SHUTTLE STRUCTURAL DYNAMICS CHARACTERISTICS, THE ANALYSIS AND VERIFICATION

C. Thomas Modlin, Jr., and George A. Zupp, Jr.
NASA Lyndon B. Johnson Space Center
Houston, Texas 77058

INTRODUCTION

The building and operation of the Space Shuttle represents a milestone in the U.S. space program. The Shuttle is the first manned spacecraft to be reusable; on its first flight on April 12, 1981, it successfully carried astronauts and a payload into Earth orbit.

Up to this point in space exploration, a launch vehicle had to successfully complete an extensive and comprehensive flight test program before being man rated. The Shuttle program philosophy, on the other hand, was to use key element testing and verified analytical models to certify the reliability of the Shuttle launch configuration.

Several engineering disciplines relied heavily on verified analytical models of the Space Shuttle, i.e., the disciplines of structural dynamics, pogo, and flutter. The verification of these models employed laboratory control testing to develop data critical to math model verification. The basic philosophy was to correlate analysis and testing to an acceptable degree of accuracy and infer from this that the launch vehicle dynamics could be predicted with the same accuracy.

During the phase B period of the program, analytical studies pointed up unique dynamic characteristics of the parallel burn configuration, in particular, a very high modal density with 200 structural modes below 20 hertz in combination with a wide spectrum of conditions involving a wide variety of dynamic problems (fig. 1). Studies conducted at the NASA Langley Research Center (LaRC) on a 1/8-scale dynamic model reinforced these concerns, and the results indicated the substantial influence of element interface stiffness on the primary low frequency modes of the system.

Immediately after approval to proceed with the Shuttle, particular emphasis was placed on developing a technical plan of action that would ensure early resolution of the key issues in the structural dynamics area. The testing portion of the verification plan that evolved consisted of three major parts: the 1/4-scale dynamics model program to provide early data, tests of full-scale elements, and a full-scale mated vertical ground vibration test (fig. 2). In the development of the 1/4-Scale Model Program, emphasis was placed on investigating enough propellant conditions to adequately represent the flight configurations from lift-off to end burn and to minimize the requirements for full-scale testing.

Further attention was directed toward planning analytical activities to support hardware development and ground testing. User requirements for structural loads, flight control, pogo, and flutter were identified and, where required, specific models were generated to meet the discipline's need.

The plan established the mechanics for generating and updating the structural dynamic math models. Each element contractor was responsible for generating and updating the models of his elements, and the system contractor was responsible for identifying requirements to the element contractor and for integrating the complete model. The objective of this system was to require each contractor to be responsible for the element-unique models and their verification. Schedules were established for the development of the structural math models to support the Shuttle program milestones, the element milestones, and the ground vibration test program.

Extensive testing was also conducted to support the verification of the pogo and flutter forcing function models. Since each of these disciplines utilizes the structural dynamic model, the testing verification was oriented toward defining the associated closed-loop forcing function. In the case of pogo, where pogo suppressors on the Space Shuttle main engines (SSME's) were baselined early in the program, the testing primarily addressed the SSME dynamics and suppressor characteristics. This was accomplished through the pulsing of the oxygen feed system to the main engines and measuring the attenuation or amplification of the pulse signal through the system. From these data, the system characteristics were extracted and used in the pogo stability analysis. The flutter models were verified using the same philosophy. Flutter testing was extensive, using wind tunnel testing with aeroelastically scaled models.

The final verification procedures of these models did require an assessment of flight data, with the bulk of these data being developed from STS-1 to STS-5. Approximately a thousand developed flight measurements were involved.

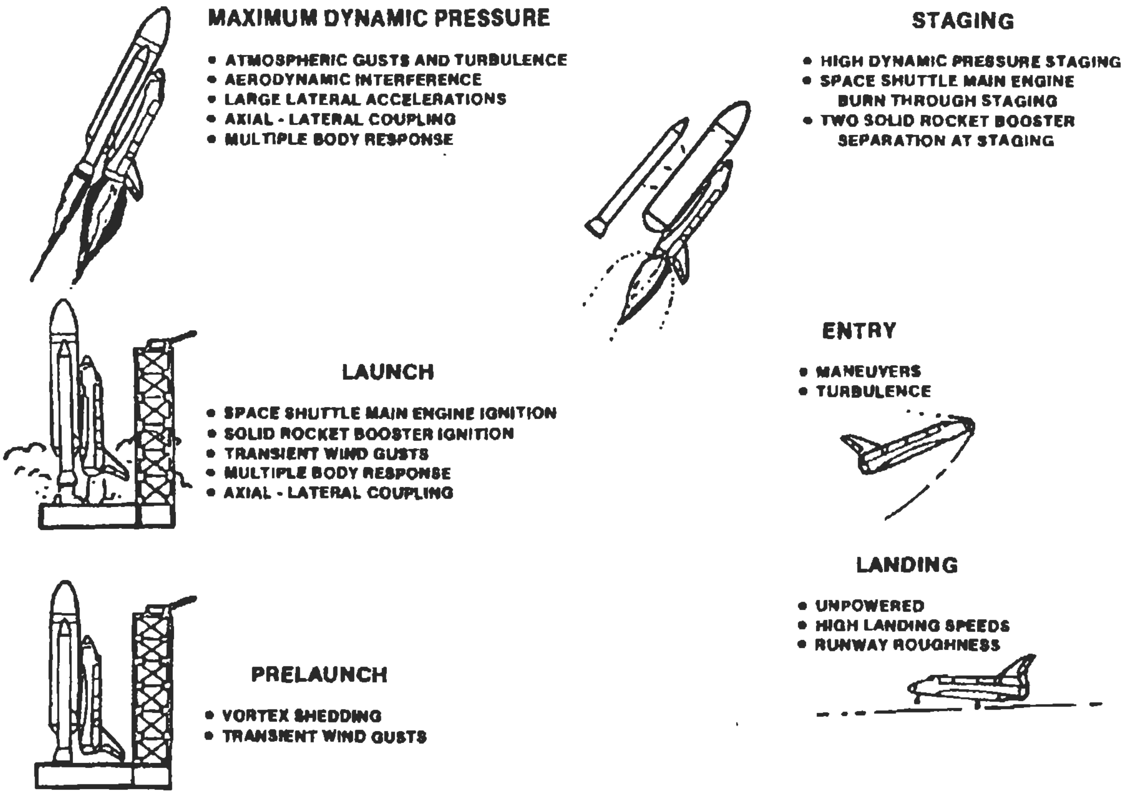

FIGURE 1.- SPECTRUM OF SHUTTLE DYNAMIC CONFIGURATIONS.

STRUCTURAL DYNAMICS

The Space Shuttle introduced a new dimension in the complexity of the structural dynamics of a space vehicle. The four-body configuration exhibited structural frequencies as low as 2 hertz with a model density on the order of 10 modes per hertz.

The structural dynamic mathematical models are derived from the "stress model," which is a detailed finite-element model of the Space Shuttle structure. The stress model has approximately 50 000 degrees of freedom (fig. 3). The dynamic models were derived from the stress model by various reduction techniques, and each has on the order of 1000 degrees of freedom.

The degrees of freedom that are retained in the dynamic models are designed to satisfy user requirements, i.e., disciplines such as pogo, dynamic loads, flutter, and flight control. For example, in the pogo structural models, a finer grid is retained in the Orbiter thrust structure and in the liquid oxygen (LOX) feed system. Since the hydrodynamics of the propellant are important to the pogo stability analysis, a hydroelastic model of the external tank (ET) is employed. Similar fidelity is preserved in critical areas of the vehicle as defined by the disciplines of dynamic loads, flutter, and flight control.

One prime driver in the degree of reduction of the model is the economy of computer operation. By virtue of the limits on computer size and speed, the eigen solutions of the reduced model will be small in comparison to the stress model. Therefore, it is of paramount importance that the frequencies and mode shape that are critical to the user are preserved to an acceptable accuracy during the reduction process.

In the verification process, certain mode shapes and frequencies were identified by the users as more important than others and, as such, the test objectives were oriented toward experimentally extracting those modes and frequencies for analysis and test correlation purposes. To provide the necessary experimental data, a series of ground vibration tests (GVT's) was conducted using test articles ranging from the 1/4-scale structural replica of the Space Shuttle to the full-scale vehicle.

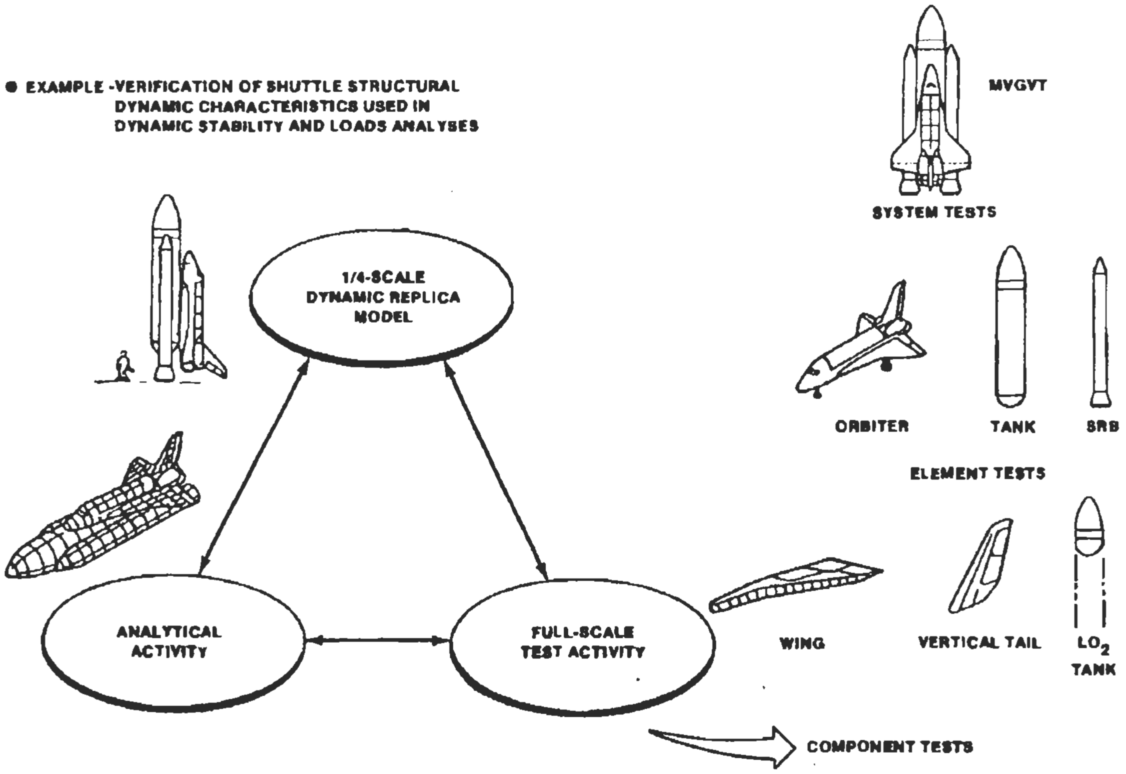

FIGURE 2.- "BUILDING BLOCK" APPROACH TO AN UNDERSTANDING OF SHUTTLE STRUCTURAL DYNAMICS.

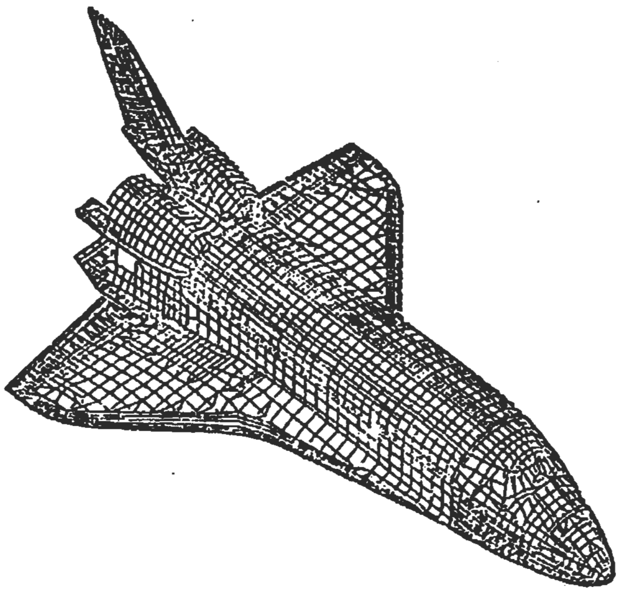

FIGURE 3.- OVERALL VIEW OF STRESS FINITE-ELEMENT MODEL.

GROUND VIBRATION TESTING

The Space Shuttle GVT program was designed to provide structural dynamic data early in the program so that if problems did occur, the solutions could be implemented with a minimum of program cost and schedule impact. The Langley Research Center was the first to start a vibration test program using a 1/8-scale structural model (refs. 1 and 2). Although the model replication was coarse, the overall configuration was representative of the Space Shuttle. The early LaRC data indicated the presence of low frequency structural modes associated with the four-body configuration and the importance of the interface stiffness on these modes. Also of concern was the lack of a verified analysis of the ET hydroelastic characteristics.

To develop the necessary experimental data for math model verification, three basic GVT programs were baselined in the Shuttle development schedule. These were the horizontal ground vibration test (HGVT), the 1/4-scale model GVT, and the mated vertical ground vibration test (MVGVT). The test and analysis schedule spanned the years from 1974 to 1981 (fig. 4).

In all major GVT programs, shakers were used to excite the structure and accelerometers were used to measure the structural response. A system known as the Shuttle Modal Test and Analysis System (SMTAS) was used to control and process the test data. The excitation was in the form of sine dwells, and sine sweeps. The frequency range of excitation was from 1.5 to 50 hertz. The test articles were usually instrumented with more than 300 accelerometers, of which about 60 accelerometer channels would be processed simultaneously during a dwell period. The vehicle instrumentation philosophy assumed that the vehicle was symmetric about the longitudinal axis, and, as such, the modal extraction would be either a symmetric or an antisymmetric mode. In selected cases, asymmetric modes were extracted. The test system, SMTAS, has an illustrative feature that computes the orthogonality between a test mode and an analytical mode. The mass matrix, [m], in this calculation was derived from the analytical model and reduced to the appropriate accelerometer grid locations. The test, Φ_{test}, and analysis, $\Phi_{analysis}$, mode shapes were normalized in such a manner that for a perfect mode shape correlation

$$\Phi_{test}^{T}\ [\, m \,]\ \Phi_{analysis} = 1$$

This feature gives a quantitative measure of the quality of the mode shape comparison between test and analysis. Judgment has to be exercised in the interpretation of the cross orthogonality calculation because of inherent error due to coarse gridding and reduction of the mass matrix to the test grid location.

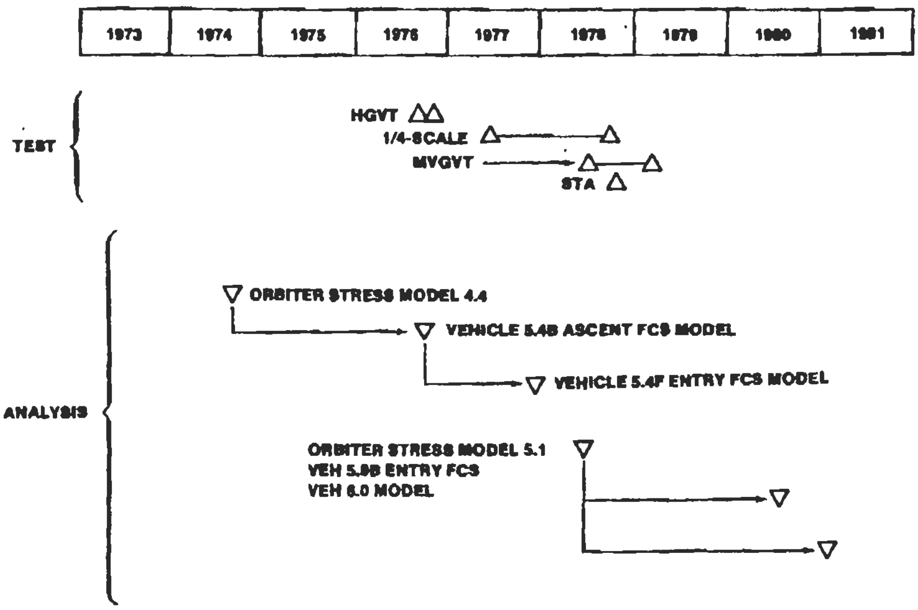

FIGURE 4.- CHRONOLOGY OF THE SHUTTLE STRUCTURAL MATH MODEL AND GROUND VIBRATION TESTS.

HORIZONTAL GROUND VIBRATION TEST

The HGVT article was the Orbiter 101 (OV-101) vehicle (the Orbiter used in the Approach and Landing Test (ALT)). These tests were conducted in the summer of 1976 at Palmdale, California. This was the first opportunity to get quality structural dynamic data for math model verification. Although OV-101 was not identical to the Orbiter 102 (OV-102) vehicle (the Orbiter used in the first Shuttle launch), the differences were accounted for in the structural math model. The primary differences were in the areas of the OMS pod (OV-101 did not have OMS pods but these were simulated by a "boilerplate" cover), the thrust structure (the thrust structure was not boron epoxy as it was in the case of OV-102), and the vertical fin (the vertical fin was made up of a skin and stringer configuration vs. integrally machined for the OV-102 flight vehicle). The payload in the Orbiter during testing was the Development Flight Instrumentation (DFI) package, which weighed approximately 10 000 pounds.

There were two basic test configurations: the Orbiter supported in a "free-free" condition to simulate the entry and landing configurations, and the Orbiter rigidly attached to the ground at the ET/Orbiter interface to simulate the boost configuration (figs. 5 and 6). Ferry locks also secured the control surfaces during testing. The test objectives were to determine experimentally selected mode shapes, frequencies, and modal damping in the frequency range from 0.5 to 50 hertz, and to acquire frequency response data at the Orbiter guidance and control sensor locations. Table 1 is a comparison of analysis frequencies and test frequencies for the free-free, or soft mount, configuration. As the analysis indicates, the structural mode shapes are quite complicated and are not generally amenable to classic descriptions, but the modal descriptions noted in table 1 are the areas of primary motion in the noted mode.

The major results from these tests were (1) the identity of friction in the payload bay door shear pins, which had the effect of increasing the pitch bending stiffness of the fuselage, (2) the modal damping, and (3) the lack of analytical correlation of the center-mounted rate gyros on the 1307 bulkhead. The modal damping data extracted from these tests were invaluable to flight controllers in the final verification of the entry flight control stability assessment. For a detailed comparison between test and analysis, refer to reference 3.

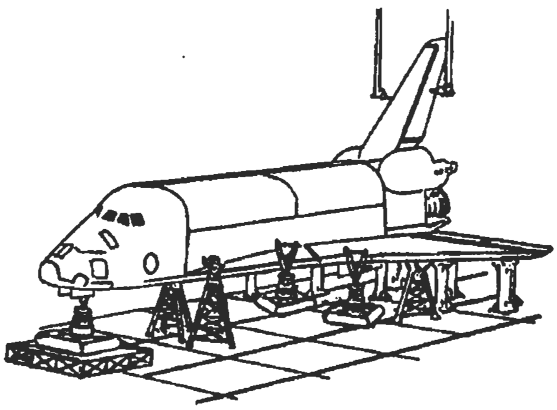

FIGURE 5.- SOFT HORIZONTAL GROUND VIBRATION TEST ARRANGEMENT.

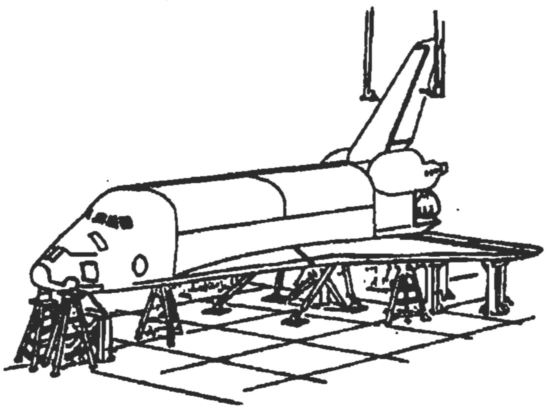

FIGURE 6.- RIGID HORIZONTAL GROUND VIBRATION TEST ARRANGEMENT.

TABLE I.- COMPARISON OF TEST AND ANALYSIS FREQUENCIES FOR THE FREE-FREE, OR SOFT MOUNT, HGVT (10^K PAYLOAD)

Modal description	Analytical frequency, Hz	Test frequency, Hz
First fuselage bending (X-Y plane)	5.09	5.97
First wing bending (Y-Z plane)	7.86	7.31
First vertical fin bending (Y-Z plane)	4.15	3.80
First vertical fin torsions	17.20	14.27

QUARTER-SCALE STRUCTURAL MODEL

The 1/4-scale model program was started in early 1975 for the purpose of developing high-quality structural dynamic data early in the Shuttle program that would be representative of the first Shuttle flight configuration. The structural model was a high-fidelity replication of OV-102, the standard ET, and three flight configurations of the solid rocket booster (SRB) (ref. 4). The 1/4-scale program was the most comprehensive element in the Shuttle GVT program. Of the test articles used in the vibration test program, the 1/4-scale model was structured most like the flight hardware.

The 1/4-scale vibration test configuration included the following.

1. Orbiter/ET/SRB configuration (with 45^k "rigid" payload)

   a. Lift-off
   b. Maximum dynamic pressure
   c. Pre-SRB separation

2. Orbiter/ET configuration (with 45^k "rigid" payload)

   a. Start boost
   b. Mid boost
   c. End boost

3. Orbiter element (with and without 45^k "rigid" payload)

4. ET element, 13^o tilt

5. SRB element

During testing, water was used to simulate the LOX in the ET and the weight and hydroelastic effects of the liquid hydrogen (LH) in the hydrogen tank were neglected. This procedure was also used in the MVGVT.

To complement the vibration test program, load-deflection tests were conducted on the SRB and the ET. The load-deflected tests were designed to provide data that could be used to resolve anomalous or unexplained vibration test data. Primarily, the load-deflection data supported the verification of the stiffness matrix in the idealized structural model.

At the start of the 1/4-scale program, there were several areas that presented problems in structural dynamic modeling. These were the ET hydroelastic analysis, the interface stiffnesses between the elements, the SRB propellant and internal pressure effects on the system structural modes, and the payload bay door effectivity in the Orbiter fuselage pitch bending stiffness.

Because of the pogo requirements for a high-fidelity hydroelastic analysis, the hydroelastic model of the ET was of particular concern in the early stages of the program. The lack of correlation between test and analysis with LaRC data indicated that the same deficiency could be expected from the hydroelastic analysis of the ET; therefore, several 1/4-scale tank configurations were selected for testing. In parallel, the Martin Marietta Company was developing a new hydroelastic analysis which became available before 1/4-scale testing. The quality of correlation between the upgraded hydroelastic analysis and the ET vibration data was judged excellent and provided the confidence in the analysis that allowed a reduction in scope of the ET vibration testing. Generally, the analysis frequencies were higher than the test frequencies. These differences were attributed to internal pressure effects in the LOX tank and the LH tank.

The Orbiter test verified the presence of friction in the payload bay door shear pin sufficient to effectively increase the pitch bending stiffness at low excitation levels. This increase in stiffness increased the bending frequency above that of the predicted value. The use of higher excitation forces on the structure overcame the friction in the shear pins and thereby allowed relative motion between the door bays and consequent reduction of the bending stiffness and frequency. The reduction in frequency was consistent with pretest analysis.

Several Orbiter configurations were tested that addressed the effects of payload weight on the Orbiter vibration characteristics. Ground vibration tests were also conducted with payload bay doors opened to simulate the on-orbit configuration.

The SRB tests identified several areas in the math model that required additional study. These were (1) the ET/SRB interface, which required additional detail in the finite-element model, (2) the incorporation of a representative shear modulus for the propellant, and (3) the incorporation of the internal pressure effects on shell stiffness. The posttest analysis incorporated changes in the math model that corrected some of these deficiencies. The internal pressure effects on the shell stiffness were handled emperically; the shear stiffness effects of the propellant were still in a state of iteration at the time of MVGVT. Comparisons of the test and analysis frequencies for the Orbiter test and the Orbiter/ET/SRB lift-off test are presented in tables 2 and 3, respectively. A detailed presentation of 1/4-scale model test data and analysis can be found in reference 5.

TABLE 2.- COMPARISON OF TEST AND ANALYSIS FREQUENCIES FOR THE "FREE-FREE" 1/4-SCALE ORBITER GVT (45^k PAYLOAD)

Modal description	Analytical frequency, Hz	Test frequency, Hz
First fuselage bending (X-Y plane)	4.6	4.8
First wing bending (Y-Z plane)	7.0	6.6
First vertical fin bending (Y-Z plane)	3.9	3.6
First vertical fin torsion	14.0	12.8

TABLE 3.- COMPARISON OF TEST AND ANALYSIS FREQUENCIES FOR THE "FREE-FREE" 1/4-SCALE ORBITER/ET/SRB LIFT-OFF CONFIGURATION (45^k PAYLOAD)

Modal description	Analytical frequency, Hz	Test frequency, Hz
SRB roll (antisymmetric)	2.0	1.8
SRB roll (antisymmetric)	2.0	2.0
First vertical fin bending (Y-Z plane)	3.7	3.4
First wing bending (X-Z plane)	6.3	6.4

MATED VERTICAL GROUND VIBRATION TEST

The MVGVT was the final major test program in the structural dynamic model verification plan. These tests were conducted between the summers of 1978 and 1979 at the NASA George C. Marshall Space Flight Center (MSFC) in Huntsville, Ala. The primary objectives of these tests were to experimentally obtain full-scale structural mode shapes, frequencies, damping data, and transfer functions at selected flight control sensor locations. The test configurations (figs. 7 and 8) were as follows.

1. Orbiter/ET/SRB configuration (payload 10^k)
   a. Lift-off
   b. Pre-SRB separation
2. Orbiter/ET configuration (payload 10^k)
   a. Start boost
   b. Mid boost
   c. End boost

The modal data extracted from these tests compared favorably with the modal data derived from 1/4-scale model testing when the known configuration differences were considered. Presented in table 4 is a comparison between test and analysis frequencies and the associated modal damping presented as percent of critical damping for the MVGVT lift-off configuration.

The major result of these tests was the identification of local resonances in the area of the SRB rate gyro locations. These resonances had the effect of corrupting the sensor signals, which, if occurring in flight, would have the effect of a lost sensor. Other anomalies were also noted on the Orbiter side-mounted rate gyros.

The issue raised during 1/4-scale testing concerning SRB propellant stiffness was not resolved. Because of the nonlinear viscoelastic properties of the SRB propellant, the eventual resolution of

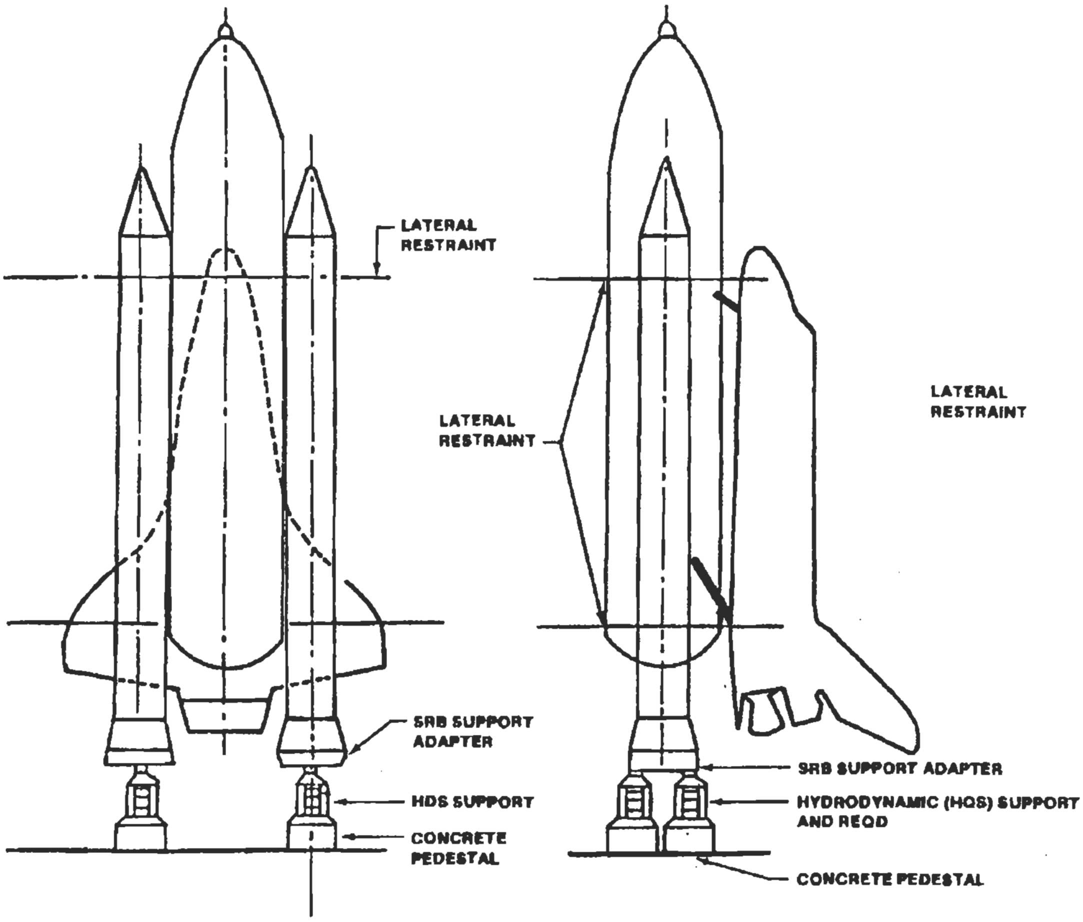

FIGURE 7.- SUSPENSION SYSTEM FOR THE SPACE SHUTTLE (FOUR-BODY CONFIGURATION).

this problem was through adjusting the analysis via the propellant shear stiffness to agree with test data. Fortunately for the users of the structural dynamic models, the structural modes with significant SRB propellant motion had relative high damping and were not significant in the performance of the various user disciplines.

The structural damping data extracted from these tests ranged from a low of about 0.1 percent for the modes with significant fluid motion to more than 10 percent for certain "local" modes. The average modal damping ranged from 1 to 3 percent. The damping data were extremely valuable in the final certification of the flight control stability margins in that measured damping values in the critical flight control modes were higher than the initial baseline of 0.5 percent.

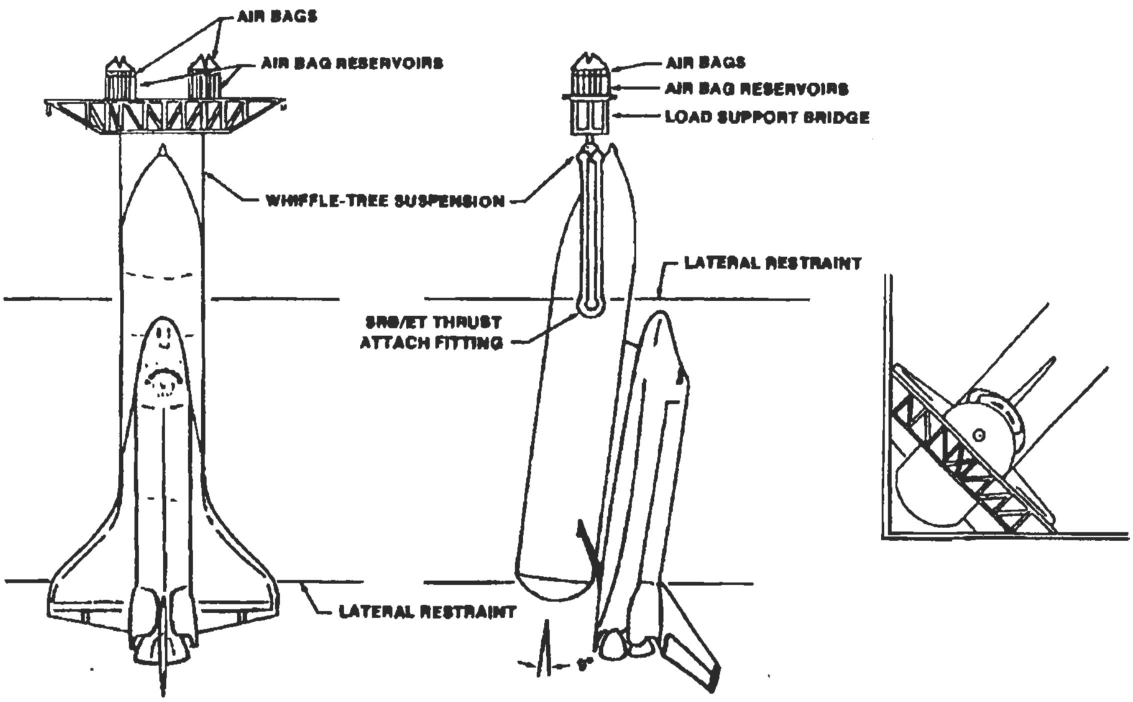

FIGURE 8.- SUSPENSION SYSTEM FOR THE ORBITER/ET CONFIGURATION (TWO-BODY CONFIGURATION).

TABLE 4.- COMPARISON OF TEST AND ANALYSIS FREQUENCIES FOR THE "FREE-FREE" MVGVT LIFT-OFF CONFIGURATION (10^{K} PAYLOAD)

Modal description	Analytical frequency, Hz	Test frequency, Hz	Damping c/cc
SRB roll (antisymmetric)	1.88	2.08	0.01
SRB roll (symmetric)	1.90	2.05	.013
First Orbiter bending (Y-Z plane)	2.97	3.24	.01
First wing bending (Y-Z plane)	6.70	6.43	.037

SUMMARY

The advent of the Space Shuttle presented unique challenges to the structural dynamics analyst in the sense that the analytical models had to be verified to an acceptable accuracy before a manned launch. This objective was accomplished in the Shuttle program by an extensive vibration test analysis program. The three main vibration test programs were HGVT, 1/4-scale model GVT, and the MVGVT. Significant analytical effort was committed to modeling the test configuration. The correlation of these results provided a foundation for model certification.

The structural dynamic model used provided an invaluable input into the certification process by defining the structural dynamic elements and modes that were critical to the discipline analysis. For example, to improve the accuracy of predicting the dynamic response of Orbiter payloads during landing and lift-off, increased fidelity in the modeling of the Orbiter longerons and payload interfaces was required.

Generally, the vibration test and analysis program revealed that the mode shapes and frequency correlations below 10 hertz were good. The quality of correlation of modes between 10 and 20 hertz ranged from good to fair and that of modes above 20 hertz ranged from poor to good. Since the most important modes, based on user preference, were below 10 hertz, it was judged that the Shuttle structural dynamic models were adequate for flight certifications.

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