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Multi-Exciter Vibroacoustic Simulation of Hypersonic Flight Vibration

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ABSTRACT

Many aerospace structures must survive severe high frequency, hypersonic, random vibration during their flights. The random vibrations are generated by the turbulent boundary layer developed along the exterior of the structures during flight. These environments have not been simulated very well in the past using a fixed-based, single exciter input with an upper frequency range of 2 kHz. This study investigates the possibility of using acoustic and/or independently controlled multiple exciters to more accurately simulate hypersonic flight vibration. The test configuration, equipment, and methodology are described. Comparisons with actual flight measurements and previous single exciter simulations are also presented.

INTRODUCTION

Hypersonic flight random vibration is an important environment that must be considered when designing and certifying many flight systems. The vibration is a result of the turbulent aerodynamic boundary layer producing a fluctuating pressure field along the exterior of the vehicle during flight. The excitation forces from the turbulent boundary layer tend to be continuously distributed over the entire vehicle. Measured flight data and analyses also indicate that the excitations contain energy over a wide bandwidth and extend to frequencies beyond the typical test bandwidth of 2kHz. Furthermore, the flight vehicles are in a free-free boundary condition as they fly, and the only external forces acting on the bodies are gravity and aerodynamic forces. The distributed nature of the high bandwidth excitations and free-free boundary conditions create problems in performing realistic laboratory simulations of hypersonic flight vibration using conventional shaker systems. The inability to perform accurate laboratory simulations of these high-level vibration environments creates difficulties in certifying designs of hypersonic flight vehicles. This project investigated three unique test configurations to more accurately simulate these environments. The first configuration was an acoustic only test with free-free boundary conditions. The objective of this test was to generate a realistic simulation of a nominal flight condition. The second configuration was a random vibration test that utilized two shakers to provide a better match for the whole body qualification requirements. The third configuration looked at the system response to a combined vibroacoustic excitation.

PAST SIMULATION TECHNIQUES

Typical vibration simulations to date have utilized a single shaker driving the aft end of the flight vehicle through some fixture interface. The input vibration is controlled during the test with an accelerometer(s) on the fixture, or more commonly, on the unit (where the system response is measured in flight) near the fixture interface. It is only possible to tailor the motion (acceleration) at one point on the test unit to match the flight response during a single exciter test. Therefore, it is unlikely that other points on the unit will also match the corresponding flight response if the boundary conditions and excitation sources are different.

In any base-driven test configuration, all of the vibrational energy is forced to come through the aft end of the vehicle, and the resulting test boundary condition is much closer to fixed-free than the actual free-free condition. The resulting vibration, both on the exterior and internally at the components, is not very representative of the actual

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flight environment. The compromise to the flight boundary conditions exists in both the axial and lateral directions but is most pronounced in the lateral axes. A typical lateral axis test configuration is illustrated in Figure 1, where the test item is hard-mounted to a horizontal vibration slip table. In the lateral direction the shaker must impart large shear forces into the aft end of the vehicle to achieve the desired vibration levels which create large bending moments in the aft region of the flight vehicle. The response of the forward end of the flight vehicle also tends to uncouple from the base input creating under-tests of components in the forward end of the vehicle particularly at the higher frequencies. In the axial direction this uncoupling effect is much less pronounced, and test tailoring of the excitation at the aft end usually leads to a satisfactory simulation. Therefore, the primary focus of this effort was to improve the environmental simulation in the lateral axes.

Other practical considerations often further compromise the test simulation. The input forces required at the aft end of the vehicle to achieve the desired vibration level (created by a distributed input) may exceed the design limits of the vehicle. Therefore, the inputs as defined at the aft end must be "notched" at certain frequencies to prevent structural damage from occurring. This results in the specification as defined at other points in the structure to be further compromised at these frequencies.

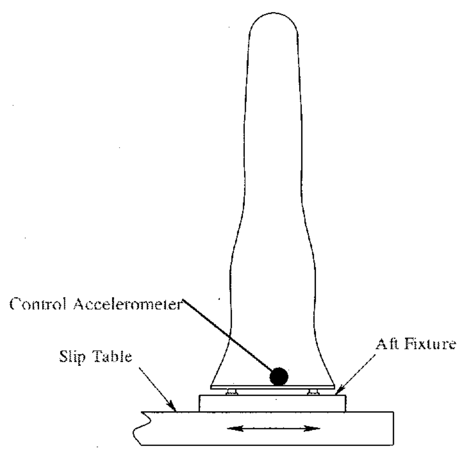

Figure 1. Lateral Axis Aft Hard-mount Test Setup

A slightly different approach that has been used at Sandia National Laboratories in the past for the lateral axes testing is illustrated in Figure 2. In this approach the test item is cantilevered from the aft fixture attached to the shaker through a flex web in an attempt to soften the boundary condition at the aft end of the flight vehicle. The flex web is stiff in the direction of exciter motion but is soft in bending to minimize the bending moments introduced into the aft section of the flight vehicle. A soft support (bungee cord) is used to support the static weight of the test item and center the flex web. This approach also eliminates the weight and dynamic response complexities associated with a slip table. This configuration represented an improvement over the hard-mount lateral setup for the simulation of free-free hypersonic flight vibration; however, the approach was still unable to simultaneously match the responses at components in the forward and aft regions of the system as observed in flight. This test configuration served as the reference for comparison of single shaker test results with the vibroacoustic simulations.

Another compromise that has accompanied earlier simulations is that the vibration specifications are truncated at 2000 Hz. Figure 3 compares the system-level, lateral axis test requirements as defined at the aft flange (denoted SPEC) against the corresponding Maximum Expected Flight Environment and the response for a single nominal flight (denoted MEFE and FLT, respectively). One can see that both the MEFE and single flight responses contain a significant portion of their energy above 2000 Hz.

The 2000 Hz test limitation is primarily a shaker performance and controllability issue. The performance of shakers of significant force capability (>20,000 lbs.) roll off above the first axial armature resonance which is typically near 2000 Hz. Control of the vibration also becomes difficult above 2000 Hz as the fixture resonances become more of a factor, and the dynamic range required to maintain the desired input spectrum becomes larger.

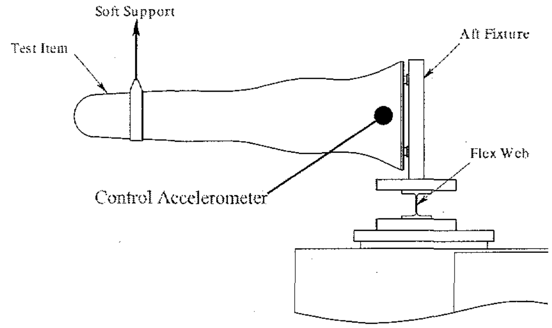

Figure 2. Lateral Axis with Flex Web and Soft Support

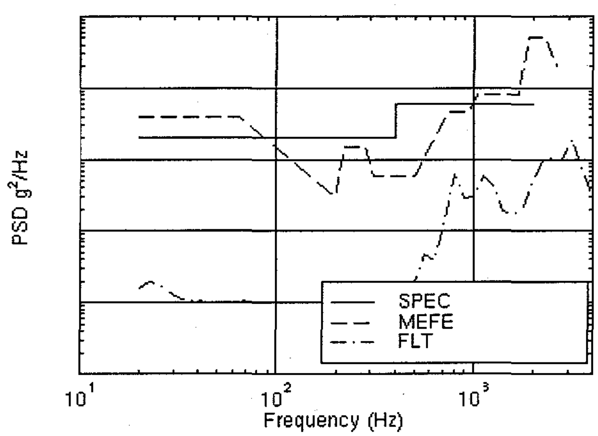

Figure 3. Test Requirement Versus Flight Data Aft Flange - Lateral

TEST RESULTS

The laboratory test results that are presented in this paper represent the response of a realistic ground test vehicle. The flight data were gathered from an ensemble of flight tests. Data from both laboratory and flight tests represent the response of the vehicle at three points (although not all three points were measured during all of the flight tests). Two of the response points, the Forward Mount and the Aft Flange (denoted FMT and AFL, respectively) represent the primary structural hard points in the vehicle. The third response point for which data are presented is a component mounted in the aft section (denoted ACP for Aft Component). While some of the available reference data is only defined for frequencies below 2 kHz, we have chosen to consider response data for frequencies from 20 Hz to 4000 Hz.

REVERBERANT ACOUSTIC SIMULATIONS

An acoustic test with the system soft supported within the acoustic chamber represents the most realistic boundary conditions for free-free flight vibration. It was realized at the initiation of the project that due to limitations in the available acoustic energy sources, even with the largest chambers, sufficient margin to perform qualification or certification tests would not be available, but it might be possible to simulate a "nominal" flight. The simulation of a nominal flight could be used for developing component-level vibration test specifications by scaling and enveloping the measured responses of the components [1]. The simulation of a nominal flight could also be used for correlating and validating analytical models of hypersonic flight systems. As part of the project to better simulate hypersonic flight vibration, reverberant acoustic tests were performed to compare the response of an acoustic environment simulation to actual flight vibration measurements.

The test vehicle was suspended with soft supports in the reverberant acoustic chamber at Sandia National Laboratories as described by Rogers [2]. The chamber has a volume of 16,000 cubic feet and is powered by gaseous nitrogen flowing through three electro-pneumatic drivers with the capability of generating an overall sound pressure level of 158 dB. Due to the limited size of the acoustic chamber, the lowest useable frequency in the chamber is approximately 63 Hz, below which the available excitation rolls off. The test setup with the flight vehicle suspended nose down in the acoustic chamber is illustrated in Figure 4.

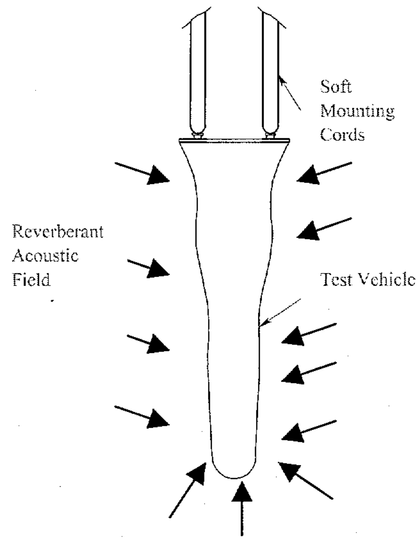

Figure 4. Acoustic Test Setup

Figure 5 presents the desired and achieved acoustic spectra (denoted SPEC... and TEST..., respectively). The desired spectrum was a theoretical prediction of the acoustic input scaled to the mean or nominal input levels. However, we had no idea at the start of this project whether it had any basis in reality. While the achieved spectrum was low everywhere (the chamber capacity was reached sooner than expected for this SPL profile), the desired shape was matched over the frequency range from 200 to 1200 Hz (which not coincidentally corresponds to the control frequency range). Therefore, all of the statements made regarding the plots presented in this section will be made in the context of this relationship between the theoretical and achieved acoustic spectrum.

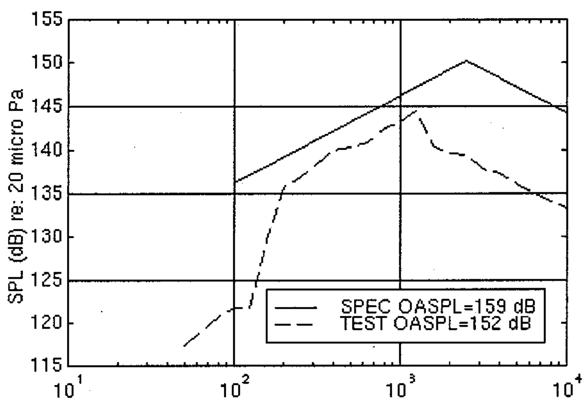

Figure 5. Acoustic Only Test
Acoustic Profiles

Figures 6 through 11 present the response data from the acoustic only test measured at the Aft Flange, Forward Mount, and Aft Component (denoted TEST FMT, TEST AFL, and TEST ACP, respectively). Figures 6 and 7 compare the Aft Flange acoustic test data against the corresponding mean flight responses and the data from a single nominal flight (denoted MEAN... and FLT..., respectively). Figures 8 and 9 compare the Forward Mount acoustic test data with the corresponding mean flight responses (denoted MEAN...). Figures 10 and 11 compare the Aft Component acoustic test data with the corresponding response data from the same single, nominal flight (denoted FLT).

Since we did a credible job of matching the low frequency (< 200 Hz) longitudinal flight responses as shown in Figures 6 and 8, it is believed that the true acoustic spectrum might actually also roll-off in a manner similar to that of the acoustic chamber. Certainly, a turbulent boundary layer induced pressure field would not be expected to generate significant low frequency excitation levels. It is speculated that the poor agreement between the low frequency test and flight responses in the lateral direction (as shown in Figures 7 and 9) is due to the fact that the flight responses are dominated by a sinusoidal vibration component in the lateral direction. This sinusoidal vibration is caused by the precessing of the vehicle during flight rather than by turbulence induced random vibration. The vehicle response to the acoustic only excitation was lower than expected at the Aft Flange for frequencies above 1200 Hz (even when one allows for the fact that the acoustic input was 12 dB low in this frequency range). However, the differences between nominal flight and test do not appear quite so bad for the other locations, and might even be considered acceptable for frequencies below 2 kHz. Therefore, the overall summary of the acoustic only test is that it produced a credible nominal or mean flight simulation for frequencies from 200 Hz to 2 kHz.

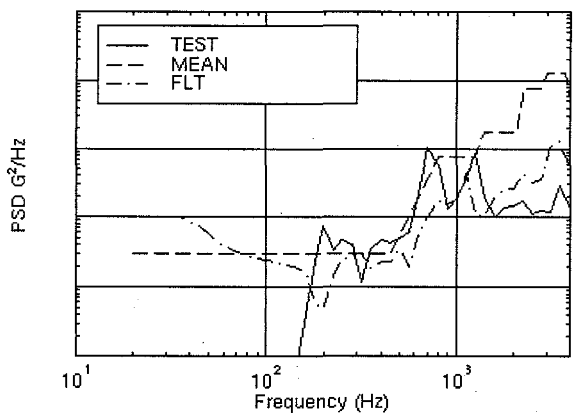

Figure 6. Acoustic Only Test
Aft Flange – Longitudinal

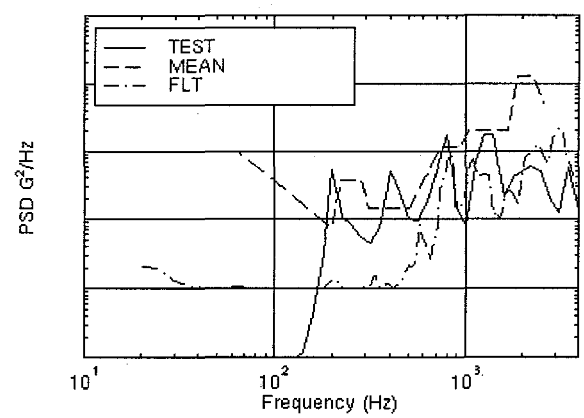

Figure 7. Acoustic Only Test
Aft Flange – Lateral

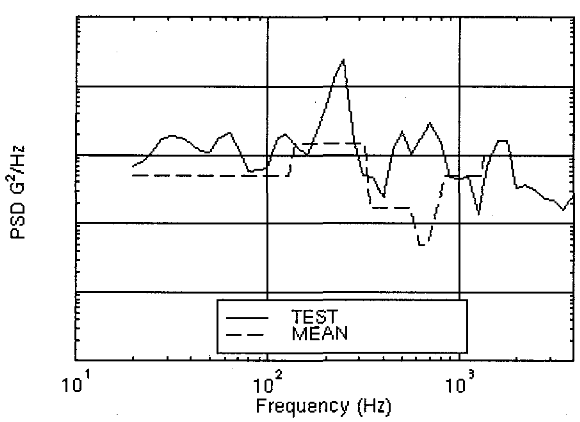

Figure 8. Acoustic Only Test
Forward Mount – Longitudinal

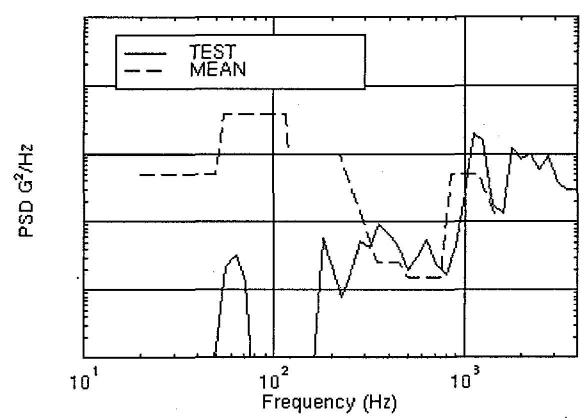

Figure 9. Acoustic Only Test
Forward Mount – Lateral

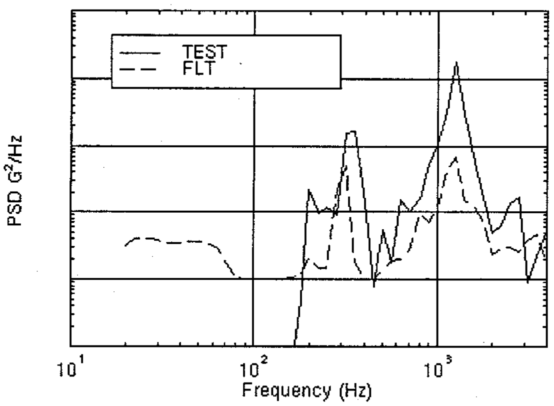

Figure 10. Acoustic Only Test
Aft Component – Longitudinal

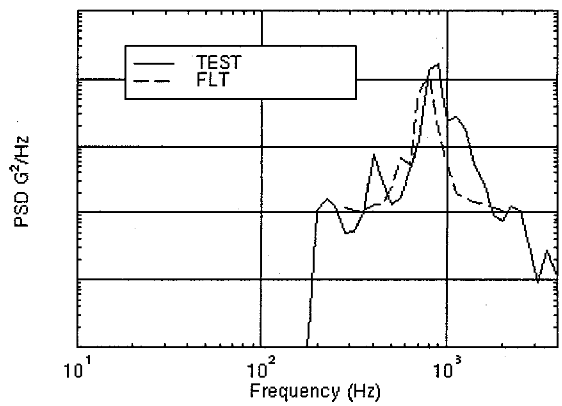

Figure 11. Acoustic Only Test
Aft Component – Lateral

MULTI-EXCITER SIMULATIONS

While an acoustic only test is considered to be the most realistic simulation of the actual environment, Sandia does not have an acoustic facility with enough capacity to generate the Maximum Expected Flight Environment (MEFE). Therefore, Sandia has historically certified full-up systems using a base-driven random vibration test. The requirements for this system certification define the desired random vibration spectra at both the Forward Mount and the Aft Flange. However, since a single shaker test can only produce the desired spectrum at one point, we have always achieved the desired spectrum at the Aft Flange and accepted whatever response level was achieved at the Forward Mount. This setup was always considered to be something less than ideal for the lateral axis testing.

Therefore, the second test configuration was implemented to study the possibility of using a two-shaker random vibration test to achieve the desired response spectra at both the Forward Mount and the Aft Flange simultaneously during lateral axis testing. Sandia National Laboratories has a long history in the development of techniques for the independent control of multi-exciters as evidenced by the work of Smallwood [3-6]. A combined multi-shaker vibroacoustic simulation was also recently shown to provide a very realistic environment for a wing carried store as discussed by Cap [7]. The successful use of multi-exciters requires that the inherent cross coupling between the exciters be properly accounted for in the control strategy. This requires a system identification step in the control scheme for identification and inversion of the full system cross-spectral density matrix. An STI multi-exciter control system was used to independently control the input to two shakers attached to the flight vehicle as illustrated in Figure 12. Each exciter is coupled to the test vehicle through a flex web and then to a forward or aft adapter plate. The test was controlled by internal accelerometers on the Aft Flange and Forward Mount locations within the test vehicle. The desired specifications for the power spectral densities (PSD's) at the Aft Flange and Forward Mount are shown as the solid curves in Figures 13 and 14.

It is appropriate to preface the discussion of the test results of the multi-exciter simulations with some comments regarding the control system and the test personnel. The STI control system was an early generation control system that was purchased only a few months before this project started, and the test personnel had limited experience in using the system. This test configuration represented a severe test for any control system due to the location of the desired control points (internal to the test vehicle and separated from the exciters by complex fixtures) and the associated nonlinearities. Some of the difficulties in meeting the specifications at the forward and aft locations, as discussed below, can probably be attributed to some software issues as well as inexperience by the operators. The important thing to note, however, is that through some test tailoring, a very acceptable match of the desired input spectrums was achieved.

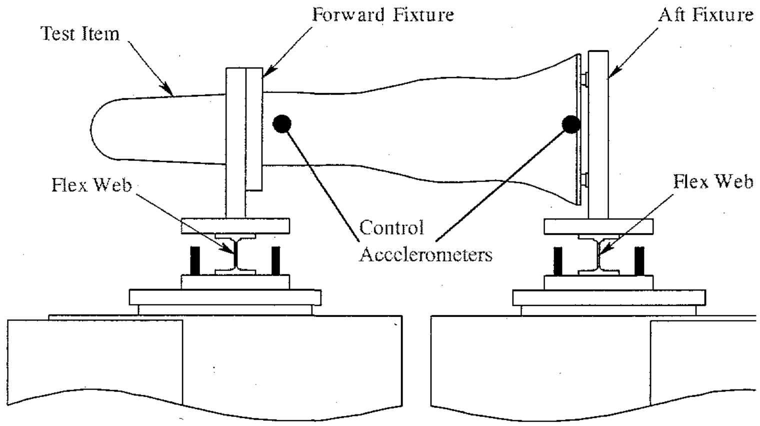

Figure 12. Multi-Exciter Test Setup

The STI system requires a pre-test characterization in which the cross spectral density matrix for the test vehicle is obtained. The STI system outputs a sine chirp to each shaker, one at a time, to obtain the response at each of the control points. Although a low-level characterization is desirable, it was found that amplitudes of 70-80 percent of the full test level were required to obtain a reasonable estimation of the system response. This is attributed to the nonlinear response of the complex test assembly. Since the test requirement did not specify the correlation between the inputs and only the power spectral density functions were specified, the coherence and phase angle at each frequency become free parameters. The initial values chosen were 40 percent coherence and 90 degree phase angle.

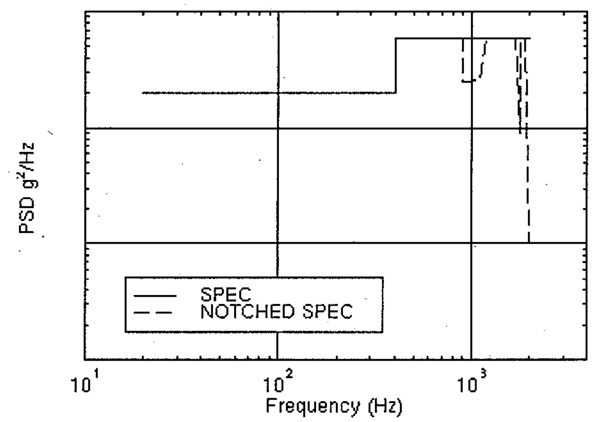

Fig 13. Random Vibration Test
Aft Flange – Lateral

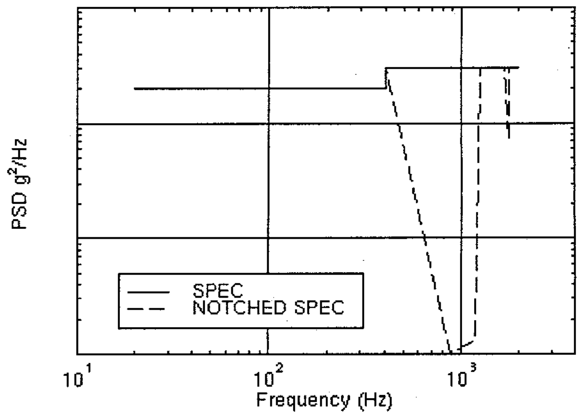

Fig 14. Random Vibration Test
Forward Mount – Lateral

The initial test showed that the control system could not equalize a peak in the control spectra and would become unstable before -6dB. The major problem area was a very high amplitude peak located in a very narrow bandwidth centered at 1780 Hz. Adjusting the control gain to apply less correction per control loop was successful in keeping this peak stable, but the control system could still not bring the peak into tolerance. The coherence and phase parameters were modified in an attempt to bring this peak back into tolerance. These changes allowed the controller to achieve the coherence and phase specified in the test file but did not improve the amplitude of the peak in the control spectra. After several iterations of coherence and phase adjustments were made without any significant improvements in the control spectra, a notch was introduced in both exciter reference control spectra. Similarly the wider out-of-tolerance band of 500-1270Hz on the forward control spectrum also required reduction in level for the forward control spectrum in this bandwidth and a smaller notch form 910- 1270 Hz for the aft control spectrum.

These "pre-notching" changes, shown as dashed lines in Figures 13 and 14, allowed the control system to bring the control spectrums near to the desired levels.

In theory the "pre-notching" of the reference spectrums at the control points should not have been required to achieve the desired spectrums. The control algorithm should make adjustments to the drive signals to reduce the input to the shakers to converge to the desired levels. It is speculated that system nonlinearities created errors in the system identification and inversion of the cross-spectral density matrix that led to problems in properly uncoupling the input between the shakers at certain frequencies.

Figure 15 presents the measured response for the two-shaker lateral axis test configuration, the old lateral axis single shaker base driven configuration, and the reference spectra (denoted TEST, OLD TEST, and SPEC respectively) for the Aft Flange. Figure 16 presents the corresponding results for the Forward Mount. It is not surprising that both test configurations produce the desired spectrum at the Aft Flange since they both use that location as a control point. However, the comparison of the responses measured at the Forward Mount show that the two-shaker configuration produces the desired levels while the single shaker configuration is grossly off the mark.

The system level random vibration requirements bear very little resemblance to the MEFE response spectra (refer to Figure 3). However, since the individual component test specifications are linked to these system level requirements, the two-shaker test would appear to be better aligned with the subsystem level tests. Whether or not any shaker test configuration can really produce a realistic match to the response distribution measured during flight is not known at this time (primarily because we don't have the necessary whole body response flight data to make the comparison). However, one would anticipate that the two shaker configuration would have the best chance of matching the MEFE response at multiple locations if the current system requirements were ever tailored.

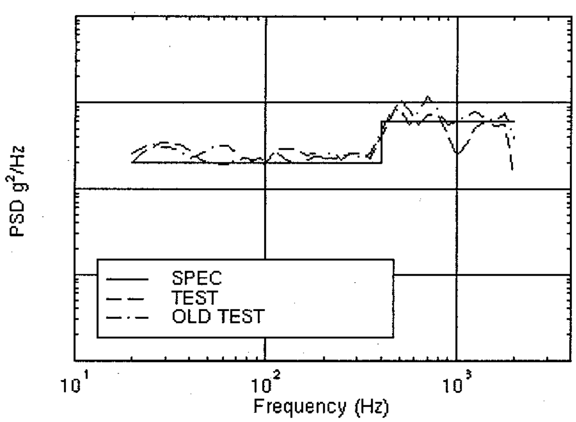

Figure 15. Random Vibration Test
Aft Flange – Lateral

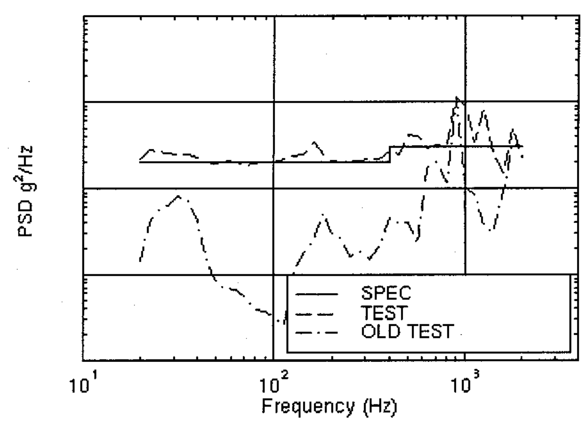

Figure 16. Random Vibration Test
Forward Mount – Lateral

COMBINED VIBROACOUSTIC TEST

The third test configuration looked at supplementing the two-shaker random vibration test with an acoustic excitation. The original supposition was that we could augment the shaker excitation for frequencies above 2 kHz with the acoustic noise. Such a combined test would be extremely useful if we ever chose to extend the test requirements shown in Figures 15 and 16 to include the high frequency portion of the MEFE response levels shown in Figures 17 and 18. At the beginning of the test program, there was a concern that the vibration control system would be adversely effected by the addition of the acoustic excitation overlapping the same bandwidth in which the shakers were operating. The results of the tests demonstrated that the vibration control system was stable with the addition of the acoustic excitation properly accounted for in the control of the total power spectral density at the Forward Mount and Aft Flange control locations.

The results of the acoustic only test showed us that the acoustic system did not have enough power at frequencies above 2000 Hz (the current definition of the acoustic spectra puts all of the controlled acoustic power below 1200 Hz and relies on harmonic distortion to create noise above 1200 Hz). The results for the combined vibroacoustic test for the Aft Flange and Forward Mount locations are shown in Figures 17 and 18, respectively. Although sufficient acoustic energy to match the MEFE above 2000 Hz was not available, the addition of the acoustic input at least exercises the system within this frequency range as opposed to completely ignoring these frequencies as in past laboratory simulations. It is speculated that the input above 2000 Hz could be improved by tailoring the acoustic input to focus all of the acoustic power at high frequency; however, any test to demonstrate this was beyond the resources available at the time of the test series.

Another possible use of a combined vibroacoustic test would be to supplement the acoustic test with low frequency lateral axis vibration to simulate the precessing wobble. In this manner we would have a very good three-dimensional simulation of a nominal flight from 20-2000 Hz.

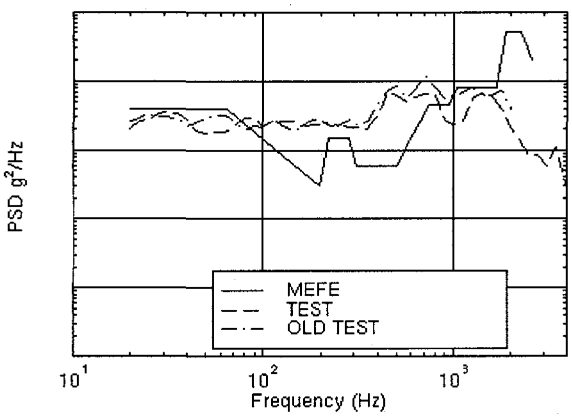

Figure 17. Combined Vibroacoustic Test
Aft Flange – Lateral

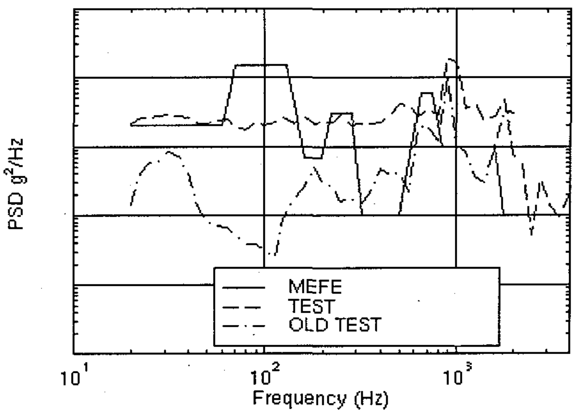

Figure 18. Combined Vibroacoustic Test
Forward Mount – Lateral

MEASUREMENT UNCERTAINTY ANALYSIS

The data presented in this paper were all measured in essentially the same manner. The accelerometer and microphones are considered to be accurate to within +/-5% and this represents a potential bias error in each and every measurement. Since there are two measurements associated with any laboratory test (a control and a response) which are uncorrelated, the total potential bias error associated with any laboratory test data will be 7%. While the flight data were measured using a somewhat more complex data acquisition system, we will assume that the bias error for flight data is also on the order of 5% (since only a single measurement is associated with flight data).

The bias error is compounded by the fact that there is an uncertainty associated with any spectral analysis of random data. Since PSD's (Power Spectral Densities) and SPL's (Sound Pressure Levels) are statistically derived estimates of the true spectral density estimates, their accuracy is directly related to the amount of data used to derive them. The conventional parameter used to quantify the uncertainty in the spectral density estimate is the Normalized Variance Error (NVE). The confidence that a spectral density estimate is equal to the true spectral density is defined by a Chi-Squared distribution. The NVE represents one standard deviation for that distribution. For more detailed descriptions of the NVE see Bendat and Piersol [8] and Wirsching and Paez [9]. Therefore, using the NVE and the desired confidence interval for the spectral analysis one can place error bars on the PSD or SPL. These error bars will then be increased to account for the bias error in the underlying data measurement.

If the spectral analysis is performed using commonly accepted windowing functions and window overlaps, the NVE is defined for a linear bandwidth analysis to be the inverse of the square root of the number of averages (or blocks) of data used in the analysis. However, based on recommended practices used in the aerospace industry, the PSD's presented in this paper have been re-averaged using a 1/6th octave analysis bandwidth. This is done specifically to reduce the variance error (the NVE is also related to the inverse of the square root of the analysis bandwidth). Figure 17 shows this relationship for the spectral analysis parameters used in this paper (the raw PSD's were computed using 32 blocks of data and a linear bandwidth of 4.88 Hz). At the very low frequencies, the constant bandwidth analysis does not provide resolution for 1/6th octave analysis therefore the NVE remains equal to the constant value for the linear bandwidth analysis.

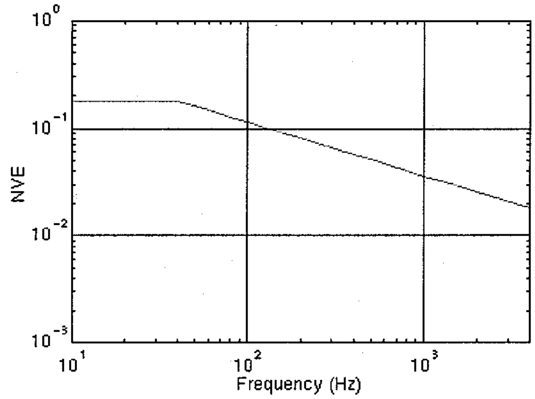

Figure 19. Normalized Variance Error for 1/6th Octave PSD's

SUMMARY

A series of vibration /acoustic tests were performed to develop techniques for better simulating hypersonic flight vibration. The acoustic only test was shown to provide a very credible "nominal" flight simulation from 200-2000 Hz. It appears that augmenting the frequency range below 200 Hz with shaker inputs could yield an even better nominal flight simulation. The multi-exciter input was successfully demonstrated to simultaneously match the test envelope requirements at both the forward and aft locations internal to the flight vehicle. Special test tailoring was needed to accomplish this, because the cross coupling between the shakers was not properly accounted for in selected frequency bands. The two-shaker input was shown to provide a much improved test at the forward end of the flight vehicle as compared to a single-shaker test. The feasibility of a combined vibration and acoustic test was demonstrated, and although the high frequency levels above 2000 Hz could not reach the maximum expected flight environment (MEFE) levels, the simulation provided at least some energy in this range that has been ignored in past laboratory simulations. Future work will include investigating the tailoring of the acoustic spectrum to focus the available energy above 2000 Hz, while using the shakers to encompass the low frequency portion of the spectrum.

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