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A Government/Industry Summary of the Design Analysis Methods for Vibrations (DAMVIBS) Program

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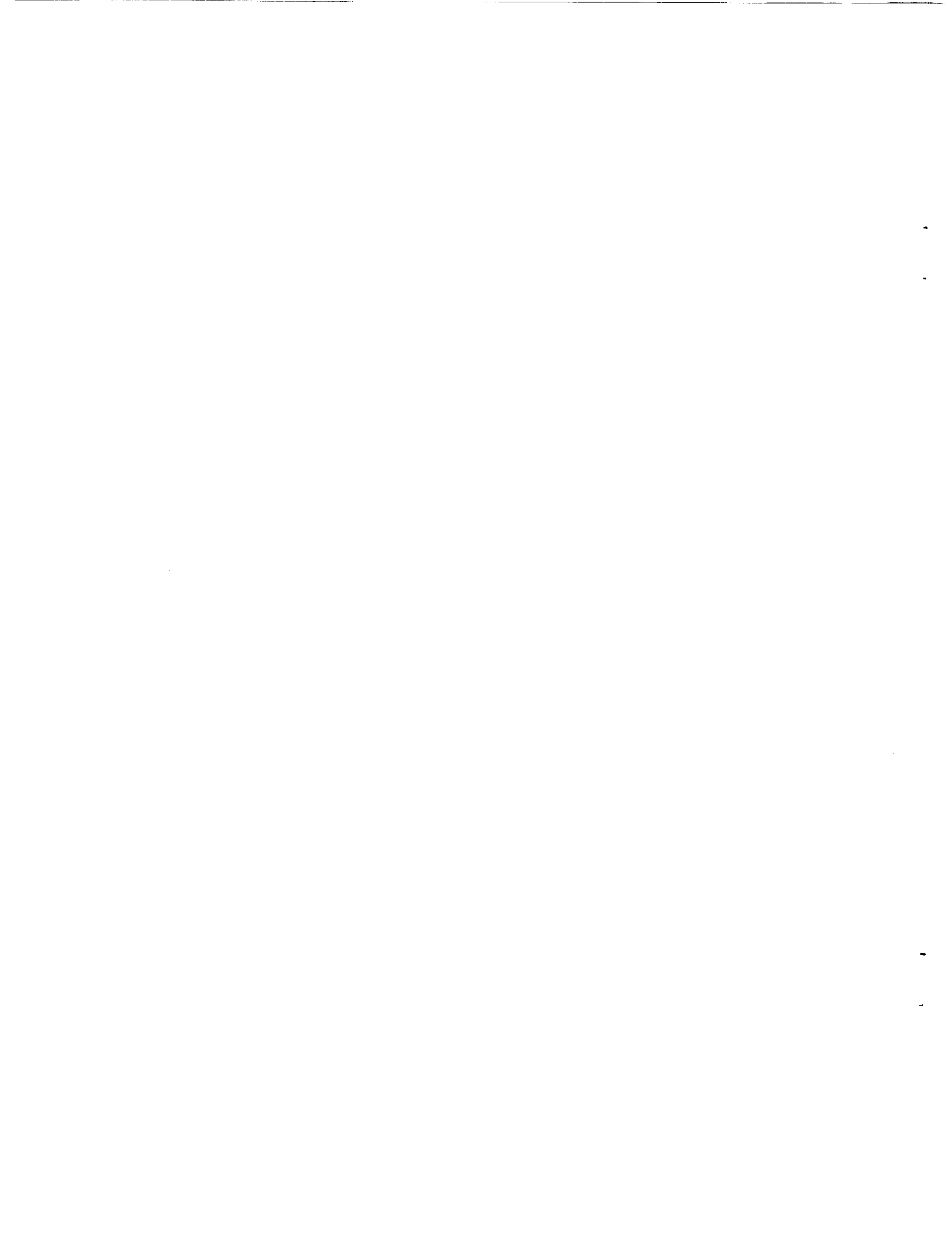
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FOREWORD

The NASA Langley Research Center in 1984 initiated a rotorcraft structural dynamics program, designated DAMVIBS (Design Analysis Methods for VIBrationS), with the objective of establishing the technology base needed by the rotorcraft industry for developing an advanced finite-element-based dynamics design analysis capability for vibrations. Under the program, industry teams from Bell Helicopter Textron, Boeing Helicopters, McDonnell Douglas Helicopter Company, and Sikorsky Aircraft have formed finite-element models, conducted ground vibration tests, and made test/analysis comparisons of both metal and composite airframes; conducted "difficult components" studies on airframes to identify airframe components which need more complete finite-element representation for improved correlation; and evaluated industry codes for computing coupled rotor-airframe vibrations. In addition, work has been initiated on establishing the role that structural optimization can play in the airframe design process and developing computational procedures useful for dynamics design work. Five Government/industry work-in-progress meetings were held in connection with the activities. An assessment of the program showed that the DAMVIBS Program has resulted in notable technical achievements and major changes in industrial design practice, all of which have significantly advanced the industry's capability to use and rely on finite-element-based dynamics analyses during the design process.

A special session on finite-element analysis of rotorcraft vibrations was held at the AIAA 33rd Structures, Structural Dynamics and Materials Conference, April 13-15, 1992, in Dallas, Texas, to collectively summarize the accomplishments and contributions of the industry participants in the DAMVIBS Program. The special session included five papers. The first paper was an overview of the program from the perspective of the NASA manager of the program. The subsequent papers presented more detailed technical summaries of the specific accomplishments of the four industry participants as viewed by their program managers. This document is a compilation of the papers presented in that special session.

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The NASA/Industry Design Analysis Methods for Vibrations (DAMVIBS) Program - A Government Overview

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Abstract

NASA-Langley, under the Design Analysis Methods for Vibrations (DAMVIBS) Program, set out in 1984 to establish the technology base needed by the rotorcraft industry for developing an advanced finite-element-based dynamics design analysis capability for vibrations. Considerable work has been done by the industry participants in the program since that time. Because the DAMVIBS Program is being phased out, a government/industry assessment of the program has been made to identify those accomplishments and contributions which may be ascribed to the program. The purpose of this paper is to provide an overview of the program and its accomplishments and contributions from the perspective of the government sponsoring organization.

Introduction and Background

Excessive vibrations have plagued virtually all new rotorcraft developments since the first U. S. helicopter went into production over 40 years ago. Although vibration levels have been reduced considerably in production aircraft during this period of time, vibration problems continue and have occurred even in modern rotorcraft designs. With only a few exceptions, vibration problems have not been identified and addressed until flight test (ref. 1). Solutions at that stage of development are usually add-on fixes which adversely impact cost, schedule, and vehicle performance. The finite-element method of structural analysis is widely used by the helicopter industry to calculate airframe static internal loads and for the usual checks on frequencies. The calculated static loads are used routinely in design for sizing structural members (refs. 2-3). Until recently, however, vibration predictions based on finite-element analyses have not been used much by the industry during design because they were considered unreliable as a basis for making design decisions (refs. 4-6).

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The problems facing analysts charged with predicting helicopter vibrations are formidable (fig. 1). The rotor system generates complex periodic aerodynamic and dynamic loads which are transmitted to the airframe both mechanically through the mounting system and aerodynamically by the rotor wake. The loads mechanically

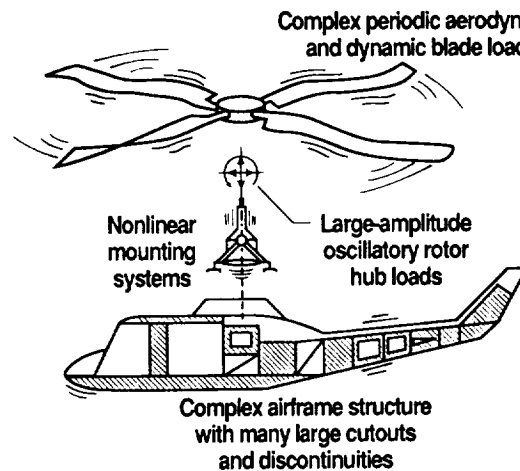


Figure 1.- Challenges confronting analysts in predicting helicopter vibrations.

transmitted are generally the larger and occur primarily at the blade passage frequency, which is equal to the product of the number of blades and the rotor rotational speed. This frequency is in the range 10 to 20 Hz for current helicopters. The airframe structural dynamics problem is complicated by the fact that helicopter airframes are light-weight, shell-type structures having multiple large cutouts and supporting several rather heavy components. Even with the advanced analysis capability offered by finite-element methods, until recently airframe structural designers have achieved only limited success in designing airframes which exhibit adequate vibratory response characteristics. A major deficiency has been an incomplete understanding of the modeling requirements for vibration analysis of complex helicopter structures. Thus, airframe dynamic analyses have not been a very effective tool in the design process. This situation has resulted in an excessive reliance on vibration control devices.

The need for more effective use of airframe finite-element models during the design process in efforts to reduce vibrations prompted industry advisory groups during the late 1970s to begin calling for NASA to work with the industry on improving the predictive capability of airframe finite-element vibration models. At about the same time, NASA's Office of Aeronautics and Space Technology formed a special task force to review rotorcraft technology needs and to prepare an appropriate agency-wide rotorcraft research program aimed at advancing technology readiness over a broad front. The draft plan cited vibrations as one of the key areas NASA intended to work as part of a proposed new 10-year rotorcraft research program. As lead center for structures research, Langley Research Center was asked to define a research activity aimed at addressing the industry's needs with respect to improving the dynamics predictive capability of finite-element models. The proposed task, which appeared in the final report of the task force (ref. 7), called for an application of finite-element vibration modeling in a workshop environment to assess and document industry modeling techniques and ground vibration test procedures. In 1980, Boeing Helicopters won a contract to conduct the subject study on the CH-47D helicopter. This study was completed in 1983.

During the course of the studies conducted on the CH-47D helicopter, it became clear that what was needed to establish the required finite-element modeling technology base was an industry-wide program in which all the companies conduct modeling, testing and correlation activities, all in a workshop environment conducive to technology transfer. As a culmination of considerable planning by NASA and the industry during the course of the CH-47D study, all in close coordination with the U. S. Army, a multi-year, industry-wide program directed at the long-term needs of the industry with respect to predicting and controlling vibrations, with primary attention to issues related to finite-element modeling, was defined. Because the objective of the expanded program was to establish the technology base needed by the industry for developing an advanced finite-element-based dynamics design analysis capability for vibrations, the new program came to be called DAMVIBS (Design Analysis Methods for VIBrationS).

The DAMVIBS Program was initiated in 1984 with the award of task contracts to the four major helicopter airframe manufacturers (Bell Helicopter Textron, Boeing Helicopters, McDonnell Douglas Helicopter Company, and Sikorsky Aircraft Division of United Technologies Corporation). Considerable work has been conducted by the industry participants in the program since that time. Five government/industry workshops have been held to review and discuss results and experiences of those activities. Because the DAMVIBS Program is being phased out, the last meeting included a special session devoted to an assessment of the program to identify

those accomplishments and contributions which may be attributed to the program.

The purpose of this paper is to provide an overview of the DAMVIBS Program and its accomplishments and contributions, including the initial finite-element modeling study which was conducted on the CH-47D, from the perspective of the government sponsoring organization. Emphasis throughout is on contractor results. A more complete summary of the DAMVIBS Program, which also includes contributions to the program resulting from in-house research activities as well as funded university work, may be found in reference 8.

Initial Finite-Element Modeling Program (The CH-47D Study)

Objective/Scope/Approach

The vibrations work proposed by the NASA rotorcraft task force (ref. 7) was to involve participation by NASA and the industry in a workshop environment to assess and document industry modeling techniques and ground vibration test procedures. All the work was to be done on a production aircraft. As a result of a competitive procurement, a contract was awarded to Boeing Helicopters in 1980 to conduct such a study on the CH-47D tandem-rotor helicopter. The contract required that plans for the modeling, testing and correlation be formulated and submitted to both government and industry representatives for review prior to undertaking the actual modeling and testing. In particular, modeling guides were required as part of the modeling plan for each unique type of structural member in the CH-47D airframe. Boeing was also required to make a study of current and future uses of finite-element models and to keep meticulous records on the man-hours required to form the vibration model. The work was deliberately slow paced to allow for the necessary extensive government/industry interactions and technical exchanges. The studies conducted on the CH-47D have been extensively documented in a series of NASA Contractor Reports (refs. 9-13).

Illustrative Results and Key Findings

The finite-element model developed as part of the study is shown in figure 2. An extensive ground vibration test was also conducted on the airframe (fig. 3). The airframe was excited by forces vertically, longitudinally, and laterally and by moments in pitch and roll at both the forward and aft hubs over the frequency range from 5 to 35 Hz. While the correlations obtained between measured and calculated responses (see, for example, fig. 4) are considerably improved over previous work, particularly at the lower frequencies, the predicted responses were found to exhibit acceptable agreement with test only up to about 15-20 Hz.

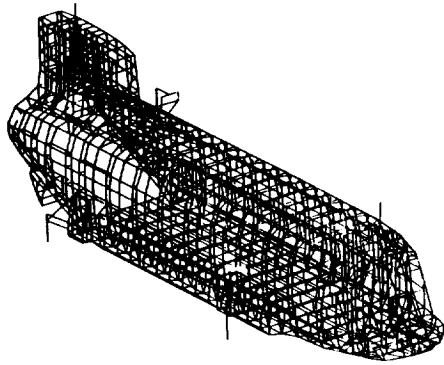


Figure 2.- CH-47D finite-element model.



Figure 3.- Ground vibration test of CH-47D.

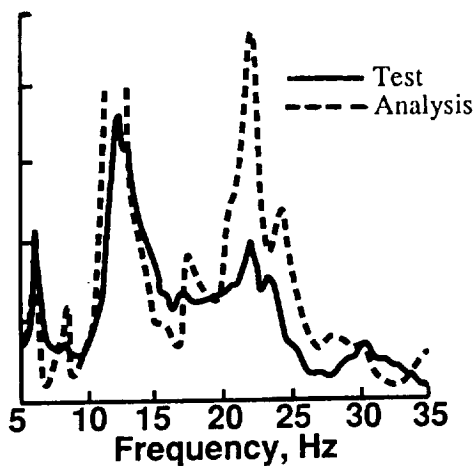


Figure 4.- Comparison of measured and calculated responses of CH-47D for lateral excitation at forward hub.

The CH-47D studies identified several modeling considerations which have the potential for improving the correlation if accounted for in the finite-element analysis. For example, the effects of support systems and excitation systems on airframe elastic responses measured in a ground vibration test are typically assumed to be negligible and finite-element models are usually formed for the airframe in a free-free (unrestrained) configuration. A method for including these effects in the finite-element dynamic analysis while taking into account the prestiffening effects due to gravity was devised by a NASA team and applied to the CH-47D by Boeing. While only minor effects were noted for the CH-47D, the effects may not be negligible for other configurations, particularly at the higher frequencies. Two issues related to the modeling of stringers were identified and shown to be important. The first concerns the treatment of stringers which are discontinuous across manufacturing splices. The upper portion of such joints is in compression under 1-g loading, resulting in effective axial continuity of unconnected stringers. The second issue concerns stringer shear area. Although airframes usually contain many stringers, the cross-sectional areas of the stringers are not considered as contributing to the total effective shear area of a cross section because of the usual assumption which is made that the skin carries all the shear load. Analytical studies made using the CH-47D finite-element model showed that the shear load carried by the stringers may not be negligible as previously assumed.

Several other findings emerged from the CH-47D studies. A finite-element model was judged to be an essential ingredient of any design effort aimed at developing a helicopter with low inherent vibrations. Modeling guides prepared during the planning phase enabled proper planning, scheduling, and control of the modeling effort. Up-front planning of the static and dynamic finite-element models before modeling begins was shown to be the key to forming a single model suitable for computing both static internal loads and vibrations and to improving the quality of the models. It was clearly established that a finite-element model suitable for the computation of both static internal loads and vibrations can be formed early enough in a new helicopter development program to actually influence the airframe design. The cost of such a model was shown to be about 5 percent of the total airframe design effort. Because 4 percent is typically expended for the static model, the vibration model is only another one percent. While the correlations which have been obtained are much improved over previous work, particularly at the lower frequencies, the correlation needs to be improved at the higher frequencies. Significantly improved correlation appears possible by including in the models effects historically considered to be unimportant dynamically, such as the shear load carrying capability of stringers and the dynamics of airframe ground vibration test suspension systems.

DAMVIBS - The Expanded Finite-Element Modeling Program

Formative Influences

During the course of the CH-47D study it became clear that the key to improving modeling technology and engendering in the industry the needed confidence to use finite-element models for vibrations design work was more hands-on experience along the lines of the CH-47D study. Also identified as being essential was a workshop environment which fostered the open discussion of airframe finite-element modeling issues, techniques, and experiences. The CH-47D experience, the continuing validity of the NASA Task Force Report, and the need of the industry for an advanced vibrations design analysis capability were the catalysts for the Langley Research Center to begin formulating an expanded finite-element modeling program involving the four primary helicopter airframe manufacturers (Bell Helicopter Textron, Boeing Helicopters, McDonnell Douglas Helicopter Company, and Sikorsky Aircraft Division of United Technologies Corporation). As a culmination of considerable planning and coordination work by NASA and the industry, a multi-year program was defined, approved by NASA, and subsequently implemented in 1984 with the award of task contracts to the aforementioned companies. As mentioned earlier, because the emphasis of the program was to be on improving finite-element analyses for supporting vibrations design work, the program came to be called DAMVIBS (Design Analysis Methods for VIBrationS).

Objective/Scope/Approach

The overall objective set down for the DAMVIBS Program was the establishment in the U. S. helicopter industry of an advanced capability to utilize airframe finite-element models in analysis of rotorcraft vibrations as part of the regular airframe structural design process. The intent was to achieve a capability to make useful analytical predictions of helicopter vibration levels during design, and to design on the basis of such predictions with confidence.

The scope of the DAMVIBS Program, as laid out in 1984 when it was made the focus of a new rotorcraft structural dynamics program which was initiated at Langley at that time, is shown in figure 5. Four technology areas were to be worked under the DAMVIBS Program: (1) Airframe Finite-Element Modeling; (2) Difficult Components Studies; (3) Coupled Rotor-Airframe Vibrations; and (4) Airframe Structural Optimization. Primary emphasis was to be on the first two elements of the program, which were intended to be mainly an industry effort focusing on industrial modeling techniques. Under the last two

elements of the program, the finite-element models formed by the industry were to be used by government, industry and academia as the basis for the development, application, and evaluation of advanced analytical and computational techniques related to coupled rotor-airframe vibrations and to airframe structural optimization under vibration constraints.

DAMVIBS - A FOCUSED PART OF THE NASA ROTORCRAFT STRUCTURAL DYNAMICS PROGRAM

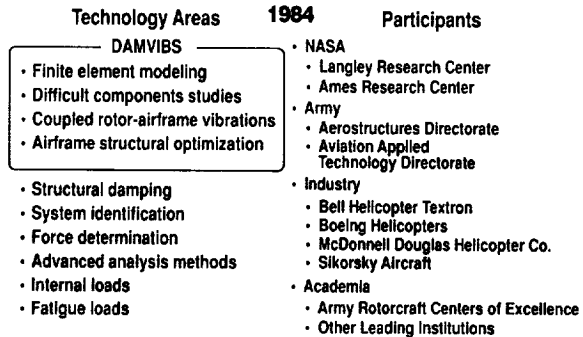


Figure 5.- DAMVIBS positioned as focus of Langley rotorcraft structural dynamics program.

To maintain the necessary scientific observation and control, emphasis throughout these activities was to be on advance planning, documentation of methods and procedures, and thorough discussion of results and experiences, all in a workshop environment to allow maximum technology transfer between companies.

Illustrative Results and Key Findings

Airframe Finite-Element Modeling.- The purpose of this program element was to develop state-of-the-art finite-element models for internal loads analysis and vibrations analysis of airframes of both metal and composite construction. The activities included modeling, testing, and test/analysis correlation. The main technical products of this series of activities were to be: (1) Basic modeling guides; (2) Validated models of significant airframes; and (3) Identification of needed research tasks aimed at strengthening finite-element modeling. Each contracted activity was to produce a well-documented model of the subject aircraft that could be used and studied by groups other than the developers. Ground vibration tests were to be conducted as required for correlation with analytical results. Whenever practical, however, existing experimental results were to be used to the fullest extent possible.

Industry teams have formed finite-element models (fig. 6), conducted ground vibration tests (fig. 7), and made extensive test/analysis comparisons (fig. 8) of both metal and composite airframes. The results of these studies are described fully in references 14-22. In a related activity, a company-developed method for identifying modeling errors which can arise while forming a finite-element model (ref. 23) was publicized and subsequently adopted by the other companies.

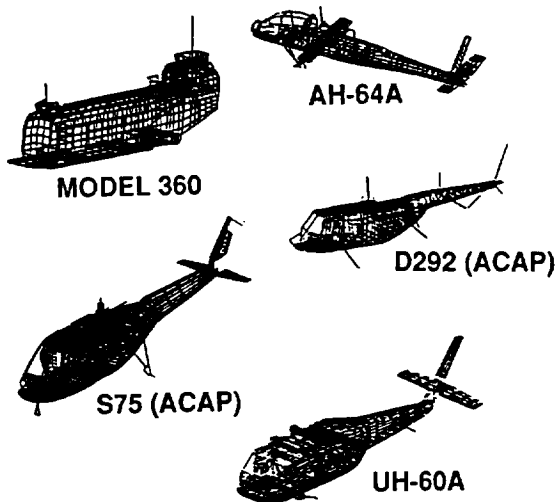


Figure 6.- Finite-element models formed.

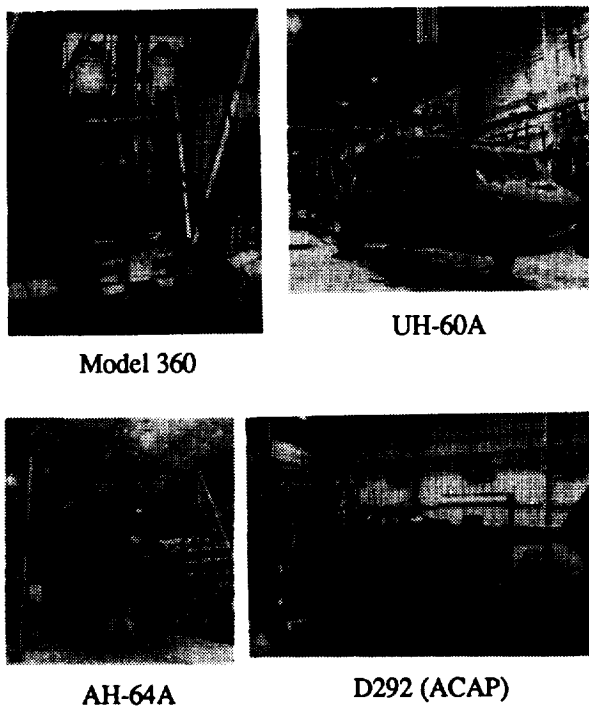


Figure 7.- Ground vibration tests conducted.

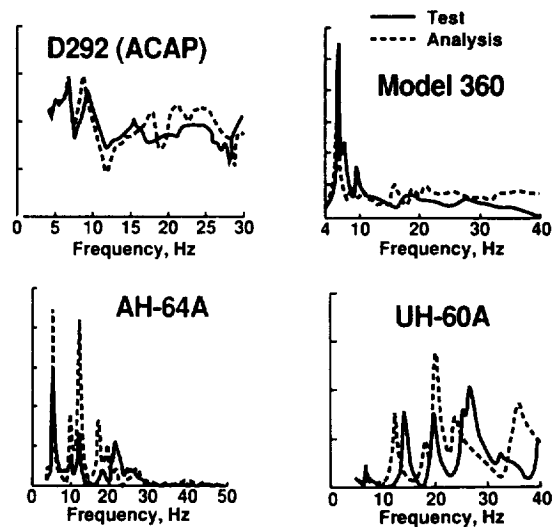


Figure 8.- Typical test/analysis comparisons of airframe frequency response amplitudes.

The Airframe Finite-Element Modeling studies have reaffirmed that up-front planning before modeling begins reduces the effort needed to form unified static and dynamic models and improves the quality of the initial models. To form such models, the statics, dynamics, and weights groups need to work closely together to adopt modeling procedures which are compatible with both static and dynamic modeling requirements. These studies have confirmed the finding of the CH-47D study that a finite-element vibration model can be formed early enough to influence the design of a new airframe and that the cost of such a model is quite nominal if the static model has to be formed. Structural modeling techniques for both metal and composite airframes are relatively uniform within the industry. Modeling techniques for metal and composite airframes are similar except for the determination of element material properties. These properties are significantly more difficult to generate for composite airframes because the composition of the laminate for each structural element must be determined from design drawings, analyzed for its resultant stiffness, and the result transferred to the finite-element model. Test/analysis comparisons for all the airframes studied indicate that agreement is good up through about 10 Hz, only partially satisfactory from about 10-20 Hz, and generally unsatisfactory above about 20 Hz. The dynamics of composite airframes are more difficult to predict than for metal airframes. Ground vibration tests indicate that support system effects can be important and may need to be routinely included as part of the airframe finite-element model. Damping levels were found to be essentially the same in both metal and composite airframes. Better definition and representation of damping is needed in finite-element analyses.

Difficult Components Studies.- In the basic modeling studies conducted under the DAMVIBS Program only the primary (major load carrying) structure was represented fully (stiffness and mass) when forming the finite-element models. However, as depicted in figure 9 for the AH-1G, there are many components and secondary structure which are represented in the model only as lumped masses. While this is consistent with customary modeling practice, this may be a major contributing factor to the poor agreement which has been noted between test and analysis at the higher frequencies of interest. The aim of the difficult components studies is to identify the effects of such modeling assumptions and to develop improved modeling guides for components which are determined to require better representation for improved correlation. Difficult components studies have been conducted on the all-metal AH-1G and the all-composite D292 and are presently underway on the all-composite S75.

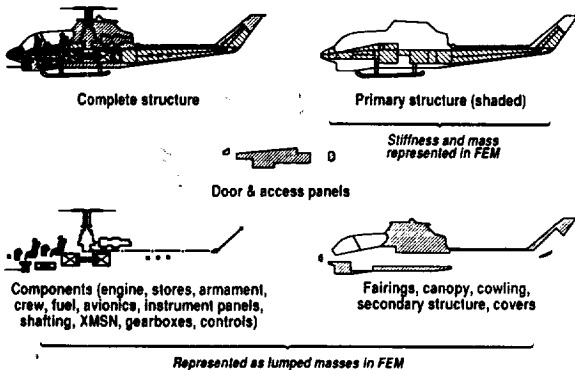
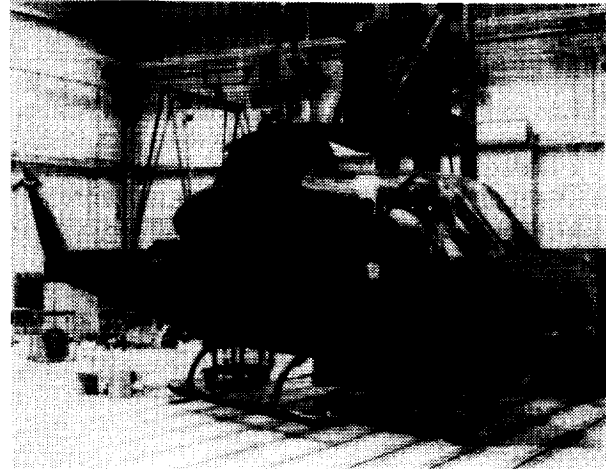
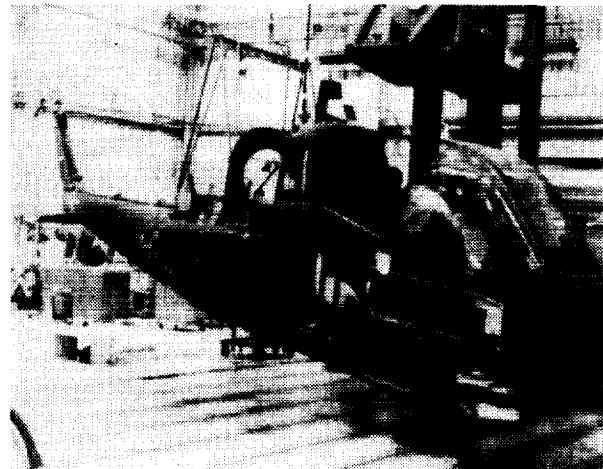


Figure 9.- Usual treatment of airframe structure in finite element modeling.

The first difficult components study was conducted by Bell on the AH-1G helicopter, a detailed account of which is given in reference 24. The airframe in its full-up ground vibration test configuration is shown in figure 10a. Components were then progressively removed from the aircraft - main rotor pylon/transmission assembly, secondary structure panels, tail rotor drive shaft, skid landing gear, engine, and fuel - to arrive at the configuration shown in figure 10b. The canopy glass, various black boxes, and the stub wings were then removed in the last step of the strip down. At each stage, a ground vibration test and an analysis based on an existing finite-element model that was modified to reflect the specific configuration tested were performed and the results compared. Comparisons of measured and predicted changes in response were then used to identify components which were causing prediction difficulties and which therefore required better modeling treatment. For example, the



(a) Complete airframe



(b) Stripped-down airframe

Figure 10.- Difficult components study of AH-1G.

secondary structure panels under the canopy from just aft of the nose to just forward of the wings and the canopy glass were found to have a considerable effect on the response at the higher frequencies.

Based on the results of such comparisons, the finite-element model was updated to include some of the effects which were found to be important. The improved model was then used to reanalyze each of the configurations tested. The improvement in the predicted frequencies is indicated in figure 11. In that figure the predicted natural frequencies are plotted versus the measured frequencies for all the major configurations tested using both the initial and updated finite-element models. In each case, perfect agreement is along the solid line. It is seen that the natural frequencies calculated using the updated model are generally within 5 percent of test values, compared to 20 percent using the initial model.

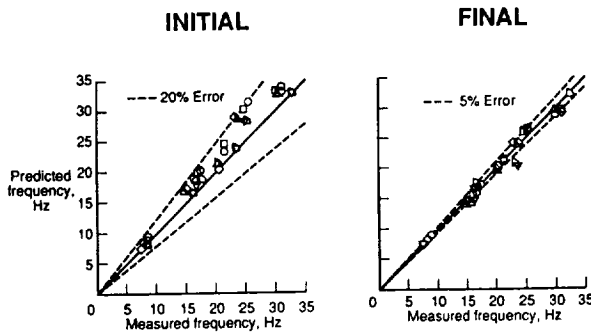


Figure 11.- AH-1G natural frequency comparisons using initial and improved models.

A difficult components study was recently completed on the D292 helicopter (ref. 25). The ground vibration test was conducted by the Army's Aviation Applied Technology Directorate at Fort Eustis as part of the subject investigation. Natural frequencies calculated using an updated model were within 10 percent of test values, compared to 20 percent using the initial model. Ground vibration tests are underway by the Army on the S75 helicopter as part of the difficult components investigation which is being conducted on that helicopter airframe. The finite-element model to be used by Sikorsky in the analytical portion of that investigation was shown in figure 6. This is the last contracted task to be performed under the DAMVIBS Program.

The Difficult Components Studies have shed new light on the importance of many airframe components on vibratory response at the higher frequencies of interest. The stiffness of tight secondary structure panels and sealed canopy glass must be modeled. A lumped-mass representation is generally sufficient for such components as the tail rotor drive shaft, engines, fuel, and soft-mounted black boxes. Elastic-line representations appear to be adequate for such components as the main rotor pylon/transmission, skid landing gear, and wings, but wholly inadequate for beam-like tail booms at the higher frequencies of vibration. Nonlinear effects of elastomeric mounts and "thrust stiffening" are important at low frequencies. Considerably improved correlation is possible if secondary effects which have typically been regarded as unimportant dynamically are taken into account when forming the finite-element model. This means that finite-element models for vibration analyses need to be substantially more detailed than the usual static model, contrary to what was previously thought.

Coupled Rotor-Airframe Vibrations.- The object of this program element is to evaluate and improve existing comprehensive methods for computing coupled rotor-airframe vibrations and to develop new computational procedures which are better suited to the repetitive analyses which are required in airframe vibrations design work. Emphasis throughout was to

be on the airframe and its coupling with the rotor to compute vibrations of the coupled system. The task did not include the improvement of rotor mathematical models for vibration predictions.

In what was the first comparative evaluation of industry codes for comprehensive analysis of coupled rotor-airframe vibrations, teams from each of the companies have applied different analysis methods to calculate the vibrations of the AH-1G helicopter in steady level flight and compared the results with existing flight vibration data (ref. 26). Figure 12 shows a representative comparison of the 2/rev (twice per rotor revolution) vertical and lateral vibrations predicted by the companies with vibrations measured in flight (refs. 27-30). (Recall that 2/rev is the primary main rotor excitation frequency for the two-bladed AH-1G.) It is seen that the predicted 2/rev vibrations are not in good agreement with measured values. This study showed that industry codes for performing comprehensive vibration analysis of coupled rotor-airframe systems are not yet good enough to be relied on during design. Some ancillary studies conducted as part of this investigation indicated that the impingement of the main rotor wake on the vertical tail contributes to the lateral vibrations. This suggests that both mechanical and aerodynamic load paths into the airframe may be equally important and may need to be included in the computation of coupled rotor-airframe vibrations. The companies have been working to improve their comprehensive coupled rotor-airframe analysis codes since the completion of this study and it is expected that a much-improved capability to predict system vibrations will emerge.

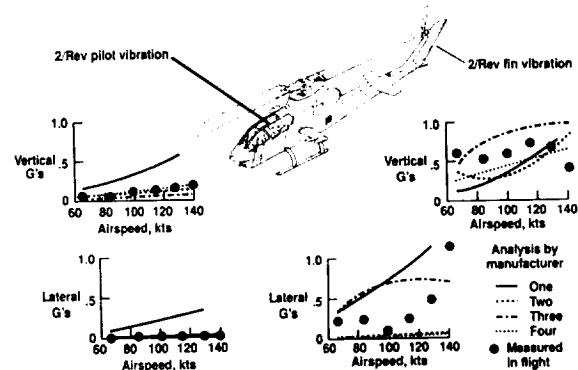


Figure 12.- Industry comparisons of measured and predicted 2/rev vibrations of AH-1G helicopter.

While the final analytical verification of a design for vibrations will require the use of a comprehensive system analysis which is based on a complex rotor mathematical model, it appears that useful predictions of airframe vibrations can be made during design using simpler models. To investigate this possibility, a

cooperative study was recently undertaken by NASA-Langley and the U. S. Military Academy which is aimed at establishing the minimum level of structural and aerodynamic sophistication required in rotor mathematical models for use in coupled rotor-airframe vibration analyses which are intended to support airframe dynamics design work.

Airframe Structural Optimization.- The use of traditional rotor and airframe design techniques to limit inherent vibrations is receiving renewed attention by the industry. It is recognized that structural optimization techniques, if properly brought to bear by the designer, could go a long way toward achieving a low-vibration helicopter. With this in mind, design optimization codes combining finite-element structural analyses with nonlinear programming (NLP) algorithms are in various stages of development in both government and industry. While the DAMVIBS Program contained a technology area called Airframe Structural Optimization, no optimization tasks were ever issued under the contracts. However, under company sponsorship, Bell Helicopter Textron conducted some limited studies related to the use of optimization techniques to improve correlation between measured and computed natural frequencies during the AH-1G difficult components study. It should be remarked that all of the industry participants in the DAMVIBS Program are now moving forward in this area under company sponsorship.

An in-house study has been underway at Langley to investigate the use of formal, NLP-based, numerical optimization techniques for airframe vibrations design work. These studies, which have made extensive use of existing finite-element models of the AH-1G, have shown that structural optimization techniques have considerable potential for playing a major role in airframe vibrations design work, but only if the design models which are required in optimization algorithms adequately reflect the nuances of airframe design.

Assessment of Program

Five government/industry workshops have been held at Langley Research Center during the course of the DAMVIBS Program to review and discuss completed work. Because the DAMVIBS Program is being phased out, the last workshop included a session devoted to an assessment of the program. The assessment, which was made by NASA-Langley and the four industry participants in the program, indicated that considerable progress has been made toward the overall objective of building a design-for-vibrations capability in the U. S. helicopter industry. The DAMVIBS Program was cited for resulting in notable technical achievements and leading to changes in industrial design practice, all of which have significantly advanced the industry's capability to use and rely on airframe finite-element models in analy-

sis of vibrations during design. The assessment also identified several key continuing and new structural dynamics challenges which must be met if the industry is to achieve the goal of a helicopter with a "jet smooth" ride.

Major Accomplishments and Contributions

The major accomplishments and contributions include the following:

- (1) Developed industry-wide standards for basic modeling of metal and composite airframes.
- (2) Improved industrial finite-element modeling techniques for analysis of airframe vibrations.
- (3) Resulted in changes/improvements in industrial design practice for vibrations.
- (4) Reversed industry management perception of the utility of finite-element models for vibration predictions. For the first time, such models are being relied on for airframe vibrations design work.
- (5) Identified critical structural contributors to airframe vibratory response which require better finite-element modeling.
- (6) Showed that considerably improved correlation can be obtained if modeling details which have been historically regarded as of secondary importance are taken into account.
- (7) Provided a unique leadership role and focal point for rotorcraft structural dynamics research in government, industry, and academia.
- (8) Provided the basis for the industry to move forward aggressively on its own to further enhance its capabilities in the subject areas.

Key Continuing/New Challenges

The key continuing and new structural dynamics challenges which were identified are:

- (1) Extend the predictive capability of finite-element models up through the 25-30 Hz frequency range.
- (2) Devise methods for improving models at the finite element level using ground vibration test data.
- (3) Develop analytical techniques which more realistically account for structural damping for use in airframe vibrations design work.
- (4) Improve the predictive capability of current comprehensive codes for analysis of coupled rotor-airframe vibrations.

- (5) Develop simplified rotor mathematical models which are suited for the repetitive analyses required in airframe vibrations design work.
- (6) Define the role of structural optimization in the airframe design process and develop computational procedures tailored for vibrations design work.
- (7) Develop new/improved methods for actively and passively controlling airframe structural response.

Concluding Remarks

In 1984, NASA-Langley, under the Design Analysis Methods for Vibrations (DAMVIBS) Program, set out to establish the technology base needed by the rotorcraft industry for developing an advanced finite-element-based dynamics design analysis capability for vibrations. Considerable work has been done by the industry participants in the program since that time and the program is now being phased out. A recent government/industry assessment of the program has indicated that the DAMVIBS Program has provided the leadership role and focal point for the type of structural dynamics research which was needed by the industry. The program has resulted in notable technical achievements and changes in industrial design practice, all of which have significantly advanced the industry's capability to use and rely on airframe finite-element models in analysis of vibrations during design. Building on the experience of the DAMVIBS Program, each of the industry participants is moving forward aggressively under company sponsorship to further enhance their prowess in the subject areas. As a result, it is expected that the industry will emerge with a substantially-improved finite-element-based dynamics design analysis capability, which should go a long way towards meeting the dynamics design challenges of the next generation of rotorcraft.

Acknowledgements

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Gabel (Boeing), Mostafa Toossi (McDonnell Douglas), and William J. Twomey (Sikorsky) were the project engineers who headed up the respective industry teams.

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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:

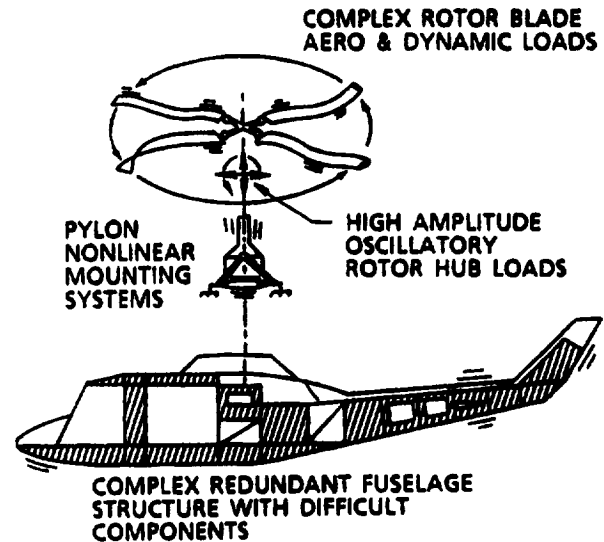


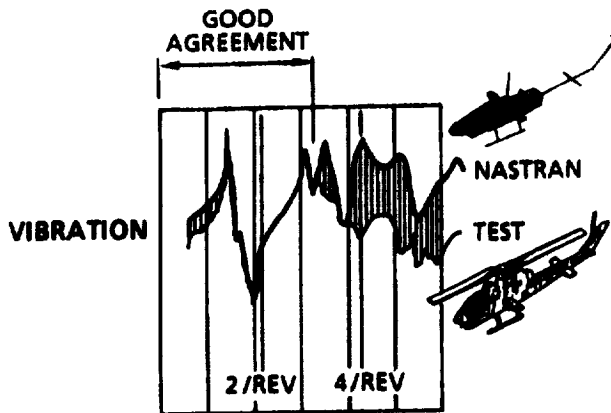
Fig. 1. Problems with vibration prediction.

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 analysis¹ 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 $2/\text{rev}$ 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 $2/\text{rev}$ 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 C81⁴ were considered adequate at 2/rev; but there was lower confidence in the higher frequency range, which requires greater sophistication in the aerodynamic representation.



PROBLEM: HIGHER FREQUENCY CORRELATION (> 3/REV) NEEDS IMPROVEMENT

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

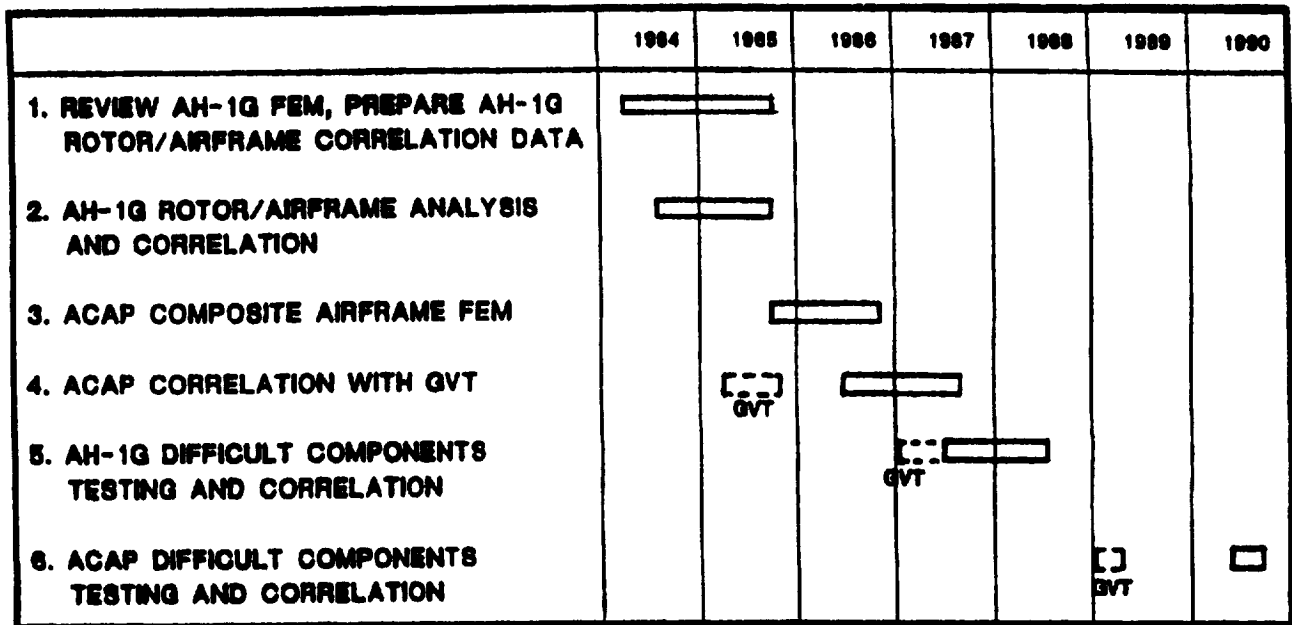
An existing AH-1G NASTRAN finite element model (FEM) that was developed under NASA/Army funding⁵ was used for correlations with flight vibration measurements and ground vibration testing to investigate the effects of difficult components. The existing original AH-1G FEM is shown in Fig. 4. This model 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 Correlations⁶

Bell's current methodology for airframe vibration prediction is illustrated in Fig. 5. A Myklesstad rotating beam analysis⁷ 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 survey⁸ 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



INDUSTRY/GOVT MEETINGS AT LANGLEY

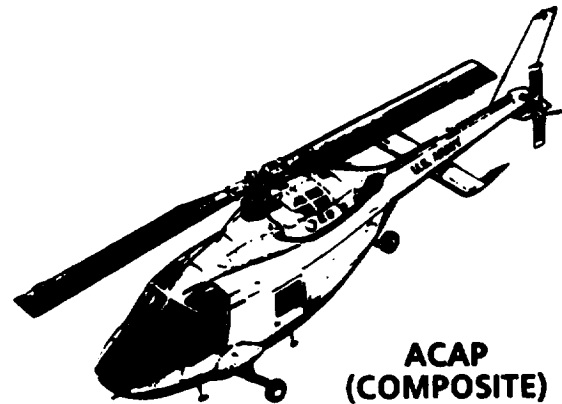
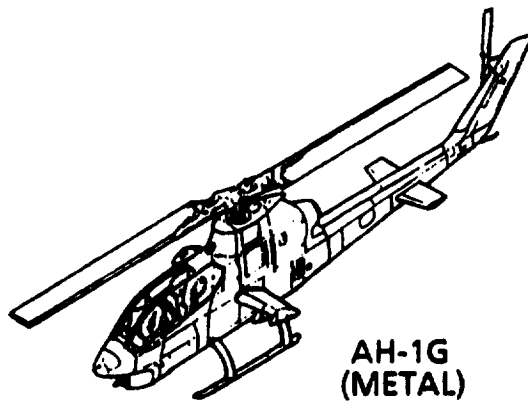
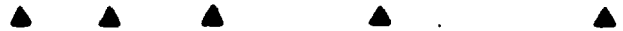


Fig. 3. Bell tests under NASA DAMVIBS research program.

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

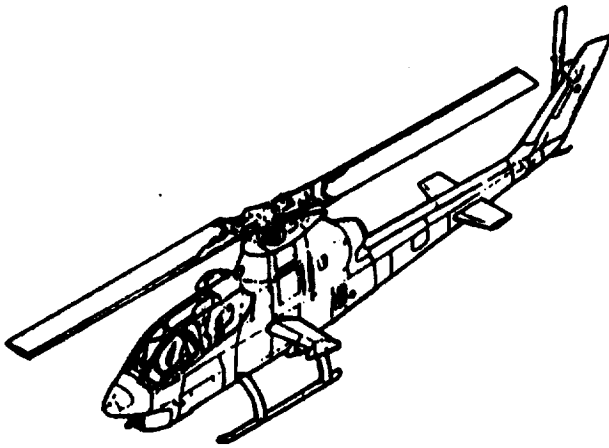
2. As shown in Fig. 6, there was fairly good agreement between calculated and measured vertical 2/rev (10.8 Hz) vibration. The 2/rev frequency is the predominant excitation frequency of the AH-1G two-bladed rotor, producing the most significant flight vibration levels.

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_{jj}	235	TRMEM	243
		ELAS2	13

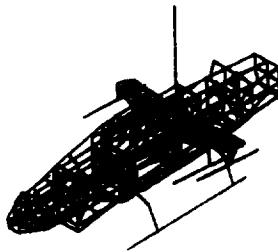


Fig. 4. Original AH-1G NASTRAN FEM.

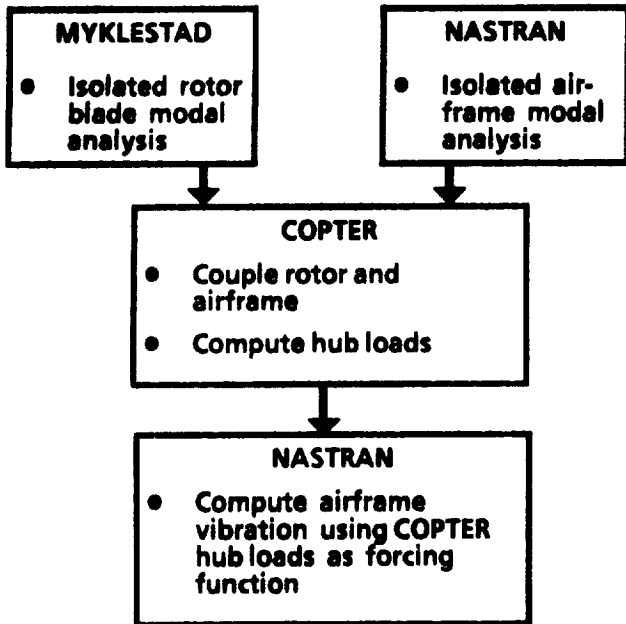
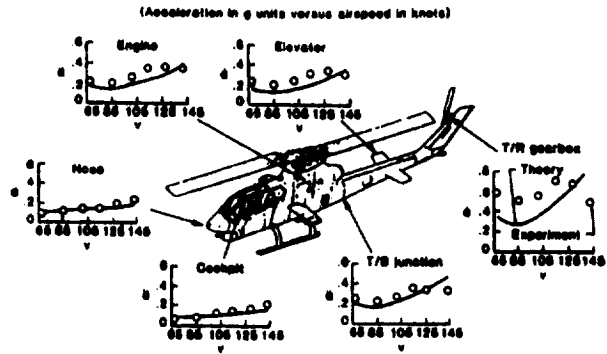
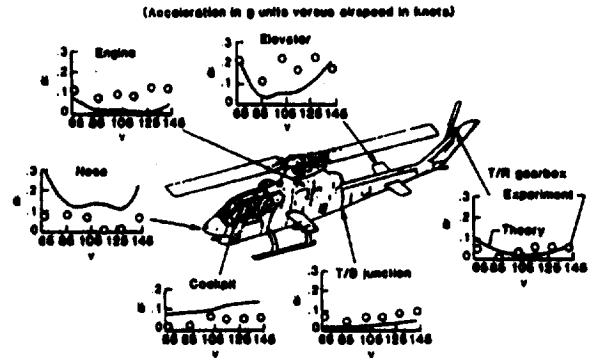


Fig. 5. Bell's procedures for airframe vibration prediction.



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.

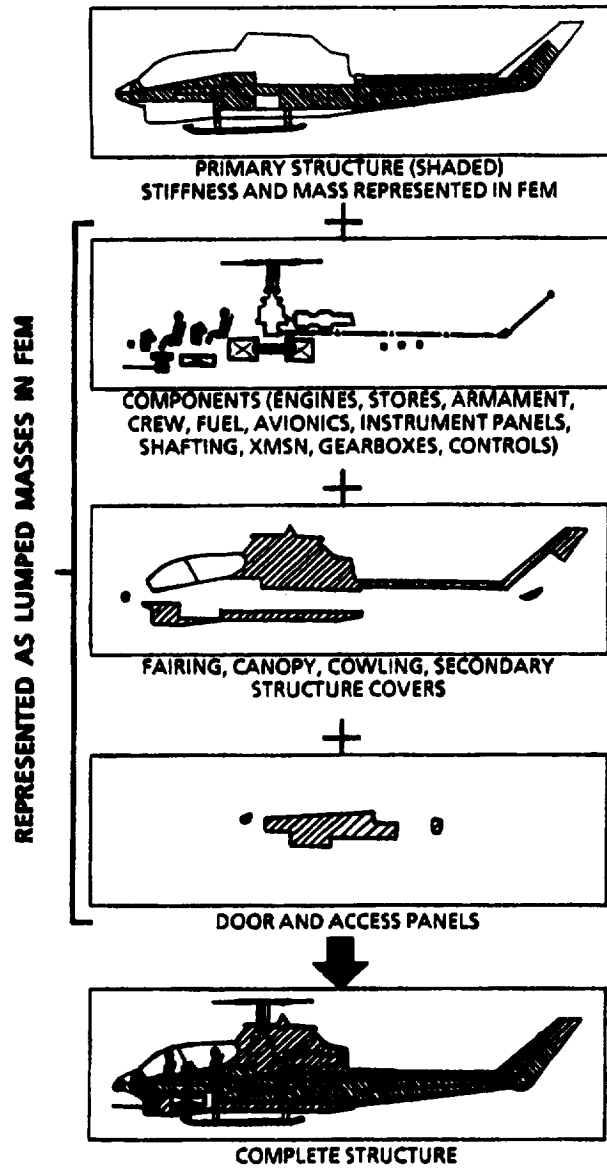
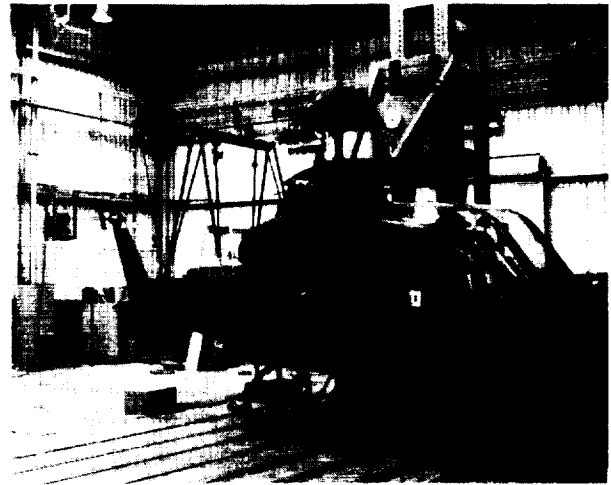


Fig. 7. Difficult components study: AH-1G model correlations with test.

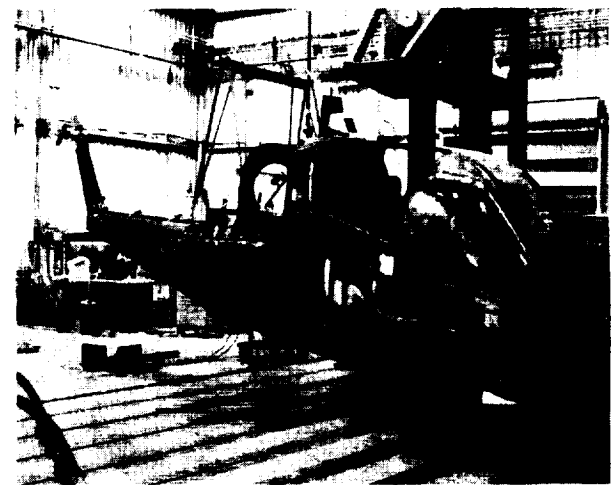
4. Tail rotor drive shaft and cover removed.
5. Skid landing gear removed.
6. Engine removed.
7. Fuel removed.
8. Canopy glass, black boxes, and wings removed.

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



FULL AIRCRAFT



ALL COMPONENTS REMOVED

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

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.

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

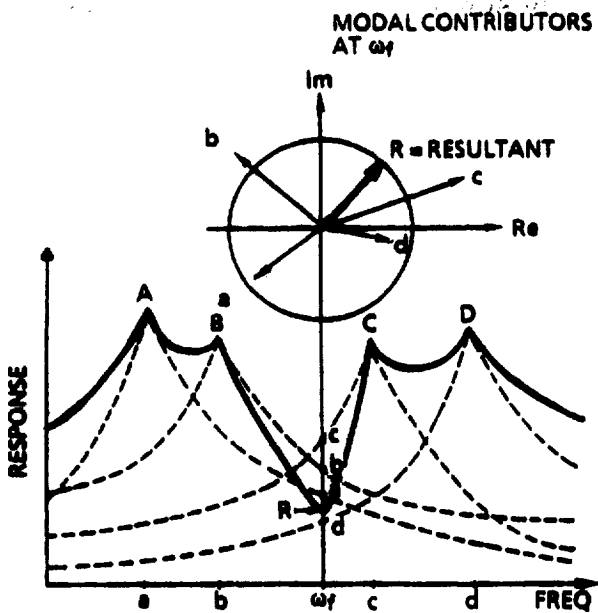


Fig. 9. Frequency response using modal contributors.

DEGREE OF FREEDOM		ELEMENTS	
$K_{\theta\theta}$	4619	BAR	358
K_{nn}	4228	ROD	3072
K_{ff}	2965	SHEAR	540
$K_{\theta n}$	241	QDMEM	160
K_{ff}	235	TRMEM	243

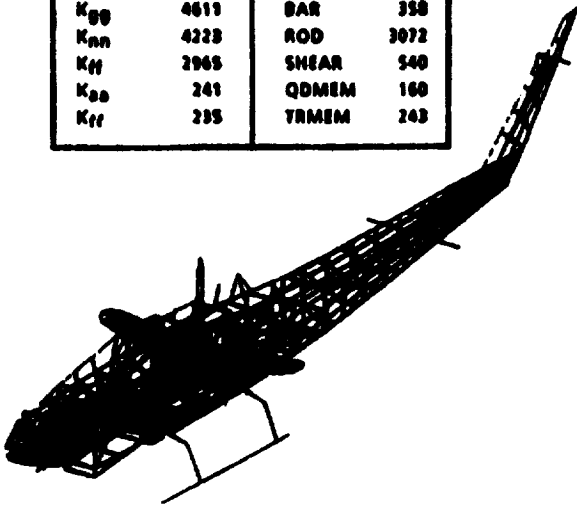
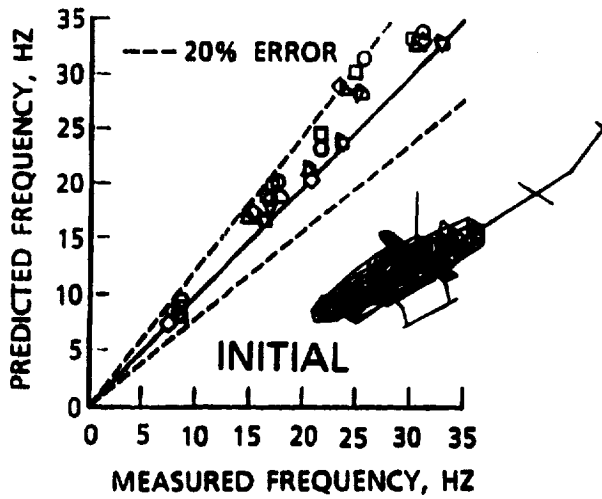


Fig. 10. Improved AH-1G NASTRAN FEM.

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



ALL COMPONENTS REMOVED } CONFIGURATION
 ○ 8
 □ 7
 ◇ 5
 △ 4
 ▽ 3
 FULL A/C } D 2
 ▽ 1

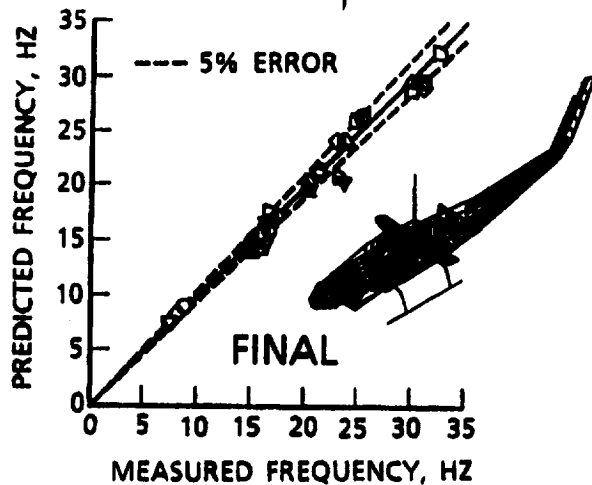


Fig. 11. AH-1G natural frequency comparisons.

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).

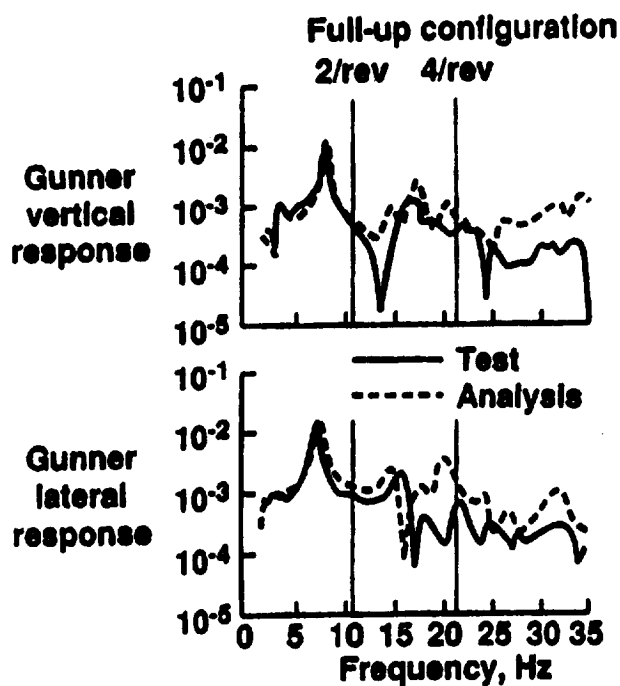


Fig. 12. Test/NASTRAN comparisons of AH-1G response.

- 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.

Composite Airframe (ACAP) Correlations

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

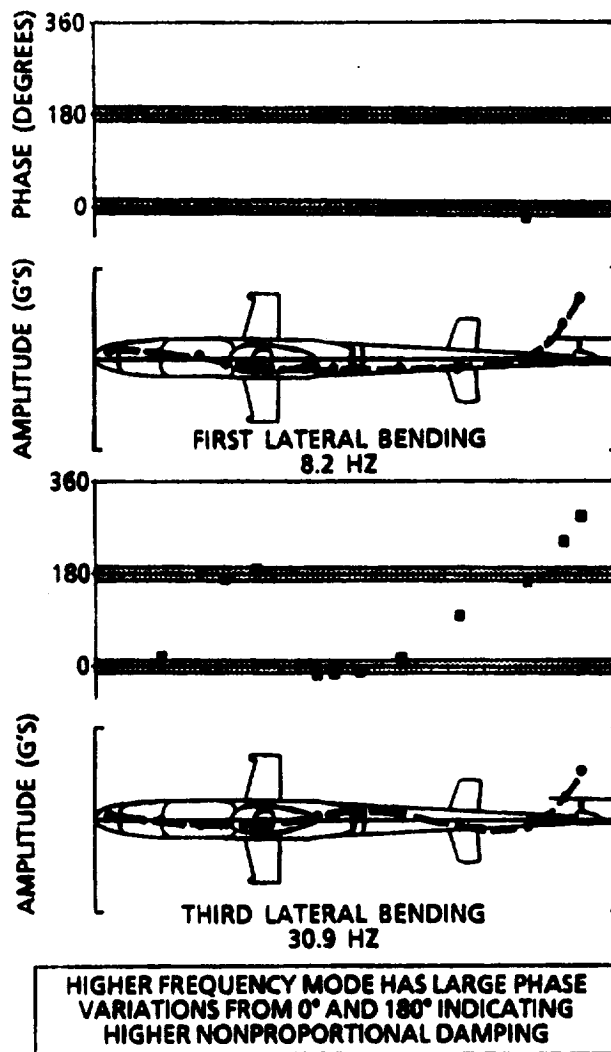


Fig. 13. Example of nonproportional damping effects.

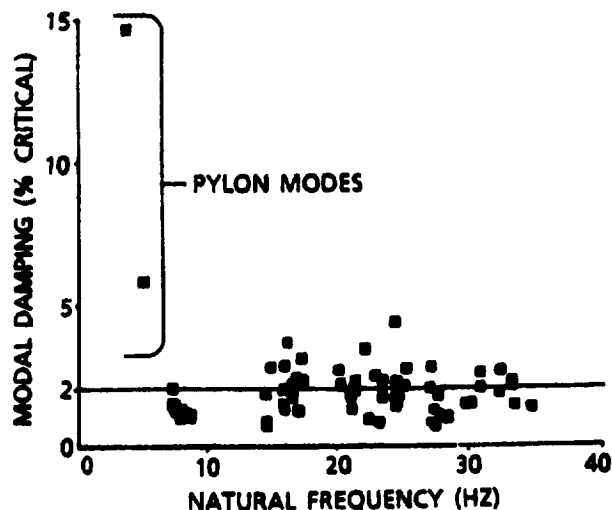


Fig. 14. AH-1G modal damping estimated from ground vibration tests.

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

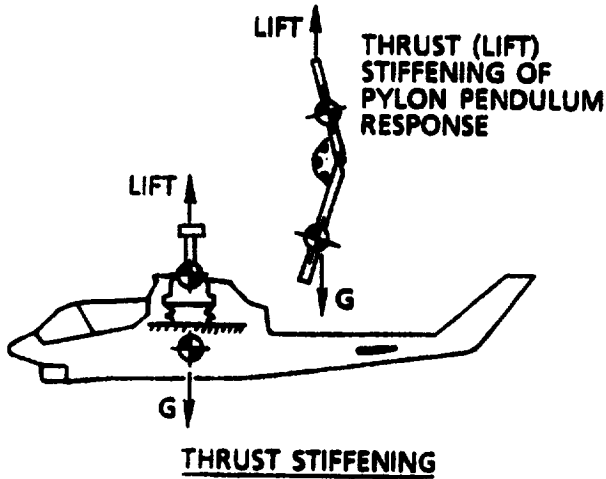
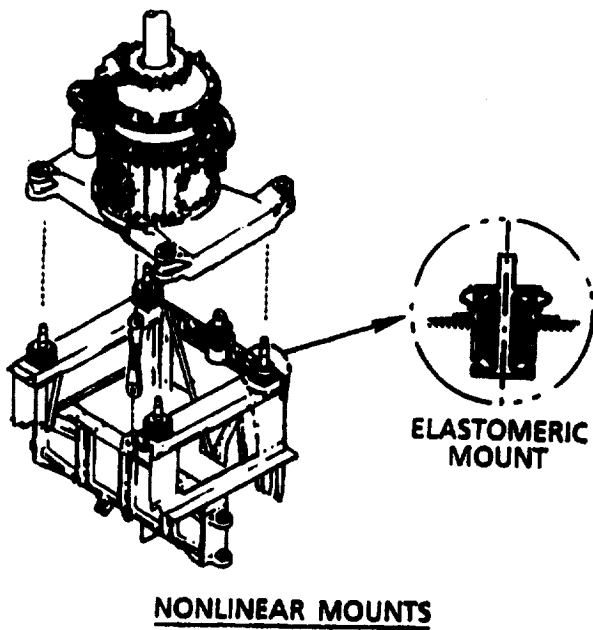


Fig. 15 AH-1G pylon nonlinearities.

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.

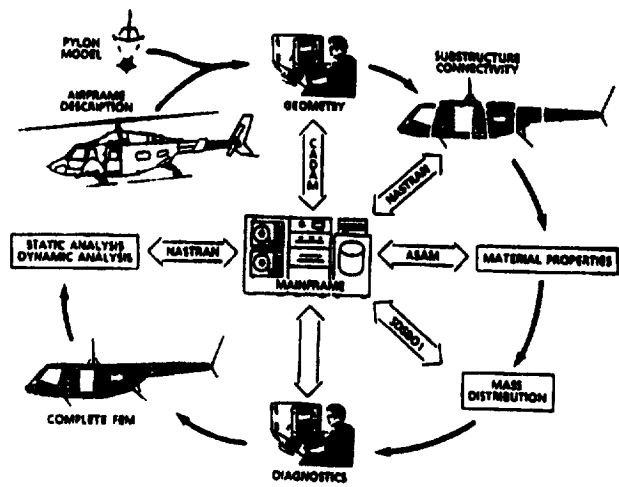


Fig. 16. ACAP NASTRAN FEM development process using common statics dynamics models.

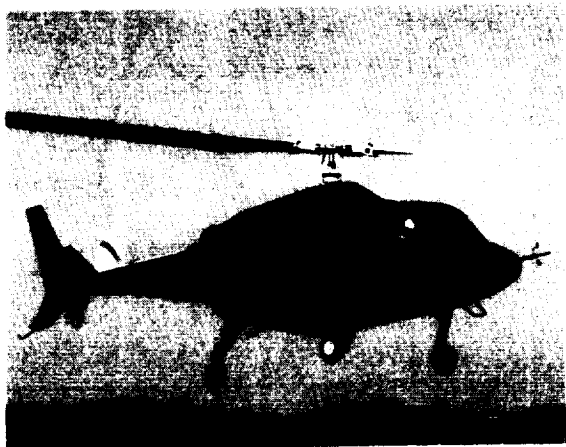
Some of the findings and accomplishments from the ACAP modeling exercise were as follows:

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

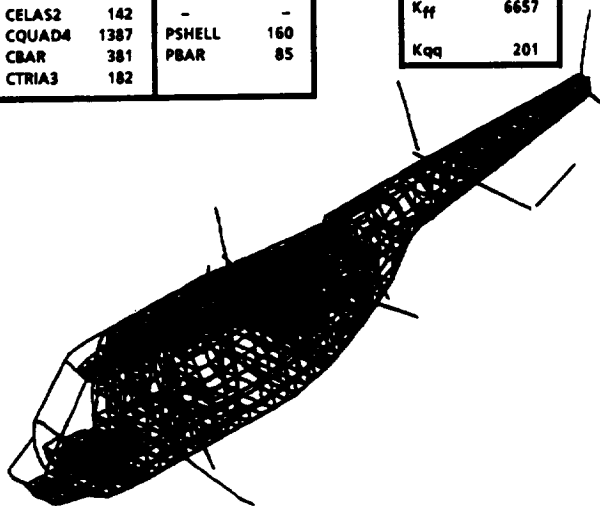


Fig. 17. Bell ACAP NASTRAN airframe vibration model.

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

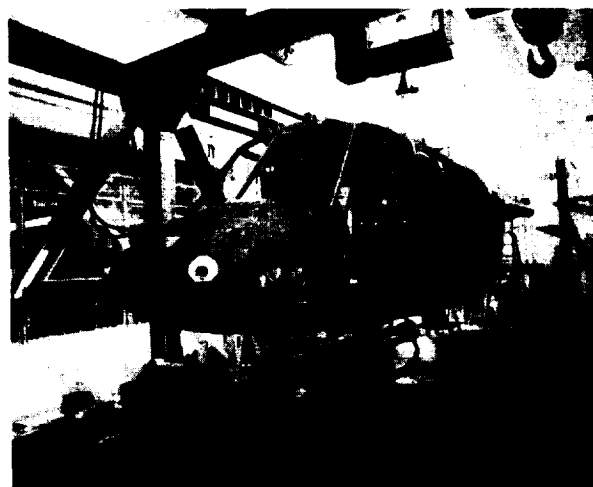
5. Horizontal stabilizer added.
6. Cargo doors added.
7. Vertical fin added.
8. Landing gears added.

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-



FULL AIRCRAFT



ALL COMPONENTS REMOVED

Fig. 18. ACAP ground vibration test airframe.

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.

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

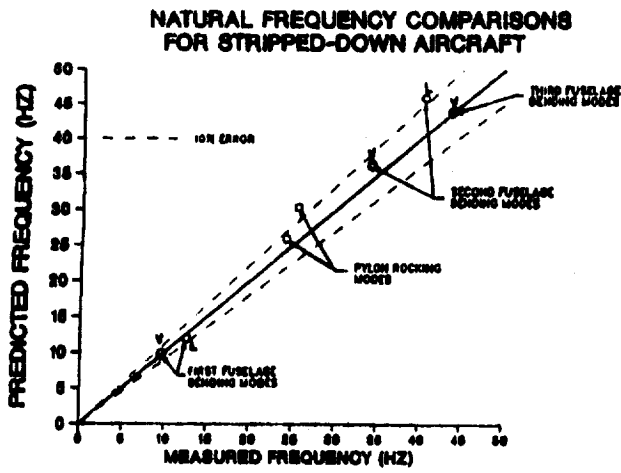


Fig. 19. ACAP natural frequency comparisons.

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

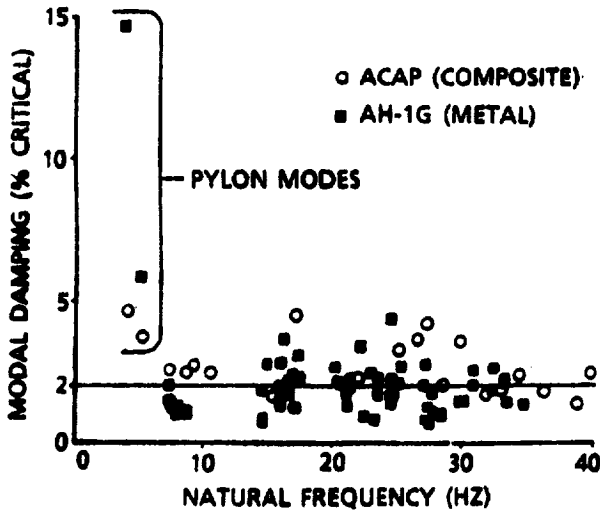


Fig. 20. Modal damping estimates from tests for composite and metallic airframes.

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

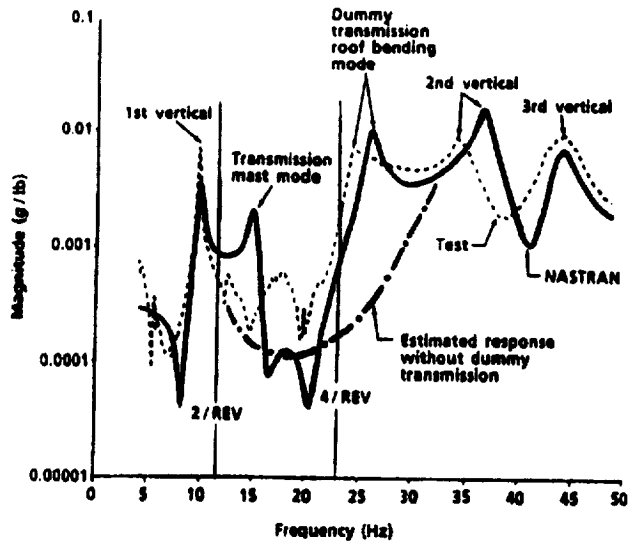


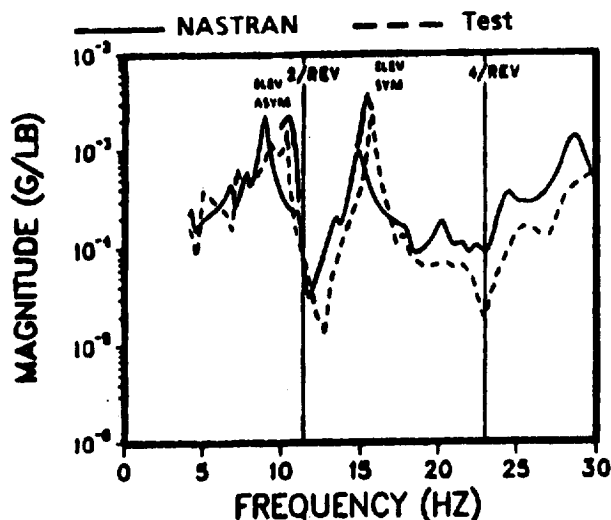
Fig. 21. Final FEM, ACAP stripped configuration - vertical load on nose, vertical response at FS 390.

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.

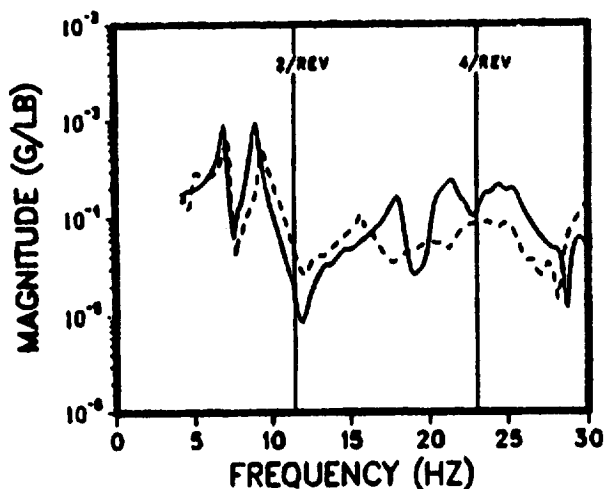
5. The correlations of the composite airframe are considered comparable to the metallic airframe. Since the basic approach to modeling the NASTRAN FEM is the same (except that the skin and panel elements are generally QUADs in composite and shear panels in metallic structures), the accuracy of vibration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



ELEVATOR-RIGHT (FB 488) VERTICAL RESPONSE



PILOT (FB 170) VERTICAL RESPONSE

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

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

Mode	Natural Frequencies (Hz)			
	Test	Original NASTRAN model	Revised 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

norm for correlation with test. SOAR is described by Smith, et al.¹²

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

The work that was accomplished under the NASA DAMVIBS program has had a major influence on the "hardening" and growth of vibration technology in the helicopter industry that will continue even though the program has been completed. The author wishes to thank the U.S. Government and industry participants who contributed to the success of the program. The technical manager from NASA Langley Research Center was Mr. Raymond G. Kvaternik, who was supported by Messrs. John H. Cline, Robert J. Huston, and Eugene C. Naumann. Mr. William C. Walton must also be recognized as the creator of the

program and its acronym. An excellent overview by Mr. Kvaternik of the entire NASA DAMVIBS program has been published.¹³

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THE NASA/INDUSTRY DESIGN ANALYSIS METHODS FOR
 VIBRATIONS (DAMVIBS) PROGRAM-
 BOEING HELICOPTERS AIRFRAME FINITE ELEMENT MODELING

N 9 3 - 2 1 8 1 3

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Abstract

Mathematical models based on the finite element method of structural analysis, as embodied in the NASTRAN computer code, are routinely used by the helicopter industry to calculate airframe static internal loads used for sizing structural members. Historically, less reliance has been placed on the vibration predictions based on these models. Beginning in the early 1980's NASA's Langley Research center initiated an industry wide program with the objective of engendering the needed trust in vibration predictions using these models and establishing a body of modeling guides which would enable confident future prediction of airframe vibration as part of the regular design process. Emphasis in this paper is placed on the successful modeling of the Army/Boeing CH-47D which showed reasonable correlation with test data. A principal finding indicates that improved dynamic analysis requires greater attention to detail and perhaps a finer mesh, especially the mass distribution, than the usual stress model. Post program modeling efforts show improved correlation placing key modal frequencies in the b/rev range within 4% of the test frequencies.

Introduction

A better capability to calculate vibration of helicopters is a recognized industry goal. More reliable and accurate analysis methods and computer aids can lead to reduced developmental risk, improved ride comfort and fatigue life and even increased airspeeds. An important element in the overall vibration calculation is the finite element airframe model. Mathematical models based on the finite element method of structural analysis as embodied in the NASTRAN computer code are widely used by the helicopter industry to calculate static internal loads and vibration of airframe structures. The internal loads are routinely used for sizing structural members. Until recently, the vibration predictions were not relied on during the design stage. Beginning in the early 1980's, NASA's Langley Research center initiated a program with the objective of engendering the needed trust in vibration predictions using these models and establishing a body of modeling guides which would enable confident future prediction of airframe vibration as part of the regular design process. This program was subsequently given the acronym DAMVIBS (Design Analysis Methods for VIBrationS).

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Boeing Helicopters overall participation in this program is summarized below:

- Contract NAS1-16460 "Planning, Creating and Documenting a NASTRAN Finite Element Vibrations Model of a Modern Helicopter" (CH-47D)

Task I-1	Planning	NASA CR 165722	April 1981
Task I-2	Modeling	NASA CR 166077	March 1983
Task I-3	Test Requirements	NASA CR 165855	April 1982
Task II-1	Ground Shake Test and Correlation	NASA CR 166107	May 1983
Task II-3	Summary Report	NASA CR 172229	October 1983

- Contract NAS1-17497 Modeling the 360 Composite Helicopter

Task 2	Ground Shake Test	NASA CR 181766	March 1989
Task 1	Plan, Formulate and Correlate Model	NASA CR 181787	April 1989

- Contract NAS1-17497 "Calculation of Flight Vibration Levels of the AH-1G Helicopters and Correlation with Existing Flight Vibration Measurements"

NASA CR 181923 Nov. 1989

Attention here will be focused on the NASTRAN modeling efforts for the CH-47D and Model 360 with particular emphasis on the CH-47D.

Technical and organizational lessons learned from the modeling exercise are discussed. Post program efforts to improve the CH-47D correlation are also presented.

Modeling Plan

As a counterpoint to most modeling efforts, this program emphasized the planning of the modeling as the prime portion of the effort. All of us have modeled by spreading out the drawings and getting down to work, typically without a very clear idea of where we were headed. In contrast to this, the NASA Technical Monitor insisted on a well thought out plan of attack, accompanied by detailed preplanned instructions, labeled "guides". These guides defined the modeling approach for each type of structure (frames, stringers, rotor shafts, etc). Even the documentation of the modeling had to be preplanned. A very extensive modeling plan report was published¹. The plan was reviewed by other industry representatives prior to undertaking the actual modeling. Another unique feature was that at the end of the modeling, deviations from the planned guides due to cause were reported.

The objectives of the modeling plan were as follows:

- Define guides for modeling, coding, documenting and demonstrating (1) stress (static) modeling, (2) mass modeling, and (3) vibration modeling (by modification of the stress model).

- Establish the organization, schedule and resources for performing detailed finite element modeling.

Modeling Guides

Guides for static, mass and vibration modeling were developed. These included:

- Grid and element numbering
- Frame, stringer, skin treatment
- Rotor shaft and transmission modeling
- Concentrated and distributed masses
- Changes from the static model to form a vibration model

The aircraft was first divided into major areas for convenience in scheduling and tracking FEM activities. For the CH-47D, the breakdown was as shown in Figure 1.

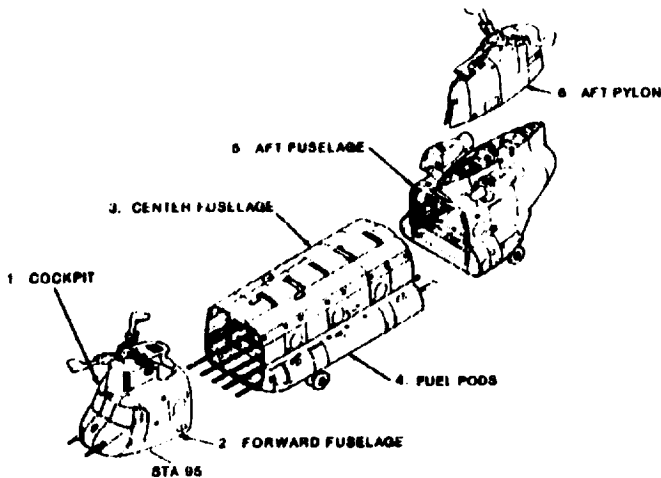


Figure 1. Breakdown into Major Areas for Static Modeling

A logical grid and element numbering scheme was selected to permit traceback of the elements. The scheme used for the Model 360, illustrated in Figure 2, was believed to be superior.

Detail Guides for modeling were described. Several typical CH-47D guides are illustrated in Figures 3 and 4

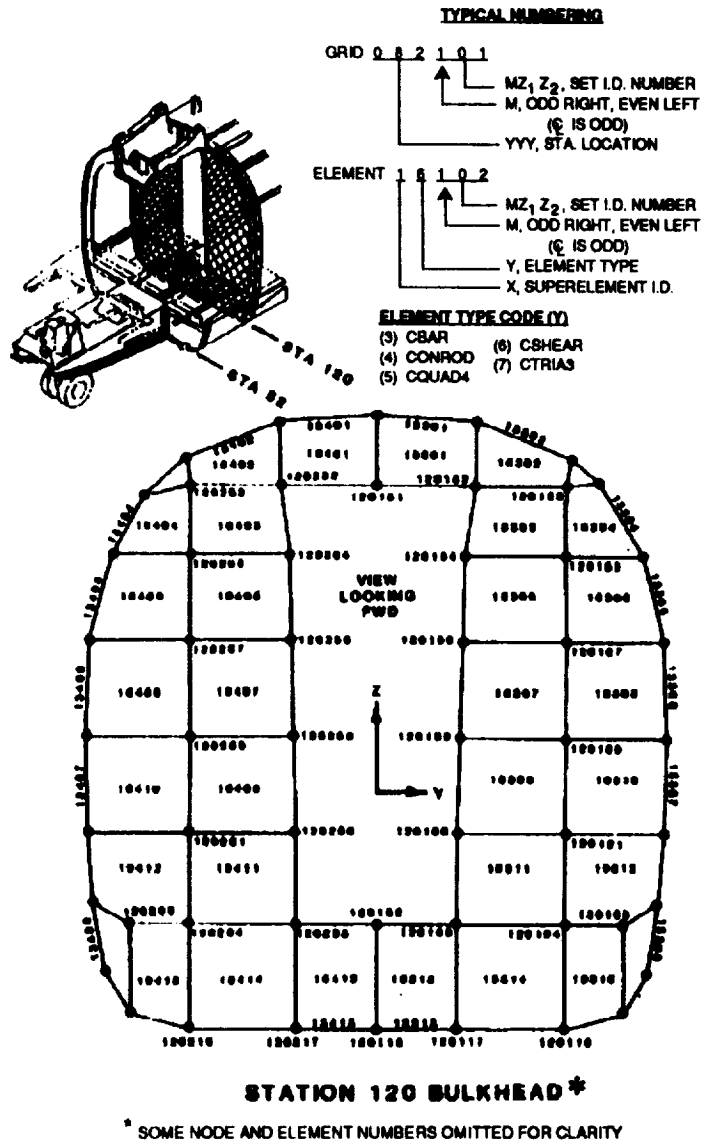
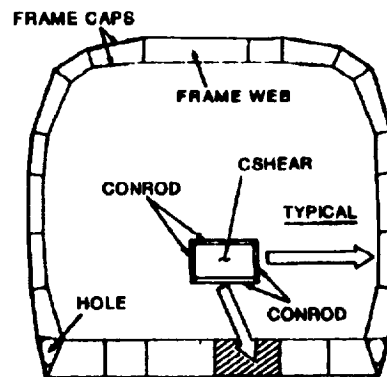


Figure 2. Model 360 Grid and Element Numbering Scheme



STRUCTURAL COMPONENT	TYPE OF LOADING	ELEMENT TYPE
CAP/STIFFENER	AXIAL	CONROD
WEBS	SHEAR	CSHEAR

Figure 3. Static Modeling Guides - Frames

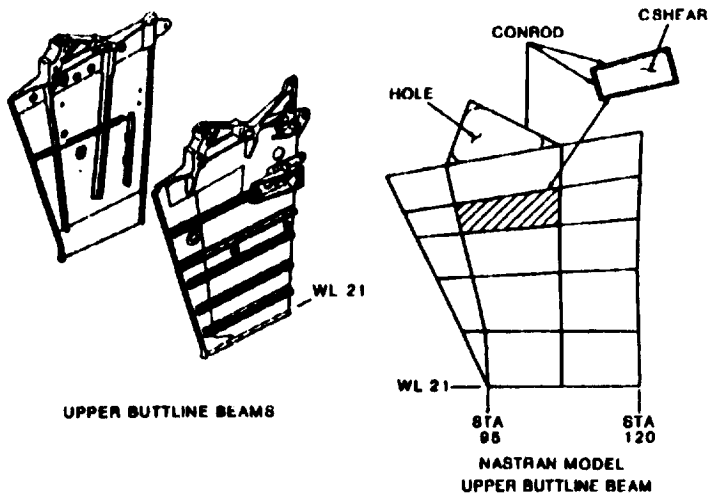


Figure 4. Static Modeling Guides - Bulkheads, Decks, and Butt-Line Beams

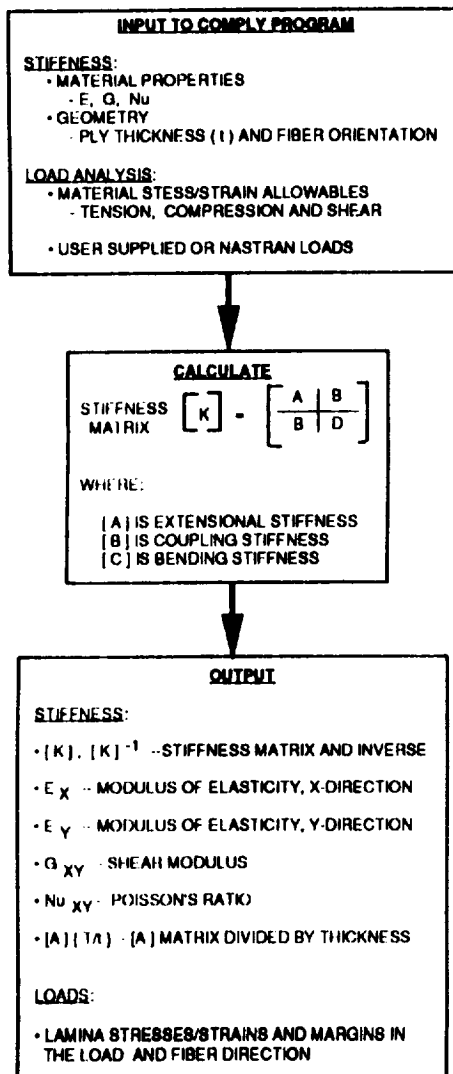


Figure 5. Static Modeling Guides - Analysis Method for Composite Laminate Properties

Despite its nearly all composite construction, the modeling procedures for the Model 360 were generally similar to the CH-47D. In the case of the composite structure, however, there is an additional step; namely, the determination of element material properties. While the structure can be analyzed using NASTRAN composite elements, this is not considered efficient (at least in the design stage) by most stress engineers. At Boeing Helicopters, a PC based laminate analysis program called "COMPLY" is used to determine overall element properties. Figure 5 illustrates the principal attributes of the program.

Actual Modeling Experience

The static model was prepared by a senior stress engineer and a technician working from the drawings of the CH-47D. Figure 6 shows the final NASTRAN model of the aircraft with the statistics indicated.

NASTRAN MODEL	
1,863 STRUCTURAL NODES 5,758 STRUCTURAL ELEMENTS	
NO. OF ELEMENTS	TYPE
398	CBAR - BEAM
76	CELAS2 - SPRING
3,253	CONROD - AXIAL
1,707	CSHEAR - QUADRILATERAL SHEAR
156	CTRIA3 - TRIANGULAR MEMBRANE
156	COUAD4 - QUADRILATERAL SHELL
12	CTRIA3 - TRIANGULAR SHELL

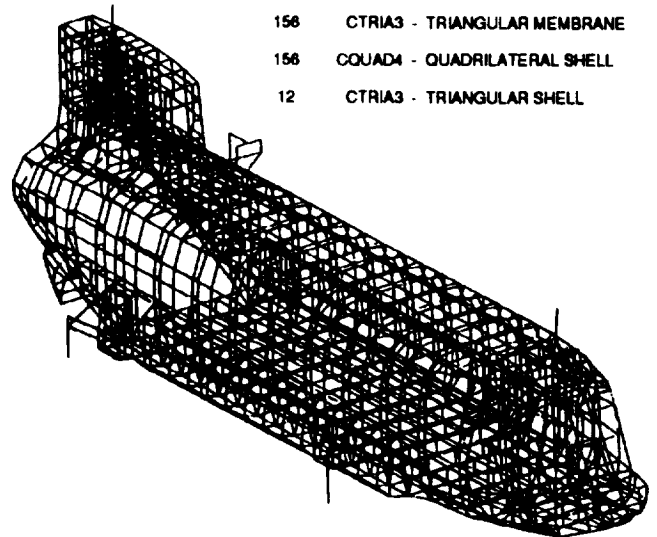


Figure 6. CH-47D NASTRAN Structural Model

A typical model detail illustrating the forward pylon upper buttlime beams is shown in Figure 7. The transmission support fitting at the top of the beam was designed to act as a truss and is modeled with axial CONROD's. Otherwise the model was like a frame in that caps were represented by CONROD's and webs by CSHEAR's. Stiffeners used only for web stability were not all modeled (some were to break up panel sizes).

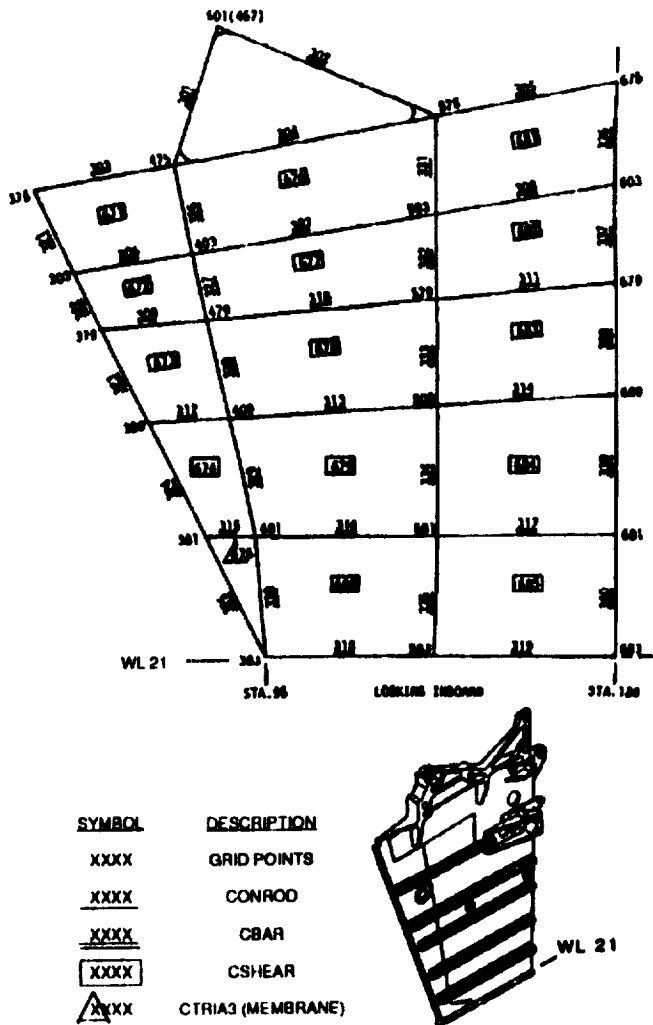


Figure 7. Static Modeling of Forward Pylon Upper Butt-Line Beam

A demonstration run was made with the static model to determine whether the model generated reasonable (error free) results. Internal loads were calculated for a 3 g pull-up at a gross weight of 50000 pounds. Element forces, grid point displacements, and grid point force balances were examined. The static deflection plot for selected grid points illustrated in Figure 8 indicates apparently rational results.

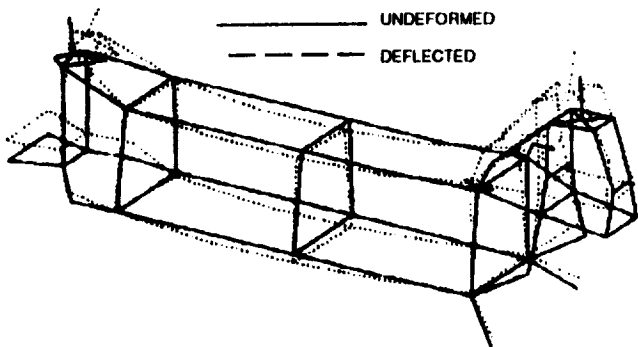


Figure 8. Static Demonstration Case, Deflection for 3.0 g Pull-Up

Next, the model had to undergo certain modifications from a static to a vibration model. One of these changes was the drag strut of the engine mount. The drag strut, Figure 9, is slotted and only acts under extreme maneuver and crash loads. It was included in the static model, but was removed from the vibration model. The inactive strut has a vibration purpose; it prevents the drag strut from adding a yaw stiffness increment which would have placed the engine yaw natural frequency on 3/rev. Further, since the forward yoke support fitting is significant in forming the stiffness of the engine mounting, this yoke was remodeled to provide better detail. Cap areas of the forging were modeled with CBAR's and the webs with CQUAD4 shell elements.

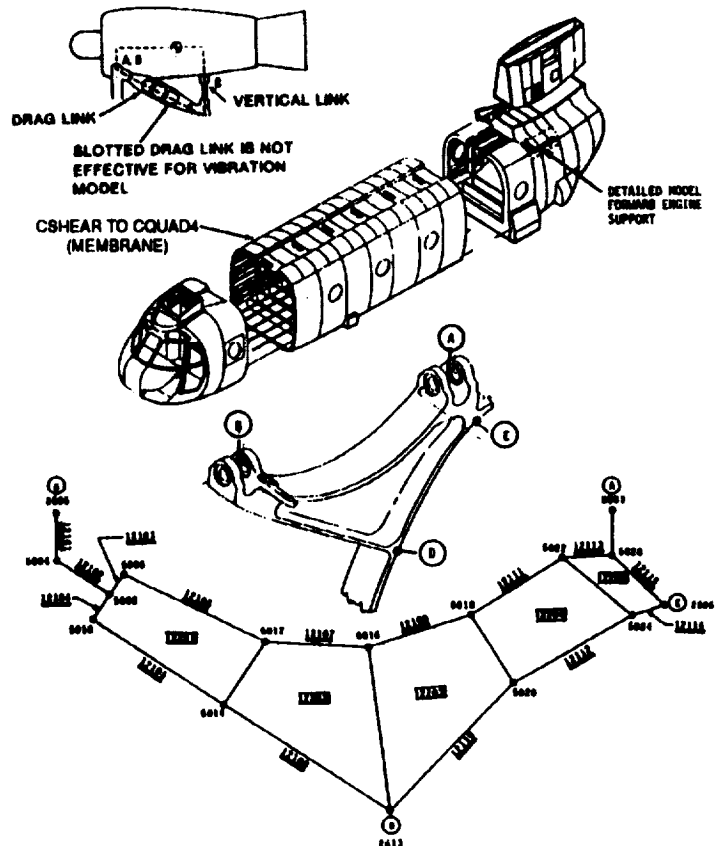


Figure 9. Vibration Modeling Structural Changes

The most important change to form the vibration model was the change of airframe skin from CSHEAR's to CQUAD4 membrane elements. In the static model, under limit load conditions, the skins are buckled and provide only shear stiffness. In the vibration model, under 1g static loads, the skins are unbuckled and the CQUAD4 membrane elements provide both shear and axial stiffness.

Concentrated weights of the engines, transmissions, and APU were initially distributed to the attachment points in the static model while preserving the mass and inertia of the overall aircraft. For the vibration model, center of gravity grid points were introduced at the engines and transmission and appropriate inertias used.

A demonstration run was performed with the vibration model. It was done in the free-free condition to represent an inflight situation. Emphasis was placed on the basic airframe structure by modeling an empty aircraft without fuel. This avoided the need for dealing with the nonlinear cargo and fuel isolation systems. The demonstration run included the calculation of natural frequencies, modes and forced response. Results of the natural frequency calculation are summarized in Table 1. Based on previous CH-47 modeling and test experience, these results were judged to be reasonable.

Table 1. Vibration Demonstration Case, Airframe Natural Modes

MODE NO.	FREQUENCY (Hz)	DISCRIPTION
1	6.36	1ST LATERAL - AFT PYLON LATERAL
2	7.24	ENGINE LATERAL YAW - OUT OF PHASE
3	7.52	1ST VERTICAL - AFT PYLON LONGITUDINAL
4	8.24	ENGINE LATERAL YAW - IN PHASE
5	11.80	2ND VERTICAL - PYLON LONGITUDINAL IN PHASE
6	12.89	2ND LATERAL - FWD PYLON LATERAL
7	13.81	3RD LATERAL - PYLON LATERAL IN PHASE
8	18.01	AFT LANDING GEAR LATERAL - OUT OF PHASE
9	18.22	UNDEFINED VERTICAL
10	17.41	UNDEFINED LATERAL
11	19.20	UNDEFINED LATERAL
12	20.71	UNDEFINED VERTICAL
13	21.81	UNDEFINED VERTICAL
14	22.92	UNDEFINED COUPLED VERTICAL - LATERAL
15	24.79	UNDEFINED COUPLED VERTICAL - LATERAL

NASTRAN Analysis of Test Configuration

The basic airframe vibration FEM initially demonstrated in the free-free condition was modified to the test configuration. Changes to the basic airframe model included incorporation of the test hub fixtures (hub weight and shaker attachment assembly) and adjustments to the mass distribution to account for equipment not installed.

The total NASTRAN model incorporated several unique features. A persistent issue with regard to analytical correlation of test and analysis has been the question of the suspension system and shaker effects. Consequently, the total model was fully representative of the test configuration including the support fixture, the shakers and the aircraft and shaker suspension system in addition to the basic airframe model. A differential stiffness correction was also developed and applied to the stiffness matrix to include gravitational effects (pendulum modes) on the suspended aircraft.

With regard to the question of the suspension system and shaker effects, the support fixture is always likely to have modes in the test range. The question, therefore, can only be resolved by a comparison of analytical aircraft responses for the free and suspended conditions. Typical results illustrated in Figure 10 show only minor effects with the most significant changes in the 30 to 35 Hz range. While these results are applicable only to the test equipment used in this

program, they generally support the accepted suspension concept. Physically, frequency shifts and amplitude variations may result from any of the following or combination of the following:

- Coupling with shaker system
- Minor coupling with the support fixture
- Presstiffening of the airframe due to gravity preload
- Other coupling mechanisms in the airframe due to gravity preload

Also, it should be remarked that the theoretical appropriateness of representing pendulum modes by a differential stiffness correction, while plausible, has not been thoroughly explored.

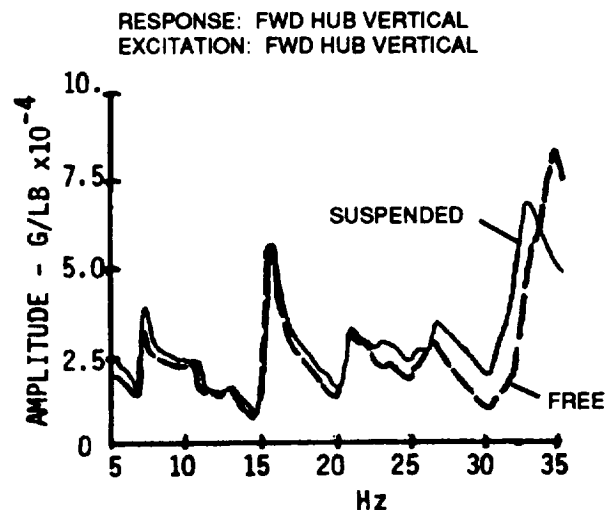


Figure 10. Typical Analytical Response for Free and Suspended Conditions

Correlation of Test and Analysis

Conventional correlation of test and analysis for airframe vibration is a comparison of natural frequencies and modes first, and forced vibration second. In this program the criteria order was reversed; more emphasis was placed on the ability of the analysis to predict reasonable forced amplitudes throughout the airframe. Natural modes were in second place, although it is recognized that specific forced peaks and valleys follow natural frequency placement. If able to predict reasonable forced amplitudes from individual rotor forces, then the analysis would be a reasonable tool for predicting vibration arising from actual mixed forces and directions.

Forced response comparisons with forward vertical excitation are presented in Figure 11; with forward pitch excitation in Figure 12; and with forward lateral excitation in Figure 13. The response scale is in $\pm g$ per pound of force.

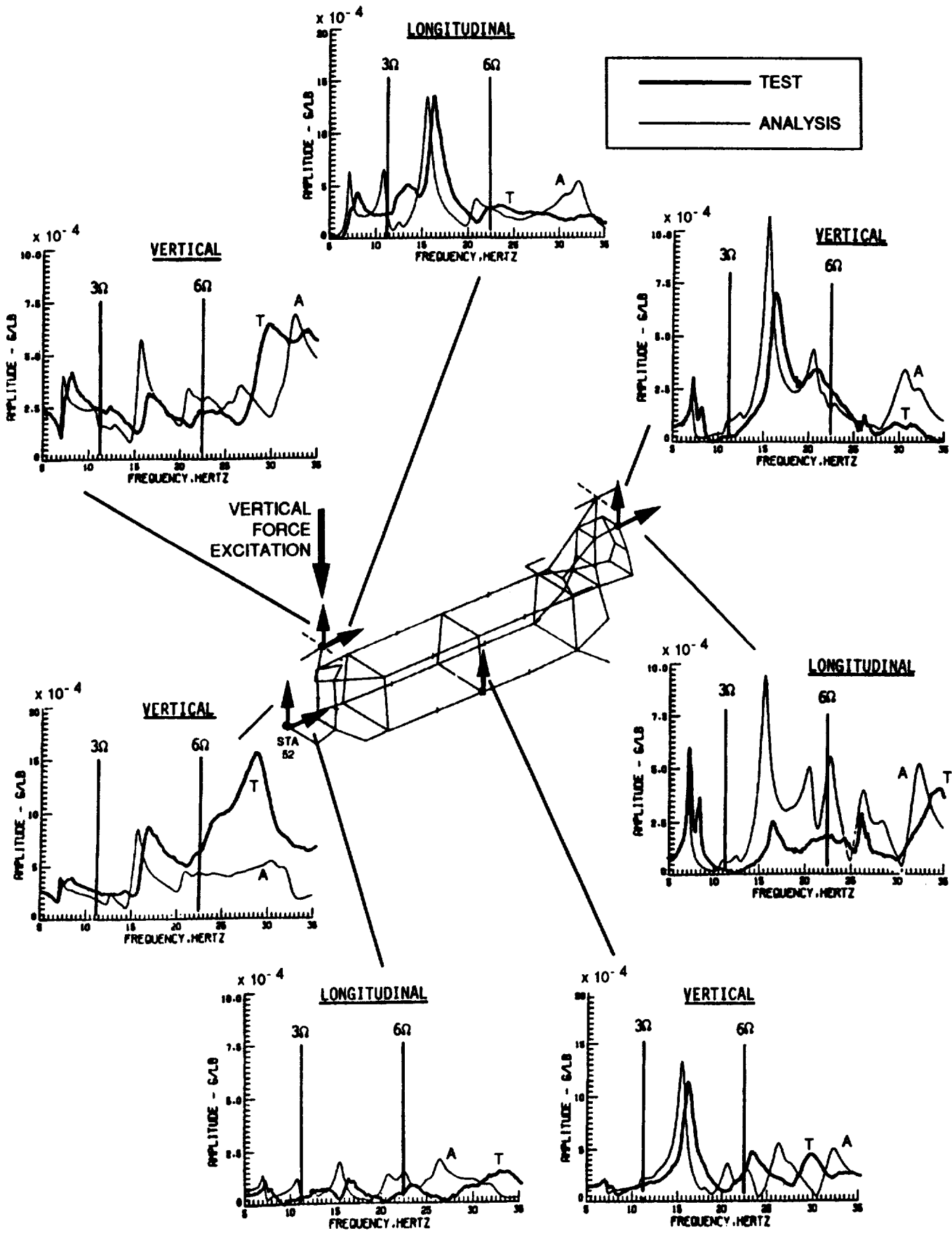


Figure 11. Comparison of Test and Analytical Forced Response with Forward Vertical Excitation

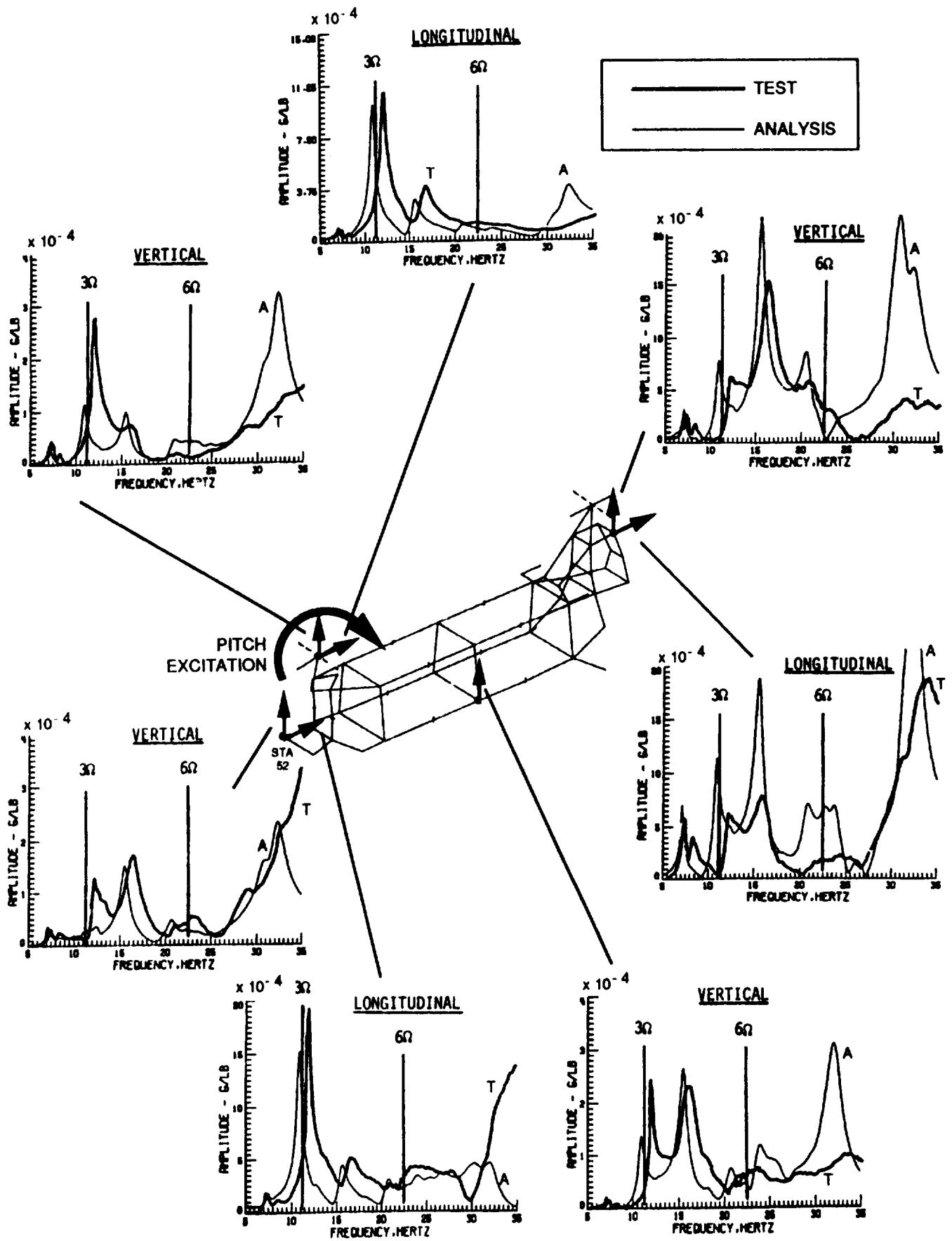


Figure 12. Comparison of Test and Analytical Forced Response with Forward Pitch Excitation

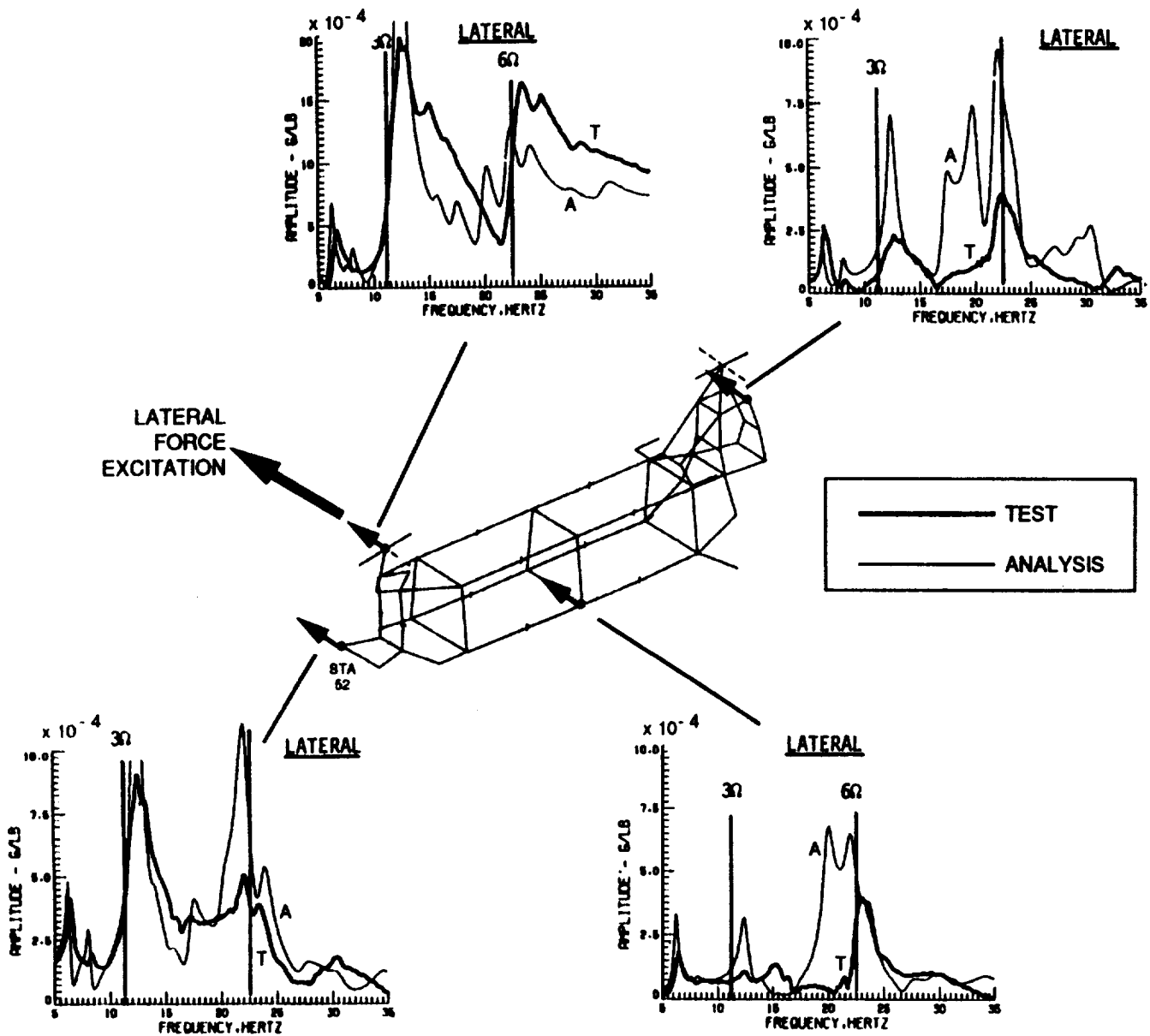


Figure 13. Comparison of Test and Analytical Forced Response with Forward Lateral Excitation

Vertical vibration predictions from forward rotor vertical excitation in Figure 11 shows fairly good absolute magnitude correlation with test at the important 3/rev and 6/rev forcing frequencies. There is generally an analytical response which can be associated with the major test peaks and usually the minor ones as well. In the coupled direction, i.e. longitudinal motion under vertical excitation, the absolute magnitudes, which are usually smaller than in the prime directions, are reasonable well produced.

On the negative side, the very prominent cockpit Sta 52 test response at 28 Hz in the vertical direction has no strong analytical counterpart.

Results of the forward rotor pitch excitation are in Figure 12. Comparison of test and analysis here gives generally good agreement. Again absolute magnitude predictions are good,

especially at 3/rev and 6/rev. Longitudinal motion at the forward hub shows the strong peak near 10 Hz that is close to the test peak. Even the secondary peak near 17 Hz is reproduced. Vertical motion from pitch excitation is acceptable on an absolute basis at 3/rev and 6/rev, but the magnitudes of the peaks disagree.

The analytical peak at 32.7 Hz is generally overpredicted in amplitude. This implies that the proper choice of damping, rather than the constant 2.5% structural critical damping assumed, would improve the correlations.

Results of the forward rotor lateral excitation are in Figure 13. Again, the absolute magnitudes are reasonable. On the negative side, the lateral peak near 21 Hz is over predicted. Again the use of non-constant structural damping would improve this situation.

Correlation Improvements

A number of items arose from the modeling and correlation experience which have the potential for further improvement of correlation.

1. Correct modeling of damping is a major need. The current use of a constant assumed value of structural damping is not adequate. Some form of nonuniformly distributed damping is required.
2. Stringer area is not included in the shear area of the cross-section, since the usual assumption of skin areas carrying all shears is made. When summed the shear area of stringers is as much as 50% of the skin area.
3. The upper portion of the splice joints is in compression under 1g loading and unconnected stringers may be axially effective.
4. More thorough modeling of the forward transmission cover, shaft, bearings and bearing clearances may be necessary to obtain a still closer match of the mode near 3/rev.
5. The hub test fixture should be remodeled to better reflect elastic effects at the interface with the rotor shaft.
6. Masses are distributed to approximately 10% of the structural grid points. A finer mesh may be necessary to improve higher mode predictions.

A preliminary effort to evaluate some of these improvements was conducted. In Figure 14, damping has been adjusted in an attempt to improve the forced response correlation. Instead of using a constant 2.5% structural damping, the damping has been varied by mode as indicated in the tabulation. The damping was varied here to obtain the best match at the bottom of the response, away from the resonance points.

A second improvement item has been explored. Table 2 summarizes the results of a number of exploratory runs to investigate the effect of splice joint continuity and stringer shear area. For expediency, the stringer shear area was simulated by modifying the shear modulus so as to effectively increase the shear area. The thrust of the effort was to raise the baseline analytical frequency at 10.85 Hz to the test value at 11.7 Hz. The chart shows that with all the stringers continuous at Stations 160 and 440, the frequency did increase from 10.85 to 11.31 Hz. This change in splice joint continuity has remarkably little effect on the frequency of the remaining modes.

Next, to represent the actual stringer shear area, the shear modulus is increased by a factor of 1.5, the frequency of this mode increased to 11.68 Hz, almost exactly the 11.7 Hz test value. Note, however, that this change also raises the other modal frequencies appreciably.

MODE	DAMPING-PERCENT CRITICAL
1-60	2.5 EXCEPT FOLLOWING
7	3.25
9	.06
11	5.0
12	8.75
14	1.25
15	1.25
16	10.0
17	5.0
18	12.5
19	7.5
20	7.5
21	8.75
23	7.5
24	5.0
25	5.0
26	7.5

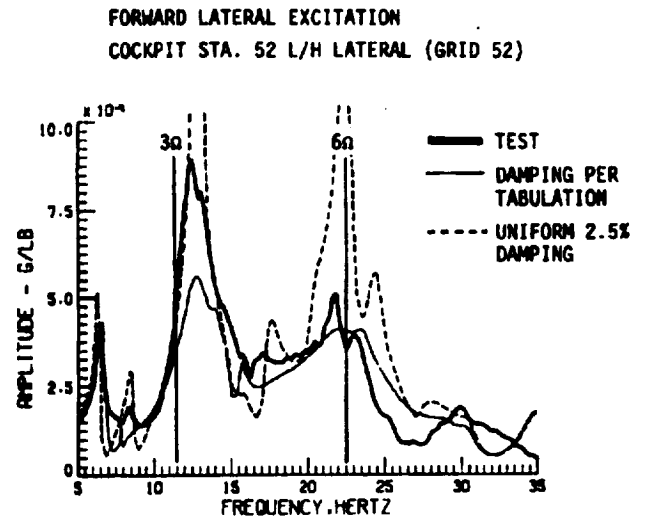


Figure 14. Effect of Model Damping on Forced Response Correlation

Table 2. Effect of Splice Joint Continuity and Stringer Shear Area on Natural Frequency

BASELINE MODEL	STA. 160 AND 440 ALL STRINGERS CONTINUOUS				STA. 160 CONTINUOUS
	BASELINE	X1.13	X1.5	X2.0	X1.13
6.26	6.26	6.40	6.73	7.08	6.40
7.00	7.11	7.18	7.40	7.84	7.18
7.91	7.92	8.00	8.19	8.37	8.00
8.48	8.49	8.59	8.82	9.07	8.59
10.85	11.31	11.42	11.68	11.97	11.42
12.62	12.63	13.00	13.84	14.68	13.00
13.81	13.89	14.28	15.15	16.07	14.28
14.87	14.88	15.99	16.42	17.05	15.99
15.47	15.59	15.84	17.74	19.18	15.84
17.30	17.34	17.70	18.90	19.81	17.70
18.09	18.11	18.44	19.25	20.72	18.44
20.01	20.02	20.36	21.12	21.43	20.36
20.64	20.78	21.00	21.29	22.00	21.00
21.69	21.74	22.00	22.98	24.23	22.00
22.10	22.17	22.81	24.32	26.92	22.81
23.41	23.52	23.91	24.98	28.30	23.91
23.99	24.09	24.61	26.03	27.35	24.61
26.30	26.38	25.93	27.35	28.83	25.94
26.12	26.29	26.81	27.81	28.96	26.81
27.42	27.46	27.78	28.85	30.47	27.77
28.41	28.46	29.16	31.07	33.27	29.16
29.30	29.33	30.02	31.72	33.81	30.02

Summary of Key Findings

Many valuable lessons were learned from the DAMVIBS finite element modeling, test and correlation program. In general, these may be divided into two broad categories; namely, technical and organizational.

Technical Lessons

Key findings and conclusions covering a wide range of subjects are summarized below:

1. Satisfactory procedures were developed for analysis of the suspended aircraft. In the case of the CH-47D, comparison of free and suspended configurations indicates only minor differences.
2. Reasonable correlation was obtained between test and analytical results. Adequate modeling of damping appears as a major stumbling block to improved correlation.
3. A non-linear response with force was observed during shake testing. The frequency at the peak responses tended to decrease with increasing force level. The amplitude increased, but not proportionally with force level. Frequency shifts up to nearly 1 Hz and amplitude changes up to 35% were observed for a 2 to 1 change in force level. The changes were neither uniform across the spectrum nor consistent with frequency.
4. Significantly improved correlation appears possible by including secondary effects such as stringer shear area and effective splice joint stringer continuity due to 1g loading.
5. Attachment of large concentrated weights or lumped masses to the airframe can be critical. The attachments must correctly transmit loads into the structure. Initial Model 360 engine and cockpit floor modeling, for example, resulted in a number of unrealistic modes.
6. Mass modeling in general has been treated rather superficially compared to stiffness. Considering the modal complexity of the higher order natural frequencies near b/rev, much more detailed modeling is needed. To accomplish this, appropriate software procedures keyed to finite element modeling requirements are needed.
7. Modeling of a composite aircraft is more difficult than a comparable metal aircraft because of the need to determine equivalent physical properties for multi-ply structures of varying ply orientations, thicknesses and material types.
8. Must be aware of details--like Stress uses buckled skins, but the vibration model needs unbuckled skins, and--shear area of axial stringers, while perhaps only 20% of side skin area, may be enough to affect correlation.

9. The grid and element numbering system used in the Model 360 analysis (6 digits for grids, 5 digits for elements) proved extremely flexible. The first three grid numbers are the fuselage station, 4th is odd right and even left, and 4th thru 6th is the I.D. First element number is the superelement, 2nd is the element code, 3rd is odd right and even left, and 3rd thru 5th is the I.D. The superelement identification permits division of the modeling effort.

10. The enforced displacement (rigid body) check is an efficient first step in checking out a model. No mass model is required and the check quickly identifies all of the over-constrained points.

11. The multi-level strain energy DMAP alter developed by McDonnell Douglas Helicopters is an effective tool for quickly identifying local modes, some of which may be due to an inappropriate mass location.

12. On average, correlation appears satisfactory up to about 10 Hz, less satisfactory between 10 and 20 Hz and inadequate above 20 Hz. From this it can be concluded that the correlation deteriorates with increasing modal complexity. Therefore, improved dynamic analysis requires greater attention to detail and perhaps a finer mesh, especially the mass distribution, than the usual stress model. This is contrary to the previously held belief that the stress model has more than enough detail for dynamics (both the CH-47D and Model 360 programs emphasized the use of a "detailed static model" for dynamics rather than forming a separate model).

13. Structural modeling techniques seem to be relatively uniform within the industry. In general there is a tendency to force the load path (via modeling assumptions) rather than letting NASTRAN determine the load path. (Example stringers modeled as axial elements with no shear capability).

14. The Stress group, as a general practice, needs to adopt modeling procedures which are compatible with both static and dynamic modeling requirements.

Organizational Lessons

The DAMVIBS program experience has had an impact on our thinking regarding the formation of an airframe NASTRAN model. Some of the more significant conclusions are as follows:

1. A planning phase is necessary during which specific guides are laid out for static, mass and dynamic modeling.
2. To insure the best possible model for dynamic analysis, the dynamicist needs to be closely involved with the stress modeler in the formation of the model.

3. Weights engineering needs to be a closer part of the techniques and requirements for finite element modeling.
4. Cost of the effort to provide a model for both static and dynamic analysis is 5% of the airframe design effort. Cost of the static model alone is 4% so the dynamics model costs only an additional 1%.

DAMVIBS Influence on Subsequent Programs

Modeling of the V-22 began under Navy Contract in 1983 by Bell and Boeing Helicopters and continues to the present. Bell has design and NASTRAN responsibility for the wing, rotor and drive, and Boeing for fuselage and empennage.

Modelers in both companies have been involved with DAMVIBS. At Boeing, Bill Kesack, current V-22 Stress Supervisor, did the DAMVIBS CH-47D static modeling. Bob Ricks, current V-22 Dynamics Senior Engineer, did the DAMVIBS CH-47D dynamic modeling.

As in DAMVIBS, Boeing Stress did the fuselage static model, Bell Stress did the wing/nacelle static model, Weights provided input to Bell's node point mass distribution program and it produced the NASTRAN mass inputs, and Dynamics at both companies prepared and ran the superelement model.

As foreseen by an early DAMVIBS modeling plan, the V-22 model was created early in the design process, and influenced much of the stiffness design details in trying to meet frequency placement criteria. The model was updated, and made more detailed as the aircraft design evolved on the CAD screens.

Post Program Efforts

Since CH-47D's are still being delivered there is a continued interest in the NASTRAN dynamic model as an investigative tool. Subsequent to the NASA contract there have been periodic efforts to improve the correlation. Following in roughly chronological order, are the more significant changes made to the CH-47 model:

1. Increased the detail of the structural modeling in the area of the center cargo hook cut-out.
2. Modified the forward and aft landing gear models to the compressed position (shake test condition).
3. Corrected fuel tank material properties and remodeled connection to the airframe.
4. Remodeled the cabin floor to correct geometry and change connections to the airframe.
5. Changed the modulus for aluminum from 10×10^6 to 10.3×10^6 (average value of alloys used).
6. Corrected splice joint MPC errors.
7. Added aft cabin cargo ramp structural model (No redistribution of ramp mass which is distributed along side beams).
8. Modified attachment of the forward rotor shaft to the transmission to incorporate bearing stiffness.
9. Modified attachment of the aft rotor shaft to the thrust deck to incorporate thrust bearing stiffness.
10. Fixed numerous SPC/mechanism problems using the multi-level strain energy check.
11. Modified splice joints to make stringers in the upper portion of the fuselage continuous.
12. Relocated forward rotor shaft bearing location grid points to reflect bearing contact angles. This significantly increases the moment stiffness between the shaft and the transmission.
13. Added stringer flange shear area contribution to cabin skins by an appropriate increase in the shear modulus of individual skin panels.
14. Replaced CONRODS in forward pylon forgings with CBARS to account for bending stiffness provided by integral ribs.

Items 1 through 10 are changes based on a review of the model by E.C. Naumann of NASA Langley. Changes to the splice joint and the addition of stringer shear area (11 and 13) are refinements of an earlier investigation of these areas. The remaining items are attempts to further improve the correlation by investigating perceived weaknesses in the model.

Table 3 is a summary indicating the effect of the post program changes outlined above. Overall, there appears to be greatly improved correlation. Improvements above 16 Hz (mode 8), however, should be viewed with caution due to a possible lack of correlation in the mode shapes. For the moment, the modes of greatest interest are modes 5 and 6 (forward pylon longitudinal and lateral respectively) and mode 8 (fundamental vertical bending). For the new baseline, observe that the frequency of both forward pylon modes (modes 5 and 6) is lower compared to the original NASTRAN results. This is due primarily to the introduction of the forward rotor shaft bearing stiffness. In contrast to the previous evaluation, the addition of stringer shear area has almost no effect. The stringer flange area is considerably less than the expected 50% of skin area and not uniformly distributed around the cross section. Stringer shear area for individual skin panels ranges from 0 to 31% of the skin area. With all of the changes incorporated, the pylon longitudinal

frequency (mode 5) is 11.5 Hz compared to 11.7 Hz test and the pylon lateral (mode 6) is 13.02 Hz with a test value of 12.6 Hz. The frequency of the vertical bending mode (mode 8) is 16.11 Hz versus the test value of 16.2 Hz.

Table 3. Effect of Post Program Model Changes

MODE NO	NATURAL FREQUENCY - Hz					
	ORIGINAL NASTRAN RESULTS	SHAKE TEST	NEW BASELINE (SEE NOTE)	RELOCATE FWD SHAFT BRNG. GRID POINTS	ADD STRINGER SHEAR AREA	ADD FWD PYLON MOD
1	6.25	6.5	6.48	6.5	6.52	6.52
2	7.0	7.2	7.04	7.09	7.10	7.1
3	7.91	8.0	7.94	7.96	7.96	7.96
4	8.48	8.56	8.58	8.59	8.59
5	10.86	11.7	10.19	11.33	11.35	11.5
6	12.62	12.6	11.73	12.74	12.88	13.05
	13.1	SECONDARY RESPONSE			
7	13.81	15.2	14.98	14.99	14.99	14.99
	14.87	LOCAL MODE				
8	16.47	16.2	16.64	16.93	16.93	16.11
9	17.3	17.7	17.21	17.24	17.21	17.22
10	18.09	18.4	17.82	17.85	17.83	17.64
11	20.01	21.2 21.7	20.57	21.5	21.58	21.58
12	20.84	Multiple Modes	21.52	21.92	22.06	22.21
13	21.89	LOCAL MODE				
14	22.1	22.8 22.9	22.15	22.18	22.2	22.26
15	23.41	Multiple Modes	22.78	22.79	22.79	22.8
16	23.99	23.8	24.0	24.03	24.04	24.04
17	28.3	24.9	24.33	24.55	24.7	24.79

NOTE: NEW BASELINE INCLUDES THE PROVISIONS MODIFICATIONS ITEMS 1 THROUGH 11.

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THE NASA/INDUSTRY DESIGN ANALYSIS METHODS FOR VIBRATIONS (DAMVIBS) PROGRAM - MCDONNELL DOUGLAS HELICOPTER COMPANY ACHIEVEMENTS

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Abstract

This paper presents a summary of some of the work performed by McDonnell Douglas Helicopter Company under NASA Langley-sponsored rotorcraft structural dynamics program known as DAMVIBS (Design Analysis Methods for VIBrationS). A set of guidelines which is applicable to dynamic modeling, analysis, testing, and correlation of both helicopter airframes and a large variety of structural finite element models is presented. Utilization of these guidelines and the key features of their applications to vibration modeling of helicopter airframes are discussed. Correlation studies with the test data, together with the development and applications of a set of efficient finite element model checkout procedures, are demonstrated on a large helicopter airframe finite element model. Finally, the lessons learned and the benefits resulting from this program are summarized.

1. Background and Introduction

Under a U. S. Government sponsored contract, McDonnell Douglas Helicopter (MDHC) was one of the four helicopter manufacturers who participated in conducting a study of finite element analysis of helicopter airframes for the enhancement of the technology base related to the area of airframe structural dynamic analysis. This work which was sponsored by the NASA Langley Research Center Structures Directorate, consisted of planning, development, and the documentation of modeling techniques and computational procedures. Additional tests were performed to obtain the necessary data to verify the finite element model and to develop procedures for correlation studies. The modeling and shake test were performed on the McDonnell Douglas AH-64A (Apache) PV01 Helicopter. Initially, a structural finite element model was prepared ⁽¹⁾.

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The guidelines were broken into three different categories which consisted of those used for modeling of the stiffness characteristics, representation of the mass distribution, and consideration of factors affecting the accurate representation of vibrational characteristics of the model. Other resources required for performing efficient model checkout ⁽²⁾, and techniques used for different types of vibration analyses, were also developed ^(3,4). The portion of this effort which is related to the dynamic aspect of these studies is the subject of this paper.

In the first section of this paper, the procedures used in converting the static model into a dynamic model are discussed. These include steps such as addition of non-structural components and extra grid points for the representation of the locations of the heavy mass items and inclusion of additional effects in shear panels to make them properly effective. For the accurate representation of the mass distribution, which is a key factor in a dynamic analysis, a procedure is developed which is discussed next ⁽⁵⁾. This procedure is used to systematically distribute the mass data over entire finite element model. In addition to these changes, a set of model quality assurance procedures is developed which helps the analyst to rapidly identify modeling errors prior to performing any analysis. These procedures are summarized.

In the second part, the efforts spent on obtaining an experimental database describing the vibrational characteristics of the aircraft structure and the finite element model enhancement process are discussed ⁽⁶⁾. The procedure used for testing, the criteria used for mode identification, and a summary of test results is discussed. A summary of correlation studies performed to check the validity of a finite element model and the associated modeling assumptions will be discussed. As a part of this enhancement process, the modeling problems that were identified as a result of correlation studies are presented. In addition, the general application of the test results is discussed.

Finally, use of a model reduction procedure for the

purpose of increasing the computational efficiency for the dynamics optimisation applications is discussed. A preliminary study was performed to demonstrate application of such a procedure. The lessons learned from this study which include the development and application of the model reduction process and the use of the reduced model in a sensitivity analysis study are summarized. Finally the lessons learned from the overall DAMVIBS effort are discussed.

II. Vibration Modeling

Generally, there are two major tasks involved in the development of a dynamic model from a static model. First step involves the additional modeling resources necessary to make a static model useful for vibration analysis. Next is the generation and addition of the mass distribution to the static model.

A static model which is primarily used for calculations of internal loads and stresses under static loads generally does not contain a detailed representation of mass information. Prior to its use for dynamic analysis, it is required that additional steps be taken to accommodate for the locations of heavy mass items such as engines, missiles, etc. In the case of Apache model, shown in Fig. 1, one of these steps involved the addition of secondary structures and non-structural parts and a set of additional grid locations required for proper representation of masses. These grid points were properly linked to the

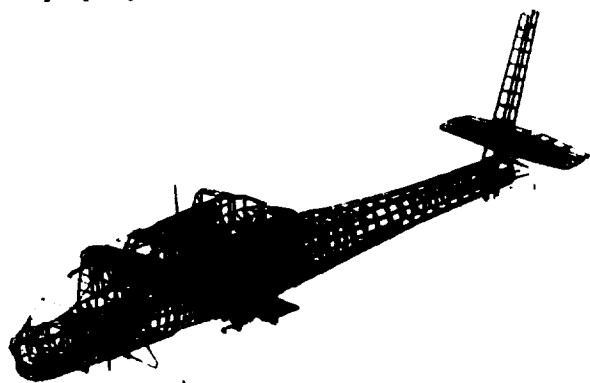


Fig. 1. AH-64A Dynamic MSC/NASTRAN Model.

surrounding areas. The next step in this conversion process was to correctly represent the structure for the in service conditions. In the case of static models, generally impending failure conditions are considered. In this case it is assumed that the skins are fully buckled and do not carry any tension/compression loads. This assumption needs to be modified for simulation of in service conditions. Thus, proper steps were taken in order to make sure that the skins were appropriately effective.

Another task in generating a dynamic model involves the development of the mass model. This process generally consists of following tasks; a) generation of a detailed weights record for the weight empty flight configuration, b) generation of a detailed listing of useful load weights, c.g.'s, and inertias, c) distribution of primary structure weight via material density parameter, d) manual distribution of large concentrated mass items (i.e., main rotor, transmission, engines, etc.), and e) automatic distribution of remaining mass data using a systematic and preferably automated mass lumping process.

Most of the information specified in the above list is generally available through the mass database and the mass density information of different geometric representation of various model components. For the purpose of distributing the the remaining mass data (i.e., item e), an automated mass lumping procedure was established. In the case of Apache model, this procedure was used to systematically distribute the mass data over the specified dynamic model grid locations and as a result a set of CONM2 cards were generated that were used in the dynamic model. The methodology used for the distribution of the finite element model mass data is discussed in detail in Ref. 5.

For the distribution of mass data, the lumping program requires two sets of information, namely, the actual aircraft mass data records and the location of the selected grid points of the finite element model. The mass data is organized and stored in a format that is consistent with the MIL-STD1374A. Starting with the first mass item in the database, the program internally generates an imaginary volume, referred to as lumping volume, around the mass item. Next, by searching through the specified grid points, it identifies those grids which are confined within this volume and then assigns a different portion of the mass item to each of the selected grid points. Then, in case where there are still some remaining portions, the program increases the size of the lumping volume and starts assigning portions of the remaining mass item to the new set of grids which may now be within the confinement of the increased volume. This process is repeated until the mass item is completely distributed to the surrounding grids. This process is repeated for each of the mass items. However, proper care is taken within the program for avoiding the relumping of the mass of those items which have already been accounted for.

Figure 2 represents the general arrangement of the lumping process and illustrates the input and output streams of the automated mass lumping program. Although this program can accommodate structural mass input, the primary intent in the development of the program was to distribute nonstructural mass

items (e.g. fasteners, wire bundles, etc.) to model grid point locations. This mass lumping process minimizes the human error through automatic generation of a set of CONM2 cards which are readily used as

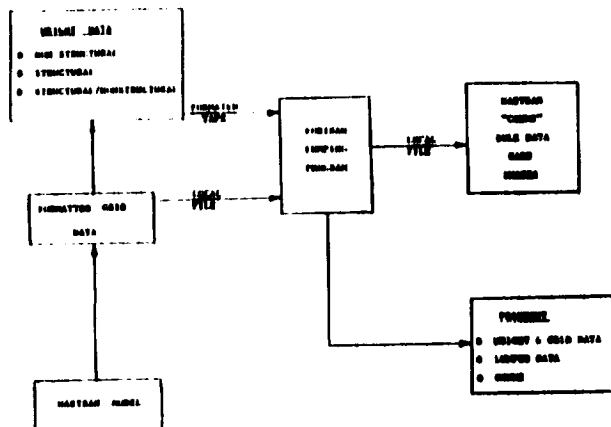


Fig. 2. Block Diagram of Mass Lumping Program.

a part of the NASTRAN bulk data deck. The structural mass (e.g. skins and stringers) is calculated via material density cards internally within NASTRAN to form the total mass matrix.

III. Model Verification Process

Model verification process is one of many tasks requiring a substantial amount of time. Thus, it is very desirable to have tools that can facilitate and automate this process as much as possible. A series of computational procedures were developed in the form of DMAPs. These DMAPs were used to identify both modeling errors and also provide certain information regarding identification of modes, energy associated with each mode and calculation of modal participation factors. The latter two DMAPs were developed prior to start of DAMVIBS program at the MDHC. However, due to their high level of effectiveness and also for the sake of completeness they are included here and are briefly discussed in the following sections.

As a result of applications of these modeling check-out DMAPs to a variety of structures, a common set of sources of errors has been identified. Those errors which occur during the assembly of the G-set stiffness matrix are due to; (a) the improper specification of the coordinate couplings where two components which are located in different coordinate systems are coupled together improperly, (b) the use of a short beam element next to a long beam element, (c) use of a large or improper aspect ratio for plate elements, or (d) the use of CELAS elements between noncoincident points. Each of these modeling practices will result in the ill-conditioning of the G-set stiffness matrix. In the second and third levels of model forma-

tion, where the N-set and F-set stiffness matrices are being assembled, improper applications of the Multi-Point Constraint equations (MPCs) and Single Point Constraints (SPCs) could result in further modeling errors. Incorrect specifications of these types of constraints will result in incorrect representation of the linear relationships among different DOFs and over-constrained boundary conditions, respectively.

Cholesky Decomposition DMAP

The purpose of this check is to identify singularities or mechanisms as well as near singularities or soft spots in the model at the F-set level. For this purpose, a DMAP was developed which employs the DCOMP functional module to perform a triangular decomposition of the F-set stiffness matrix in the static solution sequence (2). After the decomposition, a diagonal matrix results whose elements provide information about the conditioning of the stiffness matrix. A max factor diagonal value (i.e., ratio of the largest diagonal term to the lowest diagonal term) of over 10^6 indicates a soft spot (i.e., near singularity) while a value over 10^{10} is indicative of a mechanism (i.e., singularity). In addition to the max factor ratio, another parameter, ϵ , is calculated. Aside from round-off errors, any large nonzero value of ϵ is indicative of a singularity in the stiffness matrix.

Multi-Level Strain Energy DMAP

In contrast to the Choleski Decomposition Check, Multi-Level Strain Energy Check provides information about modeling problems at all three levels (i.e., G-set, N-set, and F-set) of model formation in NASTRAN. Through a DMAP, the stiffness matrix, and the rigid body modes obtained from the grid point geometry of the structure, are used to calculate the strain energy of the structure at each of the three levels of model formation. The same information is also used to calculate another parameter referred to as the nodal strain to provide further information about modeling problems at each of the levels (2). As a result, any problems which might be caused by the improper grounding of the structure (i.e., G-set), incorrect application of MPC equations (i.e., N-set), or incorrect definition of the SPC constraints (i.e., F-set) will be identified through examination of these nodal strain energy at each level. To demonstrate the applicability of this powerful tool, it was applied to the AH-1G NASTRAN model (2). Examination of the N-set strain energy matrix, shown in Table 1, revealed some problems associated with the rotational degrees of freedoms (i.e., the third through sixth diagonal elements of the matrix are much larger than 10) which are indicative of incorrect application of MPC equations. To further identify the degree of freedom associated with the MPC equation, another matrix, re-

ferred to as N-set nodal strain matrix was examined. The last

NUMBER	MODE	10TH	NAME	LOC	1	2	3	4	5	6	7	8	9	10	11	12
COLUMNS	DOWN															
11		-1.1001E-04	1	10500	-07	-9.3704E-08	-1.0512E-05	-9.3012E-03	1.0017E-04							
COLUMNS	DOWN															
11		1.7000E-07	-9	05010	-03	7.0205E-04	6.9417E-03	1.0550E-05	-1.0010E-02							
COLUMNS	DOWN															
11		-9.2002E-09	-1	10010	-00	-1.0255E-05	-9.9210E-09	1.1500E-03	-1.0741E-04							
COLUMNS	DOWN															
11		-9.1000E-06	1	11200	-03	-3.0013E-04	1.0003E+07	1.0203E+03	9.0107E+01							
COLUMNS	DOWN															
11		-1.0000E-02	1	09720	-00	0.0000E+00	1.0000E+03	1.0700E+07	-1.0000E+01							
COLUMNS	DOWN															
11		1.0700E-04	5	07070	-01	-1.2100E-04	9.0100E+01	-1.0000E+01	1.0000E+00							

Table 1. N-set Strain Energy Matrix.

three columns of this matrix, shown in Table 2, which were representative of the rotational degrees of freedom revealed the location of the troublesome grid and the associated degrees of freedom (i.e., grid points 7505 and 15218). Once the associated MPC equation was corrected the DMAP was again applied and similar problem associated with the MPC equation used for the engine support location was identified. This problem was then corrected.

COLUMNS	MODE	NAME	LOC	1	2	3	4	5	6	7	8	9	10	11	12
COLUMNS	DOWN														
11		1.0000E-02	1	09720	-00	0.0000E+00	1.0000E+03	1.0700E+07	-1.0000E+01						
COLUMNS	DOWN														
11		1.0700E-04	5	07070	-01	-1.2100E-04	9.0100E+01	-1.0000E+01	1.0000E+00						

Table 2. N-set Nodal Strain Matrix.

Kinetic Energy DMAP

One of the key recent improvements in the dynamic analysis of large finite element models is the development of efficient and accurate eigenvalue extraction techniques. Introduction of such techniques has resulted in their applications to more complex systems and consequently much larger FEMs. As a result, for the prediction of structural modal characteristics, the analyst is often confronted with the identification and post processing of large number of high density modal vectors. For very large and detailed models, this process is rather tedious and time consuming. Consequently a DMAP was developed which is referred to as Kinetic Energy Check DMAP (3,4). Application of this DMAP results in the calculation of the modal kinetic energy associated with each mode and rapidly identifies the candidate structural modes. Additionally, such results provide the necessary information to identify the local modes and any possible modeling errors. Since the development of this DMAP, it has been applied to a large number of different structures and has resulted in a substantial saving of manhours and the elimination of costly and time consuming plotting process of the local/trivial modes.

This technique was initially applied during dynamic analysis of the Hughes Advanced Attack Helicopter (AAH). At the time of application, the model had 9792 degrees of freedom. To identify the modal characteristics of the model, an eigen analysis was performed up to 25 Hz. Within this frequency range, eighty seven modes were calculated where each mode contained an eigenvector containing 10000 values. Through application of the kinetic energy DMAP, a filtered modal kinetic energy matrix was obtained which contained only a set of larger values for each mode (4). A quick examination of the filtered modal kinetic energy matrix revealed candidates for the local or actual structural modes. A structural mode is generally identified by a column containing many large numbers, since the energy is distributed and large portion of structure moves together. In the case of local modes, only a few elements of the matrix have very large values, indicating only a local area of structure is moving. Figure 3 shows a sample of a structural mode identified through this procedure.

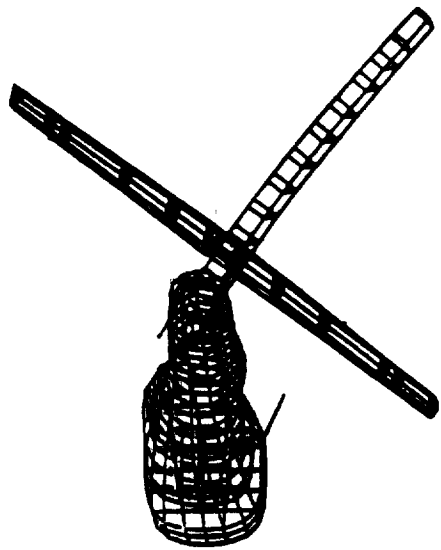


Fig. 3. AAH First Torsion Mode.

Modal Participation DMAP

An important information during studies of the dynamic structural response of linear systems is the contribution of different structural modes to the total response of a selected point or a finite region of the structure. Such information generally provides valuable insight into the vibrational characteristics of the system and points out areas where structural modifications could result in improved response. In certain applications, such data provides the necessary information for the identification and selection of an optimum location for vibration control devices. For this purpose, a DMAP was developed which calculates the modal participation factors associated with response of a selected location of the structure (7). For the ap-

plication of this DMAP, frequency response (SOL 30) is used. Application of this technique to a vibration reduction study is discussed in detail in Ref. 5.

IV. Experimental Efforts

Test Objective

The main objective of the shake test was to obtain an experimental data base describing the vibration response of the test vehicle. This data base consisted mainly of transfer functions of response acceleration to input force versus input frequency for various measurement locations throughout the fuselage structure. Although the test was not a modal survey test, the major airframe modes were extracted from the test data. These modes provided insight into the basic vibration characteristics of the fuselage and aided in the correlation with NASTRAN model.

Test Vehicle

The test vehicle used was the U.S. Army's AH-64A Advanced Attack Helicopter. The testing was performed with the vehicle in the primary mission configuration (6). The main rotor hub and blades were replaced with a rigid steel fixture which was attached to the static mast in a manner similar to the actual hub. The dummy structure was equivalent to 100% of the weight of all of the actual items except for the rotor blades. The blade weight was reduced to 60% of the actual weight to more closely represent the dynamic equivalent of the rotating system.

Test Setup

The test vehicle was suspended from a gantry. Air suspension springs located at the top of the gantry provided vibration isolation between the test vehicle and the gantry structure. This method minimized feedback from the gantry modes of vibration into the test aircraft. Link chain was used to attach the air spring system to the dummy main rotor hub. This technique removed the tendency for the aircraft to yaw. Sinusoidal vibration excitation was applied to the test vehicle at the main rotor hub and at the tail rotor. Three forces (longitudinal, lateral and vertical) were applied to the main rotor hub, as well as two moments (pitch and roll). These forces and moments were applied at the vertical and station positions equivalent to the blade plane and the center of rotation. Three forces were applied at the tail rotor location: longitudinal, lateral and vertical. The tail rotor excitation point was at the center of rotation and at a lateral position which is half way between the two rotor planes. The flight tail rotor equipment was on the aircraft during the entire shake test.

Test Procedure

During excitation, data was taken over a frequency range of 3.75 to 50 Hz except for the tail rotor input cases which extended this range to 200 Hz. The frequency was stepped up in increments of 0.5% and the input dwelled for a few seconds at each frequency step to allow the response to come to quasi-steady state. Data was taken for all accelerometers at each frequency step. Each dwell and measurement step took about 5 seconds to complete, so an entire test (3.75 to 50 Hz) could be run in less than 45 minutes.

Instrumentation

A total of 102 accelerometers were mounted on the aircraft at 39 locations and four were mounted on the gantry and suspension system. Each accelerometer was tested in a mechanical system, comprised of a load cell and a known free mass. The mass was driven in the test frequency range. The resulting transfer function from each unit was used by the computer to convert voltage to acceleration and to adjust the phase at each frequency step.

The accelerometer locations were chosen based on three criteria: (1) to identify the response at key locations such as pilot seats, engines, hubs, etc.; (2) to describe fundamental modes of the airframe; and (3) to identify important local modes such as those of the wings.

The accelerometers were mounted on one inch cubic fiberglass blocks which were epoxied to the airframe. The blocks were oriented such that their faces were aligned with three orthogonal axes of the ship. Each block had one to three accelerometers attached to it.

The use of a large number of fixed accelerometers proved to be much more effective than a few roving accelerometers, as is usually done in this type of testing. The chief reasons for this are as follows. The accuracy of accelerometer positioning was greatly increased. Errors in mounting and polarity were minimized because the accelerometers remained fixed in position for the entire test. Moreover, the time required for testing was greatly reduced because only one frequency sweep was necessary for each test case.

Data Acquisition and Control

The system used for data acquisition and control was 100% computer controlled and exclusively used Hewlett Packard instrumentation. At the heart of the system was the HP9836 computer/system controller.

At each frequency step, all data channels were scanned and 16 readings were taken over one cycle of vibration. This data was then sent from the HP6942A scanner

to the HP9836 computer where magnitude and phase data was extracted by means of a Discrete Fourier Transform. By this method the first harmonic was extracted while the higher harmonics, up to the 8th, were rejected.

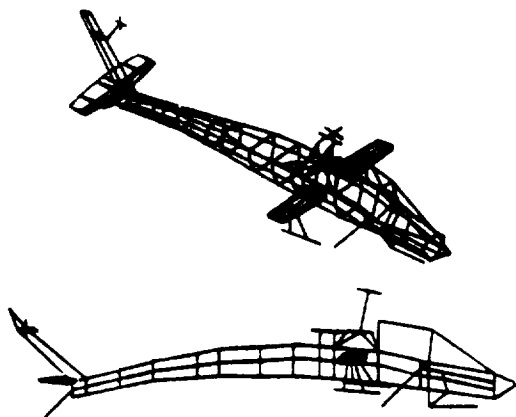


Fig. 4. Fuselage First Vertical Bending, 5.45 Hz.

Test Results

The essential results of the shake test were the response transfer functions. Additional results include natural frequencies and mode shapes which were gleaned from the transfer functions. Although not essential, this data aided in the correlation of the NASTRAN model and provided insight into the vibration characteristics of the aircraft. A sample mode shape from the test data is presented in Fig. 4. Natural frequencies were estimated from the data by means of an indicator function (6). When the value of the first function approaches unity, a natural frequency is indicated. Sample indicator function results are shown in Fig. 5.

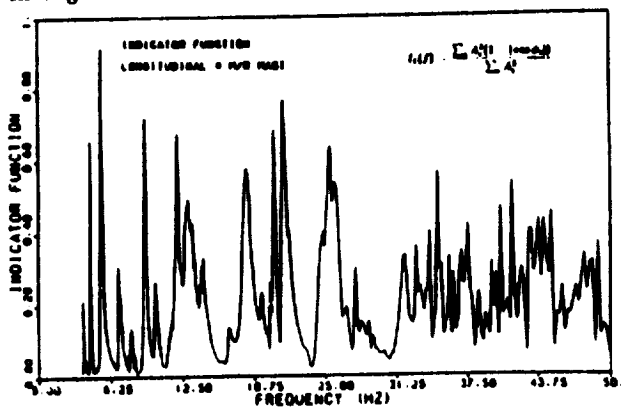


Fig. 5. Sample Indicator Function Results.

V. Correlation and Model Enhancement

An excellent correspondence between test and NASTRAN results was obtained for the frequency responses up to 13 Hz. This includes the first six modes found in the shake test. Above 13 Hz, the correla-

tion tends to deteriorate gradually as the frequency of the response increases. A comparison of natural frequencies found by test and calculated by NASTRAN is given in Table 3. Typical response correlation plots are shown in Fig. 6.

DESCRIPTION	FREQUENCY (HZ)		% DIFF.
	TEST	NASTRAN	
TAILBOOM TORSION	4.42	4.28	-3.2
1st VERTICAL BENDING	5.45	5.39	-1.1
1st LATERAL BENDING	9.39	8.79	-6.4
LONG. BENDING OF VERTICAL	10.07	9.78	-2.9
M/R MAST BENDING, LONG.	12.11	12.26	1.2
M/R MAST BENDING, LAT.	12.48	12.74	2.1
SYMMETRIC WING BENDING	13.38	15.15	13.2
ANTI-SYMM. WING BENDING	13.85	15.37	11.0
STABILATOR YAW	20.44	17.78	-13.0

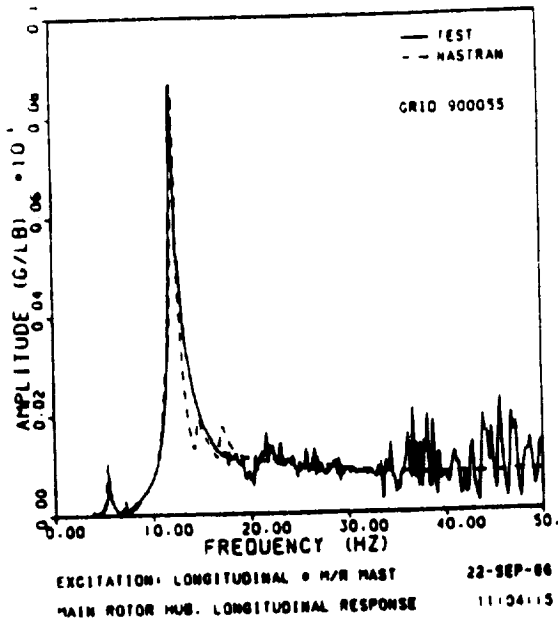
Table 3. Correlated Modes

The problem areas in the correlation were the engines, stabilator, and the wings. However, much improvement was obtained in the vertical response of the wings based on the preliminary correlation results. In addition to improving the existing finite model, much knowledge gained in the correlation effort will be applicable to future analyses. Shake test results can often be used to refine an existing finite element model. This is accomplished by comparisons of experimental and analytical results. This comparison initially indicates whether or not there are errors in the model and assists in locating probable areas in which these errors may reside. If an error has been caused by an incorrect assumption, then the correlation study can provide a guide as to how the problem might be corrected. Finally, the test comparison provides a standard by which the degree of enhancement can be measured. The following discussion describes an example of how shake test results were utilised to enhance the NASTRAN finite element model of the AH-64A airframe.

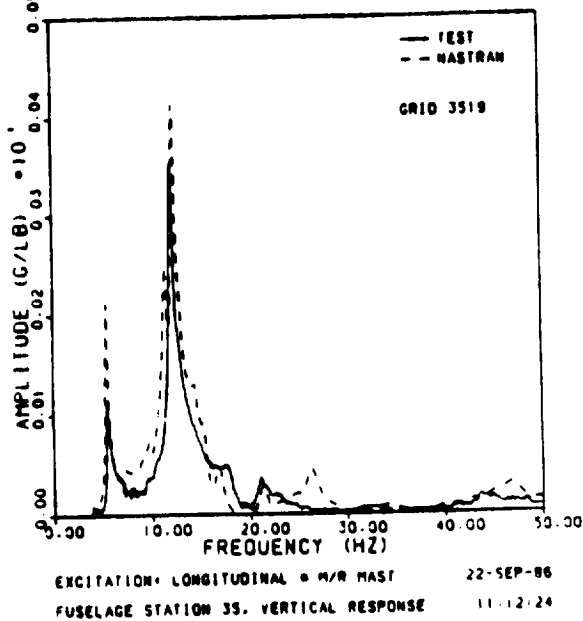
Initial comparison of the frequency response curves obtained from the test with those predicted by NASTRAN indicated that, for some cases, there were discrepancies between the two sets of results. The most noticeable problems appeared in the responses of the wings, the engines and the stabilator.

Examination of the deflected shapes obtained from test and analysis helped to further localise and identify errors in the model. A specific example of such error is a mode at approximately 8.5 Hz which is shown in Fig. 7. This mode is predominantly a wing mode although it is significantly lower in frequency than the wing modes found in the test results. In addition, one wing is undergoing pure vertical bending, while the other is experiencing nearly pure wing torsion. Such asymmetric behavior was not found in the test results. Therefore, it was concluded that there were errors in the wing portion of the finite element model.

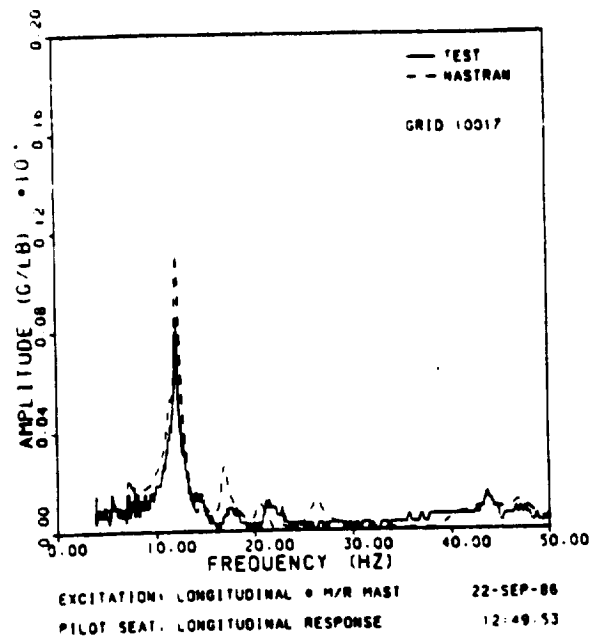
After close scrutiny of the wing portion of the model, problems were identified and corrected. The problems were mainly asymmetries in the lumped masses and element products of inertia, overly stiff modeling of the pylons, and the omission of the trailing edge. The wing trailing edge was ignored in the static model because it was considered secondary structure.



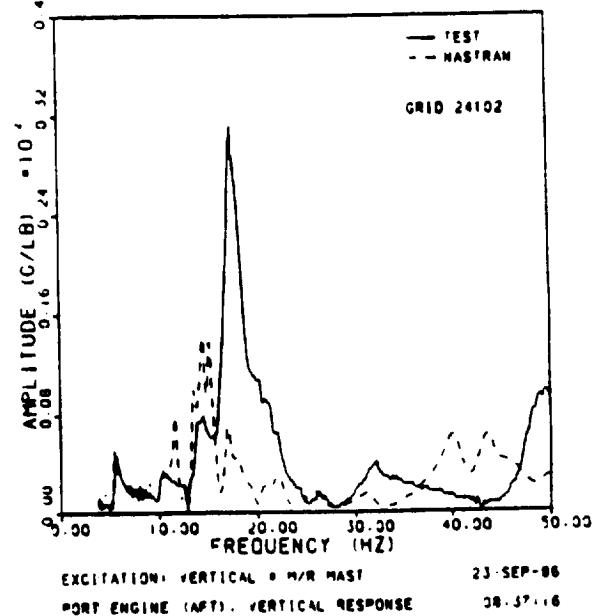
(a) Longitudinal Response at Main Rotor Hub



(b) Vertical Response at Aircraft Nose



(c) Longitudinal Response at Pilot Seat



(d) Vertical Response at Engine

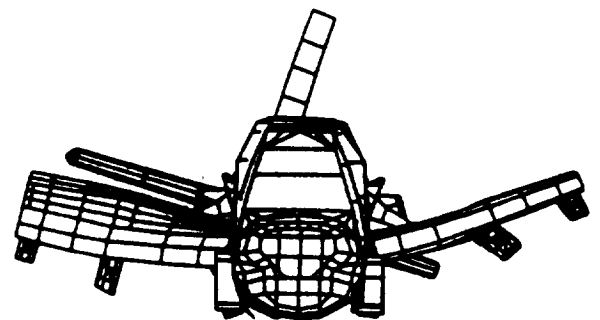


Fig. 7. Wing Mode at 8.5 Hz.

With the improvements made to the model, the analyst can use the entire inventory of test results such as frequency response plots, deflected shapes, and modal frequencies to examine the effect of the improvements. An excellent example of this is the improvement of the vertical response of the wing as a result of the changes implemented in the model. See Fig. 8.

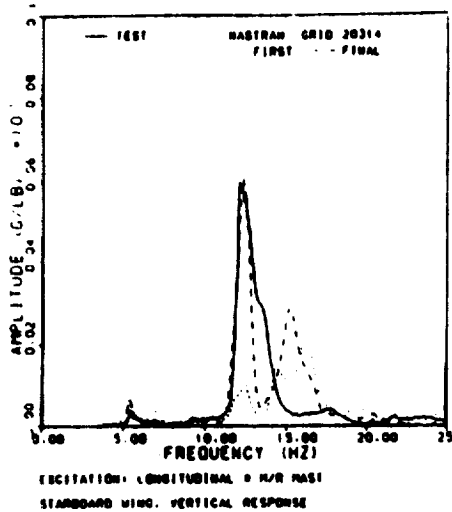


Fig. 8. Improved Correlation of Vertical Response at Wing Tip.

VI. General Application of Test Results

A comprehensive shake test, such as the one performed under this program, not only helps to enhance an existing finite element model of the test specimen, but also provides valuable guides for enhancing other models and future modeling efforts. Test results may be used to verify modeling practices used in the past, to identify questionable assumptions and practices, and to provide a reasonable level of confidence in the analysis.

It is usually necessary to make assumptions in preparing a finite element model. The validity of these assumptions must be verified by testing. In this particular case, the test results confirmed many of the assumptions used in modeling the AH-64A helicopter. For example, the assumption that stringers and longerons carry axial loads while skins and webs carry shear loads was verified. The effectiveness of using a static model for dynamic analysis with dynamic reduction was also confirmed. Good correlation associated with main rotor mast responses confirmed our modeling technique regarding the main rotor support structure and the overall representation of the airframe.

The correlation of the test results revealed some assumptions and practices which were not quite correct. The following are some examples. Although using a

static model for dynamic analysis was generally successful, some of the assumptions made for statics were not good for a dynamic model. Two examples were ignoring the trailing edge structure of the wing and the frictional load carrying capability of bolts. Some assumptions made for statics were previously recognized and corrected to meet dynamics requirements. An example of this was the shear panel effectivity. Regarding the mass distribution, some of the assumptions and methods were not strictly correct. For example, the automated mass lumping routine does consider connectivity when lumping the masses, nor does it rigorously account for rotational mass moments of inertia.

VII. Vibration Reduction Studies

Generally, use of model reduction procedures for the purpose of increasing the computational efficiency is of great interest in a dynamic analysis. This is especially true in dynamic optimization applications. Consequently, a preliminary study was done to explore the applicability of a reduction procedure to a vibration reduction study. A model reduction procedure was initially developed and was used in vibration study.

Model Reduction Procedure

A computational procedure for the reduction of large airframe finite element models was developed⁽⁸⁾. This procedure, which has been implemented as a set of DMAs, results in a significantly reduced model while retaining the essential dynamic characteristics of the full-sized model. This procedure was applied to a slightly modified version of the airframe dynamic finite element model of AH-64A Attack Helicopter. A mathematically reduced model with significantly less DOFs was obtained. This reduced model, is shown in Fig. 9.

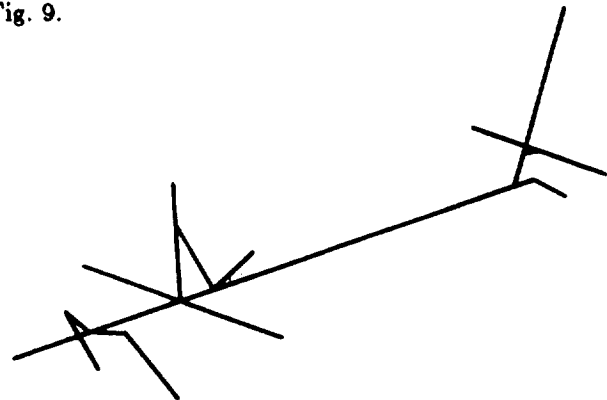


Fig. 9. Apache Stick Model.

This model is an accurate representation of the global behavior of the full model. The resulting reduced model resulted in a substantial reduction in the computation time. This reduced model which has 83 grid

points and a total of 498 DOF is only a mathematical representation of the reduced (stick) model (i.e., the elastic properties are defined in terms of stiffness matrix rather than physical elements such as bar, beam, etc.). However, further steps could be taken to carry this mathematical reduced model one step further and develop an equivalent "physical" reduced model. This process was not pursued. Instead, the "mathematical" reduced model was adapted for sensitivity analysis study which will be discussed in the following section. Following the reduction process, an eigen analysis was performed to evaluate the accuracy of the dynamic reduced model. Figure 10, represents the first vertical bending mode.

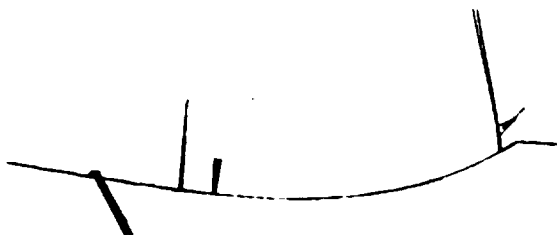


Fig. 10. Stick Model First Vertical Bending.

To further quantify the degree of correlation between the two models, an in-house computer program which provided a systematic way of checking the degree of correlation between frequencies, mode shapes or a combination of the two, was used (8). Table 4 shows the resulting correlation matrix between the two models.

MODE	FREQUENCY (HZ)		MODE SHAPE CORRELATION*
	FULL	STICK	
TAILBOOM TORSION	5.45	5.62	0.92
1ST VERT. BENDING	6.00	6.15	0.93
1ST LATERAL BENDING	10.70	9.76	0.84
SYM. ENGINE YAW AND PITCH	11.44	11.67	0.90
VERT. TAIL LONG. BENDING	11.97	12.31	0.91
MAST LONG. BENDING	13.41	14.33	0.87
ANTISYM. ENGINE YAW	14.16	16.43	0.70
STABILATOR YAW	20.63	19.60	0.81

* 1.00 = PERFECT CORRELATION
0.00 = NO CORRELATION

Table 4. Modal Correlation Matrix.

The correlation factors indicated in Table 4 are basically indicative of the degree of correlation between a pair of global modes.

Vibration Reduction study

In addition to the development and application of the model reduction procedure, another study was made to examine the applicability of the reduced (stick) model to a vibration reduction study. For this purpose, the reduced model was subjected to different four-per-rev hub excitations and the modal frequency responses (SOL 30) of different locations of the structure, together with the contribution of each mode to

the total response of each location, were calculated (7). Subsequent to the identification of the dominant modes, a design sensitivity analysis study (SOL 53) was performed to identify the pertinent model parameters (e.g., cross sectional area, area moment of inertia, etc.) which have the most effect on the vibrational response at the selected locations. Once these parameters were identified, certain incremental changes were made to each of them individually or a combination of these parameters to reduce the vibration at the selected locations.

In conjunction with the vibration reduction study, the contribution of each mode to the total response of the selected portion of the structure was determined at the location of interest. This location was the tip of the vertical tail of the AH-64A reduced model. For this purpose, an in-house DMAP (7) program was used in conjunction with the MSC/NASTRAN modal frequency response solution sequence (SOL 30). Figure 11 shows the four modes with the largest contributions to the total response of the selected point, when the aircraft is subjected to a four-per-rev vertical hub excitation.

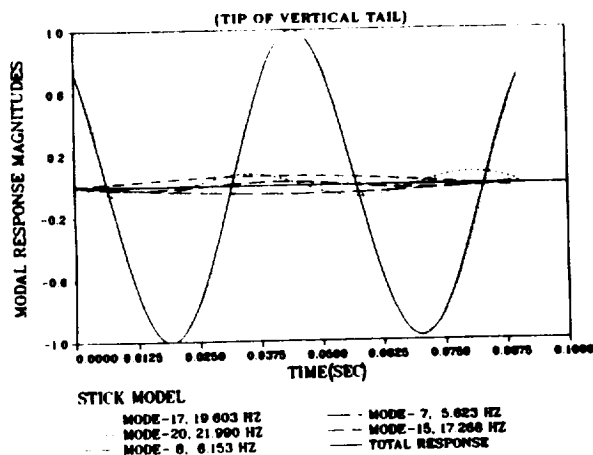


Fig. 11. Structural Modal Response.

As can be seen, mode 17 contributes the most to the total response. In addition, examination of other modes and the results obtained from the DMAP indicated that the fifteenth mode (i.e., 17.268 Hz) to be the next highest contributor to the response of the point of interest. Therefore, these two modes (i.e., modes 15 and 17) were selected to be used in a following design sensitivity analysis. This selection process was repeated for two other types of hub excitations (i.e., longitudinal and lateral excitations) and a similar pattern was obtained.

To identify those parameters which have the most effect on the response of selected normal modes in the area of interest of the structure, a sensitivity analysis was performed. For this study, the tailboom which

is in the close proximity of the vertical tail was selected. The cross-sectional area, the two area moments of inertia, and the torsional constant parameters were selected as the design variables. The two dominant stick model modes (i.e., modes 15 and 17) which represented mainly the tailboom vertical and lateral bendings, were selected as the "constraint" parameters. The design sensitivity analysis was performed for all twelve tailboom frame segments and a set of sensitivity coefficients obtained. These are shown in Fig. 11 and 12.

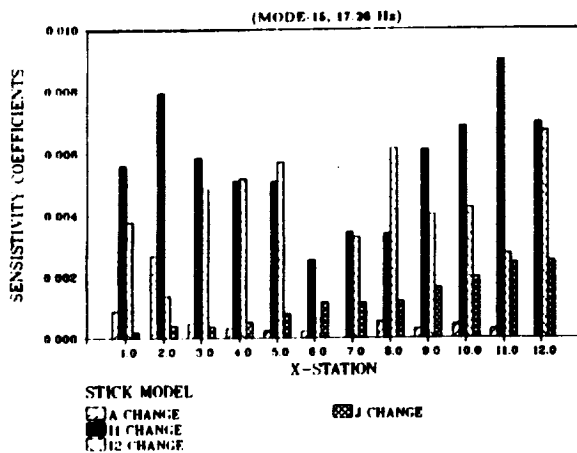


Fig. 11. Sensitivity Coefficients, Mode 15

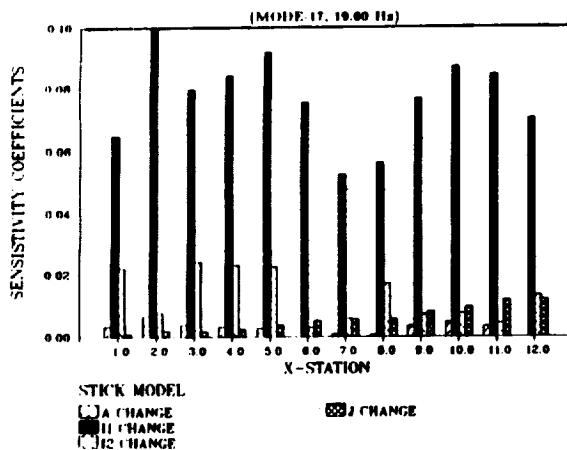


Fig. 12. Sensitivity Coefficients, Mode 17

Examination of these figures revealed that the two area moments of inertia parameters have the most effect on the frequency placement of the two selected modes. Consequently, these parameters were altered which shifted the frequencies of these two modes away from the four-per-rev excitation frequency⁽⁹⁾. This process resulted in a reduction of the vibration level at the tip of vertical tail. Similar changes were also made to the same locations of the full model and the response of the vertical tail was calculated.

VIII. Concluding Remarks

A summary of the MDHC's effort related to the development of DAMVIBS dynamic modeling guidelines, testing and the correlation studies has been presented. As a result of this work, a set of comprehensive modeling procedure and check out tools have been generated which have been used in modeling of large airframe structures. These procedures which been used in the ongoing enhancement process of the exiting MDHC product models, have also been applied to the newly developed product models. Throughout this program, a substantial amount of experienced have been gained in creating other reliable airframe finite element models⁽¹⁰⁾ which are used during the design process. Through such improved modeling capability, a better estimation for man-hour requirements and scheduling process is now possible.

In relation to performing shake tests and efficient use of this data, our capability has been substantially enhanced. This has been accomplished through use of experience gained during this program in the preparation of better test plans, performing the the shake tests where issues such as support of test structure, applications of loads or load levels are of great importance. Reduction and application of test data to the model resulted in improved correlation methodology which also brought into focus the shortcomings associated with different correlation methods and the inaccuracy associated with higher analytical modes. Further examination of the test data pointed out the degree of structural nonlinearity and provided insight into damping characteristics of the aircraft structure.

The exchange of information between MDHC and other three companies provided a means to compare methodologies used by each group and the associated results. Such an exchange of information resulted in improving certain areas of our models. One of these areas was inclusion of secondary structural components which have resulted in improving the correlation results. Finally, these studies have pointed out new challenges in terms of limitations associated with FEA which need to be further investigated.

A summary of the lessons learned during these studies are listed as follow:

- The static finite element model may be used for dynamic analysis after making the proper modifications.
- The proper modeling of the mass distribution and representation of secondary and non-structural components is essential to accurate vibration modeling. Automation of this procedure greatly reduces modeling time.

- Model checkout and verification facilitates obtaining accurate results. Automated DMAP procedures enhance the analysts capabilities in this area.
- The performance of the finite element model can be significantly improved by the application of the shake test results.
- Utilization of stationary accelerometers reduces the test time.
- Prior to performing the test, magnitude and types of excitation loads should be studied using FEM.
- Excellent correlation with AH-64 shake test results was obtained at most measurement locations up to 13 Hz.
- Knowledge gained in such a correlation study is also applicable to future analysis efforts.
- The vibration reduction obtained as a result of a preliminary dynamic optimization study demonstrated the applicability and benefits of the model reduction technique.
- Confidence in finite element analysis as a valid tool for predicting helicopter fuselage vibrations has been greatly increased.

Acknowledgements

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ABSTRACT

A short history is traced of the work done at Sikorsky Aircraft under the NASA/industry DAMVIBS program. This includes both work directly funded by the program as well as work which was internally funded but which received its initial impetus from DAMVIBS. The development of a finite element model of the UH-60A airframe having a marked improvement in vibration-predicting ability is described. A new program, PAREDYM, developed at Sikorsky, which automatically adjusts an FEM so that its modal characteristics match test values, is described, as well as the part this program played in the improvement of the UH-60A model. Effects of the bungee suspension system on the shake test data used for model verification are described. The impetus given by the modeling improvement, as well as the recent availability of PAREDYM, has brought for the first time the introduction of low-vibration design into the design cycle at Sikorsky.

INTRODUCTION

Airframe vibration has always been a problem with helicopters. Prior to the DAMVIBS program, attempts to reduce it were usually limited to making modifications or adding vibration-control devices to an already designed and built airframe, in a trial-and-error fashion. Mathematical (finite-element) models of the airframe structure were little used as aids in this process, because they were considered to be of insufficient accuracy to reliably predict either absolute vibration levels or even relative vibration sensitivities to design changes. Analysis/test comparisons at the time did not inspire confidence.

The purpose of the DAMVIBS program was to raise the level of finite-element analysis to the point where confidence in its vibration-prediction capabilities would be possible, with the ultimate objective of encouraging its use as a means of introducing low-vibration design early into the airframe structural-design process and thus lowering the weight penalty typically paid by hardware add-ons required to bring vibration within specifications. The efforts of Sikorsky Aircraft under DAMVIBS, including the directly funded as well as the indirectly encouraged, involved both of the above aspects: (1) improving the finite-element modeling tool, and (2) finding a way to apply the tool during the airframe design process to achieve a low-vibration design with a

minimum weight penalty.

IMPROVEMENT IN FINITE-ELEMENT MODELING

It was recognized that any attempt at low-vibration design would have to rest upon a base of good predictive ability of finite-element modeling of airframes. To that end, a major effort at Sikorsky, under the DAMVIBS project, involved the re-modeling, shake testing, analysis/test comparison, and model improvement, of the UH-60A airframe (Fig. 1).

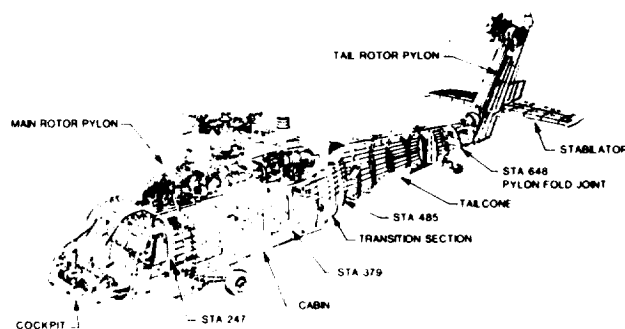


Fig. 1 UH-60A Black Hawk fuselage structure.

Re-modeling the UH-60A

Increasing the Mesh Fineness The re-modeling of the UH-60A airframe is described in detail in Ref. 1. The mesh fineness of the stiffness model was increased in many areas over the pre-DAMVIBS model. Many of the frames, beams, and longerons, which had previously been modeled as single BAR-element lines, were now modeled as double lines of BAR elements, in order to provide improved continuity at intersections of important structural components and to be better able to assess the physical parameters of the latter. This also allowed for easier input of cross-sectional properties, and a more desirable element-force output for the (static) stress analysts.

The resulting stiffness model of the DAMVIBS model has over twice the number of d.o.f. (25,000 in the g-set) as the pre-DAMVIBS model. The fineness of the mass model was increased threefold, to about 450 mass lumps.

Modeling Secondary Structure The stiffness modeling of some secondary structure, most notably the cabin floor, was included for the first

time. The complete re-modeled DAMVIBS finite element model (FEM) is shown in Fig. 2.

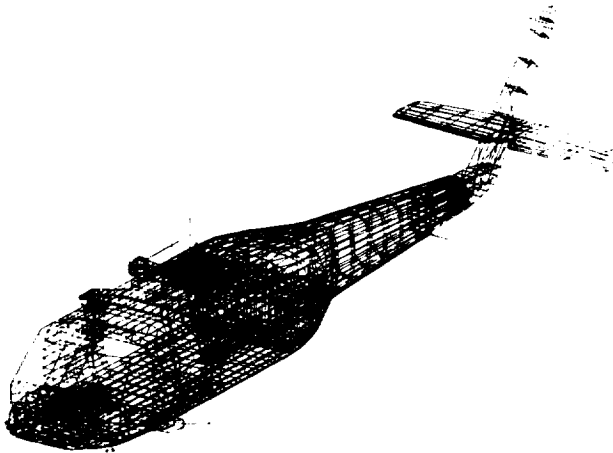


Fig. 2 UH-60A DAMVIBS finite element model.

Updating the Element Properties Prior to DAMVIBS, an FEM of a helicopter airframe would typically be created during preliminary design, and then left unchanged throughout the remaining life of the aircraft, the significant cost of updating the model not being deemed worth its uncertain rewards. Since the final airframe design would usually differ significantly from the preliminary design, it is not surprising that large discrepancies usually occurred between the FEM and the actual shake-tested airframe. An important part of the DAMVIBS re-modeling effort was the updating of all of the element properties in the FEM to match those of the final-design drawings.

Comparison of the DAMVIBS FEM with Shake Test Results

Shake Testing the UH-60A The UH-60A production airframe was rigorously shake-tested, using stepped-sine frequency-excitation sweeps with the forces applied at the main rotor hub, one direction at a time. The testing was controlled by computer software developed by Imperial College of Science and Technology. The resulting frequency response functions (FRF's) were stored on computer discs, and were subsequently curve-fitted to obtain the modal properties of the structure, using both the Imperial College and the SMS Modal 3 SE software systems. The testing and analysis of test data is described in detail in Reference 2 (for the 10,000 lb weight-empty configuration) and in Reference 3 (for the 13,500 lb minimum-flight-weight configuration).

Analysis/test Comparison Analysis/test comparisons are described in detail in References 2 and 4 (for the 10,000 lb configuration) and in Ref. 5 (for the 13,500 lb configuration). Fig. 3 shows a comparison of the natural frequencies predicted by the 13,500 lb DAMVIBS FEM compared with those extracted from the test

frequency-response functions. In general, the analytical frequencies are lower than test, with an average error of 7.5%. While this is a significant improvement over the pre-DAMVIBS model (which had an average error of 12.8%), significant differences still remained to be resolved before real confidence in the vibration-prediction ability of the model could be established.

Mode	Mode Description	Test Frequency (Hz)	NASTRAN Results			
			Pre-DAMVIBS FEM		DAMVIBS FEM	
			Freq.	% Error	Freq.	% Error
1	1st lateral bending	5.36	4.77	-11	4.96	-8
2	1st vertical bending	6.07	5.42	-11	5.83	-4
3	Stabilator roll	9.68	8.10	-16	9.13	-6
4	Stabilator yaw	10.18	9.83	-3	11.07	9
5	Transmission pitch	12.25	9.46	-23	10.63	-13
6	Transmission roll, 2nd lateral bend	13.50	11.44	-15	12.53	-7
7	Same, opposite phase	13.94	12.71	-9	13.39	-4
8	2nd vertical bending	14.10	10.52	-25	11.83	-16
			14.63			
9	Transmission vertical	15.86	14.90	-6	14.69	-7
			14.81		15.84	
10	Cabin torsion 2nd lateral bend	17.41	15.77	-9	17.27	-1
11	Same, opposite phase	21.57	17.23		18.24	
			19.84		18.32	
			20.23		20.94	
			22.44		21.22	
					21.39	

Fig. 3 Comparison of pre-DAMVIBS and DAMVIBS FEM'S with shake test.

Improvement to the UH-60A DAMVIBS FEM

Development of PAREDYM One of the most important results of the DAMVIBS project was the change in climate in industry regarding the importance of airframe finite element modeling. This change manifested itself at Sikorsky in the decision taken about six years ago to embark, with aid of the University of Bridgeport, upon a project to develop a method which would automatically modify the element properties in an FEM so that its modal characteristics would agree with those found in test; in other words, a method which would scientifically identify the causes of the discrepancies between predicted and measured values.

Based on the method described in Ref. 6, a general method, called PAREDYM (Parametric REfinement of DYnamic Models), was developed and programmed in MSC/NASTRAN DMAP language (Ref. 5). In this program, FORTRAN codes are used for iterative looping control and for updating, in each loop, the NASTRAN input bulk data.

The iteration procedure of the method is as follows:

- (1) Start with an initial FEM. Set iteration counter $k=0$.
- (2) Perform modal analysis (Rigid Format 63) to determine $\{Y_a\}_k$, where $\{Y_a\}$ includes natural frequencies $\{\omega_a\}$ and mode shapes $\{\phi_a\}$.

- (3) Compute design sensitivity matrix $[T]_k$ (Rigid Format 53) and the modal differences $(\Delta Y)_k = [Y_e] - [Y_a]_k$, where $[Y_e] =$ modal values from test.
- (4) Set $(\Delta B)_{k+1} = ([T]^T [T])^{-1} [T]^T (\Delta Y)_k$
- (5) Update FEM
- (6) Check the convergence criterion for analysis/test agreement in modal values.
 - a. Stop procedure if it is met.
 - b. Continue procedure if it is not met.
- (7) Set $k = k+1$ and go to step (2).

This process continues until the desired agreement with test is obtained. Difficulties encountered, such as matrix ill-conditioning and mode crossing, when applying the method to real large-scale structures, are discussed in Ref. 5. Ref. 7 describes an efficient way, developed and applied in PAREDDYM, of accommodating ill-conditioned equations, called epsilon-decomposition.

Applying PAREDDYM to the UH-60A FEM
 PAREDDYM was applied to the UH-60A, using the FEM of Fig. 2, generated under DAMVIBS, together with the test data obtained under DAMVIBS. To keep the computer time manageable, use was made of the linking feature in NASTRAN which allows properties of more than one element to be tied to a single "design variable". The element properties were grouped into seven regions (Fig. 4), with the cabin section further subdivided into four regions (top, bottom, and two sides). In each region the element properties were linked together into four design variables, one linking all plate (QUAD4) elements in the outer shell and one linking them in the inner structure, with plate thickness as the design-variable parameter; one linking all beam (BAR) elements in the outer shell, and one linking them in the inner structure, with beam cross-sectional area as the design-variable parameter. These, together with five stabilator attachment spring parameters, gave a total of 45 design variables. Mass properties were kept constant.

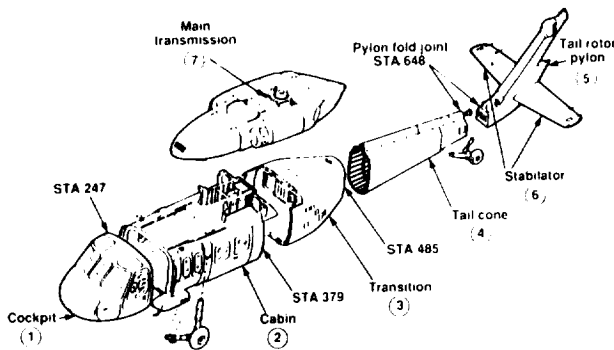


Fig. 4 UH-60A: regions within which element properties are linked for PAREDDYM program.

Figure 5 shows the iteration results of targeting six of the FEM's natural frequencies to their corresponding test values (The six modes chosen had the best mode-shape agreement with their test counterparts.). The frequency errors are all seen to converge to near zero in six iterations. Figure 6 shows the corresponding changes in design-variable properties which achieved this convergence.

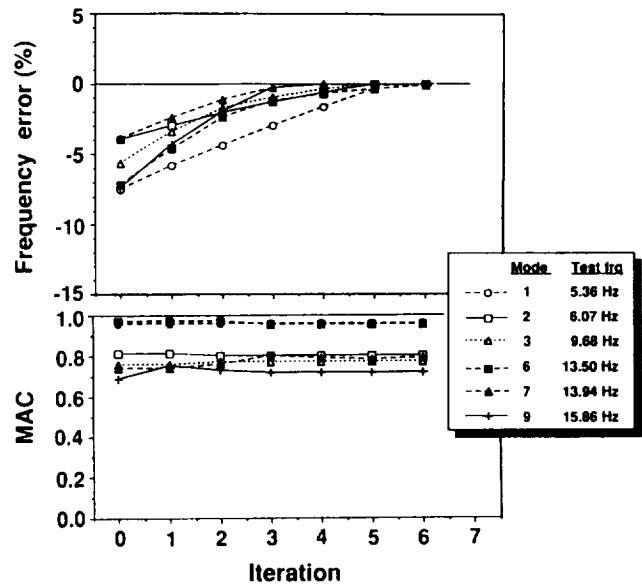


Fig. 5 UH-60A: six-mode correlation results.

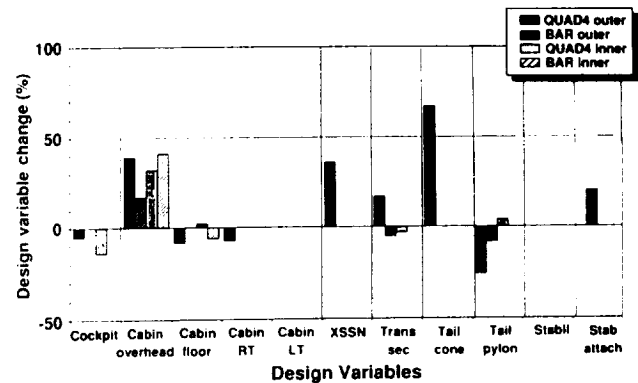


Fig. 6 UH-60A: design variable changes for six-mode correlation.

Improving the UH-60A FEM At this point the above-calculated element properties could have been incorporated into the FEM, with the knowledge that a good correlation of at least six of its natural frequencies was assured. However, a "mathematical fit" improvement to the model was not what was desired here, but rather a "correct" improvement, that is one based on physical modeling principles, which would result in a model capable of making trustworthy dynamic response predictions due to later structural or mass configuration modifications.

Thus the calculated updates to the element properties were examined as to what they might

be indicating regarding modeling deficiencies. The large stiffness increases called for in the cabin overhead region, for example, could be pointing to the considerable amount of unmodeled (from a stiffness standpoint) secondary structure in this region. A model of a major part of this secondary structure, the firewalls and their connecting structure, was created and added to the airframe FEM. It was surmised that the stiffness increase called for in the main transmission was due to the neglecting of the stiffeners in the connecting structure between the input modules and the main housing. To account for this, the thickness of the plate elements in this region were doubled. The large stiffness increases called for in the tail cone region were not acted upon since no physical justification for them could be thought of.

With the above modeling changes, plus the addition of a rough model of the windshield and cockpit doors, the agreement of the model with test has improved to the point where serious confidence in its predictions is now possible. As shown in Figure 7, there now exists a one-to-one correspondence between the first 10 analytical modes and the first 10 fuselage test modes, in the frequency range up through the blade passage frequency of 17.2 Hz (Two test modes which had their origin in the suspension system are not included here but will be discussed in the next section.). The average frequency error of these modes has now dropped from 7.5% to 3.2%, and the average MAC value has increased from 0.70 to 0.82 (the MAC value is an indicator of mode shape agreement, 1.0 indicating perfect agreement). Figures 8 and 9 show the improvement of a representative frequency response function (FRF) resulting from these latest modeling changes. Further details of the above are given in Ref. 6.

Mode	Mode Description	Test Frequency (Hz)	NASTRAN Results			
			DAMVIBS FEM		Impr. DAMVIBS FEM	
			Freq	% Error MAC	Freq	% Error MAC
1	1st lateral bending	5.36	4.96	-8.096	4.99	-7.096
2	1st vertical bending	6.07	5.83	-4.081	6.02	-1.081
3	Stabilator roll	9.68	9.13	-6.076	9.16	-5.076
4	Stabilator yaw	10.18	11.07	9.007	11.04	8.011
5	Transmission pitch	12.25	10.63	-13.028	11.57	-6.052
6	Transmission roll 2nd lateral bend	13.50	12.53	-7.087	13.05	-3.095
7	Same opposite phase	13.94	13.39	-4.074	14.06	1.090
8	2nd vertical bending	14.10	11.63	-16.065	13.33	-5.086
9	Transmission vertical	15.86	14.69	-7.069	16.06	1.085
			14.81			
			15.84			
10	Cabin roll 2nd lateral bend	17.41	17.27	-1.087	17.77	2.071
11	Same opposite phase	21.57	18.24		20.43	
			18.32		20.89	
			20.94		21.15	
			21.22		21.15	
			21.39		22.00	

Fig. 7 Comparison of DAMVIBS and improved DAMVIBS FEM's with shake test.

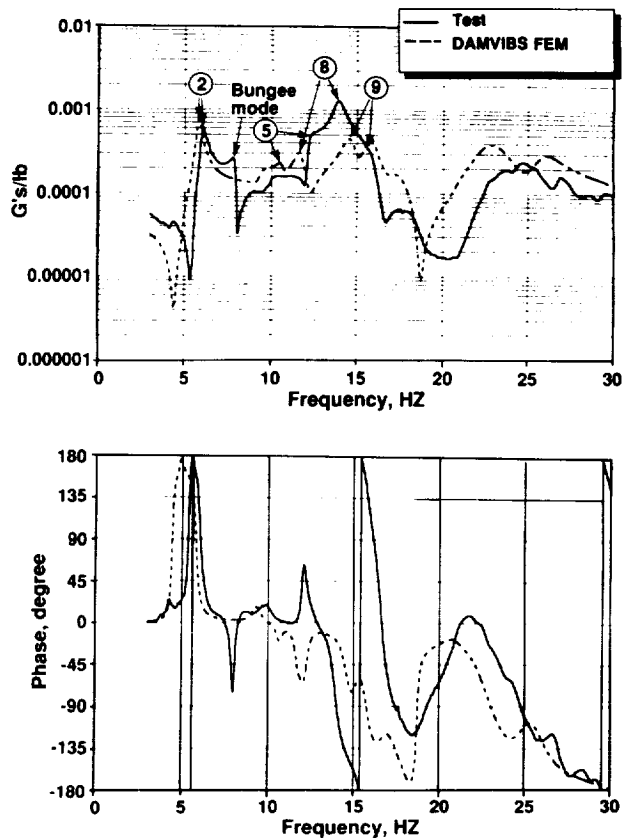


Fig. 8 Comparison of DAMVIBS FEM with test (pilot vert. response to long. excitation at main rotor head).

Effect of Bungee Suspension System

Along with the closer look given to finite element modeling, a closer look was also given to the shake test data which were being used for model verification. As an example of this closer look, the test FRF in Fig. 9 shows evidence of a test mode near 7.9 Hz for which no analytical equivalent is calculated. This test mode, and another one of similar frequency, in response to a lateral shake, were suspected of being modes originating not with the fuselage, but with transverse motions of the suspension system. A large response peak near 7.9 Hz, for an accelerometer placed on the suspension system during one frequency sweep, provided additional evidence for this.

The airframe was suspended from the ceiling, during shake testing, by a bungee system shown schematically in Figure 10. Since the bungees are made soft enough to keep the rigid body modes of the airframe low with respect to its elastic

modes, airframe analyses have traditionally been run in a free-free condition with the suspension system unmodeled. To investigate the effect of the suspension system on the test results, and thus on the analysis/test correlation, an FEM of the suspension system was formulated and added to the improved fuselage FEM. Modal analyses were done using the differential stiffness approach in NASTRAN in order to include the necessary stiffening effects of gravity on the suspension system.

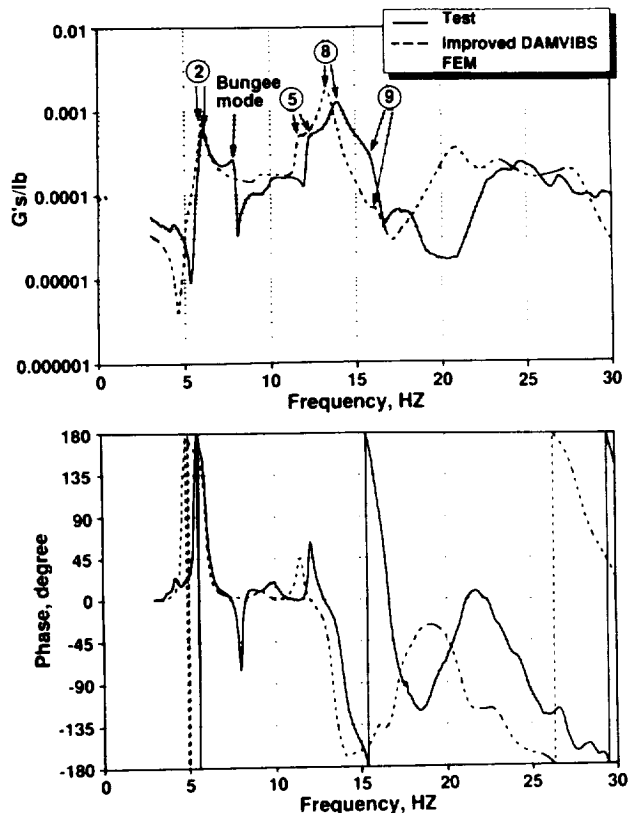


Fig. 9 Comparison of improved DAMVIBS FEM with test (pilot vert. response to long. excitation at main rotor head).

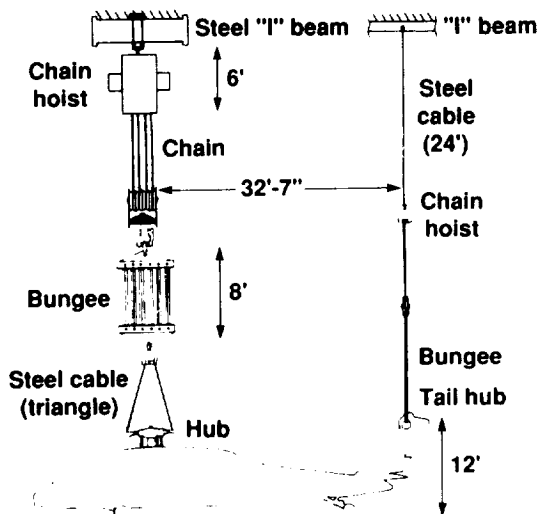


Fig. 10 Schematic of airframe suspension system in shake test.

Figure 11 shows a comparison with test of the same FRF after the addition of the model of the suspension system. It is seen that the analysis with the suspension system predicts an additional mode (at 7.37 Hz) which is close in frequency to the previously-unmatched test mode (found at 7.9 Hz). The analytical mode is basically a fore-and-aft mode of the main rotor suspension system, but, as seen in the analytical shape (Figure 12), it couples strongly with the fuselage, causing the mode to appear in test as a fuselage mode. The striking agreement between the analytical and the test mode shapes, in the fuselage region, the only region measured, adds evidence that this test mode is now being correctly predicted.

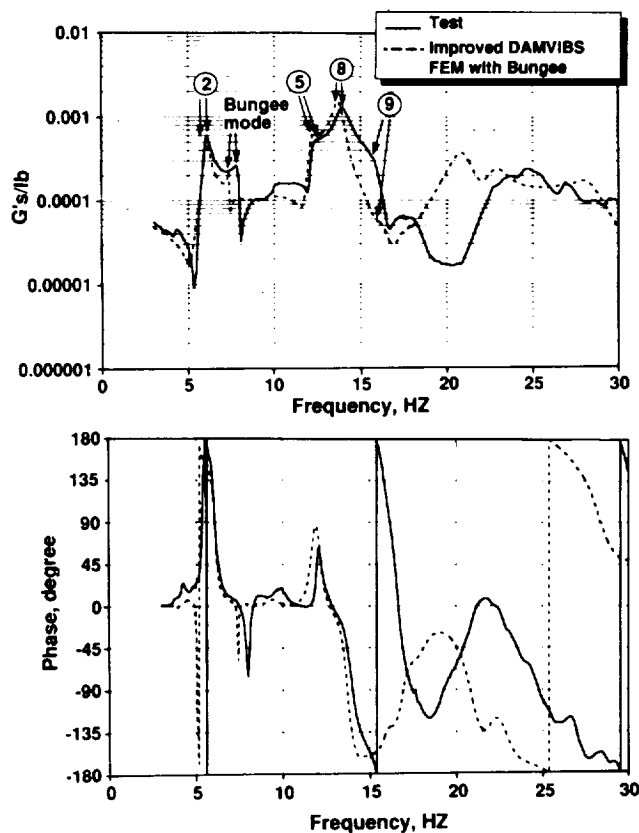


Fig. 11 Comparison of improved DAMVIBS FEM with suspension system with test (pilot vert. response to long. excitation at main rotor head).

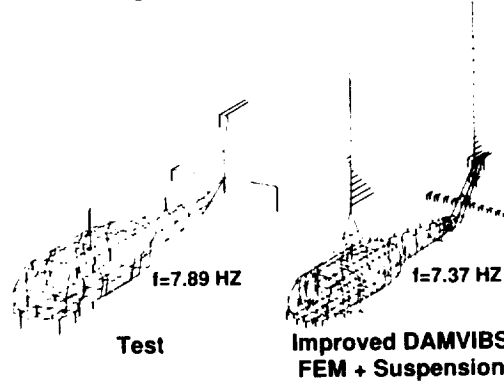


Fig. 12 Comparison of improved DAMVIBS FEM with suspension system with test (suspension-system mode shape).

DESIGNING LOW VIBRATION INTO A NEW AIRFRAME

With newly-found confidence in the ability of a FEM to predict the vibration properties of a structure, the next logical step was to move into the final area addressed by DAMVIBS, namely the introduction of low-vibration design into the airframe design process. Although the PAREDYM program was originally developed to improve a finite element model (FEM) to bring it into agreement with test, the generality of its formulation allows for its use also as a minimum-vibration design tool. In essence, the program calculates a minimum set of element property changes which cause the modal properties (natural frequencies and mode shapes) of the FEM to move in the direction of a pre-assigned set of target values. These target values can be obtained from shake test (when it is desired to bring the FEM into agreement with existing test data), or they can be a set of design goals (in the case of a structure under design) which are desired for the structure, in order for it to have low response levels, at the required critical locations, and under the expected excitation forces and frequencies.

Application to a New Design

Natural Frequency Modification With the next new helicopter design at Sikorsky, low-vibration design was attempted from the earliest preliminary-design stages. A frequency-response analysis was made of an early-design 3000-d.o.f. FEM of this aircraft, using blade-passage-frequency hub loads derived from rotor wind tunnel tests as the inflight excitation forces. Initial results are shown in Figure 13, for pilot lateral and vertical response, with the hub load frequency artificially varied over a range of frequencies, in order to better understand the nature of the response. At the blade passage frequency, the calculated responses were found to be excessive. To reduce them, six modes, all having natural frequencies near the excitation frequency, were identified as being the major contributors to the vibratory response. PAREDYM was used to move these modes away from the excitation frequency, and in Fig. 14 it can be seen that by the seventh iteration they all have moved well out of that neighborhood. The new frequency response plots reflect this shift in natural frequencies in the absence of nearby resonance peaks (Fig. 15). Pilot lateral response has accordingly been reduced by 62%. However, contrary to expectations, the pilot vertical response has actually increased.

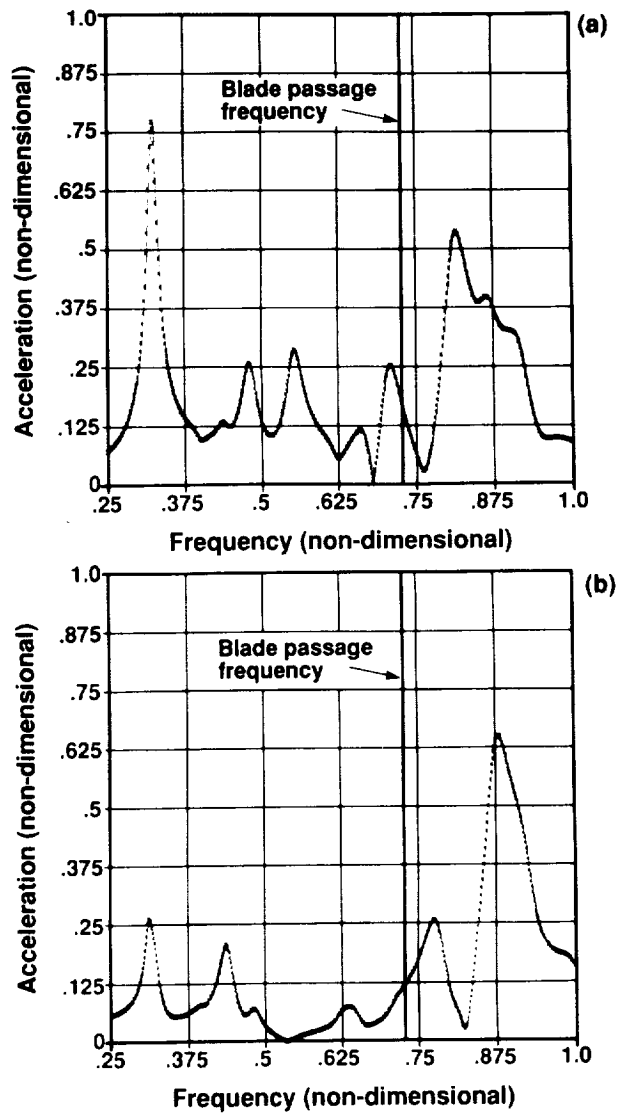


Fig. 13 Initial design: pilot (a) lateral and (b) vertical responses vs excitation frequency.

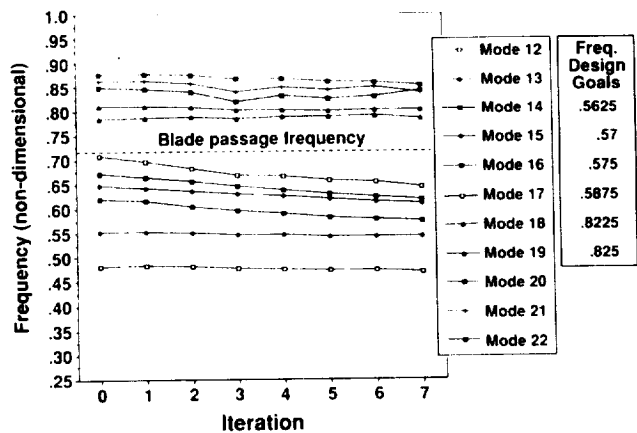


Fig. 14 Frequency optimization: natural frequencies vs solution iteration (no constraints).

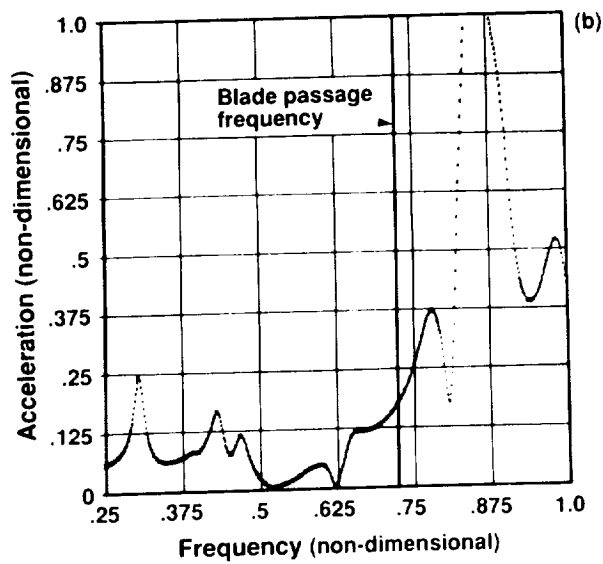
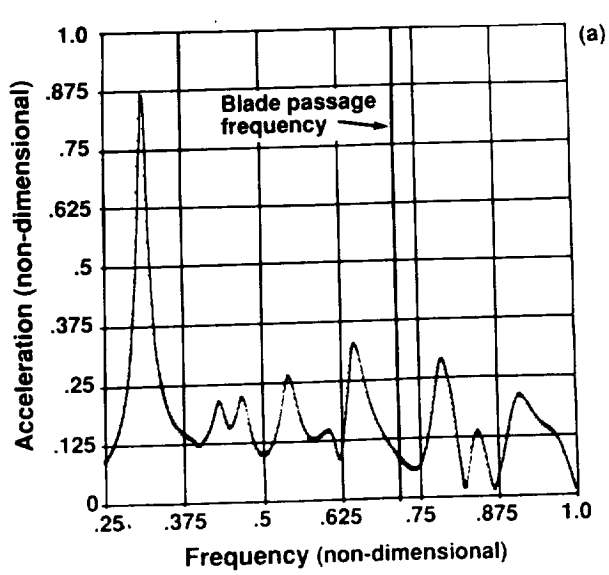


Fig. 15 Frequency optimization: pilot (a) lateral and (b) vertical responses vs excitation frequency (no constraints).

Mode Shape Modification In an effort to further reduce the responses, the critical-location components of the mode shapes contributing the most to the responses, were targeted to be reduced in PARESYM. Figure 16 shows the reduction of the mode shape components at pilot

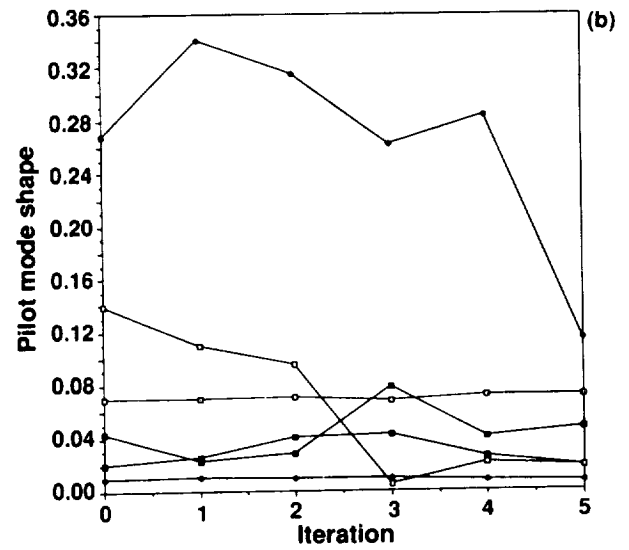
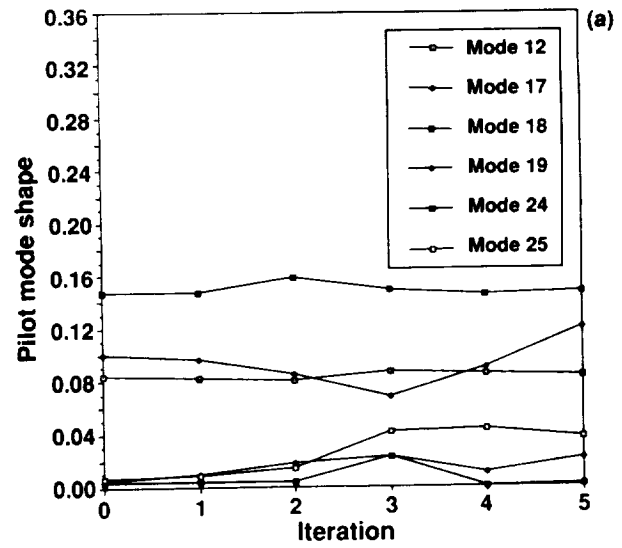


Fig. 16 Mode shape optimization: mode shape vs solution iteration, pilot (a) lateral and (b) vertical components (no constraints).

vertical after five iterations. The two largest components at pilot vertical are seen to drop by 60% and 85%. Figure 17 shows the frequency responses at the same location following the last iteration; a 67% overall reduction in pilot response has been achieved.

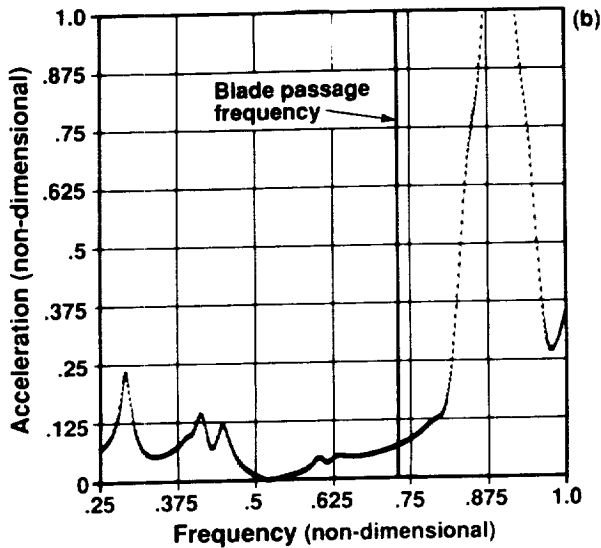
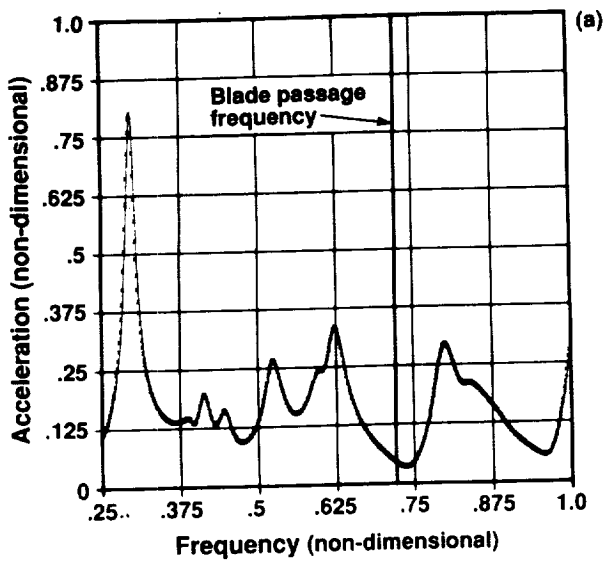


Fig. 17 Mode shape optimization: pilot (a) lateral and (b) vertical responses (no constraints).

Figure 18 shows the associated design variable changes in the cabin (beam cross-sectional areas and skin panel thicknesses), that accompanied the above vibration reduction. The changes are seen to range from a 500% increase to a 80% decrease. The extremes of these changes were not considered to be feasible, from a design standpoint. The large stiffness increases would cause a considerable weight penalty, in the present case amounting to 2% of the total weight of the helicopter. The large stiffness reductions could severely reduce the life of the structure. It was thus considered necessary to introduce into the program both the ability to minimize the total weight change, as well as the ability to put limits on the individual design variable changes.

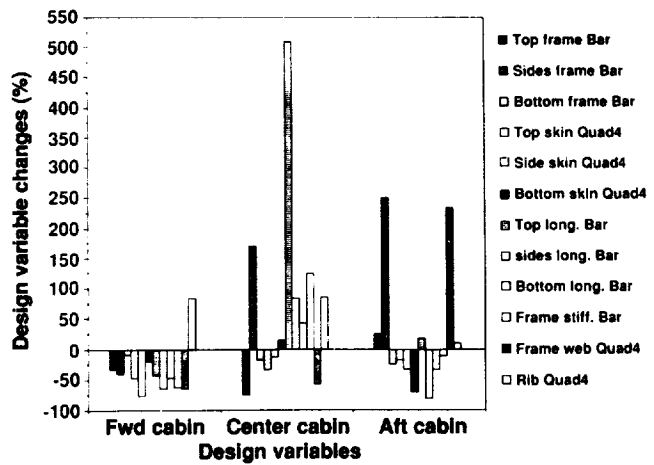


Fig. 18 Frequency and mode shape optimization: cabin design-variable changes (no constraints).

Incorporation of Total-weight-change Minimization and Design-variable Side Constraints into PAREDYM To minimize the total weight increase of the structure, the sum of all the mass changes implied by the design variable stiffness changes was introduced explicitly into the objective function, for minimization, through the use of Lagrange multipliers.

For the design problem, the size of many members can only be reduced by a limited amount to ensure the structural strength and can only be increased a certain amount to maintain proper weight distribution. In order to achieve these requirements, upper and lower bounds (side constraints) on the design variable changes are imposed in each iteration. Should the design variables become higher or lower than the respective preset limits, they are set equal to those limits.

Effect of Including Minimum Weight Change and Design Variable Constraints Following the incorporation of the above two capabilities, the low-vibration design problem was re-examined. A total-mass-change minimization was introduced, as well as $\pm 30\%$ side constraints on each design variable. Figure 19 shows the resulting new frequency-modification results with the above constraints now included. Comparing with Figure 14, it is seen that the natural frequencies now have more difficulty in converging to their target frequencies. This is expected; when the most sensitive (effective) design variables reach their limits, the program has to switch to less effective design variables to continue the frequency shifting, thus slowing down the process.

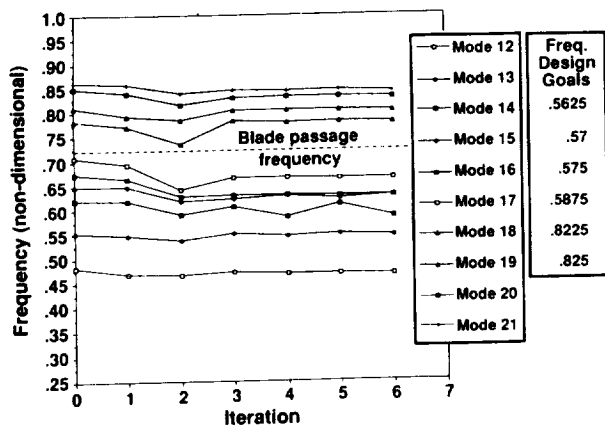


Fig. 19 Frequency optimization: natural frequencies vs solution iteration (constraints applied).

Figure 20 shows the corresponding FRF's at the pilot lateral and vertical, following these iterations, with the above constraints applied. The resulting changes in pilot response, compared to the original design, are a 54% reduction in pilot lateral, and a 1% increase in pilot vertical, giving an overall reduction of 39% in the resultant pilot response (pilot lateral was originally twice as large as pilot vertical), with the total weight increase equaling only 0.1% this time. Although this is less than the 67% overall vibration reduction achieved earlier without constraints, it now represents a more realistic goal. Further details on the methods used for low-vibration design are given in References 8 and 9.

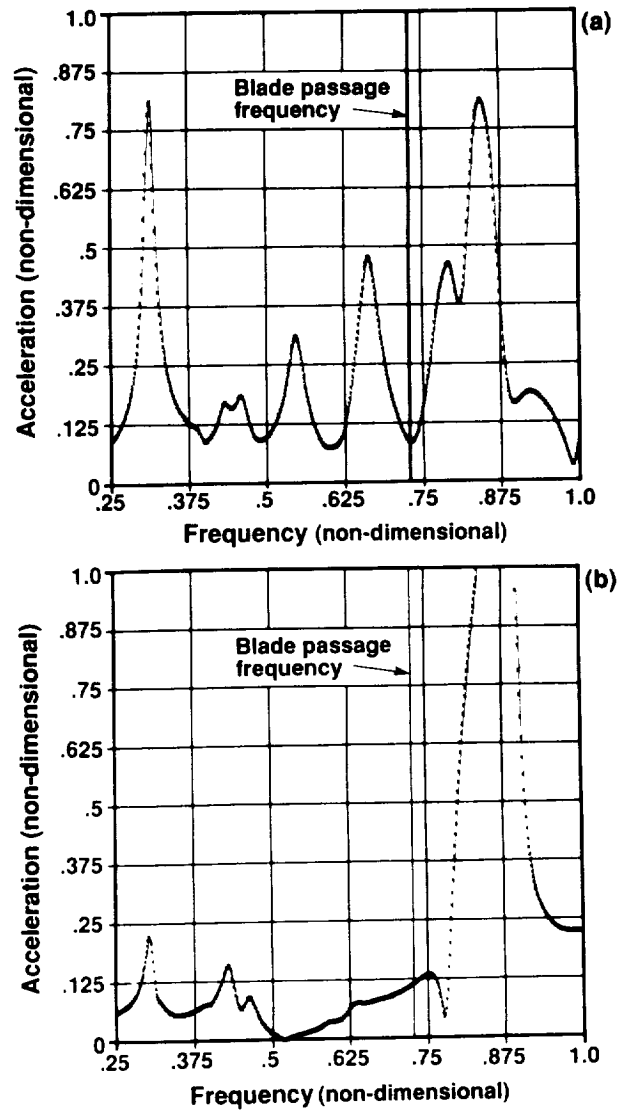


Fig. 20 Frequency optimization: pilot (a) lateral and (b) vertical responses (constraints applied).

CONCLUSIONS

A short history has been traced of the work done at Sikorsky Aircraft under the NASA/industry DAMVIBS program. This includes both work directly funded by the program as well as work which was internally funded but which received its initial impetus from DAMVIBS.

The development of a finite element model of the UH-60A airframe having a marked improvement in vibration-predicting ability has been traced. A new program, PAREDYM, which automatically adjusts an FEM so that its modal characteristics match test values, has been developed at Sikorsky. This program has shared in the improvement of the UH-60A model.

Along with the closer look at finite element modeling, which was engendered by the DAMVIBS program, came also a closer look at the shake test data which were being used for model verification. A preliminary investigation showed important effects on the airframe test data of the bungee system used to suspend the test article, effects not normally accounted for in finite element modeling.

The impetus given by the modeling improvement as well as the new availability of PAREDYM brought the introduction of low-vibration design, through the control of modal parameters, into the airframe structural design cycle at Sikorsky. A description of how PAREDYM was used to do this, along with some of the difficulties encountered, was described.

The objective of the DAMVIBS program was to raise the level of the finite-element modeling of helicopter airframes to the point where it would be taken seriously in its ability to predict vibration and in its ability to bring low vibration into the airframe design process. DAMVIBS has succeeded in doing this. Although much improvement remains to be done, it has brought respectability to the analytical prediction of inflight helicopter vibration, and its stated goal of bringing low vibration into the design process of helicopter airframes has been seriously begun.

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11. SUPPLEMENTARY NOTES
A compilation of papers presented in the special session "Finite Element Analysis of Rotorcraft Vibrations" at the 33rd Structures, Structural Dynamics and Materials Conference, April 13-15, 1992, Dallas, Texas

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13. ABSTRACT (Maximum 200 words)
The NASA Langley Research Center in 1984 initiated a rotorcraft structural dynamics program, designated DAMVIBS (Design Analysis Methods for VIBrationS), with the objective of establishing the technology base needed by the rotorcraft industry for developing an advanced finite-element-based dynamics design analysis capability for vibrations. An assessment of the program showed that the DAMVIBS Program has resulted in notable technical achievements and major changes in industrial design practice, all of which have significantly advanced the industry's capability to use and rely on finite-element-based dynamics analyses during the design process. A special session on finite element analysis of rotorcraft vibrations was held at the AIAA 33rd Structures, Structural Dynamics and Materials Conference, April 13-15, 1992, in Dallas, Texas to collectively summarize the accomplishments and contributions of the industry participants in the DAMVIBS Program. The special session included 5 papers. The first paper was an overview of the program from the perspective of the NASA manager of the program. The subsequent papers presented more detailed technical summaries of the specific accomplishments of the four industry participants as viewed by their program managers. This document is a compilation of the papers presented in that special session.

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