Closed-Loop Control for Sonic Fatigue Testing Systems

Stephen A. Rizzi, NASA Langley Research Center, Hampton, Virginia
Guido Bossaert, m+p international inc, Verona, New Jersey

This article documents recent improvements to the acoustic control system of the Thermal Acoustic Fatigue Apparatus (TAFA), a progressive wave tube test facility at the NASA Langley Research Center, Hampton, VA. A brief summary of past acoustic performance is first given to serve as a basis of comparison with the new performance data using a multiple-input, closed-loop, narrow-band controller. Performance data in the form of test section acoustic power spectral densities and coherence are presented for a variety of input spectra including uniform, band-limited random and an expendable launch vehicle payload bay environment.

The progressive wave tube (PWT) facility at NASA Langley Research Center, known as the Thermal Acoustic Fatigue Apparatus (TAFA), is used to test structures for dynamic response and sonic fatigue due to combined, high-intensity thermal acoustic environments. Prior to 1994, it was used to support development of the thermal protection system for the Space Shuttle and the National Aerospace Plane, and various generic hypersonic vehicle structures.[1-3] During the period of 1994-1995, the facility underwent significant modifications to improve its performance. A photograph of the facility following the modifications is shown in Figure 1. Following these enhancements, the facility was used for sonic fatigue studies of the wing strake subcomponents on the High Speed Civil Transport. Most recently, and the subject of this article, are enhancements to the acoustic control system. A description of the control system and selected performance characteristics are provided. Additional performance data and a description of a new thermal control system are documented in Reference 4.

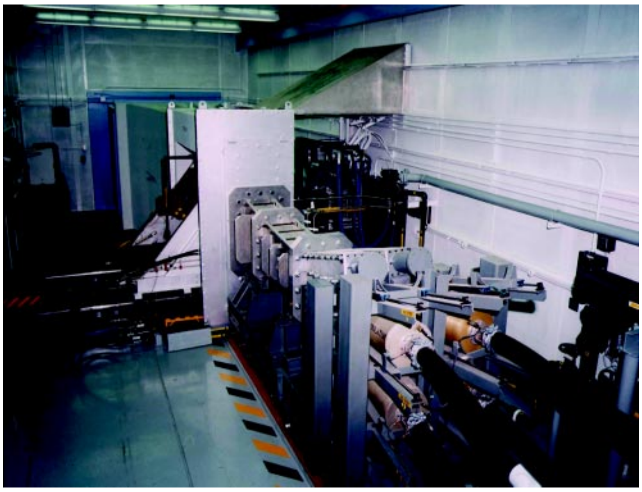

Figure 1. Photograph of the post-1995 TAFA facility in the four-modulator reduced configuration.

Pre-1995 Facility Performance

The capabilities of the TAFA facility prior to the 1995 modifications were previously documented by Clevenson and Daniels.[5] The system was driven by two Wyle WAS 3000 airstream modulators, which provided an overall sound pressure level range of 125 to 165 dB overall sound pressure level (OASPL) and a useful frequency range of 50-200 Hz. Manual control of the acoustic level was performed by adjusting the output of a white noise signal generator and gain on the amplifiers driving the air modulators. Typically, there were no attempts to adjust the acoustic spectrum shape in the test section. A 360 kW quartz lamp bank provided radiant heat with a peak heat flux of 54 W/cm^2. The lamp bank consisted of ten-36 kW lamps units, each having six-6 kW quartz lamps behind a 2.54 cm thick quartz window.

A typical test section acoustic pressure power spectral density (PSD) is shown in Figure 2 for a 160 dB OASPL. Also shown in this and in subsequent PSD plots are the specified narrow-band spectrum levels, ±1.5 dB level, and ±6 dB levels. The coherence between two test section microphones is shown in Figure 3 and helps to explain the quoted useful frequency range.

Post-1995 Facility Performance

In order to meet future testing requirements, extensive modifications were made to the sound generation system and to the wave tube itself. The heating system was left largely unchanged. A theoretical increase of 6 dB OASPL was projected by designing the system to utilize eight WAS 3000 air modulators compared to the two used in the previous system. A further increase of nearly 5 dB was expected by designing the test section to accommodate removable water-cooled insert channels, which reduced its cross-sectional area from 1.9×0.33 m to 0.66×0.33 m. The frequency range was increased through the use of a longer horn design with a lower (15 Hz vs. 27 Hz in the old facility) cut-off frequency, use of insert channels in the test section to shift the frequency of significant standing waves above 500 Hz, and design of facility sidewall structures with resonances above 1000 Hz. The uniformity of the sound pressure field in the test section was improved through several means. A new, smooth exponential horn was designed to avoid the impedance mismatches of the old design. To minimize the effect of uncorrelated, broadband noise (which develops as a byproduct of the sound generation system), a unique design was adopted which allows for the use of either two-, four-, or eight-modulators. When testing at the lower excitation levels for example, a two-modulator configuration might be used to achieve a lower background level over that of the four- or eight-modulator configurations. In doing so, the dynamic range is extended. Lastly, a catenoidal design for the termination section was used to smoothly expand from the test section. These configurations were used to benchmark the performance of the new acoustic controller.

The only substantial change to the acoustic control system was the addition of a bank of four 1/3-octave band equalizers in series between the output of the white noise signal generator and amplifiers driving the air modulators. Level control was still performed by manually adjusting the output of the signal generator and gain on the amplifiers. The process of adjusting the test section spectrum shape was both time-consuming and error prone. The effect of adjusting the level of a single 1/3-octave band was carried over to the neighboring 1/3-octave bands within one equalizer, and within the same band across equalizers. Thus, a nonunique and iterative process was required to provide a flat spectrum. The time required to adjust the equalizers could be on the order of 10-15 minutes; too long for testing at high levels where fatigue life may be short. In such cases, settings were established apriori using a dummy panel, but were still subject to day-to-day changes. Narrow-band control was not possible using this approach. Lastly, spectrum

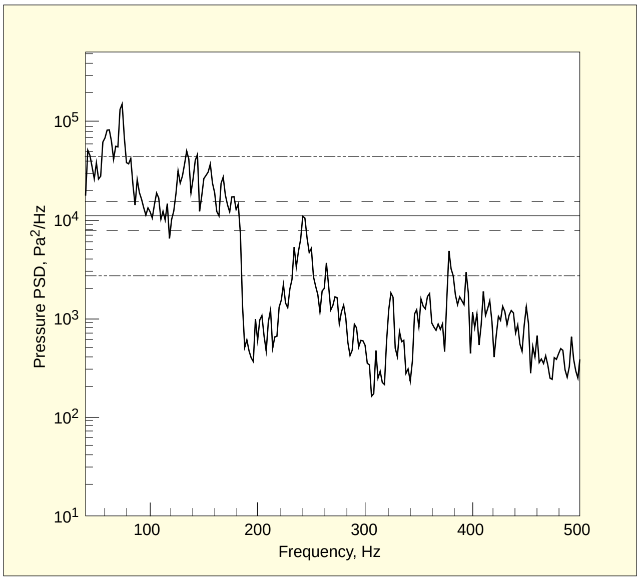

Figure 2. Test section acoustic pressure PSD of the pre-1995 TAFA facility.

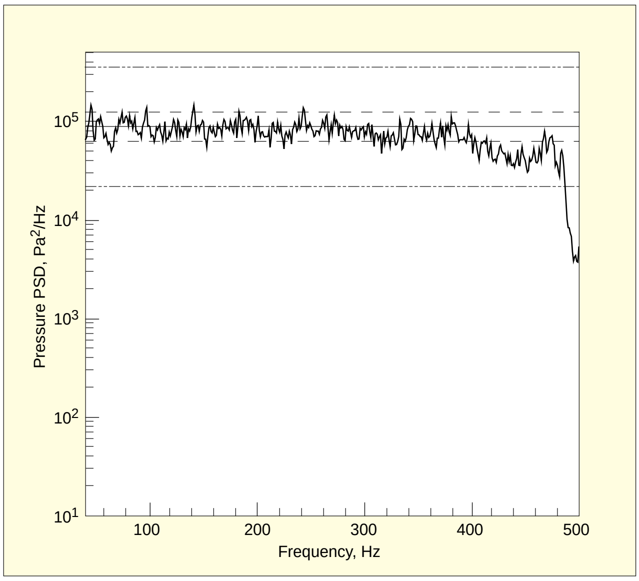

Figure 4. Average test section pressure PSD of post-1995 TAFA facility in the eight-modulator reduced configuration.

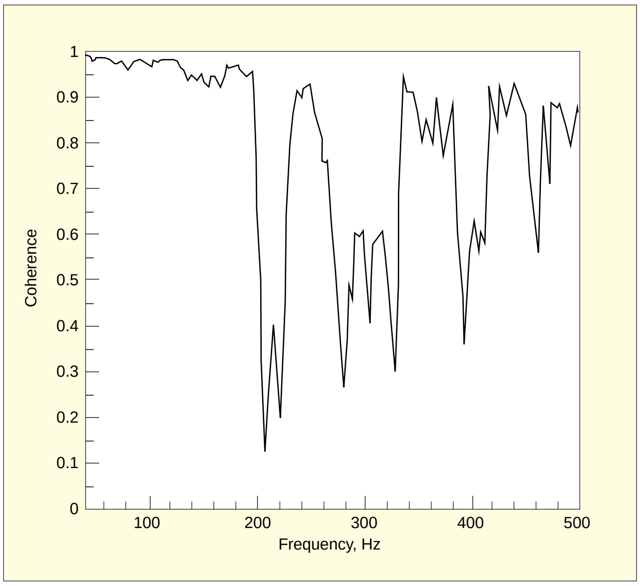

Figure 3. Test section coherence of the pre-1995 TAFA facility.

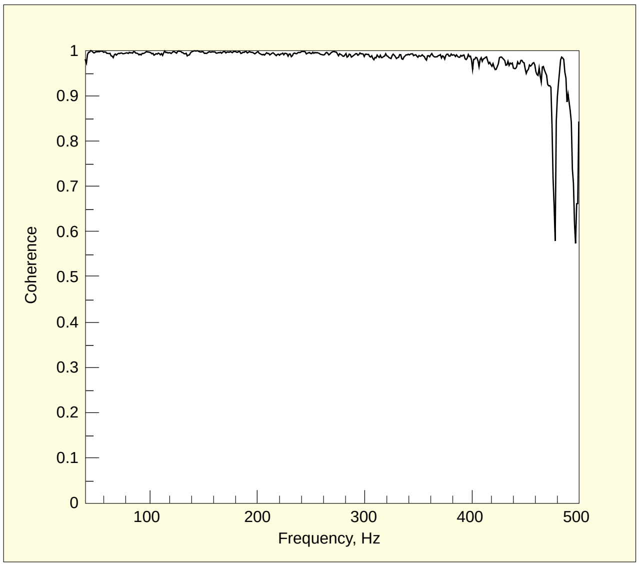

Figure 5. Coherence between the upstream and downsteam pressures of the post-1995 TAFA facility in the eight-modulator reduced configuration.

shaping was based on the spectrum at one point in the test section (typically at the upstream microphone). Thus, there was no way to control the spectrum across the extent of the test article. Even with all of these limitations, a reasonably flat and coherent spectrum could still be achieved with some effort.

The performance of the facility in all of its configurations was previously documented by Rizzi and Turner.[6] The modifications indicated above resulted in an increase in the maximum OASPL by over 6 dB relative to the pre-1995 performance and an expansion of the frequency range to 40-480 Hz for the reduced configurations. A few results are included in this article to assist in the performance evaluation of the new acoustic controller. The average test section PSD in the eight-modulator reduced configuration is shown in Figure 4, for a 170 dB OASPL. The average PSD was taken between microphones located upstream and downstream of a dummy test article. The PSD of the individual microphones may be found in Reference 6. In this case, the upstream test section pressure was used for control. A relatively flat spectrum was achieved up to about 400 Hz. The coherence between upstream and downstream locations, shown in Figure 5, is nearly unity to about 460 Hz.

Narrow Band Acoustic Controller Description

During the year 2000, a new acoustic control system was installed and tested to enhance the capabilities of TAFA and to prepare the facility for future testing. Of paramount importance was the need to have an automated means of shaping a wide variety of spectrum shapes in a fast and efficient manner. A commercial control system was selected and customized for use in this application. The system procured was the m+p international "Vib2000 Vibration Control System," heretofore referred to in this article as the control system.[7] The features of the baseline control system include:

- Narrow band closed-loop noise control.
- Multiple control transducers (limited by the number of input channels) in either averaged, maximal, or minimal control strategies.
- Test spectrum specification with up to 99 breakpoints, sigma clipping (1.42-8), low and high alarm and abort limits for each frequency range.
- Automated measurement and level scheduling.
- Runs on a host PC computer under Microsoft Windows NT.
- Watchdog channels to limit the drive signal on an overall basis (in the tolerance mode) or on a narrow-band basis (in the notch/tolerance mode).

The watchdog feature is useful in PWT testing to ensure the integrity of the facility and test article. In the tolerance mode, it can be used to limit amplifier output to less than 12 amperes RMS, as required for the Wyle WAS 3000 air modulators. It can also be used to limit test article structural response in either an RMS (tolerance mode) or narrow-band (notch/tolerance mode) basis.

As with any other feedback controller, the control software compares the specified level with the actual level (referred to as the control signal) and adjusts the drive signal to minimize the error between the two. The manner in which the control signal is computed has some bearing on the responsiveness of the control. This is briefly summarized here. For each control loop i and control channel, an averaged PSD is computed from several instantaneous PSDs using the usual formula:

$$\overline{PSD}^{(i)} = \frac{1}{K}\sum_{j=1}^{K} PSD_j$$

where K is the number of averages per control loop. For example if $K = 5$, the formula for two consecutive loops would look like this:

$$\overline{PSD}^{(1)} = \frac{1}{5}(PSD_1 + PSD_2 + PSD_3 + PSD_4 + PSD_5)$$
$$\overline{PSD}^{(2)} = \frac{1}{5}(PSD_6 + PSD_7 + PSD_8 + PSD_9 + PSD_{10})$$
$$\vdots$$

Note that no overlap is used in computing the averaged PSD. The control signal PSD is built by using a weighted average of the averaged PSDs as:

$$PSD^{(i)}_{\text{control}} = \frac{(N-1)PSD^{(i-1)}_{\text{control}} + \overline{PSD}^{(i)}}{N}$$

where N is the average weighting factor. It is clear from the above equation that it takes two loops to get the controller going. But since the averaged information from the self check results is taken into account, the system is controlling from the first loop on. For example,

$$PSD^{(2)}_{\text{control}} = \frac{(N-1)PSD^{(1)}_{\text{control}} + \overline{PSD}^{(2)}}{N}$$
$$PSD^{(3)}_{\text{control}} = \frac{(N-1)PSD^{(2)}_{\text{control}} + \overline{PSD}^{(3)}}{N}$$
$$\vdots$$

If more than one channel is used for control, then the total control signal PSD is either the average over the whole frequency range, or the maximum or minimum on spectral line by spectral line bases of the individual control PSDs depending on the control strategy selected. Note that while not a feature of the control software, a weighted average in which some control channels are more important than others can be made possible by scaling the input sensitivities of the control channels. The reader is referred to Reference 7 for additional information.

At the request of NASA, several changes were made to the baseline control software to facilitate its use in PWT testing. These included:

- Modification of the "open channel" algorithm to allow for low signal/noise ratios during the start of a test.
- Specification of test spectrum breakpoints in Pa^2/Hz, and display of RMS levels in dB.
- A "last drive" capability, which allows the use of a pre-stored drive signal to enable quick start up and equalization of a test that has previously been run. This feature allows, for example, the simulation of blast or launch loads.
- Retention of support for both the Hewlett-Packard 3565S and VXI front-ends.

The modifications were implemented in the standard software package so that new features would be available in subsequent releases of the software.

The particular implementation in TAFA is a dual-processor PC running Windows NT 4.0, an HP 3565S front-end with 32 input channels, and up to 8 watchdog channels for each of the amplifier outputs. The control channels typically consist of two fluctuating pressure measurements in the test section located upstream and downstream of the test article. Note that an averaged control strategy of this type is best for PWT testing as it ensures a good acoustic spectrum across the test article. It does come, however, at the expense of the ability to maintain the specified spectra for any particular channel. The same drive signal served as input to each of up to 8 air modulators, as it was the aggregate test section acoustic environment being controlled as opposed to the noise being generated by each modulator individually.

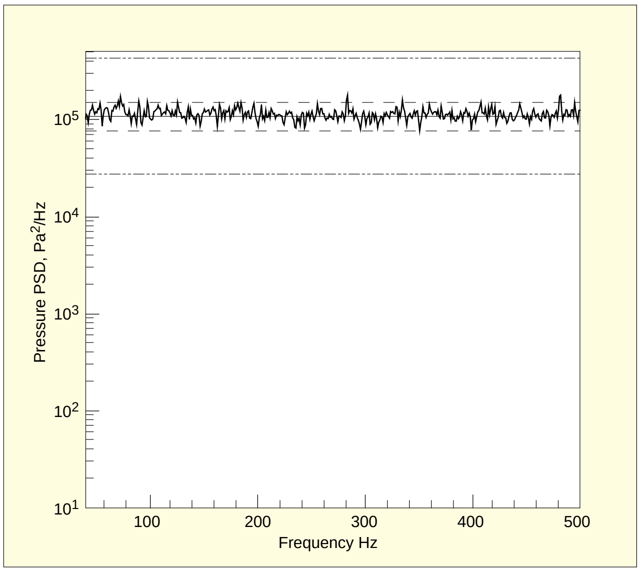

Figure 6. Control pressure PSD for the eight-modulator reduced configuration at 171 dB.

In the following cases, acoustic pressure was controlled using two Kulite model MIC-190-HT pressure transducers in the 'averaged' control strategy across the facility frequency range of 40-500 Hz. The transducers were flush mounted in a rigid panel and were located 0.3048 m upstream and 0.3048 m downstream of the test section vertical centerline, along the horizontal centerline. In the control software, the following parameters were set:

- A frequency resolution of 1 Hz.
- Sigma clipping set to three.
- High and low alarm limits set to ±1.5 dB for each frequency range.
- High and low abort limits set to ±6 dB for each frequency range. Note that for each test case, the high and low abort limits were never exceeded. Thus, these limits could probably be tightened considerably.
- Averages per loop K of 5 and average weighting factor N of 5.

Simultaneous with control data acquisition, time history data were acquired and processed on a separate computer (running MTS IDEAS Master Series 7 data acquisition software with an HP VXI front-end) for each of the control channels to measure coherence.

Uniform Spectra Results

For response validation testing, it is desirable to have as flat an input spectrum as possible, so that the shape of structural response spectra are attributable to the structural dynamics and not a reflection of the input loading condition. This is particularly true when testing in the nonlinear structural response range. Flat input spectra were specified for the two, four, and eight-modulator reduced configurations from an OASPL of 140 dB to near the configuration maximum in 6 dB increments. Results from the two- and four-modulator reduced configurations may be found in Reference 4. Results for the eight-modulator reduced configuration are shown below.

The control pressure spectrum is shown in Figure 6 at an OASPL of 171 dB. The PSD of the individual pressure trans-

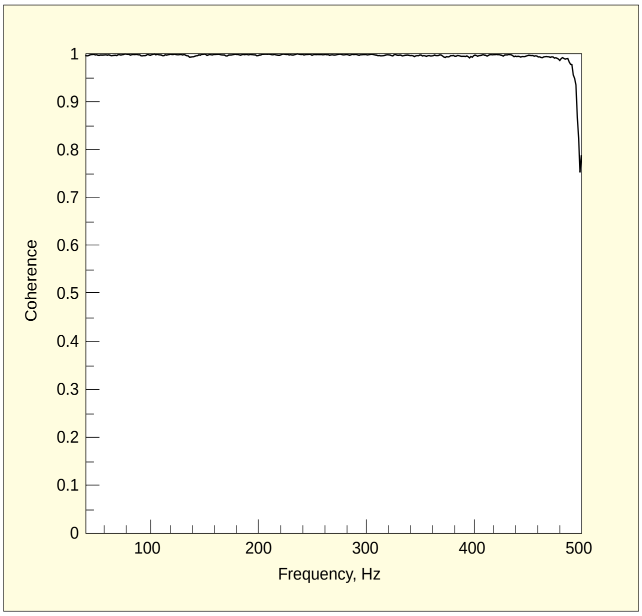

Figure 7. Coherence between upstream and downstream locations for the eight-modulator reduced configuration at 171 dB.

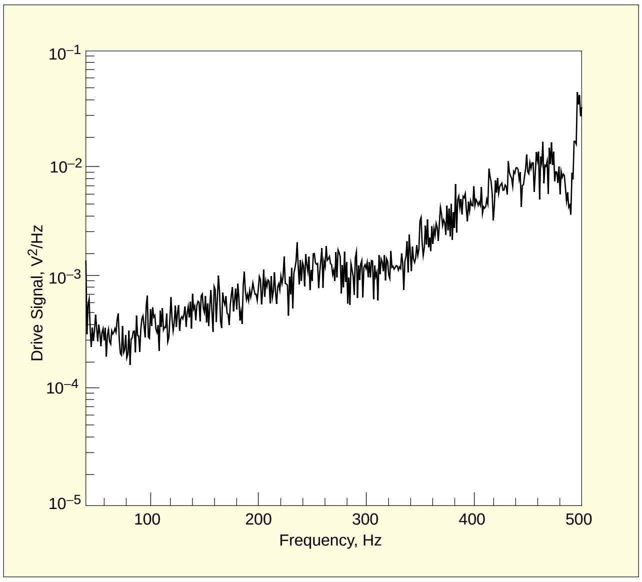

Figure 8. Drive signal PSD for the eight-modulator reduced configuration at 171 dB.

ducers may be found in Reference 4. The control pressure spectrum exhibits only a few points outside the ±1.5 dB alarm limits. Note that the spectrum is much better than previously obtained (see Figure 4) where significant reductions were observed beyond about 400 Hz. Adherence to the specified spectra for the upstream and downstream locations (not shown) is considered very good, even though no effort is being made to control these individually. It is, in fact, much better than previous manual control with 1/3-octave band equalizers, particularly at the high frequencies as noted above. Preliminary runs made using a single pressure transducer for control exhibited a much tighter control PSD than shown in Figure 6. Because this is not the normal operating mode of the facility, these results were not included in this article. Coherence is nearly unity between the two locations (see Figure 7) for the entire frequency range. This represents an improvement over the 1997 data (see Figure 5), which shows good coherence to about 460 Hz, effectively increasing the frequency range of the facility to 40-500 Hz. The drive signal PSD, shown in Figure 8, is meant to convey the distribution of energy required to maintain the desired spectrum, and the difficulty with which it would be to generate the signal using the previous 1/3-octave band equal-

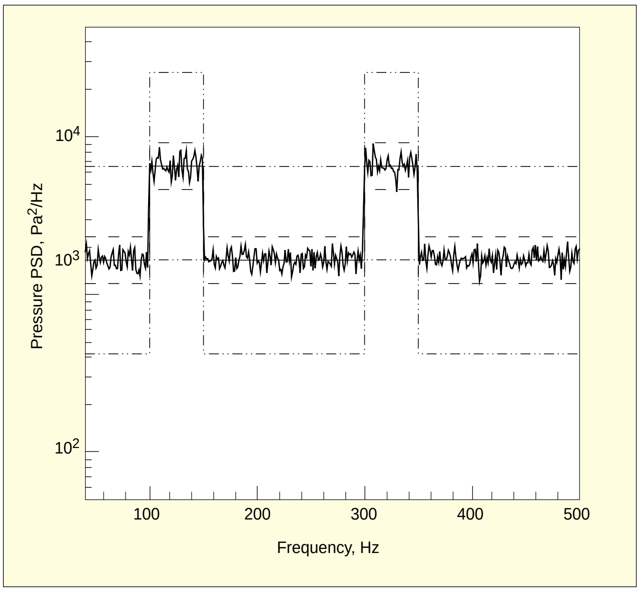

Figure 9. Control pressure PSD for a band limited random spectrum.

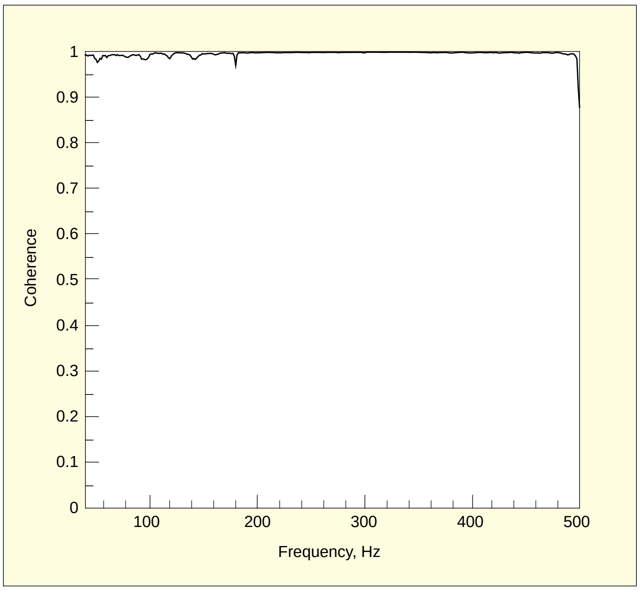

Figure 10. Coherence between upstream and downstream locations for a band limited random spectrum.

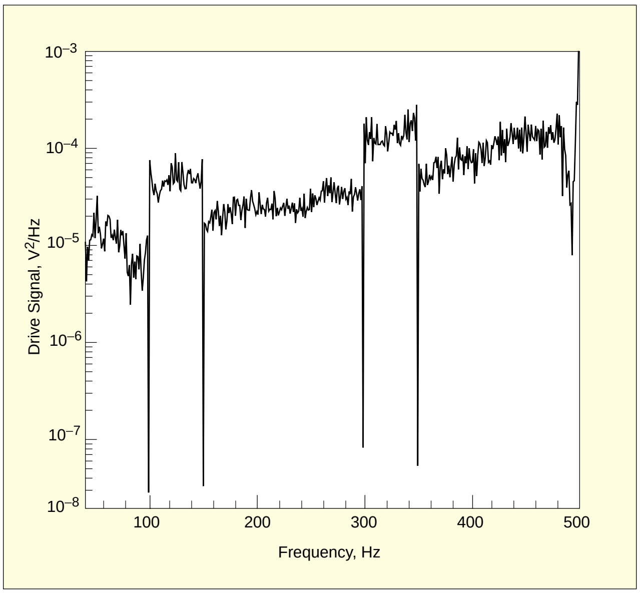

Figure 11. Drive signal PSD for a band limited random spectrum.

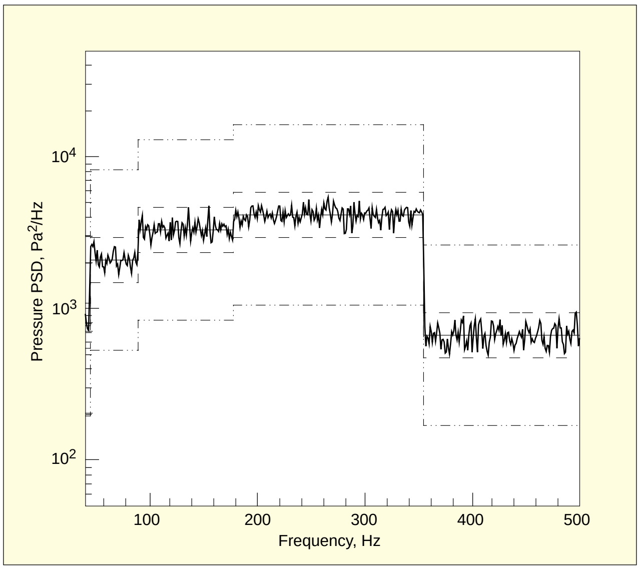

Figure 12. Control pressure PSD for a launch vehicle payload bay spectrum.

izer approach. Finally, it should be noted that the presence of the controller also resulted in an increase in the maximum overall level that can be achieved for a flat spectrum. Relative to the 1997 tests, the maximum level in the test section was increased to 172.4 dB, a gain of 0.7 dB.

Band-Limited Random Spectra

In order to excite resonant behavior without wasting acoustic power, one technique successfully employed on shakers is the application of band-limited random noise across a frequency range spanning resonant peaks. This is particularly advantageous when testing at high levels as it can increase the total power within the band compared with an otherwise uniform spectrum.

Results from a band-limited random condition with +6 dB levels between 100-150 and 300-350 Hz at 155 dB OASPL are shown in Figures 9-11. Note the ability to hit the ±6 dB jumps without overshoot. This is clearly the result of the drop in drive signal at the jumps, as shown in Figure 11, and would not be possible using 1/3-octave band equalizers. This test was performed in the two-modulator reduced configuration. Results from two variations of this condition, one with a sloped notch and one with a sharp notch, may be found in Reference 4.

Expendable Launch Vehicle Payload Bay

The interior acoustic environment of an expendable launch vehicle payload bay during launch was simulated to demonstrate the ability of the controller to generate an actual loading spectrum. The spectrum level was specified on an octave band basis and these levels were converted to narrow bands for use by the controller. As is shown in Figure 12, the controller does a good job of maintaining the specified spectra. Note again the ability of the controller not to overshoot the jumps. The coherence across the frequency range was again excellent and may be found in Reference 4.

Summary

Substantial improvements to the performance of the TAFA progressive wave tube facility were made through the addition of a new closed-loop acoustic controller. Acoustic control was improved in spectrum shaping ability, test section coherence, the addition of multiple inputs to the control, and the time required to attain control. These improvements make possible the generation of a wide variety of test spectra, including blast or transient loadings using the "last drive" feature. In addition, the frequency range of the facility was extended to 40-500 Hz from the previous 40-480 Hz and increases of up to nearly 1 dB were noted in OASPL. Facility safety can also be enhanced through the watchdog feature of limiting output power to the air modulators, and notching can be utilized to limit energy to the test article within specified frequency bands.

References

1. Rizzi, S. A., "Recent Sonic Fatigue Activities at NASA Langley Research Center," Workshop on Dynamics of Composite Aerospace Structures in Severe Environments, Southampton, England, July, 1991.
2. Rizzi, S. A., "Experimental Research Activities in Dynamic Response and Sonic Fatigue Analysis of Hypersonic Vehicle Structures at NASA Langley Research Center," Proceedings of the AIAA 31st Aerospace Sciences Meeting, AIAA-93-0383, Reno, NV, 1993.
3. Rizzi, S. A., Clevenson, S. A., and Daniels, E. F., "Acoustic Fatigue Characterization of Carbon/Carbon Panels," Proceedings of the VII International Congress on Experimental Mechanics, Vol. 2, pp. 1348-1355, Las Vegas, NV, 1992.
4. Rizzi, S. A., "Improvements To Progressive Wave Tube Performance Through Closed-Loop Control," NASA TM-2000-210623, October 2000.
5. Clevenson, S. A. and Daniels, E. F., "Capabilities of the Thermal Acoustic Fatigue Apparatus,", NASA TM 104106, February, 1992.
6. Rizzi, S. A. and Turner, T. L., "Enhanced Capabilities of the NASA Langley Thermal Acoustic Fatigue Apparatus," Structural Dynamics: Recent Advances, Proceedings of the 6th International Conference, Vol. 2, pp. 919-933, Southampton, England, 1997.
7. "VibControl/NT, Revision 2.4.0 Manual," M+P International, Inc., 1999.