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ADVANCEMENTS IN STRUCTURAL DYNAMIC TECHNOLOGY RESULTING FROM SATURN V PROGRAMS

VOLUME I

by P. J. Grimes, L. D. McTigue, G. F. Riley, and D. I. Tilden

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16. Abstract

Saturn V structural dynamic experience in replica modeling, math modeling and dynamic testing was assessed. Major problems encountered in each of these areas and their solutions are discussed. The material is presented in two volumes. Volume I contains a summary of the material presented in Volume II (NASA CR-1540) and is oriented toward the program managers of future structural dynamic programs. Volume II contains the methods and procedures used in the Apollo Saturn V structural dynamics programs. The major problems encountered and their solutions are discussed. Volume II is oriented toward the technical leaders of future structural dynamics programs.

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PREFACE

This document was produced under NASA-Langley Research Center Contract NAS1-8531. The contents are intended to carry forward to future programs the structural dynamics experience gained during the Saturn V programs.

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LIST OF SYMBOLS

A	Area (Cross Sectional)
C	Damping Coefficient
E	Modulus of Elasticity
e	Error
F	Force
G	Gain or Transfer Function
GT	Gain Tolerance
g	Gravitational Constant
h	Height
I	Moment of Inertia
[I]	Identity Matrix
j	$\sqrt{-1}$
K	Stiffness Coefficient
L	Length
M, m	Mass Coefficient
$\overline{m}$	Generalized Mass
q	Generalized Coordinate
Rx	Rotation about X Axis
Ry	Rotation about Y Axis
Rz	Rotation about Z Axis
r	Radius
S	Prestress Force for Bulkhead
[T]	Coordinate Transformation Matrix
t	Time

V	Volume
W	Work
X, x	Longitudinal Axis, Cartesian Coordinates
$\{X\}$	Mass Distribution Matrix
Y, y	Pitch Axis, Cartesian Coordinates
Z, z	Yaw Axis, Cartesian Coordinates
Δ	Deflection, Displacement
Δr	Displacement in Radial Direction
Δx	Displacement in X Direction
Δy	Displacement in Y Direction
Δz	Displacement in Z Direction
δ	Virtual (Prefix used with various symbols)
ζ	Damping Factor
θ	Angular Measurement, Spherical Coordinates
ρ	Density
$\bar{\rho}$	Dimensionless Radial Coordinate
τ	Thickness
$[\Phi]$	Matrix of Mode Shapes
ϕ	Mode Shape Function
$[\bar{\phi}]$	Matrix of Rigid Body Displacement Vectors
ω	Frequency

ABBREVIATIONS

AS-50N	Nth Apollo Saturn V space vehicle
CM	Command Module
dB	Decibel
DOF	Degree of Freedom
Hz	Hertz, cycles per second
IU	Instrument Unit
LES	Launch Escape System
LH_2	Liquid hydrogen
LM	Lunar Module
LOX	Liquid oxygen
LRC	Langley Research Center
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
Pogo	A divergent longitudinal oscillation produced by regenerative coupling between the vehicle structure and propulsion system
RP-1	A kerosene-like fuel used in the S-IC stage
S-IC	First Boost Stage of Saturn V Vehicle
S-II	Second Boost Stage of Saturn V Vehicle
S-IVB	Third Boost Stage of Saturn V Vehicle
SLA	Saturn LM Adapter
SM	Service Module

ADVANCEMENTS IN STRUCTURAL DYNAMIC TECHNOLOGY RESULTING FROM SATURN V PROGRAMS

By P. J. Grimes, L. D. McTigue, G. F. Riley,
and D. I. Tilden
The Boeing Company

SECTION 1 SUMMARY STRUCTURAL DYNAMIC TECHNOLOGY DEVELOPMENT

1.0 INTRODUCTION

The Apollo Saturn V Program was created by NASA to accomplish the objective of a manned lunar landing by the end of the decade. On July 20, 1969, the program objective was realized. This report contains a summary of the structural dynamic technology that was developed to support the Apollo Saturn V Program.

Structural dynamic characteristics of space vehicle systems must be known accurately to design the flight control system, to predict in-flight loads and to assess Pogo stability. Saturn V structural dynamic characteristics were obtained from dynamic testing of a 1/10 scale replica model, mathematical modeling, and dynamic testing of the full scale vehicle. Experience gained in these areas has been assessed and the following conclusions derived: (1) scale models are an effective tool to pilot future space programs, (2) math models can predict overall vehicle dynamic characteristics adequately, and (3) dynamic testing of the total vehicle is not required for large booster systems such as the Saturn V; however, testing of vehicle sections or stages is required to guide the analysis of major components and local deformations.

As an aid to the technical managers and engineers of future space programs, guidelines have been established for selecting, implementing and verifying structural dynamic prediction techniques. These guidelines are presented so that the major pitfalls and problems encountered in the Saturn V Program may be avoided in future programs.

1.1 DEFINITION OF SATURN V

The Apollo Saturn V space vehicle consists of the three stage Saturn V launch vehicle, an instrument unit (IU) and the Apollo spacecraft. Schematics of the three boost configurations are shown in Figure 1-1. The first stage boost configuration consists of the three stage Saturn V launch vehicle, the instrument unit, plus the Apollo spacecraft. The second stage boost configuration consists of the second and third stage of the launch vehicle, the IU, and the Apollo spacecraft. The third stage boost configuration consists of the third stage of the launch vehicle, the IU, and Apollo spacecraft.

The first stage of the launch vehicle, the S-IC stage, is 33 feet (10 m) in diameter, weighs 4.5 million pounds (2 million kgs)

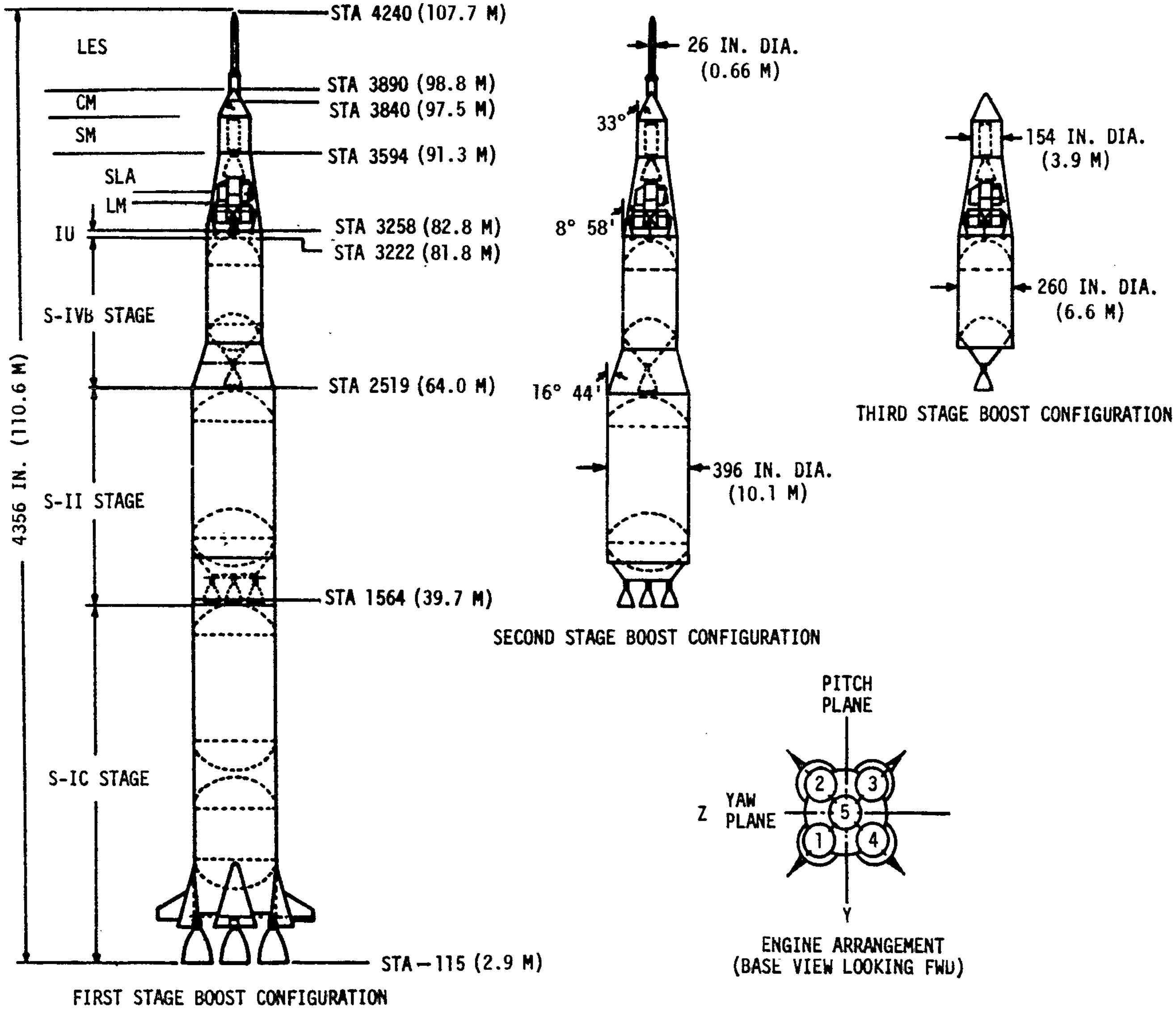


FIGURE 1-1 APOLLO SATURN V CONFIGURATIONS

1.1 (Continued)

fully fueled and develops 7.5 million pounds (33,000,000 N) of thrust. The S-II, or second stage, is also 33 feet (10 m) in diameter, weighs 700,000 (320,000 kgs) fully fueled and develops one million pounds (4,400,000 N) of thrust. The S-IVB third stage is 22 feet (6.6 m) in diameter, weighs 300,000 pounds (140,000 kgs) fully fueled and develops 200,000 pounds (890,000 N) of thrust. The instrument unit (IU), which is located immediately forward of the S-IVB stage, contains the control gyros and flight computer used to guide the flight of the vehicle during boost. The Apollo spacecraft includes a launch escape system (LES), a command module (CM), a service module (SM), a lunar module (LM), and a conical fairing known as the Saturn lunar module adapter (SLA), which attaches the spacecraft to the IU. The LES is a propulsion package which is used to lift the crew free in case of a malfunction during first stage boost or second stage ignition. The CM contains the crew plus all life support systems. It is also the re-entry body that is designed to dissipate the heat that develops during re-entry to the earth's atmosphere. The SM is a propulsion system that performs translunar midcourse corrections, brakes the spacecraft into lunar orbit and propels the crew out of lunar orbit back to earth. The LM is a two stage vehicle that is designed to land two men on the surface of the moon and return them to the orbiting command and service module.

1.2 PROGRAM DESCRIPTION AND HISTORY

The objective of the Apollo Saturn V structural dynamic program was to predict accurately the characteristics of flight vehicles. The technical approach selected to meet this objective was to develop flight vehicle math models whose accuracy could be demonstrated by ground test. As shown in Figure 1-2 there were four major steps in this approach.

1. Develop program requirements for dynamic test and analysis.

2. Conduct a replica model analysis and test program.

3. Conduct a full scale analysis and test program.

4. Develop a test-verified math model of the flight vehicle.

The 1/10 scale replica model program was conducted in advance of full scale testing. The objectives of this program relevant to the Apollo Saturn V program were to assess the adequacy of math modeling techniques and to obtain vehicle response characteristics required to support ground test and flight of the full scale vehicle. A mathematical analysis of this scale model vehicle was performed using the same methods proposed for full scale analysis. Analytical results were compared with 1/10 scale model test data. From this comparison the shortcomings in the mathematical methods were identified in time to be corrected in advance of full scale test. Correlation was maintained between the scale model program and the full scale program so that the scale model could serve as a pilot to the full scale program. From the scale model program it was possible to identify

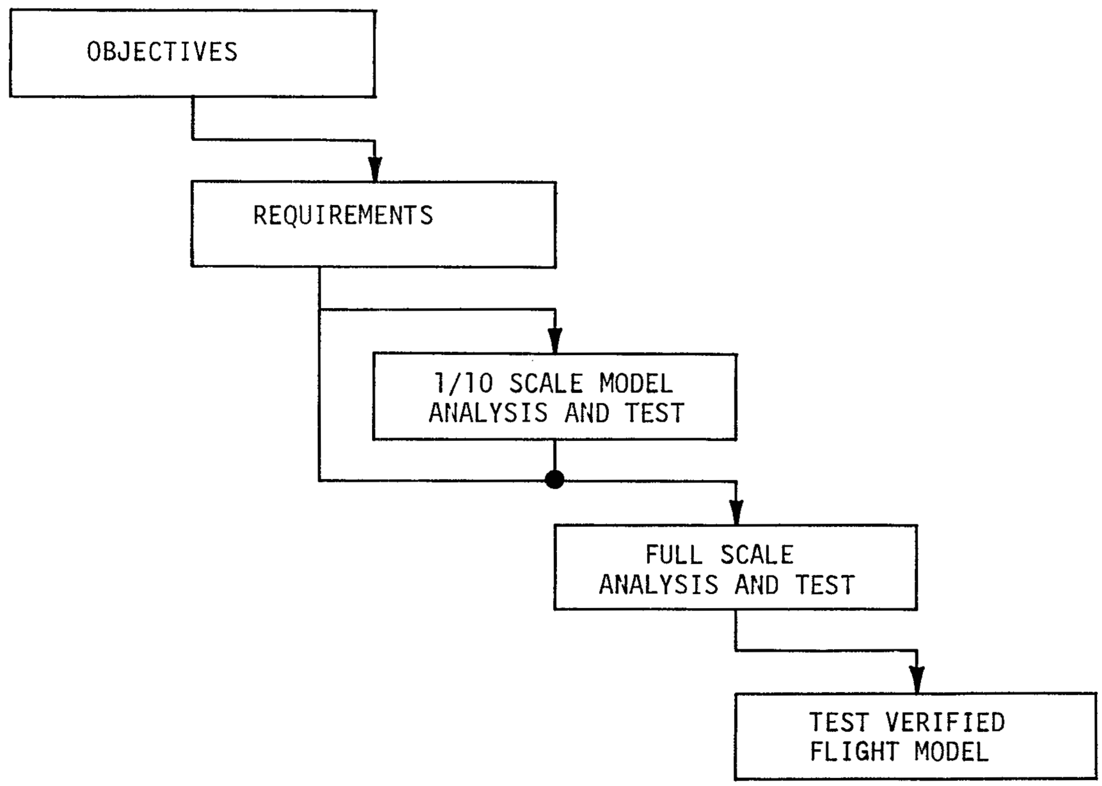


FIGURE 1-2 SATURN V STRUCTURAL DYNAMIC TECHNICAL APPROACH

1.2 (Continued)

the major problem areas in time to develop solutions to these problems and support full scale testing.

The dynamic characteristics of the full scale vehicle were predicted mathematically and documented in advance of full scale testing. These predicted characteristics proved invaluable in the conduct of the test program itself. Test results were validated and then correlated with the math model predictions. In areas where the math model proved inadequate, the model was improved as required to establish satisfactory correlation. Hardware differences between the test article and the flight article were then modeled. The end result was a math model of the flight vehicle in which all major characteristics had been verified by ground tests. The correlation cycle also allowed tolerance data to be developed for the math model as explained in Section 4.5.1 of Volume II.

1.3 SUMMARY OF 1/10 SCALE MODEL TECHNOLOGY

1.3.1 Introduction

With the inauguration of the Apollo Saturn V program, it was recognized that a replica model testing concept could pilot the program and result in resolution of technical problems before they became insurmountable from both a cost and schedule standpoint.

The 1/10 scale Apollo Saturn V model was conceived by Langley Research Center as an early, economical source of vibration response data to support the Saturn V program. Several research objectives were established for the scale model, however, they were not directly concerned with the Apollo Saturn V program and will not be discussed in this document. The model was built in advance of the full scale vehicle so that dynamic test data from the model could be used to validate the methods and procedures developed for both analysis and test of the prototype. The scale model was also used as an investigative tool for problems observed during flight test of the full scale vehicle. A complete description of the scaling and manufacturing techniques is presented in Reference 1-1.

1.3.2 Description and History

The 1/10 scale replica model consisted of five basic units, representing the S-IC, the S-II, the S-IVB, the instrument unit and the Apollo spacecraft. The Apollo spacecraft was composed of the lunar module, service module, command module and launch escape system. Below the Saturn LM adapter the primary structure was geometrically scaled. Above the SLA only the external dimensions and gross stiffness properties were scaled. The LM itself was mass simulated. The close relationship maintained between scale model and prototype stiffness is illustrated in Figure 1-3. A view of the interior of the 1/10 scale fuel tank is shown with that of the prototype in Figure 1-4 to demonstrate the fidelity with which the Saturn V was modeled.

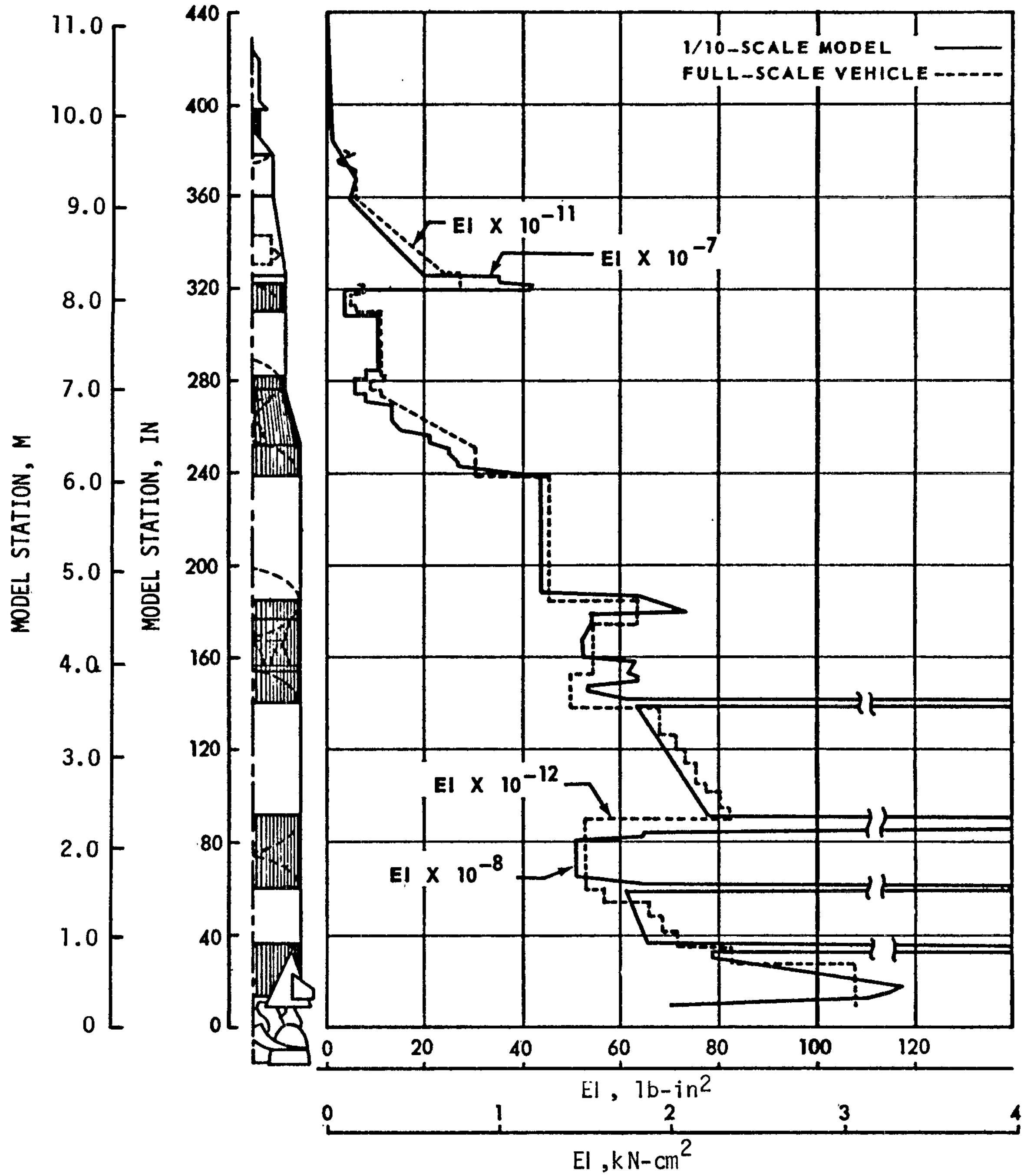
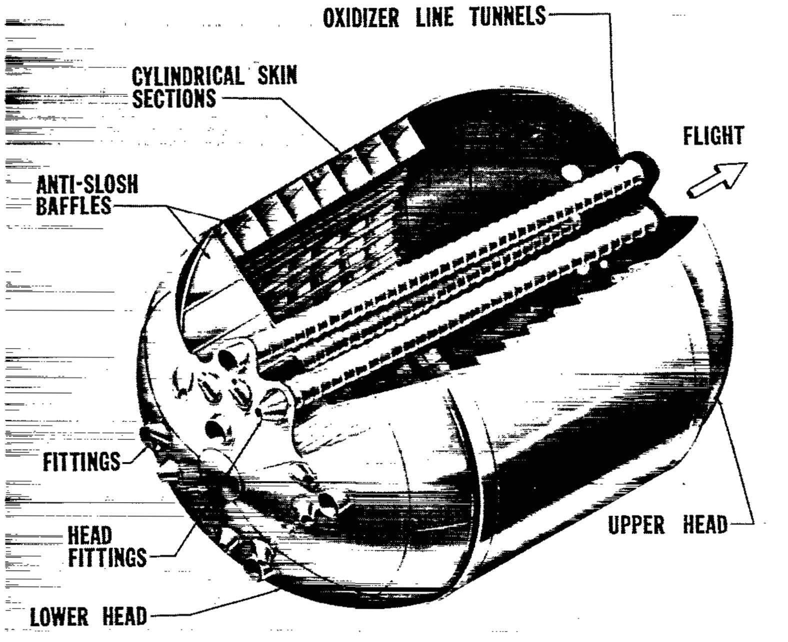
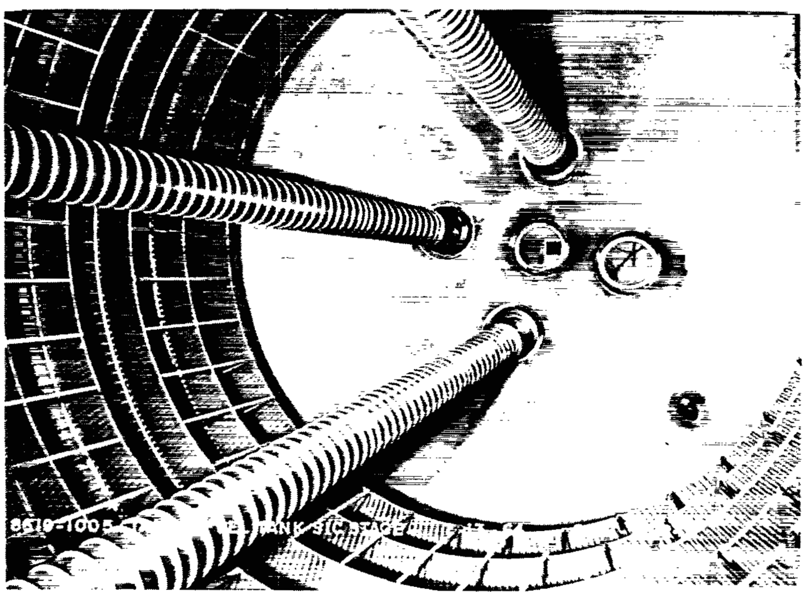


FIGURE 1-3 COMPARISON OF 1/10 SCALE MODEL AND FULL-SCALE VEHICLE BENDING STIFFNESS



SATURN V S-IC FUEL TANK ASSEMBLY



1/10 SCALE S-IC FUEL TANK MODEL

FIGURE 1-4 ILLUSTRATION OF DETAIL ACHIEVED IN MODELING

1.3.2 (Continued)

The scale model was used to investigate the dynamic properties of each of the three stages of launch vehicle boost. The test conditions were selected to parallel those planned for the full scale test. For example, water was used to simulate the liquid oxygen (LOX) and first stage fuel (RP-1), and the same tank pressures were used. This allowed scale model test results to carry forward and directly support the prototype test program as discussed in the following section.

1.3.3 Scale Model Cost and Accuracy

The 1/10 scale model was built at a cost of approximately 1/20 of the full scale test vehicle. Dynamic tests that were conducted on the model required a crew of four engineers and technicians. The cost of the scale model program was roughly 1/10 the cost of an equivalent full scale test program.

A correlation between the 1/10 scale model test and full scale test frequencies, mode shapes, and responses per unit force was made to assess the accuracy of scale modeling techniques. This comparison showed that the scale model provided a fair prediction of the vehicle response characteristics. The shapes and frequencies of the first two pitch modes are presented in Figure 1-5. The correlation of the mode shapes is good, but the full scale frequencies are 22 and 14 percent higher than those of the 1/10 scale model. The first two longitudinal mode shapes and frequencies are presented in Figure 1-6. These two modes correlate only grossly in shape, and the full scale frequencies are 23 and 11 percent higher, respectively, than the 1/10 scale model frequencies.

The major cause of differences between the scale model and full scale results was the joint flexibility of the model. The flexibility of the CM and SM interface and the IU joints can be seen in the dynamic test results in Figure 1-6. However, this was not detected until static tests were conducted. Results from the math models indicated that had the model been redesigned to eliminate this flexibility, overall correlation would have been excellent.

1.3.4 1/10 Scale Model Contributions and Areas of Improvement

The scale model program was cost effective and provided much useful information to the full scale program. Because of the technological advances gained from the 1/10 scale program, replica scale modeling could provide even greater benefits to future space programs.

Saturn V experience is summarized as follows to illustrate the potential benefits of a scale model program and areas where models could be improved for future programs.

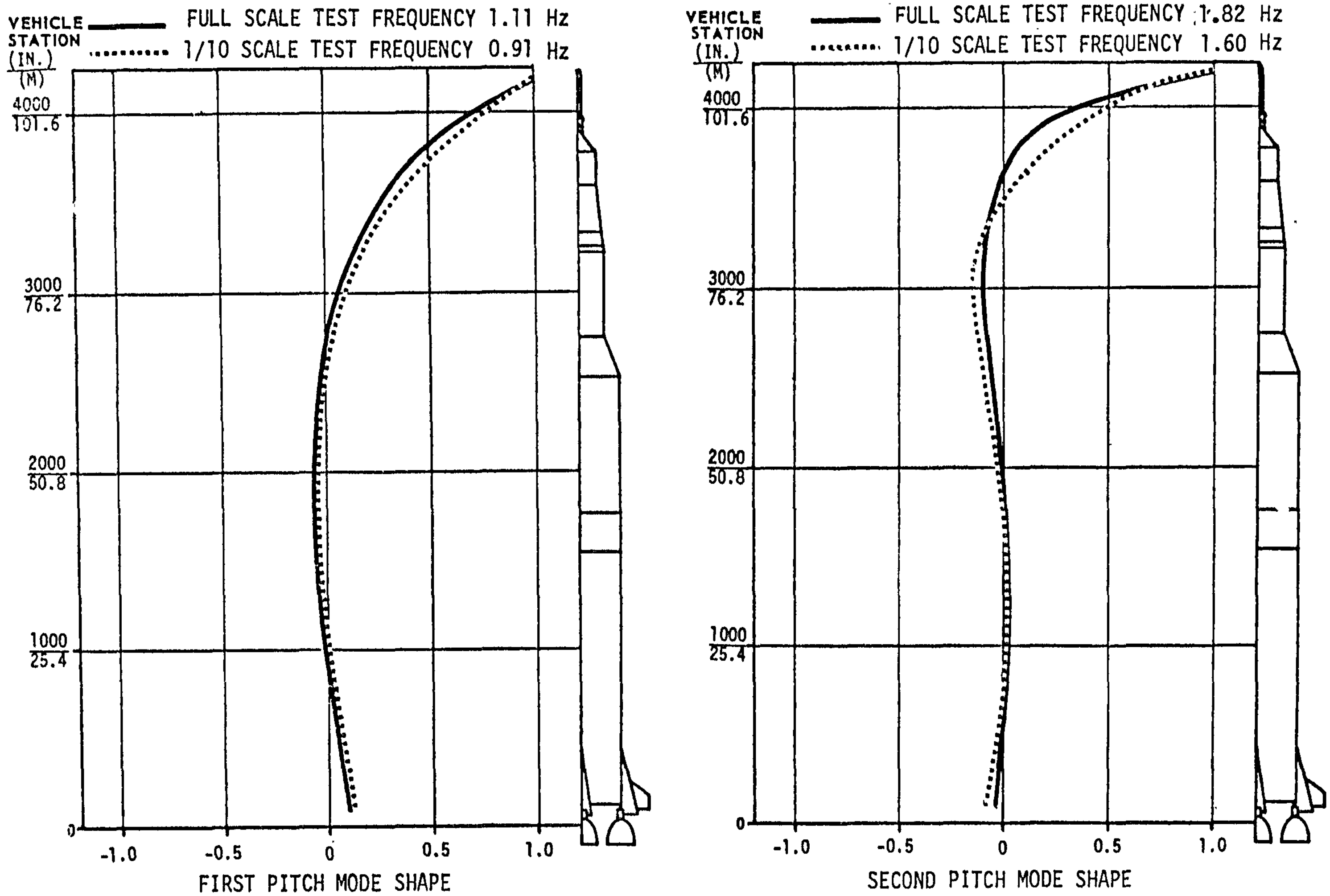


FIGURE 1-5 COMPARISON OF 1/10 SCALE AND FULL SCALE TEST RESULTS OF FIRST AND SECOND PITCH MODES - 100 PERCENT PROPELLANT

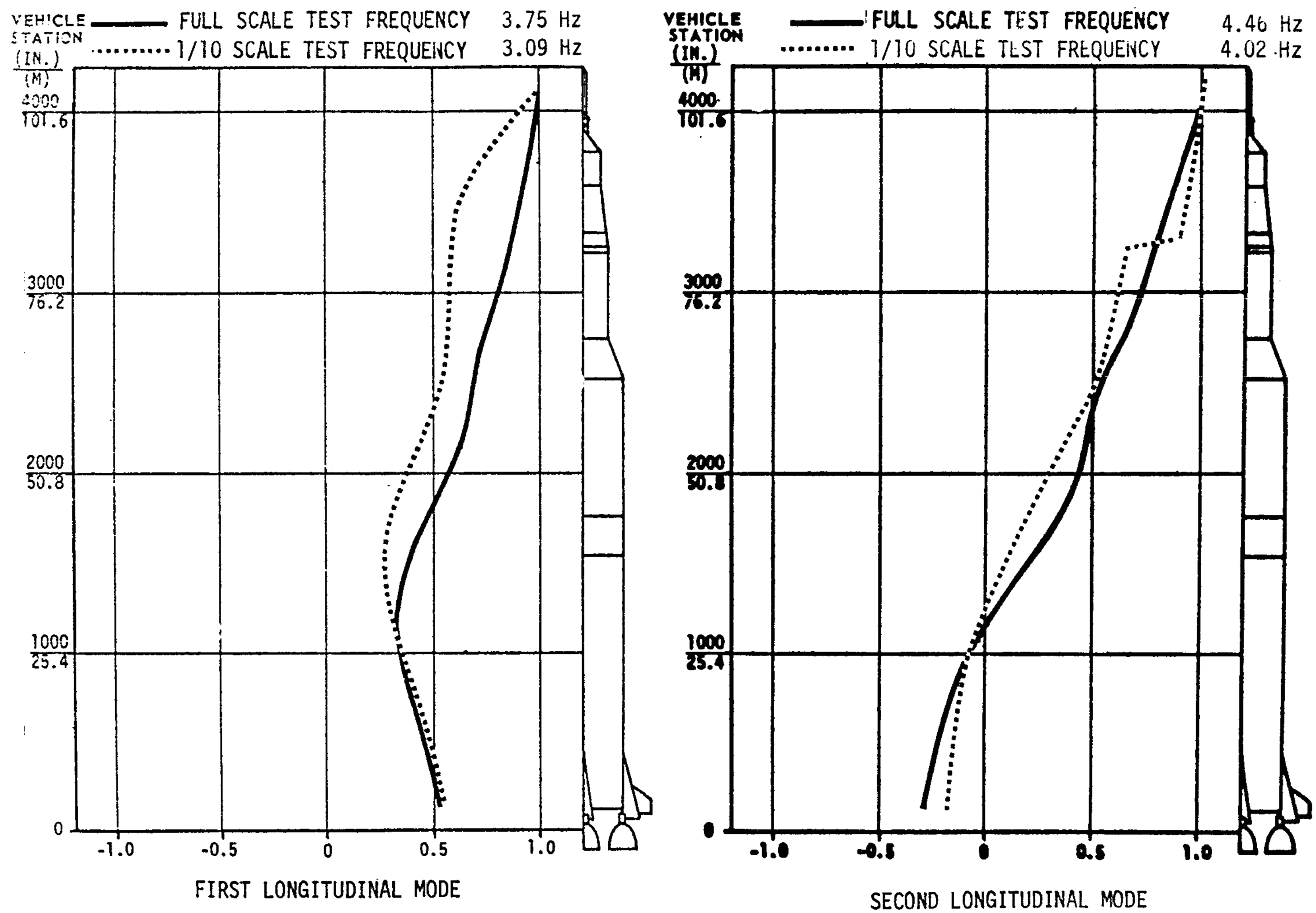


FIGURE 1-6 COMPARISON OF 1/10 SCALE AND FULL SCALE TEST RESULTS OF FIRST AND SECOND LONGITUDINAL MODES - 100 PERCENT PROPELLANT

1.3.4 (Continued)

A. Use a scale model to checkout full scale test requirements and procedures

Data from the scale model was used to assist in locating sensors on the full scale test article. The scale model showed that the most complex modal deflection patterns occurred in the spacecraft region of the vehicle and that it would be necessary to instrument this region in considerably more detail than other vehicle locations to obtain accurate modal information.

The objective of defining the transfer function between the control engines and the flight sensor locations required that the prototype vehicle had to be excited through the gimbal blocks of the control engines. Also, it was desirable to excite all modes from the gimbal blocks. Preliminary math model work indicated that the modes of interest probably could be excited to readable levels from the gimbal block, although there was concern that coupling between modes would make it difficult to isolate single mode properties. The 1/10 scale model was used to investigate this problem with the shaker located at the gimbal block. Results indicated that all modes of interest could be excited from the proposed thruster location and furthermore that the modes obtained from exciting at this location were essentially uncoupled normal modes. Also, data from this same scale model test were used to confirm that the thrusters being developed for the full scale tests could force the vehicle to readable response levels in all modes of interest.

B. Use a scale model to evaluate math models

The frequencies and mode shapes of the 1/10 scale model were calculated using the same methods being developed for the full scale vehicle. From the correlation of scale model analyses and scale model test results, several shortcomings of the math modeling approaches were uncovered. Most significant of these was the manner in which the liquid was represented in the longitudinal analysis. The correlation also showed that the truncated cones used to make vehicle diameter transitions produced a longitudinal and bending stiffness characteristic which was not being adequately modeled. The remodeling of the liquid and structural coupling and the cone areas enabled the math model of the full scale vehicle to predict the dynamic characteristics adequately. This helped to prevent a schedule impact by allowing major math modeling problems to be resolved prior to the full scale test program.

C. Use a scale model to investigate flight problems

During the flight of the second Apollo Saturn V vehicle, Pogo oscillations developed in the S-IC stage. During the Pogo oscillations, a local failure of one of the SLA panels occurred. Scale modeling techniques were used to demonstrate the integrity of the structure around the LM attach points. To accomplish this, a special scale model of the SLA, LM and SM was built. A harness was designed and constructed to

1.3.4 (Continued)

simulate the vehicle acceleration loads on the SLA. Dynamic loads equivalent to those imposed on the full scale structure were obtained by exciting the scale model in the longitudinal and pitch directions simultaneously, but no failure was produced. From this and other related studies it was established that localized failure around the LM attach points was not a factor in the failure.

D. Avoid replica modeling of joints

While the scale model program did achieve its basic objectives, its value to the Saturn program was reduced because the frequency and mode shape correlation was not achieved to the accuracy desired between the model and the prototype. Because of scaling effects, testing the 1/10 scale model in a one G environment is equivalent to testing the prototype in a 1/10 G environment. Also, the fabrication tolerances of the scale model are the same order of magnitude as those of the full scale vehicle. This caused several joints along the model to open slightly in this equivalent low G environment resulting in local flexibility being introduced into the scale model. The joints would have required redesign to eliminate this flexibility. Results from the math models indicated that had the joint flexibility been eliminated, the dynamic characteristics of the scale model would have provided an excellent simulation of the prototype. On future programs, structural joints should either be designed to transmit load effectively, or the model should be tested in a gravity simulation harness.

E. Update the model to reflect improved knowledge of the prototype

Following comparison of scale model and full scale results, the scale model itself should have been revised to establish correlation, as was the math model. Because the scale model was built before all secondary structure and major components were designed on the prototype, the replica did not adequately simulate important spacecraft components. The model should have been updated as the program progressed to include definition of this hardware. Had these changes been made, the anomaly observed on the second flight could have been investigated without the delay required to redesign and fabricate the SLA, LM, and SM models.

1.4 SUMMARY OF MATHEMATICAL MODEL TECHNOLOGY

1.4.1 Introduction

Saturn V math models were used to project ground test results to flight vehicles. The dynamics of the full scale test vehicle could not simulate the actual flight conditions because:

1. Important hardware substitutions had to be made on the test vehicle, due to cost and availability of flight hardware.

1.4.1 (Continued)

2. The free-free flight condition could not be duplicated in ground test.

3. The cryogenic propellants of the vehicle had to be replaced with less hazardous simulants for test.

4. The configuration of each flight vehicle was different, particularly in the spacecraft area.

The initial math models were simple beam-rod types and were used to support full scale test requirements. The models were used to determine the effect of replacing LOX with water, the effect of replacing flight hardware with dynamic simulators, the thruster force required to excite the vehicle to readable levels, and the sensor locations required to obtain accurate mode shape characteristics. The initial models were also used for sensitivity studies to guide the development of more accurate math models. A schematic history of the math modeling is shown in Figure 1-7.

Due to symmetry of the launch vehicle and computer size limitations, quarter shell models were used in the next step of model evolution. These models were designed to predict the modal response at each flight sensor produced by gimbaling of the control engines. Consequently, local detail was included in the engine/thrust structure areas and flight control sensor locations. At the start of the dynamic test program, the forward skirt of the S-IC and the aft skirt of the S-IVB were considered backup sensor locations to the primary location in the IU. Separate math models were developed emphasizing local detail in each of these areas. These models had the advantage of small size. However, the multiple model concept was cumbersome. Each model predicted slightly different modal frequencies and mode shapes.

To eliminate these problems and at the same time to be able to respond to local anomalies that might become evident from test or from flight, a single model was developed which had local detail throughout the vehicle. This model was basically a quarter shell representation of the total vehicle. The size problem in analyzing this model was resolved by a process of modal stacking. In this approach, cantilevered modes of the S-IVB stage and spacecraft were obtained. These were then used in the analyses of the second stage boost configuration, which consisted of the S-II stage, the S-IVB stage, and spacecraft. Cantilevered modes from this combination in turn were used to analyze the total vehicle. The modal stacking approach required additional flow time (time required to develop and conduct dynamic analysis), but proved to be an accurate and economical means of analyzing the individual configurations. This was the baseline model used to predict the characteristics of the dynamic test vehicle.

The model proved highly accurate in predicting overall modal properties of the dynamic test vehicle. For example, the frequencies

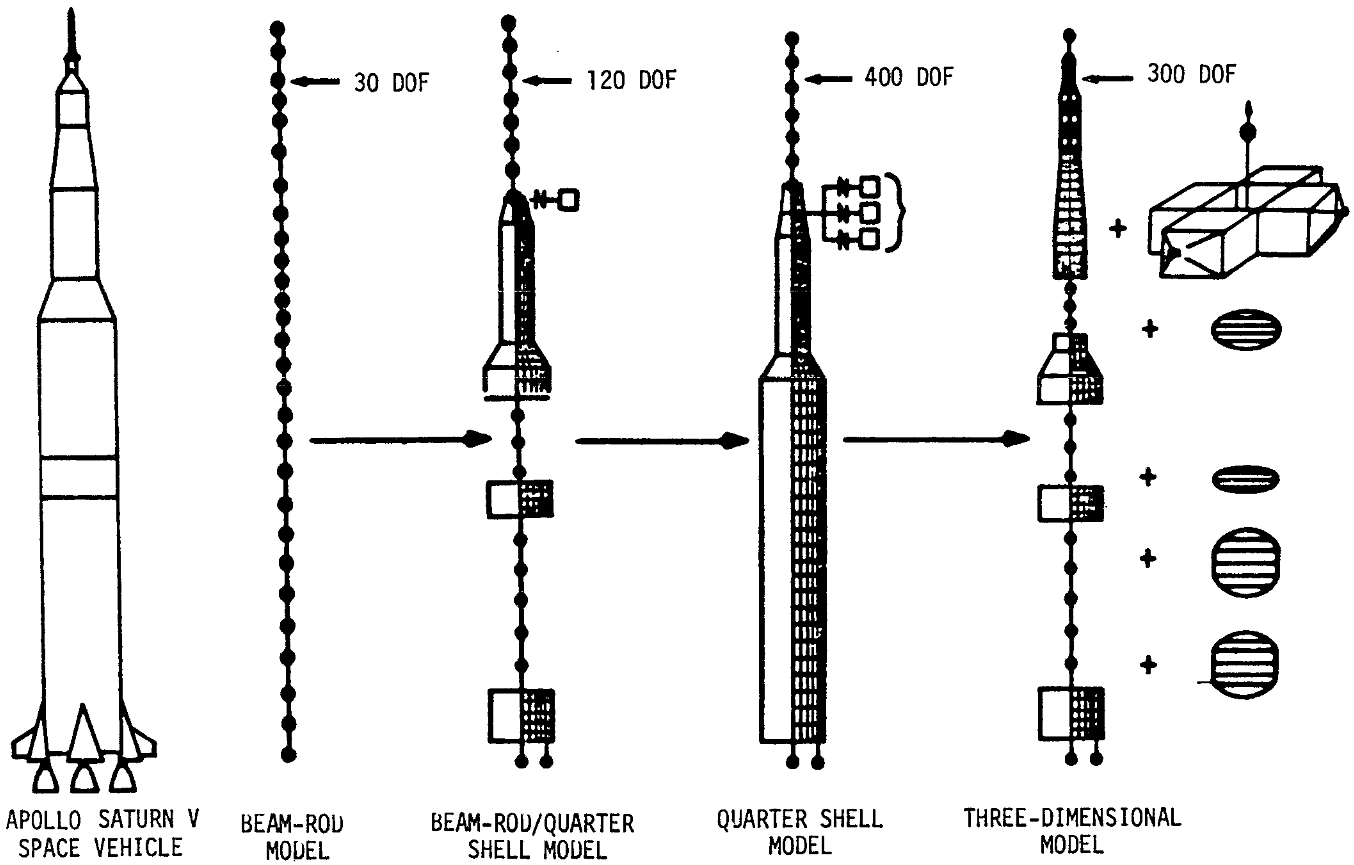


FIGURE 1-7 MATH MODEL EVOLUTION

1.4.1 (Continued)

of the bending modes of interest were predicted within four percent, and the overall mode shapes were predicted with equal accuracy for the first stage boost configuration. There were, however, several areas where the math model proved inadequate. First, the model did not predict local flight sensor slopes with desired accuracy. Second, the eccentricities in the spacecraft introduced coupling between pitch, yaw, and longitudinal planes which the model did not have the capability of predicting.

The model was revised to establish correlation in the flight sensor areas. This test-verified model became the baseline for all subsequent analyses.

In order to represent the interplane coupling, a three-dimensional model of the total vehicle was developed. This model was simplified in insensitive areas. The test-verified baseline model was used to insure that these simplifications did not degrade overall model accuracy. A computer program was developed to handle the new three-dimensional model, which had 12,000 stiffness degrees of freedom which reduced to 300 dynamic degrees of freedom. This simplified full shell model became the new baseline and was used in Pogo, loads, and flight control predictions on a vehicle-by-vehicle basis to support Saturn V flights.

1.4.2 Technical Approach

Finite element models are used to represent the structural dynamic characteristics of Saturn V vehicles. The methods used in the pretest analysis are documented in Reference 1-2. These methods have since been revised and documented in internal Boeing documents. The equations of motion for a finite element model have the form

$$\underbrace{[M_{ij}]\ \{\ddot{q}_j\}}_{\text{Inertia Forces}} + \underbrace{[C_{ij}]\ \{\dot{q}_j\}}_{\text{Damping Forces}} + \underbrace{[K_{ij}]\ \{q_j\}}_{\text{Elastic Forces}} = \underbrace{\{F_i\}}_{\text{Applied Forces}} \quad (1.1)$$

The generalized coordinates, the q_j's, used in a finite element analysis are frequently chosen to be the Cartesian components of displacement and/or rotation at discrete points on the system. These points are known as nodes.

In the finite element approach, the actual structure is represented by a system of idealized beam, plate and stringer elements, which are connected at the nodes. The properties of each finite element, such as thickness, moment of inertia, and length, are calculated from structural drawings and provided to a computer program as input data. The computer program generates stiffness matrices for each structural element defined in the input data.

Each matrix is generated in the local coordinate system of the element. Transformation matrices are computed and applied to obtain the stiffness coefficient components of each element in a common coördinate system. These elemental stiffness matrices are then added together to obtain the stiffness model for the total structure. Boundary conditions for the nodes are then imposed. Fixed boundary conditions are imposed on a stiffness matrix by deleting the rows and columns associated with the degrees of freedom at underformable points on the structure. A pin joint is introduced by reducing the appropriate rotational degree of freedom prior to adding the elements together.

Boundary conditions for a stiffness analysis are determined by structural symmetry or antisymmetry as well as by physical constraints. For example, a typical launch vehicle, which may have two orthogonal planes of symmetry, can be represented by a quarter shell model. The effects of the missing three quadrants of the structure can be represented by appropriate boundary conditions.

The size of a stiffness matrix can be reduced by a process of matrix reduction, or by application of constraints transformations. Some nodes on the idealized structure may be subject to small loads and can be assumed to be unloaded. The displacements of these "unloaded" nodes can be eliminated from the force/displacement equations by a process known as matrix reduction (Reference 1-3).

Assumed relationships between the nodal displacement are often used to reduce problem size. These relationships are frequently based on mode shapes or polynomial shape functions. Relationships which express the motion of an N degree of freedom system in terms of fewer than N variables are known as constraint transformations.

In the Saturn V models, the motion of many of the nodes was expressed in terms of constraint functions satisfying the appropriate geometric boundary conditions. These functions were used to represent ring modes, simplify bulkhead models, and idealize nearly rigid substructure. The transformations, which were applied to both stiffness and mass matrices to maintain consistency, proved an effective technique for reducing problem size with minimum loss of accuracy.

In a dynamic analysis, inertia matrices are developed to represent the distributed inertia characteristics of the system. Improved accuracy is obtained by developing inertia matrices and stiffness matrices in an identical manner (Reference 1-4). The Saturn V inertia coefficients were generated for the same fine nodal breakdown used in the stiffness analysis. The inertia matrices were "reduced" or constrained using the same transformations applied to the stiffness matrices (Reference 1-3).

The inertia characteristics of liquid filled tanks were obtained by using the property of liquid incompressibility to relate motion of the liquid to the elastic deformation of the tank structure.

1.4.2 (Continued)

The damping properties of an actual system vary nonlinearly with response amplitude. Damping through the vehicle is also nonproportional; that is, the damping characteristics vary between vehicle components. On the Saturn V, equivalent linear, proportional damping characteristics were used. These were obtained by exciting the test article to expected flight response levels and extracting equivalent modal damping constants from the test data.

The normal modes, generalized mass, and frequencies of a system are referred to as dynamic characteristics. Dynamic characteristics are used as source data in three types of analyses on the Saturn V vehicle: dynamic loads analyses, flight control analyses and Pogo stability analyses. For large booster systems, the region of interest lies in characteristics below 25 Hz in frequency. The fundamental bending mode frequency of the Saturn V vehicle is approximately one Hz.

After generating consistent inertia and stiffness matrices, the normal modes and frequencies of the system are obtained by rooting the equation of undamped free vibration.

$$[M_{ij}] \quad \{\ddot{q}_j\} \quad + \quad [K_{ij}] \quad \{q_j\} \quad = \quad \{0\} \qquad (1.2)$$

If the system is free-free, the equation above will have up to six zero frequency solutions which are the rigid body modes of the system. These zero frequency solutions can be developed directly from the geometry of the system. Modern computer techniques will obtain all of the frequencies, mode shapes, generalized masses, plot tapes, and gain factors of the 300th order system in 75 minutes of computer time, for properly conditioned systems.

1.4.3 Math Model Analysis Guidelines

The modeling techniques used in the Saturn V structural dynamics program were adequate for predicting the overall vehicle dynamic characteristics. Most of the difficulties encountered in the program were associated with local deformation or component dynamics. These difficulties occurred because: (1) proper emphasis was not given to modeling local and component dynamics effects, and (2) structural dynamic techniques require test results to guide the modeling of these effects.

The Saturn V program demonstrated that overall vehicle characteristics such as mode shapes and frequencies could be predicted accurately with available modeling techniques. As a result, dynamic testing of the total space vehicle is not required to support future programs similar to Saturn V. However, dynamic testing of major components and major structural assemblies is mandatory where mathematical models for predicting local characteristics are to be established to a high level of confidence.

The problems encountered during conduct of the Saturn V struc-

1.4.3 (Continued)

tural dynamic programs have been assessed. From this assessment guidelines for conduct for future programs have been established. These guidelines are summarized in the paragraphs that follow.

A. <u>Establish and maintain math model baseline</u>

In large programs such as Saturn V the requirements of the mathematical models continually change as the program matures. Because of the constant state of change there are two ground rules listed below that cannot be over-emphasized.

1. Establish a baseline model that where possible is test verified.

2. Develop new models in parallel with the baseline model. Do not change the baseline until the new models are completely verified.

Once a baseline model is established all subsequent models should be validated by comparison with baseline results. These models should be accepted as the new baseline only after they have proven their superiority to the previous baseline model.

Saturn V dynamicists were trapped in several instances by not adhering to this guideline. The 'man-on-the-moon-in-this-decade' goal required strict adherence to schedules. Pioneering with new models and new software programs should not be attempted when the matrix order is large and the analysis results are program critical both from a schedule and quality standpoint. Engineers and programmers habitually underestimate the cost and flow time for math model changes.

B. <u>Maintain checking and documentation discipline in the face of schedule pressure</u>

With large analysis programs involving critical schedules, there is a tendency to relax normal engineering discipline in checking and documenting engineering calculations. In other words, the program tends to move faster than the documentation. Engineering management must be firm in controlling checking procedures and insuring the preparation of good engineering documentation. A good check of whether adequate engineering documentation is being maintained is whether an engineer familiar with structural dynamics but unfamiliar with the problem at hand can take the available engineering notes and reconstruct the analysis. If this test fails, documentation needs to be improved.

The following guidelines for avoiding a schedule squeeze resulted from Saturn V experience.

1. Scope the model effort allowing a realistic "pad" for contingencies.

1.4.3 (Continued)

2. Never make model changes or improvements on a tight schedule if an existing model can produce acceptable results.

3. Place the most experienced engineers in the checking loop.

C. Maintain a proper physical perspective

In conducting a computer analysis of a complex system, it is easy to lose sight of the physical realities of the problem being solved. It should be kept in mind that computer programs are an aid to experience and engineering judgement, not a substitute for them. A computer solution requires all of the skills displayed in a hand solution, plus an intimate knowledge of how the computer program works, what its limitations are, and what numerical problems are apt to occur. At all points in the computer analysis, checkpoints with physical reality need to be planned in. The following checklist can be used as a guideline for keeping math models free from error.

1. Always precede a complex analysis with a good simplified analysis. This will provide a gross check on the answers the complex analysis is giving.

2. Cantilever the system and invert the stiffness matrix. Plot the force/deflection coefficients from this inverse and interpret them physically. Does point B deflect to the left when engineering judgement says it should go to the right? If so, stop and investigate until the physical mechanism that makes point B deflect to the left is understood or a modeling error has been identified.

3. Take advantage of all available test data. The major structural assemblies such as thrust structures, interstages, and tanks, are usually subjected to static loading. Learn about these tests and try to influence them so data can be obtained to check the model.

4. Never pass up an opportunity to put the model to the test. Has another model been developed for the same structure? If so, meet the developer and compare notes; where differences exist, resolve them on the basis of physical arguments rather than size and complexity. Simple models often reveal flaws in much more complex models.

D. Be aware of numerical limitations

The idealization will be determined more by the limitations, both in size and numerical accuracy, of the computer programs than by physical properties of the structure itself. For example, if a stiff structure connects to a flexible structure, the difference in stiffness introduces numerical difficulties that may invalidate the analysis. The stiff structure will require wider spacing of the nodes, or will have to be represented as a rigid body. On flexible structure, too fine a breakdown can introduce numerical difficulties that destroy accuracy. At each step in the analysis, the results should be checked for numerical accuracy.

The rigid body check should be used to test the numerical accuracy maintained in generating the stiffness matrix. This computation, used in a free-free system only, involves multiplication of the stiffness matrix by as many rigid body displacement vectors as the system has kinematic singularities. The resulting column matrices should show residual forces that approach zero. Due to numerical round-off errors in forming and reducing the stiffness matrix, the residual forces will not equal zero. For each row of the stiffness matrix, the permissible round-off error resulting from a unit displacement should be at least five orders of magnitude lower than the diagonal stiffness element in that row.

Numerical error in the flexibility influence matrix should be checked as follows: Restrain rigid body motion and invert the stiffness matrix; then multiply the stiffness matrix by its inverse. The product should produce an identity matrix. Check this product matrix. If the diagonal terms differ from unity by more than ± 0.001, or the off-diagonal terms differ from zero by more than ± 0.001, review the idealization and eliminate the source of numerical difficulty.

The eigenvalue solution should be checked by the orthogonality condition of the modes. This is accomplished by checking the off-diagonal terms of the generalized mass $[\phi]^T[M][\phi]$ and stiffness $[\phi]^T[K][\phi]$ matrices. The off-diagonal terms are theoretically zero because of orthogonality. In reality the off-diagonal terms are never zero because of numerical error. A good rule of thumb is that six orders of magnitude difference between diagonal and off-diagonal terms should be a minimum objective for the mass matrix, with three orders of magnitude required for the stiffness matrix.

E. <u>Give special care to modeling liquid filled tanks</u>

In analyzing the Saturn V propellant tanks, it was recognized that idealizing the lower bulkheads would be a particular challenge. Approximately 90 percent of the total weight of the Saturn V vehicle is in the form of liquid propellant whose longitudinal inertia reaction is supported by the lower bulkheads. A special technique was derived to represent the deformed shape of the bulkheads in terms of a polynomial power series. The liquid contained within the tank was related to the elastic tank deformations by assuming it to be incompressible. A consistent stiffness model was derived to represent the dynamic characteristics of each tank. This technique proved adequate for predicting the tank modes of the S-IC stage. However, the tank modes of the second and third stage, which occurred at a much higher frequency and involved much

1.4.3 (Continued)

more complex elastic deformations of the bulkheads, were not modeled adequately by this technique.

In ellipsoidal shells a major section in the bottom of the tank is quite flat. Using finite elements to represent this curved surface exaggerates the flatness. Under load the shell stretches until the bulk of the load is carried by membrane action. This geometrically nonlinear mechanism is analogous to a stretched cable. In the Saturn V analysis no attempt was made to model this geometric nonlinearity. Instead polynomial shape functions were used to simulate the correct inertial load and to distribute this reaction to the remainder of the bulkhead where this problem does not occur. This approach represented the dynamics of the primary structure, but did not predict tank bottom pressures accurately. The latter characteristics proved to be important in investigating high frequency Pogo problems. It is recommended that the stiffening effect of bulkhead prestress be represented in future math models.

F. Determine the influence of major components on vehicle dynamics

Major components which are located in dynamically active sections of the vehicle can have a surprising influence on overall response. Both the stiffness and inertia characteristics of major components need to be investigated thoroughly before establishing math models.

The Saturn V lunar module exerts a strong influence on the dynamic characteristics of the total vehicle, which outweighs the LM by a factor of 200. On the flight of the second Saturn V, a Pogo instability developed in the first longitudinal mode of the vehicle. Pogo is a closed loop response involving engine thrust oscillations, which excite a strong vehicle longitudinal mode, producing pressure pulses in the liquid propellant that in turn reinforce the thrust perturbations. The second flight Pogo phenomenon was characterized by strong coupling between longitudinal and pitch responses. The mechanism producing this coupling was traced to the LM.

The lunar module is a two-stage vehicle in which the ascent stage is coupled to the descent stage by an asymmetrical stiffness arrangement. This arrangement is illustrated in Figure 1-8. While the inertia properties of the lunar module are symmetrical within two percent, the stiffness asymmetry alone provides a mechanism for coupling pitch and longitudinal motions. Because of the dynamic activity of the lunar module this local coupling mechanism induces pitch and longitudinal coupling into the total space vehicle. This dynamic coupling increased the strength of the first longitudinal mode by three dB, which was sufficient to induce the Pogo instability. A special dynamic test was required to support the development of an accurate LM math model.

G. Recognize areas that require test verification

Some structural configurations require test guidance to model accurately. The S-II stage LOX tank and thrust structure assembly is an

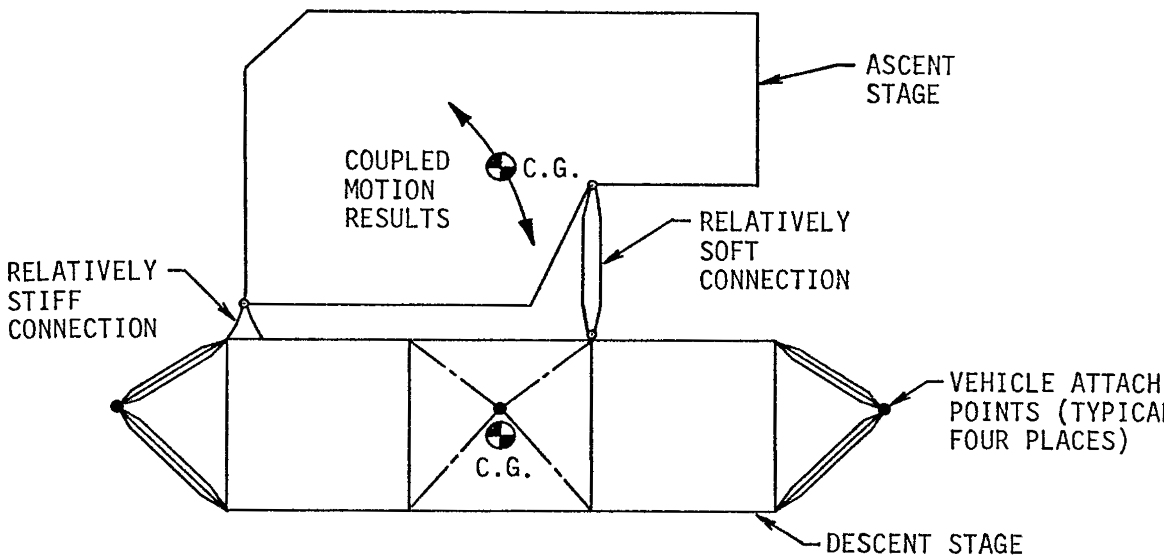


FIGURE 1-8 LM ASYMMETRY EXAMPLE

example of such a structural configuration. As Figure 1-9 illustrates, the aft LOX bulkhead supports a heavy sump and LOX propellant lines. This sump is reacted by membrane prestress forces in the bulkhead. The crossbeam supporting the inboard engine is pin connected to the thrust cone. Under thrust load, the pins bind and the end conditions become indeterminant. The effective damping of the crossbeam changes as a function of beam loading and response amplitude.

After the second flight, additional instrumentation was installed on subsequent flight vehicles in the thrust structure and tank areas. From this instrumentation, strong longitudinal oscillations of the S-II stage were observed in data from the third flight. These oscillations were also reported by the astronauts. The oscillations were produced when the frequency of the first LOX tank mode coalesced with the 18 Hz first mode of the crossbeam, producing Pogo in the inboard engine. The crossbeam and thrust structure models were revised, but correlation with flight data indicated that the coupling between crossbeam and tank was not being adequately predicted. Models developed throughout the industry proved inadequate to simulate this Pogo condition. It was necessary to conduct dynamic testing to identify model inadequacies.

H. <u>Treat the stiffness and mass matrices consistently</u>

Modeling conducted on the Saturn V program has demonstrated the advantages of treating stiffness and mass matrices consistently. The mass matrices were subjected to the same transformations and constraints applied to the stiffness matrix. One method of consistent mass reduction is the Guyan approach presented in Reference 1-3. The accuracy of the consistent mass reduction method was compared with that of the lumped mass method by using a baseline model of the S-IVB forward skirt, the IU, and the SLA shown in Figure 1-10. The baseline dynamic model contained 181 degrees of freedom. Normal modes were obtained from this model and used as a baseline for comparing the accuracy of the reduction methods. Two 78th order models were then developed from the baseline model. The first 78th order model was obtained using Guyan consistent mass reduction. The second 78th order model was developed by relumping masses.

The frequency of the first free-free bending mode of the three models and the ring mode shapes, at the top and bottom of the IU, associated with the first bending mode are presented in Figure 1-11. The frequency of the 78th order Guyan consistent mass model is within 6 1/2 percent of the baseline model. Also, the ring mode shapes have the same general trends as those of the baseline model. The frequency of the 78th order relumped mass model is 20 percent lower than the baseline model and the ring mode shapes show little resemblance to the baseline shapes. This comparison shows dramatically the improvement in accuracy obtained from the consistent mass approach.

The consistent mass approach imposes a small constraint on the system and accounts for the slightly higher frequencies that are obtained

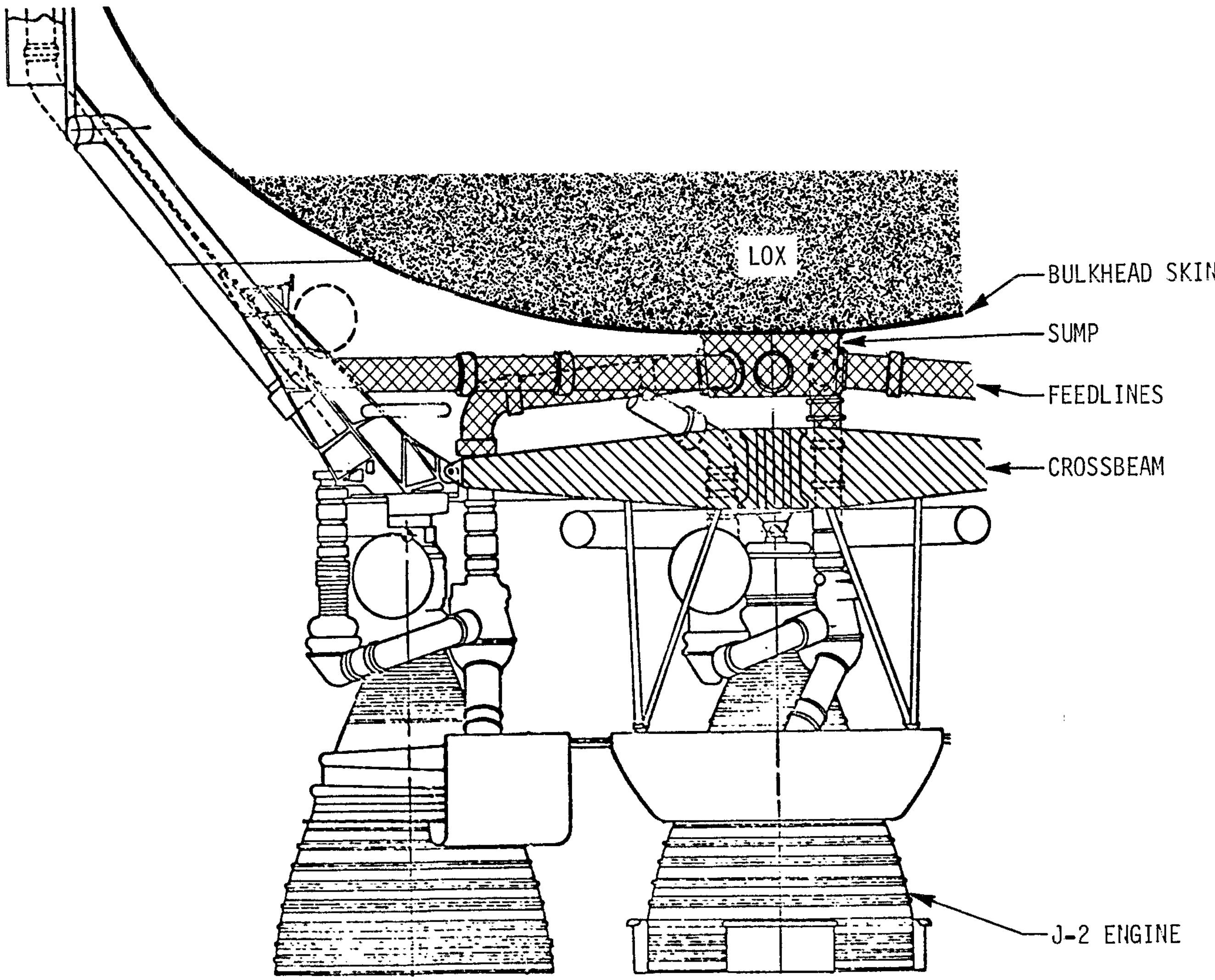
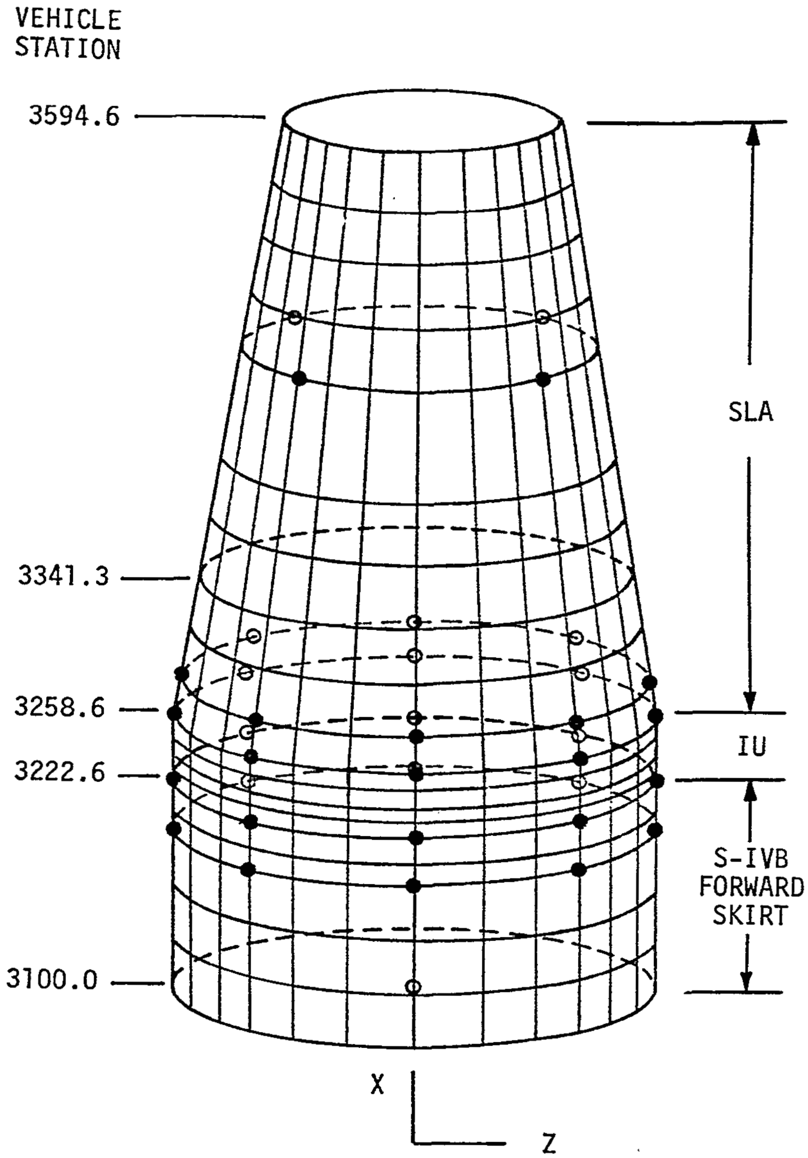
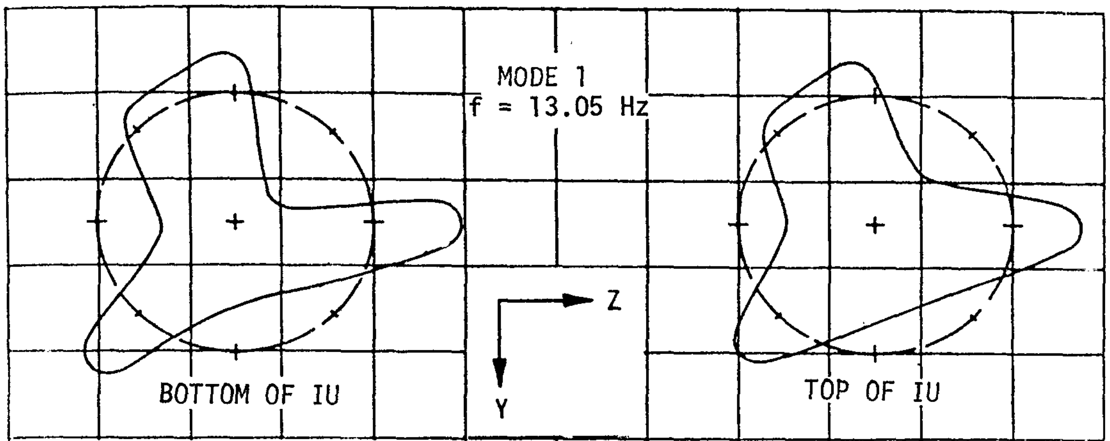


FIGURE 1-9   S-II AFT LOX BULKHEAD

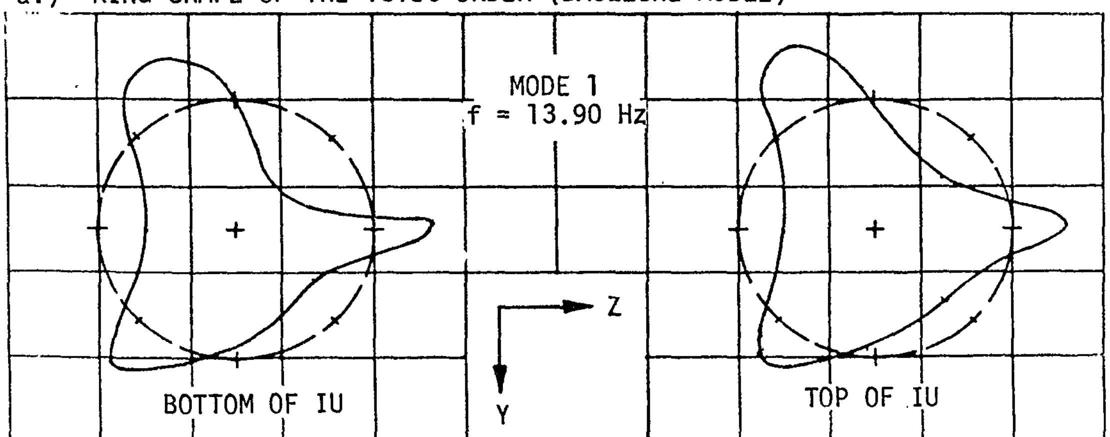


S-IVB FORWARD SKIRT,
I.U. & LEM ADAPTER

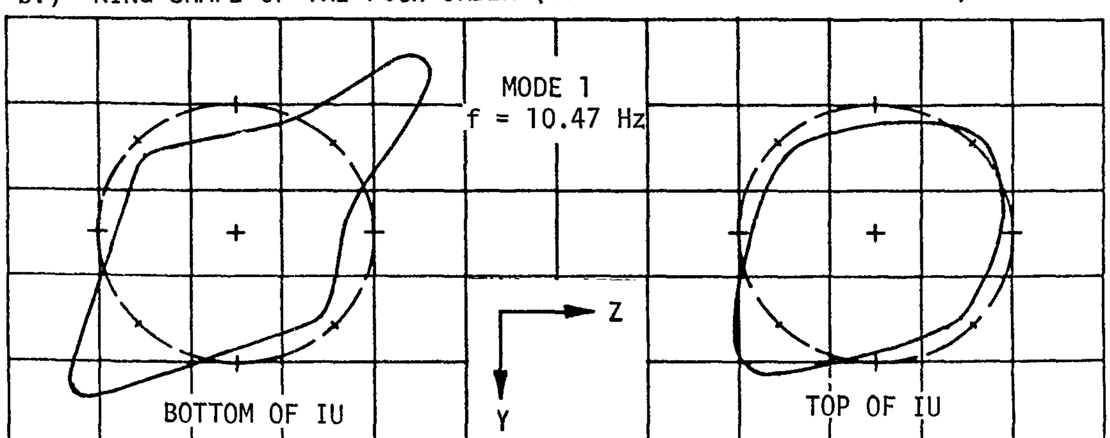
FIGURE 1-10 S-IVB FORWARD SKIRT, IU AND SLA NODAL BREAKDOWN



a.) RING SHAPE OF THE 181st ORDER (BASELINE MODEL)



b.) RING SHAPE OF THE 78th ORDER (GUYAN CONSISTENT MASS MODEL)



c.) RING SHAPE OF THE 78th ORDER (RELUMPED MASS MODEL)

FIGURE 1-11 CONSISTENT MASS REDUCTION COMPARISON using this approach. The relumped mass produces a concentration of mass and accounts for the lower frequencies that are obtained using this approach. The consistent mass approach is a powerful technique for obtaining accurate solutions from math models of reasonable size.

I. Beware of static effects when using modal synthesis

Modal synthesis is a process of representing the dynamic properties of a component or major subassembly in terms of selected normal modes of that subsystem. This process is frequently used to simplify math models and achieve local detail with a minimum of modeling complexity. This approach was used to obtain a detailed math model of the S-IVB forward skirt, IU, and SLA for purposes of predicting accurate elastic rotations of the flight sensor supports. A free-free modal analysis of the structure shown in Figure 1-10 was made. Modes up to 50 Hz from this analysis were used to represent this structure in the modal analysis of the total vehicle.

When results were obtained from the full scale dynamic test, it was discovered that local deformation in the IU caused large rotations of the control gyros that were not predicted by modal synthesis. The local deformation was produced by the way the dynamic loads from the CSM and LM were transmitted through the IU. These local deformations proved to be associated with high frequency modes of the S-IVB forward skirt, IU, and SLA model that were not included in the modal coupling. The local deformation was determined by:

1. Obtaining modal displacements at the bottom of the forward skirt and at the top of the SLA from a dynamic model of the total vehicle which had a simple shell model of the forward skirt, IU, and SLA.

2. Applying these boundary displacements to the detailed forward skirt/IU/SLA model and solving the static deformation problem to obtain local IU rotations.

The modal synthesis technique proved to be powerful and accurate, but care must be taken in selecting the modes. High frequency modes from a subsystem may be required to produce low frequency modes of the total system.

J. Establish and maintain direct communication with all user organizations

The dynamic characteristics generated from the Saturn V mathematical models were used by many government and contractor agencies. Structural dynamic characteristics were developed for each space vehicle and rigorously documented in source data documents. The configuration of each vehicle was tracked. When major changes were made, new structural dynamic characteristics were generated and the source data document updated. Despite

1.4.3 (Continued)

this rigor, the dynamic characteristics were used improperly on a number of occasions. Experience has shown that written communication, although necessary, is not sufficient. Continuing face-to-face communication between the model developers and the users of the data is essential.

In addition, the structural dynamicist should review and become familiar with the equations of motion employed by the data users. On the Saturn V program this check of user organization equations revealed incompatibilities between the way that propellant slosh and control engine dynamics were represented in the structural dynamic analysis and the way that they were handled in the flight control stability and flight loads analyses.

1.4.4 Math Model Cost and Accuracy

Cost and flow time are prime considerations in model development. As an aide to future Government and industry engineering groups involved in math modeling of complex structures, an estimate has been made of the costs of developing the present Saturn V model. In forming this estimate, the following assumptions have been made:

1. An adequate software and hardware program capability exists.
2. Structural drawings are available.
3. No evaluation of data is involved except the mechanical checks.
4. Detailed mass data breakdowns of each stage and payload module are available.
5. No allowance has been made for learning.
6. Computer hours are based on the IBM-360 system.
7. No documentation of data has been included.

The planning estimate is shown in Table 1-I. Computer hours, manpower resources in manmonths, and flow time are shown for the stiffness matrix development, the merge of component modules and the generation of dynamic characteristics for one fuel level condition. This cost breakdown is based on experienced personnel and with the provision that the model nodal network is defined. For the engineering group with average talent faced with a new program such as the Saturn V, factors should be applied to the estimates shown. It is suggested that a factor of 2.0 be applied to manpower, computer hours and flow time to bring an organization up to an adequate experience level. Even experienced engineers in this type of analysis must iterate solutions many times to determine the proper structural idealization with a practical number of degrees of freedom. A factor of 2.5 should be applied to account for the formulation of the optimum network.

TASK	COMPUTER HOURS	MANMONTHS	FLOW TIME (MO.)
Module Development	50	65	13
System Merging and Eigenvalue Solution	11	9	5

TABLE 1-I MATH MODEL DEVELOPMENT PLANNING ESTIMATE

1.4.4 (Continued)

The modeling techniques used in the Saturn V structural dynamics program were adequate for predicting overall vehicle dynamic characteristics. The frequencies of the first four vehicle modes were predicted within 4 percent, with the mode shapes predicted with equivalent accuracy. A correlation of the math model and full scale test results for the first two longitudinal and pitch modes of the first stage boost configuration are presented in Figures 1-12 and 1-13, respectively. However, major component effects and local deformations could not be predicted to the same accuracy. Mathematical models capable of predicting these local characteristics with a high level of confidence must be established by test data.

1.5 SUMMARY OF DYNAMIC TEST TECHNOLOGY

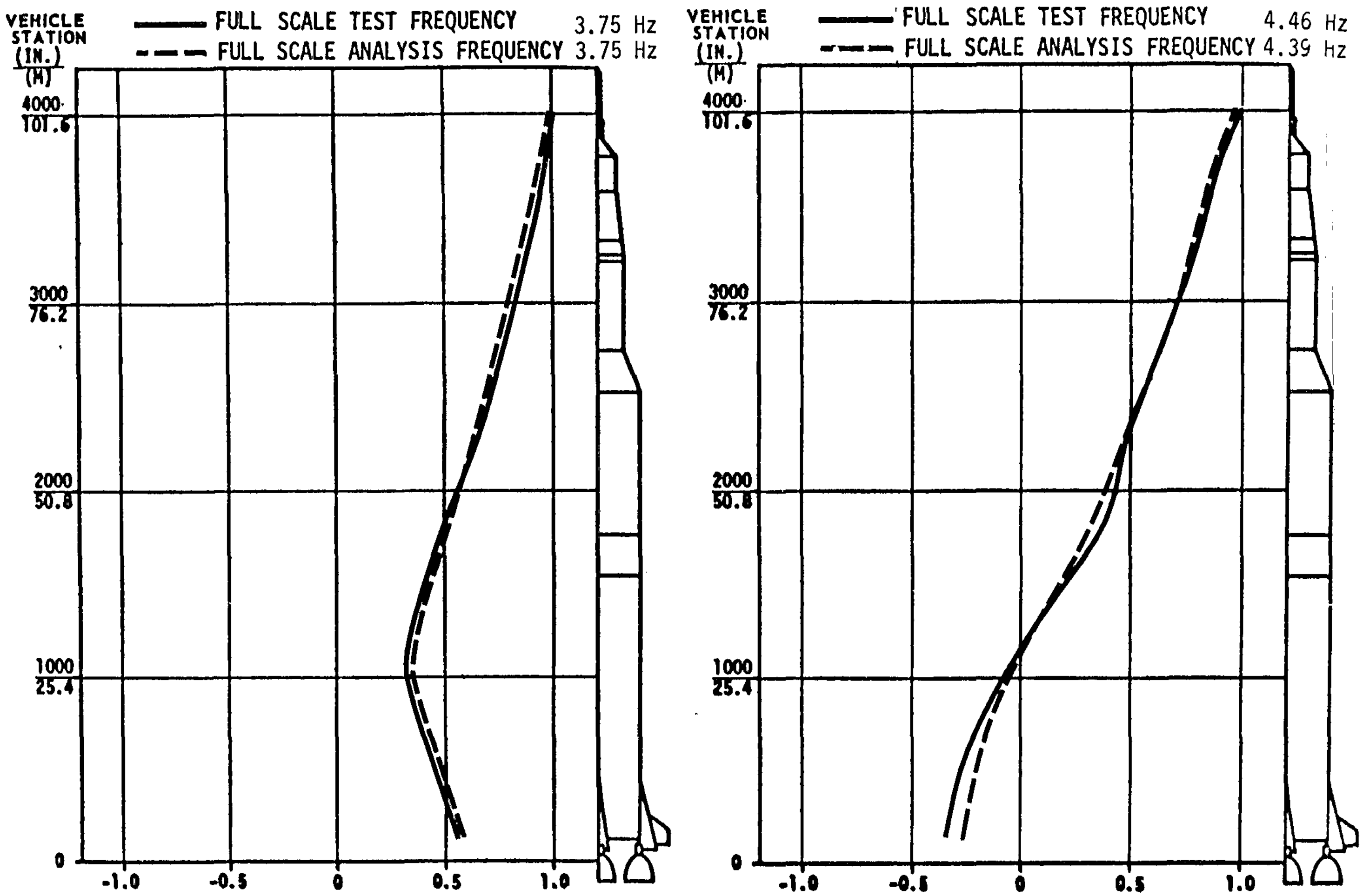
1.5.1 Introduction

Dynamic testing of the full scale Saturn V vehicle was conducted at the Marshall Space Flight Center between October 1966 and August 1967. The objective of this test program was to support the development and verification of accurate mathematical models of the flight article. The testing was also intended to investigate vehicle nonlinearities and measure structural damping.

Approximately 18 months of planning preceded the start of the dynamic test program itself. Every major facet of the total test program was planned in fine detail. The results of this planning formed a requirements baseline. The detailed requirements forming the baseline for the program were documented. No aspect of the test program itself could be altered without a revision to this baseline document. It was this document that provided the necessary program continuity and control. The document covered not only requirements for the test program itself but also identified how the various programs would interrelate to support the final objective of establishing verified math models.

The test article consisted of flight hardware in all mainline structures and major components with few exceptions. These exceptions were the LM and the mainstage engines, where mass simulators were substituted. A test tower was constructed to shield the test article from wind and rain, to facilitate access to the vehicle, and to provide a means of assembling the various stages of the vehicle. The test article in the test tower is shown in Figure 1-14.

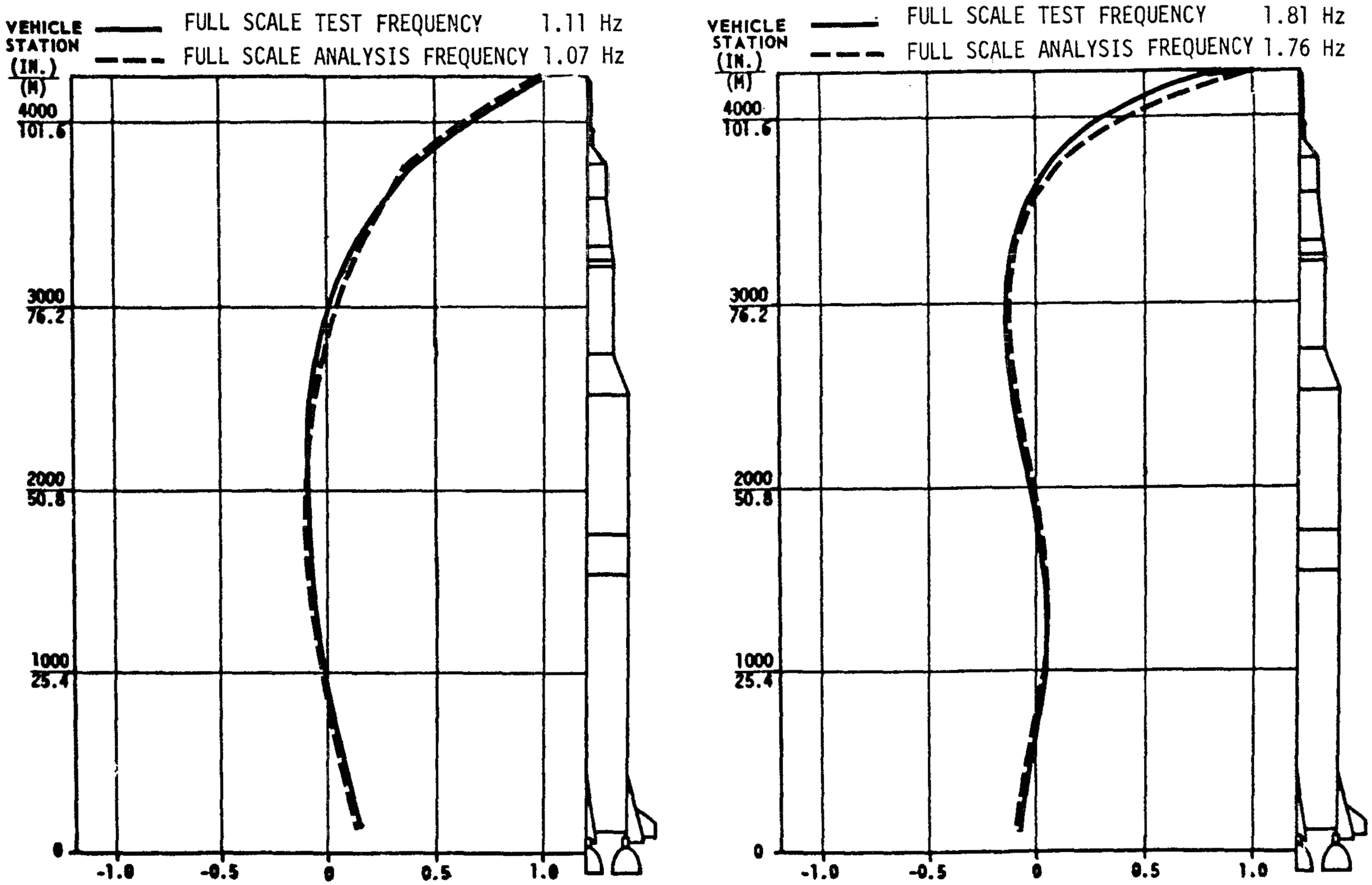
A special suspension system was developed for the test article to simulate the free-free boundary conditions experienced in flight. The heart of the suspension system was a hydrodynamic support in which oil under pressure was pumped between flat contacting surfaces to provide a near frictionless support. This suspension system represented an advancement in state-of-the-art. It was so effective that the six million pound vehicle could be excited in its low frequency suspension modes by two personnel pushing on the fins of the first stage. These two people



FIRST LONGITUDINAL MODE SHAPE

SECOND LONGITUDINAL MODE SHAPE

FIGURE 1-12 COMPARISON OF FULL SCALE LONGITUDINAL TEST AND ANALYSIS RESULTS 100 PERCENT PROPELLANT



FIRST PITCH MODE SHAPE

SECOND PITCH MODE SHAPE

FIGURE 1-13 COMPARISON OF FULL SCALE PITCH TEST AND ANALYSIS RESULTS - 100 PERCENT PROPELLANT

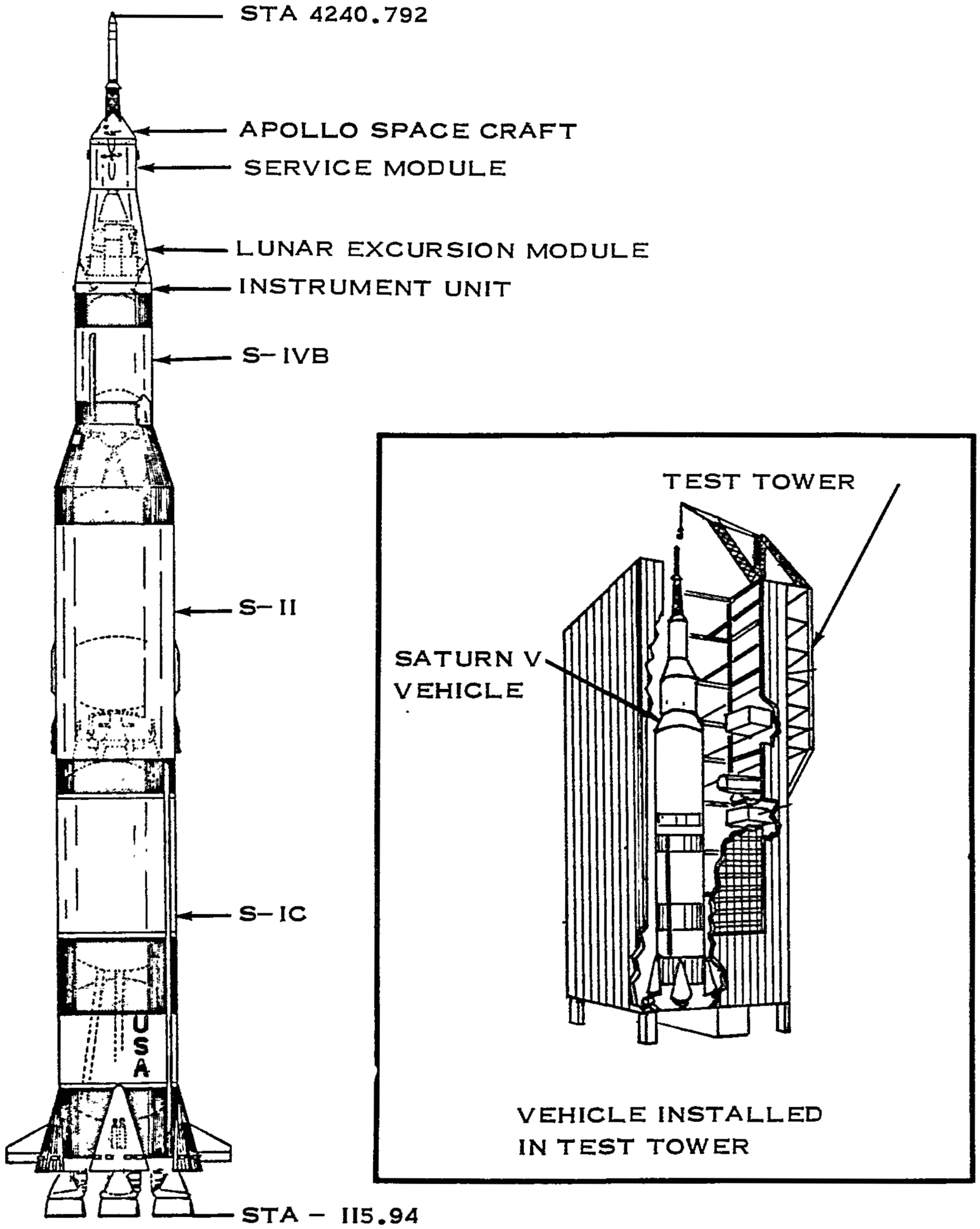


FIGURE 1-14 FULL SCALE VEHICLE IN TEST TOWER

1.5.0 (Continued)

could easily move the stage about on its support system through amplitudes of two inches or more.

Both scale model test results and math model results were used to support the test program itself; for example, the scale model test results were used to confirm that the force level requirements of the shakers being built for the dynamic test would be adequate. The math model results were used for locating the sensors along the vehicle, for verifying force requirements and for providing data that was invaluable for on-site evaluation.

At the start of the program 23 engineers and technicians were required on-site at all times to conduct the test. After the learning curve had been established, however, the same task was performed using only 15 people. The first hardware to arrive on the test site, the S-IC stage, was used as a test specimen to gain familiarity with the test operation procedures. This shake-down test proved to be an essential activity for eliminating problems in the data acquisition and data reduction procedures. Future programs should schedule time for a similar shake-down test series.

Because of the volume of data being recorded-- up to 132 channels of information were monitored continuously-- a computerized data acquisition system was developed and installed in a trailer on the test site. This system was used to monitor the data, record it on analog tape, display it in the data trailer for on-site evaluation and convert analog signals to digital tape. A flow chart illustrating the dynamic test technical approach is shown in Figure 1-15.

Selected data from the test article were reduced in real time and displayed within the data trailer to allow the structural dynamicists on-site to evaluate the validity of the data being obtained. Major deviations between the mathematical predictions and the measured results were assessed on the spot. When these deviations did occur, the test would not progress to the next series until the structural dynamics personnel making the evaluation had determined that either the math model was incorrect, or had identified the cause of the test data anomaly and had rectified it. In this way a high level of confidence was established in the test results obtained from each series. It was never necessary to go back and repeat a test after the program had proceeded to another configuration setup.

While the test was in progress, the computerized data acquisition system would transfer the 132 channels of recorded analog information onto digital tape. At the end of each complete test (which took from one to two days to complete), the digitized data would be transferred to the contractor facility for data reduction. These 132 channels of information covering a frequency range from 1/2 Hz up to 40 Hz could be reduced overnight using an IBM 7094 computer. The automated data acquisition and data reduction system allowed test data to be reduced, plotted and tabulated in a useful format, assessed for accuracy, and distributed to the user or-

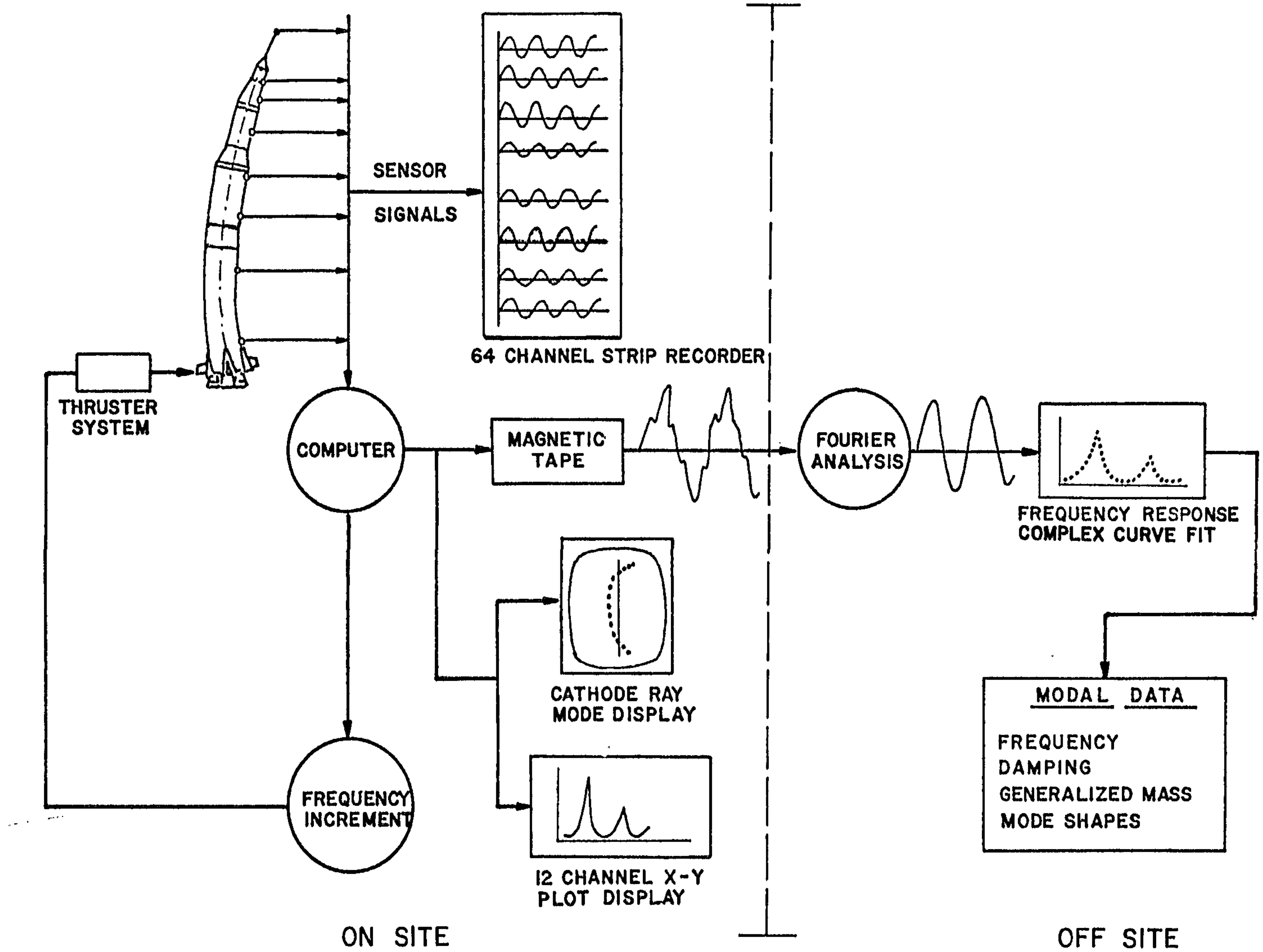


FIGURE 1-15 FULL SCALE DYNAMIC TEST TECHNICAL APPROACH

1.5.1 (Continued)

ganizations within a few days after each test was concluded.

The test results were obtained by exciting the vehicle at a fixed frequency until the system had settled out and steady state conditions were achieved. Once the data had been recorded for a given frequency, the thruster input signal would be stepped up to a slightly higher frequency and the process repeated. Thus the data on the tapes consisted of the cycles of oscillation recorded for a series of stepped frequency inputs. Each cycle of digitized data was first fit by a Fourier series. Only the first order terms were considered. This allowed each cycle of data to be represented by only two numbers, one for the in-phase (cosine) component and one for the quadrature (sine) component. The Fourier series solutions for each of these different frequency inputs were in turn fit by a ratio of two complex polynomials. This least squares curve fit procedure transformed the test results into a form that was directly comparable with math model predictions

The results of the complex curve fit could be expanded into quadratic factors, one factor for each mode, from which natural frequency, generalized mass and modal damping could be obtained directly. These parameters were compared directly with the values predicted by the math model.

The exact form of the polynomial used in the fit process had to be assumed. A certain amount of trial and error was required to achieve the best fit of the test data. As experience was gained with this approach, the number of iterations required to achieve the best fit was reduced to 3 or 4. A direct communication link with the computer, including a graphics display system, is required to make these iterations rapidly. The reduced test results obtained from the different sensors were highly repeatable; that is, the modal frequencies, damping, and generalized mass values obtained from different accelerometers along the vehicle compared closely with each other. The process proved to be highly superior to the other techniques used throughout test as backup means of measuring model damping and generalized mass. The use of complex curve fit techniques can be highly recommended for future programs.

The modal properties predicted by the math model were compared directly with the modal properties obtained from curve fitting test results. Particular emphasis was placed on local predictions in the areas where the flight sensors were located. Shortcomings of the math model were obtained directly from this correlation. Mathematical shortcomings, where they existed, were rectified and the model recorrelated until satisfactory comparisons with test results were achieved. Once the math model had been established to this level of accuracy, it could be used with high confidence to predict flight vehicle characteristics.

1.5.2 Dynamic Test Program Guidelines

The Saturn V experiences have been assessed to establish guide-

1.5.2 (Continued)

lines for future programs. The major guidelines for dynamic test are listed below.

A. Plan each facet of the test program in detail

Much of the success of the dynamic test program can be attributed to the detailed planning that preceded the test. In addition to the documented requirements that supported the program, every aspect of the test itself was planned down to finest detail. For example, a point-by-point checklist was established for bringing the test article up to test readiness, for conducting the test itself, and for converting the test article to the next test condition. This checklist clearly identified the individual responsible for each aspect of the test. This individual had to sign the checklist showing that all items had been accomplished properly. In reviewing the several dynamic test programs used to support Saturn V, the ones in which detailed planning was completed prior to test met their objectives. The ones in which the planning was less rigorous did not complete their objectives. As a general guideline to managers of future programs, it can be said that unless the technical team can demonstrate that they have completed the planning to this detail, the test itself is not ready to start.

B. Plan for growth in program objectives

The program manager should plan for growth in the program. The total program plan should account for the fact that as the program progresses the problems that have to be resolved traditionally occur at higher and higher frequencies. The test requirements should account for this growth and obtain data to support long term program problems. During the development of test requirements, the technical experts associated with predicting structural characteristics of the Saturn V felt that if a math model could be accurately developed to cover the zero to 10 Hz frequency range, that model would be adequate for all problems encountered during the program. As the test program evolved, problems in the zero to 10 Hz range were identified and remedied prior to flight. However, most of the serious problems of a continuing nature proved to occur at a higher frequency. For example, Pogo developed on the second stage of the Saturn V in an 18 Hz mode involving the S-II stage crossbeam, the LOX tank and the short LOX feedline. Fortunately, data had been taken to 40 Hz during full scale dynamic test just to cover such a contingency. This data provided a baseline for assessing the math models.

C. Assess requirements for overconservation

The documented requirements baseline, despite its success, was not without flaws. The initial documented requirements were in several cases unnecessarily rigid. The requirements for the electro-dynamic thruster used to excite the vehicle is a case in point. Long lead items

1.5.2 (Continued)

like the thruster must be specified many months in advance of the test program when test article hardware definition is in a primitive stage. Thruster requirements were based on simplified math model results which used conservative estimates of flight article modal damping. The end result of this conservatism was a specification for a thruster that could not be met by any available off-the-shelf item. A major contract was let for the development of thruster hardware that would meet these specifications. The most demanding specification was the requirement for a four-inch stroke at low frequencies.

The thruster which was developed to support the test proved on delivery to have a number of major problems associated with it. For example, the thruster output to a sinusoidal input was highly distorted and showed many strong harmonics in addition to the fundamental frequency. Due to the ingenuity of the technical crew, these thruster disadvantages were eliminated by suitable work-arounds. However, had the program of shake down testing of all equipment not been planned into the test program itself, a major schedule impact could have resulted. In retrospect it can be said that the requirement for a four-inch stroke was not realistic but was a result of ultra-conservatism. A 1/2 inch stroke would have been sufficient and excellent thrusters were available which satisfied this requirement. It was also determined that the vehicle itself was not capable of withstanding the force inputs that were made a requirement for the development of the thruster. This is an example of what can happen if requirement screening is inadequate.

D. Understand how test results will be used

Before detailed instrumentation requirements can be established, it is essential that the structural dynamic organization become familiar with the structural parameters that are important to each user organization. For example on the Saturn V, test requirements were written by people intimately familiar with flight control design problems. However, they were not as familiar with requirements for a Pogo stability assessment. As a result, no problems involving flight control design have ever occurred that could not be supported directly by available test data. However, Pogo problems have occurred in which available test data was not adequate to support a complete assessment of the problem. A checklist of significant sensitive parameters is shown in Table 1-II. These parameters are listed by area of application and cover Pogo, flight loads and flight control design. Problems in each of these areas on previous programs should be researched to provide a baseline for anticipating what might occur on the continuing program. Communication between the organization preparing the requirements and the users of the structural dynamic data is essential. It is only when user organization requirements are fully understood that the test article can be instrumented properly.

TABLE 1-II SATURN V SENSITIVE PARAMETERS

POGO

1. Frequency Range
2. Longitudinal Mode Frequencies
3. Propellant Line Liquid Mode Frequencies
4. Longitudinal Mode Shapes
5. Modal Damping
6. Frequency Response of the Following to a Unit Longitudinal Force Applied at the Engine Thrust Pad:
    a. Thrust pad longitudinal acceleration
    b. Tank pressure at propellant line outlet
    c. Pump inlet longitudinal acceleration
    d. Pump inlet pressure

LOADS

1. Frequency Range
2. Pitch (Yaw) Mode Frequencies
3. Bending Mode Slopes
4. Bending Mode Shapes
5. Modal Damping
6. Frequency Response of the Following to a Unit Pitch (Yaw) Force Applied at the Engine Thrust Pad:
    a. Pitch (yaw) bending moment at key vehicle stations
    b. Pitch (yaw) slope at thrust pad
    c. Reactions at major component attach points
7. Pitch/Yaw/Torsional Response at Key Vehicle Stations Produced by Unit Longitudinal Force Applied at Thrust Pad

FLIGHT CONTROL

1. Frequency Range
2. Pitch/Yaw/Torsional Mode Frequencies
3. Pitch/Yaw/Torsional Mode Damping
4. Frequency Response of the Following to a Unit Pitch/Yaw/Torsional Force Applied at the Engine Thrust Pad:
    a. Pitch/yaw/torsional slope at Control Gyro brackets
    b. Pitch/yaw/torsional accelerations at thrust pad
5. Slosh Mode Frequency
6. Slosh Mode Damping

1.5.2 (Continued)

E. Control test article configuration

In the test article, as in any other piece of program hardware, there is a need for complete configuration control. At any point in time the exact physical description of the test specimen must be known completely, to the last detail, including structural drawings, and detailed weights and balance information. Because of cost and schedule considerations, it is not always feasible for the ground test article to contain all flight hardware. An intensive review system should be established for all proposed hardware substitutions. This review system should include engineering evaluations, detailed math modeling, and simulation studies to determine the effect that any substitution will have on overall test results.

On the Saturn V program a math simulator was substituted for the flight article LM. This had little effect on the overall characteristics of the vehicle. However, the stiffness asymmetry in the lunar module caused the actual flight article to couple between longitudinal and pitch planes of motion. On the second flight a Pogo instability developed in the first stage. The Pogo instability provided a longitudinal thrust oscillation which excited the first longitudinal mode of the vehicle. Because of the asymmetry in the LM, the longitudinal motion also produced strong pitch response. Because this coupling changed the environment that the crew in the CM would be exposed to, it was highly important to be able to predict the coupling mathematically. Results from the dynamic test were not useful in developing this coupled math model. A special dynamic test program had to be established in which a major section of the vehicle including the spacecraft components was dynamically tested. Results from this test were then used to support the development of adequate math models.

As a general rule the ability to mathematically predict the characteristics of complex components is limited. In planning a test program, verification of major components should be included. If hardware substitutions have to be made, they can better be made in main line structure whose characteristics can be readily predicted mathematically.

F. Deal with established reputable vendors

In selecting instrumentation for dynamic test the reputation of the vendor is a far more important item than the specification on the instrument itself. Sensitive accelerometers for the Saturn V test article were needed to measure the characteristics of all modes of interest by exciting the vehicle at a single location. None of the accelerometers readily available met the requirements. A contract was let with a vendor who agreed to meet these specifications in the time frame allowed. However, the accelerometers he delivered proved to have a rejection rate of eight out of ten. A serious impact in the test schedule was avoided by purchasing at considerable cost off-the-shelf instruments from another vendor. These accelerometers proved to have far greater accuracy than

1.5.2 (Continued)

their specifications indicated, and their accuracy and repeatability were never a problem on dynamic test.

G. Simulate static thrust forces

Static thrust forces from each mainstage engine may change the local dynamic characteristics of the thrust structure. On the S-II stage the center engine is supported by a crossbeam which is then connected by pin joints to the outer thrust ring which carries loads into the stage itself. Data from Saturn V flight indicates that the crossbeam under load exhibits a change in dynamic characteristics and a higher rate of damping than it displays in the unloaded condition. The possible effect of thrust loads should be kept in mind when considering simulation of a flight article in ground test.

H. Excite the test article to expected flight levels

Structural damping is a highly nonlinear mechanism. If linearized approximations to structural dynamic damping are desired from test, then it is highly important that the test specimen be excited to response levels typical of the flight environment. Structural damping values measured on dynamic tests of the Saturn V exhibited significant change with respect to amplitude. In general the effective structural damping increased as the response of the system increased. The sensitivity of structural damping to amplitude would tend to rule out the use of impedance or other low level test techniques to measure damping.

I. Evaluate test results intensively

Test data is only useful if it can be established to a high level of confidence. Each item of test data needs to be rigorously evaluated and verified before it is compiled in a bank of test information. It is better to settle for fewer channels of information which are rigorously evaluated than to gather a lot of data which can only be partially evaluated. Each item of data should be simulated in advance by a math model. The mathematical predictions provide a baseline for evaluating the test data as they are obtained. Differences should be resolved before the test is allowed to progress to the next condition.

J. Use a replica model program to pilot the full scale program

On a major program such as the Saturn V dynamic test, the use of replica model testing as a pilot program can be highly recommended. If this approach is used, complete compatibility between the replica model test program and the full scale test program needs to be established. For example, the same locations on the vehicle should be instrumented, the same propellant conditions should be simulated, the same shaker locations should be used and the same data reduction procedures should be used. This would provide an end-to-end shake down of all test and

1.5.2 (Continued)

data reduction procedures prior to the full scale test. It would allow the shortcomings of each procedure to be identified in time for work-arounds to be established.

K. <u>Understand the limitations of the data reduction routines</u>

Each data reduction procedure has inherent problems and limitations that must be accounted for. The complex curve fit technique used to extract the modal properties from Saturn V test data exhibited several problems. First, the frequency range that could be accurately fit was approximately 10 Hz. Second, the number of modal resonances that could be fit in this 10 Hz frequency range was a maximum of 6. These limitations were due to the numerical algorithm used in obtaining the curve fit. Double precision arithmetic had to be used in the computer routines in order to obtain even this degree of flexibility. In order to obtain the best possible fit of the test results, a trial and error procedure is required. This procedure is time consuming unless the data reduction program is wired directly to a graphics display system. The type of fit that each approximation gives can then be observed. If the fit is not satisfactory, the display will guide the engineer to a better choice. The use of on-line communication with the computer can reduce the flow time required to adequately fit test results. At the start of Saturn V full scale testing as much as three weeks of flow time were required to obtain a satisfactory fit. Each iteration obtained from the computer had to be observed manually and recycled.

The curve fit scheme was able to separate modes as close together as two percent in frequency if they were of nearly equal strength. Modes closer than approximately one percent in frequency were never successfully separated. In a typical vehicle strong modes and weak modes are intermixed. As a rule of thumb, if the strength of a mode is less than one-fifth of the modes it is adjacent to, the curve fit may not be able to pick up that mode. In other words, the least squares solution often eliminates weak modes from the test data. In most instances these weak modes are of no consequence and nothing is lost by this elimination.

L. <u>Bring all related tests under single point control</u>

On the Saturn V program several major dynamic tests were conducted by different NASA and contractor agencies. The flow of useful test data between the various agencies was minimal. The major reason that test results did not carry over from one area to another was that each used its own data reduction system, its own library system, and its own identification system. As a result, if one wanted to use test results obtained on another program, an extensive period of familiarization was required in order to understand the test results. It is strongly recommended that all the dynamic test programs conducted to support a given space program be brought under single-point control to the extent that each test uses the same data reduction procedures. Furthermore, a library

1.5.2 (Continued)

system should be established so that results from each of the tests are stored in a consistent format in a single source location. This would expedite communication of results across a given program, and also serve as a baseline of test experience to carry forward to future programs. Much of the Saturn V test experience has been lost because a well defined library system has not been established. If test data are not carefully validated and documented, much of their potential value is lost.

1.6 CONCLUSION

This document has presented a summary of the experience gained during the Apollo Saturn V 1/10 scale and full scale analysis and test programs. The material presented in this document is oriented towards the program managers of future structural dynamic programs.

The following points are emphasized based on the experience gained during the Saturn V programs:

1. Replica models can be an effective tool to pilot structural dynamic programs of future space vehicles,

2. Math models can be used to predict the overall vehicle dynamic characteristics accurately, provided the guidelines presented in this document are followed,

3. Local deformations and major component dynamics can be predicted with limited confidence; static or dynamic testing of major assemblies or stages is required to guide math model development,

4. Automated data acquisition and reduction systems should be used on all major dynamic test programs.

5. A single technical test plan should be developed for each space program. Consistent data acquisition, data reduction, and data library procedures should be used for all major dynamic tests within a program.

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