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THE NASA/INDUSTRY DESIGN ANALYSIS METHODS FOR VIBRATIONS (DAMVIBS) PROGRAM - ACCOMPLISHMENTS AND CONTRIBUTIONS

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ABSTRACT

A NASA Langley-sponsored rotorcraft structural dynamics program known as DAMVIBS (Design Analysis Methods for VIBrationS) with the objective of establishing the technology base needed by the industry for developing an advanced finite-element-based dynamics design analysis capability for vibrations has been underway since 1984. Under the program, teams from the four major helicopter manufacturers have formed finite-element models, conducted ground vibration tests, and made test/analysis comparisons of both metal and composite airframes, performed "difficult components" studies on airframes to identify components which need more complete finite-element representation for improved correlation, and evaluated industry codes for computing coupled rotor-airframe vibrations. Studies aimed at establishing the role that structural optimization can play in airframe vibrations design work have also been initiated. Five government/industry meetings have been held in connection with these activities during the course of the program. Because the DAMVIBS Program is coming to an end, the fifth meeting included a brief assessment of the program and its benefits to the industry. The assessment indicated that the DAMVIBS 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 finite-element-based dynamics analyses during the design process. The purpose of this paper is to present a summary of the major accomplishments and contributions which may be ascribed to the program.

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 (refs. 1-3). For example, during the Army UTTAS and AAH development programs in the mid-1970s all four competing aircraft experienced major vibration-related problems during initial flight testing. 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 as embodied in the NASTRAN computer code 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. 4-5). However, even though vibration is usually one of the significant problems of helicopter design, until recently 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. 6-9). A notable exception to this situation is the Rotor Systems Research Aircraft (RSRA) in which the design was reported to have been influenced considerably by vibration considerations (ref. 10).

The problems facing analysts charged with predicting helicopter vibrations are depicted in figure 1. The rotor system generates complex periodic aerodynamic and dynamic loads which are transmitted to the airframe through both mechanical and aerodynamic load paths. The largest oscillatory loads transmitted to the airframe are usually those which are mechanically transmitted through the mounting system. These loads occur at frequencies which are integer multiples of the so-called blade passage frequency which is equal to the product of the number of blades and the rotor rotational speed. The largest vibratory forces transmitted to the airframe are usually those occuring at the blade passage frequency. For most helicopters, the blade passage frequency is typically in the range 10 to 20 Hz and thus the airframe response will be dominated by the modes in the range from 0 Hz to (about) two times the blade passage frequency or 40 Hz. Helicopter airframes are rather light-weight, usually thin-skinned structures which are complicated structurally by multiple large cutouts and abrupt discontinuities. The dynamic

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situation is complicated further by the fact that these structures are required to support several rather large-weight dynamic 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 so that the industry has not regarded finite-element dynamics analysis as a sufficiently-mature discipline on which to base design decisions. Thus, airframe dynamic analyses have not been a very effective tool in the design process. This situation has resulted in a heavy reliance on vibration control devices rather than passive design techniques. Indeed, the development of vibration control devices of one type or another has been the dominant factor in the reduction in the level of vibration which has been achieved over the years. Vibration prediction is an industry-wide problem and remains a barrier to achieving the goal of a helicopter with a "jet smooth" ride (refs. 11-15).

There has emerged within the industry a consensus on the need for more effective use of passive design techniques to reduce vibrations by relying more fully on airframe finite-element vibration models during the design process. It is now recognized that the goal of a truly low-vibration (jet-smooth) helicopter can only be attained if vibrations are addressed effectively during design and not relegated to ad hoc treatment during ground and flight test. It was with this need in mind that, during the late 1970s, rotorcraft industry advisory groups began calling for NASA to work with the industry on improving the predictive capability of airframe finite-element vibration models so that such models could be relied on more fully during design in efforts to reduce vibrations. In 1978, NASA's Office of Aeronautics and Space Technology, in an unrelated move, formed a special rotorcraft 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 predictive capability of finite-element dynamics models. The proposed task, which appeared in the final report of the task force (ref. 16), called for an application of finite-element modeling with emphasis on predicting structural vibrations in a workshop environment (that is, a working arrangement which was conducive to the free and open exchange of ideas) to assess and document industry modeling techniques and ground vibration test procedures. All work was to be done on a production aircraft. As a result of a competitive procurement, Boeing Helicopters won a contract to conduct the subject study on the CH-47D tandem-rotor helicopter. This work was conducted during the period 1980-1983.

During the course of the studies conducted on the CH-47D helicopter, it became clear that what was needed to firmly establish a body of modeling guides suitable for attaining confidence in the prediction of vibrations during design was an industry-wide program in which all the companies conduct modeling, testing and correlation activities in a workshop environment along the lines of the CH-47D study. 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. The proposed program was formally presented to the helicopter industry in 1983 at a workshop focusing on problems associated with the modeling of rotorcraft airframe structures (ref. 17). It was the consensus of the industry attendees that the proposed new initiative on rotorcraft airframe finite-element modeling was needed and should proceed as planned. Because the objective of the "new" 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). It should be remarked that because the new program was in essence a continuation of the type of work conducted under the unnamed program represented by the CH-47D study but expanded to include contracted participation by the other three major helicopter companies, the CH-47D activity is oftentimes considered part of the DAMVIBS Program and the two programs came to be regarded as one program.

The DAMVIBS Program was made the focus of a new and broader rotorcraft structural dynamics program which was initiated at NASA Langley at that time (fig. 2) and called for industry teams to carry out modeling, analysis, testing and correlation studies on both metal and composite airframes. The finite-element models developed in these studies were then to be used in follow-on studies to identify those "difficult components" which require refined representation in the finite-element model, to improve analyses for computing coupled rotor-airframe vibrations, and to develop techniques for airframe structural dynamics optimization. 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 (fig. 3). 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 (there is one contracted activity which is still underway), the fifth meeting included a special session devoted to an assessment of the program and its benefits to the industry. The assessment indicated that the DAMVIBS Program has resulted in notable technical achievements and changes in industrial design practice, all of which have advanced the industry's capability to use and rely on finite-element-based dynamics analyses during the design process.

The purpose of this paper is to present a summary of the accomplishments and contributions which may be ascribed to the DAMVIBS Program, including the study which was conducted on the CH-47D. Because the CH-47D study represents the initial and distinct phase of what eventually came to be called the DAMVIBS Program, and because several aspects of that study were unique, the paper begins with a summary of the results and experiences of the CH-47D study. This is followed by a description of the objective, scope and approach of the expanded program and the presentation of illustrative results in each of the four DAMVIBS technology areas indicated in figure 2. Emphasis throughout will be on contractor results. However, contributions to the DAMVIBS Program resulting from in-house research activities as well as funded university work will be described where appropriate.

INITIAL FINITE-ELEMENT MODELING PROGRAM

Objective/Scope/Approach

As previously mentioned, the vibrations portion of the NASA rotorcraft research program defined in 1978 (ref. 16) contained an airframe modeling/test assessment activity which was intended to resolve difficulties expressed by the industry in applying the finite-element analysis method to calculate vibrations of airframe structures in helicopter design efforts. The objective was to establish industry wide a body of modeling guides which would enable future confident prediction of airframe vibrations as part of the regular structural design process. This proposed task was to involve participation by NASA and the industry in a workshop environment to assess and document industry modeling techniques and shake 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 (fig. 4). An unusual requirement of the contract was that each major step of the program be presented to and critiqued by the other three helicopter airframe manufacturers. Thus, 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 latter "time and motion" study was intended to provide a basis on which to schedule finite-element modeling for any new helicopter development program. The contract also called for a thorough documentation of the modeling and testing procedures. The study was deliberately slow-paced (It extended over the 3-year period 1980-1983) to allow for the necessary extensive government/industry interactions and technical exchanges. Plans for the modeling and ground vibration testing as well as the results of the modeling phase of the study were presented on-site to the other companies for critique by a NASA/Boeing team. The results of the test and correlation task were presented to industry representatives at Langley Research Center in February 1983. The studies conducted on the CH-47D have been extensively documented in a series of NASA Contractor Reports (refs. 18-22). The results presented in the next section have been adapted from these reports, to which the reader is referred for details.

Illustrative Results

The subject aircraft is the CH-47D tandem-rotor helicopter designed for aerial transport of troops and cargo (fig. 4). The three-bladed rotors turn at 225 rpm (3.75 Hz) giving it a blade passage frequency of 11.25 Hz. A drawing of the CH-47D primary fuselage structure is shown in figure 5. The finite-element model developed as part of the study is shown in figure 6 wherein are indicated the number and type of the different elements used to form the structural (static) model. An extensive ground vibration test was also conducted on the airframe (fig. 7). The airframe was excited by forces vertically, longitudinally, and laterally and moments in pitch and roll at both the forward and aft hubs over the frequency range from 5 to 35 Hz. Acceleration measurements in three orthogonal directions were recorded at 35 locations distributed throughout the airframe. Illustrative results showing the type of comparisons which were obtained between measured and calculated forced responses for pitch excitation at the forward hub are given in figure 8. As has been customary, a single value of structural damping (2.5 percent critical in this case) was assumed for all of the modes used in the analysis and the modes were calculated assuming a free-free (unsupported) condition. Taken as a whole, the correlations which have been obtained are considerably improved over similar attempts of the past (particularly at the lower frequencies) and go a long way toward removing the uncertainty about the limits of applicability of finite-element models for vibration predictions. Important events (peaks, valleys, phase shifts) related to the major airframe modes in the test data are predicted by the analysis. The exception is that events tend to occur at slightly lower frequencies in the analysis than in the test data. That is, there appears to be an unwarranted softness in the finite-element model. Further, the agreement is acceptable only up through about 15-20 Hz.

The CH-47D modeling work demonstrated that a finite-element model suitable for static internal loads and vibrations can be developed simultaneously and that there is no need to form separate static and dynamic models as had usually been done in the past. The cost of such a combined static and dynamic model was established to be 4430 man-hours or about 5 percent of the man-hours of a typical airframe design effort. Of the 5 percent, 4 percent is already typically expended in most companies to form the so-called static or internal loads model; the vibrations model is another 1 percent. The time and motion study has answered the question: "Can a finite-element model be assembled and used in time to influence the design of a new helicopter?" The CH-47D study showed that it appears that initial vibration results can be obtained in 6 months from contract award and thus be available early enough to influence the airframe design.

The modeling and correlation studies identified several items which have the potential for improving the correlation. These include: use of nonuniform modal damping in the frequency response calculations and the inclusion of so-called "secondary effects" such as stringer shear area, stringer shear continuity across splice joints, and suspension system dynamics. A preliminary effort to evaluate these (and other) effects was made during the course of this study. Some results from studies of the aforementioned secondary effects are given here.

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. However, if there are differences between test and analysis, the question of possible extraneous effects associated with these systems often arises. It is clear that correlations would be interpreted with more confidence if these effects were included in the analysis. A NASA team devised a method for including the effects of support systems and excitation systems in the finite-element dynamic analysis while taking into account the prestiffening effects due to gravity. Boeing applied this method to the CH-47D. The predicted effects of these systems on the response of the CH-47D are shown in figure 9. While only minor effects are noted for the CH-47D, the effects may not be negligible for other configurations, particularly at the higher frequencies.

Manufacturing splices often occur in a fuselage structure. The CH-47D has two such splices: one at Station 160 and the other at Station 440 (see fig. 5). Under a 1-g loading condition such as associated with steady-state level flight, the upper portion of such a joint is in compression and unconnected stringers may be axially effective. Figure 10 shows the effect of splice joint continuity on frequency response correlation. The assumption that the stringers are effective across the joint has raised the frequency of a major structural mode and brought it closer to its measured value of 11.7 Hz with little effect on the remaining modes.

Helicopter airframe structures typically contain many stringers. However, the cross-sectional areas of the stringers are not considered as contributing to the shear area of the fuselage cross section since the usual assumption that the skin carries all the shear is made. Because the total cross-sectional area of the stringers at a station can be as much as 50 percent of the total cross-sectional area of the skin at the same station, it is not unreasonable to expect that the stringers will also carry some of the shear load. In the study, the stringer shear area was simulated by the simple expedient of increasing the shear modulus of the skin so as to effectively increase the shear area. A representative frequency response comparison including the effects of both stringer shear continuity and stringer shear area is shown in figure 11. The inclusion of these two "secondary" effects made a significant improvement in the correlation of the 11.7 Hz mode.

Summary of Key Findings

(1) A finite-element model is an essential ingredient of any design effort aimed at developing a helicopter with low inherent vibrations.

(2) Modeling guides prepared during the planning phase enabled proper planning, scheduling, and control of the modeling effort.

(3) Cooperation of design-stress-weights-dynamics is the key to achieving a unified finite-element model suitable for both static internal loads and vibrations.

(4) Such a finite-element model can be formed early enough in a new helicopter program to actually influence the airframe design.

(5) Cost of total modeling effort is 4430 man-hours or about 5 percent of a typical airframe design effort. Of the 5 percent, 4 percent is already usual for the statics model; the vibration model is another 1 percent.

(6) Correlation has been improved over similar attempts in the past, particularly at the lower frequencies. High frequency correlation needs further improvement.

(7) The current practice of using a constant assumed value of structural damping in the analysis is not adequate.

(8) Significantly improved correlation appears possible by including secondary effects.

(9) Procedure developed for the analysis of a suspended airframe while taking into account the prestiffening effects due to gravity.

DAMVIBS - THE EXPANDED FINITE-ELEMENT MODELING PROGRAM

Formative Influences

The CH-47D studies demonstrated an improved capability to predict vibrations and showed that a finite-element model could be formed early enough to influence the design of a new helicopter. However, during the course of that 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 work. 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 enduring 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 the industry, 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 at Langley, is indicated in figure 2. 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.

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 with industry-wide critique to allow maximum technology transfer between companies. Because of the number of tasks and industry teams involved in the expanded program, it was decided to hold workshops at Langley rather than make on-site presentations at the companies as was done for the CH-47D study.

Description of Program Elements

A brief description of the four technology areas which constitute the four major elements of the DAMVIBS Program is presented here.

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 traditional sheet-metal construction and advanced composites material 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 "on-the-shelf"; 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 which 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.

Difficult Components Studies.- Typically, only the primary (major load carrying) structure is represented fully (stiffness and mass) when forming the finite-element model of an airframe. There are many components (e.g., transmissions, engines, and stores) and secondary structure (e.g., fairings, doors, and access panels) which are represented only as lumped masses. The aim of this activity was to identify the effects of such "difficult components" on airframe vibratory response and to develop techniques for improved representation of such components if required. The activities included modeling, testing, and test/analysis correlation. The main technical products were to be: (1) Modeling guides for difficult components; (2) Refined airframe models "on-the-shelf"; and (3) Identification of needed research tasks.

Coupled Rotor-Airframe Vibrations.- The purpose of this program element was to improve the understanding of the strengths and weaknesses of existing methods for analysis of coupled rotor-airframe vibrations and to provide guidelines for improving those methods or developing new methods. The products were to be a series of verified analysis procedures "on-the-shelf" for predicting vibrations of coupled rotor-airframe systems in the design of helicopter airframe structures. 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.

Airframe Structural Optimization.- The intent of this program element was to develop computational procedures for structural optimization which are applicable to finite-element models of helicopter airframes and which properly and effectively take into account vibration constraints. The methods were ultimately to be applicable to large-order systems and be compatible with typical design practice for airframe systems.

Illustrative Results

Selected results from each of the four technology areas addressed by the DAMVIBS Program are presented in this section. All the results have been adapted from the series of NASA Contractor Reports which have been published during the course of the program.

Airframe Finite-Element Modeling.- Industry teams have formed finite-element models, conducted ground vibration tests, and made test/analysis comparisons of five airframes (two metal and three composite). Synopses of the results of these studies are presented here.

AH-64A: The McDonnell Douglas AH-64A Apache (fig. 12) is an attack helicopter with a four-bladed main rotor which turns at 289 rpm (4.8 Hz) so that its blade passage frequency is 19.2 Hz. A drawing showing the primary fuselage structure is given in figure 13. The NASTRAN finite-element model for the complete airframe is shown in figure 14 wherein are indicated the number and type of the different elements comprising the static model. Details of the modeling are contained in reference 23. The results of a ground vibration test (fig. 15) and subsequent correlation are described in reference 24. Typical comparisons of calculated frequency responses with those obtained from test are shown in figure 16. The major vertical and lateral bending and torsion modes are predicted but only up through about 10-15 Hz.

UH-60A: The Sikorsky UH-60A BlackHawk (fig. 17) is a single-rotor helicopter designed for transport of troops and cargo. Its four-bladed main rotor turns at 258 rpm (4.3 Hz) so that its blade passage frequency is 17.2 Hz. The primary fuselage structure is shown in figure 18. The NASTRAN finite-element model which was formed is shown in figure 19. A complete description of the modeling is given in reference 25. The results of a ground vibration test conducted on the airframe (fig. 20) and comparisons with finite-element model predictions are described in reference 26. Illustrative results are shown in figure 21. In general, the major structural modes were all predicted by analysis but the frequencies were low by 4-12 percent. That is, there was an unwarranted softness in the model.

D292 (ACAP): The Bell D292 aircraft (fig. 22) is a technology demonstrator built under the U. S. Army's Advanced Composite Airframe Program (ACAP). The basic airframe has a design gross weight of 7525 lb. The two-bladed main rotor turns at 348 rpm (5.8 Hz) giving it a blade passage frequency of 11.6 Hz. The structural breakdown of the airframe is shown in figure 23. The results obtained by using the finite-element model of the D292 developed under the Army program did not agree well with the results of a ground vibration test which was conducted at that time. For this reason, a completely new and considerably-improved model was formed (fig. 24) under the DAMVIBS Program (ref. 27). Results calculated using this new model were then compared (ref. 28) with results obtained from the earlier Army-sponsored test (fig. 25). Typical comparisons of measured and calculated responses are shown in figure 26. Overall, generally-good agreement was obtained through about 20 Hz.

Model 360: The Boeing Model 360 (fig. 27) is an all-composite tandem-rotor helicopter built as a technology demonstrator. It has a design gross weight of 30,000 lb and four-bladed main rotors turning at 269 rpm (4.48 Hz) so that its blade passage frequency is 17.9 Hz. The distribution of composite materials used in its construction is indicated in figure 28. It should be noted that the fuselage was built using a modularized construction technique characterized by rather large honeycomb-sandwich skin panels and minimum use of frames and stringers. The finite-element model of the Model 360 is fully described in reference 29. The resulting model is depicted in figure 29. The ground vibration test which was conducted on the airframe (fig. 30) is described in reference 30. Typical results obtained from the correlation studies (ref. 29) are given in figure 31. In general, the correlation between test and analysis for the frequency responses was poor in terms of both frequency placement and amplitude, even at the lower frequencies where the CH-47D metal airframe studied earlier exhibited improved correlation. The reasons for the large discrepancies are not known but the combination of analytical and test results suggests that more detailed modeling may be necessary to improve the correlation.

S75 (ACAP): The Sikorsky S75 (fig. 32) is a single rotor experimental utility helicopter which was built under the Army ACAP Program. The aircraft has a design gross weight of 8470 lb. Its four-bladed main rotor turns at 293 rpm (4.88 Hz) which gives it a blade passage frequency of 19.5 Hz). A finite-element model formed under the Army ACAP Program was used as a basis to develop the improved model shown in figure 33. The new model is described fully in reference 31. The evaluation of this model is to be made as part of a difficult components study on the aircraft which is now underway.

Related Activities: There are three activities related to this program element which are of note. The first is a contracted study (ref. 32) aimed at describing a (previously proprietary) company-developed method for identifying modeling errors which may arise in developing a structural finite-element model. The procedure is implemented as a set of NASTRAN DMAP alters and identifies errors at each of the three different levels of model formation which are employed in NASTRAN. The method, which was reported to have been used successfully for several years by the developer, has been adopted by the other companies for their own use. The second effort involves ground vibration testing and finite-element modeling and analysis which have been conducted on the tail boom of a Sikorsky S-55 helicopter under a grant with Rensselaer Polytechnic Institute (ref. 33). The third activity represents some recently completed work (ref. 34) aimed at developing a method for predicting the effects of damping treatment on structural vibrations which is suited for use in preliminary design work.

Summary of Key Findings: A summary of the key findings and conclusions which have emerged from the Airframe Finite-Element Modeling technology area are listed below:

(1) Up-front planning before modeling begins reduces the effort needed to form unified static and dynamic models and improves the quality of the models.

(2) 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.

(3) Structural modeling techniques seem to be relatively uniform within the industry.

(4) A well-defined set of modeling guides, properly applied, can provide an improved model.

(5) Modeling procedures for metal and composite airframes are similar except for determination of the material properties of multi-ply structures of varying ply orientation, thickness, and material types.

(6) Test/theory comparisons for all the aircraft 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.

(7) The dynamics of composite airframes appear to be more difficult to predict than for metal airframes.

(8) Ground vibration tests indicate that support system effects can be important and may need to be included as part of the airframe finite-element model.

(9) Damping levels are essentially the same in both metal and composite airframes (about 2-4 percent of critical damping).

(10) Damping and nonlinearities are an impediment to improved correlation. Improved definition and representation of damping is needed.

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 34 for the AH-1G, there are many components (e.g., transmission, engines, stores) and secondary structure (e.g., fairings, doors, and access panels) 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 more complete representation for improved correlation. Difficult components studies have been conducted on the all-metal AH-1G and the all-composite D292. The results of these studies are summarized here.

AH-1G: The first difficult components study was conducted by Bell on the AH-1G helicopter (fig. 35). A detailed account of the results of this investigation is given in reference 35. The primary fuselage structure of the AH-1G is depicted in figure 36. The finite-element model which was used in the initial test/theory comparisons is shown in figure 37. This model was developed by Bell in the early 1970s under Army sponsorship (ref. 36) and modified to reflect the specific configurations tested in the present investigation.

The airframe in its full-up ground vibration test configuration is shown in figure 38. 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 39. 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 the finite-element model of figure 37 modified to reflect the specific configuration tested were performed and the results compared. Some illustrative results which show the importance of secondary structure panels and canopy glass on airframe response are given in figures 40 and 41, respectively.

The effect of removing the secondary structure panels under the canopy frame from just aft of the nose to just forward of the wings on the measured and calculated responses at the gunner seat is shown in figure 40. The shift in the measured frequency of the torsion mode reflects the combined effect of stiffness and mass. The stiffness of the panels was not represented in the model so the shift in the calculated frequency of that mode is due only to the removal of mass. The particular frequency shifts exhibited for the torsion mode indicate that the panels have a considerable stiffening effect not only on the torsion mode but also at the higher frequencies. Similar consideration of the measured and calculated effects associated with the removal of the canopy glass (fig. 41) indicate that the stiffness of this glass also has an appreciable effect on the torsion mode and on the response at 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 (fig. 42) was then used to reanalyze each of the configurations tested. A test/theory comparison of the vertical and lateral responses at the gunner seat for the full-up and stripped-down configurations using both the initial and updated models is shown in figure 43. It is seen that the agreement between test and analysis is improved over the entire frequency range using the updated model. While the improvement in the predicted response appears modest, the improvement in the predicted frequencies is much more evident, as indicated in figure 44. 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.

D292: A difficult components study was recently completed on the D292 (ACAP) helicopter (ref. 37) using the finite-element model developed under the DAMVIBS Program (fig. 24). Systematic testing and analysis of several airframe configurations, ranging from the stripped-down configuration shown in figure 45 (airframe stripped of engines, landing gears, rotor isolation system, fuel, stabilizers, drive shafts, doors, cowlings, avionics, seats, etc) to a full-up configuration, were performed to quantify the effects of each component on overall vibratory response of the airframe. The ground vibration test was conducted by the Army's Aviation Applied Technology Directorate at Fort Eustis (ref. 38) as part of the subject difficult components investigation. Based on the results of test/theory comparisons using the initial finite-element model, the model was updated and used to reanalyze each of the configurations tested. Test/theory comparisons using the initial and updated models for the full-up and stripped-down configurations are shown in figures 46 and 47, respectively. It should be noted that the predicted responses are in much better agreement with measured responses using the updated model. Natural frequencies calculated using the updated model (see ref. 37) were found to be within 10 percent of test values, compared to 20 percent using the initial model.

S75: Preparations are underway at the Army's Aviation Applied Technology Directorate to conduct a ground vibration test of the S75 (ACAP) helicopter (fig. 32) as part of the difficult components investigation to be conducted on that helicopter airframe. The finite-element model to be used by Sikorsky in the analytical portion of that investigation is shown in figure 33. This is the last contracted task to be performed under the DAMVIBS Program.

Summary of Key Findings: The key findings and conclusions which emerged from the Difficult Components Studies technology area are listed below:

(1) The answer to the oft-asked question: "What's the problem?" is finally beginning to be answered.

(2) Several important structural contributors to airframe vibratory response at the higher frequencies of interest have been identified.

(3) Elastic-line models of beam-like tail booms are inadequate for representing the response at the higher frequencies.

(4) A lumped-mass representation is generally sufficient for such components as the tail rotor drive shaft, engines, fuel, and soft mounted black boxes.

(5) Elastic-line representations appear to be adequate for such components as the main rotor pylon/transmission, skid landing gear, and wings.

(6) The effects of nonproportional structural damping are important at the higher frequencies of vibration.

(7) Nonlinear effects of elastomeric mounts and "thrust stiffening" are important at low frequencies.

(8) The use of improved modeling techniques can dramatically improve the quality of the predictions.

(9) Finite-element models for vibrations analysis may need to be more detailed (i.e., require a finer "mesh") than the usual stress model. This is contrary to the previously held belief that the stress model had more than enough structural detail for dynamics.

<u>Coupled Rotor-Airframe Vibrations</u>.- 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 design work. Attention is directed to the coupling of the rotor and the airframe to account for their interaction in producing vibrations. The emphasis is on the response of the airframe as part of a coupled rotor-airframe system.

With regard to the first objective, teams from each of the four companies have separately and independently applied different analysis methods, one method per company, to calculate the vibrations of the AH-1G helicopter (fig. 35) in steady level flight and compared the results with existing flight vibration data. As the manufacturer of the subject aircraft, Bell was required to provide to the other companies a summary of the modeling, testing and correlation work conducted on the AH-1G (ref. 39). Bell was further required to assemble the flight vibration data to be used in the correlations and to describe the rotor system both mechanically and aerodynamically to the other participants (ref. 40). An existing NASTRAN finite-element model of the airframe (ref. 36), adjusted by Bell to correspond to the flight condition for which the comparisons were to be made, was furnished by Bell to the other participating manufacturers as part of the common data to be utilized for the subject activity. The results of this study are contained in references 41 to 44. Illustrative results are given in figures 48 and 49. Figure 48 shows a comparison of the measured 2/rev and 4/rev vertical vibrations with predictions made by the manufacturer of the subject aircraft (ref. 41). Figure 49 shows a representative comparison of the 2/rev vertical and lateral vibrations predicted by each of the industry participants with vibrations measured in flight. With regard to this latter comparison, it is seen that the predicted 2/rev vibrations are not in good agreement with measured values. (Recall that 2/rev is the primary main rotor excitation frequency for the AH-1G.) In general, the best agreement was obtained for the vertical vibrations; the worst for the lateral vibrations. Some ancillary studies conducted as part of this investigation indicated that the impingement of the main rotor wake on the vertical tail contributes substantially to the lateral vibrations. This suggests that in the computation of coupled rotor-airframe vibrations, both mechanical and aerodynamic load paths into the airframe may need to be considered. It should be remarked that 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 capabilty to predict system vibrations will emerge.

With regard to the second objective of this program element, that is, the problem of developing computational procedures for coupled rotor-airframe analysis which are suited to airframe vibrations design work, there are two in-house activities which are relevant. Both deal with efforts at Langley to establish foundations for adequate representation and treatment of the airframe structure in design analysis of helicopter vibrations. Reference 45 represents the result of the initial effort in this direction. The report presents a body of formulations for coupling airframe finite-element analysis models to rotor analysis models and calculating airframe vibrations. All the relations are presented in matrix form. Matrix partitioning schemes are developed for the quick recalculation of vibrations in design studies when only a relatively few airframe members are varied. Explicit formulas, FORTRAN-like notation, and blueprint-like representation of matrices are used throughout the report to facilitate computer implementation.

While the final analytical verification of a design for vibrations will require the use of a complex rotor math model, it appears that useful predictions of airframe vibrations can be made during design using simpler models. To investigate this possibility, a study was recently undertaken which is intended to establish the minimum level of structural and aerodynamic sophistication required in a rotor math model in coupled rotor-airframe vibration analyses which are intended to support airframe dynamics design work. The study is a cooperative effort between NASA-Langley and the U. S. Military Academy. As part of this effort, the DYSCO code (ref. 46) has been modified to compute rotor impedances which can be used in analysis of coupled rotor-airframe vibrations. Validation studies using the dynamic equations of motion for a two-bladed, horizontal-axis wind turbine rotor under gravity loading and a Langley-developed harmonic balance code have been completed. Work is now underway to model the OH-6A rotor in DYSCO with the objective of performing systematic studies to evaluate the effects of various rotor aerodynamic and structural modeling assumptions on calculated rotor impedances and on airframe vibrations calculated using simplified rotor models. The finite-element model to be used in these latter studies (fig. 50) was obtained under the DAMVIBS Program (ref. 47). The intention is to eventually encode the computational procedures outlined in reference 45.

In a peripheral activity, conducted under a grant with Rensselaer Polytechnic Institute, a report has been published (ref. 48) which describes two new methods for modeling the dynamics of general, multi-body elastic systems undergoing large arbitrary motions.

Airframe Structural Optimization.- The use of traditional rotor and airframe design techniques to limit inherent vibrations is receiving renewed attention. It is recognized that structural optimization techniques, if properly brought to bear by the designer, can play a major role in establishing an integrated approach to helicopter design. In particular, such techniques could go a long way toward achieving a low-vibration helicopter. With this in mind, design optimization codes combining finite-element structural analysis with nonlinear programming (NLP) algorithms are in various stages of development in both government and industry. The DAMVIBS Program as initially defined (see fig. 2) contained a technology area called "Airframe Structural Optimization", but no optimization tasks were ever issued under the DAMVIBS contracts. However, a preliminary investigation into the use of optimization techniques to improve correlation between measured and computed natural frequencies was conducted by Bell Helicopter Textron (BHT) in cooperation with the University of Texas at Arlington (UTA), and Hughes Aircraft as a subcontractor to Bell. The subject aircraft was again the AH-1G. The frequencies of three modes were chosen for improved test/theory correlation: fuselage first and second vertical bending and a skid-gear mode. The BHT/UTA team used an NLP-based approach using nine design variables with extensive design variable linking to represent the cap areas and skin thicknesses of the main fuselage beams, the vertical bending stiffnesses of the tail boom, the bending/torsion stiffnesses of the vertical tail, and the bending stiffnesses of the skid landing gear. Hughes did not use design variable linking but simply changed the value of all the design variables which a sensitivity analysis indicated had a large influence on the frequencies of the target modes. The results of this exercise, which were presented at a NASA/industry meeting in May 1988, are summarized in table 1 which shows the initial and final calculated frequencies compared with test frequencies. It should be remarked in closing that at least two of the industry participants in the DAMVIBS Program have moved forward aggressively in this area under company sponsorship.

Finite-element models of helicopter airframes typically contain many thousands of degrees of freedom and thousands of elements. Such large models may be impractical to use in airframe structural dynamics optimization work. A preliminary investigation into methods for significantly reducing the size of large finite-element models for increased computational efficiency while preserving the essential dynamic characteristics of the full model is reported in reference 49.

An in-house study was undertaken at Langley in 1985 to investigate the use of formal, NLP-based, numerical optimization techniques for airframe vibrations design work. Considerable progress has been made in connection with that study (ref. 50). The objective of that study is to develop and evaluate computational procedures for dynamics optimization of helicopter airframe structures represented by finite-element models. The methods ultimately are to be applicable to large-order systems and be compatible with typical airframe design practice. To this end, a system of integrated computer programs called DYNOPT for the dynamics optimization of airframes subject to strength, frequency, dynamic response, and fatigue constraints has been developed. DYNOPT features an unique operational combination of the MSC/NASTRAN structural analysis program and the CONMIN optimizer program. Applications of DYNOPT to the AH-1G helicopter have been conducted with the objective of assessing the role that optimization techniques can play in airframe vibrations design work. These studies have shown that structural optimization techniques have considerable potential for playing a major role in design. The same studies have identified a key need of those who are engaged in optimization work. That is, at least a rudimentary understanding of the airframe structural design process is necessary to allow the structural optimization engineer to properly and adequately formulate the types of design models which are required for industrial design work. Such an understanding is needed if practical design optimization methods are to be developed. The scope of the in-house work on airframe optimization has been broadened recently (ref. 51) to support a major new rotor design optimization activity at Langley (ref. 52). This new activity, which is aimed at developing an integrated, multidisciplinary, optimization-based approach for rotorcraft design, is a cooperative effort between NASA-Langley and the Army Aerostructures Directorate which is collocated at Langley.

There are two university activities funded under the DAMVIBS Program which are related to this program element. Both deal with the use of system identification techniques to improve airframe finite-element models using frequency response test data while preserving the physical interpretability of the system mass, damping, and stiffness matrices. At Georgia Tech, studies are underway on a method which is based on using linear sensitivity matrices to relate changes in physical parameters to changes in the system matrices. The values for the physical parameters are determined using constrained optimization techniques in combination with singular value decomposition. Applications are being made to the AH-1G airframe using the finite-element model and data generated as part of the difficult components study of that aircraft. At the University of Bridgeport, a method which relies on the design sensitivity analysis procedures in MSC/NASTRAN to determine the physical parameter changes needed for correlation has been implemented using the DMAP language. Applications are being conducted using data from ground vibration tests of a 7-ft long composite semimonocoque cylinder with cutouts and concentrated masses.

ASSESSMENT OF DAMVIBS PROGRAM

As previously mentioned, five workshops have been held at Langley Research Center during the course of the DAMVIBS Program to review and discuss completed work and to critique plans for future work. These meetings, which took place September 24-25, 1984, October 1-3, 1985, December 2-4, 1986, May 3-4, 1988, and September 11-12, 1990, provided an excellent forum for technical discussions related to airframe finite-element modeling issues, particularly as they relate to airframe design (something rarely presented or discussed in more formal public forums). Indeed, the workshops provided the necessary atmosphere where difficult-to-obtain experiences (not usually recorded in journals or discussed at conferences) were freely discussed.

Because the DAMVIBS Program is being phased out, the fifth government/industry workshop included a session devoted to an assessment of the program and its benefits to the industry. The assessment was made by the Langley sponsoring organization in cooperation with the Army Aerostructures Directorate and the four industry participants in the program. The assessment 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 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 finite-element-based dynamics analyses during the design process. The assessment also identified several key continuing and new structural dynamics technology needs. The results of this assessment are presented here.

Summary of Major Accomplishments and Contributions

The major accomplishments and contributions which may be attributed to the DAMVIBS Program are summarized below:

(1) Consensus has been achieved on the basic modeling techniques for both metal and composite airframes.

(2) 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 both internal static loads analyses and vibrations analyses as well as to improving the quality of the models.

(3) It was established that a finite-element model can be formed early enough in a new helicopter development program to actually influence the airframe design.

(4) The cost of such a model is about 5 percent of the total airframe design effort, of which 4 percent is already usual for the static (internal loads) model; the vibration model is another 1 percent.

(5) Comparisons of the results of finite-element analyses with results from ground vibration tests of both metal and composite airframes have demonstrated an improved capability for predicting the low frequency response up through about 10 Hz, acceptable agreement from about 10-20 Hz, and generally unacceptable agreement at higher frequencies.

(6) Results from studies on composite airframes differing in both size and construction have shown that composite airframe dynamics are more difficult to predict than for metal airframes.

(7) Damping levels measured in tests have been found to be essentially the same in both metal and composite airframes (about 2-4 percent of critical damping).

(8) Support system dynamics may have to be included in the finite-element models which are employed in correlations with ground vibration tests.

(9) The airframe finite-element modeling/ground vibration test activities and difficult components studies have led to improvements in both modeling techniques and ground vibration test methods throughout the industry.

(10) For the first time finite-element models are being relied on by the industry for airframe vibrations design work.

(11) Industry IRAD dealing with vibrations has been revitalized and expanded. The companies have also established new ties with universities to work with them on vibration-related problems.

(12) Technical interchange between the companies has been increased considerably because of the workshops which have been held under the program. These meetings have provided a unique forum for technology transfer.

(13) Difficult components studies of both metal and composite airframes have shed new light on the importance of many airframe components on vibratory response at the higher frequencies of interest.

(14) These studies showed that considerably improved correlation can be obtained if modeling details which have been historically regarded as secondary effects are taken into account.

(15) Finite-element models which are to be employed in vibrations analyses may need to be more detailed than models for static internal loads analyses, contrary to what was previously thought.

(16) The models developed under the program are being used by government, industry and academia in a wide variety of advanced basic and applied research studies.

(17) The first comparative evaluation of industry codes for comprehensive analysis of coupled rotor-airframe vibrations has spurred the industry to reexamine their codes and to make them more accurate.

(18) Studies have shown that optimization techniques can play a major role in airframe vibrations design work if they are properly brought to bear by the design engineer.

(19) The same optimization studies have revealed that structural optimization engineers must have at least a basic understanding of the airframe design process if they hope to properly and adequately formulate the types of design models which are required for industrial design optimization work.

Key Continuing/New Challenges

Notable progress has been made under the DAMVIBS Program in advancing the technology base needed for the prediction of airframe vibrations. In particular, airframe designers can now use finite-element models with confidence to avoid frequency placements which would result in resonance with rotor excitation frequencies up through about 10 Hz. This frequency range includes both the once-per-revolution (1/rev) frequency of all practical rotor systems and the twice-per-revolution (2/rev) frequency of typical two-bladed rotors. However, most new or planned helicopters have rotors with four (or more) blades and have predominant excitation frequencies which extend above 20 Hz. Thus, to encompass even the lowest excitation frequencies of typical four-bladed rotors which are at 4/rev, the predictive capability of finite-element models needs to be extended up through about 25-30 Hz. To achieve such a modeling capability, as well as to establish the necessary advanced dynamics analysis techniques which utilize these models, additional work is needed in several areas. The major needs identified as part of the assessment are summarized below:

(1) Extend the predictive capability of finite element models up through the 25-30 Hz frequency range. This will require continued attention to difficult components-type studies to identify further what components of an airframe are contributing to the lack of correlation at the higher frequencies and to develop the appropriate improved modeling techniques.

(2) Devise practical methods for improving (or adjusting) models at the finite-element level using ground vibration test data.

(3) Develop analytical techniques which more realistically account for damping and which are suitable for use in airframe vibration design work.

(4) Improve the predictive capability of current comprehensive codes for analysis of coupled rotor-airframe vibrations.

(5) Develop computational procedures for coupled rotor-airframe analysis that are based on simplified rotor mathematical models which are better suited for the repetitive analyses required in airframe vibrations design work.

(6) Continue definition of the role structural optimization can play in the airframe design process and develop computational procedures useful for vibrations design work.

(7) Establish a basic understanding of the airframe design process to allow structural optimization engineers to properly and adequately formulate the types of design models required for industrial design optimization work.

(8) Develop new/improved methods for actively and passively controlling airframe structural response.

With the phasing out of the DAMVIBS Program, several of the key areas which the assessment identified as needing additional work or representing a new technical challenge were made part of the Langley in-house rotorcraft structural dynamics program (fig. 51). The in-house program will continue to focus on the development and validation of design analysis tools but with emphasis on the technology needed to support the design of advanced rotorcraft, such as tiltrotors.

CONCLUDING REMARKS

The paper has presented a summary of the accomplishments and contributions of a NASA/industry rotorcraft structural dynamics program known as DAMVIBS (Design Analysis Methods for VIBrationS) which has been underway since 1984. The overall objective of the program was to establish the technology base needed by the industry for developing an advanced finite-element-based dynamics design analysis capability for vibrations. Under the program, teams from the four major helicopter airframe manufacturers have formed finite-element models, conducted ground vibration tests, and made test/analysis comparisons of both metal and composite airframes, performed difficult components studies on airframes to identify components which need more complete finite-element representation for improved correlation, and evaluated industry codes for computing coupled rotor-airframe vibrations. Studies directed at establishing the role that structural optimization can play in airframe vibrations design work were also initiated. Because the DAMVIBS Program is being phased out, an assessment of the program and its benefits to the industry was recently made by the NASA sponsoring organization and the four industry participants in the program. The assessment indicated that the DAMVIBS Program has provided an important leadership role and focal point for rotorcraft structural dynamics research in government, industry and academia. 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 finite-element-based dynamics analyses during the design process.

The assessment also identified a number of key continuing and new structural dynamics technology needs. Several of these have been included in the Langley in-house rotorcraft structural dynamics program. The in-house program will continue to focus on the development and validation of design analysis tools but with emphasis on the technology needed to support the design of advanced rotorcraft, such as tiltrotors.

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TABLE 1

OPTMIZATION STUDIES ON AH-1G HELICOPTER AIRFRAME FOR IMPROVED TEST/ANALYSIS CORRELATION

(Comparison of Natural Frequencies)

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 Helicopter Textron/University of Texas at Arlington

*Hughes Aircraft Company

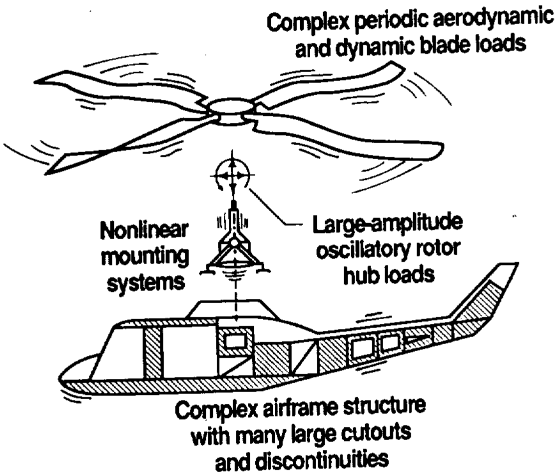

Figure 1.- Challenges confronting analysts in predicting helicopter vibrations.

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

Technology Areas **1984** **Participants**

DAMVIBS

- Finite element modeling
- Difficult components studies
- Coupled rotor-airframe vibrations
- Airframe structural optimization

- Structural damping
- System identification
- Force determination
- Advanced analysis methods
- Internal loads
- Fatigue loads

- NASA
  - Langley Research Center
  - Ames Research Center
- Army
  - Aerostructures Directorate
  - Aviation Applied Technology Directorate
- Industry
  - Bell Helicopter Textron
  - Boeing Helicopters
  - McDonnell Douglas Helicopter Co.
  - Sikorsky Aircraft
- Academia
  - Army Rotorcraft Centers of Excellence
  - Other Leading Institutions

Figure 2.- DAMVIBS positioned as focus of a new Langley rotorcraft structural dynamics program.

- Bell Helicopter Textron
  - AH-1G data
  - AH-1G flight vibrations
  - D292 (ACAP) FEM
  - D292 FEM correlation
  - AH-1G difficult components
  - ACAP difficult components
- Boeing Helicopters
  - CH-47D FEM
  - CH-47D GVT/correlation
  - Model 360 FEM
  - Model 360 GVT/correlation
  - AH-1G flight vibrations
- McDonnell Douglas
  - AH-64A FEM
  - AH-64A GVT/correlation
  - AH-1G flight vibrations
  - OH-6A FEM
  - FEM reduction method
  - FEM checkout method
- Sikorsky Aircraft
  - UH-60A FEM
  - UH-60A GVT/correlation
  - AH-1G flight vibrations
  - S75 (ACAP) FEM
  - ACAP difficult components

Figure 3.- Summary of industry activities conducted under DAMVIBS program.

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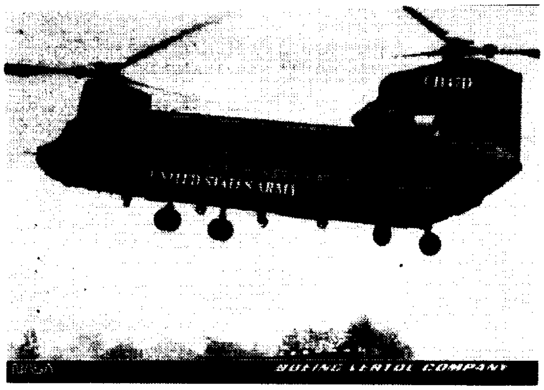
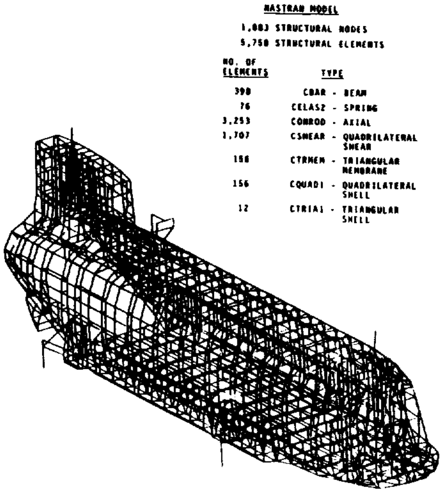


Figure 4.- CH-47D helicopter.


NASTRAN MODEL

1,083 STRUCTURAL NODES

5,750 STRUCTURAL ELEMENTS

NO. OF ELEMENTS	TYPE
390	CBAR - BEAM
76	CELAS2 - SPRING
3,253	CONROD - AXIAL
1,707	CSHEAR - QUADRILATERAL SHEAR
158	CTRMEM - TRIANGULAR MEMBRANE
156	CQUAD1 - QUADRILATERAL SHELL
12	CTRIA1 - TRIANGULAR SHELL

Figure 6.- CH-47D NASTRAN structural model.

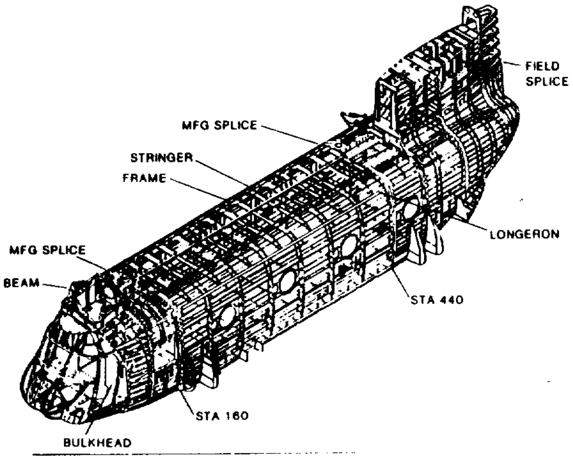


Figure 5.- CH-47D primary fuselage structure.

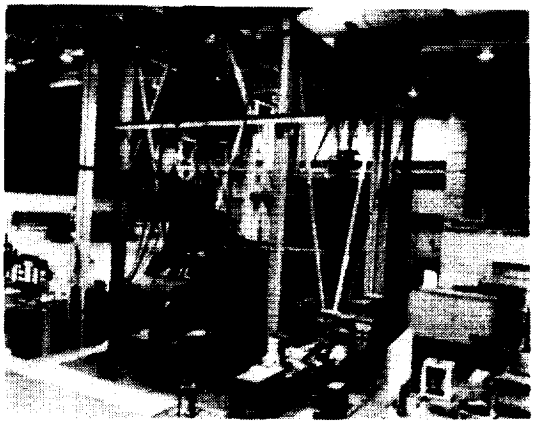


Figure 7.- Ground vibration test of CH-47D.

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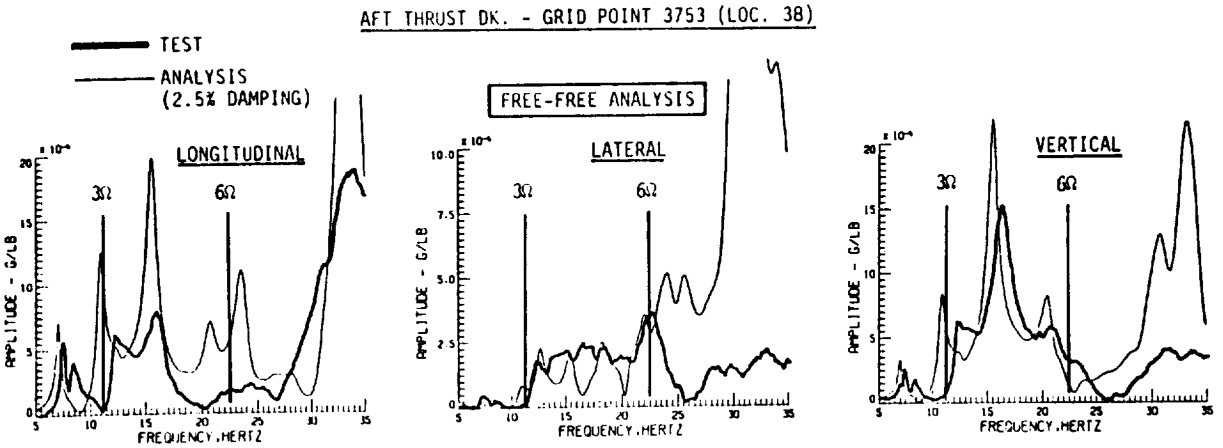
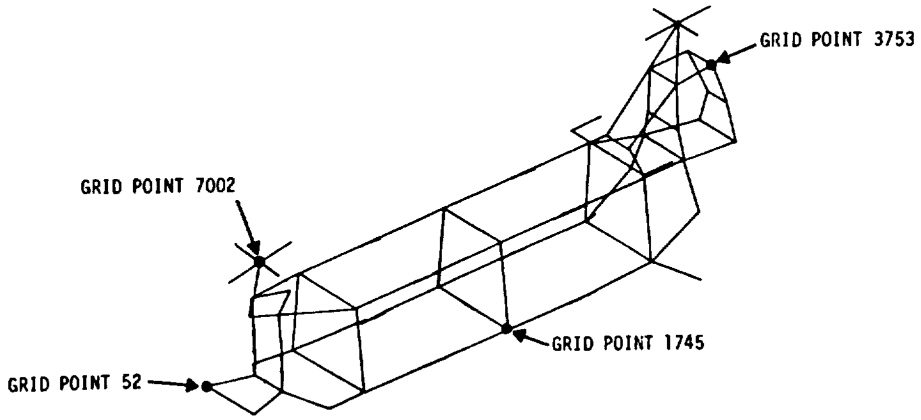




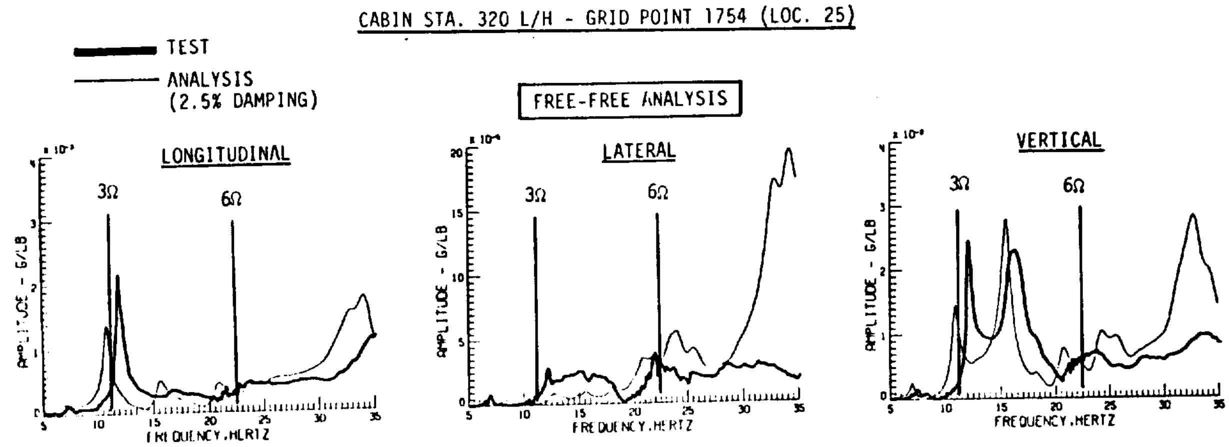


Figure 8.- Comparison of test and analysis for pitch excitation of CH-47D at forward hub.

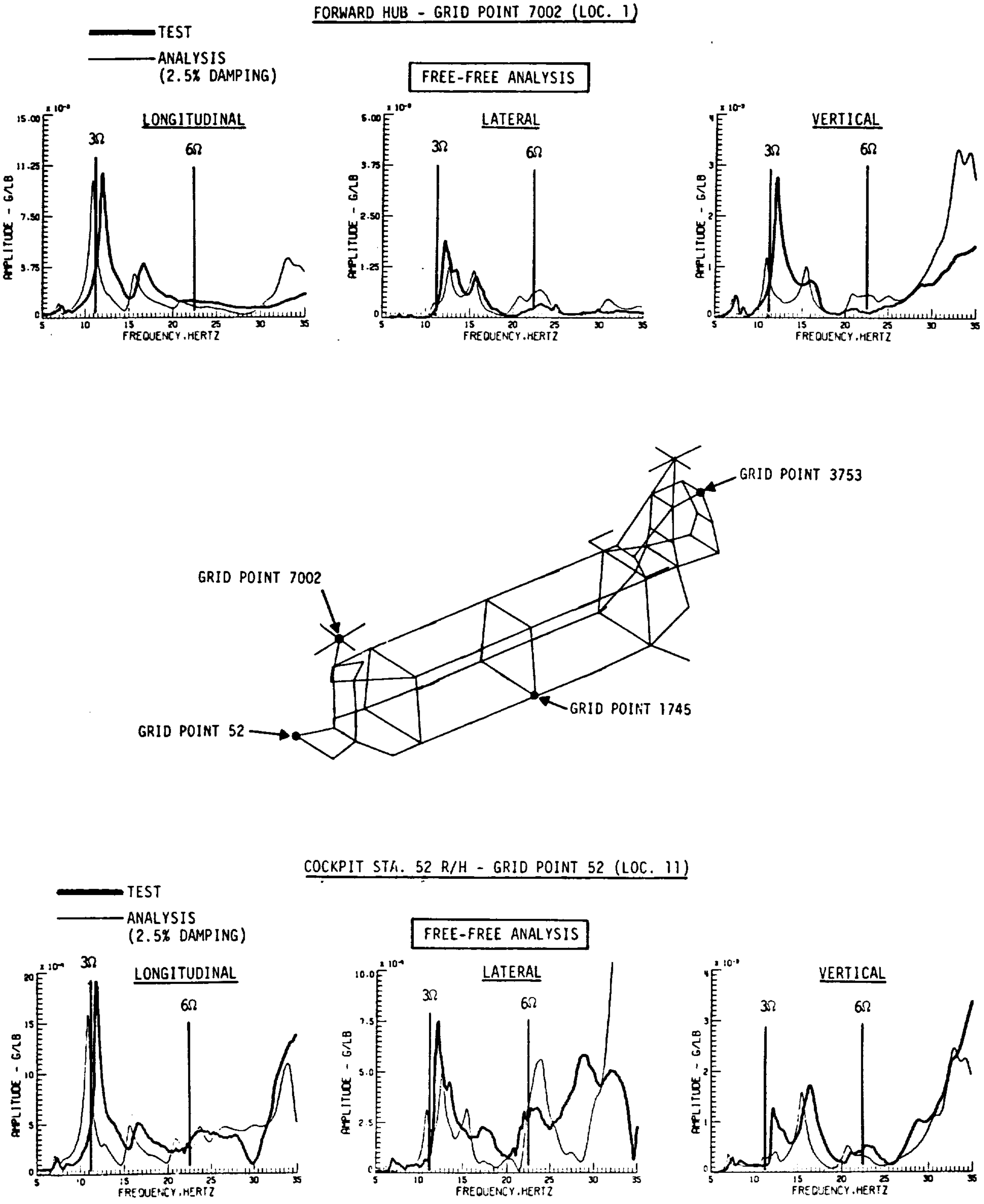


Figure 8.- Comparison of test and analysis for pitch excitation of CH-47D at forward hub (Concluded).

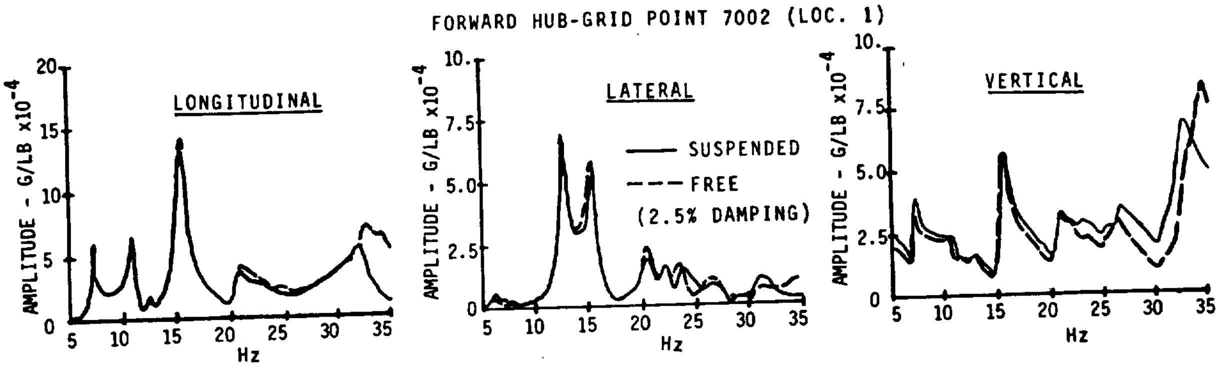


Figure 9.- Predicted effect of suspension system on response of CH-47D.

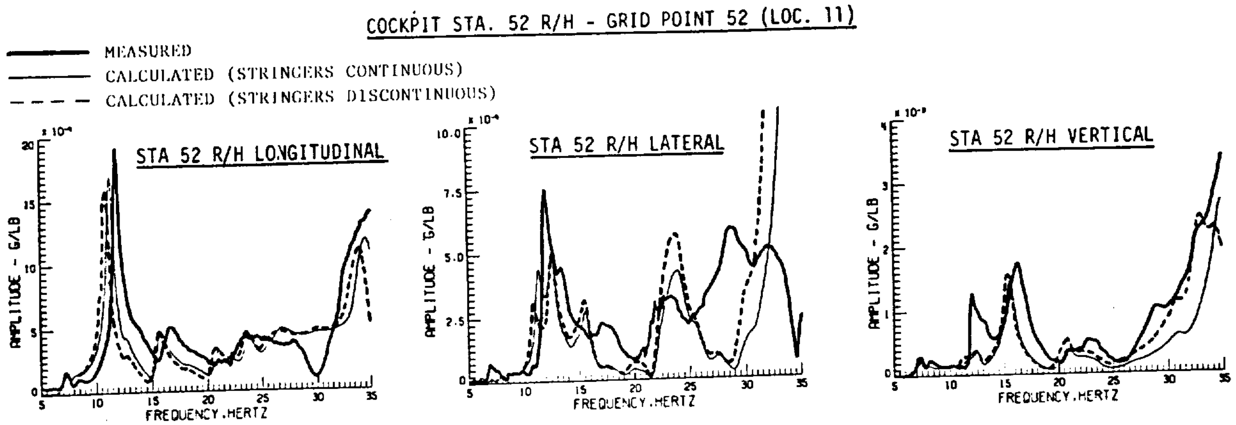


Figure 10.- Predicted effect of splice joint continuity on CH-47D forced response correlation.

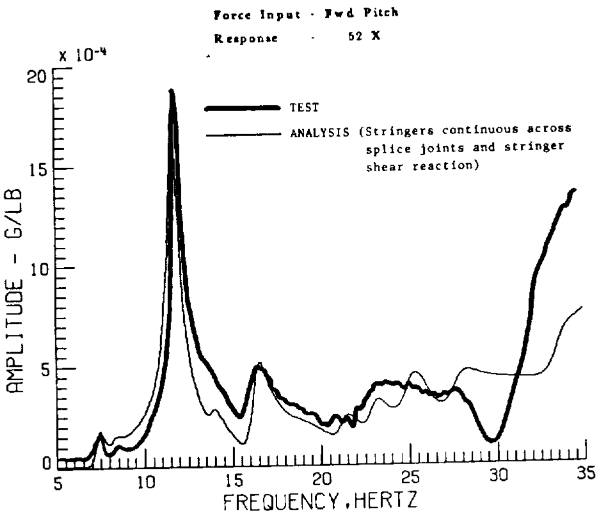


Figure 11.- Combined effect of splice joint continuity and stringer shear on forced response correlation.

Figure 12.- AH-64A helicopter.

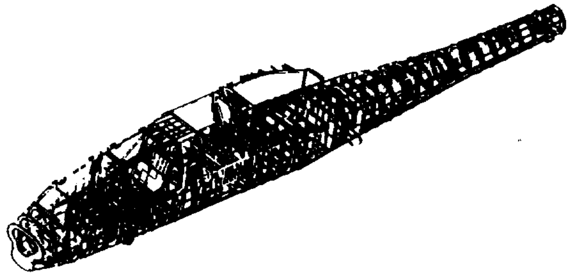
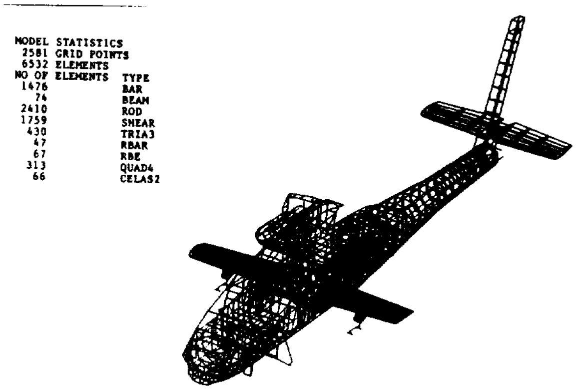


Figure 13.- AH-64A primary fuselage structure.



```
MODEL STATISTICS
 2581 GRID POINTS
 6532 ELEMENTS
NO OF ELEMENTS  TYPE
 1476           BAR
   74           BEAM
 2410           ROD
 1759           SHEAR
  430           TRIA3
   47           RBAR
   67           RBE
  313           QUAD4
   66           CELAS2
```

Figure 14.- AH-64A NASTRAN finite element model.

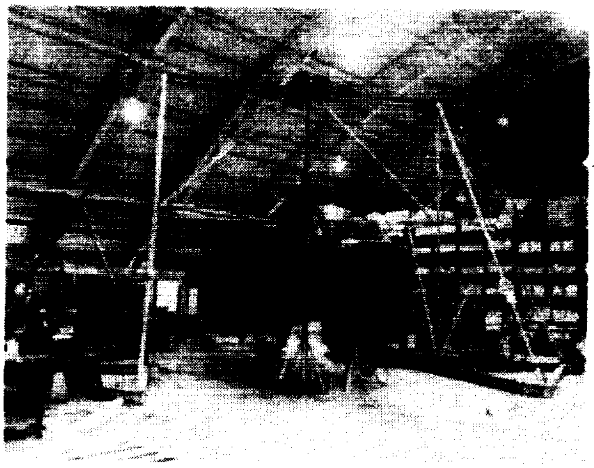
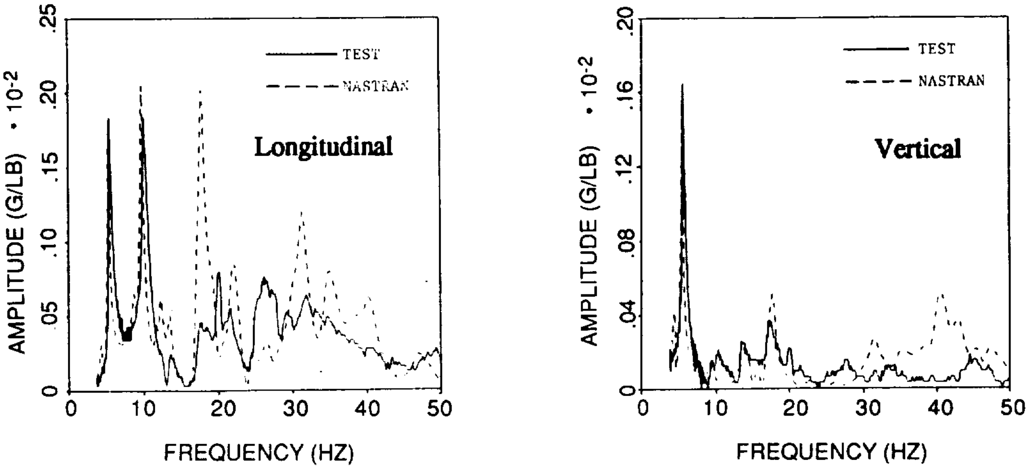
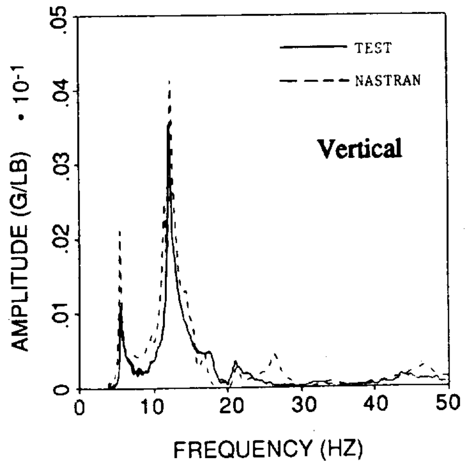


Figure 15.- Ground vibration test of AH-64A.

VERTICAL EXCITATION AT M/R MAST
RESPONSE AT THE VERTICAL STABILIZER





LONGITUDINAL EXCITATION AT M/R MAST
RESPONSE AT FUSELAGE STATION 35

LONGITUDINAL EXCITATION AT M/R MAST
RESPONSE AT THE VERTICAL STABILIZER

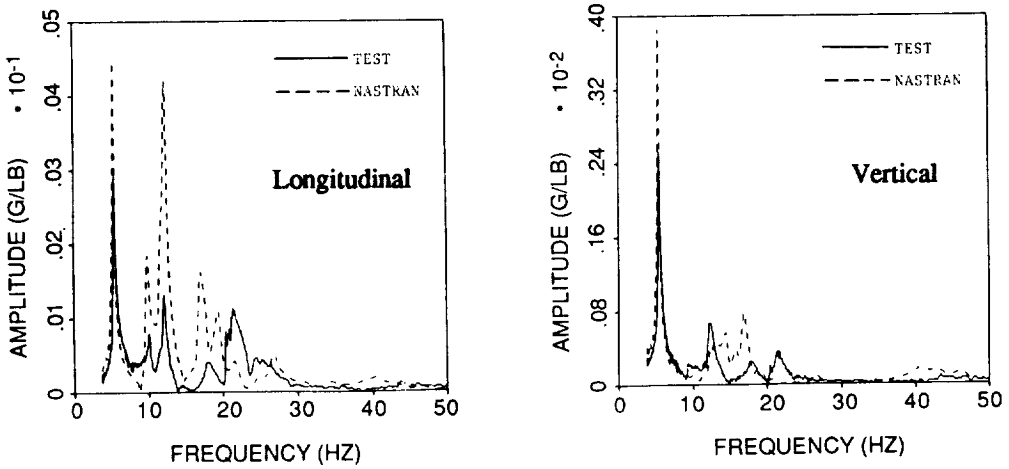
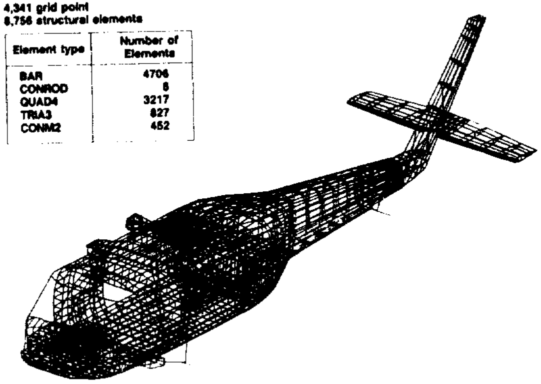


Figure 16.- Comparison of test and analysis for vertical and longitudinal excitation of AH-64A at main rotor mast.

Figure 17.- UH-60A helicopter.



NASTRAN model
4,341 grid point
8,756 structural elements

Element type	Number of Elements
BAR	4706
CONROD	6
QUAD4	3217
TRIA3	827
CONM2	452

Figure 19.- UH-60A NASTRAN model.

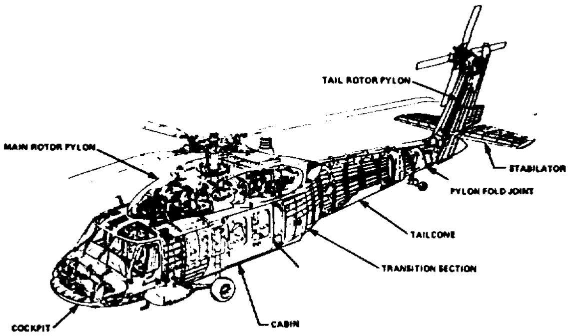


Figure 18.- UH-60A primary fuselage structure.

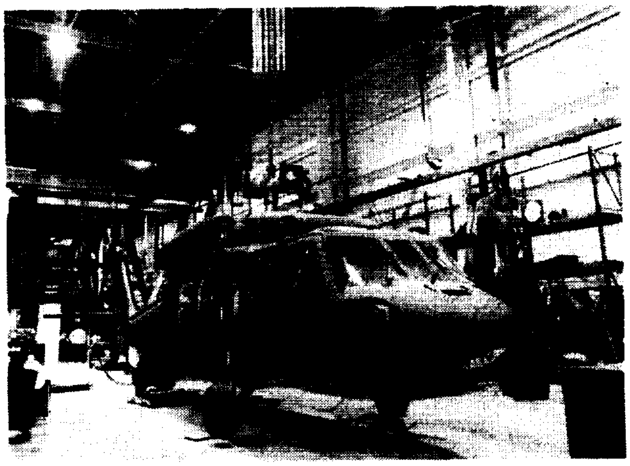


Figure 20.- Ground vibration test of UH-60A.

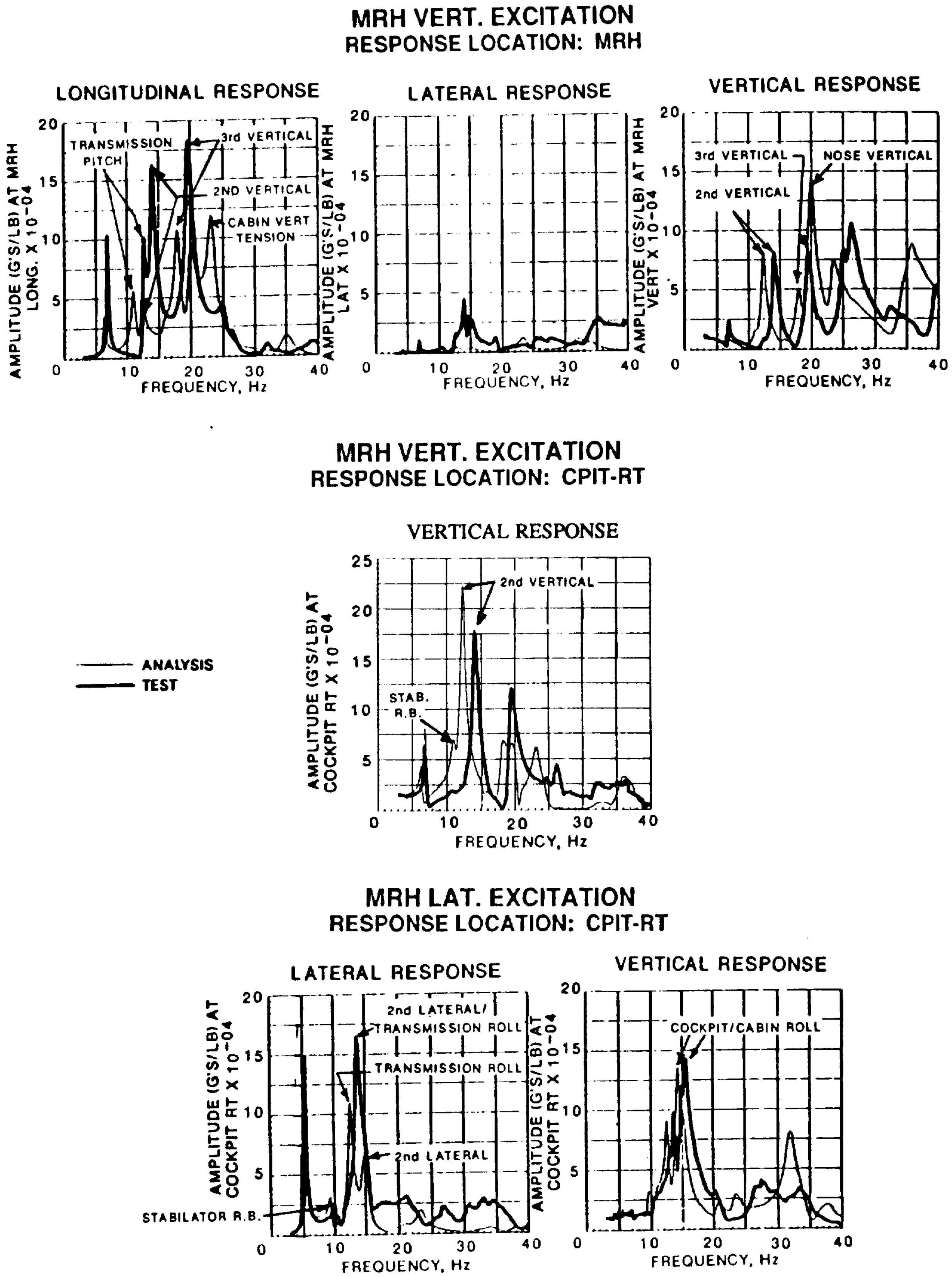


Figure 21.- Comparison of measured and calculated responses of UH-60A for excitation at main rotor hub.

Figure 22.- D292 (ACAP) helicopter.

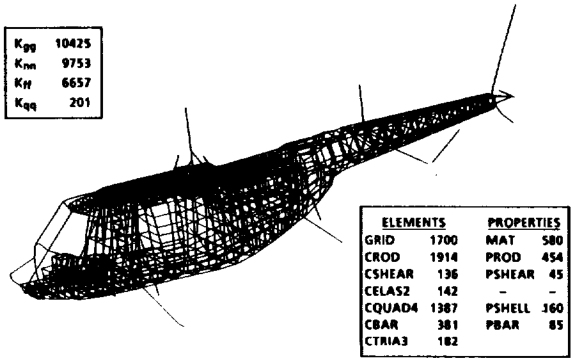


Figure 24.- NASTRAN finite element model of D292.

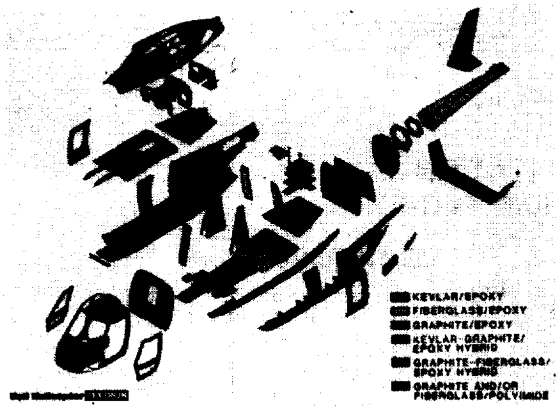
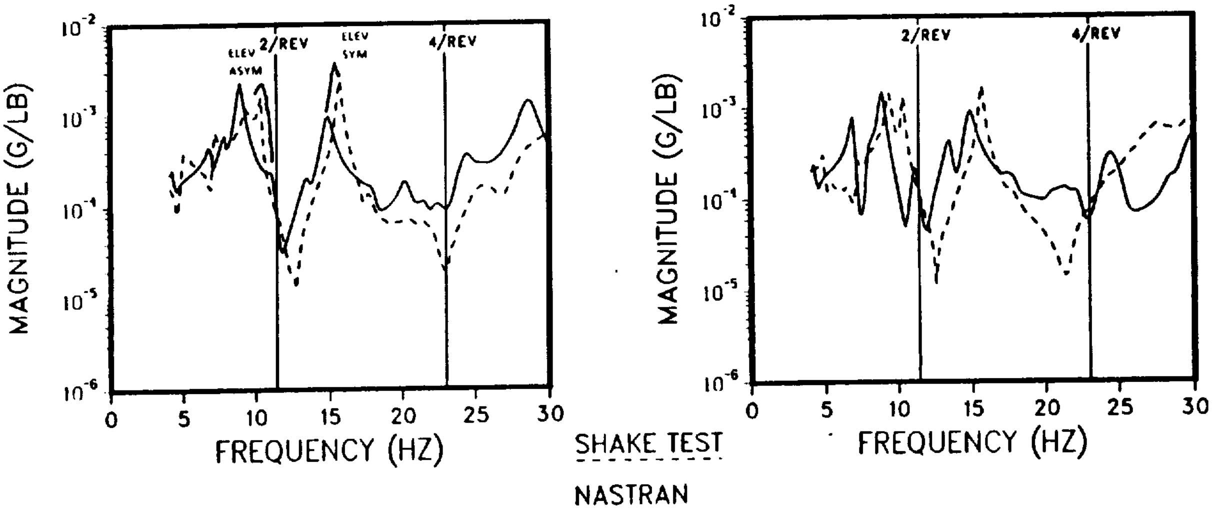


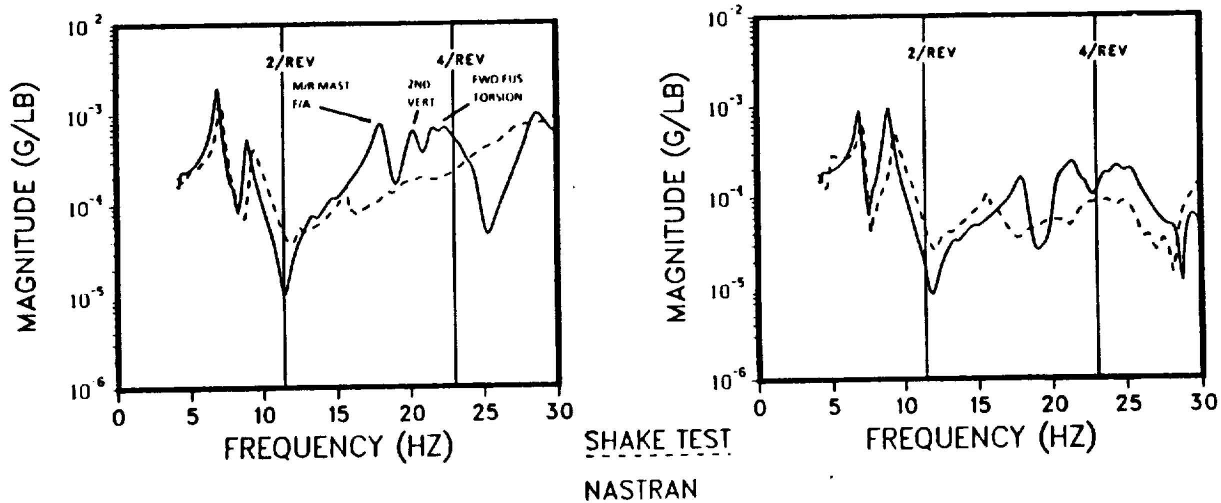
Figure 23.- Structural breakdown of D292.

Figure 25.- D292 during ground vibration testing.



ELEVATOR-RIGHT (FS 433) VERTICAL RESPONSE

ELEVATOR-LEFT (FS 433) VERTICAL RESPONSE



NOSE (FS 97) VERTICAL RESPONSE

PILOT (FS 170) VERTICAL RESPONSE

Figure 26.- Comparison of measured and calculated responses of D292 (ACAP) for vertical excitation at main rotor hub.

Figure 27.- Model 360 helicopter.

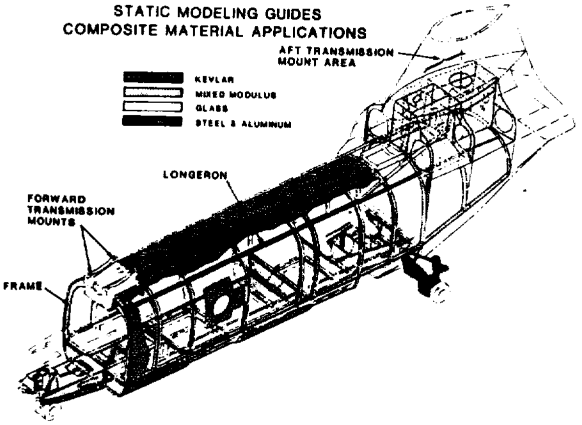
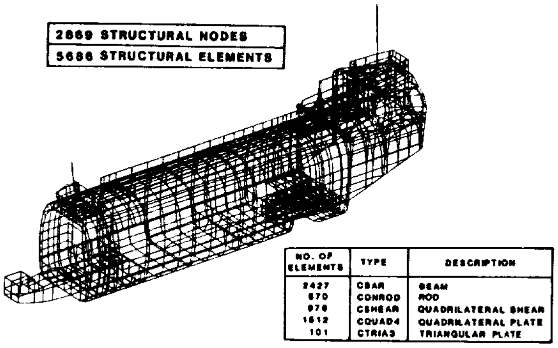


Figure 28.- Composite materials applications in Model 360.



NO. OF ELEMENTS	TYPE	DESCRIPTION
2427	CBAR	BEAM
670	CONROD	ROD
976	CSHEAR	QUADRILATERAL SHEAR
1512	CQUAD4	QUADRILATERAL PLATE
101	CTRIA3	TRIANGULAR PLATE

Figure 29.- Model 360 NASTRAN structural model.

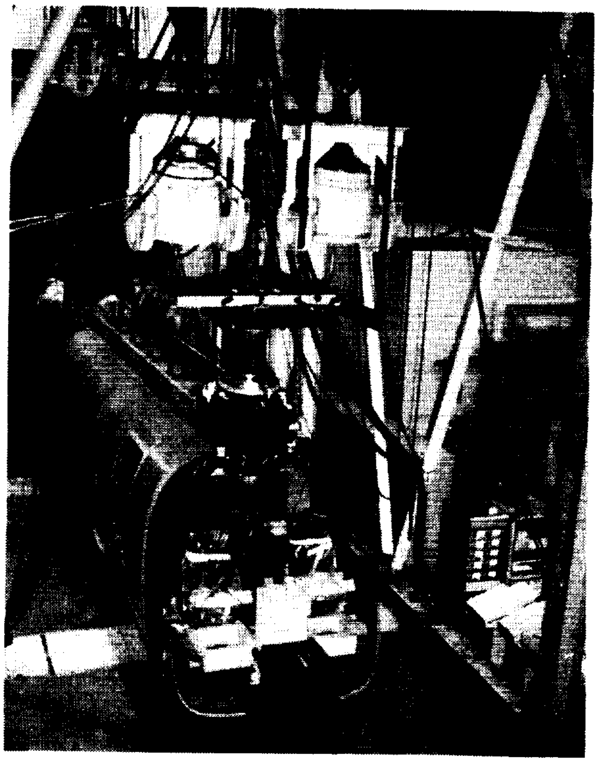
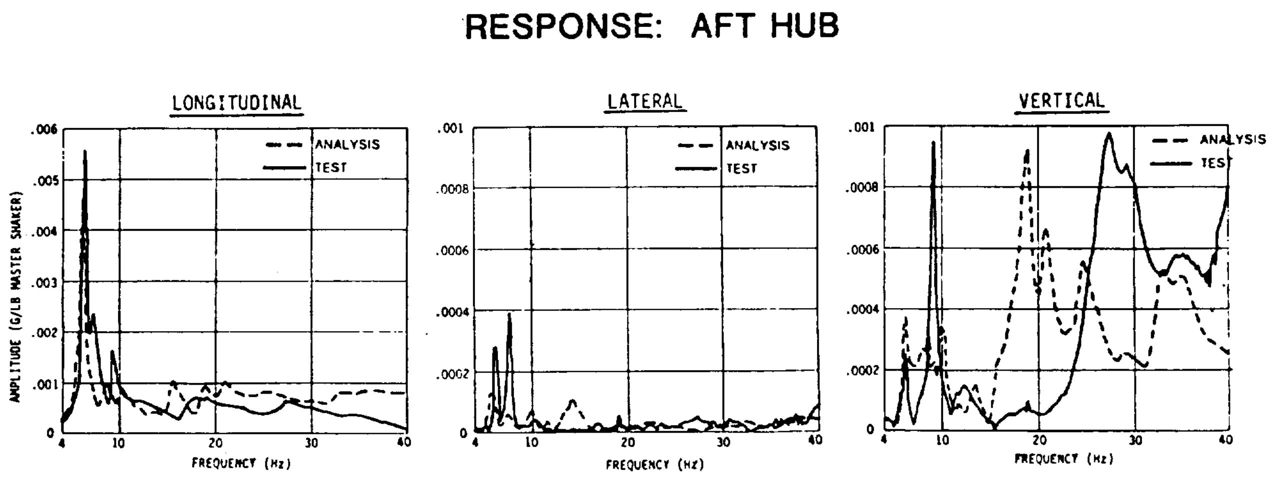
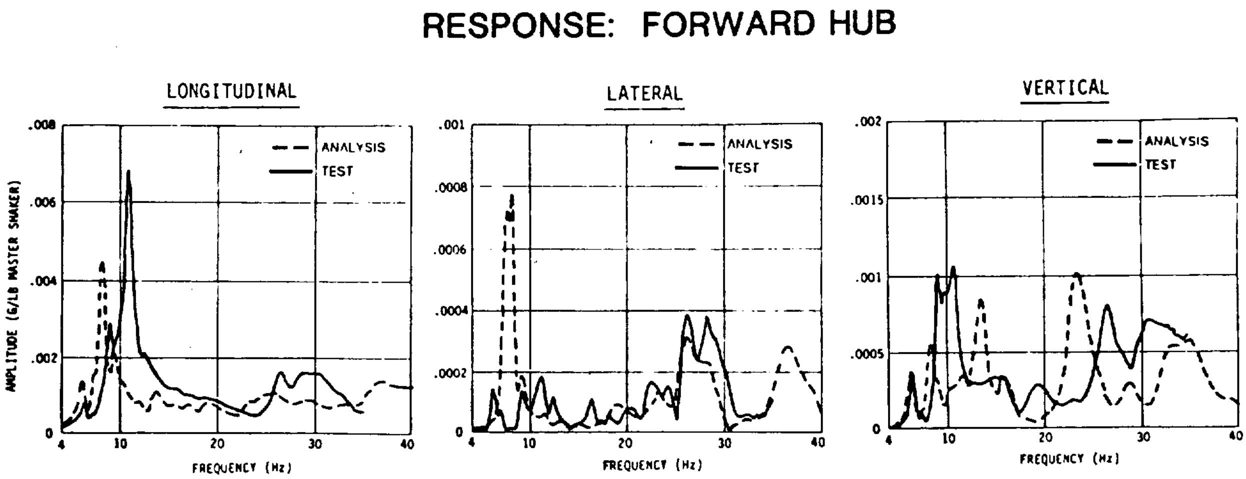


Figure 30.- Ground vibration test of Model 360.


RESPONSE: AFT HUB

(a) Aft hub pitch excitation


RESPONSE: FORWARD HUB

(b) Forward hub pitch excitation

Figure 31.- Comparison of measured and calculated responses of Model 360.

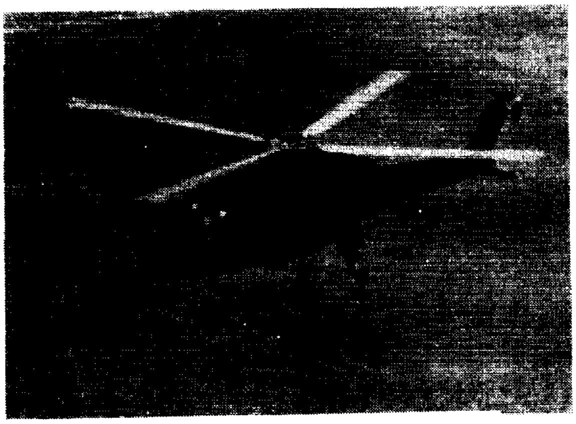
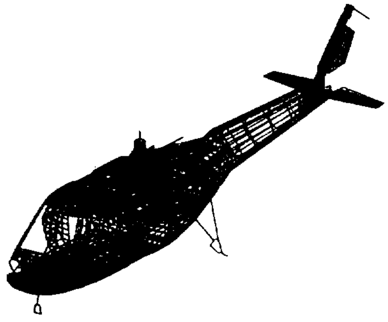


Figure 32.- S75 (ACAP) helicopter.



NASTRAN Model
5042 Grid Points
9194 Structural Elements

Element Type	Number Of Elements
BAR	1956
CONROD	1773
QUAD4	4326
TRIA3	1139
CONM2	382

Figure 33.- S75 NASTRAN model.

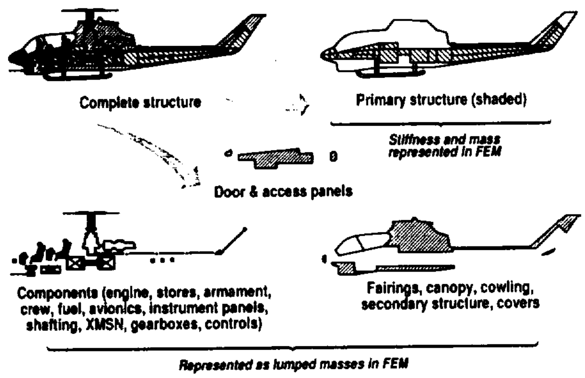


Figure 34.- Usual treatment of airframe structure in finite element modeling.

Figure 35.- AH-1G helicopter.

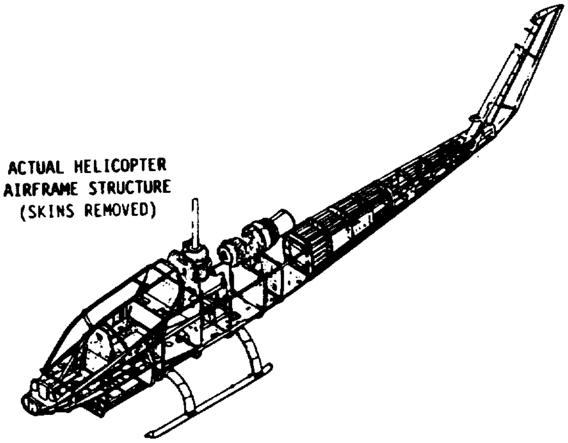
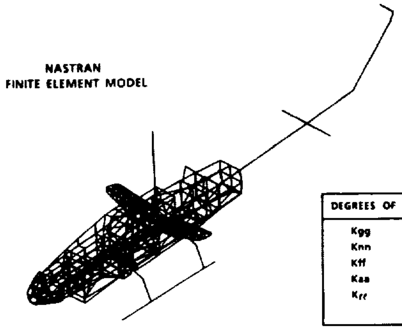


Figure 36.- AH-1G airframe structure.



DEGREES OF FREEDOM		ELEMENTS	
Kgg	2940	BAR	197
Knn	2699	ROD	2012
Kff	1714	SHEAR	340
Kaa	241	QDMEM	160
Krr	235	TRMEM	243
		ELAS2	13

Figure 37.- Initial AH-1G NASTRAN finite element model.

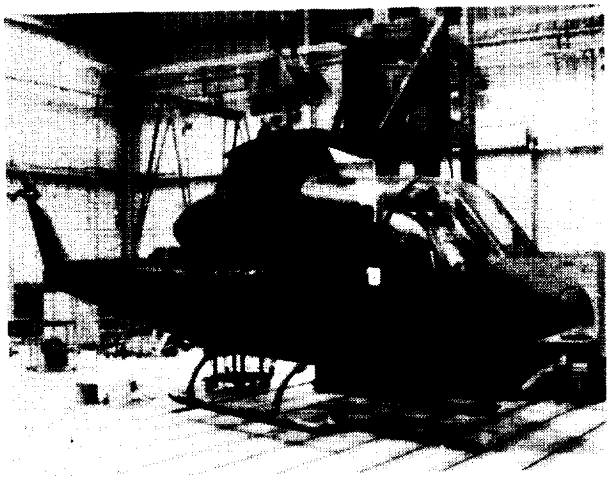


Figure 38.- AH-1G airframe in full-up ground vibration test configuration.

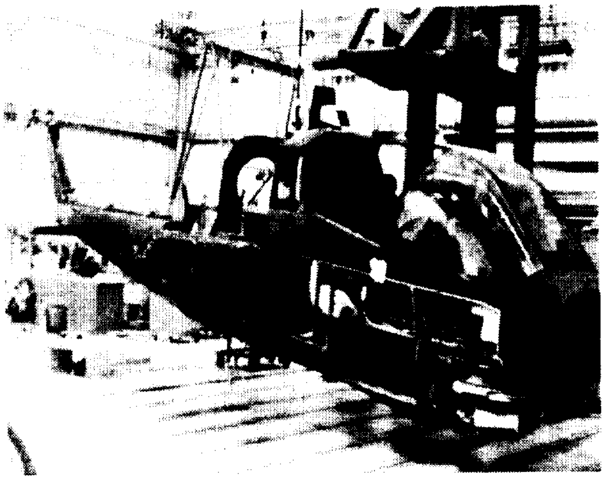


Figure 39.- AH-1G airframe in stripped-down ground vibration test configuration.

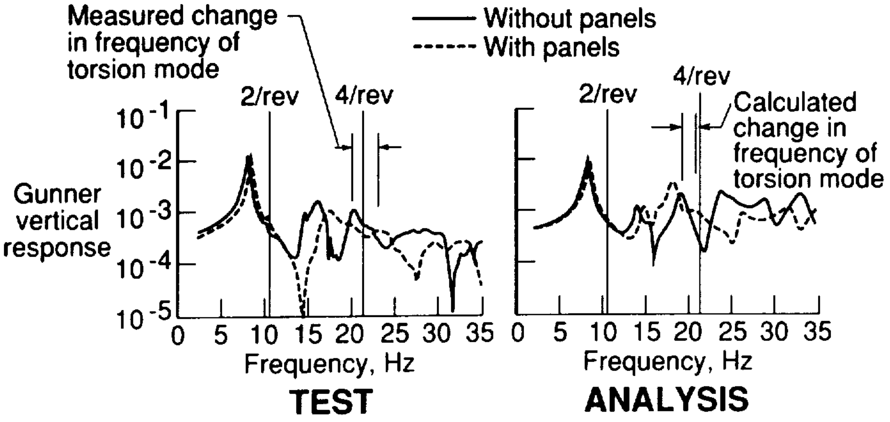


Figure 40.- Effects of secondary structure panels on AH-1G frequency response amplitudes.

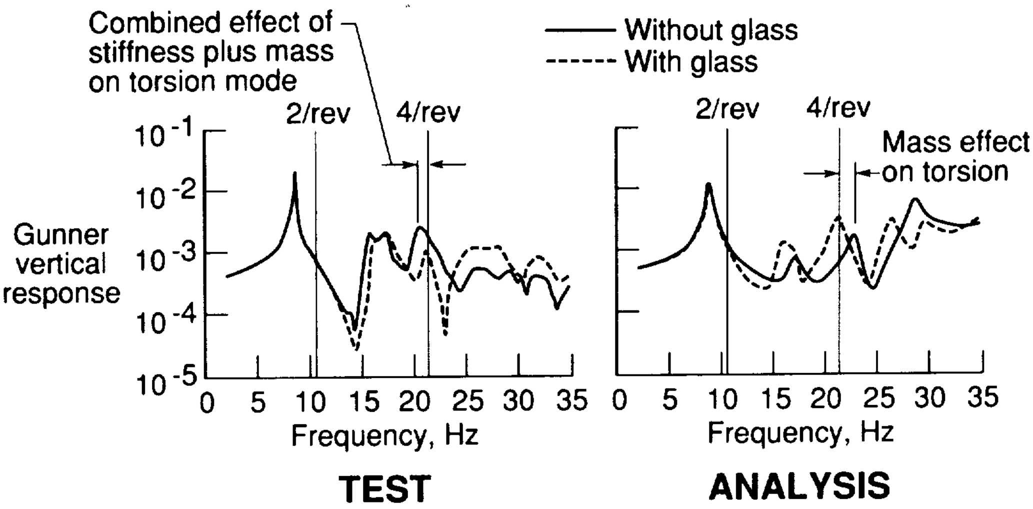
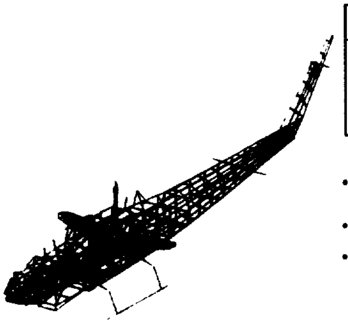


Figure 41.- Effects of canopy glass on AH-1G frequency response amplitudes.



DEGREES OF FREEDOM		ELEMENTS	
K_{gg}	4611	BAR	358
K_{nn}	4223	ROD	3072
K_{ff}	2965	SHEAR	540
K_{aa}	241	QDMEM	160
K_{ll}	235	TRMEM	243

- CONTOUR STRUCTURE (FS 61 – 148) STIFFNESS REMOVED FROM CONFIGURATIONS 3 – 8
- BUILT-UP TAILBOOM REPLACES ELASTIC LINE ON ALL CONFIGURATIONS
- MODAL DAMPING
  - UNIFORM DAMPING ASSUMED FOR SIMPLICITY (2% LOSS)
  - WOULD BE MODIFIED ACCORDINGLY FOR ACTUAL RESPONSE PREDICTION

Figure 42.- Final AH-1G NASTRAN finite element model.

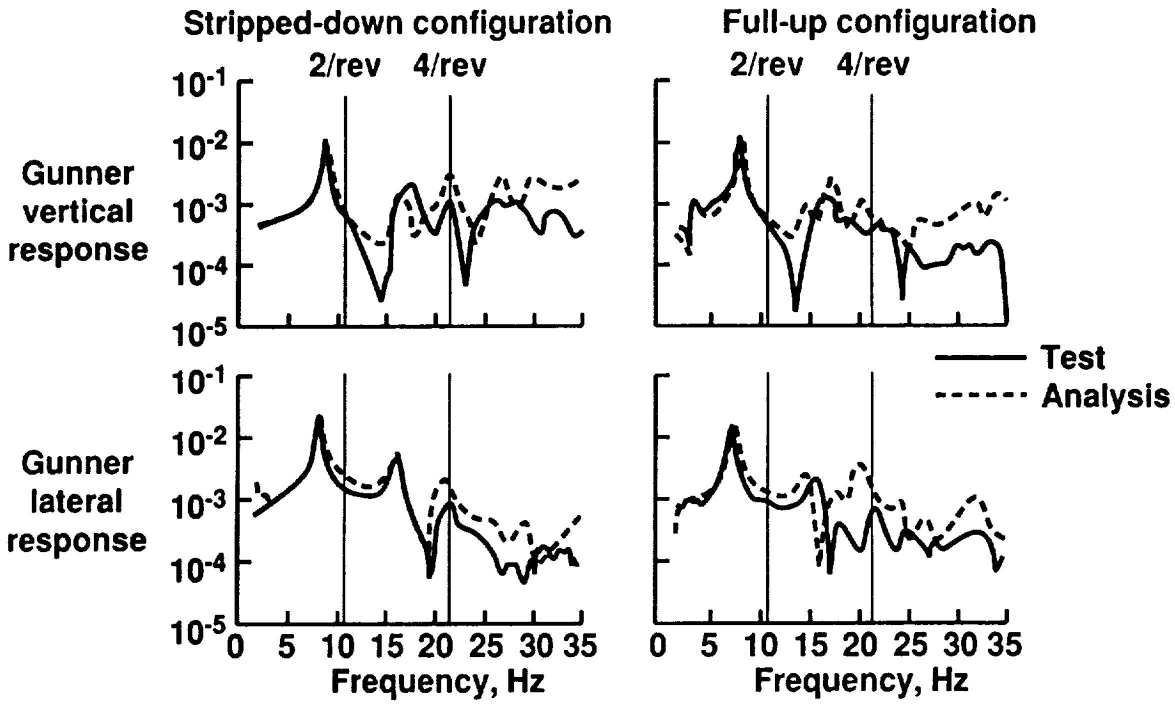


Figure 43.- Final test/theory comparisons for AH-1G frequency response.

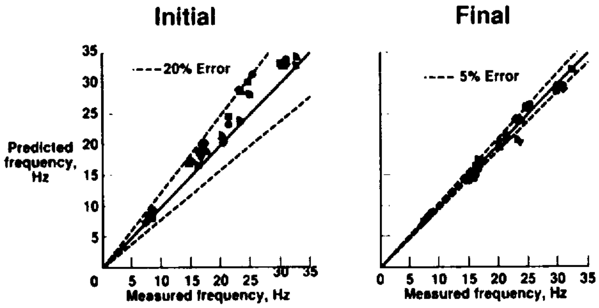


Figure 44.- AH-1G natural frequency comparisons using initial and final (improved) models.

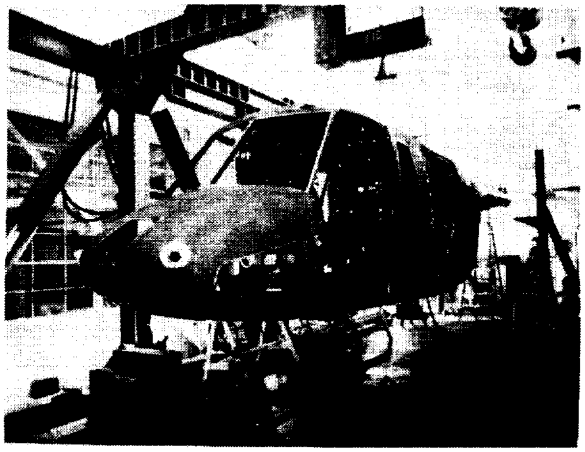


Figure 45.- D292 (ACAP) airframe in stripped-down ground vibration test configuration.

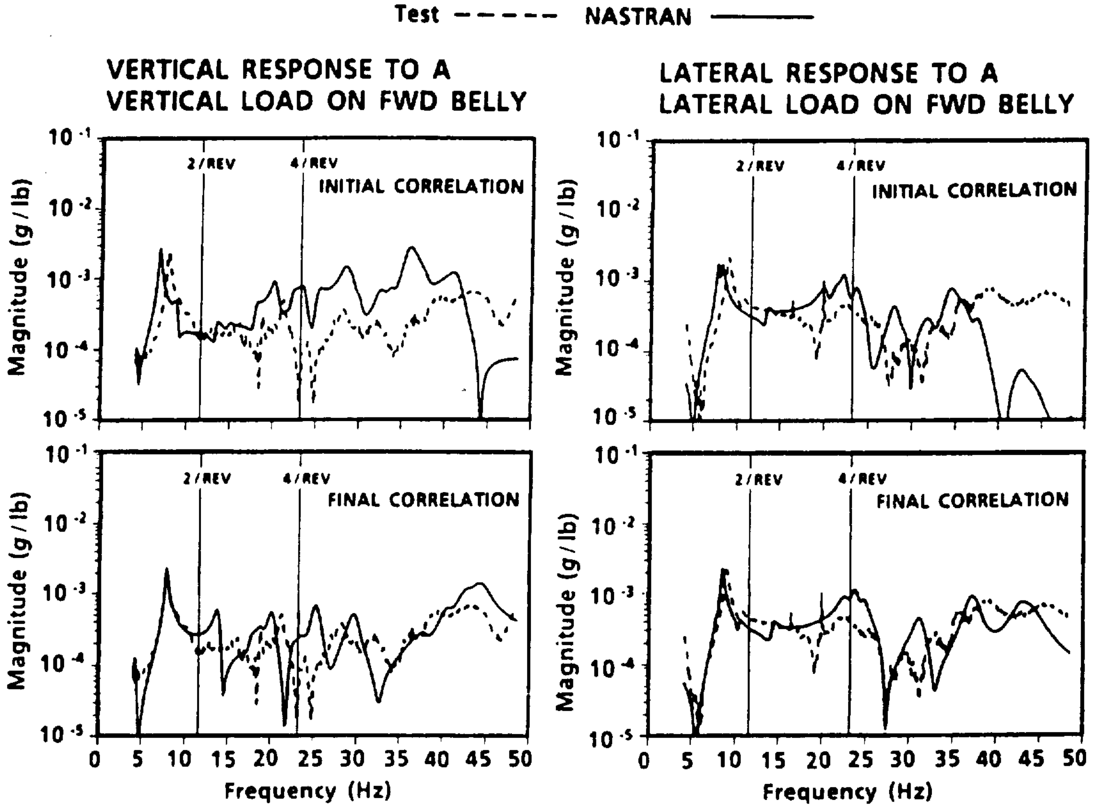
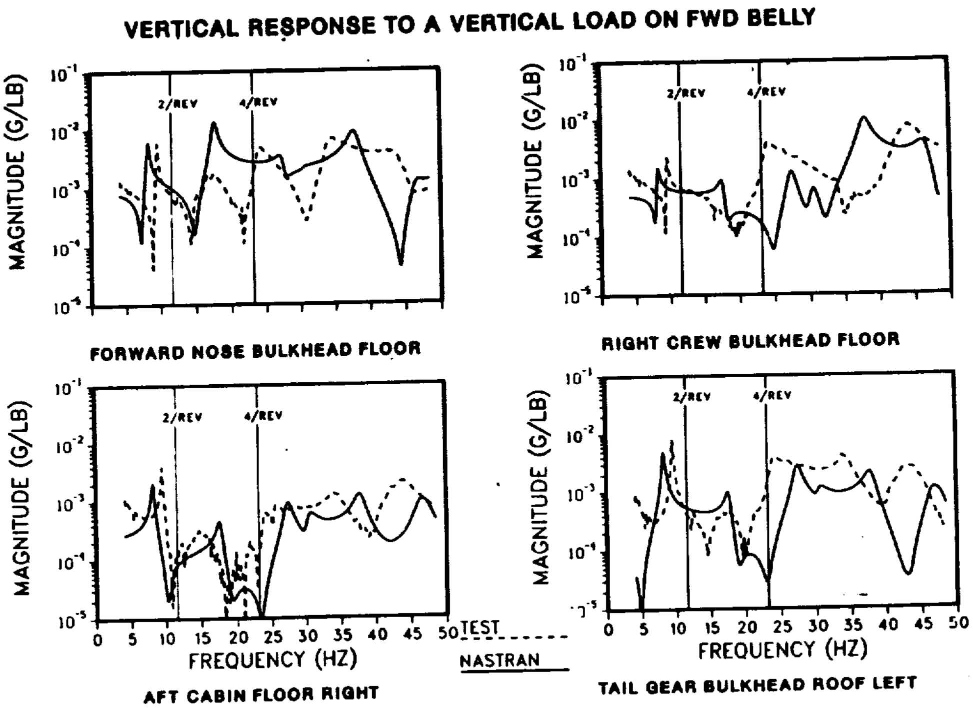
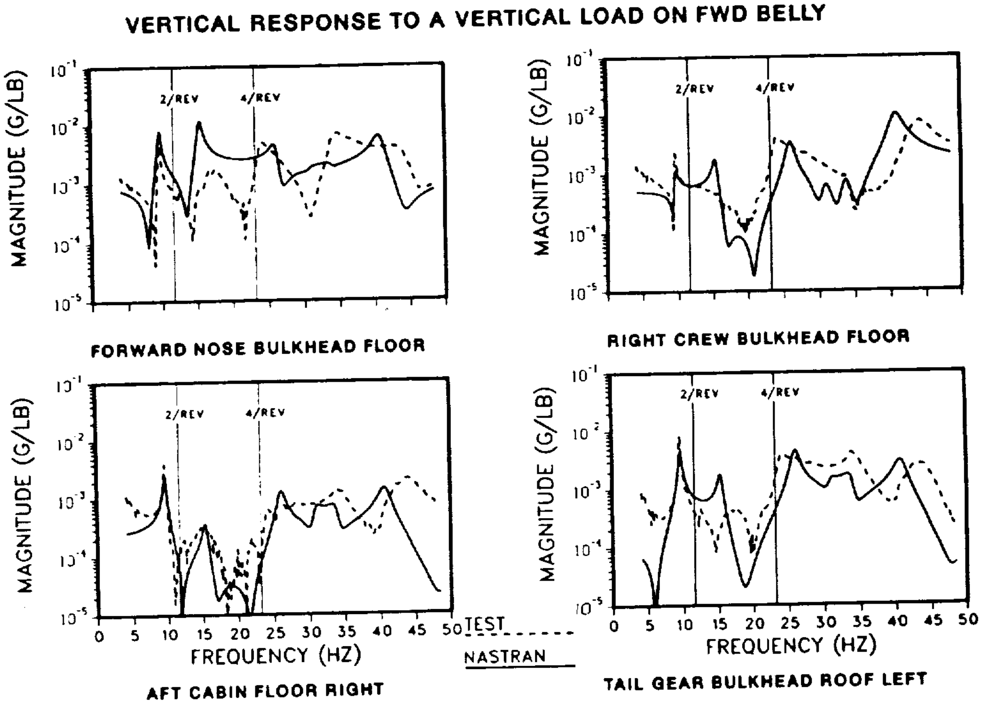


Figure 46.- Initial and final correlation of D292 (ACAP) responses at engine deck for full-up configuration.

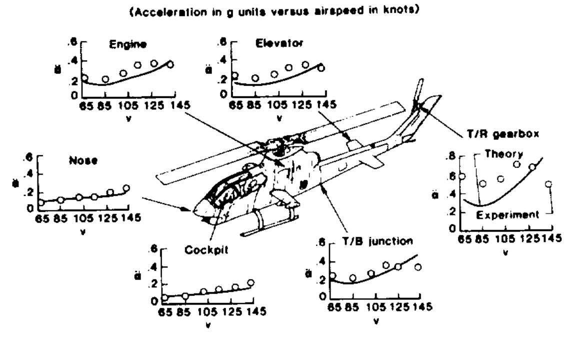


(a) Initial correlation

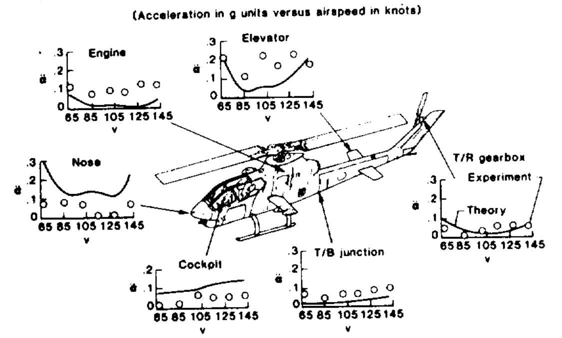


(b) Final correlation

Figure 47.- Initial and final correlation of D292 (ACAP) responses for stripped-down configuration.



(a) 2/rev vertical response



(b) 4/rev vertical response

Figure 48.- Comparison of measured AH-1G 2/rev and 4/rev vertical vibrations with predictions made by aircraft's manufacturer.

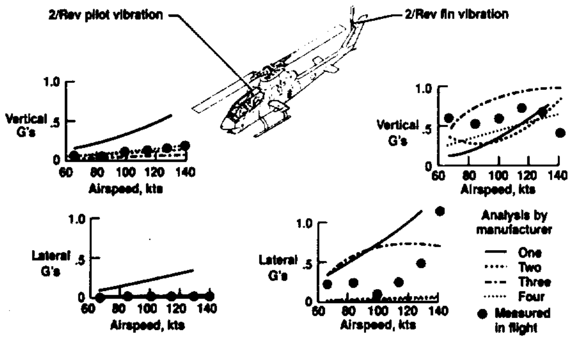


Figure 49.- Industry comparisons of measured and predicted 2/rev vibrations of AH-1G helicopter.

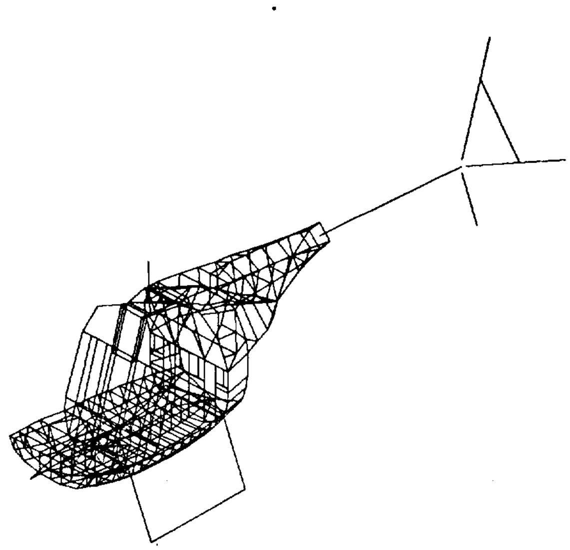


Figure 50.- NASTRAN model of OH-6A.

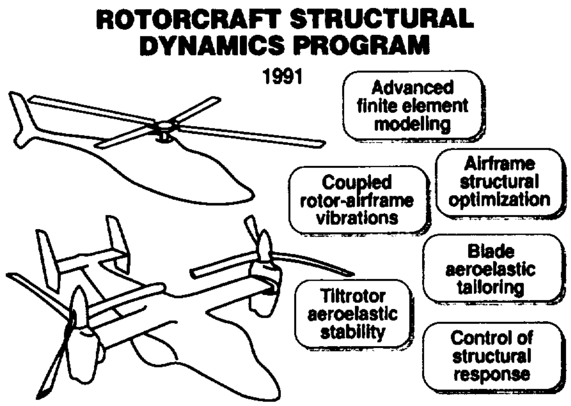


Figure 51.- Major research areas of current Langley rotorcraft structural dynamics program.

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13. ABSTRACT *(Maximum 200 words)*

A NASA Langley-sponsored rotorcraft structural dynamics program known as DAMVIBS (Design Analysis Methods for VIBrationS) with the objective of establishing the technology base needed by the industry for developing an advanced finite-element-based dynamics design analysis capability for vibrations has been underway since 1984. Under the program, teams from the four major helicopter manufacturers have formed finite-element models, conducted ground vibration tests, and made test/analysis comparisons of both metal and composite airframes, performed "difficult components" studies on airframes to identify components which need more complete finite-element representation for improved correlation, and evaluated industry codes for computing coupled rotor-airframe vibrations. Studies aimed at establishing the role that structural optimization can play in airframe vibrations design work have also been initiated. Five government/industry meetings have been held in connection with these activities during the course of the program. Because the DAMVIBS Program is coming to an end, the fifth meeting included a brief assessment of the program and its benefits to the industry. The assessment indicated that the DAMVIBS 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 finite-element-based dynamics analyses during the design process. The purpose of this paper is to present a summary of the major accomplishments and contributions which may be ascribed to the program.

14. SUBJECT TERMS
Finite element modeling; rotorcraft airframe vibrations; coupled rotor-airframe vibrations; airframe structural optimization

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