Piezoelectric Shunt Vibration Damping of
An F-15 Panel under High Acoustic Excitation

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ABSTRACT

In the last year's SPIE symposium, we reported results of an experiment on structural vibration reduction of an F-15 underbelly panel using the piezoelectric shunting. The panel was 15.87 x 13.68 x 0.063 in. in size, and bonded with five 2 in. x 1.5 in. lead-zirconate-titanate (PZT) transducers. The panel vibration was induced with an acoustic speaker at an overall sound pressure level (OASPL) of about 90 dB. Amplitude reductions of 13.45 and 10.72 dB were achieved for the first and the second modes, respectively, using the single- and multiple-mode shunting.

It was the purpose of this investigation to further extend the passive piezoelectric shunt damping technique to control of structural vibration induced at higher acoustic excitation levels. This is important particularly on the dynamic (or sonic) fatigue problems of the fighter aircraft that experiences high vibro-acoustic loads from turbulent flows or from direct flow impingement during high angle of attack maneuvers. It is also important to examine the controllability and survivability of the bonded PZT transducers at these high vibration levels.

The shunting experiment was performed with the Thermal Acoustic Fatigue Apparatus (TAFA) at the NASA LaRC using the same F-15 underbelly panel mentioned above. The TAFA is a progressive wave tube facility with eight air modulators. The panel was mounted in one wall of the Apparatus test section using a specially designed mounting fixture such that the panel was subjected to grazing-incidence acoustic excitation. Five PZT transducers were used with two shunt circuits designed to control the first and the second modes of the structure. We determined the values of the shunt inductance and resistance at an OAPSL of 130 dB first. These values were maintained while we gradually increased the OASPL from 130 to 154 dB in 6 dB steps. During each increment the frequency response curves before and after shunting were measured. Good damping reduction was observed up to the 148 dB level. The experiment was stopped at 154 dB due to a wire disconnection. The PZT transducers, however, survived at this dB level. We also observed shifting of the frequency peaks towards lower frequency when the OASPL was increased. Detailed experimental results will be presented.

Keywords: passive, piezoelectric shunting, structural vibration, damping, sound pressure level, acoustic excitation, PZT transducer, structural modes, mode frequency, panel.

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ABSTRACT

At last year's SPIE symposium, we reported results of an experiment on structural vibration damping of an F-15 underbelly panel using piezoelectric shunting with five bonded PZT transducers. The panel vibration was induced with an acoustic speaker at an overall sound pressure level (OASPL) of about 90 dB. Amplitude reductions of 13.45 and 10.72 dB were achieved for the first and second modes, respectively, using single- and multiple-mode shunting.

It is the purpose of this investigation to extend the passive piezoelectric shunt-damping technique to control structural vibration induced at higher acoustic excitation levels, and to examine the controllability and survivability of the bonded PZT transducers at these high levels. The shunting experiment was performed with the Thermal Acoustic Fatigue Apparatus (TAFA) at the NASA Langley Research Center using the same F-15 underbelly panel. The TAFA is a progressive wave tube facility. The panel was mounted in one wall of the TAFA test section using a specially designed mounting fixture such that the panel was subjected to grazing-incidence acoustic excitation. Five PZT transducers were used with two shunt circuits designed to control the first and second modes of the structure between 200 and 400 Hz.

We first determined the values of the shunt inductance and resistance at an OASPL of 130 dB. These values were maintained while we gradually increased the OASPL from 130 to 154 dB in 6-dB steps. During each increment, the frequency response function between accelerometers on the panel and the acoustic excitation measured by microphones, before and after shunting, were recorded. Good response reduction was observed up to the 148dB level. The experiment was stopped at 154 dB due to wire breakage from vibration at a transducer wire joint. The PZT transducers, however, were still bonded well on the panel and survived at this high dB level. We also observed shifting of the frequency peaks toward lower frequency when the OASPL was increased. Detailed experimental results will be presented.

Keywords: passive, piezoelectric shunting, structural vibration, damping, sound pressure level, acoustic excitation, PZT transducer, structural modes, mode frequency, panel, progressive wave tube.

1. INTRODUCTION

Many military aircraft experience fatigue problems at several locations. In the case of the F-15 military aircraft, one area of concern is panel 1082, located on the lower fuselage surface of the aircraft. Cracks have been found near one end of the lateral former and along chemically milled edges near the LANTIRN Pod carry-through bulkhead. The fatigue failure is believed to be due to long dwell at high dynamic loading.

One possible method to reduce this kind of damage is to add damping to the structure near the weak area. Several damping approaches have been undertaken by Boeing to investigate and remedy the problem. One approach used visco-elastic materials to increase structural damping[1]. Another approach, which will be reported in this paper, is the passive piezoelectric shunting technique. This damping control approach

utilizes the piezoelectric properties of transducers made of ferroelectric ceramic materials such as lead-zirconate-titanate (PZT). The transducer converts the mechanical energy of the vibrating structure to electrical energy which is then dissipated by Joule heating in the resistor of the external shunt circuit.

Many papers on the subject of the piezoelectric shunting for vibration damping control have been reported in the literature. A few typical papers are listed in references 2-10. Piezoelectric shunting is accomplished by connecting a shunt circuit, consisting of an inductor and a resistor, to the two terminals of a PZT ceramic transducer bonded to the structure. Since the PZT is electrically a capacitive element, in order to reduce a high structural vibration mode at frequency ω, one has to tune the shunt circuit with the inductor first so that the parallel reactance of the inductance and the PZT capacitance becomes very large, or open-circuited, at mode frequency ω. This leaves only the resistor in the shunt circuit. When the shunt resistor is adjusted to its optimum value, energy from the vibration mode flowing through the resistor can be dissipated.

At last year's SPIE symposium, we reported experimental results of structural vibration damping performed on an F-15 underbelly panel using the piezoelectric shunt-damping approach[10]. It was an aluminum panel with a size of 15.87 in. x 13.68 in. x 0.063 in. Its four edges were bolted onto a rectangular fixture made from four 1-in.-thick plywood blocks. The panel was slightly curved, retaining the original curvature of the fuselage near the lower central belly section of the F-15 fighter. The inner surface of the panel was chem-milled to 60-mil thickness in four areas, resulting in four thinner rectangular zones. A lateral former ran horizontally through the non-chem-milled area in the middle of the panel.

In the previous tests, panel vibration was excited with an audio speaker. The OASPL at the front of the panel was about 90 dB. Five 2-in. x 1.5-in. PZT Quickpack[11] transducers bonded on the inner surface of the panel were used for the shunt-damping experiment. An accelerometer mounted closer to the PZTs in the upper right-hand zone was used to monitor the vibration signal. Figure 1 illustrates the frequency response curve measured with the accelerometer when a random white noise signal was applied to the speaker from an HP spectrum analyzer. It is a replot from Figure 9 of Ref. 10. The solid curve shows the response before the shunting; the dotted curve, after shunting with a double-mode shunt circuit for mode 1 and mode 2; and the dashed curve, after shunting with the two shunt circuits. There were two high-amplitude modes on the before-shunting curve in the frequency range of 200-400 Hz. The natural frequencies of these modes were around 235 and 354 Hz. Using the multiple-mode shunting techniques, we had successfully reduced peak amplitudes 13.35 dB and 10.72 dB for the first and second modes, respectively.

It is the purpose of this investigation to extend the passive piezoelectric shunt-damping technique to control structural vibration induced at higher acoustic excitation levels. This is particularly important for the dynamic (or sonic) fatigue problems of fighter aircraft that experience high vibro-acoustic loads from turbulent flows or from direct flow impingement during high-angle-of-attack maneuvers. It also becomes important to evaluate the controllability and the survivability of the bonded PZT transducers at these high vibration levels. The experiment was performed with the Thermal Acoustic Fatigue Apparatus (TAFA)[12] at the NASA Langley Research Center using the same F-15 underbelly panel mentioned above.   Good vibration reduction was obtained using bonded PZT transducers at acoustic excitation levels up to 148 dB. Detailed experimental results and observed nonlinear vibration behavior of the panel will be presented.

2. EXPERIMENTAL ARRANGEMENT

The piezoelectric shunting experiment was performed using the TAFA facility at the NASA Langley Research Center on an F-15 panel, mentioned in the previous section. The TAFA is a progressive wave tube facility used to simulate the combined high-intensity thermal-vibro-acoustic environment experienced by high-performance aircraft and spacecraft structures. A photograph of the facility is shown in Figure 2.

During the test, the F-15 panel was subjected to grazing-incidence acoustic excitation. It was mounted on the mounting plate, which had an open window of 32 in. x 32 in., on one wall of the apparatus test section. Since the F-15 panel was smaller than the window, we redesigned the support fixture of the panel

by attaching four wide wooden frames on the four sides of the panel. This allowed the whole panel and the new frame to cover the window on the TAFA wall. We also modified the depth of the support fixture so that the front surface of the panel was in the same surface plane with the mounting plate when the panel was mounted on the TAFA wall. This would allow smooth airflow in the progressive wave tube. Several monitoring devices were used during the experiment. Two B & K microphones were positioned in the waveguide close to the leading and trailing edges of the panel. The upstream microphone, Mic 1, was used as the reference sensor. Five PCB accelerometers, model 353B15, were mounted at different locations on the panel and the support fixture. Figure 3 shows the back view of the panel with five PZT patch transducers bonded on it, and the surrounding wooden support fixture. The insert, on the right, shows a schematic of the locations of the PZT transducers and test instruments

3. EXPERIMENTAL RESULTS

We first ran the TAFA by gradually increasing the airflow in the waveguide to the normal operating condition without the use of any modulator, which produced an OASPL of about 130 dB. Figure 4 shows the magnitude of the frequency response function between 100 and 400 Hz measured between accelerometer A1 and microphone Mic 1. Note that all subsequent plots of the frequency response function are between accelerometer A1 and microphone Mic 1. There were several differences between this curve and the before-shunting curve (solid curve) in Figure 1. First, three new low-frequency modes appeared below 200 Hz. Second, the peak amplitudes of the modes near 235 Hz and 354 Hz shown on the solid curve in Figure 1 were already reduced and damped. Third, the peak frequency of the mode at 354 Hz was also shifted toward lower frequency near 320 Hz. We believed that these changes were associated with the newly added support fixture. The addition of the fixture for mounting the panel to the larger open window in the wall of the TAFA test section apparently induced these three low-frequency modes. It increased the inherent damping of the panel. It also reduced its overall stiffness, which caused frequency lowering, in particular, at the higher-frequency modes.

Two shunt circuits were used during the shunt-damping experiment. One circuit designed for controlling the 235 Hz mode was either connected to the PZT transducer A, B, or C individually, or was connected to them in parallel. Another circuit for controlling the 320 Hz mode was either connected to PZT transducer D or E individually or was connected to them in parallel.

Shunt Configuration 1. After the OASPL level was increased to 130 dB, we recorded the frequency response function for the non-shunted condition. We proceeded to perform the shunting experiment by turning on the first shunt circuit. It was first connected to the transducer C. Our intention was to shunt-damp the first mode around 235 Hz using a single transducer. After setting the shunt inductance and the shunt resistance to proper values, we obtained the frequency response function shown in Figure 5.

Several interesting points on the curve are worth mentioning. First, the curve around 235 Hz remained split, as before shunting. When we tried to decrease the shunt resistance to see whether the valley would disappear and become plateau-like in shape, the attempt was not successful. This indicated that the panel had two modes around this frequency. Second, the peak on the right was higher than that on the left. The response at the dip frequency was reduced about 7 dB, but the mode on the right was reduced less, by only about 3 dB. Although we could try to balance the two heights by adjusting (decreasing) the shunt inductance, the dip frequency would shift away from the initial 235 Hz and move toward higher frequency. Third, the shoulder on the left was widened and moved toward lower frequency. The total amplitude reduction would have been greater if the panel had not been affected by the inherent structural damping associated with the support fixture.

Shunt Configuration 2. We next turned on the second shunt circuit while the first shunt circuit remained on. The second shunt circuit was designed to shunt-damp the second mode around 320 Hz. We connected it to the terminals of PZT transducer E and conducted the shunting experiment. After some adjustments to the inductance and the resistance of the second shunt circuit, we obtained the frequency response function shown in Figure 6. The top of the curve at 320 Hz became a normal flat plateau-like shape after shunting. The peak amplitude was reduced about 4 dB. Note that the frequency response curve near 235 Hz was not affected during the operation.

Shunt Configuration 3. We returned again to the first shunt circuit for shunt-damping the mode near 235 Hz only, but this time we connected three PZT transducers A, B, and C in parallel to the shunt circuit. We first set the OASPL in the TAFA to the same 130dB level as used previously. We then recorded the frequency response function before shunting. We noticed that the curve near 235 Hz was changed somewhat from what was observed previously. The amplitudes of the two peaks were not of the same height; the right-hand peak was much lower. The exact cause of the change was not known. After adjusting the shunt inductance and resistance, we recorded the frequency response function. Figure 7 shows the frequency response functions before and after shunting. The average reduction of the response curve for the modes around 235 Hz was about 8 dB. We also observed a slight increase on the inclined plateau around 275 Hz. It was believed to be due to spillover of the control.

Shunt Configuration 4. Next, we used two shunt circuits for shunt-damping the modes around 235 Hz and 320 Hz. The first shunt circuit was connected to PZT transducers A, B, and C in parallel, and the second shunt circuit was connected to PZT transducers D and E in parallel. The inductance and resistance of the first shunt circuit were not changed from configuration 3. After adjusting the inductance and resistance of the second shunt circuit, we measured the frequency response function. Figure 8 shows the frequency response functions before and after shunting. We observed that the mode near 320 Hz was reduced by about 5 dB after the activation of the second shunt circuit. A slight change also occurred for the modes near 235 Hz after shunting. The amplitudes of the modes above 350 Hz were also increased slightly, due probably to some spillover.

We next turned on two air stream modulators of the TAFA to increase the OASPL, and increased it from 130 dB in 6-dB steps. After each increment, we measured the frequency response functions before and after shunting, using the shunt circuits of Shunt Configuration 4. The shunt circuit inductance and resistance, however, were unchanged; they were maintained at the same values as used before the OASPL increase. The reason for not changing the shunt circuit parameters was to examine the controllability of the shunt circuit at high OASPLs. Since the peak frequencies and the mode shapes of the panel change at high acoustic excitation levels, we want to evaluate whether the shunt circuit with its circuit parameters set at some predetermined values will still be able to control structural vibration as it can at a low excitation level.

Figure 9 - Figure 11 show the frequency response functions before and after shunting at the OASPL of 136 dB, 142 dB, and 148 dB, respectively. The shunt-damping result at 136 dB was nearly the same as that measured at 130 dB. The average amplitude reductions of the modes near 235 Hz was about 8 dB, and that near 320 Hz was about 5 dB. When the OASPL was increased over 136 dB, we noticed that the damping reduction decreased with the increase of the excitation level for both modes. At the level of 148 dB, the average amplitude reduction for the modes near 235 Hz was about 5 dB, and that near the 320 Hz was only 2.5 dB. Although the shunt circuits were able to reduce the modes at the OASPL of 148 dB, the reduction seemed decreased slightly. This prompted us to examine why the shunt-damping efficiency decreased at high OASPLs.

We reexamined the before-shunting frequency response curves measured at 130 dB, 136 dB, 142 dB and 148 dB, which are displayed in Figure 12. By examining these curves, we have discovered non-linear phenomena on the panel structure with the increase of the OASPL. Above 136 dB, the peak frequencies of the modes shifted toward lower frequency with the increase of the OASPL. The largest shift observed was about 10 Hz, when the OASPL was increased from 130 dB to 148 dB. It occurred for the 320 Hz mode. The amplitudes of the modes also changed with the OASPL increase. While most peaks decreased about 1 to 3 dB, the peak near 243 Hz increased about 4 dB during this OASPL increase.

When the OASPL was increased to 154 dB, we discovered that a wire had become disconnected due to vibration at an adapter joint between the transducer and the connecting wire. Therefore, the experiment was stopped. After the experiment, we examined the five PZT transducers. They were still intact on the panel and had survived the severe vibration.

Although the F-15 panel underwent a wide variation in frequency and amplitude at high OASPLs, the shunt-damping experiment demonstrated for us that the passive shunting technique was able to control this kind of structural vibration.

One last note on the passive shunting technique: it should be able to produce better damping results than those shown above if the shunt inductance and resistance were adjusted after each OASPL increase. One way of doing this automatically is with the use of shunt circuits implemented with automatic frequency tracking circuits[13].

4. SUMMARY

We have reported the result of an extended passive piezoelectric shunt-damping experiment for structural vibration control. The experiment was performed on the same F-15 underbelly panel as we used earlier[10], but at higher acoustic excitation levels ranging from 130 dB to 148 dB.

Five PZT transducers were used with two shunt circuits designed to control the first and second modes of the structure between 200 and 400 Hz. We first determined the values of the shunt inductance and resistance at an OASPL of 130 dB. These values were maintained while we gradually increased the OASPL from 130 to 154 dB in 6-dB steps. During each increment the frequency response functions before and after shunting were recorded. Good damping reduction was obtained up to the 148dB level. The experiment was stopped at 154 dB due to wire breakage from vibration at a transducer wire joint. The PZT transducers, however, were still bonded well on the panel and survived at this high dB level.

We discovered that the damping reduction decreased slightly with the increase of the acoustic excitation level over 136 dB. We believe this to be due to non-linear behavior of the panel at the high levels. The peak frequencies of the modes shifted toward lower frequency with the increase of the OASPL. The largest shift was about 10 Hz for one mode when the OASPL was increased from 130 dB to 148 dB. Even with this large shift in frequency, the passive shunting technique was still able to control the panel vibration. The shunt-damping result could be better if the shunt circuits were designed and implemented with automatic frequency tracking circuits.

REFERENCES

1. S. L. Liguore, K. Hunter, R. Perez and T. H. Beier, "Flight Test Evaluation of Damped Composite Repairs for Sonic Fatigue," 40th AIAA/ASME/ASCE/AHS SDM Conference, St. Louis, MO, April 12-15, 1999, AIAA-99-1378.
2. N. W. Hagood and A. von Flotow, "Damping of Structural Vibrations with Piezoelectric Materials and Passive Electrical Networks," *J. Sound and Vibration*, 146, 2, 243 (1991).
3. N. W. Hagood and E. F. Crawley, "Experimental Investigation of Passive Enhancement of Damping for Space Structures," *J. Guidance, Control and Dynamics*, 14, 6, 1100 (1991).
4. D. L. Edberg, A. S. Bicos, C. M. Fuller, J. J. Tracy and J. S. Fechter, "Theoretical and Experimental Studies of a Truss Incorporating Active Members," *J. Intell. Mater. Syst. and Struct.,* 3, 333 (1992).
5. J. J. Hollkamp, "Multimode Passive Vibration Suppression with Piezoelectric Materials and Resonant Shunts," *J. Intell. Mater. Syst. and Struct.*, 5, 49 (1994).
6. S. P. Kahn and K. W. Wang, "Structural Vibration Control via Piezoelectric Materials with Active-Passive Hybrid Networks," ASME/Active Control of Vibration and Noise, DE-75 (1994).
7. S. Y. Wu, "Piezoelectric Shunts with a Parallel R-L Circuit for Structural Damping and Vibration Control," *Proceedings of the International Society for Optical Engineering*, vol. 2720, pp. 259-269, 1996.
8. S. Y. Wu and A. S. Bicos, "Structural Vibration Damping Experiments Using Improved Piezoelectric Shunts," *Proceedings of the International Society for Optical Engineering*, vol. 3045, pp. 40-50, 1997.
9. S. Y. Wu, "Method for Multiple Mode Shunt Damping of Structural Vibration Using a Single PZT Transducer," *Proceedings of the International Society for Optical Engineering*, vol. 3327, pp. 159-168, 1998.

10. S. Y. Wu, "Multiple PZT Transducers Implemented with Multiple-Mode Piezoelectric Shunting for Passive Vibration Damping," *Proceedings of the International Society for Optical Engineering*, vol. 3672, pp. 112-122, 1999.
11. Registered trademark of ACX, Cambridge, MA 02142.
12. S. A. Rizzi and T. L. Turner, "Enhanced Capabilities of the NASA Langley Thermal Acoustic Fatigue Apparatus," *Proceedings of the 6th International Conference on Recent Advances in Structural Dynamics,* vol. 2, pp. 919-933, 1997.
13. "Synthesis and Processing of Intelligent Cost Effective Structures," Final Report, section 2.5.5, Advanced Research Projects Agency (ARPA), Contract No. MDA 972-93-2-0010, 1996.
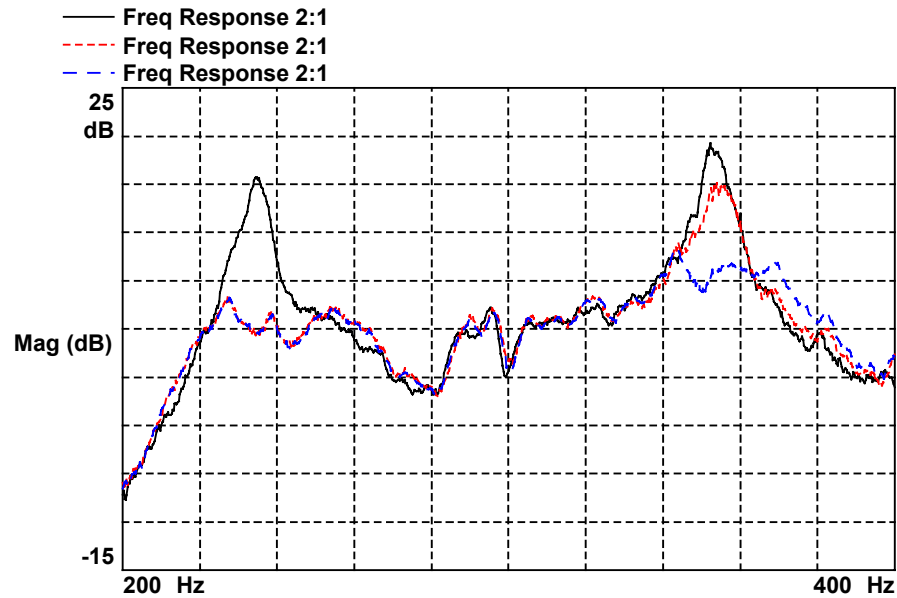
Figure 1: Frequency response functions of F-15 panel measured at OASPL of 90 dB. (Solid curve: before shunting; dotted curve: after shunting with a double-mode shunt circuit; dashed curve: after shunting with two shunt circuits.)
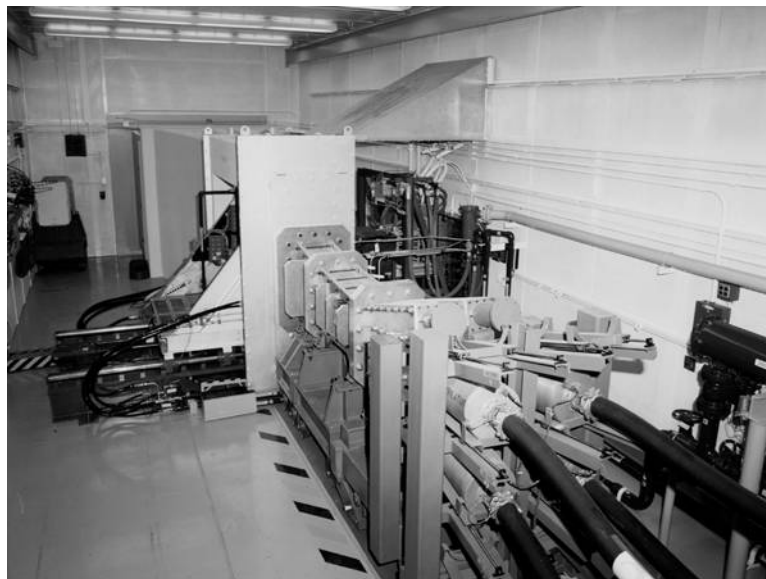
Figure 2: Photograph of the TAFA facility.
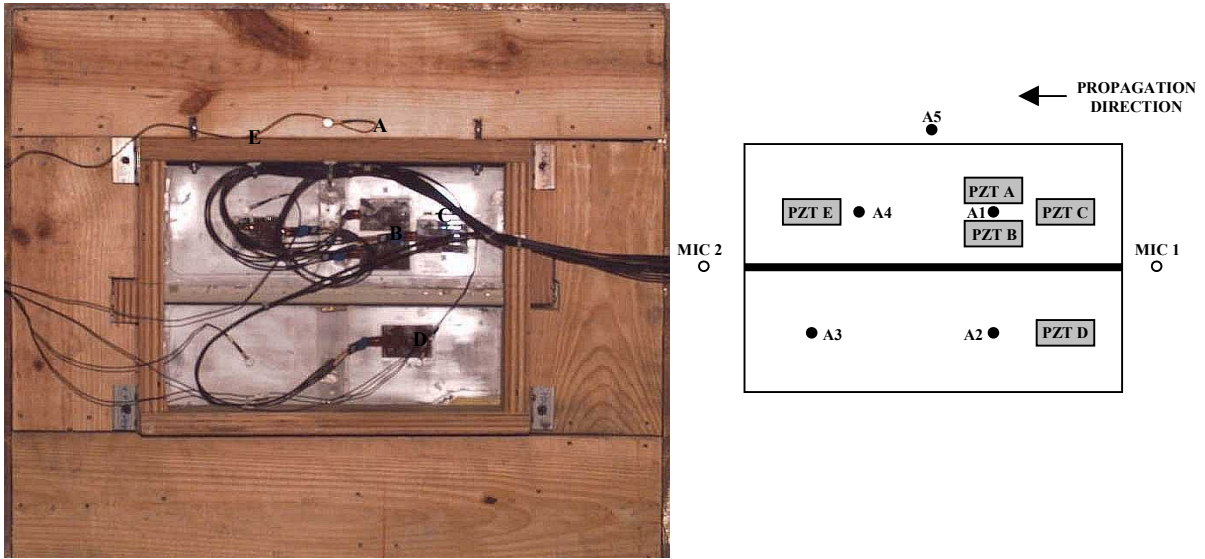
Figure 3: Back view of F-15 panel after being mounted on TAFA plate with specially designed wooden frame fixture. The insert shows a schematic of the locations of the PZT transducers and test instruments (A, accelerometer; MIC, microphone).
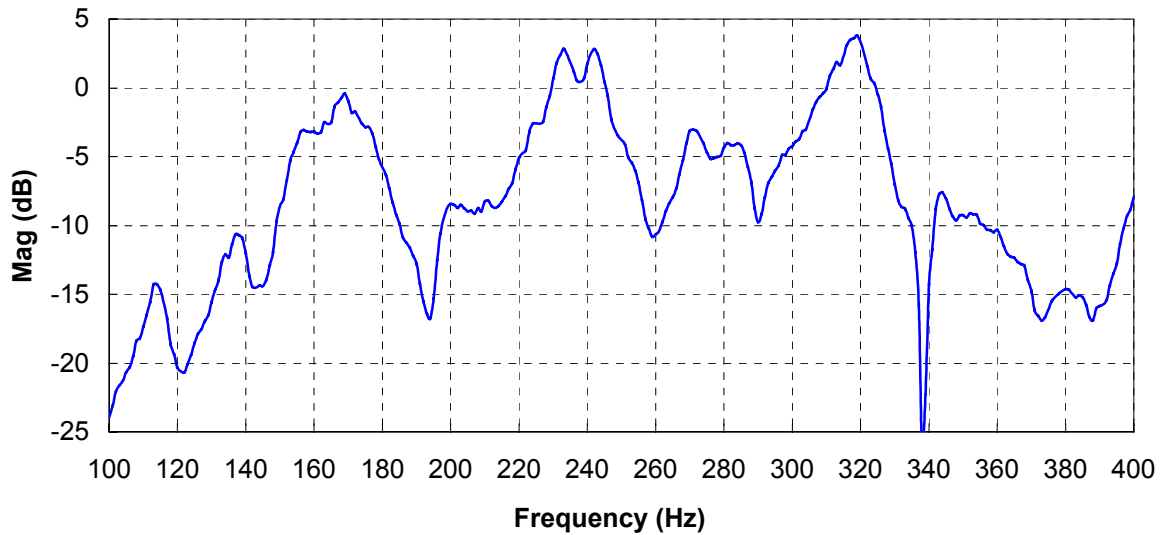
Figure 4: Frequency response function between 100 and 400 Hz measured at OASPL of 130 dB before shunting.
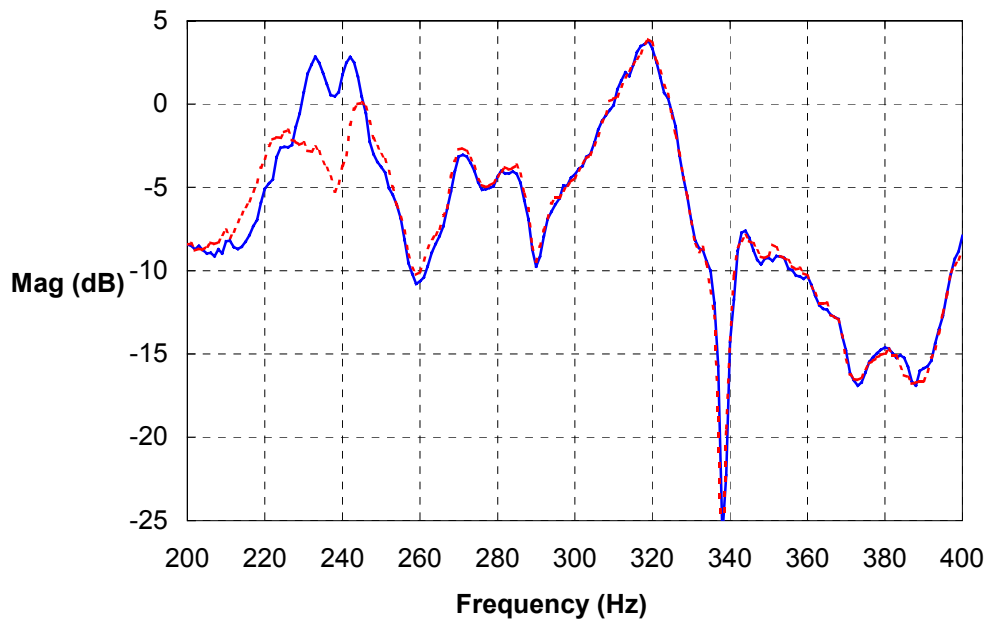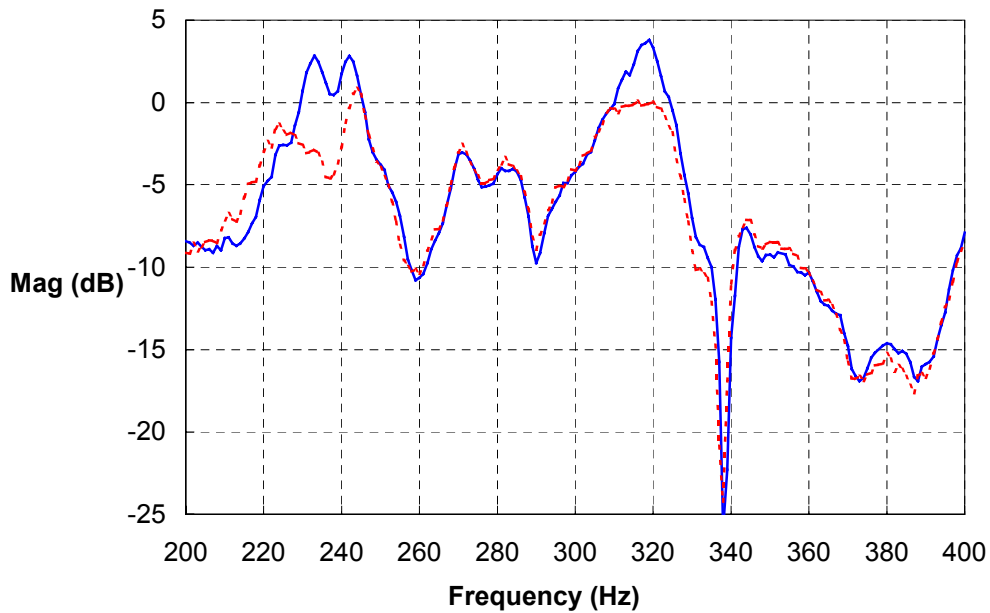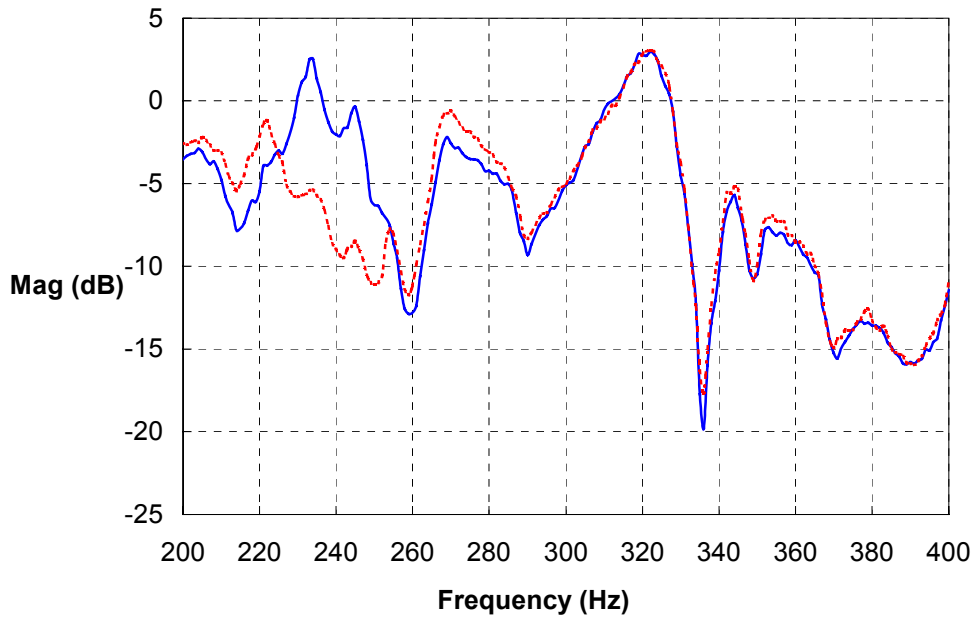
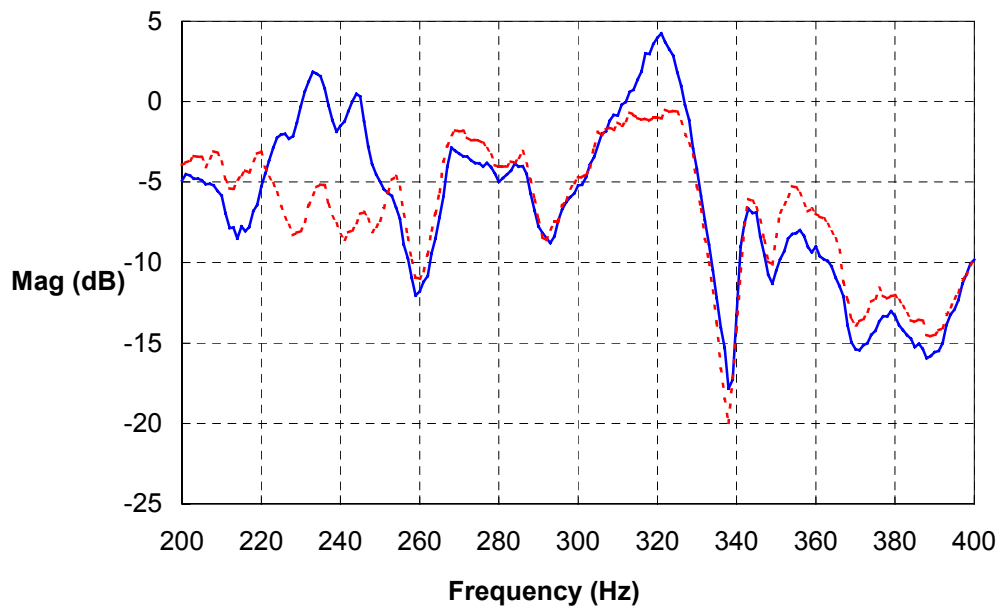Figure 5: Frequency response functions before (solid) and after (dashed) shunting using one shunt circuit with transducer C for modes near 235 Hz; shunt configuration 1.

Figure 6: Frequency response functions before (solid) and after (dashed) shunting using one shunt circuit with PZT transducer C for modes near 235 Hz, and another shunt circuit with PZT transducer E for mode near 320 Hz; shunt configuration 2.

Figure 7: Frequency response functions before (solid) and after (dashed) shunting using one shunt circuit with PZT transducers A, B, and C for modes near 235 Hz; shunt configuration 3.

Figure 8: Frequency response functions before (solid) and after (dashed) shunting using one shunt circuit with PZT transducers A, B, and C for modes near 235 Hz, and another shunt circuit with PZT transducers D and E for mode near 320 Hz; shunt configuration 4.
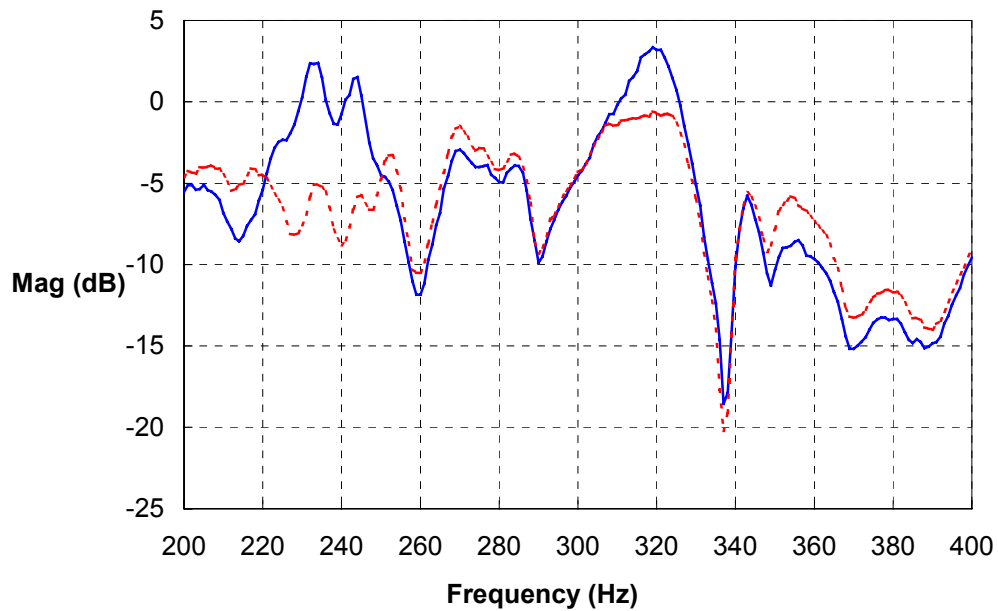
Figure 9: Frequency response functions before (solid) and after (dashed) shunting measured at OASPL of 136 dB; shunt configuration 4.
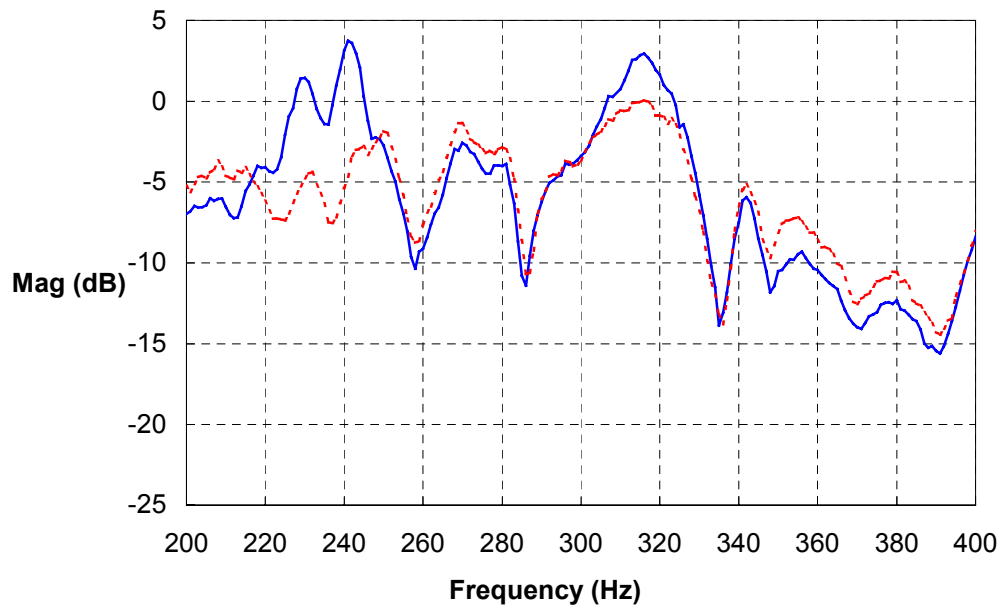

Figure 10: Frequency response functions before (solid) and after (dashed) shunting measured at OASPL of 142 dB; shunt configuration 4.
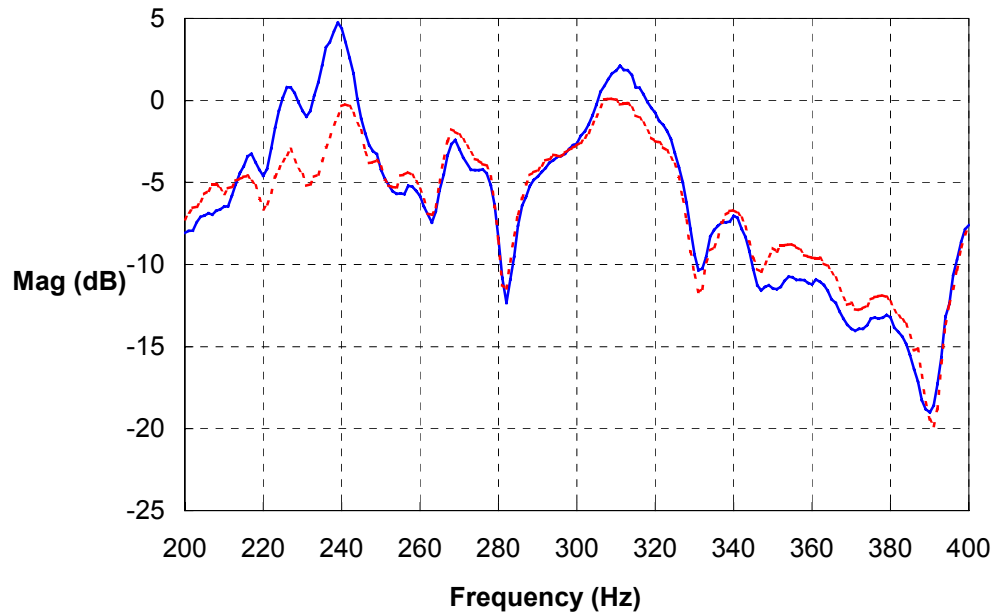
Figure 11: Frequency response functions before (solid) and after (dashed) shunting measured at OASPL of 148 dB; shunt configuration 4.
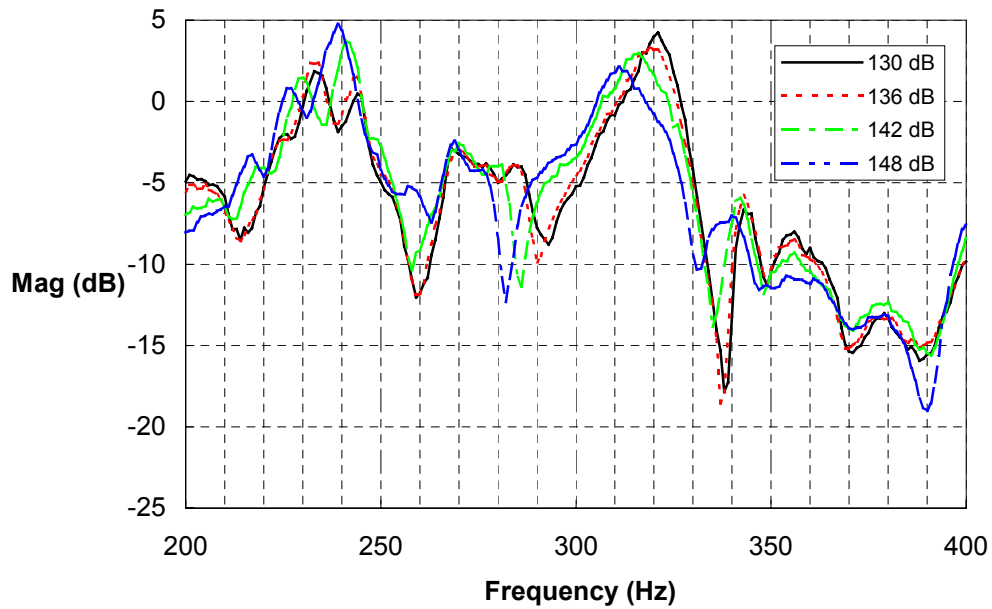

Figure 12: Before-shunting frequency response functions measured at OASPL of 130 dB, 136 dB, 142 dB and 148 dB.