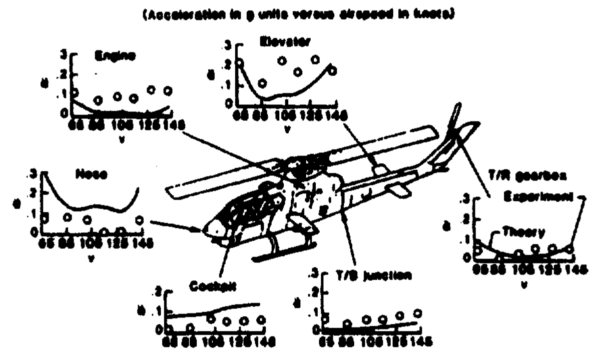


Fig. 5. Bell's procedures for airframe vibration prediction.



a. 2/rev vertical response



b. 4/rev vertical response

Fig. 6. Comparison of measured AH-1G 2/rev and 4/rev vertical vibrations with Bell predictions.

conducted in a stepwise manner by successively removing components from the airframe, conducting ground vibration tests, and then comparing measured vibrations to the NASTRAN FEM with components removed. As shown in Fig. 7, the difficult components are typically represented as lumped masses in the model. The NASTRAN FEM was improved by including more modeling detail in the tailboom and including stiffness for secondary structure; then the correlations were repeated.

In order to isolate the effects of various components on overall airframe vibratory response, multiple vibration tests were conducted. Progressive removal of selected difficult components was done for each test until the primary structure remained. Eight configurations were tested:

1. Baseline airframe (rotors replaced with lumped masses).

2. Main rotor pylon removed.

3. Secondary structures, cowlings, fairings, and doors removed.

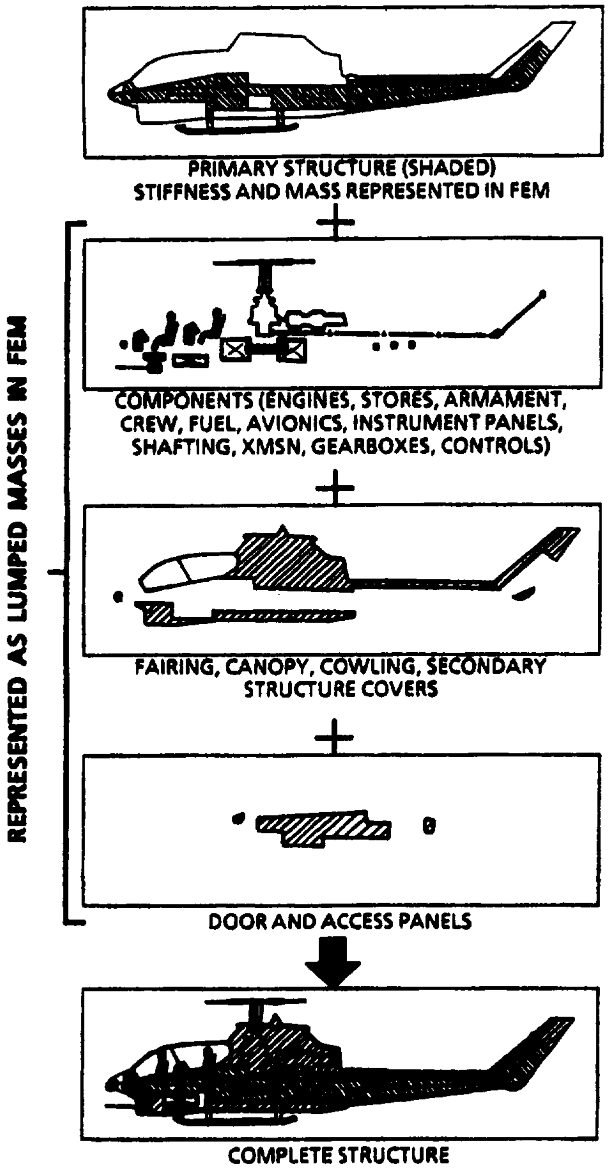


Fig. 7. Difficult components study: AH-1G model correlations with test.

4. Tail rotor drive shaft and cover removed.

5. Skid landing gear removed.

6. Engine removed.

7. Fuel removed.

8. Canopy glass, black boxes, and wings removed.

The baseline and stripped-down AH-1G GVT airframes are shown in Fig. 8.

Natural frequencies of important modes, vibration vs. frequency response, and damping were considered in the correlations of the NASTRAN FEM with test. Using the natural vibration modes is a convenient way to understand the forced vibration response of the airframe and the effects of damping as well. The airframe total harmonic vibration response can be broken down into its modal components using NASTRAN modal analysis. Viewed in this way, the airframe vibration response is the vector sum or superposition of the contribution from each mode as shown in Fig. 9. Plotting each modal contributor in the complex plane (to relate the magnitude and phase of the modes that significantly contribute to the response at a given location and frequency) identifies which modes are the primary contributors to the vibratory response. Also, the effect of damping, both proportional and nonproportional, can be determined by the relative phase relationship of the modal contributors in the complex plane.

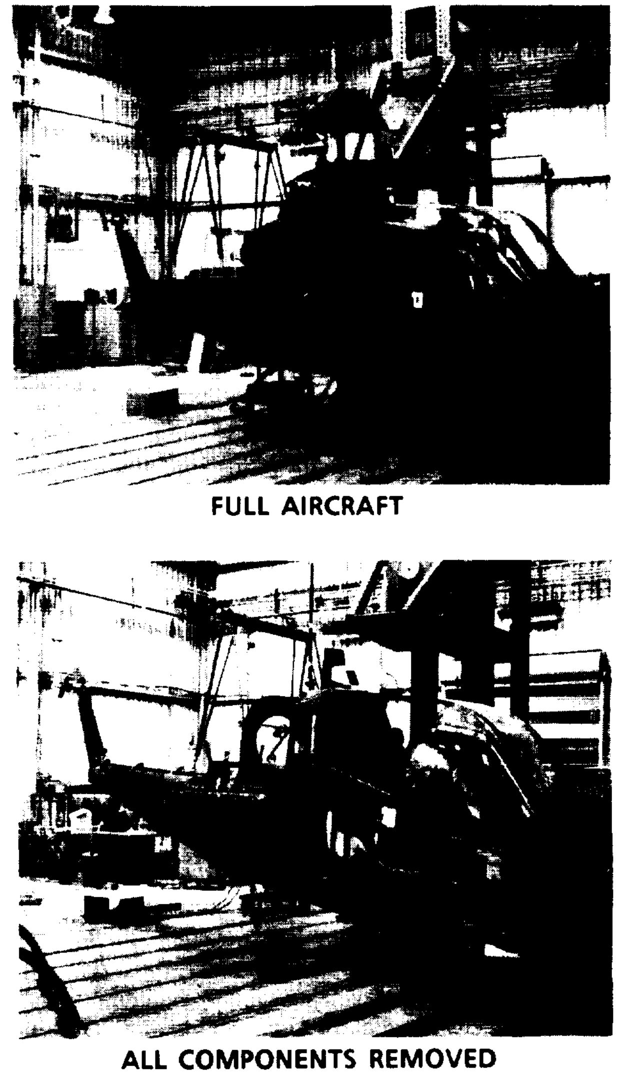


Fig. 8. AH-1G ground vibration test airframe.

The improved, AH-1G NASTRAN FEM, shown in Fig. 10, was compared with each of the

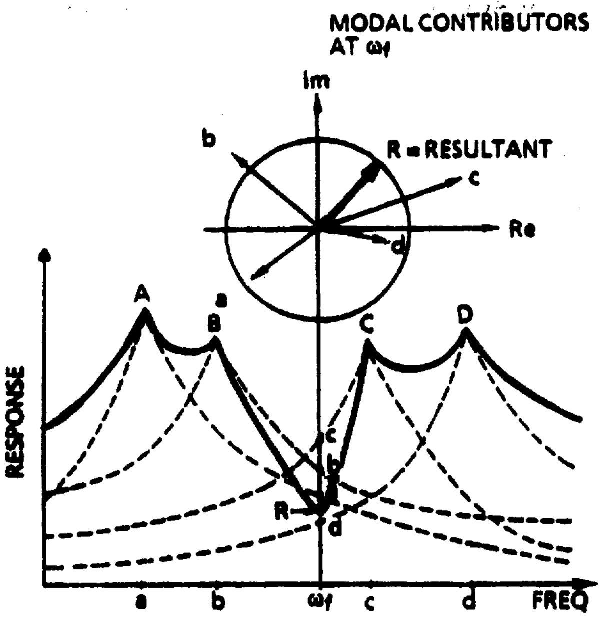


Fig. 9. **Frequency response using modal contributors.**

DEGREES OF FREEDOM		ELEMENTS	
K_{gg}	4611	BAR	350
K_{nn}	4223	ROD	3072
K_{ff}	2965	SHEAR	540
K_{aa}	241	QDMEM	160
K_{ee}	235	TRMEM	243

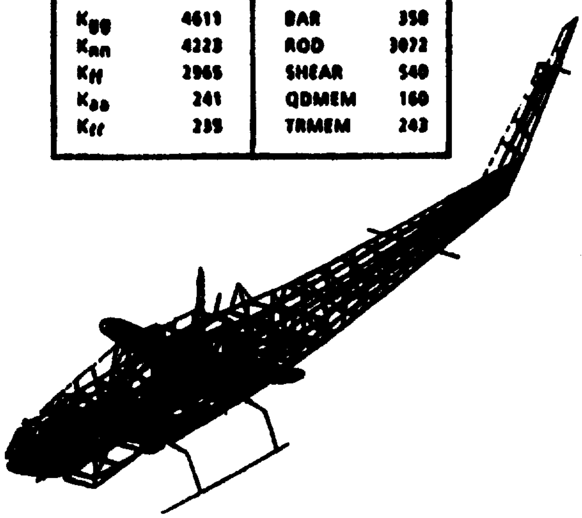


Fig. 10. Improved AH-1G NASTRAN FEM.

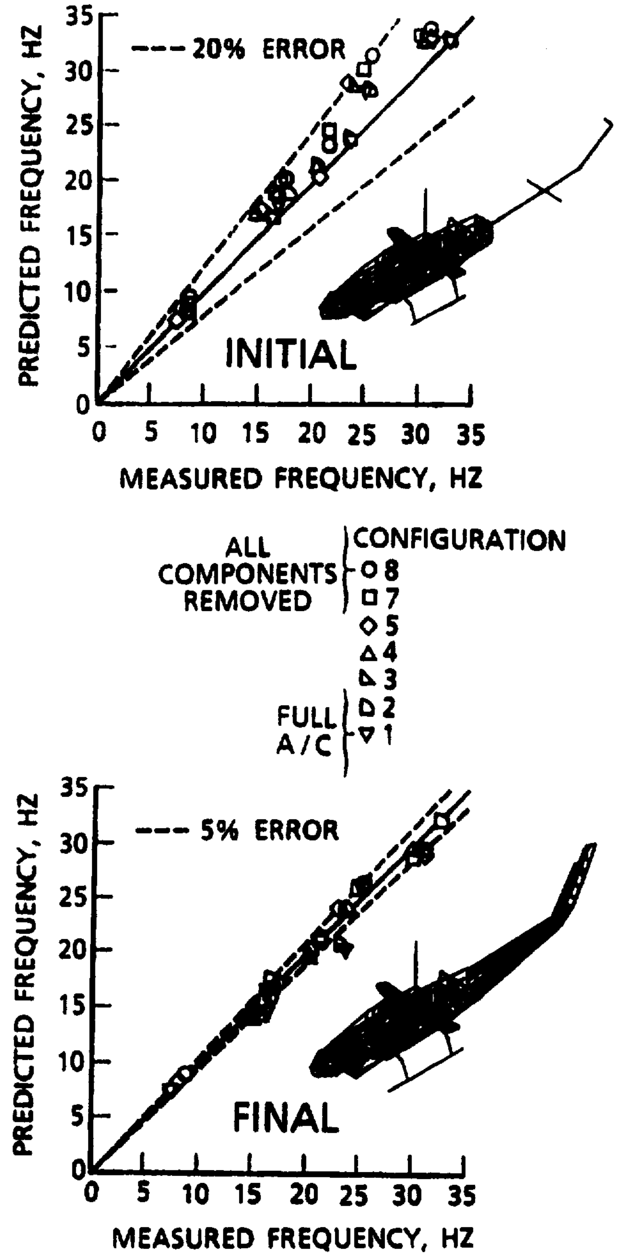


Fig. 11. AH-1G natural frequency comparisons.

eight test configurations. The findings from the correlations are summarized as follows:

1. As shown in Fig. 11, the natural frequency correlation at the higher frequencies was improved from 20% error to less than 5% error for rotor frequencies up to 30 Hz (4/rev = 21.6 Hz for the AH-1G) by adding more detail in the tailboom and by including tightly fastened panels, doors, and secondary structure in the forward fuselage.

2. The vibration vs. frequency response comparisons of test and the final AH-1G NASTRAN FEM are shown in Fig. 12. The overall vibration levels and trends generally agree well in the higher frequency range through 4/rev (21.6 Hz) and above, compared to the original FEM (refer to Fig. 2).

3. Lack of proper treatment of damping in the FEM can affect the higher frequency correlations. The effects of damping (both nonproportional and modal) on the vibration response were investigated using the ground vibration test data.

- The effects of nonproportional damping in the test data were identified as significant in the vibration response at the higher 4/rev frequencies and not as significant at 2/rev (see Fig. 13).

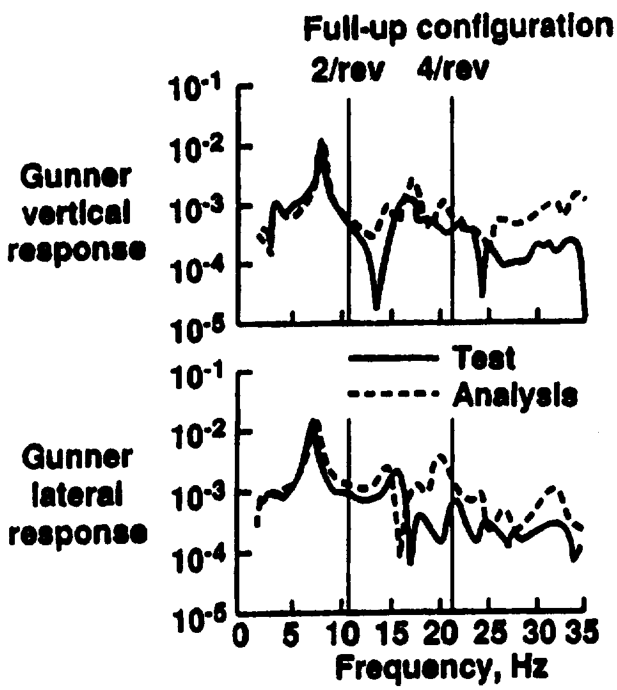


Fig. 12. Test/NASTRAN comparisons of AH-1G response.

- Modal damping estimates for the eight AH-1G airframe configurations are shown in Fig. 14. Except for the pylon modes which lie below 1/rev, the fuselage modes average around 2% of critical damping and never exceed 5%. The complex nature of most damping mechanisms is difficult to model with linear FEMs. The usual NASTRAN modeling procedure is to assume the same value of modal damping, generally 2% of critical, for each mode with computing airframe responses.

4. Nonlinearities in the elastomeric mounts and in thrust stiffening effects, shown in Fig. 15, were found to have a significant effect on the pylon and mounting stiffness. Correlations of the AH-1G pylon indicate that the mount stiffness is dependent on frequency and deflection and should be considered in the FEM along with differential stiffening of the pylon due to thrust.

<u>Composite Airframe (ACAP) Correlations</u>

A NASTRAN FEM of the composite airframe, which was developed by Bell under the U.S. Army's Advanced Composite Airframe Program (ACAP), was correlated with ground vibration tests (GVT). The ACAP correlations included a difficult components investigation, the testing for which was conducted by the Aviation Applied Technology Directorate (AATD) of the U.S. Army Aviation Systems Command (AVSCOM). The results of the difficult components investigation are described by Dompka and

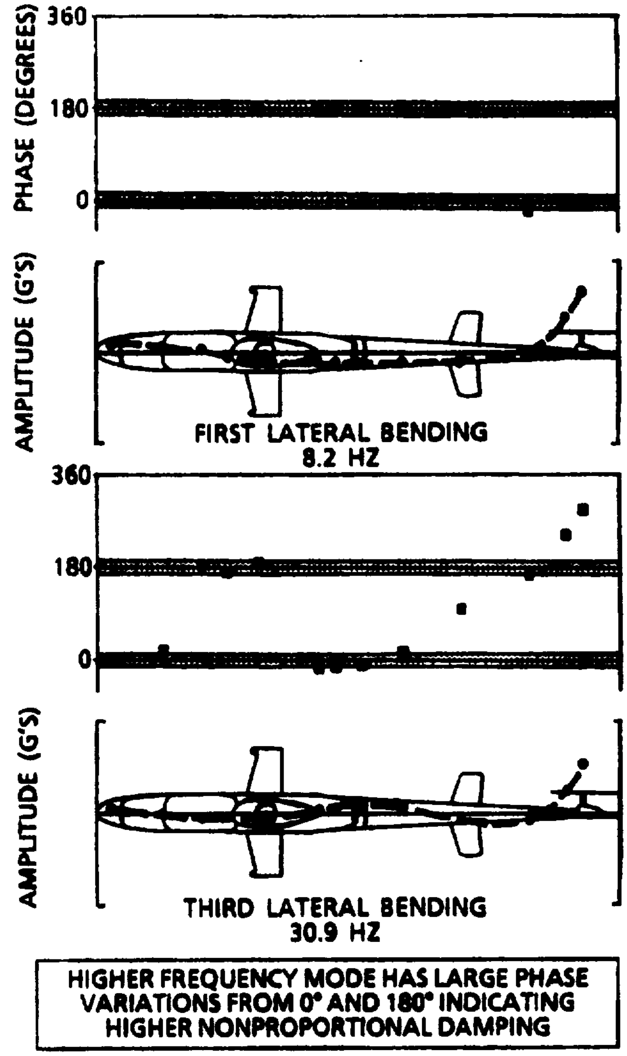


Fig. 13. Example of nonproportional damping effects.

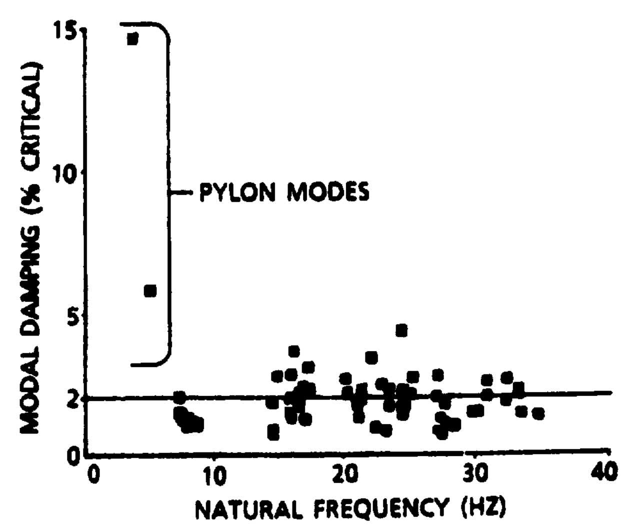


Fig. 14. AH-1G modal damping estimated from ground vibration tests.

Calapodas.[10] The primary objective of the ACAP exercises was to assess the differences in modeling and

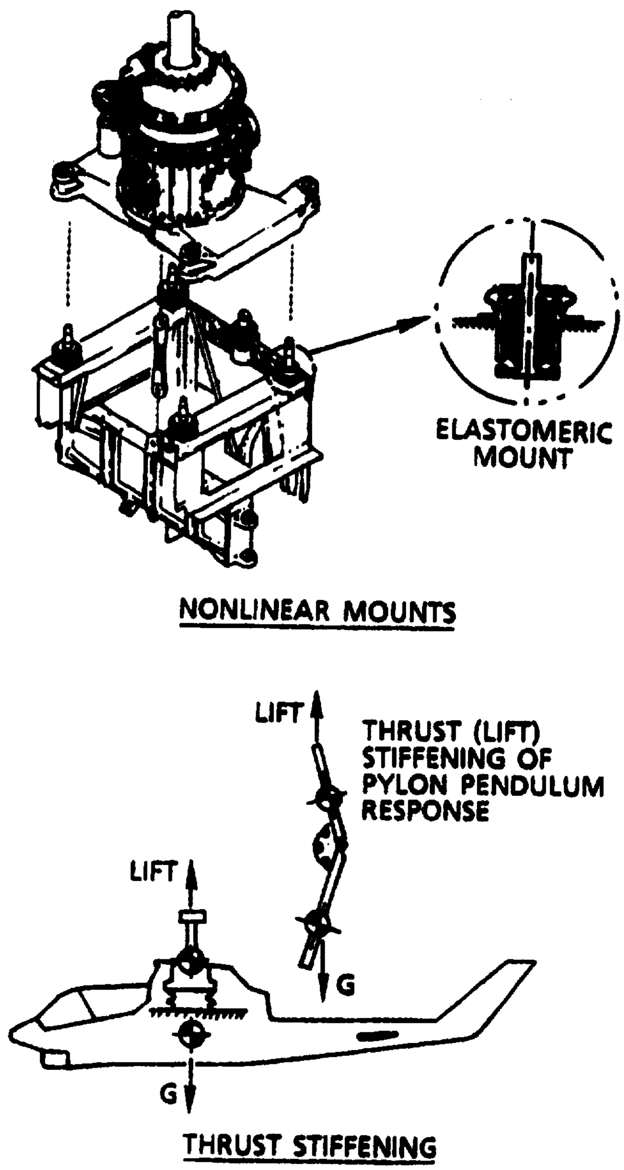


Fig. 15 AH-1G pylon nonlinearities.

correlation of composite airframes compared to metallic airframes.

Model Development

The process that was used in developing the ACAP NASTRAN FEM is shown in Fig. 16. The stiffness properties of the statics (stress analysis) model are used directly in the dynamics fuselage FEM, with only minor structural modifications. The masses are then distributed to the fuselage FEM and the pylon model is added to complete the airframe dynamics model used for vibration prediction. Based on the experiences from the AH-1G correlations, a relatively detailed FEM was used with built-up tailboom rather than elastic line in order to obtain good correlation at higher frequencies through 4/rev (23.2 Hz). The ACAP FEM is shown in Fig. 17.

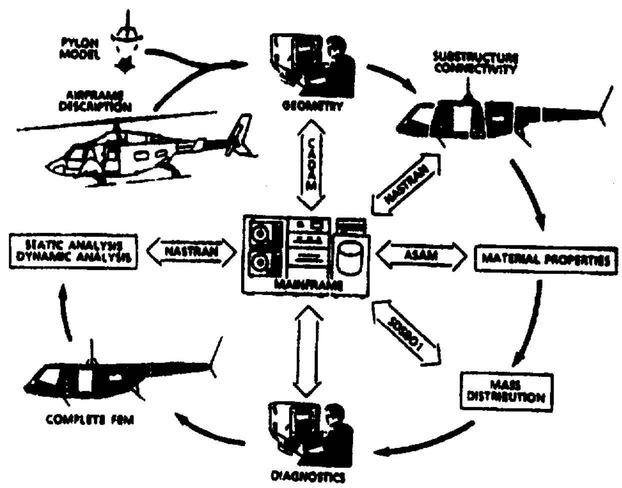


Fig. 16. ACAP NASTRAN FEM development process using common statics dynamics models.

Some of the findings and accomplishments from the ACAP modeling exercise were as follows:

1. Up-front planning helped expedite modeling process. For example, following development of a static model, only a minimum effort (about 50 manhours) was required for development of a dynamic model.

2. Some of Bell's automated modeling tools were exercised for the first time. These experiences helped in other programs, such as V-22.

3. For the first time, automated diagnostics, in the form of NASTRAN DMAP alters, were exercised for model checking and mode identification for large FEM development.

4. Composites were found to require an order-of-magnitude greater effort for material property identification than for metallic structures.

ACAP Difficult Components Investigation

A series of GVTs of the ACAP were conducted by AATD at its vibration test facility in Ft. Eustis, VA. The NASTRAN correlations were performed by Bell. Eight configurations were tested in the following sequence:

1. Baseline with simulated fuel (1250 lb water), rigid engine masses, and lumped masses for main and tail rotors.

2. Crew doors removed.

3. Transparencies removed.

D292 (ACAP) helicopter

ELEMENTS		PROPERTIES	
GRID	1700	MAT	580
CROD	1914	PROD	454
CSHEAR	136	PSHEAR	45
CELAS2	142	-	-
CQUAD4	1387	PSHELL	160
CBAR	381	PBAR	85
CTRIA3	182		

K_{gg}	10425
K_{nn}	9753
K_{ff}	6657
K_{qq}	201

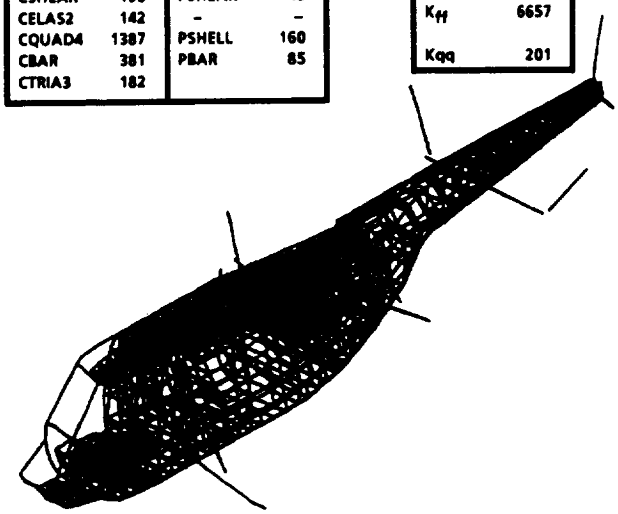


Fig. 17. Bell ACAP NASTRAN airframe vibration model.

4. Stripped down to primary structure with dummy transmission fixture, lumped mass tail rotor gearbox, and nose ballast.

5. Horizontal stabilizer added.

6. Cargo doors added.

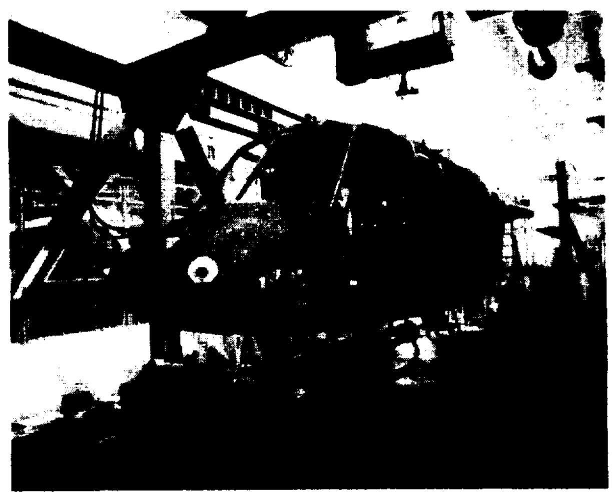
7. Vertical fin added.

8. Landing gears added.

The ACAP baseline and stripped-down GVT configurations are shown in Fig. 18.

To conduct the difficult component investigations, the ACAP NASTRAN FEM was modified to represent each configuration from the stripped-down configuration (airframe stripped of engines, landing gear, rotors, pylon [replaced by fixture], fuel, stabilizers, drive shafts, doors, cowlings, electronics, wiring, seats, etc.) to the full-up baseline configuration.

FULL AIRCRAFT



ALL COMPONENTS REMOVED

Fig. 18. ACAP ground vibration test airframe.

The findings from the ACAP GVT and FEM correlations are summarized as follows:

1. Predicted and measured natural frequencies for the stripped-down configuration are compared in Fig. 19, which shows the major airframe modes are generally within 10% difference, except for the lateral model of the dummy pylon fixture.

2. The modal damping estimates from the ACAP GVT are shown in Fig. 20 and compared to the AH-1G. This comparison indicates there is not a significant difference in the damping of metallic and composite airframes. The 2% damping line on the

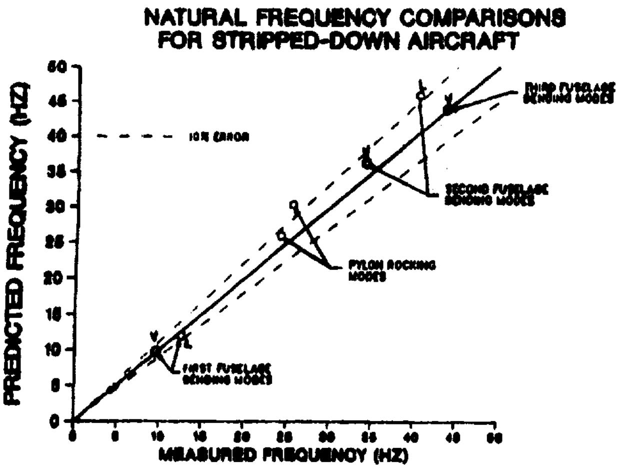


Fig. 19. ACAP natural frequency comparisons.

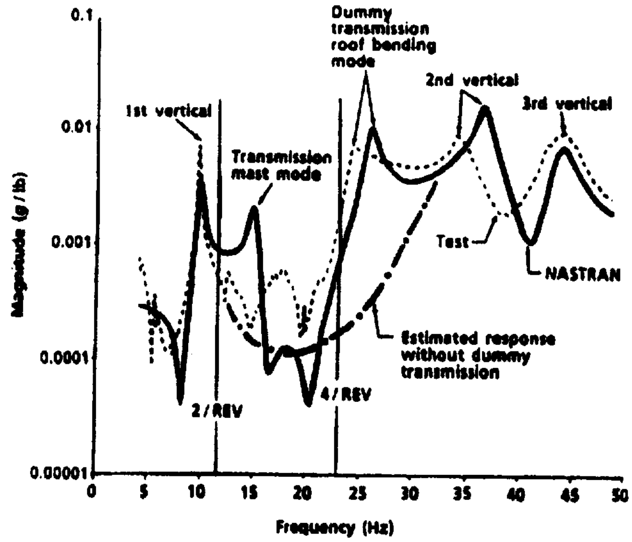


Fig. 21. Final FEM, ACAP stripped configuration – vertical load on nose, vertical response at FS 390.

figure is for reference; it indicates the modal damping value typically used for NASTRAN vibration predictions.

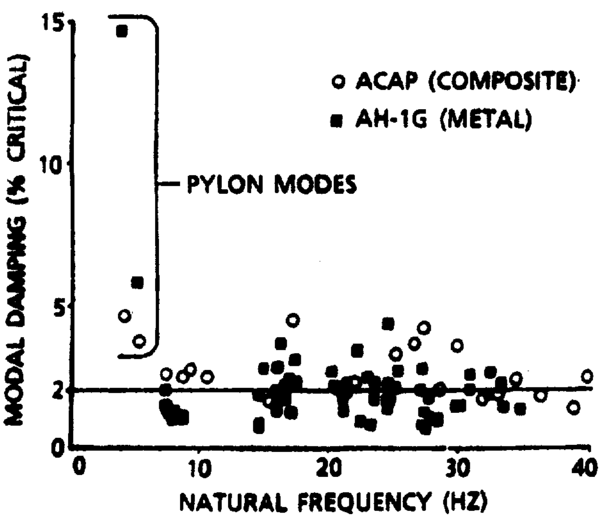


Fig. 20. Modal damping estimates from tests for composite and metallic airframes.

3. A representative comparison of the vibration vs. frequency response for the stripped-down configuration is shown in Fig. 21 and for the baseline in Fig. 22. In Fig. 21, a response line is also shown in the figure to approximate the estimated response as if the dummy pylon fixture modes (not representative of the actual structure) were eliminated and only primary structure response were included.

4. The relative stiffness of composite and metallic airframes were found to be quite different. Note in Figures 19 and 21 the relatively high frequencies of the second and third vertical modes (around 35 and 45 Hz) compared to those for the AH-1G (around 18 Hz and 30 Hz, as shown in Fig. 11). This is primarily due to the high stiffness of graphite/epoxy used in the fuselage compared to aluminum for the same strength. Note also that the ACAP first vertical bending mode is primarily tailboom bending, and that the tailboom longerons had been softened by design using glass/epoxy composite material. This helps illustrate the potential for stiffness tailoring with composites (graphite/epoxy for stiffening and glass/epoxy for softening) relative to metallic structures.

5. The correlations of the composite airframe are considered comparable to the metallic airframe. Since the basic approach to modeling the NASTRAN FEM is the same (except that the skin and panel elements are generally QUADs in composite and shear panels in metallic structures), the accuracy of vibration prediction is expected to be comparable.

Optimization

Optimization offers the opportunity to more efficiently identify key design variables early in the design, thereby leading to designs with lower vibration and lower weight.[11] A preliminary investigation into the use of optimization techniques to improve the correlations between test and analysis was conducted based on the AH-1G testing and original NASTRAN FEM before improvement. Both the University of Texas at Arlington (UTA) and Hughes Aircraft (HA) subcontracted to Bell and applied nonlinear programming (UTA) and sensitivity analysis (HA) to improve correlation of three modes of the AH-1G, i.e., the first and second vertical bending (overall airframe) and landing gear (component)

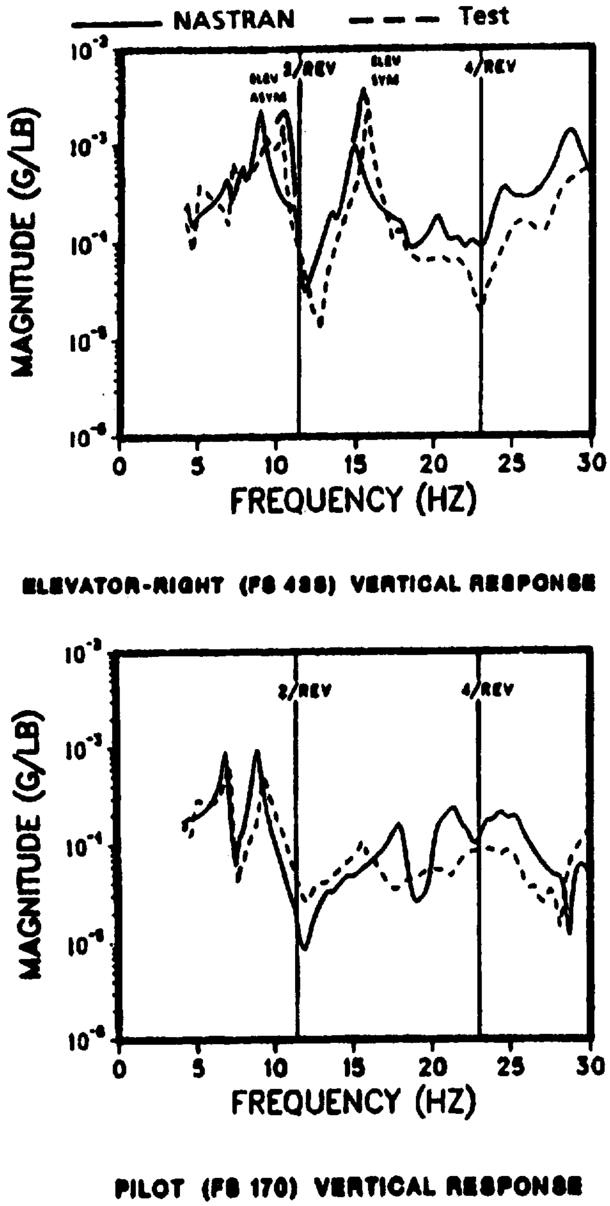


Fig. 22. Test/NASTRAN comparisons of ACAP frequency response.

modes. Structural elements of the FEM were grouped into nine design variables to reduce the size of the problem. The results are shown in the table below.

Bell has continued to pursue structural optimization and has developed a program called the Structural Optimization and Analysis Routine (SOAR) in collaboration with UTA. The SOAR program, which uses NASTRAN in the optimization analysis, includes objective functions of weight, vibration response, static displacement, and error norm for correlation with test. SOAR is described by Smith, et al.[12]

Table 1. Optimization studies on AH-1G helicopter airframe for improved test/analysis correlation.

	Natural Frequencies (Hz)			
			Revised NASTRAN model	
Mode	Test	Original NASTRAN model	Nonlinear programming*	Design sensitivity analysis**
First vertical bending	7.9	8.2	7.6	7.8
Landing gear	14.6	13.4	14.4	14.6
Second vertical bending	16.8	17.8	17.0	16.5

* Bell/University of Texas at Arlington
** Hughes Aircraft Company

Summary of Findings and Accomplishments under DAMVIBS

The NASA DAMVIBS research program provided understanding of higher frequency vibration predictions for metallic (AH-1G) and composite (ACAP) airframes and identified modeling deficiencies and potential areas for improvement in 4/rev vibration predictions. The findings and accomplishments are summarized as follows;

1. Bell conducted NASTRAN modeling, testing, and correlation exercises on the AH-1G and ACAP airframes, which were planned and reviewed with NASA and industry experts in order to ensure scientific control as well as to promote technical exchange between the companies. This approach allowed the companies to benefit from each other's knowledge and experiences as well as converge on industry modeling and correlation standards for NASTRAN vibration analysis of airframe structures.

2. Vibration correlations and measured modal damping were found to be comparable for metallic (AH-1G) and composite (ACAP) airframes.

Composites allow more design freedom for stiffness tailoring while meeting strength requirements.

3. More detail in the FEM was found to be required for higher frequency vibration correlation. For example, in the AH-1G modeling and correlation exercise, a detailed built-up FEM of the tailboom (rather than an elastic line) improved higher frequency correlations.

4. In the AH-1G correlations, inclusion of secondary structure in the forward fuselage was found to improve higher frequency correlations. The effects of the secondary structure, nonstructural panels, and canopy should be considered during the design phase.

5. Accurate vibration analysis of the main rotor pylon and isolation mounts should properly account for elastomerics, thrust stiffening, rotor dynamics effects, transmission case flexibility, and mast support bearing stiffness.

6. Further work is required to quantify the effects of nonproportional damping that appears to be more significant at the higher 4/rev frequencies than at 2/rev.

7. In the future, aeroelastic rotor analysis improvements are needed in the representation of rotor downwash and the calculation of hub loads for multibladed rotor systems. The current technology in force determination should be extended and used as a means of verifying and improving the flight vibration correlation of FEMs.

8. Structural optimization was found to be a useful tool and Bell is continuing with development of this methodology and integrating it into the design process to efficiently achieve minimum weight and vibration levels in future designs.

Acknowledgements

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