Sine Dwell or Broadband Methods for Modal Testing

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For large, complex spacecraft structural systems, the objectives of the modal test are outlined. Based on these objectives, the comparison criteria for the modal test methods, namely, the broadband excitation and the sine dwell methods are established. Using the Galileo spacecraft modal test and the Centaur G Prime upper-stage vehicle modal test as examples, the relative advantage or disadvantage of each of these methods is examined. The usefulness or shortcoming of the methods is given from a practicing engineer's view point.

I. Introduction

MODAL testing plays a significant role in spacecraft development activity in which experimentally determined structural dynamic characteristics are used to verify the analytical model for design purposes. Although the classical modal test method, the so-called "multi-shaker sine dwell method," is still being used in the aerospace industry, the use of broadband excitation techniques has become dominant in recent years in structural dynamic testing. This is due to the advent of affordable Fast Fourier Transform (FFT) processors, refined impulse hammers, tailored random generators, and a more widespread understanding of digital signal processing. In the last few years, we have witnessed a large number of papers devoted to the development of data processing techniques for extracting modal characteristics from broadband responses. Also, numerous reports describing many successful modal tests using broadband excitation methods appeared in the literature, and prominent authors have predicted the demise of traditional sine dwell methods.[1] Commonly heard comments from those advocating the abolishment of sine dwell methods are that the broadband methods provide more accurate modal parameter extraction, especially for closely spaced modes, and that the success of the sine dwell method is heavily dependent upon the test engineer's experience as compared to the almost total automation of the broadband method. The purpose of the present paper is to compare the sine dwell and broadband modal testing methods, considering not only data extraction but also the test objectives and the ultimate use of the data. This will put the modal test in the proper perspective and, consequently, a more meaningful comparison of the methods will be made. All the considerations discussed herein are limited to aerospace applications.

II. Modal Test Objectives

Designing a structure to survive a prescribed dynamic environment is generally accomplished today by using an analytical model of the structure. Since many structural systems will not be subjected to their design dynamic environments prior to their commission, it is very important that the analytical model accurately predict the behavior of the physical system. In other words, the analytical model must be valid for the given design environment.

Although advancements in modern analytical techniques and ever-increasing capabilities in computer technology make it possible for engineers to model a physical system to any desired degree of accuracy, cost and schedule constraints preclude such an approach during the design process. Thus, an engineering model for the purpose of the design analysis process will always be an approximate representation of the physical system. Nevertheless this approximate model must accurately predict the loads and other significant behavior of the structural system.

For aerospace payload structural systems, where the responses and loads dictate the design and thus the size and weight of the structure, the accuracy of the analytical model is of major importance because of the stringent weight constraints. A test-verified analytical model is often required for the final verification of loads analysis. Usually, the model is a finite-element formulation in which the continuous structural system is represented by discrete mass and stiffness matrices and modal damping. It should be noted that the model verification is not made on the model parameters such as the mass and stiffness matrices, but rather of the eigenvalues and eigenvectors calculated from the model. The modal test, from which the natural frequencies, mode shapes, damping, and other dynamic characteristics are determined experimentally, is often used for the analytical model verification. Because of the indirect verification, the comparison between the analytically predicted values and their corresponding measured quantities must be selective to ensure the validity of the model within the range of interest. For instance, regardless of the number of correctly predicted modes, the model is not valid if the frequencies of the modes within the range of the forcing functions are incorrectly predicted. For a large complex structural system, the model generally can predict hundreds of modes. However, only a few of them are important for the loads analysis; the model must predict these modes accurately. Other dynamic characteristics such as the orthogonality, cross-orthogonality, effective mass, modal forces, kinetic energy distribution, and strain energy distribution are used to compare the test data to the analytical predictions in addition to the frequency and mode shape.

Another implicit objective of the modal test is for the engineer to obtain an intimate knowledge of the structural behavior. The acquired knowledge will help the model verification by using the engineer's intuitive intellect and will provide valuable insight when design modifications are required.

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It is important to note that the modal test objective remains unchanged regardless of the selected modal test method.

III. Modal Analysis/Test Procedure

A successful modal test involves three integrated activities. These are

1) Pretest activities:

a) Determination of the important modes based on the forcing function and loads requirement.

b) Construction of the test-analysis model to bridge the size difference between the analysis degrees-of-freedom and the measured test data. (The test measurement is usually a small subset of the analysis degrees-of-freedom).

c) Selection of instrumentation location based on the requirement of mode shape resolution, kinetic energy distribution, and other factors.

2) Test activities:

a) Preparation of the test article.

b) Instrumentation and installation of the excitation systems.

c) Test system check out and calibrations.

d) Test operations: data acquisition and processing.

e) Modal parameter extraction.

3) Post-test activities:

a) Interpretation of the test result and evaluation of the accuracy of the test data.

b) Update of analytical model.

Except for the modal test and the modal parameter extraction during the modal test, which are only small fractions of the total modal test effort, all the modal test activities remain unchanged regardless of the chosen test method. For large complex structural systems, it is quite common that extensive pretest and posttest activities are required. Even during the test period, often the time for actual data acquisition and data processing are relatively insignificant compared to the test system setup, calibration, check out, and seemingly never-ending trouble shooting.

IV. Comparison Criteria

Based on the modal test objectives and procedures, the criteria for the test method comparison should be:

1) Accuracy with respect to loads model requirement. It is important that modal parameters obtained from the modal test should be accurate and relevant in the proper frequency and amplitude range that are significant to the loads model.

2) Interaction between engineers and test article. The test method should provide an opportunity for engineers to understand and explore the behavior of the test article. The hands-on experience is vital for the judgment required in model verification. The test is incomplete if the test article is treated as a black box and transfer functions are the only results from the test.

3) Cost and schedule effectiveness. The cost and schedule should be examined in the light of its impact on the total modal test, including the modal analysis update activity. The cost and time saved during the conduction of the test may be offset by penalties paid during model verification.

These criteria for comparison should put the modal test method in proper perspective with respect to the entire modal analysis and test effort.

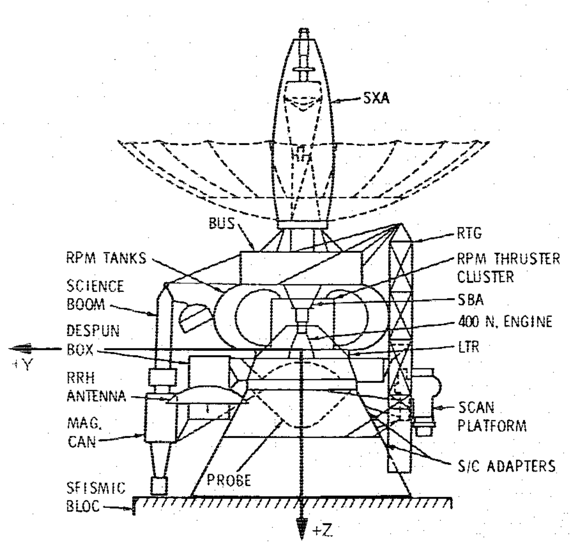

Fig. 1 Galileo in modal test configuration.

V. Comparison

Several modal analysis and test efforts for large complex spacecraft structural systems were performed with both the sine dwell and broadband test methods, and some of these results were reported previously.[2-5] The comparisons of the methods, however, were made with respect only to the extracted modal data. In the present investigation, some of the results previously reported will be used for the evaluation of the above mentioned comparison criteria.

In the summer of 1983, an extensive modal test was performed on the Galileo spacecraft using sine dwell as well as many other broadband methods. The results and their comparison were reported previously.[4,6,7] Figure 1 is a schematic of the Galileo spacecraft with its major components identified. The total weight of the spacecraft is approximately 5300 lbs. A finite element model using the NASTRAN code was constructed for performing the design loads analysis, which consisted of approximately 10,000 static degrees of freedom (DOF) and 1600 mass DOF. This loads analysis model required verification by modal test.

In comparison to many previous spacecraft, the Galileo structural system exhibited some peculiar characteristics. These were:

1) The Galileo consists of seven appendages and a core structure. The low frequency modes are the appendage modes.

2) Some appendage modes are coupled with the core modes and are important in the loads analysis.

Table 1 Frequency comparison for Galileo spacecraft

Mode no.	Frequency, Hz Broad-band	Sine dwell	Description
1	11.46	12.70	SXA in Y
2	14.02	13.11	SXA in X
3	17.44	17.76	Global Y-bending
4	18.54	17.41	Global X-bending
5	19.33	18.59	1st global torsion
6	22.06	21.67	RTG walking mode
7	22.52	23.10	Appendages in Z
8	25.19	23.66	Science boom in Z
9	25.80	25.46	2nd global torsion
10	26.36	–	Probe in Y
11	27.84	–	RRH in Y
12	28.29	–	RRH in Y
13	30.50	26.12	Damper in Y
14	31.84	–	Damper in X
15	33.42	29.71	Thrust bm. in Y, O/P
16	33.76	–	Thruster in X
17	34.50	–	Science boom in $X-Z$
18	37.91	37.92	Global Z mode
19	39.14	42.20	Thrust bm. in Y, I/P
20	39.77	–	Science boom in Y
21	41.73	–	400 N. engine in Y
22	42.35	–	400 N. engine in Y
23	42.36	–	Thruster in Y
24	44.61	–	Thrusters in Y, I/P
25	44.98	42.53	Scan platform in X
26	46.00	–	Thrusters & RRH in Y

3) The appendages' support systems are designed for strength, and therefore, large deformations are predicted in the loads analysis.

4) Several areas of the spacecraft such as the high gain antenna, the Radioisotope Thermalelectric Generator (RTG), and the load transfer ring exhibited inherent nonlinearities. The frequency/amplitude dependency required that certain modes be excited at large amplitude responses.

Table 1 shows the frequency comparison between the sine dwell method and the broadband method in which four shakers were used and the modal parameters were extracted by the polyreference technique.[7] The frequencies are in fair agreement with those modes obtained by both methods. It should be noted that the first nine modes are the important modes for the loads analysis because of their relatively large component of the effective mass and the frequency ranges relative to those of the forcing functions. Also, within these nine modes, five of them are appendage modes and only four are global modes. Figure 2 shows frequency as a function of the vibration amplitude for a typical nonlinear mode. The amplitude excited by the broadband method was a fraction of one G, and the sine dwell method produced an antenna tip response as high as 20 G. Although the loads analysis indicated that the antenna tip response was approximately 50 G, it appeared that the frequency became invariant when the amplitude exceeded 20 G. For comparison purposes, the values in Table 1 were obtained from low-response sine dwell testing. Although the broadband method obtained 26 modes as compared to 14 modes obtained by the sine dwell method, many modes from the broadband method have insignificant effective mass and are unimportant in the loads analysis. Also, the existence of some of the modes obtained by the broadband method are questionable.

Table 2 shows the mode shape comparison for the first mode, which is a local antenna mode. Only the 10 DOF with the largest modal amplitude are compared, and the largest value is normalized to unity. The mode shape comparison for the first mode is excellent with minimum deviations between the important DOF. In Table 3, a similar comparison is made for mode 6 which is a RTG mode. Although mode 6 appears to be an appendage mode, this mode is heavily coupled with core motion; therefore, it is more important than mode 1 in the loads analysis. The discrepancy in the extracted mode shape is attributed to the difference in the response level for the modes obtained by the two methods. Unlike mode 1 which is less stiff, mode 6 is too stiff for the broadband method to excite the test article into higher response level.

The second example is the Centaur G Prime modal test. Prior to the Challenger accident, this vehicle was to be used with the Space Shuttle as a high-energy interplanetary launch vehicle for Galileo, Ulysses, and Magellan. The Centaur G Prime weighed approximately 25,000 kg, and its finite-element model had approximately 30,000 static DOF. This vehicle was to attach to the space shuttle cargo bay at eight points by the trunnion/latch system for a total of ten restrained DOF. Sliding trunnions are designed to reduce the loads as well as to relieve the thermal expansion. Figure 3 shows the schematic of the Centaur G Prime in its modal test configuration. Again, the modal test was performed using both sine dwell and broadband methods, and selected results were reported previously.[8,9] One of the peculiar requirements of this test was that the vibration amplitudes be sufficiently high to force the trunnions to slide. If the trunnions did not slide, the boundary conditions would be different, resulting in frequencies and mode shapes that are unrealistic. The effect of the stick/sliding trunnions is represented by the dependency of the frequencies, damping, and mode shapes on amplitude as shown in Fig. 4. Table 4 shows the frequency comparison

Table 2 Mode shape comparison for Galileo spacecraft

	Mode 1 – local antenna mode	
DOF description	Sine dwell, 12.70 Hz	Broadband, 11.46 Hz
SXA tip in Y	1.00	1.00
SXA base ring in Y	0.47	0.49
SXA c.g. in Y	0.30	0.30
SXA tip in X	−0.22	−0.27
Science bm. in Z	0.07	0.09
EDP in Z	0.06	0.06
Mag. canister in Z	0.05	0.06
Mag. canister in Z	0.05	0.05
Mag. canister in Z	0.05	0.05
PLS in Z	0.04	0.03

Table 3 Mode shape comparison for Galileo spacecraft

	Mode 6 – global RTG walking mode	
DOF description	Sine dwell, 21.67 Hz	Broadband, 22.06 Hz
Canister I/F in X	1.00	0.28
$-X$ RTG in Z	−0.94	−1.00
$+X$ RTG in Z	0.69	0.35
RRH in Y	−0.66	−0.65
EPD in X	0.66	0.21
Bus in X	0.62	−0.18
Bus in X	−0.56	−0.16
Mag. canister in X	−0.37	0.26
$-X$ thruster in Z	−0.21	0.17
SXA tip in X	−0.11	0.15

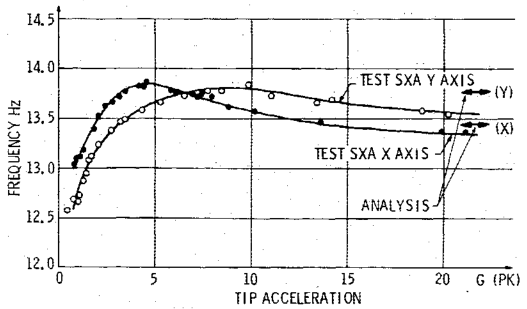

Fig. 2 High-gain antenna frequency vs tip acceleration.

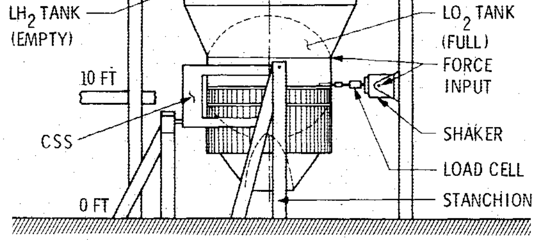

Fig. 3 Centaur G Prime in modal test configuration.

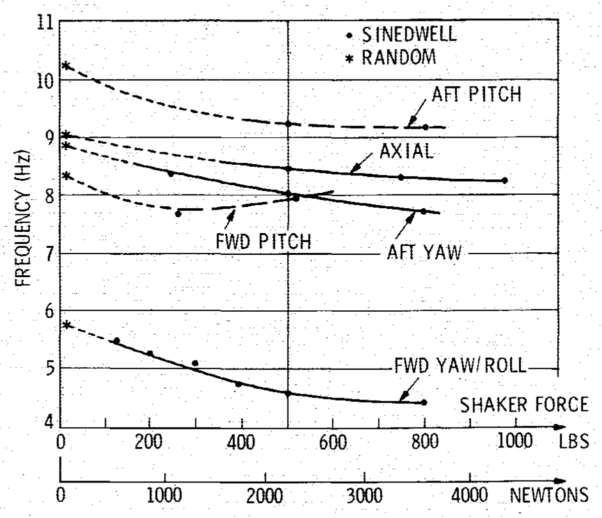

Fig. 4 Frequency variation as function of shaker forces.

Table 4 Frequency comparison for Centaur G Prime vehicle

Mode no.	Frequency, Hz Broad-band	Sine dwell	Description
1	5.791	4.410	Forward yaw
2	8.376	7.870	Forward pitch
3	8.870	7.660	Aft yaw
4	9.050	8.220	1st axial
5	10.242	9.190	Aft pitch
6	20.105	20.249	Engine yaw
7	20.575	–	Engs. & CSS yaw
8	20.675	–	Engs. & CSS
9	22.500	–	CSS yoke axial
10	22.959	–	Engs. sym. pitch
11	24.951	–	Engs. asym. pitch
12	25.473	27.879	2nd axial
13	26.149	–	Roll/torsion
14	27.895	–	3rd yaw
15	28.940	–	Engs. sym. pitch
16	29.100	–	3rd axial
17	30.495	–	4th yaw
18	31.262	–	3rd pitch

which indicates relatively poor agreement between the two methods. Similar to the previous example, Tables 5 and 6 show the mode shape comparison for global and local modes, respectively. Again, these data indicate that very good agreement is achieved for the local mode and poor agreement is found for the global mode. The reason, as indicated in Fig. 4, is that the external force level for the broadband method was too small to achieve the required response amplitude for the trunnions to slide. The global modes are important for the loads analysis, and low-level modes did provide appropriate data for the verification of the analytical model.

VI. Discussion

The discussions of the results will be based on the comparison criteria previously outlined.

A. Accuracy

The modal parameters were extracted accurately at the structural response levels. The broadband method, however, did not provide sufficient energy at the resonant frequencies for the structures to respond at levels required by the loads analysis. Therefore, the results from broadband method cannot be used reliably for the loads model verification.

Table 5 Mode shape comparison for Centaur G Prime vehicle

DOF	Global aft yaw bending mode Broadband, 8.870 Hz	Sine dwell, 7.660 Hz
26	1.000	1.000
101	0.667	0.789
48	0.401	0.638
2	0.357	0.584
55	−0.086	0.556
5	−0.173	0.531
32	−0.687	−0.450
58	−0.212	0.442
97	−0.644	−0.433
34	−0.621	−0.423
43	−0.801	−0.422
98	−0.649	−0.415
45	−0.784	−0.403
122	−0.877	−0.399
119	−0.881	−0.395
61	0.620	0.381
88	−0.721	−0.378
4	0.375	−0.351
59	−0.257	−0.344
54	0.598	0.333

Table 6 Mode shape comparison for Centaur G Prime vehicle

DOF	Local engine assembly mode Broadband, 20.575 Hz	Sine dwell, 20.249 Hz
97	1.000	1.000
32	0.906	0.844
34	0.837	0.812
98	0.780	0.768
43	0.498	0.491
45	0.447	0.448
96	0.102	0.075
119	0.071	0.070
44	0.075	0.065
122	0.061	0.058
46	−0.048	−0.051
33	0.040	0.045
118	0.041	0.044
94	0.048	0.042
121	−0.035	−0.040
70	−0.034	−0.036
76	−0.032	−0.031
58	−0.033	−0.030
105	0.034	0.024
109	0.035	0.023

B. Gaining Confidence

The broadband method did not provide opportunities for the engineers to interact with the test articles to develop an intimate knowledge about the behavior of these structures. For example, during the Galileo modal test, test engineers for the broadband method were very confident of the data because of the "cleanness" of the Frequency Response Functions (FRF) compared to those observed during other tests. In contrast, those responsible for the loads analysis model were concerned because of the extremely low response level of the broadband test and a lack of knowledge of the structural behavior at higher response levels. If only the broadband tests were performed, the loads analysis model verification process would have been inadequate.

C. Cost and Schedule Effectiveness

The data acquisition time for the broadband test is only a small fraction of the time required for the sine dwell method.

However, for the sine dwell method, the test is completed shortly after the completion of the data acquisition whereas for the broadband method, the test is completed after data aquisition when the data have been processed and modal parameters extracted. Also, for large complex structures, the actual test time often is not very significant compared to other testing activities such as system check out and trouble shooting. For the modal analysis/test effort, the cost and schedule effectiveness is somewhat improved using broadband methods but is not very significant for complex structures.

In both examples, the broadband test method failed the test objective, namely, the verification of the loads analysis, because of the nonrepresentative response level and lack of interaction between the engineers and the test article.

Another disturbing fact is the chaotic damping values extracted from the broadband test results. Extremely high damping values were obtained for the Galileo spacecraft appendages, although no obvious mechanism existed which would produce such high damping values. The fact that different broadband inputs produced an order of magnitude scatter in damping results for the same mode was quite unsettling. For the Centaur G Prime test, the broadband method predicted low damping for those modes in which the trunnions were supposedly in action. This is obviously due to the low amplitude response which failed to exercise the trunnions. The question of damping measurements will be discussed in another study.

VII. Concluding Remarks

The authors recognize that many successful modal tests have been performed by the broadband modal test method and that this method has many advantages over the sine dwell method. For certain types of structures, the resonance frequencies and mode shapes cannot be measured by the broadband methods. The purpose of the present paper is to emphasize that the sine dwell method can provide relevant modal data for such cases for the verification of loads analysis.

The preferred test method for these examples is obvious because the amplitude-dependent nonlinearity resulted in substantial differences in mode shape measurements. However, for those tests in which the results of the two methods are extremely close, some engineers have also preferred the sine dwell method over the broadband method.[5,10] The reason given is that the sine dwell method provided the interaction between the engineers and the structures which was necessary as part of the loads analysis model verification. An elegantly written editorial[11] mentioned that

> More importantly, sinusoidal testing provides a unique opportunity for the tester to interact with the test specimen on a mode-by-mode basis. The structure can be explored with eye, ear and hand during the examination. This "hand" on the structures approach is key to gaining personal insight of the structure's behavior. Broadband techniques do not lend themselves to such interaction and thus fail to capitalize upon intuitive intellect.

The value of the sine dwell modal testing method should not be dismissed, and its unique capability should not be ignored, at least not before a true replacement can be found.

At this junction, it appears that the academic and modal testing services communities are strongly advocating the exclusive use of the broadband method for all future modal testing. On the other hand, it is the practicing engineers and the project managers that support retention of the sine dwell method as a viable alternative for the modal testing. Perhaps the responsibilities of these two groups have something to do with their preferences. If so, it is unfortunate that the views of the practicing engineers and project managers have not been documented publicly and discussed as they should be.

The ultimate responsibility of the structural dynamics discipline is to ensure that the structural system is properly designed and manufactured to meet the given requirements. The analysis and test activities are techniques used to predict the behavior of the structure during its mission and whether failure would occur under the anticipated loading. The broadband test may provide good reliable data for a given structure; unfortunately one cannot determine whether the broadband test results are adequate unless a sine dwell test is performed. One reason for abolishing the sine dwell method is its potential for causing damage at a high response level for an extended number of cycles. If the response level is indeed realistic and representative of the actual dynamic environment, the structure will not be overtested because the design loads are approached during modal testing, not exceeded. Then, the failure will be caused by the inadequate design or manufacturing defect whose detection is precisely the purpose of the entire effort. Every practicing engineer and project manager would prefer that the failure occur during the ground test rather than during the mission. Additionally, failure during the sine dwell test most likely will provide detailed information about causes and clues for modification because of the precise knowledge about the response amplitude and the frequency. Therefore, the net effect of a structure failure due to ground test will be the increasing reliability after the corrective actions.

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