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Quarter-Scale Space Shuttle Design, Fabrication, and Test

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This paper discusses the design, fabrication, and dynamic testing of the quarter-scale model of the Space Shuttle system. As an integral part of the Shuttle design verification effort, the quarter-scale ground vibration test program was implemented to provide early verification of the dynamic characteristics of the Shuttle elements, both individually and in mated configurations. This paper presents the prominent aspects of the design and fabrication phases of the quarter-scale program and summarizes the ground vibration test program. Typical dynamic test data are presented and discussed. Future tests utilizing the quarter-scale vehicles are outlined.

Introduction

THE Space Shuttle design has presented many technical challenges to the aerospace industry. In the discipline of structural dynamics, the Shuttle offered a new problem: the assembly of four distinct elastic structures subjected to the dynamic environments of liftoff and boost into orbit. The ability to predict accurately the structural dynamics of such an assembly is greatly dependent on the approach taken to mathematically describe the structure and its characteristics in the program input data. Prudence demanded that the math modeling techniques employed to predict mode shapes and frequencies be verified at the earliest possible date. Thus, the quarter-scale Shuttle ground vibration test (GVT) was conceived and introduced into the Shuttle program.

Its principal objectives were to determine experimentally the modal characteristics of the quarter-scale Shuttle and to provide early verification of the predicted dynamic responses of the elements individually and in mated configurations. Substantiation of the coupled/uncoupled dynamic math models would provide high confidence in the design of the orbiter flight control system, the pogo analyses, structural load predictions, and flutter analyses.

Selection of Model Scale

The use of dynamically scaled models for test verification of predicted vibration response has been successfully employed on several launch vehicles.[1-4]

During the Saturn program, a one-tenth scale model was dynamically tested to obtain mode shapes and response frequencies.[2] The model was intended to be a near replication of the primary structure of the Saturn V. However, at one-tenth scale, it was necessary to elastically simulate some upper stage structure and joints. Although the test results proved satisfactory in general, the simulated areas and joints did not provide the same degree of correlation with theory as the near-replicated stages.

The one-eighth scale Shuttle dynamic test model was designed to retain the significant stiffness characteristics of each element.[3] However, their physical size and cost considerations prompted model simplifications, particularly in local structural details. As with the Saturn V model tests, the simulated areas created some correlation difficulties.[4]

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At the outset of the Space Shuttle program, a GVT program of the individual and mated Shuttle elements was included in the overall test and verification planning. However, production schedules and availability of the Shuttle flight elements indicated that the full-scale vibration test data could not be obtained until late in the development program. Therefore, based on the successful history of dynamic scale-model tests, a model GVT program was included in the Shuttle effort.

The lessons of the previous scale-model tests prompted consideration of a larger model size. One-fifth scale was the size most favored, but early Shuttle structural layouts showed that considerable elastic simulation of structure and joints would still be required. The final size selection of a one-fourth scale was large enough to permit near replication of all primary structure and joints, while still meeting the size limitations of the available test facilities. Additionally, selection of this large size meant that more off-the-shelf hardware would be available, particularly in fasteners and bearings.

Test Program Outline

The vibration test program concentrated on the dynamic characteristics of the mated configurations associated with the initial phases of the Shuttle mission profile. Figure 1 illustrates the complete mission profile from liftoff through landing. As indicated in this illustration, the dynamic tests focused on the liftoff and boost phases of the mission. These phases involve both a four-body and a two-body configuration, necessitating evaluation of the dynamic coupling effects.

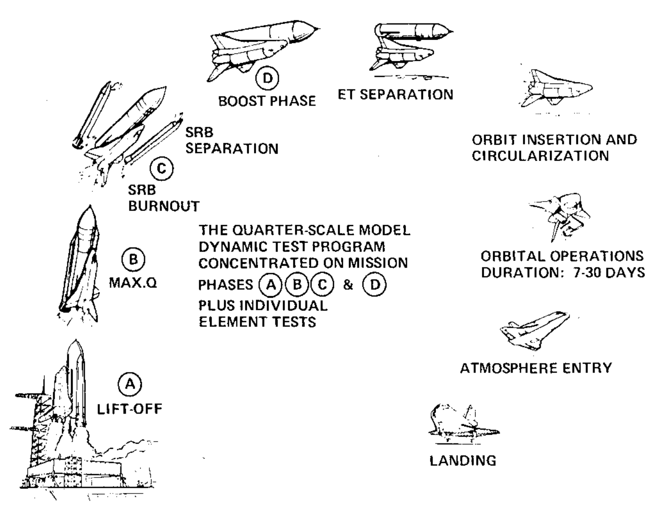


Fig. 1 Profile of Shuttle mission.

Table 1 Quarter-scale test conditions

Mission phase (per Figure 1)	Test configuration	Test weight (lb)	Test rationale
Single element tests	External tank	19,523	Verify math model of quarter-scale external tank with lift-off LO_2 loading
	Solid rocket booster-right hand		Verify math model of quarter-scale solid rocket booster
		19,917	- with lift-off propellant loading
		2,525	- with all propellant gone
	Orbiter – horizontal GVT	3,496	Verify math model of quarter-scale orbiter with and without 500 lb payload (32,000-lb equivalent)
Ⓐ Lift-off (T + 0.3 sec)	Orbiter-external tank-solid rocket boosters	62,853	Verify math model of quarter-scale Shuttle with heaviest four-body assembly; includes 500 lb payload
Ⓑ Max Q (T + 66 sec)	Orbiter-external tank-solid rocket boosters	40,870	Verify math model of quarter-scale Shuttle four-body configuration at critical flight time with about half solid rocket booster propellant remaining; including 500 lb payload
Ⓒ SRB burnout (T + 122 sec)	Orbiter-external tank-solid rocket boosters	24,283	Verify math model of quarter-scale Shuttle four-body configuration with least weight; includes 500 lb payload
Ⓓ Boost	Orbiter-external tank tilted 13 degrees		Verify math model of quarter-scale two-body configuration, including effects of tilt and 500 lb payload; H_2O level in LO_2 tank adjusted for each test.
(T + 122 sec)		19,113	- at post-SRB separation
(T + 296 sec)		12,278	- at mid-boost
(T + 471 sec)		5,403	- at end-boost

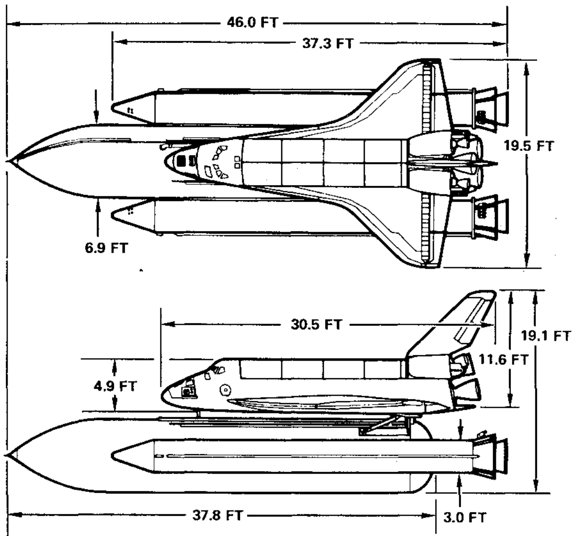
The specific configurations included in the dynamic test program are listed in Table 1. Tests on the individual Shuttle elements were included (i.e., orbiter, external tank, and solid rocket boosters) as well as the significant mated configurations. The required variations in mass were obtained by providing three different pairs of boosters and simulating the amount of oxidizer in the external tank. One pair of boosters was filled with an inert propellant loading simulating liftoff; a second pair was filled to simulate the max-Q condition; and a third pair, empty, simulating booster burnout. The LO_2 and LH_2 tanks within the external tank model were designed to be pressurized during tests, 6 psig maximum in the LH_2 tank and 8 psig maximum in the LO_2 tank. The liquid oxygen mass, with a specific gravity of 1.14, was simulated with deionized water in the model LO_2 tank. The level of water was adjusted according to the mission phase being simulated in each test. The mass fraction of the liquid hydrogen fuel, with its specific gravity of 0.071, was considered small enough to omit from the quarter-scale model.

Test Vehicle Design

Basic Approach

The basic approach taken for the design of the quarter-scale Shuttle elements was to provide models with the inherent scaled structural stiffness characteristics of the originals. The primary structure of each element was a near replication of the full-scale hardware. Replication is the exact scaling of a component; near replication allowed for some minor simplifications for cost savings without compromising the overall elastic stiffness characteristics. For complex structure and highly contoured areas, near replication was, in fact, the only practical way to achieve the goal of a high-fidelity structure that faithfully reproduced the essential stiffness characteristics of the real flight vehicles. This was the approach taken for all skin panels, whether skin and stringer, machined integral stiffeners, or honeycomb sandwich panels. All frame caps and webs, longerons, spars and ribs, as well as all structural interface fittings and joints were near replicated.

SPACE SHUTTLE
QUARTER-SCALE MODEL



MODEL SCALE FACTORS

LENGTH, WIDTH, THICKNESS:	1/4	MASS:	1/64
AREA:	1/16	MASS MOMENTS OF INERTIA:	1/1024
AREA MOMENTS OF INERTIA:	1/256	FREQUENCY:	4/1
LINEAR STIFFNESS:	1/4	ROTARY STIFFNESS:	1/64

Fig. 2 Model configuration and scale factors.

A brief explanation of the scale factors is as follows. All linear dimensions, width, length, and thickness were reduced to 1/4 of their original value. Thus, cross-sectional areas became 1/16th of the original. Since model component volumes were reduced to 1/64th of full scale, the model mass was also 1/64th, and the model mass moments of inertia became 1/1024th of the original value. The configuration and dimensions of the quarter-scale Shuttle elements are shown in Fig. 2. A listing of the pertinent scale factors is also presented.

For secondary structure (web stiffeners, clips, formers, truss tubes, etc.), stiffness simulation was used. In general, these were straightforward structural elements that could be elastically simulated quite accurately without affecting the vehicle overall stiffness. Where nonstructural components were concerned, mass simulations were employed. This included such items as fairings, hydraulic and electrical subsystems, pressure vessels, radiators, insulation, thermal protection, etc. Mass simulation was accomplished by installing lead ballast blocks at the proper locations to meet the mass property requirements. Heavy items (more than 500 lb full scale) were elastically and mass simulated. See Figs. 3-5 for configuration definitions of the quarter-scale orbiter, external tank, and solid rocket boosters.

Model Drawings

The most cost-effective design approach for the release of quarter-scale model drawings was to maximize the use of the available full-scale released engineering drawings. The actual dimensions were lined out and the scale values substituted on a Mylar of the full-scale part. Whenever feasible, design details were simplified to save fabrication costs. The same numbering system was used, except that a quarter-scale vehicle (QSV) prefix was added. Essentially, the basic guideline was to avoid reengineering the primary structural design details. This had a two-fold benefit in that it

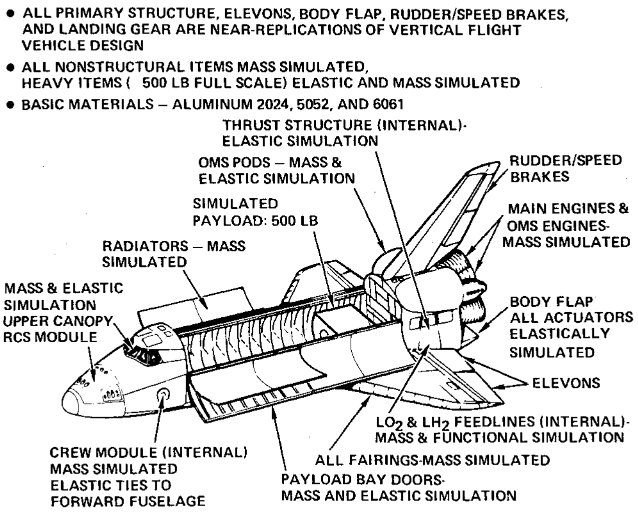


Fig. 3 Quarter-scale orbiter configuration.

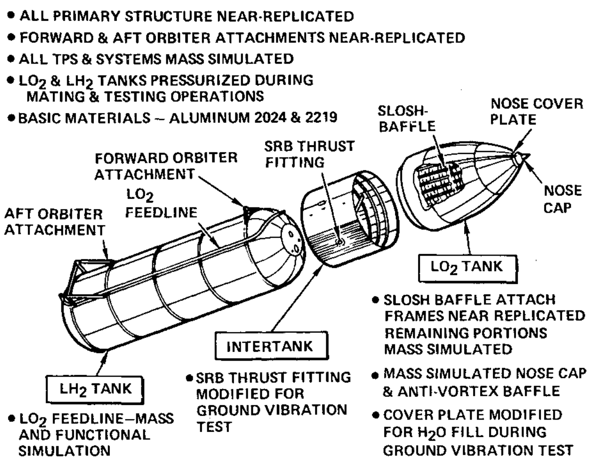


Fig. 4 Quarter-scale external tank configuration.

guaranteed the attainment of a high-fidelity structural replication and it minimized the time of the design phase of the model program. Several detail parts relating to an assembly were often placed on one released QSV drawing to minimize the physical number of drawings required for the model vehicles. In this fashion, approximately 3000 model drawings were released covering more than 10,000 original full-scale drawings.

Another cost-reduction guide was to use readily available and lower-cost materials to substitute for the materials required for the full-scale parts. Basically, the required material modulus E was retained, but with less costly substitutes whenever feasible.

Joint Design

One of the more demanding tasks during the model design phase was to achieve a near replication of the structural joints. Historically, joint simulations in dynamic models had created data irregularities and correlation difficulties. Therefore, the basic goal in quarter-scale design was to reproduce each joint design with scaled fasteners and replicated patterns. Special screws and aluminum rivets were fabricated for this purpose with screws as small as 0.060-in. diam, and rivets down to 0.039-in. diam. Rivets were used in the model joints where Hi-Loks and blind fasteners had been used on the full-scale design. When model thickness and edge distances became too small for fasteners, weldable aluminum alloys were used and spot welds made in the proper scaled patterns. Liquid shim techniques were used to ensure fit-up of joints. To avoid rattles during dynamic tests, many interface joints used mechanical fasteners installed in reamed holes, or fasteners were selectively fit into holes to ensure tight joints. Where near replication was not possible, some model joints were designed with equivalent scaled fastener shear area and modified patterns. All nuts were self-locking; all tapped holes had self-locking inserts or a locking adhesive on the installed fastener. All primary structural joints on the model hardware were mechanically fastened or spot-welded. Although some adhesive bonding of detail parts was permitted in noncritical areas, it was never employed as the sole means of load transfer in any primary structural joint.

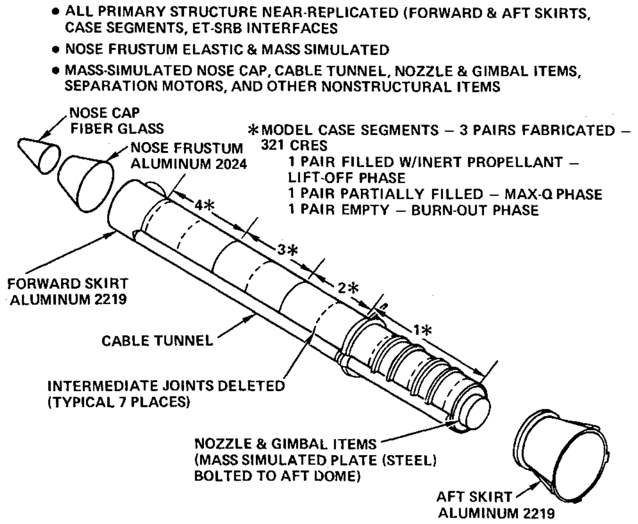


Fig. 5 Quarter-scale solid rocket booster configuration.

Special Design Problems

A significant design effort resulted from the cost-reduction decision to use elastically simulated structure for all composite construction. The orbiter payload bay doors are graphite epoxy designs that were changed to aluminum versions on the model. The model design requirement was to match the scaled in-plane shear stiffness of the doors since they function primarily as fuselage torsion members on the full-scale orbiter. The pods on the orbiter aft fuselage housing the orbital maneuvering subsystem are also graphite epoxy designs. For the model, they were changed to fiberglass skins and aluminum frames with scaled stiffness. The orbiter thrust structure has composite members of titanium overlaid with boron epoxy strips. These were changed to equivalent-scaled axial stiffness members of aluminum material on the model orbiter. In addition to the thrust structure, the LO_2 and LH_2 engine feedlines were mass and functionally simulated within the aft fuselage.

Additionally, there were several design tasks imposed in conjunction with the total test program effort. All the unique hardware and ground support equipment required for handling, transportation, mass property experiments, and the multiple test configurations involved supporting design activity. This effort became significant since many of the hardware requirements were unique to the quarter-scale elements with no full-scale design approach to copy. Also, while the model scale was relatively larger than previous models, it was still too small to adopt some full-scale design approaches, particularly in the forward external tank-solid rocket booster interface joint. (The interface bolt is torqued from inside the full-scale booster, which is not possible with the quarter-scale booster). When such modifications in approach were taken, the effects on the local structural stiffness were given careful consideration. In some instances, the model GSE design phase was well ahead of the full-scale design effort, and conceptual designs had to be utilized and adapted to model requirements.

Test Vehicle Fabrication and Assembly

A Model Shop Task

The design, fabrication, and assembly of the quarter-scale Shuttle models was entrusted to the aerospace model shop which had designed and fabricated the tenth-scale Saturn V model. The versatility of personnel and the close liaison between engineering and the fabrication shop were the main considerations in their selection, and for the successful accomplishment of the model design and fabrication task.

Detail Parts

Approximately 90% of machined detail parts and subassemblies were subcontracted to various aerospace manufacturers. These vendors reviewed prereleased drawings and often suggested cost-effective manufacturing approaches for these unique model-scale parts. There was a very low scrap rate on these parts, due mainly to high-quality workmanship and partly to the ability to utilize reworked parts. (The low structural loads anticipated during dynamic tests posed few stress-related problems, and only the essential stiffness characteristics were required.)

Mass Properties Experiments

In order to provide accurate mass matrix data for the math models of the QSV's, a series of mass property experiments were performed. As each major subassembly was completed, it was weighed and ballasted to meet the target values based on the full-scale construction. Ballasting was accomplished by lead blocks bedded in epoxy and bolted to hard points on the structure. The distribution of the blocks was calculated to place the center of gravity of the item being simulated in its required *X, Y, Z* target position. After each Shuttle element was completed and delivered, mass properties experiments were performed to establish the actual weights, c.g.'s, and mass moments of inertia. Table 2 lists the actual QSV weights and the mass properties that were experimentally established. Although most weights and mass properties were within 5% of target values, the attainment of precise, scaled mass properties was not an important requirement. Rather, it was necessary only to know what the actual properties were, and to reflect them in the mass matrices of the quarter-scale math models.

Dynamic Test Program

Test Facility

All vertical dynamic tests were performed within a vertical test fixture assembled inside a high-bay facility. The test fixture was an open, rectangular, bolted steel framework 56 ft high, 30 ft wide, and 26 ft deep anchored to the facility floor slab. One entire side was removable to allow installation of the test articles. Personnel access was provided by fixed and removable platforms and stairways at all six levels of the test fixture. Two overhead bridge cranes provided the capability to place vehicles in the fixture and rotate them from horizontal to vertical. The test fixture was required to have a design resonant frequency greater than 8.5 Hz. This structural response level, when combined with the soft suspension system employed, was sufficient to avoid coupling with the lowest expected modal response frequency. A sketch of the test facility, with pertinent dimensions, is shown in Fig. 6.

Table 2 Quarter-scale mass property experiments

			Mass moments (slug-ft^2)					
Model element	Actual weight (lb)	%[1]	I_{XX} (roll)	%[1]	I_{YY} (pitch)	%[1]	I_{ZZ} (yaw)	%[1]
Orbiter	2,996	1.2	847	5.3	NME	-	7,046	6.2
External tank	1,300	0	402	5.1	NME	-	4,894	8.9
SRB-burnout	2,585	1.3	151	10.2	10,184	1.4	10,184	1.4
SRB-max Q	10,500	2.0	602[2]	0.4	23,723[2]	10.8	23,723[2]	10.8
SRB-lift-off	19,917	1.0	878[2]	1.5	46,294[2]	1.6	46,294[2]	1.6

[1]Percent difference versus scaled target value
[2]Calculated from weights and c.g.'s of individual filled casing segments and mass properties of burn-out configuration

NME: not measured experimentally

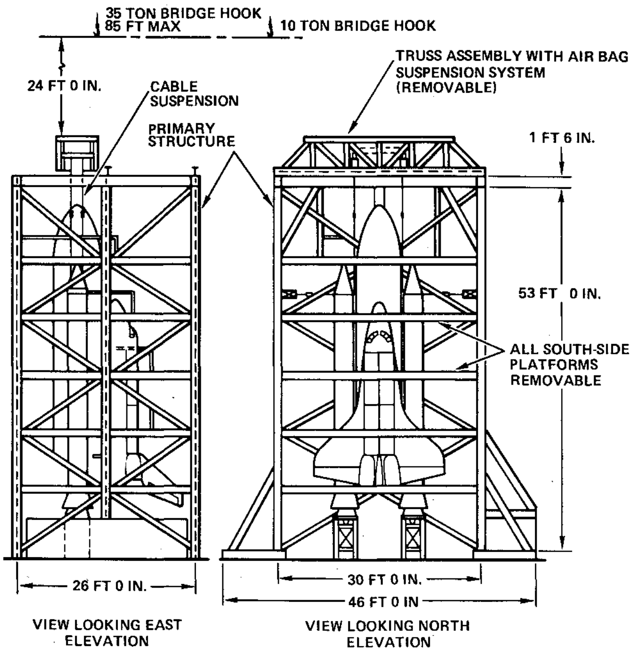


Fig. 6 Sketch of vertical test fixture.

Suspension and Restraining System

To approximate the free-flight conditions, a soft suspension and restraint system was designed. The test articles were suspended by cables from air springs attached to the test fixture. These springs were commercially available, reinforced rubber assemblies with a variable air volume for obtaining the desired spring rate. In most cases, the air-spring suspension (rigid body) frequencies were kept below 1.5 Hz, which was 20-25% of the lowest elastic modal frequencies expected during the tests. Lateral restraints were required for stability of the test articles; air springs and cables were also used for this purpose.

Analysis Models

Pre-test analytical models were prepared using the same techniques employed in the development of flight vehicle mathematical models. Each element contractor was responsible for producing a dynamic analysis model. The orbiter model was formulated using multiple-level substructuring. An ASKA finite element model for each substructure was developed with more than 20,000 degrees-of-freedom representing the orbiter structure. The substructure models were reduced to create a half-orbiter dynamic model containing 350 degrees-of-freedom. The external tank was represented by a hydroelastic model, created by overlaying a fluid model and the structural shell model. The resulting dynamic model contained 600 degrees-of-freedom in a half-tank configuration. The solid rocket booster was the most difficult Shuttle element to model analytically due to the presence of the viscoelastic propellant. A beam-type model was created for this, which included springs at the external tank interfaces. These springs were empirically calibrated to represent the combined stiffness of the solid rocket booster shell and the propellant. This model contained 140 degrees-of-freedom. The symmetric and antisymmetric models of the Shuttle launch and boost configurations were created by combining the element models, using the Craig-Bampton method of model synthesis.

Modal Excitation

Modal excitation of the test vehicles was accomplished with Unholtz-Dickey shakers with force capabilities of ± 50 lb_f or ± 150 lb_f. These shakers generate a sinusoidal force and have an axial armature suspension system with very low stiffness and negligible damping. They were distributed over the test elements at preselected, antinode locations so as to produce the desired modal excitation. Figure 7 shows typical shaker installations for a mated configuration test, one at the orbiter wing trailing edge and another at the aft fuselage. The cruciform fitting above the latter shaker is a lateral restraint point.

Test and Analysis System

A sophisticated control, data acquisition, and data processing system labeled SMTAS (Shuttle modal test and analysis system) was employed during the quarter-scale dynamic test program. The same system was also used for the full-scale dynamic tests of the orbiter and the full-scale mated configuration (MVGVT) tests. SMTAS provided automatic control for a maximum of 24 individual shakers or 38 shaker units in pairs. It controlled the multipoint, sinusoidal, low-force levels, and polarity for vibratory excitation of the test vehicles by a force feedback system and continuous monitoring of the excitation currents. The monitor system contained 24 limit channels as problem warning indicators with automatic shutdown capability if established limits were exceeded. SMTAS included the capability for acquiring, conditioning, recording, processing, analyzing, and reproducing the test data in engineering units.

A typical illustration of the SMTAS display of test data is shown in Fig. 8. This display of acceleration vectors was obtained during the orbiter-external tank-booster mated max-Q excitation, identified as test mode number 20, at 21.135 Hz. This mode was dominated by booster rigid-body axial

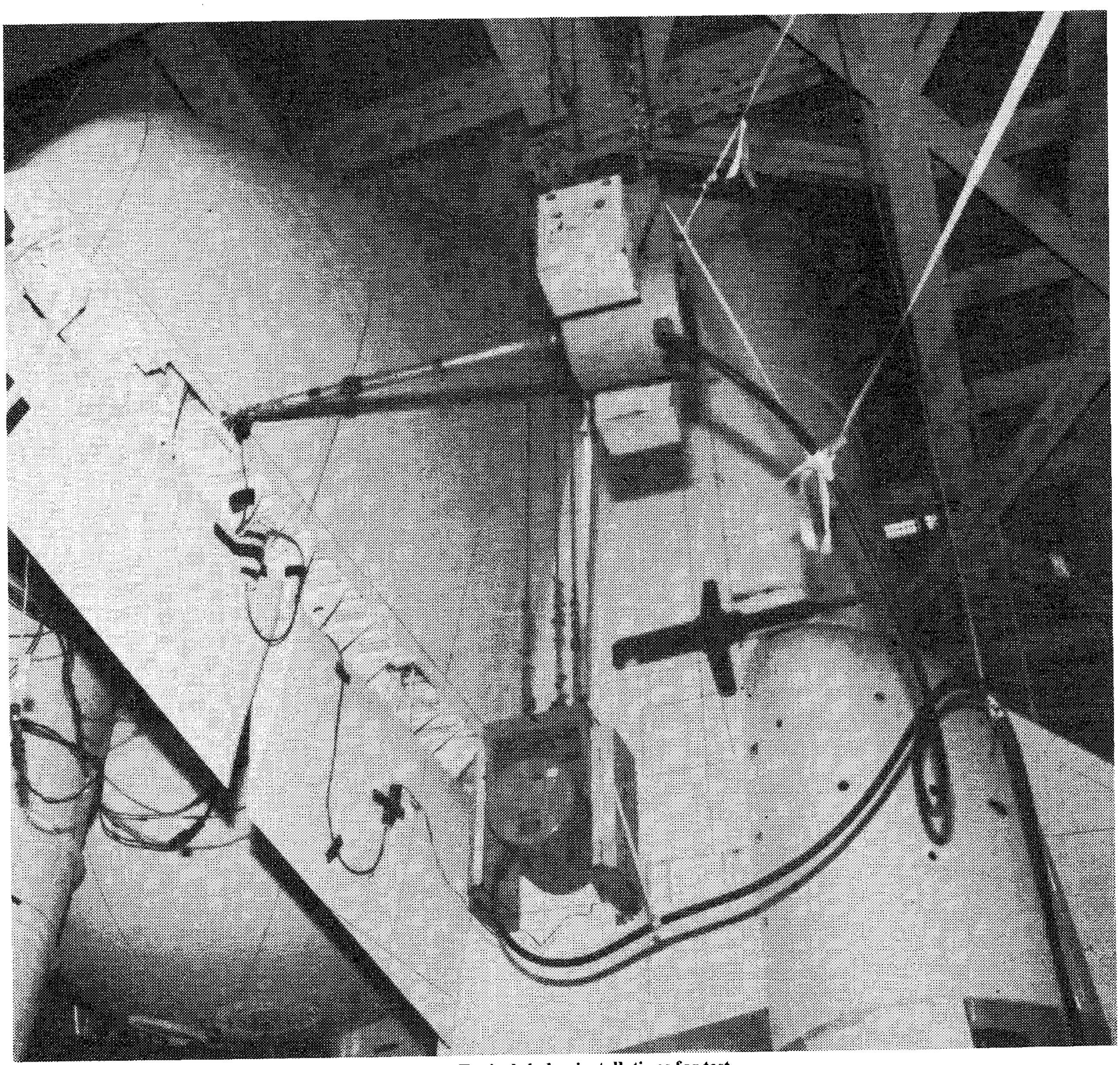


Fig. 7 Typical shaker installations for test.

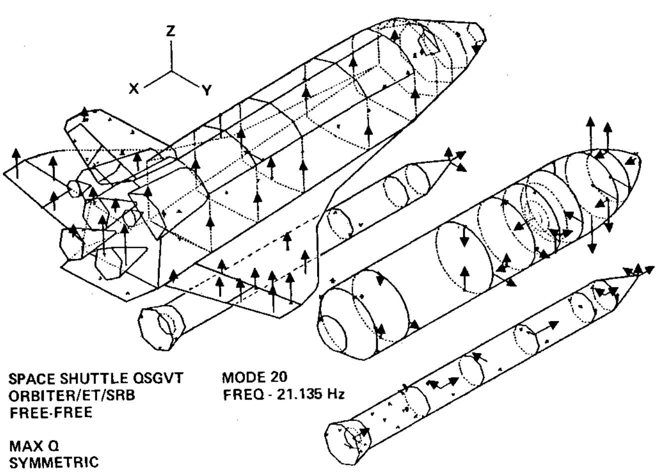


Fig. 8 Typical SMTAS acceleration vector plots.

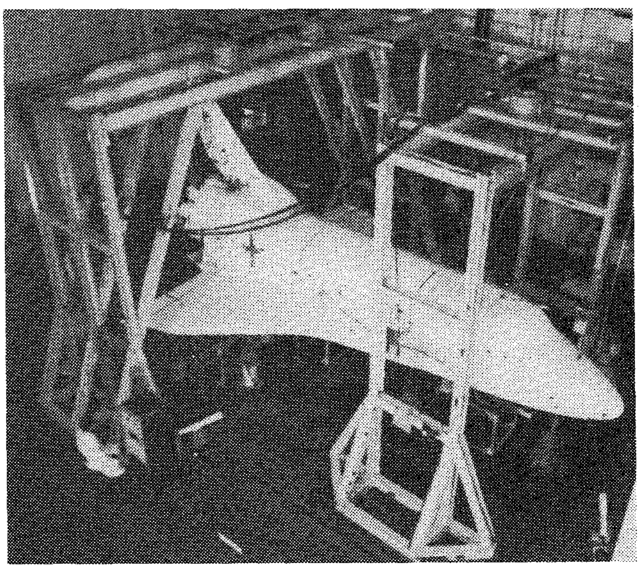


Fig. 9 Horizontal vibration test—quarter-scale orbiter.

response, accompanied by external tank symmetric shell modes and orbiter pitching. The presentation of data in this fashion permitted rapid visualization of the element responses and coupling characteristics.

Instrumentation

Acceleration amplitude and phase were measured at various locations. SMTAS could devote up to 320 channels for such data using Piezoresistive-type accelerometers with operational frequency ranges from 0.1-160 Hz. Force amplitude and phase were obtained at each shaker location using electrical resistance strain gage force links. The dynamic pressure was measured in the external tank-LO_2 tank and LO_2 feedlines. Silicon diaphragm pressure transducers were used to measure the amplitude and phase of the simulated LO_2 (H_2O) during modal vibration. Since the dynamic properties of the booster inert propellant were sensitive to temperature, thermocouples on the propellant and casings were measured during tests.

Modal Vibration Tests

After each test setup was finished, the initial test was to verify that the soft suspension rigid-body modes were well below the expected response frequencies of the test elements. Subsequently, low-force, sinusoidal excitation was imposed on the test configuration symmetrically and unsymmetrically through the frequency range of 6.0-200 Hz to accomplish the following tests: 1) wide-band sweeps to provide a preliminary definition of mode shapes and modal frequencies, 2) narrow-band sweeps, as required, to define unusual or complex responses in regions of high-modal density, and 3) modal dwells to define in detail the mode shapes of an elastic response at a particular frequency.

The orbiter model in its horizontal test fixture is shown in Fig. 9. The air springs of the soft suspension system are apparent on the overhead structure, and shakers are visible under the wing and over the nose of the model.

Table 3 Summary of quarter-scale dynamic tests

Test condition	Modes identified Sym	Antisym	Correlation with theory; remarks
External tank–lift-off	36	21	Generally very good correlation. Test frequencies often higher than predicted. Identified math model deficiencies in effect of internal pressure and stiffness of LO_2 tank upper ogive.
Solid rocket booster–lift-off	15	0	Excellent correlation for beam-bending modes. Significant propellant activity noted in first axial and torsional modes. Identified math model deficiencies in modeling propellant.
Solid rocket booster–empty	14	0	Eight beam modes and six shell modes identified. Good correlation for beam modes. First axial and shell modes overestimated. Math model corrections indicated.
Orbiter	28	20	Generally good correlation, several modes identified with no corresponding predicted mode. Identified upper main engine axial modes, OMS tanks and engine modes, and aft bulkhead modes. Tests with and without payload, and payload bay doors unlatched. Non-correlated modes showed math model deficiency.
Orbiter-external tank-solid rocket boosters–lift-off	43	34	Generally very good correlation. Math model overestimated low-frequency responses dominated by SRB roll/pitch modes, which were nonlinear.
Orbiter-external tank-solid rocket boosters–max-Q	30 4	33 4	Generally good correlation. Low-frequency modes dominated by SRB again in evidence, and overestimated by math model. Eight unique modes acquired during special external tank-booster and external tank-orbiter interface tests.
Orbiter-external tank-solid rocket boosters–SRB burn-out	29	23	Generally good correlation. SRB rigid body roll modes over-estimated. SRB roll, pitch, and yaw mode nonlinearity indicated.
Orbiter-external tank (13-degree tilt) post-SRB separation	28	24	Generally good correlation. First five LO_2 feedline mode shapes and frequencies obtained. Low-frequency modes involving orbiter-external tank interface stiffness indicates need for math model improvement.
Orbiter-external tank (13-degree tilt) mid-boost	6	6	Modal dwells concentrated on those most difficult to correlate in previous test. Some deviations from symmetry observed in test responses.
Orbiter-external tank (13-degree tilt) end-boost	6	7	Modal dwells concentrated on those most difficult to correlate in first tilted test. Deviations from symmetry of test responses more pronounced than in previous test. Review of math model assumptions of symmetry is warranted for this portion of mission profile.

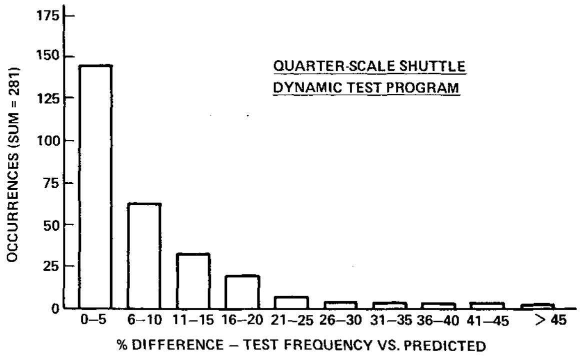


Fig. 10 Frequency correlation distribution.

Shuttle Element Test Results

In general, the Shuttle element test frequencies correlated very well with predictions, usually within ±5%. External tank test modes were consistently higher than predicted, indicating a need to improve the math model representation for internal pressure effects. Significant propellant axial and torsion displacements were noted during the solid rocket booster liftoff tests, with associated high damping values. The booster burnout test frequencies usually exceeded predictions slightly except for the first axial and shell modes, which were lower than expected. The orbiter test data correlation was also very good except that several test response frequencies had no corresponding prediction. This indicated a need to improve the math model in several structural locations. The math model deficiencies from all these Shuttle element tests were noted and corrected as required.

Mated Configuration Test Results

The data from the mated configuration tests (orbiter-tank and orbiter-tank-booster) provided the most significant information relative to the test objectives. For example, significantly lower than expected frequencies were obtained for the liftoff and max-Q test responses dominated by booster pitch and roll modes. The booster burnout symmetric and antisymmetric rigid-body roll modes also occurred at lower than expected frequencies. The responses were nonlinear with input shaker force. Eight unique modes were acquired during special tests for the effects of the external tank-orbiter interface attachments on modal frequencies.

The orbiter-external tank data were significant in two aspects: 1) low-frequency test modes affected by interface stiffness indicated a need for further math model interface definition; and 2) evidence of response asymmetry was increasingly apparent with the approach of Space Shuttle main engine end-burn.

A summary tabulation of the dynamic tests is presented in Table 3, which lists the test configurations, modes obtained, and comments. As previously stated, there was generally good data correlation with predictions from all the test configurations. As with most tests there were some anomalies, e.g., a few test modes that had no corresponding prediction, significant differences between test results and theory, complex modes involving unknown interactions between mated vehicles, etc. For the latter, a series of structural influence coefficient tests were performed to establish interface stiffness characteristics. For the others, some retests and/or adjustments in the math model were indicated and accomplished. A sample comparison of predicted and test fundamental frequencies for several test configurations is presented in Table 4.

The correlation of test frequency vs prediction from all the tests has been presented in Fig. 10. The distribution of the correlation ratios indicates that 74% of the test response frequencies were within 10% of the prediction. However, it was the remaining 26% that received the most attention since they highlighted math model deficiencies that required further study.

Table 4 Comparison of predicted and experimental frequencies

Test condition	Dominant motion and fractional kinetic energy	Type mode	Frequency - Hz Predicted	Frequency - Hz Test
External tank - lift-off	LO_2 tank shell mode	S	18.7	20.3
	1st Z-bending mode	S	28.9	29.8
	LH_2 tank shell mode	S	48.0	47.7
	1st Y-bending mode	AS	29.4	30.9
	1st torsion mode	AS	87.6	87.9
- empty	1st Y-bending mode	AS	-	60.9
	1st Z-bending mode	S	-	62.9
	1st torsion mode	AS	-	82.7
Solid rocket booster - lift-off	1st Z-bending mode	S	18.1	17.5
	1st Y-bending mode	AS	18.1	17.5
	1st torsion mode	AS	60.7	56.4
	1st axial mode	S	59.8	66.1
- empty	1st Y-bending mode	AS	38.1	37.0
	1st Z-bending mode	S	38.1	37.4
	1st torsion mode	AS	119.7	124.0
	1st axial mode	S	161.4	150.3
Orbiter	1st fuselage Z-bending (.57)	S	18.3	19.3
	Payload pitch mode (.75)	S	19.6	21.6
	Wing & elevon Z-bending (.50), tail pitch (.18), main engines pitch (.14)	S	27.9	27.1
	Wing torsion (.55), elevons roll (.21)	S	95.7	101.7
	Tail Y-bending (.92)	AS	15.6	14.3
	Fuselage torsion (.33), wing bending (.40)	AS	26.8	26.2
	Tail torsion (.71)	AS	55.9	51.0
Orbiter, external tank, solid rocket boosters - lift-off	SRB roll (.38) and pitch (.18)	S	8.0	6.7
	SRB yaw (.95)	S	10.2	10.5
	Orbiter pitch (.62), SRB roll (.13) & yaw (.13)	S	12.4	11.7
	SRB axial (.45) & yaw (.35)	S	17.4	15.8
	SRB 1st Y-bending (.95), orbiter wing 1st Z-bending	S	32.4	27.5
	Orbiter tail Y-bending (.33), SRB Y-bending (.13)	AS	14.6	13.7
	SRB and ET roll (gear train mode)	AS	15.1	14.1
	Orbiter 1st wing bending (.29), SRB 1st Z-bending	AS	25.1	20.1
Orbiter, external tank - post-SRB separation	Orbiter pitch (.47)	S	12.7	12.2
	Orbiter 1st Z-bending (.22), tail pitch (.27), ET 1st Z-bending (.24)	S	33.4	30.0
	Orbiter tail Y-bending (.87)	AS	14.8	13.5
	Orbiter yaw (.49), out of phase with ET yaw (.23)	AS	18.2	16.1
	Orbiter wing bending (.23), out of phase with fuselage torsion (.10), ET roll & yaw (.46)	AS	23.4	21.3

S = symmetric mode AS = antisymmetric mode

Future Use

The structural fidelity and availability of the Shuttle quarter-scale elements will prompt consideration for many uses. For instance, a three-month program was recently completed to obtain payload bay acoustic data using the orbiter model. Acoustic transmission losses through the structure and sound levels within the payload bay were obtained. The data will be used to verify and update predictive techniques for acoustic levels within the orbiter payload bay. The program was completed in a timely fashion at a relatively nominal cost and provided the data needed to establish payload acoustic design requirements.

A test program is currently investigating payload dynamics. The orbiter model and a simulated payload with variable mass and stiffness are used for this test. The program will generate data to verify dynamic math modeling techniques for the interaction effects of orbiter modes and payloads.

Additionally, the availability and quick-test capability of the model Shuttle elements will permit timely evaluation of future design changes affecting Shuttle stiffness characteristics. And, if a dynamic anomaly should occur on a Shuttle flight, the models will prove the means for expedient test assessment of the possible causes.

Summary

The quarter-scale Shuttle dynamic test program has met its objectives of providing verification of predicted dynamic response characteristics early in the Shuttle effort. The design and fabrication of the one-fourth-scale, near-replica models of the Shuttle elements provided the necessary test hardware with scaled stiffness and mass characteristics. The data obtained from the dynamic tests have verified the math modeling techniques for predicting modes and frequencies of Shuttle configurations. The quarter-scale Shuttle elements will be used for additional dynamic tests in the future. The achievements of this program have provided convincing evidence of the versatility and economics of using dynamic scale models in any launch vehicle program.

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