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

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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).

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 published[1]. 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.

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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.

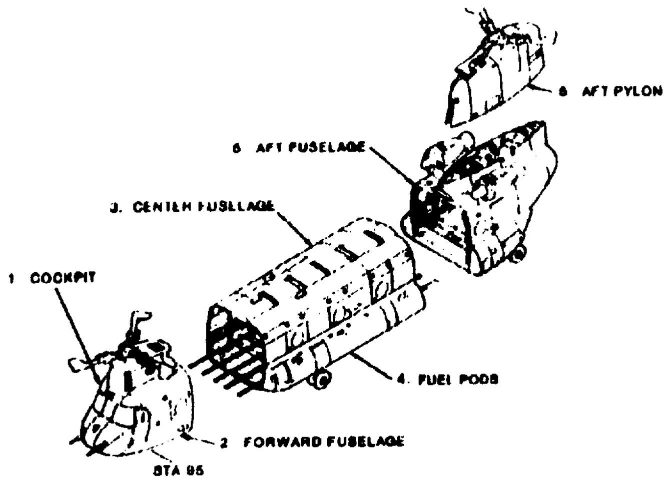


Figure 1. Breakdown into Major Areas for Static Modeling

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

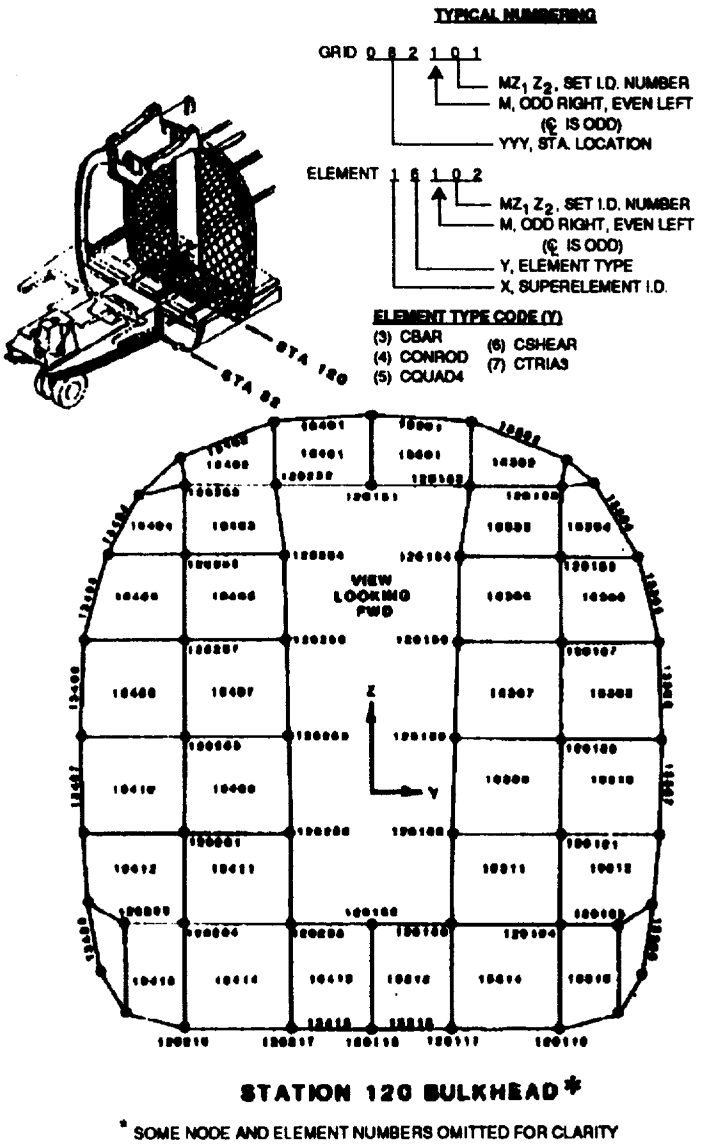
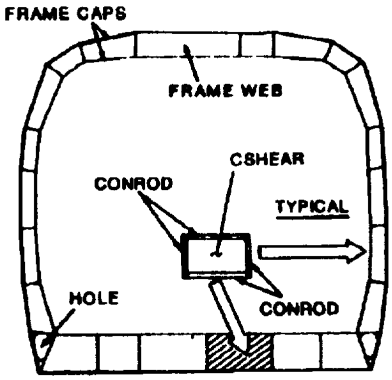


Figure 2. Model 360 Grid and Element Numbering Scheme



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

Figure 3. Static Modeling Guides - Frames

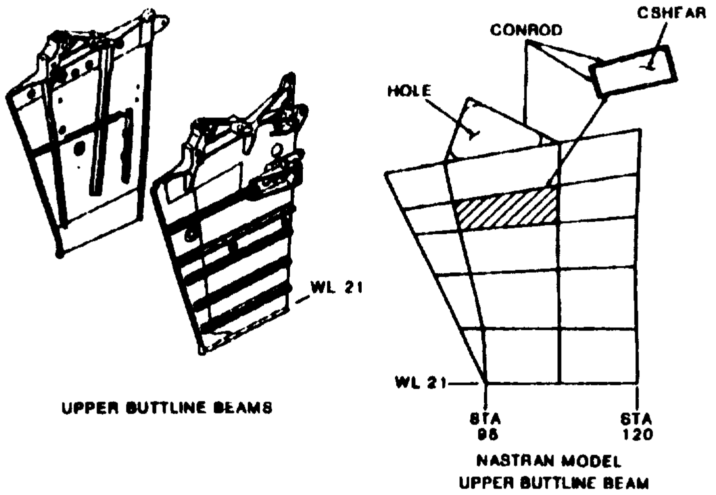


Figure 4. Static Modeling Guides - Bulkheads, Decks, and Butt-Line Beams

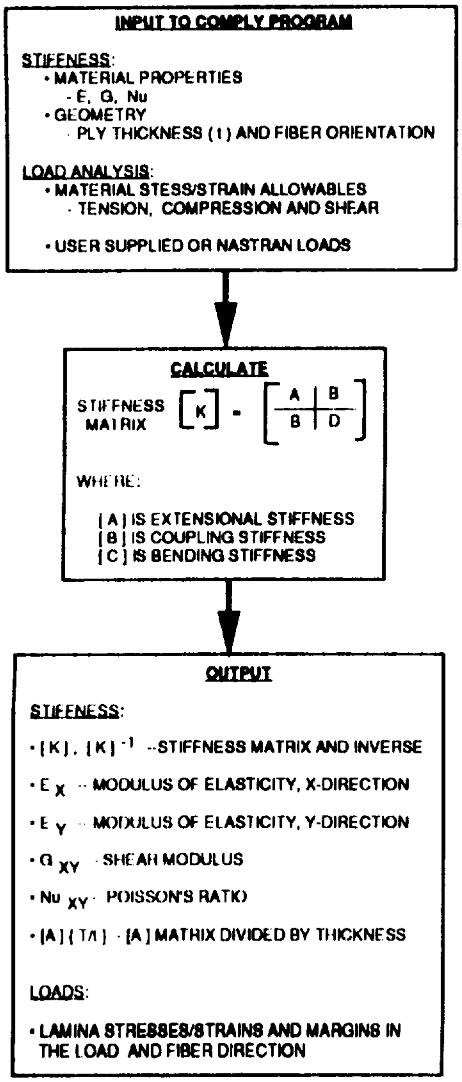
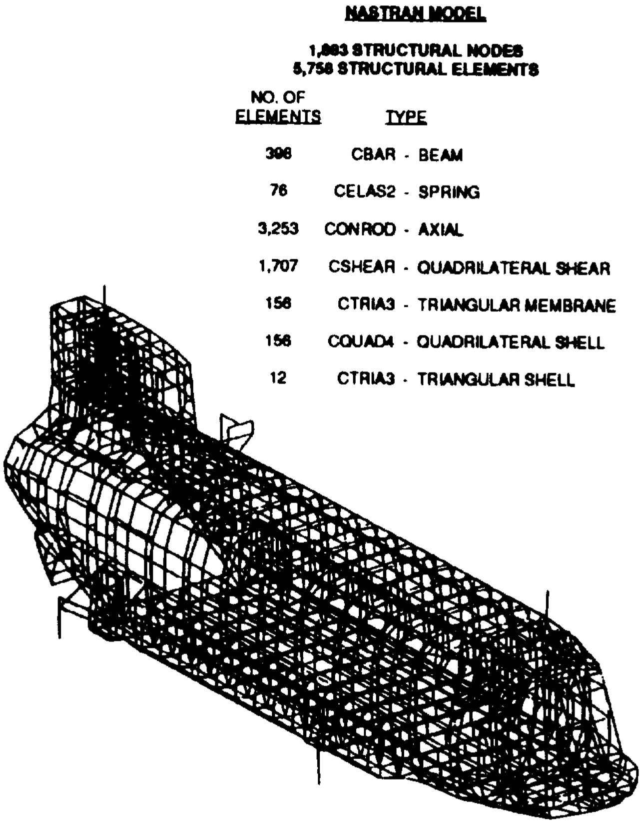


Figure 5. Static Modeling Guides - Analysis Method for Composite Laminate Properties

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

1,883 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	CQUAD4 - QUADRILATERAL SHELL
12	CTRIA3 - TRIANGULAR SHELL

Figure 6. CH-47D NASTRAN Structural Model

A typical model detail illustrating the forward pylon upper buttline 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).

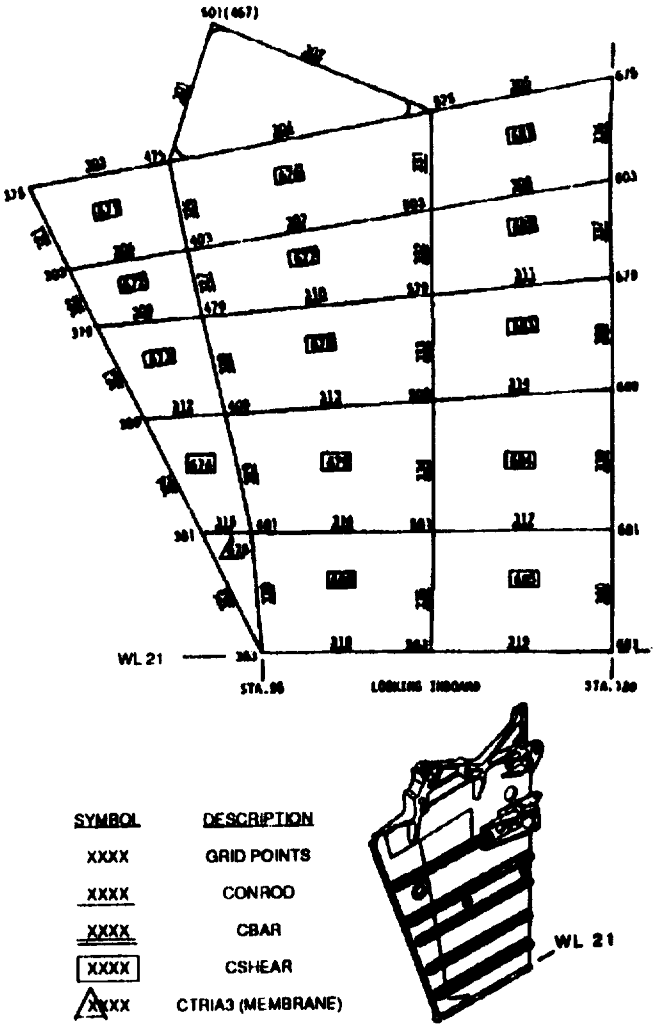


Figure 7. Static Modeling of Forward Pylon Upper Butt-Line Beam

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.

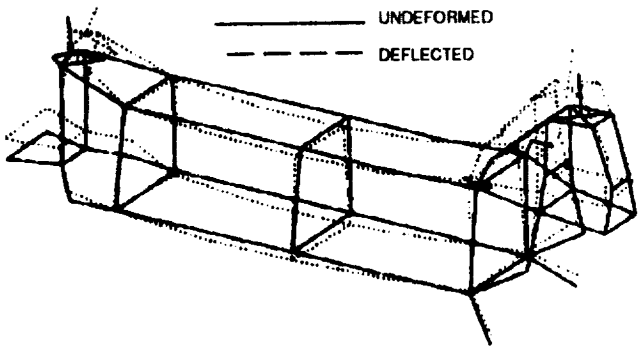


Figure 8. Static Demonstration Case, Deflection for 3.0 g Pull-Up

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.

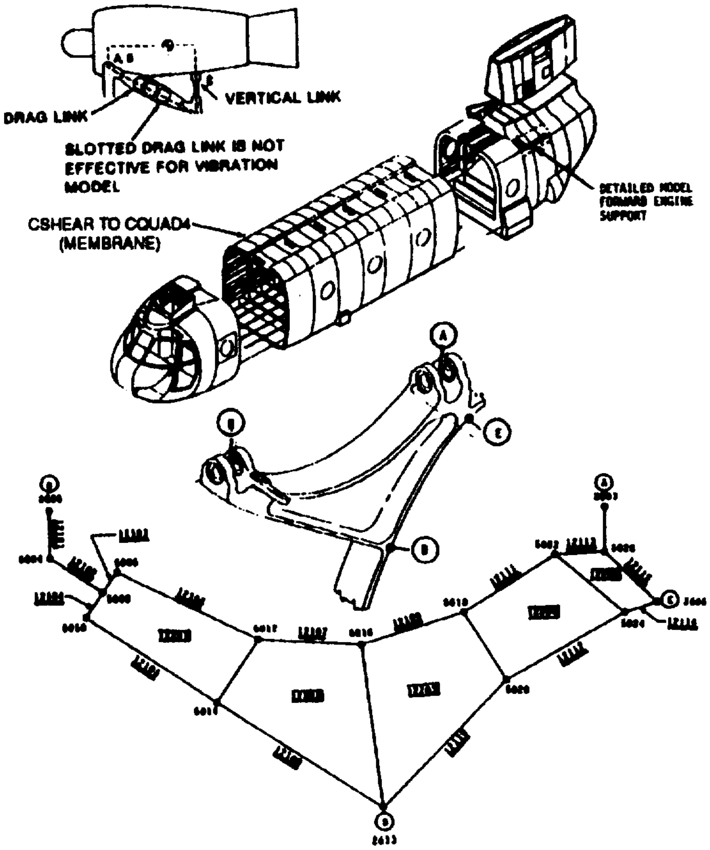


Figure 9. Vibration Modeling Structural Changes

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	6.38	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	11.89	2ND VERTICAL - PYLON LONGITUDINAL IN PHASE
6	12.89	2ND LATERAL - FWD PYLON LATERAL
7	13.81	3RD LATERAL - PYLON LATERAL IN PHASE
8	16.01	AFT LANDING GEAR LATERAL - OUT OF PHASE
9	16.22	UNDEFINED VERTICAL
10	17.41	UNDEFINED LATERAL
11	19.20	UNDEFINED LATERAL
12	20.71	UNDEFINED VERTICAL
13	21.61	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
- Prestiffening 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.

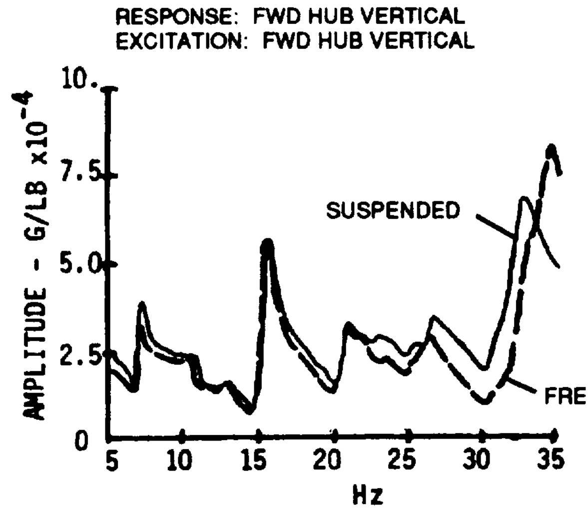


Figure 10. Typical Analytical Response for Free and Suspended Conditions

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 ±g per pound of force.

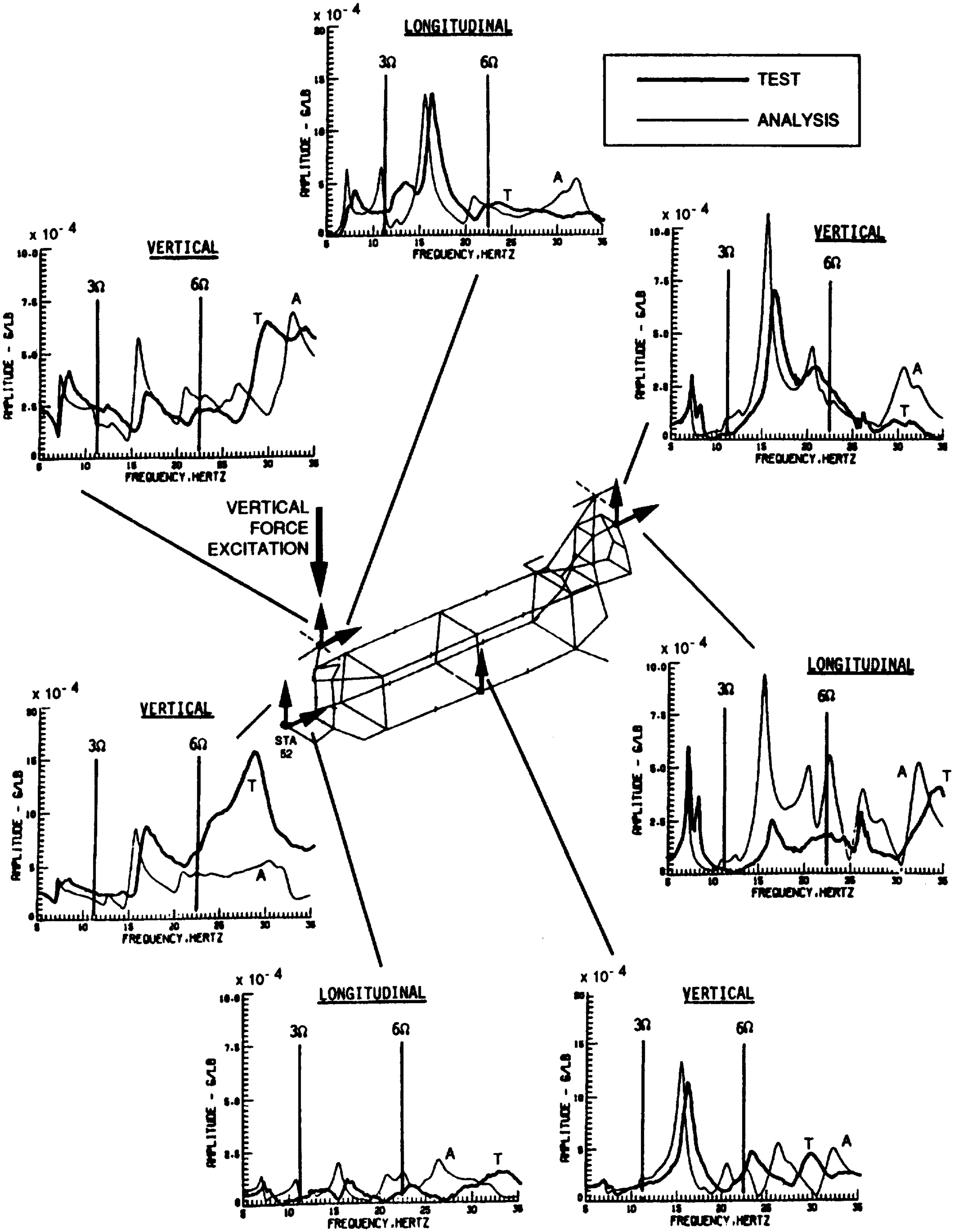


Figure 11. Comparison of Test and Analytical Forced Response with Forward Vertical Excitation

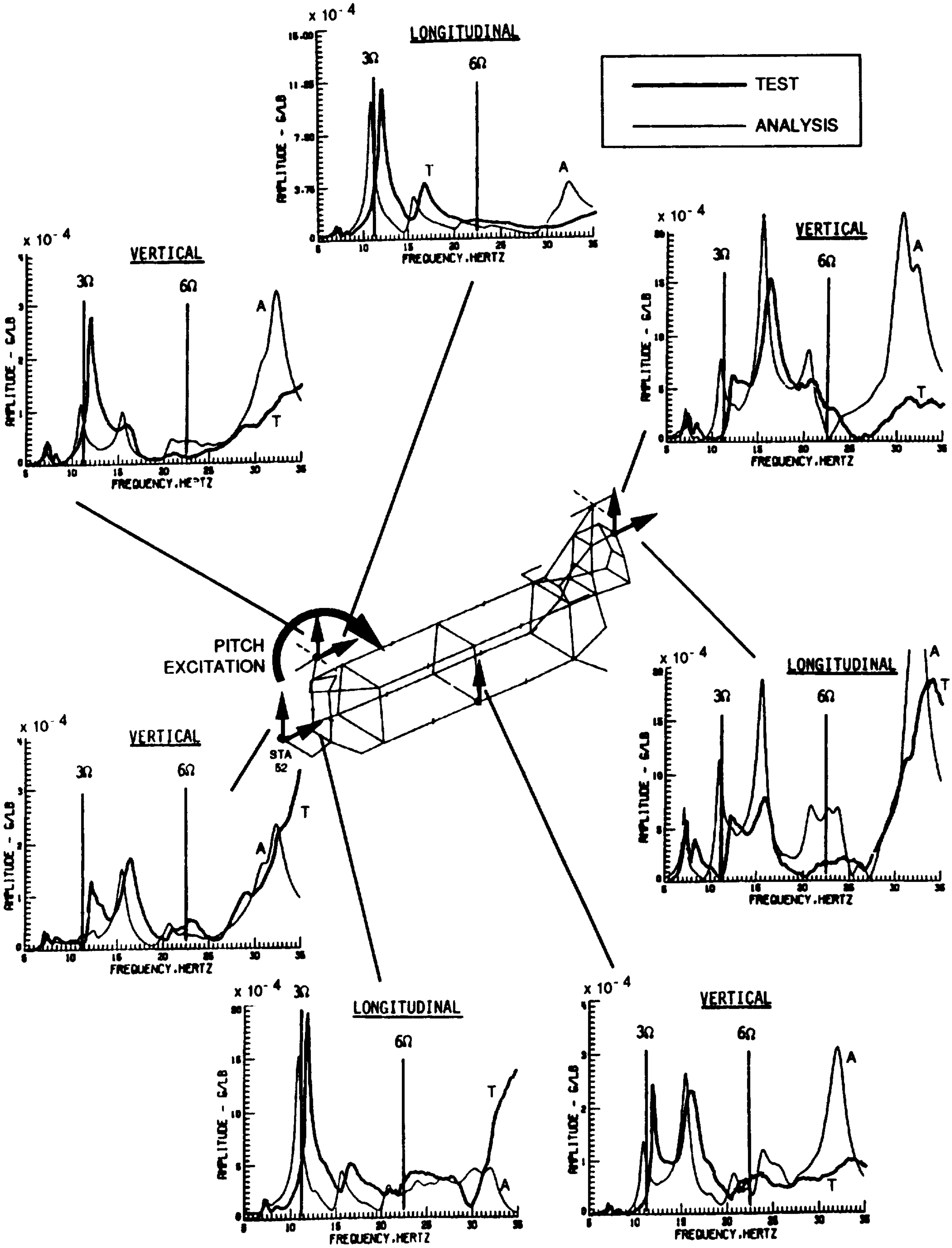


Figure 12. Comparison of Test and Analytical Forced Response with Forward Pitch Excitation

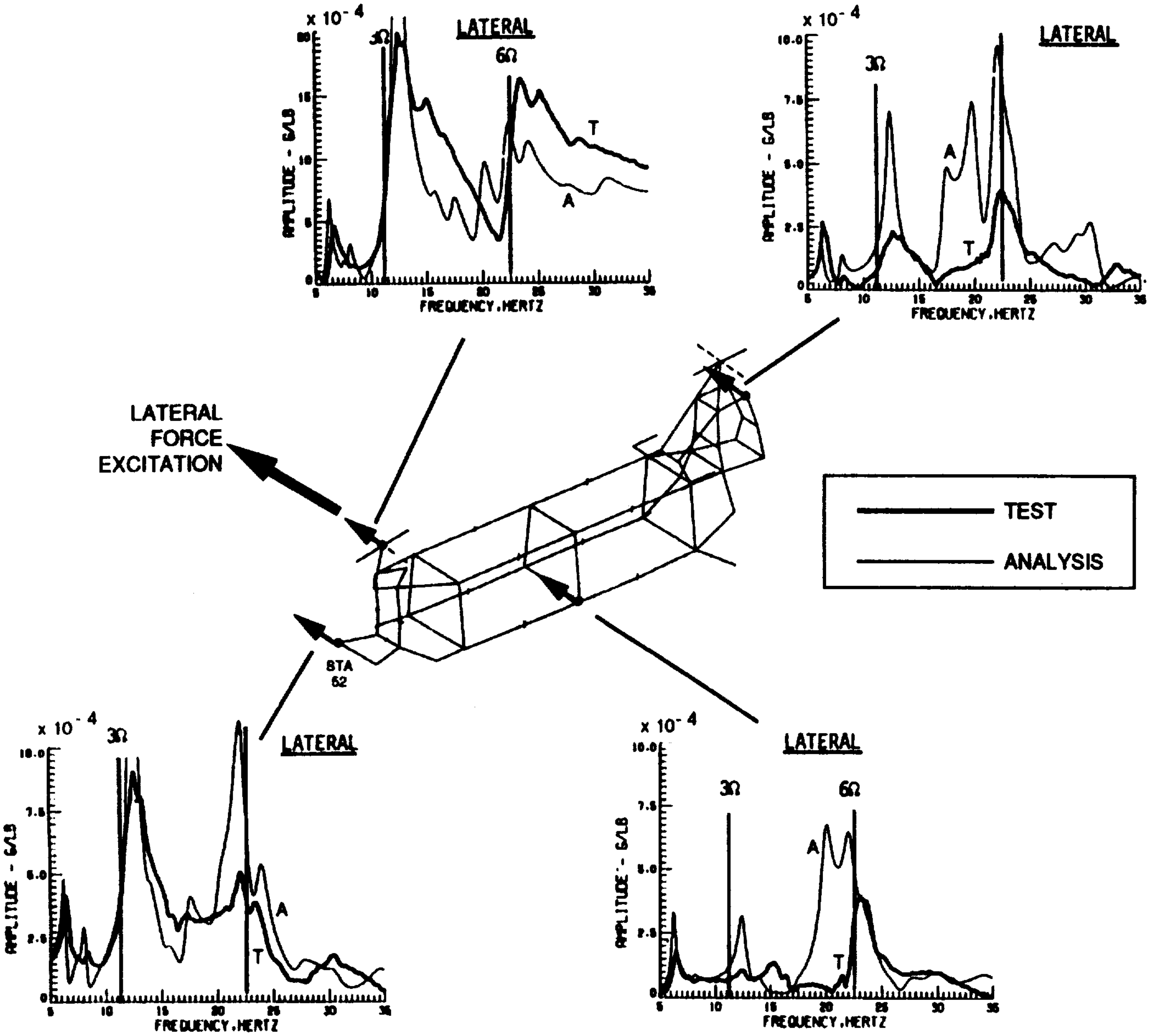


Figure 13. Comparison of Test and Analytical Forced Response with Forward Lateral Excitation

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	.05
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

FORWARD LATERAL EXCITATION
COCKPIT STA. 52 L/H LATERAL (GRID 52)

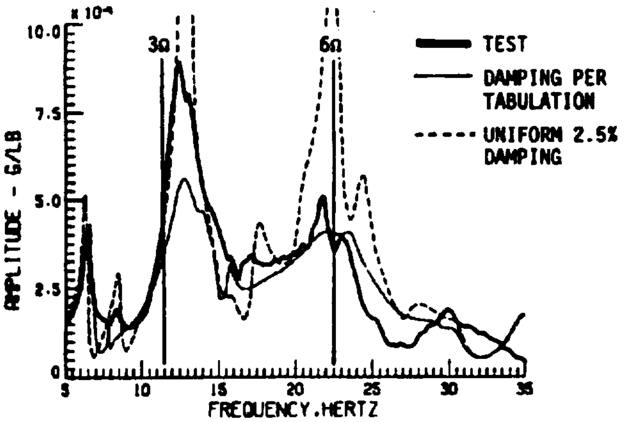


Figure 14. Effect of Model Damping on Forced Response Correlation

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	BASELINE	X1.13	X1.5	X2.0	X1.13
6.25	6.26	6.40	6.73	7.08	6.40
7.00	7.11	7.18	7.40	7.64	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	15.69	16.42	17.05	15.69
15.47	15.59	15.84	17.74	19.18	15.84
17.30	17.34	17.70	18.60	19.81	17.70
18.09	18.11	18.44	19.26	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	22.96	24.23	22.00
22.10	22.17	22.81	24.32	25.92	22.81
23.41	23.52	23.91	24.98	26.30	23.91
23.99	24.09	24.61	26.03	27.35	24.61
25.30	25.38	25.93	27.36	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 $10x10^6$ to $10.3x10^6$ (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	.....	8.55	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	14.96	14.99	14.99	14.99
	14.87	LOCAL MODE				
8	15.47	16.2	15.64	15.93	16.03	16.11
9	17.3	17.7	17.21	17.24	17.21	17.22
10	18.09	18.4	17.62	17.66	17.63	17.64
11	20.01	21.2 21.7 Multiple Modes	20.57	21.5	21.58	21.58
12	20.64		21.52	21.92	22.06	22.21
13	21.69	LOCAL MODE				
14	22.1	22.0 22.9 Multiple Modes	22.15	22.18	22.2	22.26
15	23.41		22.78	22.79	22.79	22.8
16	23.99	23.8	24.0	24.03	24.04	24.04
17	25.3	24.9	24.33	24.56	24.7	24.79

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

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