NASA TECHNICAL MEMORANDUM

NASA TM-78287

ET LOX MODAL SURVEY ANALYSIS AND TEST ASSESSMENT

By R. L. McComas
Systems Dynamics Laboratory

May 1980

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

TABLE OF CONTENTS

PRECEDING PAGE BLANK NOT FILMED

LIST OF ILLUSTRATIONS

LIST OF TABLES

TECHNICAL MEMORANDUM

ET LOX MODAL SURVEY ANALYSIS AND TEST ASSESSMENT

I. INTRODUCTION

The requirement that no "pogo" effects would be present during flight of the Space Shuttle made it mandatory that accurate dynamic models be available for analysis. To accomplish this task, a new methodology (asymmetric hydroelastic analysis) would be necessary. The Martin Marietta Corporation (MMC) developed a three-dimensional finite element hydroelastic capability to perform the dynamic analysis. The Marshall Space Flight Center (MSFC) set forth requirements and performed a liquid oxygen (LO_2) modal survey for the LOX portion of the External Tank to verify the math model and to determine what, if any, anomalies might be present in the structure.

The test article consisted of a full-scale LO_2 tank and flight intertank mated to a stiff support test ring fixture. The test article was supported in a soft spring mode by 33 airbags arranged into three groups (Fig. 1).

The test conditions were selected to be representative of the flight environment. Four conditions were selected to represent liftoff, Solid Rocket Booster (SRB) separation, midrange flight, and end burn. Since the thrust angle of the Space Shuttle is maintained through the c.g., a canted angle of 13° was selected for the last three test conditions. Additional test conditions were added as the test progressed to obtain a better understanding of the low damping observed in the test results of the second bulge mode.

The LO_2 modal survey began in February 1978 and was completed in July 1978. The pretest analysis of the test article and test support structure proved to be an excellent representation of the test results of the tank and simulated propellant (H_2O). Minor changes were required in the SRB cross beam model to match the test data.

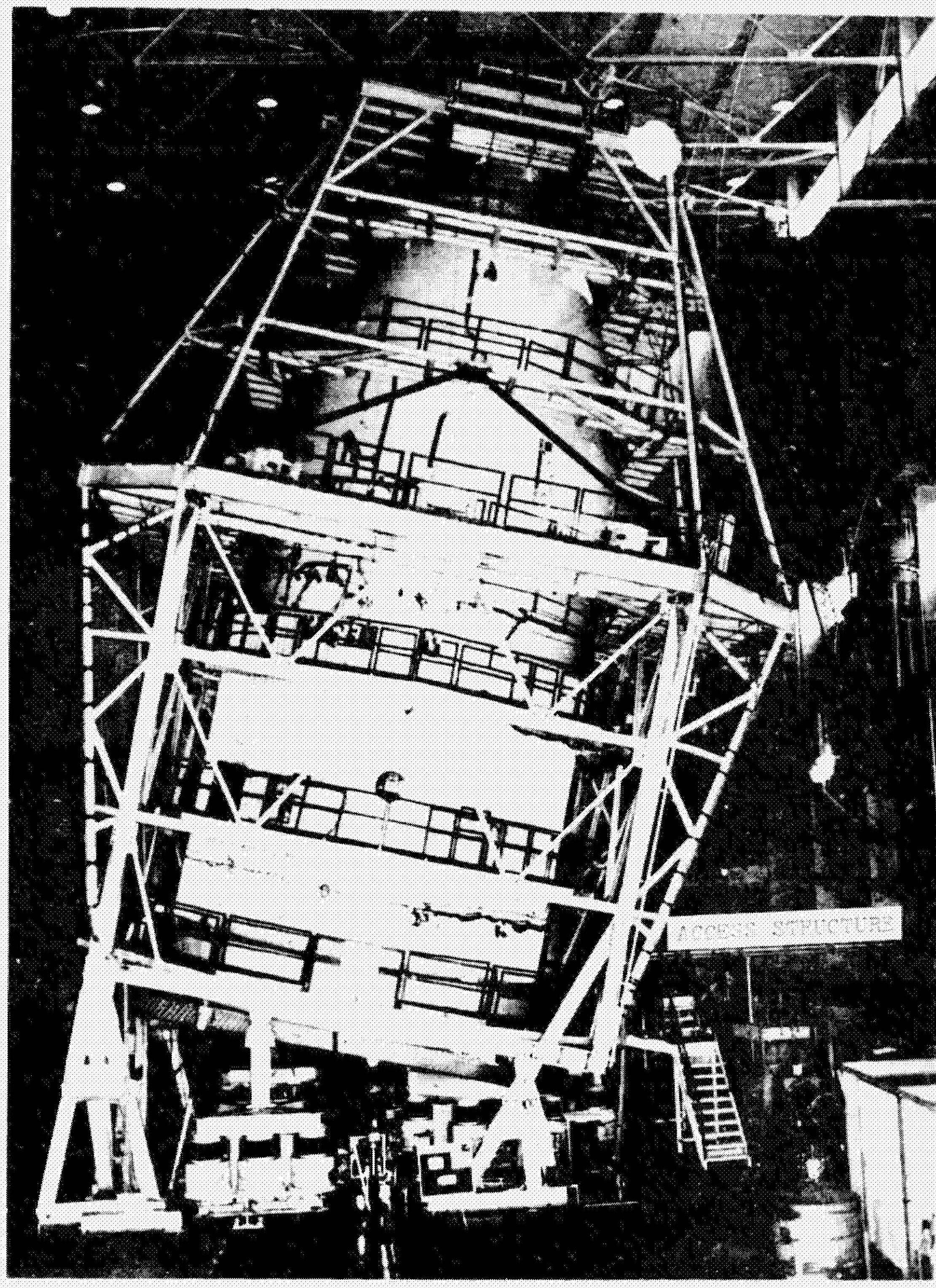

Figure 1. LO_2 modal test setup (cant angle 13°).

II. MATH MODEL

A. Modeling Overview

The selection of a test article and support system was followed by a mathematical modeling exercise to exactly duplicate the structure and test supporting equipment. These models will determine the final frequencies, mode shapes, and dynamic pressure.

A new analysis technique was developed by Martin-Marietta Company (MMC) who was responsible for the analysis and model/test data correlation. This analysis, an asymmetric finite element hydroelastic capability, was formulated by using the standard structural finite elements and a potential function approach with assumed incompressibility for the fluid.

A backup for this modeling capability was undertaken by the Systems Dynamics Laboratory at MSFC to assure modeling success. A hydroelastic asymmetric analysis capability was developed for the MSFC version of NASTRAN$^{(R)}$. This capability is available to NASTRAN users through the COSMIC Library at the University of Georgia.

B. Structural Model

A convenient plane of symmetry of the test article and support hardware allowed one-half of the test article to be modeled. The nodes (grid points or collocation points) are at the intersections of 13 longitudinal and 29 transverse planes. The longitudinal planes are 15° apart, Figure 2. The transverse planes were established by structural features such as weld lands, reinforcing rings, structural interfaces, etc. Additional nodes were incorporated where necessary to model the SRB cross beam, test support ring, and suspension system.

1. <u>Liquid Oxygen Tank (LO_2 Tank)</u>. The LO_2 tank is a three-part monocoque aluminum structure (Fig. 3) consisting of a half oblate spheriod lower dome, a cylindrical mid-section and a forward ogive section. A Y-shaped (Y) ring connects the cylinder/lower dome, supports the slosh baffles, and is the bolt ring interface for the LO_2 tank to the intertank. A second ring, T ring, stiffens the tank, supports the slosh baffles, and forms the interface where the ogive is welded to the cylinder. A line of nodes was located at the T ring and Y ring. The location of the other node lines (transverse cuts) was determined by consideration of the aspect ratio of the plate elements representing the tank skin.

The slosh baffles were constructed as a substructure with 208 nodes; 104 were synchronous with the nodes on 8 of the LO_2 tank shell

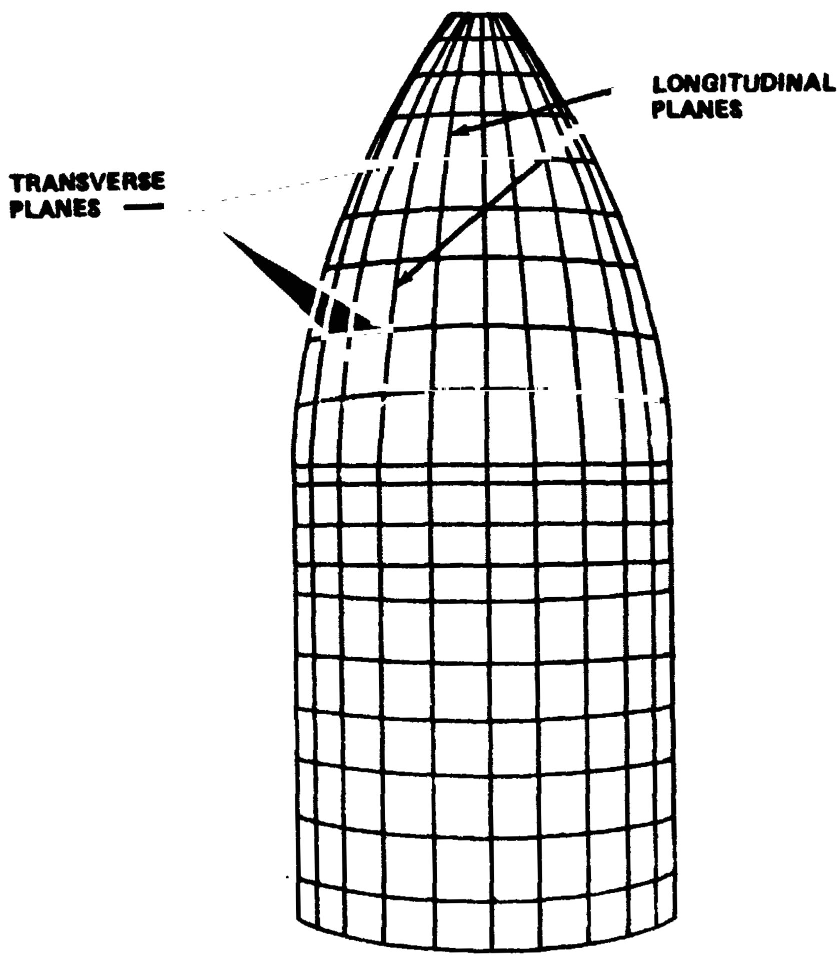

Figure 2. Pictorial of model grid.

transverse planes and 104 were unique nodes inside the tank on the same transverse planes. The slosh baffle structure was modeled using bar and plate elements.

2. Intertank. The intertank is a semi-monocoque cylindrical structure with flanges on each end and has a large box beam assembly (SRB beam) running transversely through the intertank (Fig. 3).

The intertank and SRB beam were modeled as separate substructures which were subsequently assembled. A remodeling of the SRB beam was necessary after test data demonstrated that the SRB beam modes were incorrectly predicted. The final model differed only in the representation of the cross section of the beam at the tank plane-of-symmetry which forms the half model boundary.

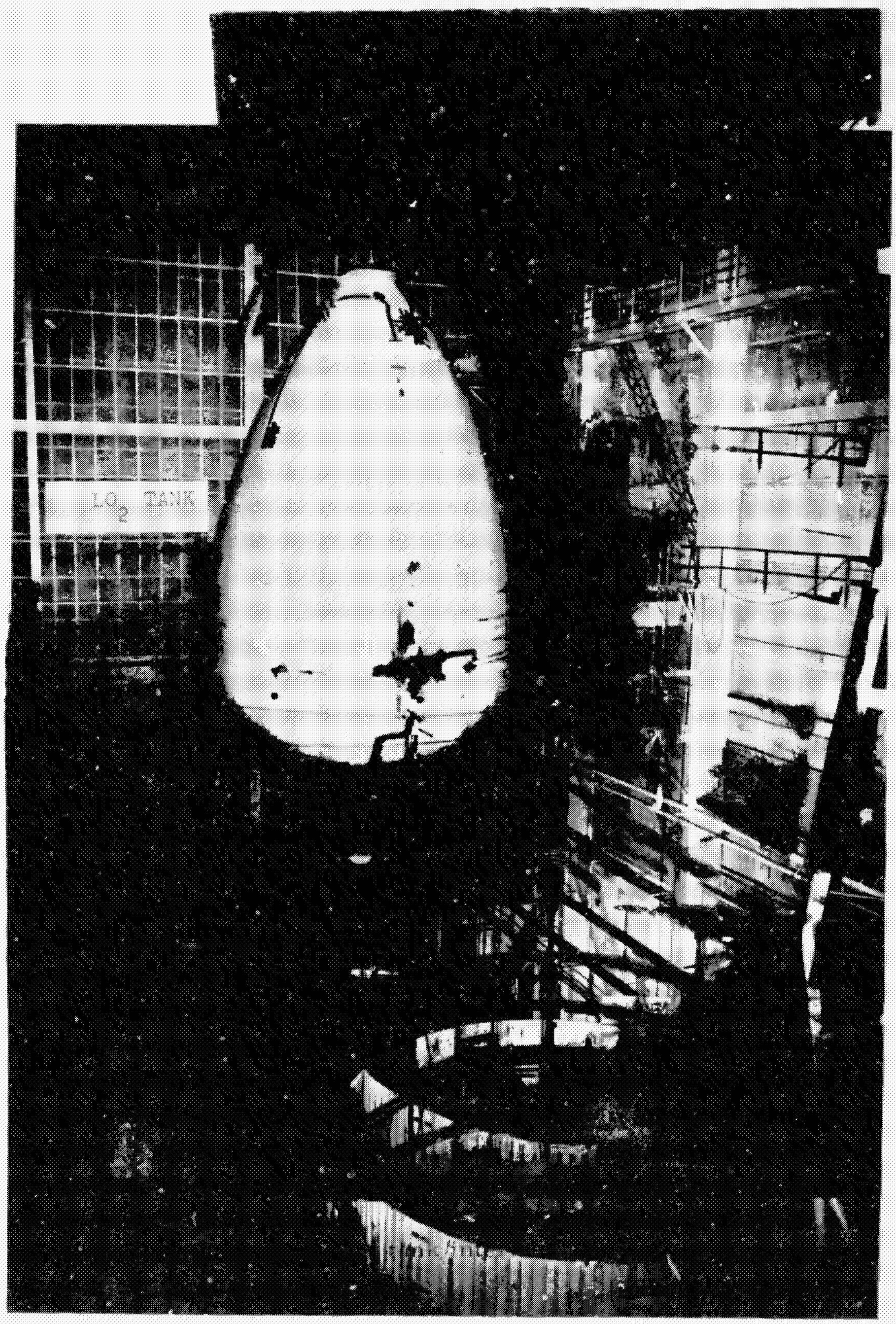

Figure 3. LO_2 tank/intertank test article.

The elements used were plate elements for the skin and beam elements for flanges, longerons, and circumferential frames. Smearing techniques (grouping of stringers or ribs into a single finite element) were used to reduce the model size.

The intertank nodal geometry was similar to the LO_2 tank nodal geometry with grid points at the intersection of the 13 longitudinal planes with 6 transverse planes which represented the frames and flange rings.

3. Support Ring. The support ring is a circular box beam designed to be rigid compared to the LO_2 tank/intertank assembly and to simulate the mass of an empty liquid hydrogen (LH_2) tank. It mates with and attaches to the intertank flange ring provided for attachment to the LH_2 tank. It was modeled as a substructure represented by 12 prismatic beam elements.

4. Airbag Suspension System. The suspension system consists of three clusters of airbags. One cluster spans the analysis plane of symmetry. The other two clusters are located at equal angular intervals from it. The suspension system was modeled as a substructure of eight nodes and six axial elements. Two of the nodes coincided with nodes common to the intertank and support ring. The axial elements were sized to provide stiffness characteristics of the airbag cluster. Those elements representing the airbag cluster which spanned the analysis plane-of-symmetry were halved to conform to the half-model consistently used. Since the number of airbags pressurized and contributing to the system support varied with the test configuration, a separate model was made for each configuration analyzed.

5. Fluid Model. The fluid models were generated using a potential function approach with incompressibility being assumed. The method utilizes a surface grid. The tank wall nodes were defined to be synchronous with the structural model. In addition to these nodes a set of nodes was necessary to represent the liquid free surface. The surface was divided into elements bounded by the 13 longitudinal planes and 3 concentric circles; the outermost circle is coincident with the tank wall. Two fluid models were necessary for each of the test configurations, one with symmetric boundary conditions applied and one with asymmetric boundary conditions applied.

III. TEST CONFIGURATION ANALYSES

Model solutions of the structural and fluid model of the test configuration were obtained from a MMC computer program, FORMA. The final solution degree-of-freedom set was obtained by a sequence of operations involving reduction, overlays, reduction and deletion.

This resulted in two half modal models of the LO_2 tank/intertank/ring assembly supported on soft springs for each of the original four test conditions and the eight supplementary test conditions added during the testing. All of the modes up to 50 Hz were obtained. The resulting modal deflections and dynamic pressures were determined at the locations where test data sensors would be located.

Hard copy plots of the resulting mode shapes were then made using an identical format as the test data plots.

IV. TEST DATA

A. Data Acquisition

The test configurations investigated during the test program are described in Table 1. Wide band sine sweeps were made over the range of interest (3 to 50 Hz) and co-quad plots were made. Discrete frequencies and mode forms were identified from these plots. The MMC data evaluation team then chose those modes which they considered to be prime pogo oriented modes. The frequency of each significant mode was tuned until an acceptable force-response/phase relation was achieved. Modal dwells and decay functions representative of the modes were then recorded on magnetic tape and on an on-line computer data storage unit.

TABLE 1. LO_2 TANK TEST CONFIGURATIONS

Configuration No.	Liquid Level (in.)	Cant Angle (deg)	Ullage Pressure (psi)
1	487.0	0	3.3
2	320.7	13	3.3
3	162.0	13	3.3
4	58.0	13	3.3
5	320.7	0	3.3
6	320.7	0	1.6
7	320.7	0	8.0
8	320.7	4	3.3
9	384.5	0	3.3
10	384.5	0	8.0
11	218.0	0	3.3
12	162.0	0	3.3

Modal dwell data were processed by the MSFC Computation Laboratory into a tabular listing of the acceleration and phase response of each instrument and normalized mode shape plots of the test article for the longitudinal and lateral planes.

Modal decay data from selected instrumentation were processed by the MSFC test team into decay plots.

Dynamic pressure responses in the LO_2 tank aft dome were also recorded for well defined modes. These data were normalized to a local acceleration response and incorporated into the modal dwell tabular listing.

Tables 2 through 5 present a summary of the test modal frequencies, their description and the percentage of critical damping for test configurations 1 through 4.

Table 6 presents a summary of the dynamic pressure response of the LO_2 tank aft dome for test configurations 1 through 4.

Table 7 presents a summary of the modal properties for test configurations 5 through 12. These are the supplementary tests that were performed to study the effect that fluid level, cant angle, and/or ullage pressure combinations would impose on lightly damped modes.

Table 8 presents a summary of the modal frequencies and damping variations due to cant angle/fluid level/ullage pressure changes on the first three symmetric bending and bulge modes for test configurations 1 through 12.

B. Data Evaluation

A preliminary list of target modes, for which modal dwell and decay data were obtained, was compiled from pretest assessment of the analytical data for configurations 1 through 5.

These data were reviewed by the MMC data evaluation team for validation of its modal character and acceptance. The primary criterion for its acceptance was the phase relation between the instruments and the primary force input. The tolerance established for phase deviation, the differential between the measured and theoretical phases, was 10° for all modes having high acceleration response. The secondary criterion was for high quality decay functions, a basic modal frequency absent of any harmonic modulation. The Fourier analysis method designed into the instrumentation computer system was employed as an aid to define any low response or potentially coupled modes.

Tables 9 through 14 and Figures 4, 5, and 6 present summaries of the analytical and experimental data resulting from this program. Configuration 5 (Table 13) was introduced into the program as part of a supplementary test program required by information acquired in the test of configuration 1. An analysis of the symmetric half-case was performed for this configuration concurrent with the testing and provided additional test/analysis correlation data.

TABLE 2. TARGET MODE SUMMARY FOR
TEST CONFIGURATION 1

Test Modes			
TSS No.	Frequency (Hz)	Damping (%)	Description
009	4.90	1.6	SYM Shell, M=1, N=2
018	4.88	1.6	SYM Shell, M=1, N=2
021	9.04	1.2	SYM First Pitch Bending
025	5.72	2.5	SYM First Bulge
028	9.48	.72	ASM First Yaw Bending
036	12.76	.13	SYM Second Bulge
069	18.95	.20	SYM Third Bulge
044	21.26	.10	SYM Fourth Pitch Bending
045	19.29	.18	SYM Third Pitch Bending
048	16.63	.28	ASM Third Yaw Bending
050	21.55	.12	ASM Fifth Yaw Bending
054	23.83	1.5	SRB Beam, Z Bending
056	45.41	1.0	SRB Beam, X Bending
058	9.18	.32	SYM Shell, M=2, N=3
059	16.54	.32	SYM Dome Bending, Ogive Shell
060	14.08	.17	SYM Second Pitch Bending
063	25.75	.43	SYM Dome Bulge, Ogive Shell
064	19.68	.51	ASM Fourth Yaw Bending
066	13.81	.58	ASM Second Yaw Bending
070	9.75	.19	SYM Shell, M=1, N=7

TABLE 3. TARGET MODE SUMMARY FOR
TEST CONFIGURATION 2

Test Modes			
TSS No.	Frequency (Hz)	Damping (%)	Description
091	6.64	.60	SYM Shell, M=1, N=2
092	11.97	.66	SYM First Bulge
097	13.02	.44	SYM First Pitch Bending
098	20.72	.27	SYM Third Pitch Bending
099	6.54	.51	ASM Shell, M=1, N=2
105	12.48	.70	ASM First Yaw Bending
106	19.82	.76	ASM Second Yaw Bending
111	19.76	.33	SYM Second Pitch Bending
114	14.14	1.2	SYM Second Bulge
125	8.31	.70	SYM Shell, M=1, N=3
126	9.04	1.4	SYM Shell, M=1, N=4
127	9.99	.70	SYM Shell, M=1, N=5
128	10.66	1.3	SYM Shell, M=1, N=6
129	13.97	1.4	SYM Dome Bulge, Ogive Shell

TABLE 4. TARGET MODE SUMMARY OF TEST CONFIGURATION 3

Test Modes			
TSS No.	Frequency (Hz)	Damping (%)	Description
149	13.35	.60	SYM Dome Bulge
150	13.47	.62	SYM Second Bulge
154	20.04	.50	SYM Second Pitch Bending
155	14.91	.90	ASM First Yaw Bending
156	22.56	.46	SYM Distorted Dome Bulge, Ogive Bending
158	16.54	.60	ASM Second Yaw Bending
159	19.36	.90	ASM Third Yaw Bending
160	25.37	.57	SYM Dome Shell, Ogive Bending
168	13.31	.50	SYM Shell, M=1, N=2

TABLE 5. TARGET MODE SUMMARY OF TEST CONFIGURATION 4

Test Modes			
TSS No.	Frequency (Hz)	Damping (%)	Description
078	15.67	.23	SYM Second Bulge
079	18.53	.18	SYM First Pitch Bending
081	25.59	.12	SYM Shell and Pitch Bending
082	21.56	.44	ASM Second Yaw Bending
085	18.58	.41	ASM First Yaw Bending
087	21.12	.11	SYM Second Pitch Bending

TABLE 6. DYNAMIC PRESSURE SUMMARY OF LO_2 TANK AFT DOME FOR PRE-SELECTED MODE FROM TEST CONFIGURATIONS 1 THROUGH 4

Configuration				Modal Pressure (psi/g)			
No.	Cant Angle (%)	Depth (in.)	Mode Frequency (Hz)	P_1	P_2	P_3	P_4
1	0	487.	4.90	-	-2.65	-	3.30
			9.04	-	-2.62	-	4.88
			5.72	-	-5.84	-	-5.08
			12.76	-	-2.31	-	-2.12
			18.95	-	.126	-	.541
2	13	320.7	11.97	-2.12	.598	1.76	2.36
			13.97	[illegible]	-1.79	-2.67	-2.06
			14.14	1.00	-1.72	-2.94	-2.90
			13.02	- .045	-2.51	-2.41	.162
3	13	162.	13.35	- .788	2.03	2.63	1.22
			13.47	.862	-1.52	-2.13	-1.69
			20.04	.032	.727	1.25	-1.18
4	13	58.	15.67	- .024	-1.08	-2.00	-1.99
			18.53	- .003	- .989	-1.00	3.21
			21.12	- .009	1.20	- .465	-1.20

TABLE 7. TARGET MODE SUMMARY SUPPLEMENTARY TESTING
(TEST CONFIGURATION 5 THROUGH 12)

Configuration					Test Mode		
	TSS No.	Depth (in.)	Cant Angle (deg)	Ullage Pressure (psi)	Frequency (Hz)	Damping (%)	Description
	193	320.7	0	3.3	11.99	.64	SYM First Bulge
	194	320.7	0	3.3	13.82	.78	SYM Second Bulge
5	195	320.7	0	3.3	18.36	.32	SYM Third Bulge
	196	320.7	0	3.3	16.81	.28	SYM Second Bending
	197	320.7	0	3.3	20.38	.22	SYM Third Bending
	204	320.7	0	1.6	11.98	.27	SYM First Bulge
	205	320.7	0	1.6	13.77	.64	SYM Second Bulge
6	206	320.7	0	1.6	18.32	.31	SYM Third Bulge
	207	320.7	0	1.6	16.93	.38	SYM Second Pitch Bulge
	208	320.7	0	1.6	20.26	.30	SYM Third Pitch Bending
	209	320.7	0	8.0	12.06	.45	SYM First Bulge
	210	320.7	0	8.0	13.87	1.1	SYM Second Bulge
7	211	320.7	0	8.0	18.45	.32	SYM Third Bulge
	212	320.7	0	8.0	16.84	.33	SYM Second Pitch Bending
	213	320.7	0	8.0	20.50	.25	SYM Third Pitch Bending
	178	320.7	4	3.3	13.87	0.90	SYM Second Bulge
	179	320.7	4	3.3	18.38	.35	SYM Third Bulge
8	180	320.7	4	3.3	12.10	.35	SYM First Bulge
	181	320.7	4	3.3	20.44	.22	SYM Third Pitch Bending
	182	320.7	4	3.3	16.96	.34	SYM Second Pitch Bending
	183	320.7	4	3.3	22.16	.63	SYM Shell, N Number Varies

TABLE 7. (Concluded)

Configuration					Test Mode		
No.	TSS No.	Depth (in.)	Cant Angle (deg)	Ullage Pressure (psi)	Frequency (Hz)	Damping (%)	Description
	215	384.5	0	3.3	15.85	.06	SYM Second Pitch Bending
	216	384.5	0	3.3	19.04	.21	SYM Third Pitch Bending
9	217	384.5	0	3.3	9.42	.86	SYM First Bulge
	218	384.5	0	3.3	13.30	.13	SYM Second Bulge
	219	384.5	0	3.3	18.58	.37	SYM Third Bulge
	220	384.5	0	8.0	9.46	.94	SYM First Bulge
	221	384.5	0	8.0	13.36	.14	SYM Second Bulge
10	222	384.5	0	8.0	18.70	.36	SYM Third Bulge
	223	384.5	0	8.0	15.86	.10	SYM Second Pitch Bending
	224	384.5	0	8.0	19.09	.22	SYM Third Pitch Bending
	225	218.0	0	3.3	13.22	.13	SYM Second Bulge
	226	218.0	0	3.3	18.87	.13	SYM Third Bulge
11	228	218.0	0	3.3	15.12	1.5	SYM First Pitch Bending
	228A	218.0	0	3.3	17.00	.50	SYM Shell, N=3
	229	218.0	0	3.3	19.70	1.1	SYM Third Pitch Bending
	230	162.0	0	3.3	14.78	.48	SYM Dome Shell, N=2
	231	162.0	0	3.3	16.11	.29	SYM First Pitch Bending
12	232	162.0	0	3.3	13.38	.29	SYM Second Bulge
	233	162.0	0	3.3	23.37	.16	SYM Shell, N=2
	234	162.0	0	3.3	24.31	.69	SYM Third Pitch Bending
	235	162.0	0	3.3	17.87	.18	SYM Second Pitch Bending

T BLE 9. MODAL FREQUENCY AND DAMPING VARIATIONS DUE TO CHANGE IN CANT-ANGLE, FLUID-LEVELS AND ULLAGE PRESSURE (FIRST THREE TANK SYMMETRIC BENDING, AND DOME BULGE MODES)

Ca t Angle (deg)	0					4	13			Ullage Pressure (psi)
Depth (in.)	162.	218.	320.7	384.5	487.	320.7	58.	162.	320.7	
Bulges Modes										
First			11.98/.2[illegible] 11.99/.5[illegible] 12.06/.4[illegible]	9.42/.86	5.72/2.2	12.10/.35			11.97/.66	1.6 3.3 8.0
Second	13.38/.29	13.22/.13	13.77/.61 13.82/.7[illegible] 13.87/.1[illegible]	3.30/.13 3.36/.14	12.76/.13	13.87/.90	15.67/.23	13.47/.62	14.14/1.2	1.6 3.3 8.0
Third		8.87/.13	18.32/.3[illegible] 18.36/.32 18.45/.3[illegible]	8.58/.37 8.70/.36	18.95/.20	18.38/.35				1.6 3.3 8.0
Bending Modes										
First	16.11/.29	15.12/1.5			9.04/.20		18.53/.18		13.02/.44	1.6 3.3 8.0
Second	17.87/.18		16.73/.3[illegible] 16.81/.[illegible] 16.84/.3[illegible]	15.85/.06 15.86/.10	14.08/.17	16.96/.34	21.12/.11	20.04/.50	19.76/.33	1.6 3.3 8.0
Third	24.31/.69	19.70/1.1	20.26/.3[illegible] 20.38/.2[illegible]	19.04/.21	19.19/.18	20.44/.22			20.72/.27	1.6 3.3 8.0

TABLE 9. MODAL CORRELATION FOR TEST CONFIGURATION 1
(487 in. DEPTH, 0° CANT-ANGLE)

Test Mode			Analysis Mode		Mode Description	Correlation Assessment
TSS No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Mode No.		
009	4.90	1.6	4.75	12	SYM Shell, M=1, N=2	Excellent
018	4.88	1.6	5.00	10	ASM Shell. M=1, N=2	Excellent
021	9.04	1.2	8.91	19	SYM First Pitch Bending	Excellent
025	5.72	2.5	5.16	13	SYM First Bulge	Excellent/Good
028	9.48	.72	8.93	16	ASM First Yaw Bending	Excellent
036	12.76	.13	12.96	26	SYM Second Bulge	Excellent/Good
039	18.95	.20	15.74	35	SYM Third Bulge	Fair/Poor
044	21.26	.10	20.92	48	SYM Fourth Pitch Bending	Excellent/Good
045	19.29	.18	18.81	43	SYM Third Pitch Bending	Good
048	16.63	.28	14.80	25	ASM Third Yaw Bending	Fair
050	21.55	.12	21.72	39	ASM Fifth Yaw Bending	Excellent/Good
054	23.83	1.5	23.10	--	SRB Beam, Z Bending	Excellent
056	45.41	1.0	45.80	--	SRB Beam. X Bending	Excellent
058	9.18	.32	9.68	22	SYM Shell, M=2, N=3	Excellent
059	16.54	.32	16.30	32	SYM Dome Bending, Ogive Shell	Poor
060	14.08	.17	13.17	27	SYM Second Pitch Bending	Good
063	25.75	.43	26.03	60	SYM Dome Bulge, Ogive Shell	Poor
064	19.68	.51	19.50	35	ASM Fourth Yaw Bending	Fair
066	13.81	.58	12.79	22	ASM Second Yaw Bending	Good
070	9.75	.19	11.18	24	SYM Shell, M=1, N=7	Fair

TABLE 10. MODAL CORRELATION FOR TEST CONFIGURATION 2 (320.7 in. DEPTH, 13° CANT-ANGLE)

Test Mode			Analysis Mode			
TSS No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Mode No.	Mode Description	Correlation Assessment
091	6.64	.60	6.36	10	SYM Shell, M=1, N=2	Excellent
092	11.97	.66	11.06	13	SYM First Bulge	Excellent /Good
097	13.02	.44	12.11	15	SYM First Pitch Bending	Excellent
098	20.72	.27	21.59	32	SYM Third Pitch Bending	Excellent /Good
099	6.54	.51	6.44	10	ASM Shell, M=1, N=2	Excellent
105	12.48	.70	11.70	14	ASM First Yaw Bending	Excellent /Good
106	19.82	.76	20.24	26	ASM Second Yaw Bending	Excellent /Good
111	19.76	.33	18.94	26	SYM Second Pitch Bending	Good
114	14.14	1.2	14.24	20	SYM Second Bulge	Good
125	8.31	.70	7.65	11	SYM Shell, M=1, N=3	Excellent
126	9.04	1.4	9.22	12	SYM Shell, M=1, N=4	Excellent
127	9.99	.70	11.61	14	SYM Shell, M=1, N=5	Good
128	10.66	1.3	13.77	18	SYM Shell, M=1, N=6	Fair
129	13.97	1.4	13.65	17	SYM Dome Bulge, Ogive Shell	Good

TABLE 11. MODAL CORRELATION FOR TEST CONFIGURATION 3
(162 in. DEPTH, 13° CANT-ANGLE)

Test Mode			Analysis Mode		Mode Description	Correlation Assessment
TSS No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Mode No.		
149	13.35	.60	14.07	13	SYM Dome Bulge	Excellent/Good
150	13.47	.62	14.34	14	SYM Second Bulge	Excellent/Good
154	20.04	.50	18.10	17	SYM Second Pitch Bending	Excellent/Good
155	14.91	.90	13.26	11	ASM First Yaw Bending	Good/Fair
156	22.56	.46	21.81	22	SYM Distorted Dome Bulge, Ogive Bending	Fair
158	16.54	.60	17.37	15	ASM Second Yaw Bending	Good/Fair
159	19.36	.90	19.96	18	ASM Third Yaw Bending	Good/Fair
160	25.37	.57	26.75	29	SYM Dome Shell, Ogive Bending	Good/Fair
168	13.31	.50	12.66	10	SYM Shell, M=1, N=2	Excellent/Good

TABLE 12. MODAL CORRELATION FOR TEST CONFIGURATION 4
(53 in. DEPTH, 13° CANT-ANGLE)

Test Mode			Analysis Mode			
TSS No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Mode No.	Mode Description	Correlation Assessment
078	15.67	.23	16.51	13	SYM Second Bulge	Excellent
079	18.53	.18	18.44	14	SYM First Pitch Bending	Excellent
081	25.59	.12	25.94	18	SYM Shell and Pitch Bending	Poor
082	21.56	.44	21.33	14	ASM Second Yaw Bending	Fair
085	18.58	.41	18.53	12	ASM First Yaw Bending	Excellent
087	21.12	.11	22.08	15	SYM Second Pitch Bending	Good

TABLE 13. MODAL CORRELATION FOR TEST CONFIGURATION 5
(320 in. DEPTH, 0° CANT-ANGLE)

Test Mode			Analysis Mode		Mode Description	Ullage Pressure (psi)	Correlation Assessment
TSS No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Mode No.			
193	11.99	.64	11.35	12	SYM First Bulge	3.3	Excellent/Good
194	13.82	.78	13.73	15	SYM Second Bulge	3.3	Excellent/Good
195	18.36	.32	20.53	28	SYM Third Bulge	3.3	Fair
196	16.81	.28	16.12	19	SYM Second Bending	3.3	Excellent/Good
197	20.38	.22	20.22	27	SYM Third Bending	3.3	Excellent/Good

TABLE 14. PRESSURE CORRELATION FOR TEST CONFIGURATIONS 1 THROUGH 5

Configuration		Mode Frequency (Hz)		Modal Pressure (psi/g)									
				P_1		P_2		P_3		P_4		P_5	
Cant Angle (deg)	Depth (in.)	Test	Anal.	Test	Anal.	Test	Anal.	Test	Anal.	Test	Anal.	Test	Anal.
0	487.	4.90	4.75	-	-5.16	-2.65	[illegible]84	-	1.72	3.30	3.25	16.9	9.83
		9.04	8.91	-	2.38	-2.62	3.99	-	5.59	4.88	9.55	8.91	13.76
		5.72	5.16	-	-12.3	-5.84	-10.[illegible]	-	9.78	-5.08	-10.2	-6.70	-12.1
		12.76	12.96	-	.439	-2.31	-2.31	-	-4.11	2.12	-2.85	.636	-.320
		18.95	15.74	-	1.29	.126	-2.24		-4.08	.541	-2.29	1.75	.388
13	320.7	11.97	11.06	-2.12	-3.20	.598	-.074	1.76	1.53	2.36	3.01	.190	2.48
		13.97	13.65	.377	.661	-1.79	-2.31	-2.67	3.50	-2.0[illegible]	-1.72	-.645	1.33
		14.14	14.24	1.00	.955	-1.72	-2.10	-2.94	-3.85	-2.90	-2.99	-.878	.136
		13.02	12.11	-.045	.704	-2.51	-1.25	-2.41	-1.16	.[illegible]2	1.88	3.06	5.81
13	162.	13.35	14.07	-.788	1.33	2.03	4.29	2.63	5.29	1.[illegible]	2.87	-.130	-.207
		13.47	14.34	.862	2.13	-1.52	-1.84	2.13	3.20	-1.[illegible]	-2.32	.287	.465
		20.04	18.10	.032	1.11	.727	.117	1.25	.992	1.[illegible]	2.85	1.22	.341
13	58.	15.67	16.51	-.024	-.552	-1.08	-1.81	-2.00	-1.93	-1.99	1.23	.245	-.159
		18.53	18.44	-.003	-.141	-.989	.905	-1.00	-.320	3.21	-1.88	1.31	.817
		21.12	22.08	-.009	-.135	1.20	-1.24	-.465	1.22	-1.20	.833	.821	-.310

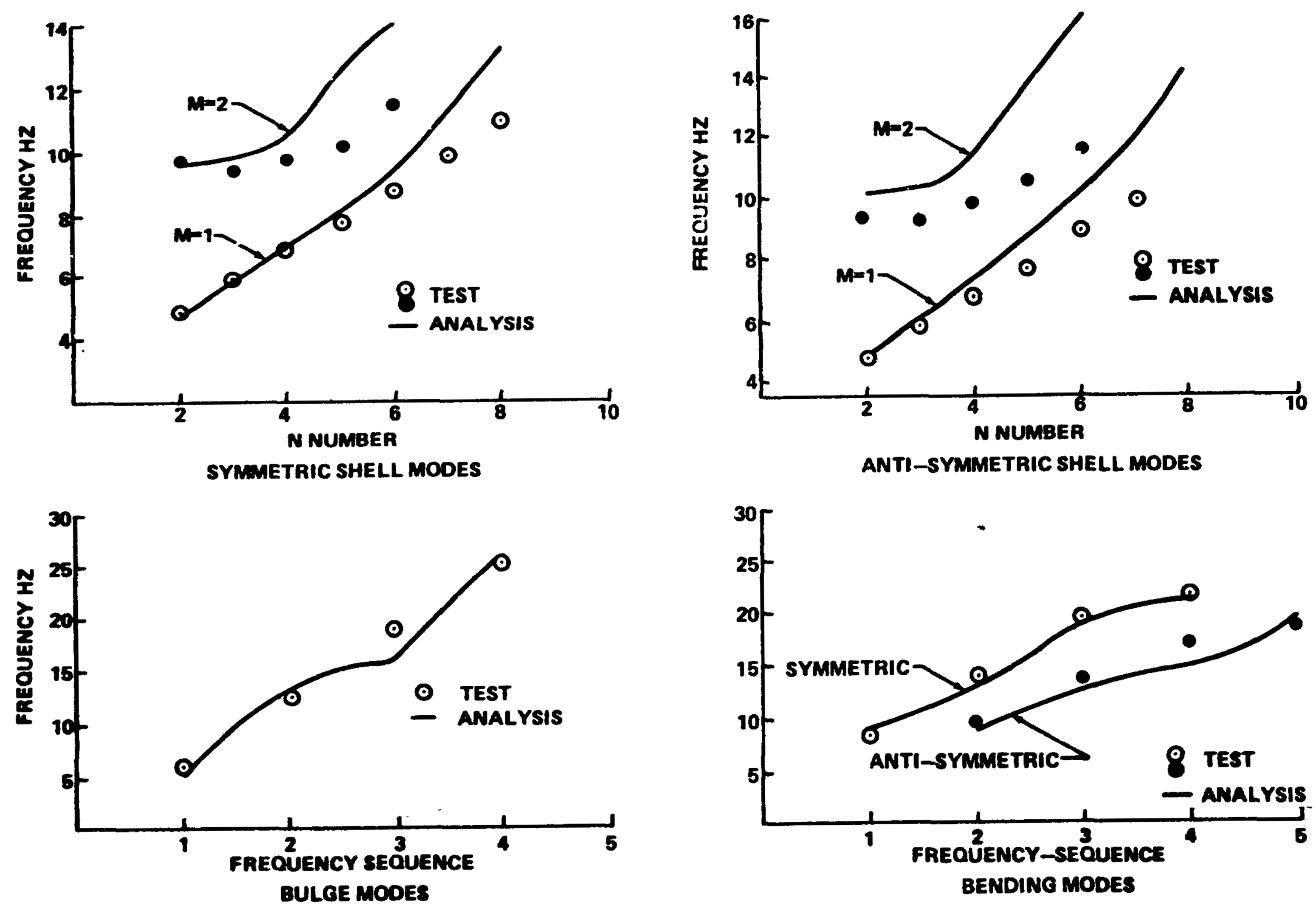

Figure 4. Modes for configuration 1.

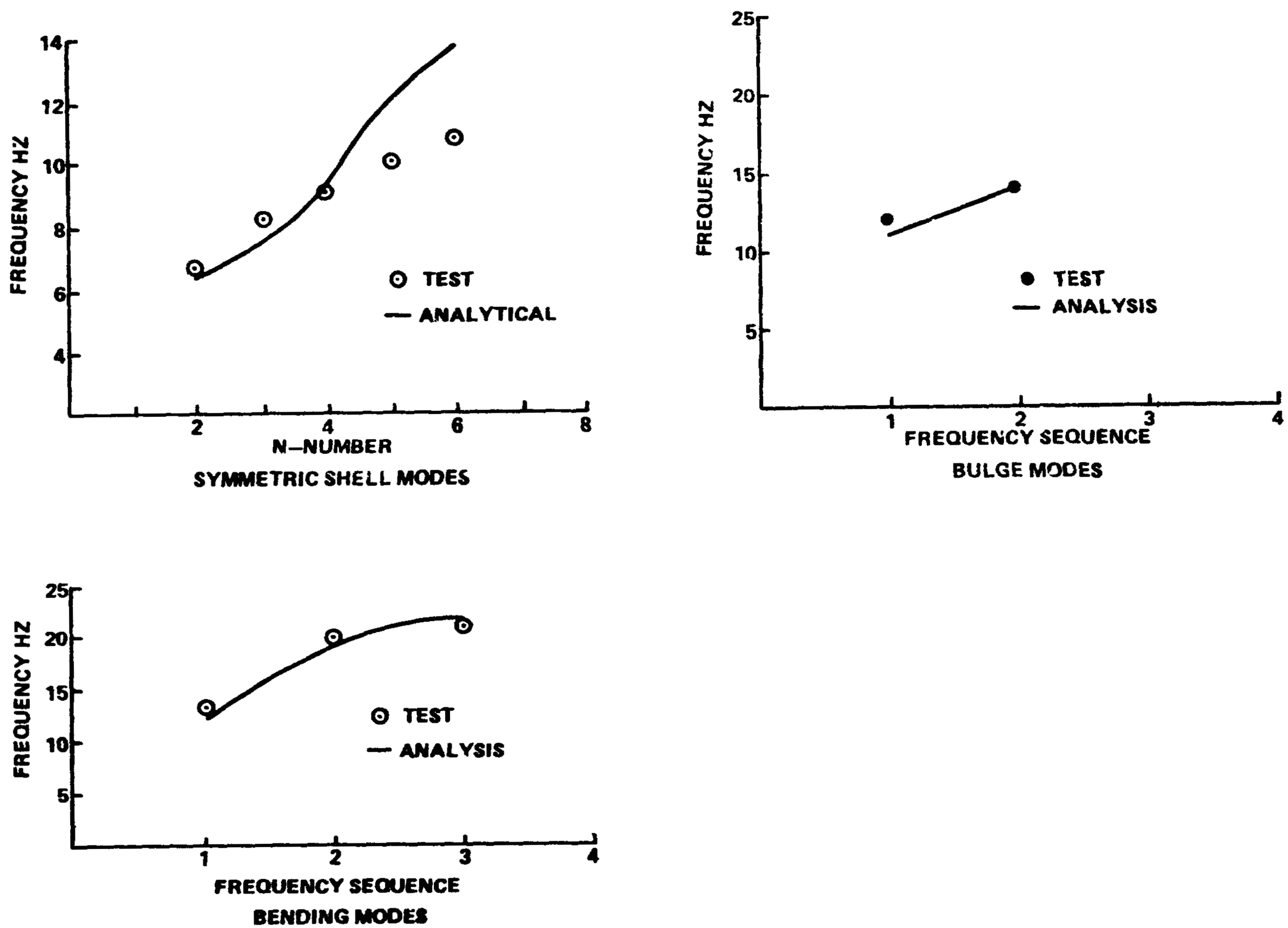

Figure 5. Modes for configuration 2.

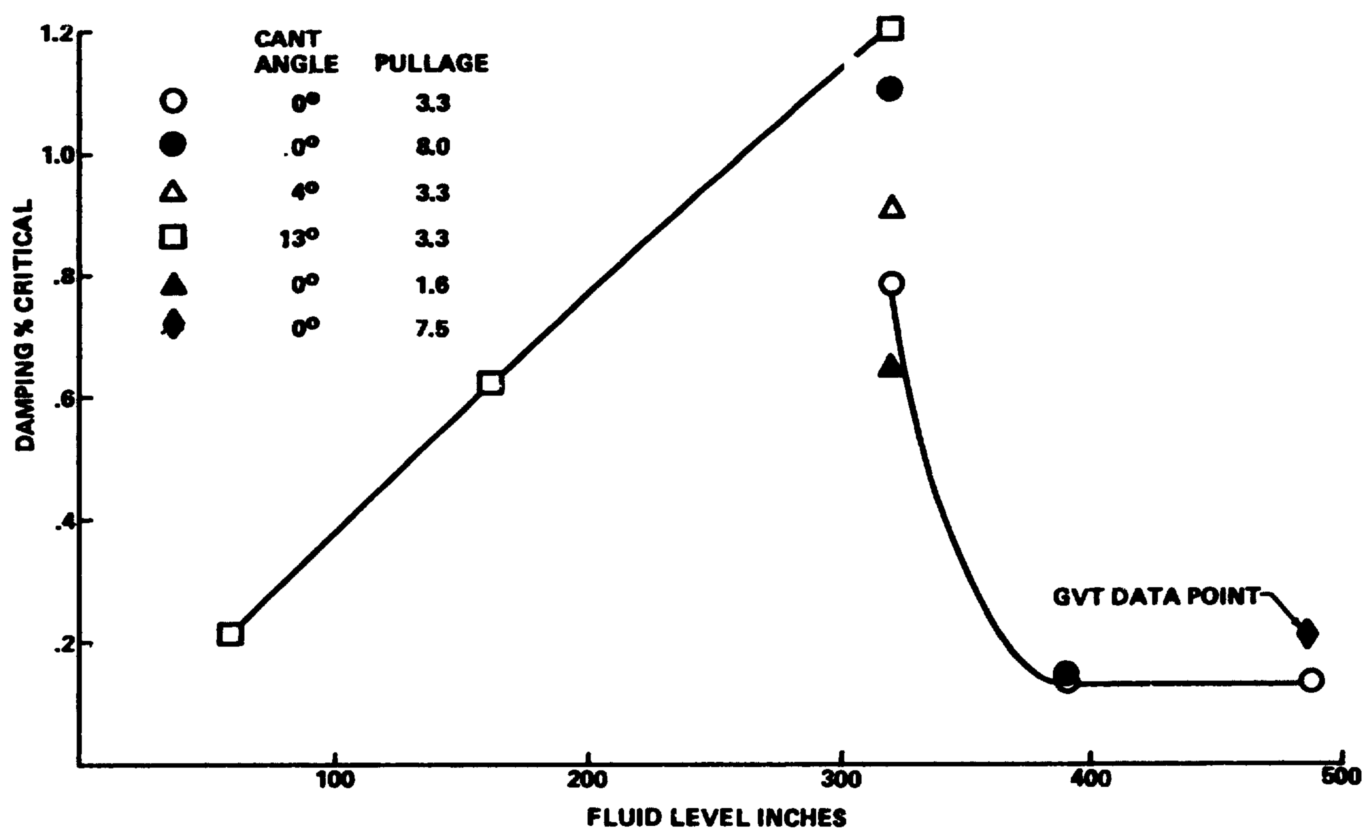

Figure 6. Second LO_2 tank bulge mode damping.

Tables 9 through 13 present the test dwell data which were judged to have modal quality. Table 14 presents the normalized modal pressure data for these modes.

Part of this data is shown graphically in Figures 4 and 5. The plots also show shell modes identified from sweep data only. This presentation is included to give insight into the trend of the test data relative to the analysis. The shell modes are identified by an M number and N number notation, where the M designates the number of half sine waves in the axial direction and the N designates the number of sine waves in the circumferential direction. The bending and bulge modes are identified as "first," "second," etc., in order of ascending frequency.

The data for the 54 test and corresponding analysis modes listed in Tables 9 through 13 were subjected to careful detailed assessment in this test/analysis correlation. The assessment procedure started with examination of the analysis data for candidate target test modes. It continued through the evaluation of the test data as describing valid modes. The establishment of corresponding test/analysis mode pairs was through detailed consideration of the matching and the differing features of the mode shapes. The frequency match or mismatch was accepted after satisfaction of the shape criteria.

Thirty-nine of the 54 mode pairs were rated as having good or excellent correlation. The ratings were the result of subjective judgments of the correlation quality. Rigid criteria were not applied in arriving at the ratings as the relative importance of the various features concerned was different for different types of modes. Generally, the mode shape match of the lower dome was accorded the greatest weight. This was followed closely by frequency correspondence, then by mode shape match in the cylinder/ogive and finally by mode shape match in the intertank.

Modal results from test configurations 1 through 4 identified several lightly damped modes within the 12 to 18 Hz frequency range. They were the symmetric bending and bulge modes.

As a result of the SRB thrust oscillatory condition that was discovered at approximately 15 Hz during the SRM DM-1 and/or DM-2 static firings, supplementary test configurations were authorized for the purpose of studying the damping phenomena of these modes while varying the fluid level, cant angle, and ullage pressure parameters.

Table 8 presents a summary of the modal frequency and damping properties of the first three symmetric bending and bulge modes for all test configurations (1 through 12).

The trend established by these data indicates that modal frequency is a direct function of pressure and cant angle. It increases with higher pressure and with higher cant angle. Modal frequency, however, cannot be directly related to fluid level variations due to the coupling effects of shell modes. No general trend can be established for modal decay. It can, however, be related to these variables on a per mode basis. To demonstrate this, part of this data is shown graphically in Figure 6. It is related to the second dome bulge mode and describes the modal decay as a function of these variables and its correlation within the thrust oscillatory time increment. The trends described by this mode during test were:

a) Within the 0 to 320.7 in. level:

1) It increased with higher fluid level for a constant pressure (3.3 psi) and cant angle (13°) test configuration.

b) At the 320.7 in. level:

1) It increased with higher ullage pressure for a constant fluid level (320.7 in.) and cant angle (0°) test configuration.

2) It increased with higher cant angle for a fluid level (320.7 in.) and pressure (3.3 psi) test configuration.

c) Within the 320.7 to 487 in. level:

1) It decreased with higher fluid level for a constant pressure (3.3/8.0 psi) and cant angle (0°) test configuration.

The trend previously described showed that the modal decay was low (0.13 percent) at liftoff as well as at the commencement of the potential thrust oscillatory condition. It did, however, increase significantly during this interval, from 0.13 percent to 0.78 percent at 3.3 psi or 0.14 percent to 1.1 percent at 8.0 psi.

Additional instrumentation was installed to the MVGVT test article to obtain an independent check of these damping values. The one data point that was obtained during the preparation of this report is shown in Figure 6 and correlates with the LO_2 modal results.

V. CONCLUSION

It is concluded from the assessment of the LO_2 modal test and analysis data that the MMC hydroelastic finite element methodology is sufficiently accurate to duplicate the structural/fluid dynamic characteristics of a full scale flight external tank. The modeling technique used by MMC will accurately predict the primary "pogo" modes of the External Tank in all flight configurations.

BIBLIOGRAPHY

Martin Marietta Document MMC-ET-SET1-4, Flight Tanl Hydroelastic Models for Twenty Fill Conditions, June 1978.

Martin Marietta Document MMC-ET-TM07, Test Requirement Specimen, Structural Strength and LO_2 Tank Modal Tests, February 1977, as amended by SCN-004.

Martin Marietta Document 8262101, Test Plan Report — Structural Strength and LO_2 Tank Modal Survey — STA Major Ground Tests, Volume II, October 1977.

NASA Document DST-0-TR-001, ET Lox Modal Test Report.

APPROVAL

ET LOX MODAL SURVEY ANALYSIS AND TEST ASSESSMENT

By R. L. McComas

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.

ROBERT S. RYAN
Chief, Structural Dynamics Division

GEORGE D. HOPSON
Director, Systems Dynamics Laboratory

U.S. GOVERNMENT PRINTING OFFICE 1980–640-247/57 REGION NO. 4