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VISCOELASTIC PROPELLANT EFFECTS ON SPACE SHUTTLE DYNAMICS

By Frank Bugg
System Dynamics Laboratory

March 1981

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16. ABSTRACT

An extensive program of solid propellant research has been conducted to support the Space Shuttle Dynamics modeling effort. The research is discussed in three parts. The first describes studies performed to define characteristics of the propellant itself, i.e., the stiffness, damping, compressibility, and the effects of many variables on these properties. The second concerns the relationship between the propellant and SRB dynamics, such as effects of propellant stiffness on free-free SRB modes. The third deals with coupled modes of the Shuttle system and the effects of propellant stiffness on SRB/ET interfaces.

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TECHNICAL MEMORANDUM

VISCOELASTIC PROPELLANT EFFECTS ON SPACE SHUTTLE DYNAMICS

INTRODUCTION

The Space Shuttle vehicle consists of an Orbiter with three liquid fueled engines, an external tank (ET) which supplies oxygen and hydrogen to those engines, and two solid fueled booster rockets (SRBs). The configuration of these assembled parts is shown in Figure 1.

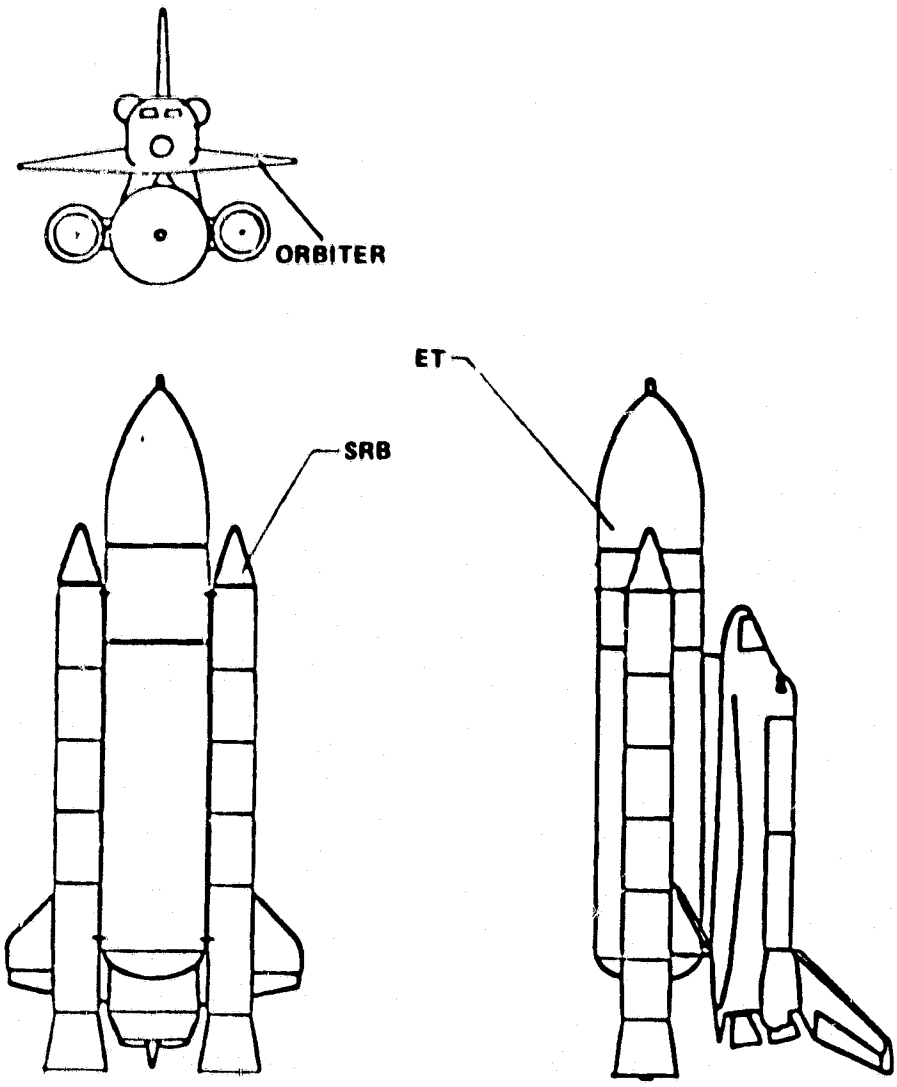

Figure 1. Space Shuttle configuration.

This report describes various research and analysis tasks conducted to define dynamics of the solid propellant and the effects on SRB and Space Shuttle dynamics during liftoff and boost flight conditions. Very little solid rocket propellant dynamics research had been performed prior to Space Shuttle. Solid propellant was used primarily in small, high acceleration, short burn time military rockets; therefore, its dynamics did not affect the flight loads or control. In contrast, the Shuttle SRBs are large (146 in. diameter), long burn time (120 sec) rockets used in a configuration for which the first natural mode is a function of the solid propellant stiffness. Many of the design loads occur at Shuttle liftoff where the lowest frequency vibration mode is a strong participant. Due to the effects of propellant dynamics on Shuttle dynamics, an extensive program of solid propellant research has been conducted to support the Shuttle dynamics modeling effort.

The research is discussed in three parts. The first describes studies performed to define characteristics of the propellant itself, i.e., the stiffness, damping, compressibility, and the effects of many variables on these properties. The second concerns the relationship between the propellant and SRB dynamics, such as effects of propellant stiffness on free-free SRB modes. The third deals with coupled modes of the Shuttle system and the effects of propellant stiffness on SRB/ET interfaces.

PROPELLANT PROPERTIES RESEARCH

The solid propellant is a viscoelastic material and, therefore, has mechanical properties represented as complex numbers. For example, the dynamic shear modulus is:

$$G^* = G' + i\,G'' \quad ,$$

where G' is the storage modulus and G'' is the loss modulus. The ratio G''/G' is called the loss tangent and is a measure of the material damping. Storage modulus, G', is convenient to use in math modeling to represent the propellant elasticity, and for this reason property studies have focused on determining values of this parameter. Solid propellant is nearly incompressible; therefore, its Poisson's ratio is near 0.5 and the dynamic tensile modulus can be expressed as $3G^*$.

Basic propellant dynamic properties research is reported in References 1 through 6. In Reference 1 an attempt was made to discover all variables which affect propellant properties and to determine which of these are significant in the SRB application. Some of the variables known to affect solid propellants in general are:

1) Excitation frequency

2) Humidity

3) Strain

4) Pressure

5) Aging

6) Epoxy/curative ratio

7) Internal heat generation

8) Damage effects

9) Temperature.

Reference 1 found excitation frequency and propellant bulk temperature to have significant effects on propellant stiffness in the Space Shuttle application. Humidity is reported to affect only the propellant exposed surface with little penetration compared to the SRB propellant thickness. Strain, pressure, internal heat generation, and damage effects are not significant, due to the low Shuttle accelerations. At high acceleration, high strains ($\epsilon \geq 10$ percent) occur causing a dewetting of oxidizer particles in the propellant grain and an accompanying decrease in stiffness. Motor combustion pressure tends to press the propellant together if it is in this high strain condition, thus repairing the damage and increasing the stiffness; but at low strain, the propellant is essentially incompressible and unaffected by pressure. If the propellant oscillates at a high strain amplitude, internal heat is generated, raising the bulk temperature and decreasing propellant stiffness. The effect of aging on the SRB propellant was found to be negligible during the first six months after casting. Propellants of the type used in the SRB (Polybutadiene Acrylo-Nitrile, PBAN) normally stiffen by about 25 percent during the first year and remain unchanged thereafter. The epoxy/curative ratio is controlled in the SRB propellant to achieve a target value of tensile modulus and is, therefore, approximately constant.

Reference 2 reports results of tests conducted to measure properties of an inert PBAN propellant used by NASA/Langley Research Center in a 1/8-scale model of the SRBs. The machine used to perform the dynamic tests required very small test specimens (0.06 × 0.06 × 0.12 in.) which were oscillated in shear while bonded between parallel plates. The resulting data show considerable scatter. The propellant consists of relatively rigid particles bound together in a rubber matrix and these small test specimens were apparently not large enough to approximate a homogeneous material. Some observations from this report are:

1) Static strain of 0.5 to 5 percent had no measurable effect on dynamic moduli.

2) Exposure to high relative humidity had a significant but inconsistent (sometimes stiffening, sometimes softening) effect on propellant modulus.

3) The bulk modulus was measured and the material found to be essentially incompressible.

The variation of propellant properties in repeated tests was measured and studied in Reference 3 along with variations between batches. In one series of tests, six batches of live SRB propellant were tested to find dynamic shear modulus through a range of temperature and frequency. Three measurements were made at each condition. The higher the shear modulus, the lower the variation between repeated tests. The average within batch variations for the six batches was 8.1 percent at 90°F, where the propellant is soft, and 3.5 percent at 40°F, where the propellant is very much stiffer. Similarly, the deviation between batches was 7 percent at 90°F and 6 percent at 40°F.

References 4 through 6 report dynamic shear modulus data obtained by the oscillating disk method. A circular disk of propellant (3.5 in. diameter by 0.5 in. thick) was clamped around its circumference and oscillated perpendicular to its surface by a rod bonded into a hole through the center of the disk. Forces and displacement were recorded as a function of time and used with a stress analysis of the disk to compute shear modulus. An example of dynamic shear modulus measured by this technique is shown in Figure 2.

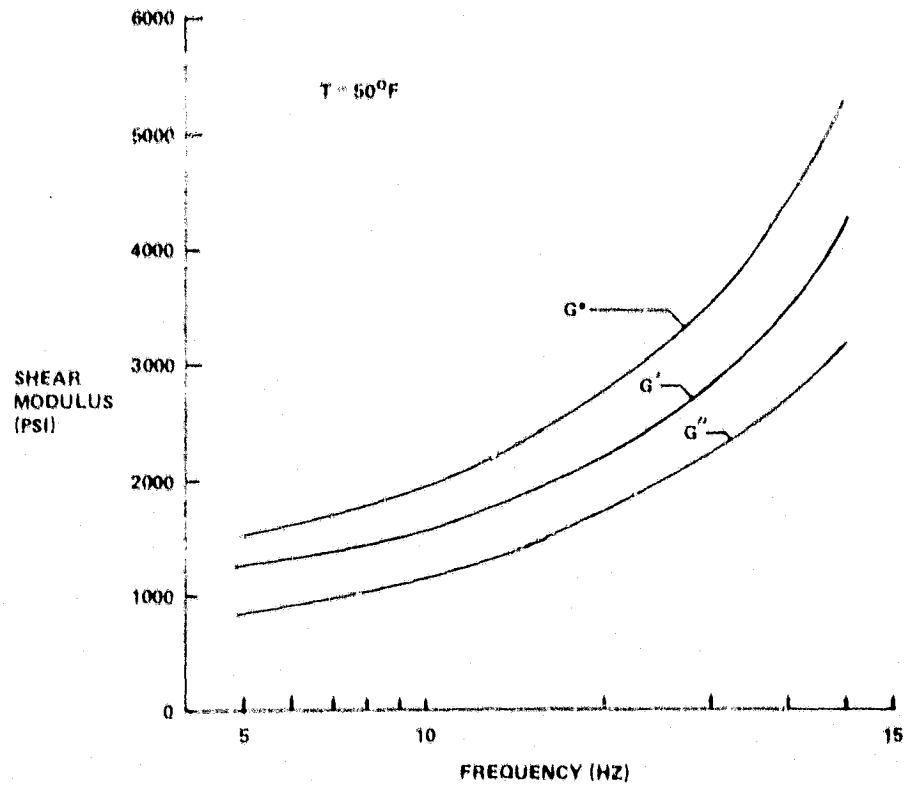

Figure 2. Dynamic shear modulus for TPH 1148 propellant (T = 50°F).

Data obtained by the oscillating disk method were used in the analysis of SRB and Shuttle System vibration modes.

Reference 7 reports a study of propellant properties which includes contributions of several factors to the propellant shear modulus. The abstract from this report is given below.

"This report presents an analytical technique for implementing simultaneously the temperature, dynamic strain, real modulus, and frequency properties of solid propellant in an unsymmetrical vibrating ring mode. All dynamic parameters and sources are defined for a free vibrating ring-grain structure with initial displacement and related to a forced vibrating system to determine the change in real modulus. Propellant test data application is discussed.

The technique was developed to determine the aft attach ring stiffness of the Shuttle booster at lift-off."

PROPELLANT/SOLID ROCKET BOOSTER INTERACTION

The SRB configuration is shown in Figure 3. The rocket motor is assembled from four preloaded casting segments. The assembled motor has gaps between the propellant segments which are filled with inhibitor to prevent end burning.

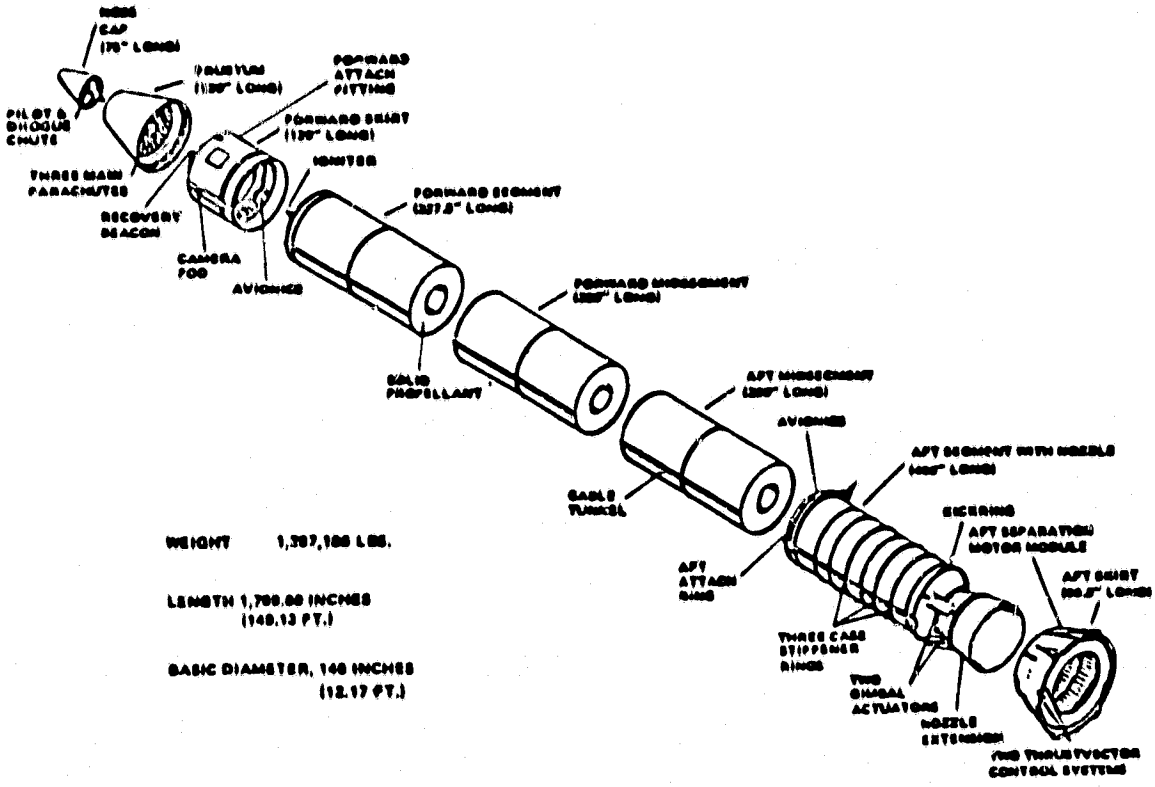

Figure 3. SRB configuration.

Structural vibration modes with forces in the longitudinal direction can couple with combustion and thrust by way of fuel pressure oscillations in tanks or feedlines for liquid fueled rockets. This coupling can produce an instability called pogo. Accurate definition of significant Space Shuttle longitudinal modes is important for avoidance of pogo involving the liquid fueled main engines.

References 8 and 9 report results of SRB vibration analyses which utilized the NASTRAN structural analysis computer program. Both normal mode analyses and complex eigenvalue analyses were completed for longitudinal modes. The damped frequencies were less than 1 percent different from the undamped. Modal damping was 12.8 percent of critical for the first mode (frequency = 15.17 Hz) and was 20 to 24 percent for other modes computed up to 20 Hz. The undeformed model and first mode shape are shown in Figure 4. The elements used to form the propellant were axisymmetric rings. The four SRB casting segments were modeled separately and the first mode, shown at right in Figure 4, involves motion of the two lower segments out of phase with the upper segments.

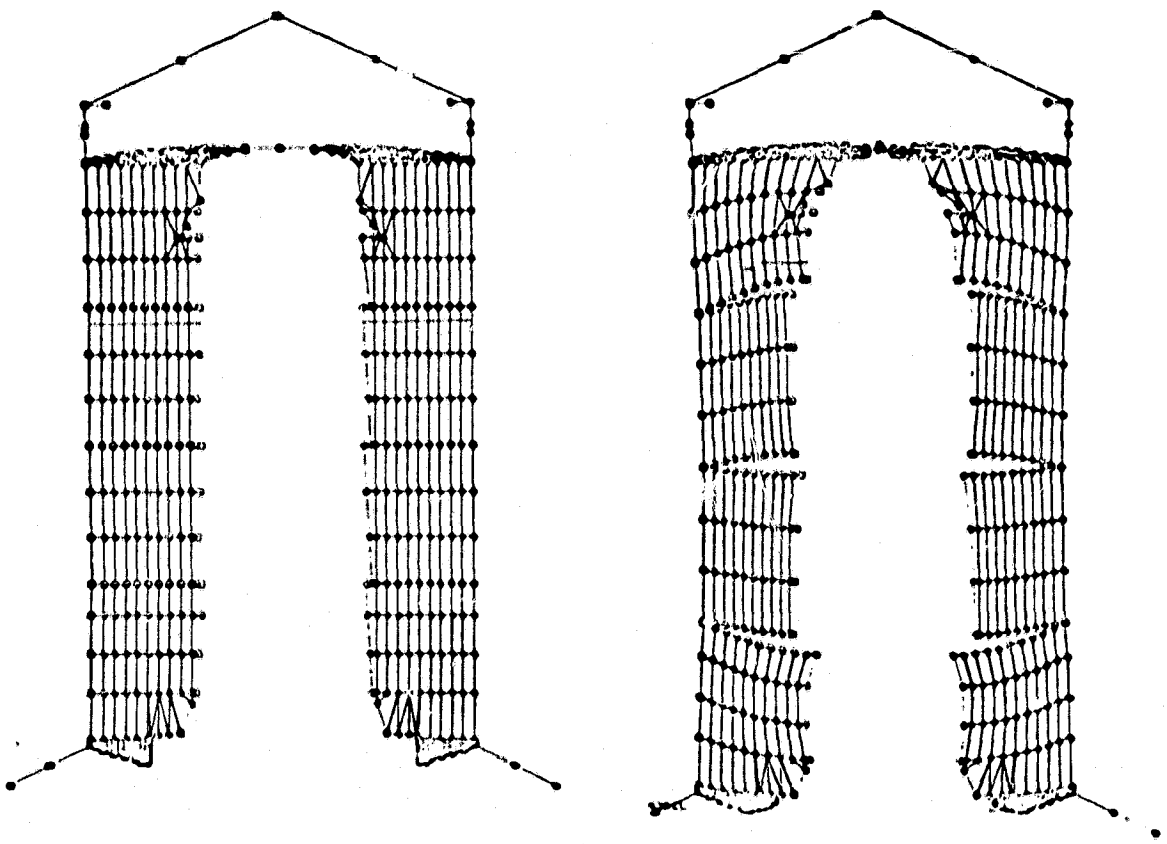

Figure 4. Reference (8) NASTRAN model.

The first representation of longitudinal propellant modes in a model for Shuttle system analysis is reported in Reference 10. Again the NASTRAN program was used to find axisymmetric propellant modes. Three of the modes are shown in Figure 5 for the forward SRB casting segment.

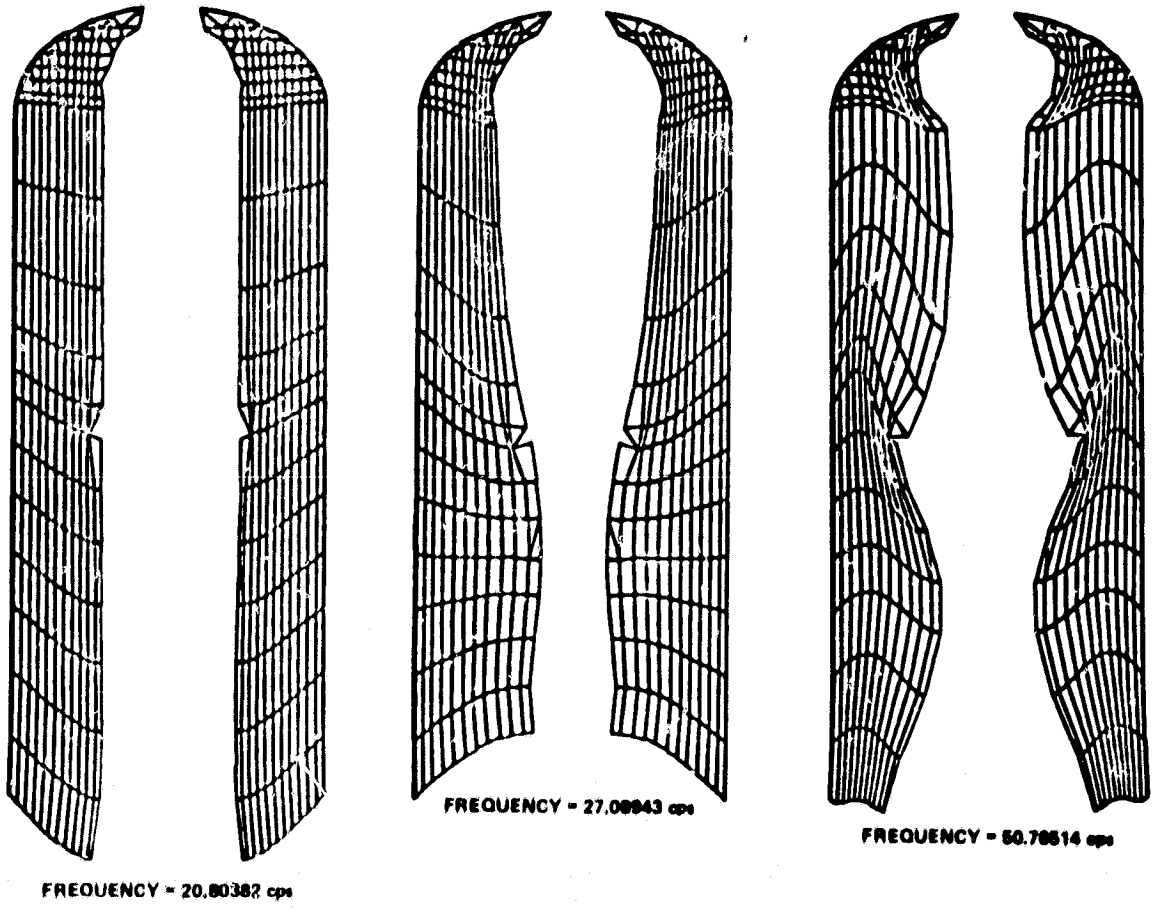

Figure 5. Reference (10) NASTRAN model.

For each casting segment the two modes with greatest mass participation in the longitudinal direction were added to an existing structural SRB model in the form of one spring and one mass per mode. A schematic of this "stick" model SRB shown in Figure 6. Two propellant masses are attached to the model at each of the four locations marked "propellant." This model was used in early Space Shuttle system loads, controls, and pogo studies.

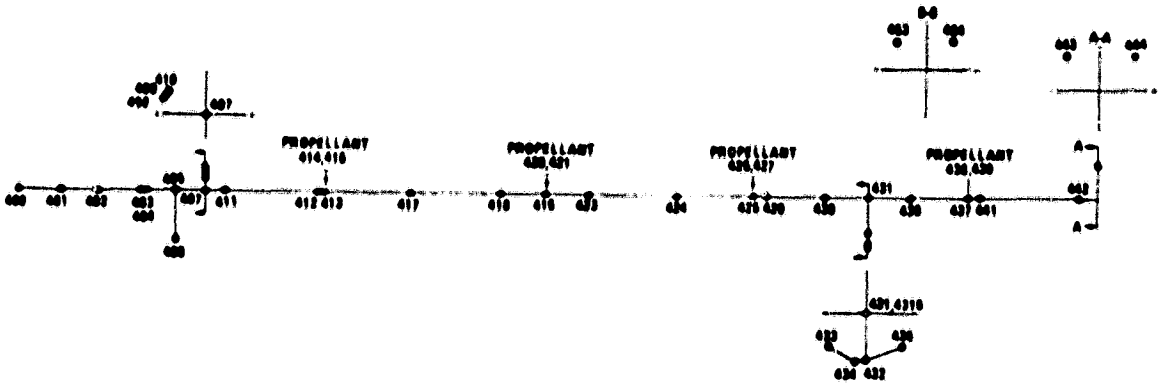

Figure 6. SRB stick model.

Vibration tests were conducted using a one-quarter scale Shuttle model as described in Reference 11. Various configurations were tested including the quarter-scale SRB (QSSRB) in free-free support condition. A comparison of free-free experimental and analytical modes is shown in Table 1. The analysis used the SRB stick model with spring/mass longitudinal propellant representation.

A significant test finding relevant to propellant dynamics was the absence of modes involving propellant motion relative to the case. For example, in the first axial mode, propellant moved with the case (no apparent shearing of propellant). The propellant modes are suppressed by the high damping, such that mass loading of propellant on the case structure was found to give the best analytical representation of longitudinal modes.

PROPELLANT EFFECTS ON SRB/SYSTEM INTERFACE STIFFNESS

The SRBs are attached to the ET through a ball joint at the SRB forward skirt and by a truss system near the aft end of the SRB motor case. SRB thrust is transmitted through the forward ET/SRB attachment (putting the ball joint in compression) to lift the Shuttle. The three strut truss arrangement at the aft attachment carries no thrust load (x-direction) but constrains Y, Z, and roll motion of the SRB relative to the ET. The three struts and the SRB attach ring are shown in Figure 7. Propellant stiffness contributes significantly to the roll stiffness of this aft interface; thus, system modes involving SRB roll relative to the ET are affected by propellant stiffness.

TABLE 1. FREE-FREE MODES OF LIFTOFF QSSRB

Mode Description	Experimental Frequency (Hz)	Pretest Analytical Frequency (Hz)	Pretest Δ Frequency (%)
First Z Bending	17.53	18.10	3.25
First Y Bending	17.46	18.11	3.72
Second Z Bending	42.98	43.37	0.91
Second Y Bending	43.44	43.42	0.05
First Torsion	56.36	60.74	7.77
First Axial	66.05	59.75	9.54
Third Y Bending	72.21	72.90	0.96
Third Z Bending	72.92	72.66	0.47
Fourth Z Bending	97.26	93.17	0.94
Fourth Y Bending	98.36	98.73	0.38
Second Torsion	107.14	118.04	16.2
Fifth Z Bending	122.74	120.78	1.60
Fifth Y Bending	127.12	121.12	4.72
Third Torsion	192.30	172.88	10.1

The QESRB tests described in Reference 11 included tests with the QSSRB constrained to ground at its forward and aft ET attach points. Modes excited in this constraint system are related to some of the symmetric Shuttle system modes which feature hi(SRB participation. Results from these tests were used with the stick SRB model to develop an empirical model including aft attachment stiffness. A description of the math model and constrained SRB test are given in Reference 12.

The empirical model mode shapes and frequencies are compared with the first three test modes in Figure 8. The first mode shown corresponds to the system SRB roll mode (the lowest system mode) and the math model was tuned to match this mode in frequency and shape. Fortunately, it also matches very closely the second mode, but correlation is poor for the third and higher modes.

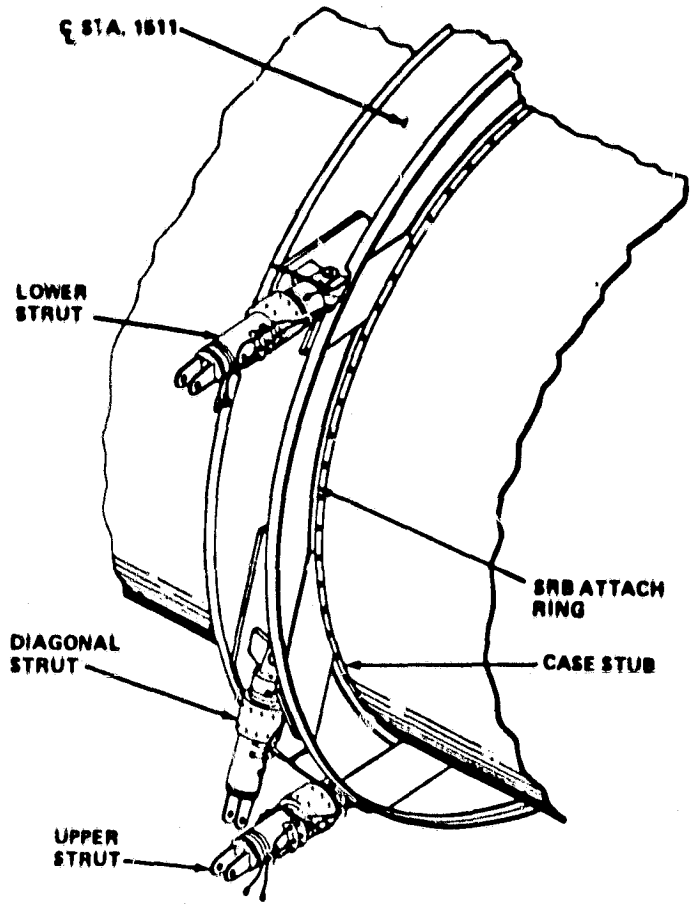

Figure 7. SRB aft attachment structure.

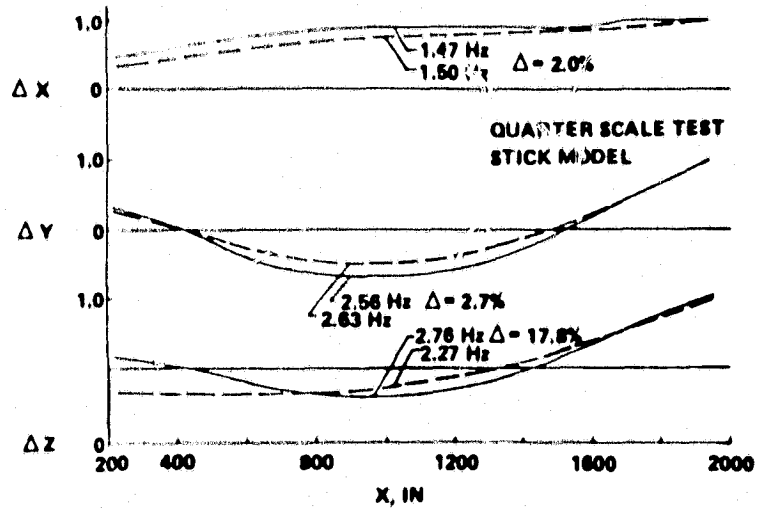

Figure 8. Empirical stick model and test correlation (constrained test).

A shell model of the SRB was developed primarily to give accurate aft SRB/ET interface stiffness and eliminate the need for empiricism. This model is described in Reference 13. Figure 9 shows a computer plot of representative shell model parts, and shows a schematic of the reduced model.

The model was developed using the NASTRAN computer program. Quadrilateral and triangular plate elements form the forward skirt, motor case, and aft skirt, with bar elements used to represent case stiffeners, stringers, and the added thickness at case joints. Propellant is modeled by quadrilateral plate elements oriented such that plate shear stiffness represents the propellant shear stiffness and plate mass is the propellant mass.

The basic liftoff model contains 2480 grid points of which 1448 are in the propellant. There are 8932 degrees of freedom. The burnout model has 1032 grid points and 6042 degrees of freedom. Both liftoff and burnout models were reduced to 53 grid points retaining 234 degrees of freedom by means of the Guyan reduction technique internal to the NASTRAN computer program. Proper location and distribution of the retained degrees of freedom was critical for maintaining accuracy in the modes of interest. The best results were obtained by keeping four circumferential grid points at approximately ten longitudinal stations and giving each of these freedom in three translations and rotation about X (the longitudinal axis).

Comparison of QSSRB test data and shell model modes and frequencies (Fig. 10) shows excellent correlation with all test frequencies and with six of the seven mode shapes (the seventh test mode appears unlikely and may be the result of bad accelerometer data near the SRB nose).

A modal test of the complete, full scale Shuttle was performed to evaluate the total system math model. This test, the mated Vertical Ground Vibration Test (MVGVT), was conducted in the free-free test condition and is described in Reference 14. A total of approximately 80 modes were documented for the liftoff and SRB burnout configurations. Pretest Shuttle system math models showed an average of 6.83 percent error in frequency (average for all liftoff modes and all burnout modes). A post-test system model was generated using improved element models (Orbiter, ET, SRB, and the average frequency error was reduced to 5.75 percent). The SRB model improvement pre- to post-test consisted of replacing the SRB empirical stick model with the shell model in the Shuttle system analysis.

Table 2 compares pretest and post-test analytical results with test data for some liftoff modes which contained a large fraction of total energy in the SRBs (the energy fractions are shown in parentheses). Good correlation was observed with pretest and post-test models for these SRB dominated modes, with post-test showing the better correlation.

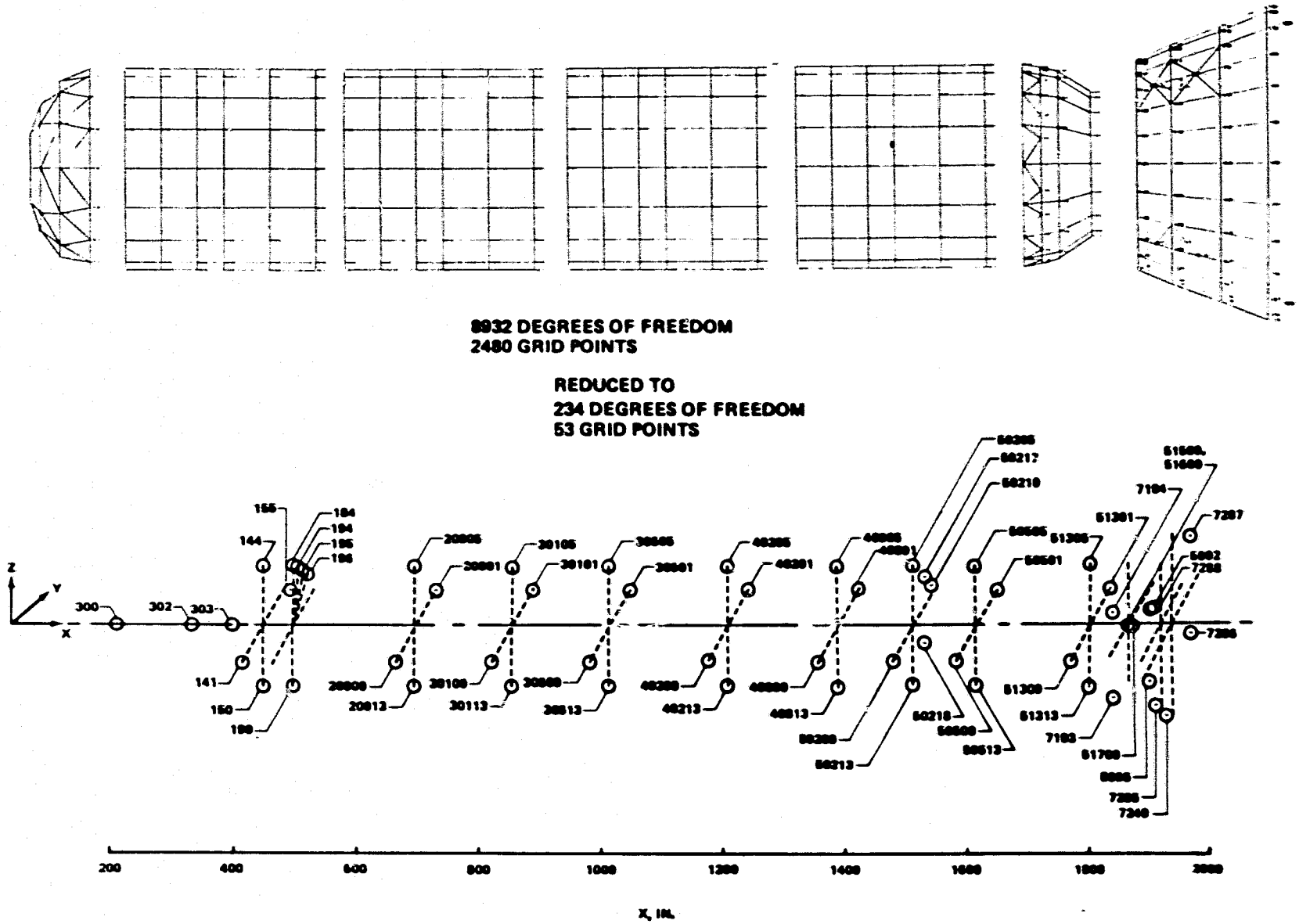

Figure 9. Shell model.

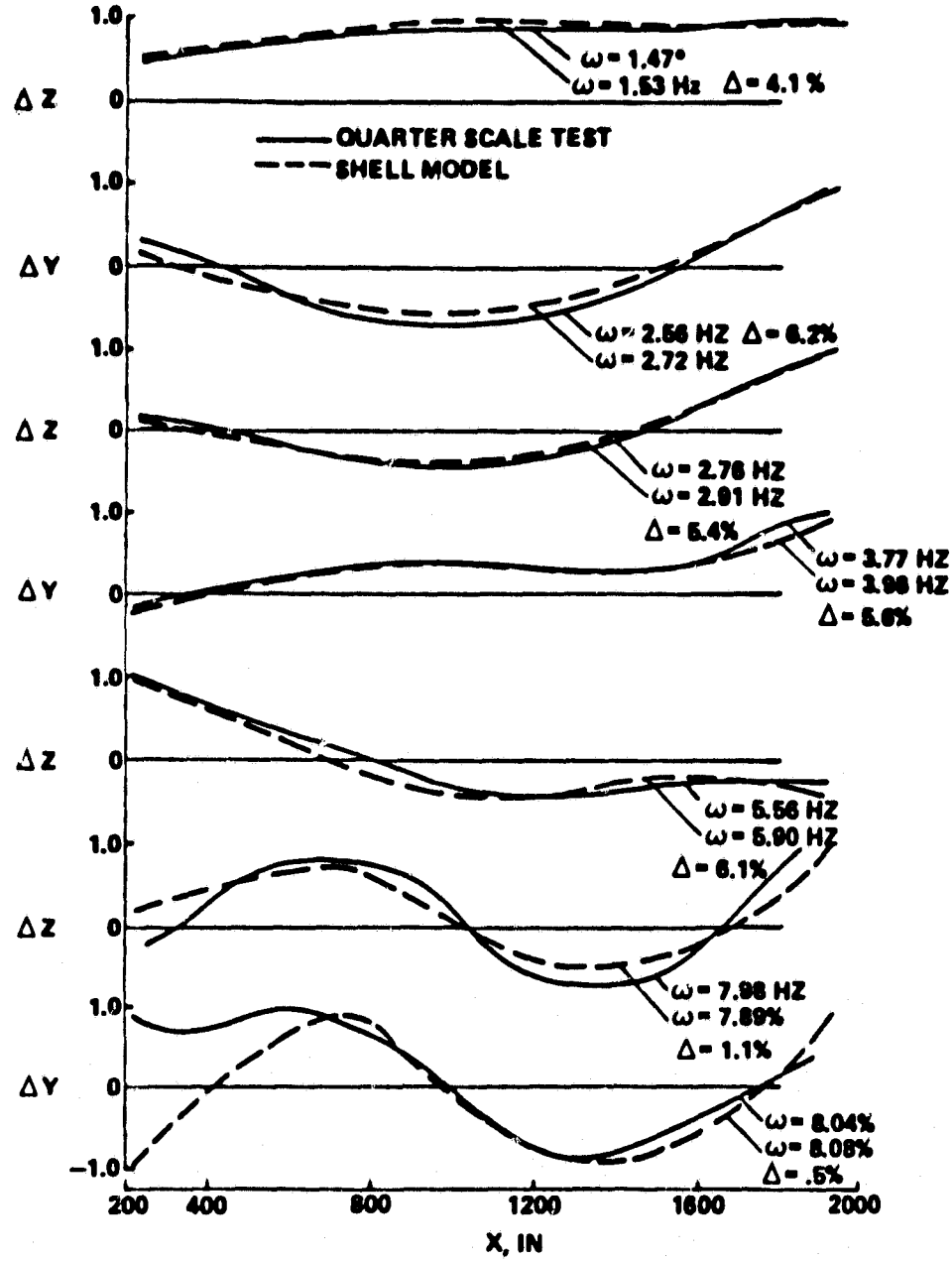

Figure 10. Shell model test correlation (liftoff SRB constrained modes).

TABLE 2. MVGVT/ANALYSIS CORRELATION (LIFTOFF ANTI-SYMMETRIC)

Test Mode			Pretest			Post Test		
No.	Freq., (Hz)	Description	No.	Freq., (Hz)	Error, (%)	No.	Freq., (Hz)	Error, (%)
10	2.08	SRB Yaw and Y-Bending (0.63)	4	2.20	5.8	1	2.19	5.3
8	2.24	SRB Pitch (0.33), Roll (0.18)	5	2.31	3.1	2	2.25	0.4
11	2.47	SRB Pitch (0.60), Roll (0.13)	6	2.73	10.5	3	2.44	1.2
15	3.37	SRB X (0.35)	7	3.61	7.1	4	3.44	2.1
5	4.12	SRB Roll (0.20)	9	3.86	6.3	6	4.17	1.2
21	4.71	SRB Roll (0.27), Pitch (0.12)	11	4.88	3.6	7	5.09	8.1
20	5.14	SRB Y-Bending (0.59)	12	5.42	5.4	8	5.28	2.7
1	5.45	SRB Z-Bending (0.43)	14	5.55	1.8	7	5.09	6.6
2	10.10	SRB 2nd Z-Bending (0.60)	32	10.63	5.2	24	10.68	5.7
19	10.65	SRB 2nd Y-Bending (0.61)	35	11.24	5.5	26	11.23	5.4
17	14.56	Gear Train, SRB Torsion (0.36)	47	14.20	2.5	30	14.13	3.0
12	14.72	Gear Train, SRB Torsion (0.59)	47	14.20	3.5	30	14.13	4.0
3	16.85	SRB 3rd Z-Bending (0.65)	64	16.69	0.9	38	16.25	3.6
14	18.90	SRB Axial (0.78)	87	20.75	9.8	52	19.36	2.4
7	23.84	SRB 4th Z-Bending (0.65)	112	24.89	4.4	70	23.53	1.3
30	24.81	SRB 4th Y-Bending (0.63)	123	26.35	6.2	73	24.68	0.5
		Ave. Error for SRB Modes			5.1			3.3

CONCLUSIONS

The SRB propellant stiffness was found to be a strong function of propellant bulk temperature and excitation frequency. Many other parameters were investigated and found to have negligible effect for the Space Shuttle application.

Coupling between propellant and SRB structure dynamics was studied by analysis and test. Analysis showed propellant longitudinal modes in the frequency range of structure modes. Tests demonstrated that the high propellant damping (not included in analysis) suppressed the propellant modes, such that the propellant moved with the motor case. The most accurate propellant representation for free-free SRB modes was, therefore, mass loading of the structure with propellant.

Propellant stiffness is an important part of the total SRB/Shuttle System interface stiffness. A finite element shell model of the SRB was developed which accurately represents the SRB portion of this interface. The shell model was verified by quarter-scale and full-scale testing and is being used in Shuttle System loads and control studies.

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APPROVAL

VISCOELASTIC PROPELLANT EFFECTS ON SPACE SHUTTLE DYNAMICS

By Frank Bugg

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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