Test Verification of the Cassini Spacecraft Dynamic Model

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Abstract—The Cassini spacecraft mission to Saturn will be launched in October 6, 1997 on a Titan lV/ Centaur launch vehicle. Cassini is the largest interplanetary spacecraft ever developed. The purpose of the mission is to release a Probe through the atmosphere of Titan, while the spacecraft remains in orbit around Saturn. Before launch approval can be obtained, a test verified finite element model of the Cassini spacecraft must be completed and approved by NASA, The correctness of this model is critical to the final verification coupled loads analysis and margin of safety assessments.

Modal surveys were performed in August 1995 and January 1996 on a Cassini test article to provide experimental data for the verification of the Cassini test analytical model (TAM). In addition to the modal surveys, static test and component sine swept test results were also used to corroborate analytical model results. Since the Cassini spacecraft is a complex system with numerous components taking part in global modes, a systematic approach was developed to complete the model verification task.

The model verification strategy included the selection of modal survey test modes, correlation goals, and the model updating approach based on hardware knowledge, engineering judgment, and analytical methods to produce the final test correlated finite element model.

The analytical approach used sensitivity to select optimum incremental improvements to the model parameters, solving an eigenvalue problem to compute the modal properties of the updated model. This method made it possible to vary many model parameters in unison to obtain good agreement between test and analytical modes, especially for complicated global modes. Through the implementation of these various tools, the Cassini spacecraft model was successfully correlated to test verification goals.

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The ability of the Cassini spacecraft to fulfill its mission is largely influenced by the numerous pre-launch analyses and testing, The most critical analysis is the final verification coupled loads cycle. Results from this analysis represent the most accurate loads for the Cassini spacecraft launch environment. These final loads are then used to verify that all structural margins of safety are positive and ultimately lead to the acceptance and approval by NASA of Cassini's flight worthiness.

In order to provide the most accurate dynamic flight model for the final verification load cycle, the Cassini Developmental Test Model (DTM) was subjected to a static test in the spring of 1995 and modal testing in August of 1995 and January of 1996. The DTM structure consisted of flight hardware, flight spares, and flight-like structure. For modal testing, mass mockups were added to the D'I'M.

The objective of the correlation activity was to demonstrate the agreement of the Cassini spacecraft test analytical model (TAM) modes to the test measured modal survey modes, Although modal survey test results were used as the primary comparison, component vibration test results along with static test stiffness data were used as a confirmation to the validity of the model updates. The resulting updated TAM was then used in the preparation of the flight dynamic model for the final verification loads cycle. The steps taken to produce the correlated model are described in the sections to follow. Figure 1 illustrates the process used to validate the dynamic launch model for the verification load cycle.

2. STATIC TEST

objective

The primary objective of the Cassini static loads testing was twofold: to demonstrate the" integrity of the Cassini spacecraft structure by meeting structural strength requirements and to provide partial verification of the Titan IV strength requirement. The secondary objective was to obtain a limited set of stiffness and load deflection data which may be used to assist in the verification of the Cassini spacecraft finite element model.

Test Requirements

The Cassini pre-launch static test requirement was to exercise the test article to 1.25 times the future December 1996 verification load cycle. In order to ensure that this requirement will be met, the static test loads were at least 1.25 times the load cycle analysis of October 1994.

Philosophy

A philosophy was developed to effectively qualify all required structure without developing separate qualification tests for each subsystem component, Target loads were developed for each test condition based upon this philosophy. Target load levels were chosen after an evaluation of the design loads and structural capability. Test instrumentation was primarily for hardware protection and verification of the successfulness of each test.

The qualification ofa subsystem was obtained when the subsystem was subjected to an overall flight like, qualification level loading defined by inertial loading. Consequently, inertial loads were the primary target, while loads in structural elements or joints were secondary targets of each test. The selection of targeted elements was based on an engineering assessment of the structural design and structural margins of safety.

The static test objectives were met by applying external test loads. Verification of the applied test loads were determined by the measured load levels in the load cells assembled with each ram, Other instrumentation consisted of strain gages, load cells, linear variable displacement transducers (LVDT), and limit switches as well as a data acquisition system.

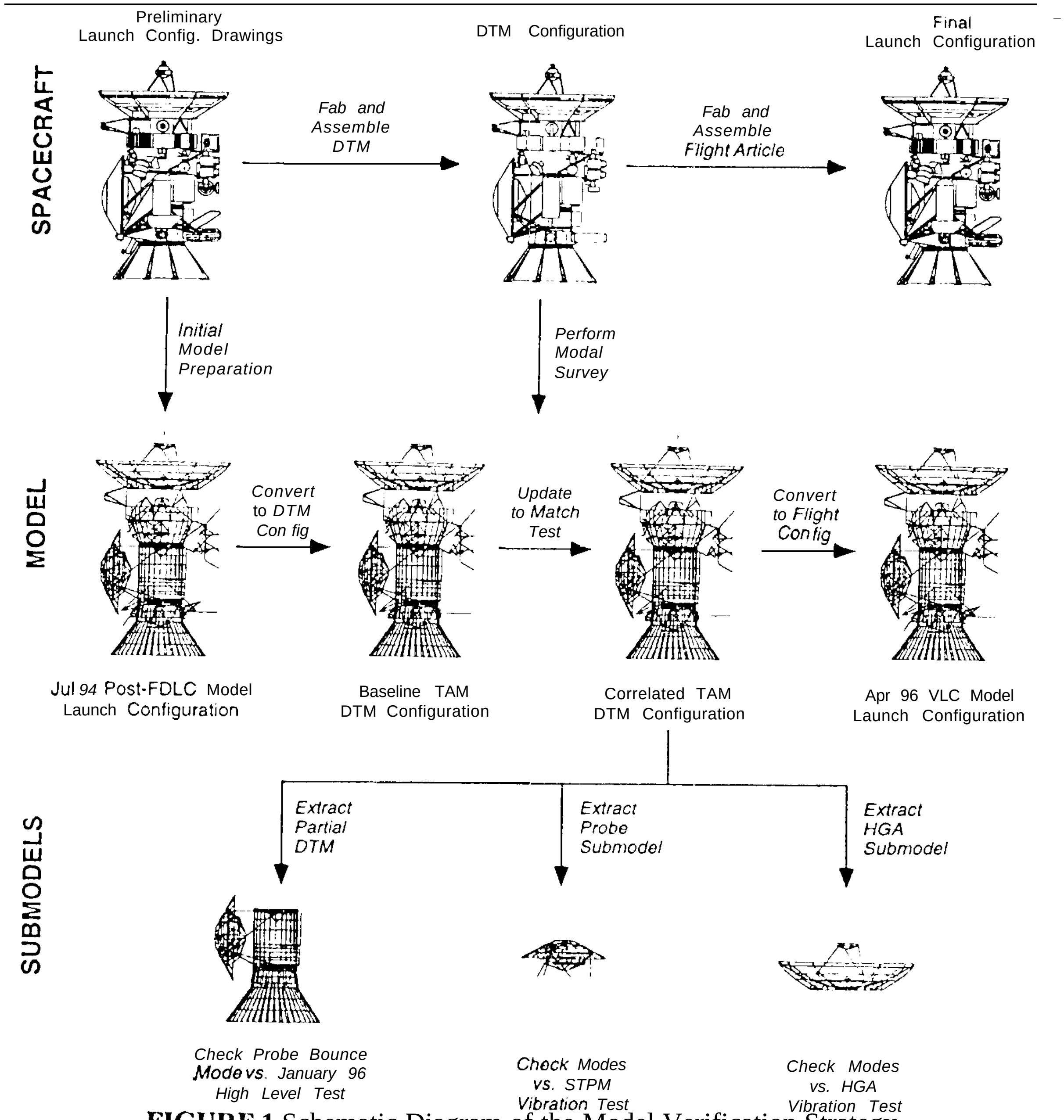

FIGURE 1 Schematic Diagram of the Model Verification Strategy

Results

The static test program was successful in meeting its objectives and in demonstrating the strength and structural integrity of the Cassini spacecraft structure.

3. MODAL TEST

Objective

The objective of the Cassini modal test was to provide experimental data for the verification of the NASTRAN finite model of the Cassini spacecraft in its launch configuration. This model verification must be completed and approved prior to the final verification load cycle and subsequent launch approval.

Test Requirements

The test requirement was to measure the frequency, damping, and mode shapes of all significant modes of the Cassini spacecraft test article below 70 Hz, with the structure fixed at the Centaur 8-hardpoint interface.

Pre-Test Analysis

In order to prepare for modal testing, a TAM was created from the existing launch model and modified to represent the actual mass and configuration of the test article, This model was used in test planning to determine shaker locations and assess instrumentation adequacy. During the test, this TAM was utilized to expand mode shape measurements to full model size for visualization. The Guyan-reduced mass matrix from the TAM was used for orthogonality and effective mass calculations to determine test data quality.

Test Method

The overall test philosophy was to use a combination of the burst random and stepped sine techniques. The burst random testing is quick and efficient, but it is limited to fairly low levels of motion in the structure. In order to generate the highest possible response levels within the capability of the shakers, stepped sine testing was employed. The stepped sine test results were essential in assessing nonlinear characteristics of the structure.

The shaker locations were determined by two criteria. The first criterion was to excite all significant modes of the structure. The second criterion was accessibility. In all, a total of 9 shaker locations and/or orientations were used during the test.

The choice of accelerometer locations for the test was based on the following criteria:

Orthogonality Checks—The set must allow orthogonality and cross-orthogonality checks to be performed using the Guyan-reduced analytical mass matrix. This criterion was checked using the pre-test TAM. The analytical eigenvectors were partitioned to the instrumented set, then the orthogonality of the partitioned eigenvectors was computed using the Guyan-reduced mass matrix. The resulting matrix should be close to an identity matrix. Typically, a poor instrumentation set would be evidenced by diagonal terms much less than 1.0, and off-diagonal terms which are not small.

Redundancy—To the greatest possible extent, redundance should be built into the set to compensate for possible dropped channels. This criterion was a particularly important consideration for the areas which were inaccessible during the test.

Engineering Judgment--In some places, modeling idealizations could be questioned. Wherever possible, additional accelerometers were placed to be able to observe dynamic behavior which was not predicted by the model.

7&Mode *Selection*

After all test runs were implemented, a total of 248 test modes had been identified by eight burst random tests at various force levels. The selection of test modes to be retained for model correlation was based on the following criteria:

Eliminate Duplicate Modes—Distinct modes were identified based on the self-orthogonality of test modes.

Select *the Highest Level* Modes—Where possible, mode shapes from the runs with the highest force levels were selected, in order to best reflect the behavior of the structure at flight vibration levels.

Select the Best Quality Modes—in some cases, the mode shape from a high level run was clearly contaminated with noise. In this case, the advantage of using higher level data was outweighed by the questionable nature of the data, and a lower level shape was retained.

Select a Consistent Set of Modes—In cases where there was no obvious discriminator between repeated measurements, selection was made so that a series of modes came from a consistent test run.

Results

The Cassini modal test program was successful in meeting its objectives. The final product was a set of recommended frequencies and mode shapes for the subsequent model correlation task. A total of 68 distinct test modes were selected in the set.

The core structure is very linear. But the major modes of the probe on its support structure showed signs of nonlinearity due to accumulation of gaps in joints. However, at high level this mode can be characterized conservatively by a linear model.

4. CORRELATION GOALS

The correlation goals were chosen based on past experience with model verification of similar spacecraft structures. Since correlation of 68 test modes would have been impractical, only the significant modes were required to be correlated to test results. The designation of significant modes was based on effective mass. Modes with high effective mass tend to be more important for determining primary loads through the launch vehicle interface. For the Cassini model correlation, the test modes were categorized as follows:

Primary Modes—Primary modes were those modes with effective mass at least 15°/0 of the total test article mass.

Secondary Modes—Secondary modes were those modes with effective mass between 5% and 15°/0 of the total test article mass.
Based on the 5% and 15% criteria, there were a total of 5 primary modes and 9 secondary modes.

Frequency Goals

The most important correlation goal was the frequency agreement between test and analysis modes. For a lightly damped system, even small frequency errors can cause large differences in loads due to coupling effects between the launch vehicle and spacecraft modes. For the Cassini correlation effort, the following goals were set.

Primary modes analysis frequencies should be within 2'%0 of the corresponding test frequencies. Secondary modes analysis frequencies should be within 5% of the corresponding test frequencies.

Cross Orthogonality Goals

For mode shape comparison, goals were set based on cross orthogonality between analysis and test modes. The cross orthogonality matrix is generated as the triple product $\emptyset_A^T M \emptyset_T$, where the columns of $\emptyset_A$ are the analytical mode shapes at the accelerometer degrees of freedom, the columns of $\emptyset_T$ are the test modes at the accelerometer degrees of freedom, and M is the Guyan-reduced analytical mass matrix. Both $\emptyset_A$ and $\emptyset_T$ are first normalized to unit generalized mass. For perfect agreement between test and analysis, the cross orthogonality product gives ±1 for corresponding pairs of test modes, and zero for all other pairs. For the Cassini correlation effort, the following cross orthogonality goals were set:

Primary modes cross orthogonality between corresponding modes should be greater than 0.90 in absolute value. Secondary modes cross orthogonality between corresponding modes should be greater than 0.85 in absolute value.

Other Comparisons

In order to gain additional insight, comparisons were made between test and analytical predictions of modal effective mass and modal kinetic energy. .

5. MODEL UPDATING APPROACH

The TAM updating occurred in four phases. First, the mass properties were thoroughly reviewed and updated. Second, known pre-test TAM deficiencies were corrected. Third, major discrepancies between test results and the analytical predictions were addressed by engineering judgment, Significant components in each mode were identified by reviewing the kinetic energy distributions in both the test and analytical modes and by reviewing the strain energy distributions in the analytical modes. In order for the TAM mass to remain constant, items such as Young's modulus, shear modulus, moments of inertias, torsional constants were modified as well as the addition of spring elements to account for joint/local flexibilities and stiffness. In addition, modeling idealizations were investigated for correct representation of the actual hardware. In some cases, static test results were used to provide further stiffness data. Lastly, a sensitivity-guided parameter updating method was applied to fine tune the model.

6. ANALYTICAL METHODS

For complex models such as Cassini where many different parts of the model are participating in complicated global modes, it is almost impossible to manually adjust the model to completely match test data. In order to obtain good agreement, many different model parameters must be adjusted in unison. A powerful approach is to calculate optimum parameter updates based on sensitivity of modal results to the parameters.

Model parameters were selected based on engineering judgment and previous manual updates. A total of 123 model parameters were included in this phase. Generally, changes to the skin properties were limited to 10'YO, and changes to ring and stiffener were limited to 15%.

The approach uses sensitivity to select optimum incremental improvements to the model parameters, but solves an eigenvalue problem rather than relying on sensitivity to compute the modal properties of the updated model.

Goodness of the model was measured by the error shown in the equation below:

$$e = \sum_{pairs\, j,k} W^{F}_{jk} (f^{A}_{j} - f^{T}_{k})^2 + \sum_{pairs\, j,k} W^{X}_{jk} (X_{jk} - X^{*}_{jk})^2$$

where W^{F}_{jk} and W^{X}_{jk} are diagonal weighting matrices for frequency and cross orthogonality, with nonzero values at matching analysis/test mode pairs; f^{A}_{j} and f^{T}_{k} are the analytical and test frequencies; X_{jk} is the cross orthogonality matrix between analytical modes j and test modes k; and X^{*}_{jk} is the desired cross orthogonality matrix.

Optimal model updates were obtained based on first order sensitivity of the error e to various model parameters. The percentage change in each model parameter was chosen to minimize a weighted sum of e and the parameter changes. The model was updated in such a way that the best possible improvement was achieved with the minimum changes to the nominal parameter values. Because the update was based on linear sensitivity, only small parameter updates could be made at one time. However, small steps could be accumulated by recomputing new sensitivities after each incremental change.

Once the correlation goals were achieved, the magnitude percentage change to the model parameters was carefully reviewed for reasonable justification. The majority of the updates involved model idealizations, joint flexibilities, and stiffness. In most cases, stiffness changes were made to determinate supports, and load distributions were unchanged.

7. RESULTS

Comparisons of frequencies and cross orthogonalities for the baseline TAM and the final correlated TAM are shown in Table 1. The first five modes are designated primary modes while the remaining nine are secondary modes. All primary and secondary modes match in frequency within 2°/0, compared to the goal of 2°A for primary modes and 51% for secondary modes. The correlation goal for the primary modes was at least 90% cross

Table 1. Summary of Frequency and Cross Orthogonality for Primary and Secondary Modes

			Baseline TAM				Final TAM			
Test Mode	Freq (Hz)	Description	Mode No.	Freq (Hz)	Error (9)	Cross Ortho	Mode No.	Freq (Hz)	Error (%)	cross Ortho
1	7.51	Primary bending +X+Y	1	7.85	+4.5	99.3	1	7.48	-0.4	99.3
2	7.75	Primary bending +Y-X	2	8.18	+5.5	99.4	?	-1.79	0.5	99.3
3	15.52	Primary torsion	3	16.26	+4.7	9?.8	3	15.57	0.3	93.7
4	18.13	Probe bounce	4	18.95	+4.5	98.0	4	18.03	-0.6	98.0
28	37.28	Fuel, Ox tanks -Z, Probe front shld	21	35.92	-3.6	36.6	30	37.55	0.7	88.7
6	20.95	Probe/RSP Y butterfly	8	21.28	+1.6	84.5	6	20.74	-1.0	95.3
7	21.34	RTG lateral, RSP bounce	6	20.49	-4.0	75.7	7	20.99	-1.6	97.0
12	26.55	Second Y bending, RTG vertical	13	27.36	+3.0	78.1	13	26.65	0.4	94.5
17	29.43	Second X bending	16	30.70	+4.3	82.0	18	29.65	0.8	88.9
18	30.17	Helium, Hydrazine tanks bounce	63	62.50	+107.2	48.5	19	30.69	1.7	89.0
19	31.55	Hydrazine tank bounce	21	35.92	+13.9	44.5	21	32.03	1.5	87.9
20	31.59	Probe FRSS torsion	NA	NA	NA	NA	20	31.38	-0.7	92.6
21	32.11	FPP bounce	20	33.30	+3.7	65.9	22	32.52	1.3	91.9
27	36.67	Fuel, Ox tanks -Z, Probe +torsion	72	36.30	-1.0	47.9	29	37.07	1.1	89.2

orthogonality, which was achieved for all except test mode 28 with 89%. Due to the large participation of several spacecraft components and the pre-test model having the highest cross orthogonality with this mode, the achievement of 89°/0 was considered acceptable. The primary bending modes are extremely well correlated. The goal of 85% cross orthogonality for secondary modes was also reached.

In addition to cross orthogonality, a qualitative comparison of test to analysis mode shape is based on effective mass. For the test modes, effective mass was computed using the Guyan reduced analytical mass matrix from the baseline TAM. For the analysis modes, effective mass was computed using the full mass matrix. Figures 2-a through 2-f show the cumulative effective mass vs. frequency, which sums over modes below that frequency, in each direction. In each plot, the dashed line is computed from the mode shapes, and the solid line from the final correlated model.

Figures 2-1 and 2-b demonstrate that the effective mass characteristics of the model are very close to the test results in the X and Y directions.

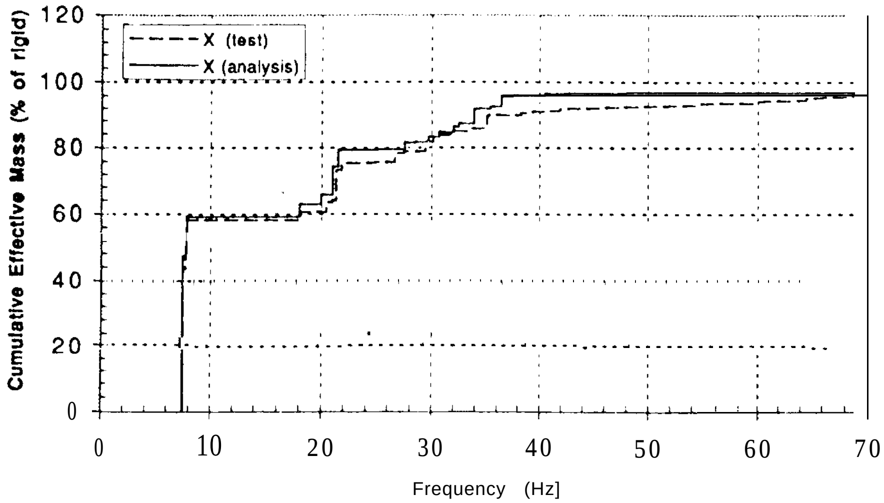

Figure 2a Test vs. Analysis Cumulative Effective Mass (X)

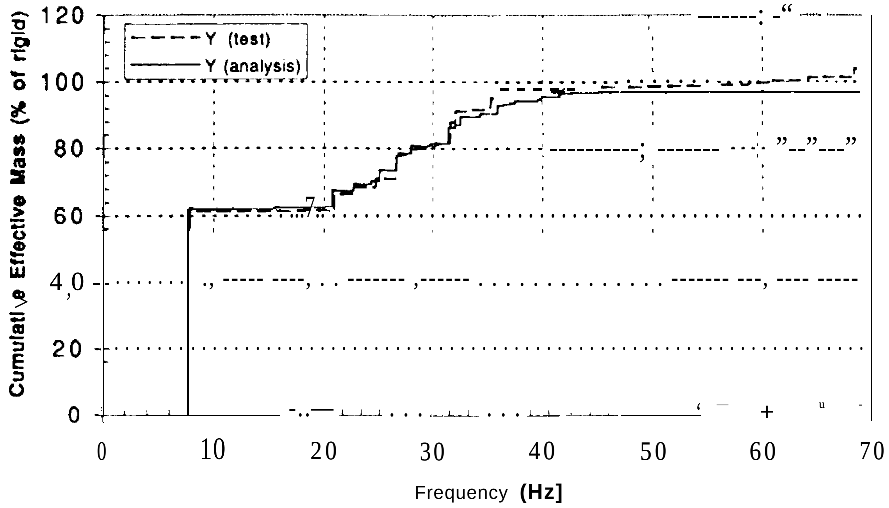

Figure 2b Test vs. Analysis Cumulative Effective Mass (Y)

Figure 2-c of the Z or axial direction shows good agreement between test and analysis below 30 Hz. The differences between test and analysis are about 8% of the total mass between 32 and 38 Hz and about 5% above 38 Hz.

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Figure 2-f shows the error in the primary mode dominating the comparison. The test data stays considerably below the analytical value. It is possible that there were some problems with the test measurements for the torsion mode. The analytical model is conservative in that it provides more reaction mass in the torsional direction and the torsional input from the launch vehicle is significantly low.

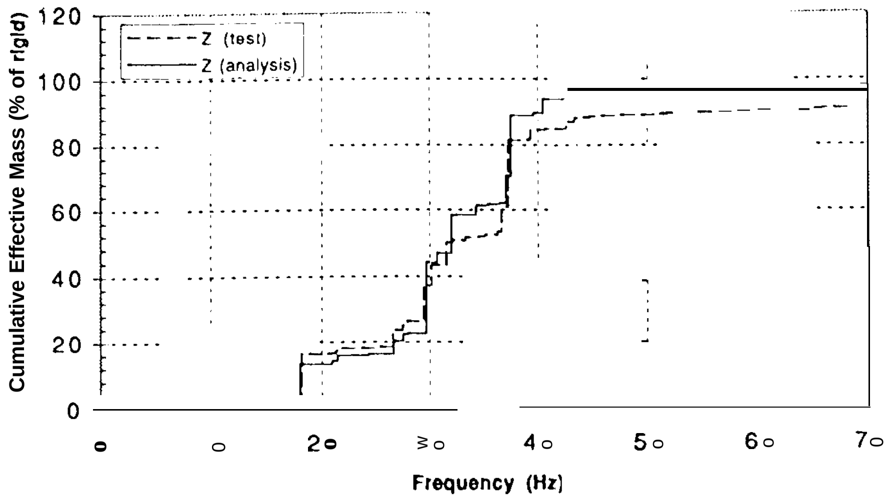

Figure 2c Test vs. Analysis Cumulative Effective Mass (Z)

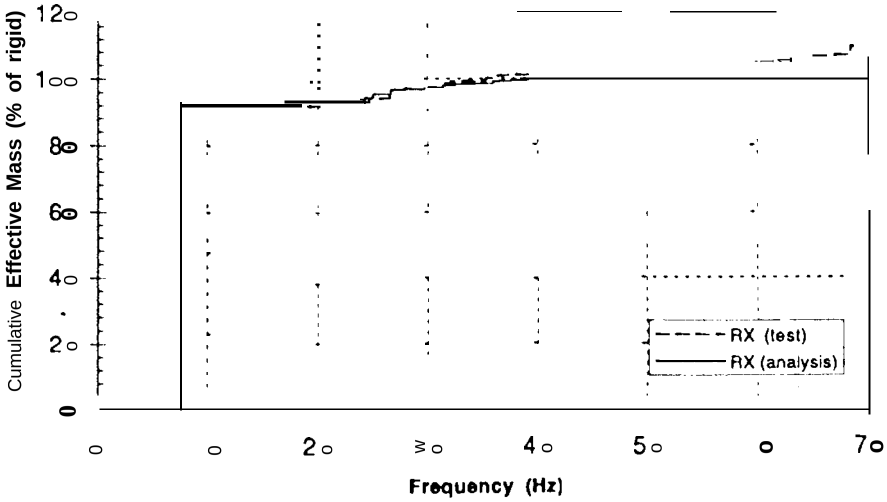

Figure 2d Test vs. Analysis Cumulative Effective Inertia (RX)

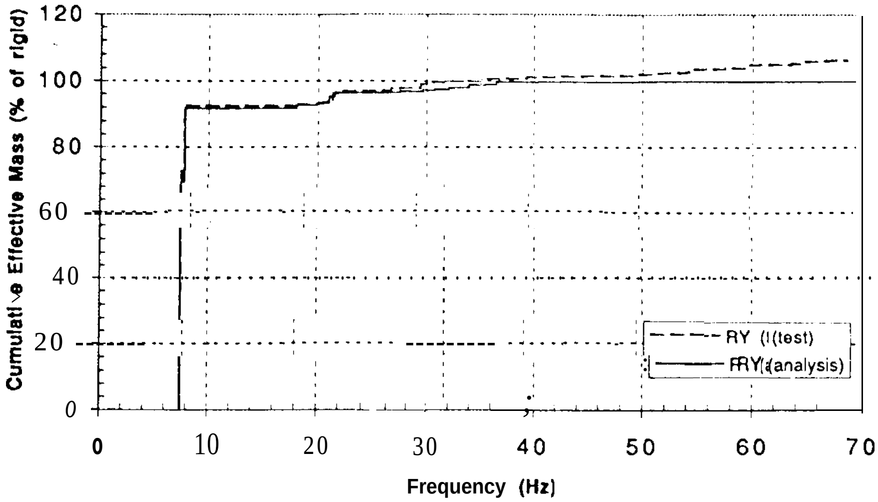

Figure 2e Test vs. Analysis Cumulative Effective Inertia (RY)

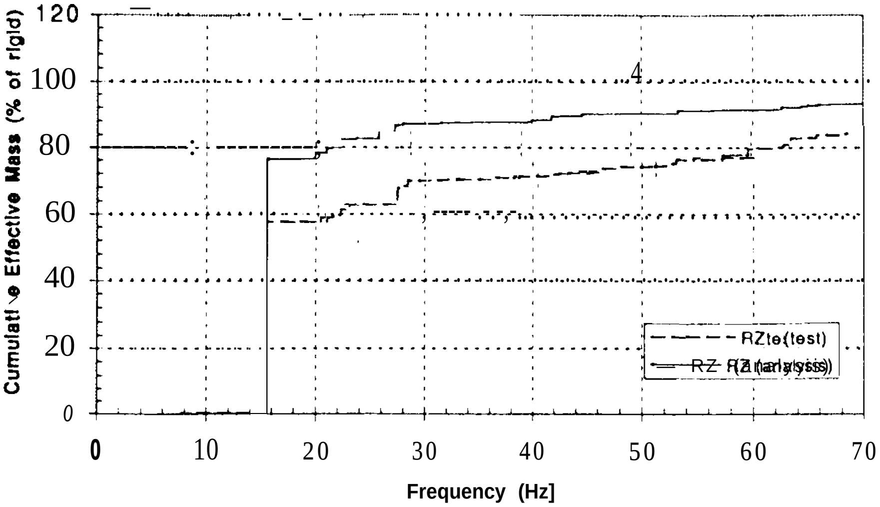

Figure 2f Test vs. Analysis Cumulative Effective Inertia (RZ)

In order to further verify model correlation updates, submodel modal results were compared with earlier modal and sine vibration test results. In fact, the TAM updates to the submodels improved correlation to previous vibration test results.

8. CONCLUSION

The Cassini modal test correlation was a challenging task, and a complex one. Many different elements, both analytical and experimental, had to come together to make the approach work.

The availability of the static and component vibration test results complemented the modal test results and were instrumental to the verification process. With this additional data, sanity checks were performed to further justify the TAM updates.

Both engineering judgment and hardware knowledge aided in modifying the TAM toward agreement with test results. Analytical methods provided the additional tool to meet the correlation goals.

The resulting test verified model successfully met the frequency and cross orthogonality goals established at the onset of the verification process. The model updates were then used to produce the final verification load cycle dynamic model.

ACKNOWLEDGMENT

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