Sound Transmission through Glass Panels: A Building Case Study

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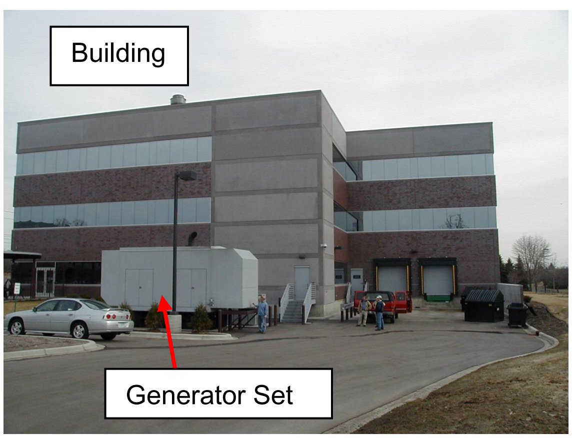
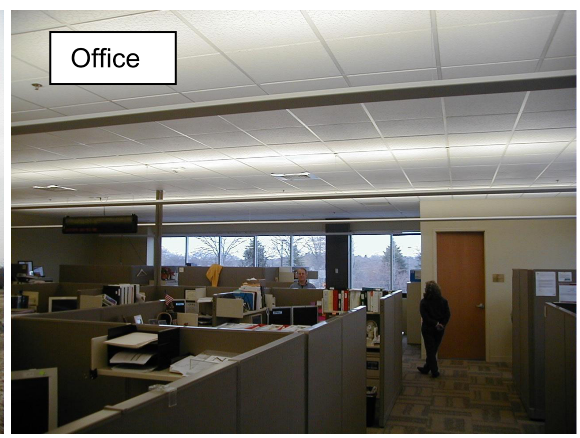
ABSTRACT

This paper documents solving a noise complaint of a generator set installation. The operation of a 1000 kW generator set located next to an office building, resulted in excessive noise inside the building, with a particularly annoying tone that irritated the office workers. The problem was identified as a resonant response of the building's windows. A correlated analytical modal model was built to investigate possible solutions. A proposed solution was tested and the annoying tone was reduced by 15 dB, with an overall noise level reduction of 10 dB.

The Complaint

Pictured below is the 1000 kW generator set next to the building. The office windows shown below are on the second floor facing the generator set.



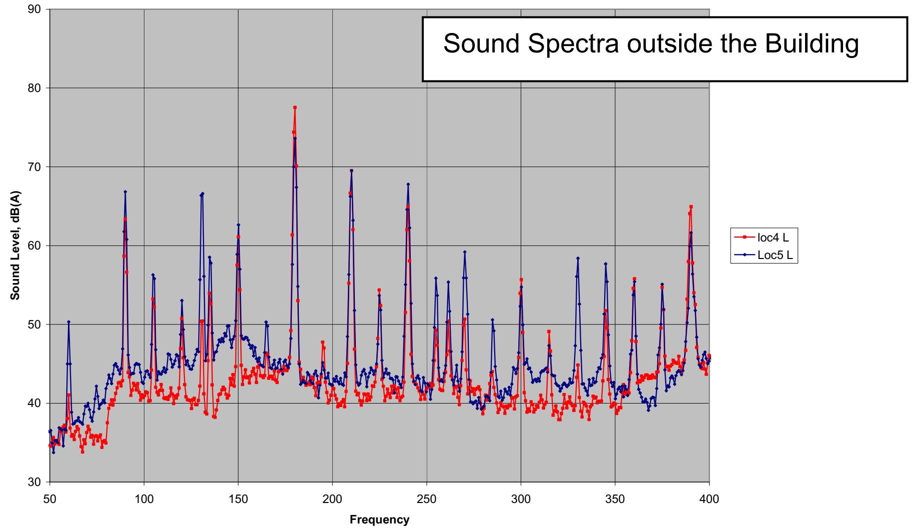


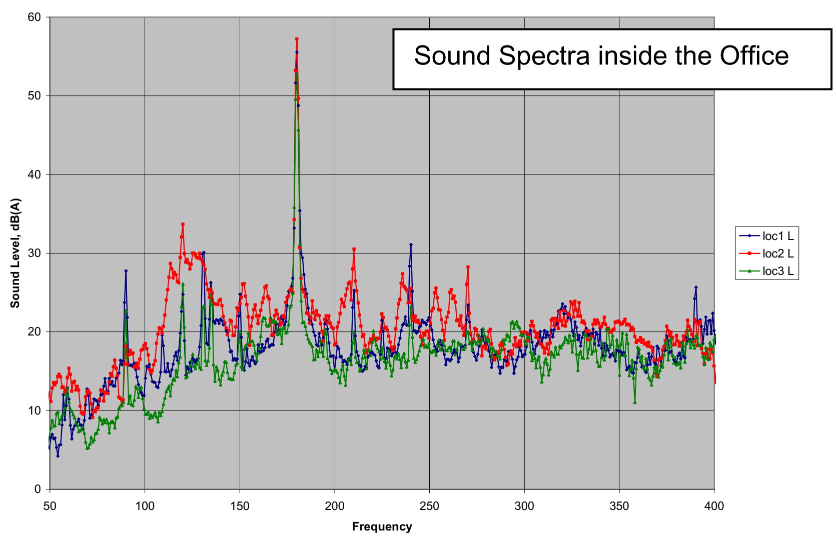
Beyond supplying emergency electrical power, this generator set was sized to provide interruptible power. When the electric utility experiences a high power demand, such as on hot summer days, the utility asks the building owners to disconnect from the power grid, lowering the utility's load. The utility compensates the building owners by offering lower electric rates. As a consequence of this, the generator set can run several hours with people working in the building.

During generator set operation, the office workers complained of excessive noise to the point where some employees went home.

First Site Visit - Identifying the Cause of the Complaint

Simple sound measurements were taken both inside and outside the building. Powered by a 4-cycle diesel engine running at 1800 rpm (30 Hz), the generator set's noise was multiples of 15 Hz. Since the engine was a V12, it was not surprising that the loudest frequency was 180 Hz. Given that the 180 Hz tone was so dominant inside the building, a resonant response was suspected.

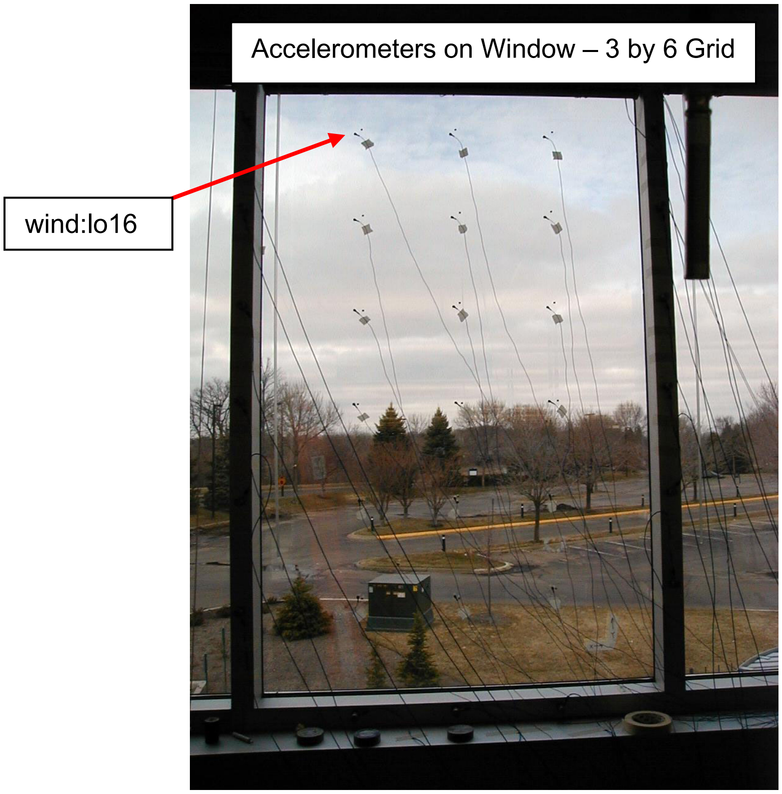




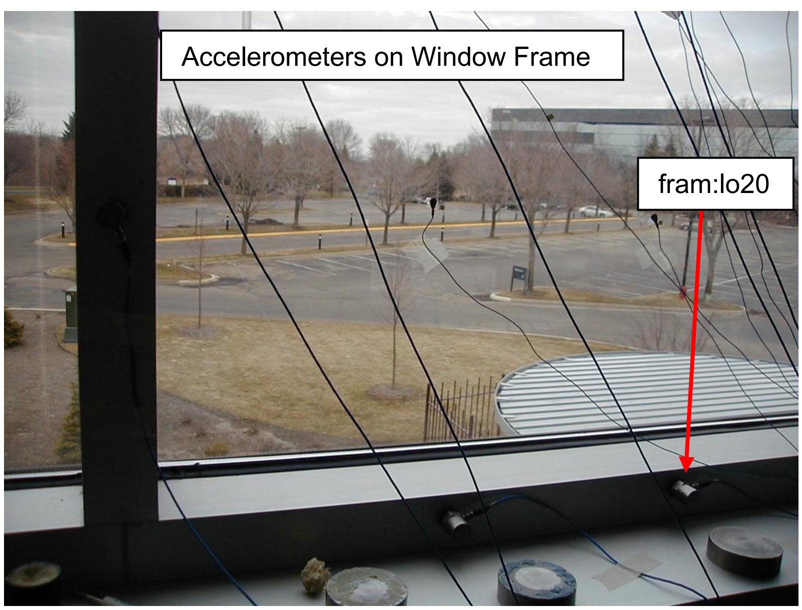
Second Site Visit – Searching for the Resonant Behavior

Instrumentation

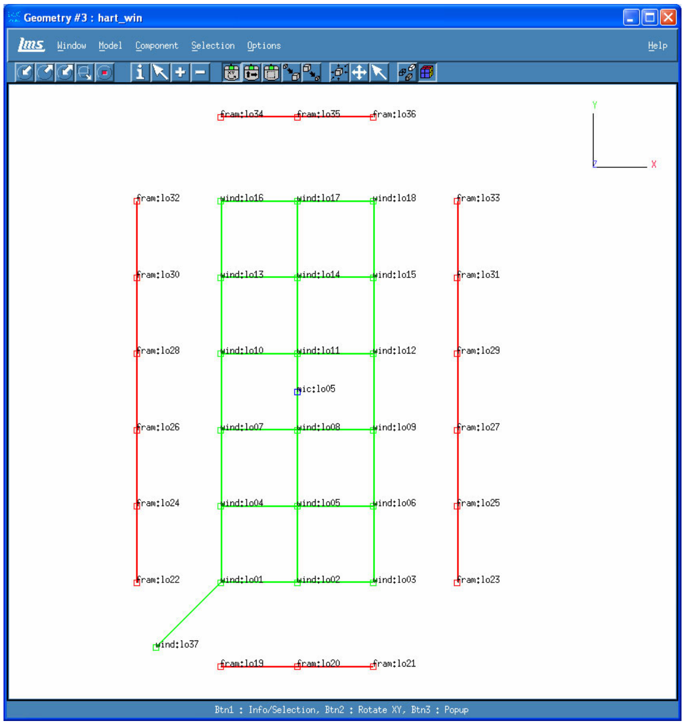
Both sound and vibration measurements were taken inside the building. Eighteen very light weight single axis accelerometers (0.5 gram) were waxed to a window, as shown below. They were sensing perpendicular to the window's surface. The window is approximately one meter wide and 1.8 meters tall.



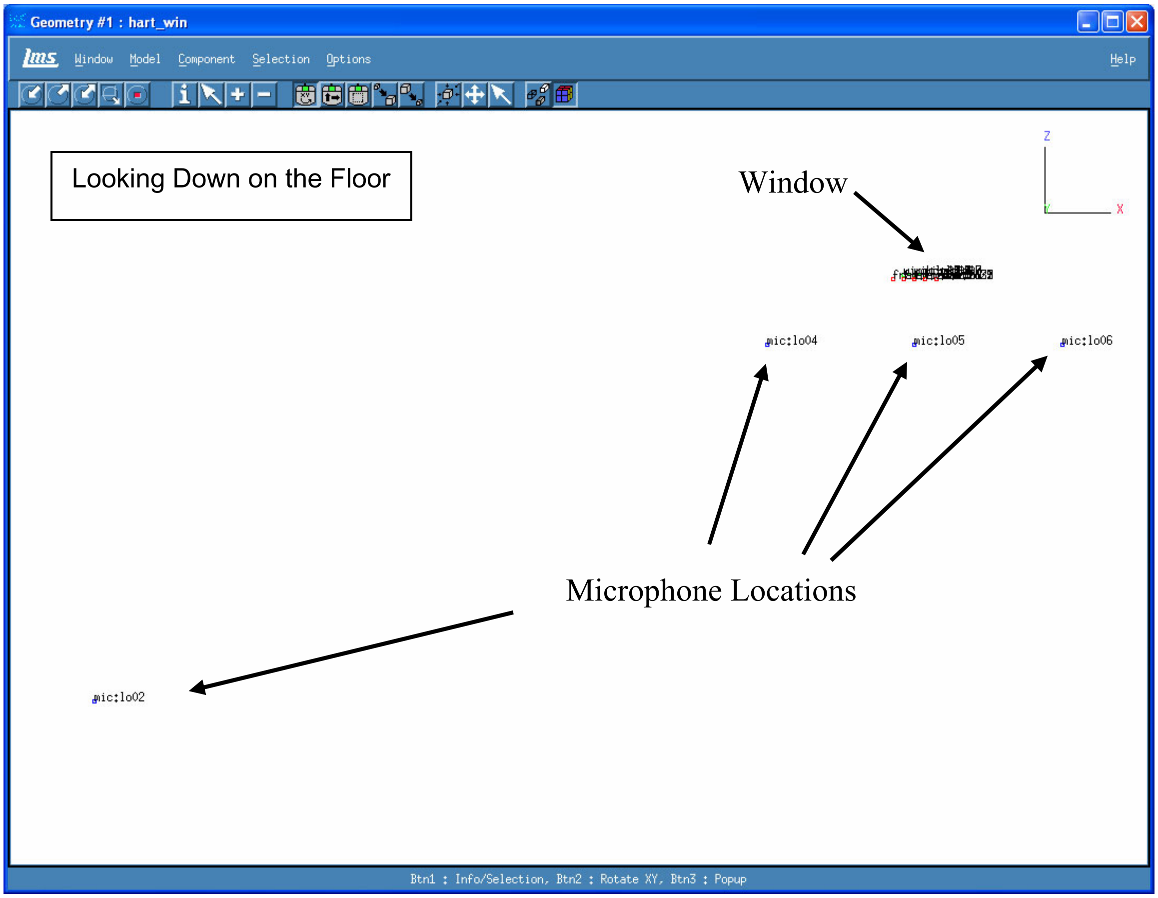
Eighteen large single axis accelerometers (25 gram) were placed around the window's supporting frame, again sensing perpendicular to the window's surface.



The diagram below shows the accelerometer placements. The green locations are on the window and the red locations are on the window's supporting frame. The one window location in the lower left-hand corner was added for the modal test.



The diagram below shows the locations of the four microphones and their placement relative to the instrumented window.



Generator Set Operating Tests

During normal operation, this generator set operates at a fixed speed. However, for testing purposes, the engine can be swept through a narrow speed range: 1650 to 1950 rpm. Since a 4-cycle engine shakes at all whole and half multiples of engine speed, running such a speed sweep is roughly equivalent to running a swept sine test where one does not know excitation levels. Fortunately, over such a narrow speed range, each order's amplitude remains fairly constant. Resonant behaviors can be identified by looking for orders whose amplitude significantly rise and then fall during such a speed sweep. To capture steady state behaviors, said speed sweeps are very slow, on the order of 1.25 rpm per second. Varying engine speed changes the generator's output frequency, requiring that these speed sweeps be done with the generator set electrically disconnected from both the building and utility. Lacking a portable load bank, these speed sweeps were done at no load.

To get an understanding of loaded behavior, three minutes of steady state data was acquired at both no load and at building's load, which at the time was 160 kW.

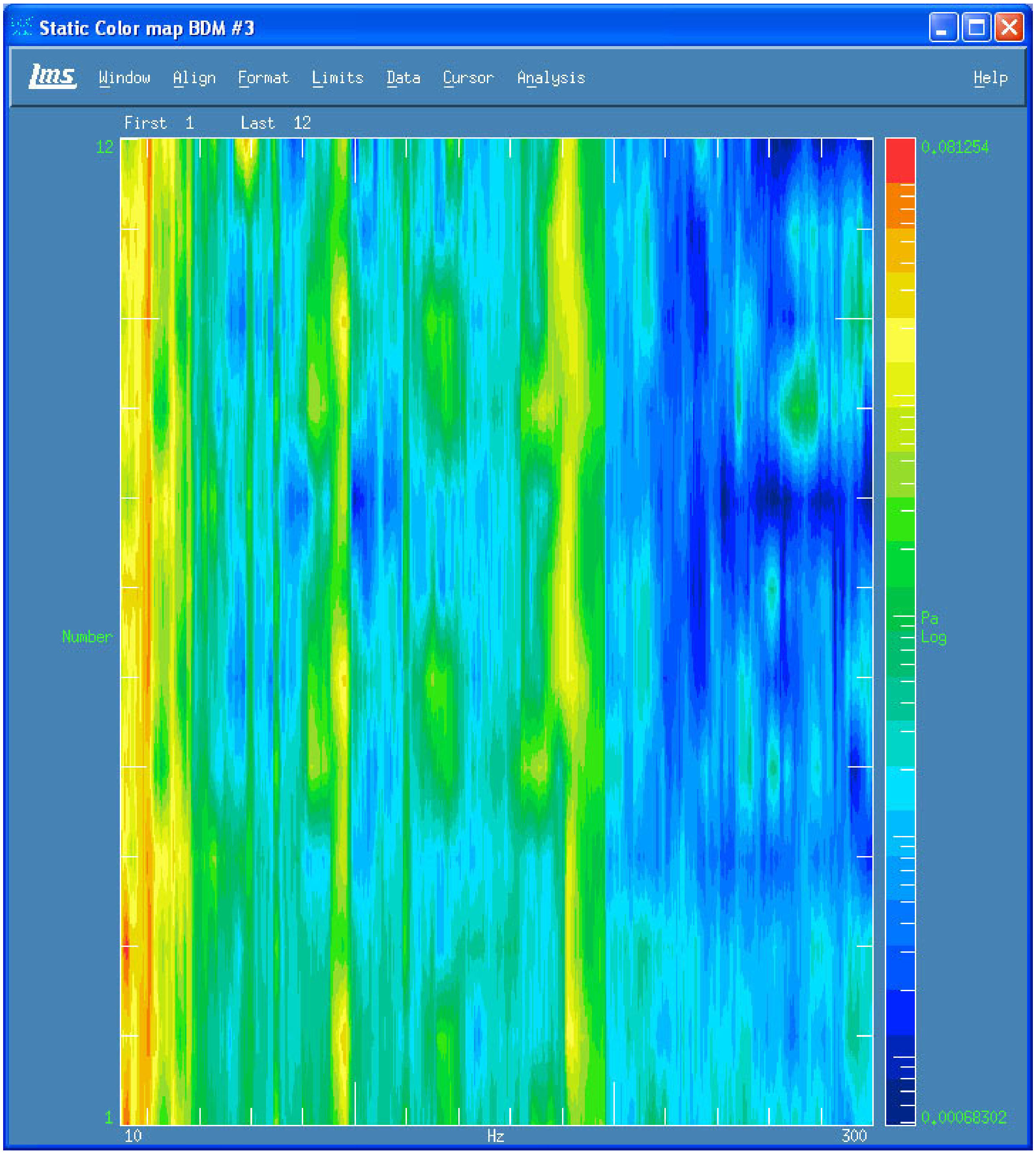
All of this data was recorded simultaneously at a sample rate of 8192 Hz.

These tests were run on Saturday, when there were minimal people present.

Speed Sweep Results - Microphones

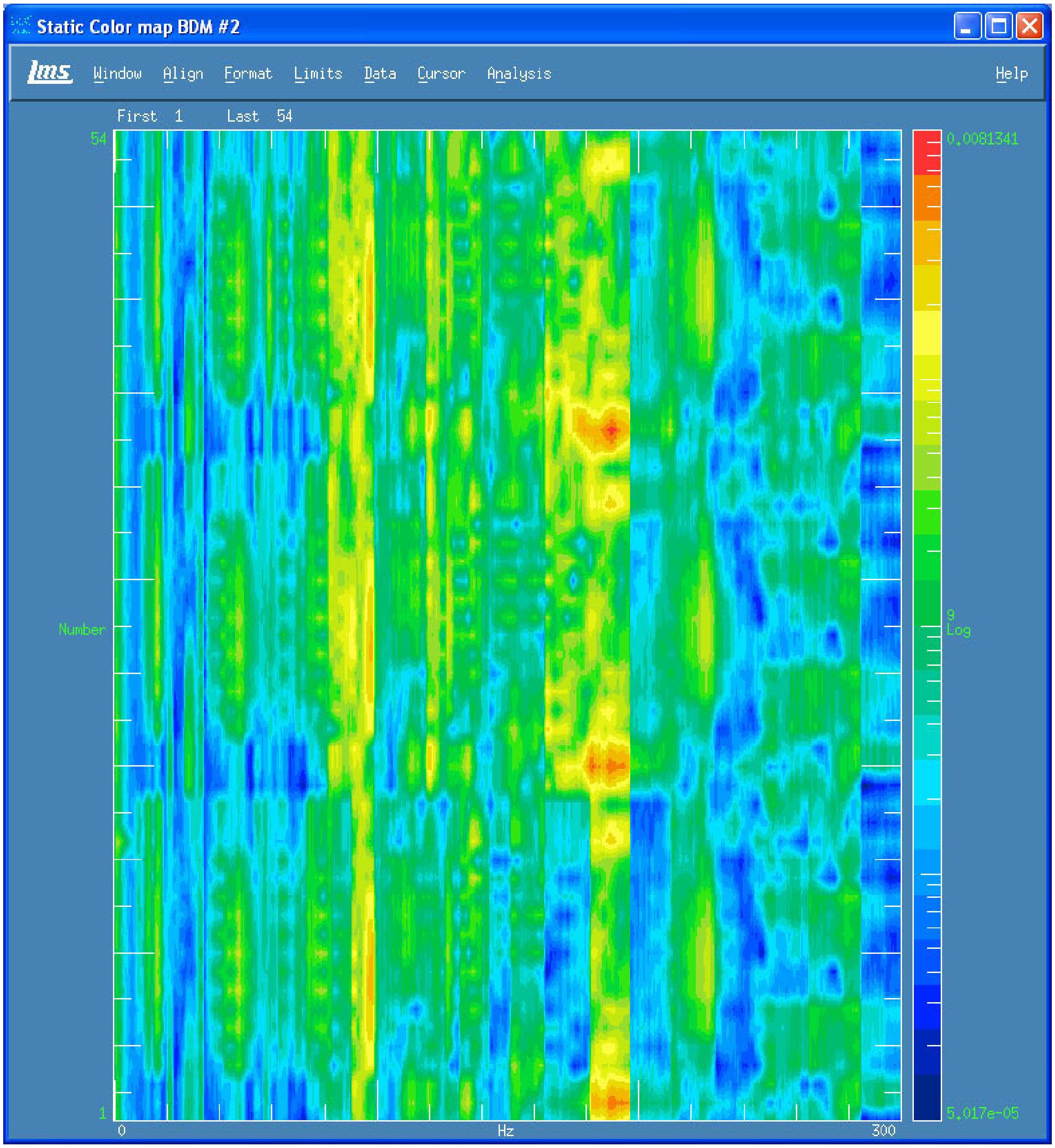
Three speed sweeps were recorded. Peak hold spectrums were generated of this time data.

All of the resulting microphone peak hold spectrums are plotted below. The following frequencies exhibited possible resonant behaviors: 6, 11.5, 20.5, 30.0, 96.0, 181.0, and 183.5 Hz.



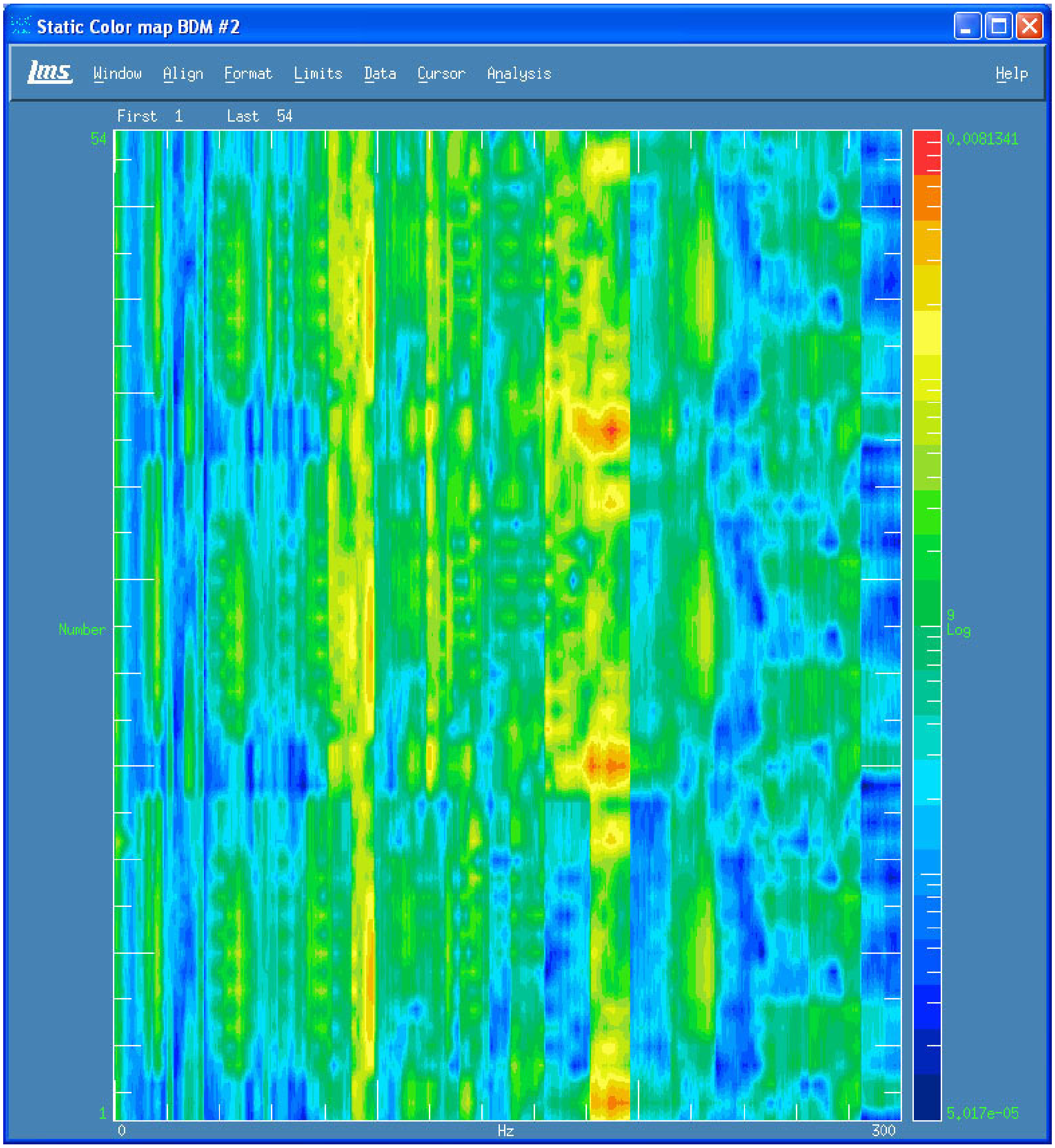
Speed Sweep Results – Window Frame

All of the resulting window frame peak hold spectrums are plotted below. The following frequencies exhibited possible resonant behaviors: 97.5, 120.25, 182.5, and 189.5 Hz.



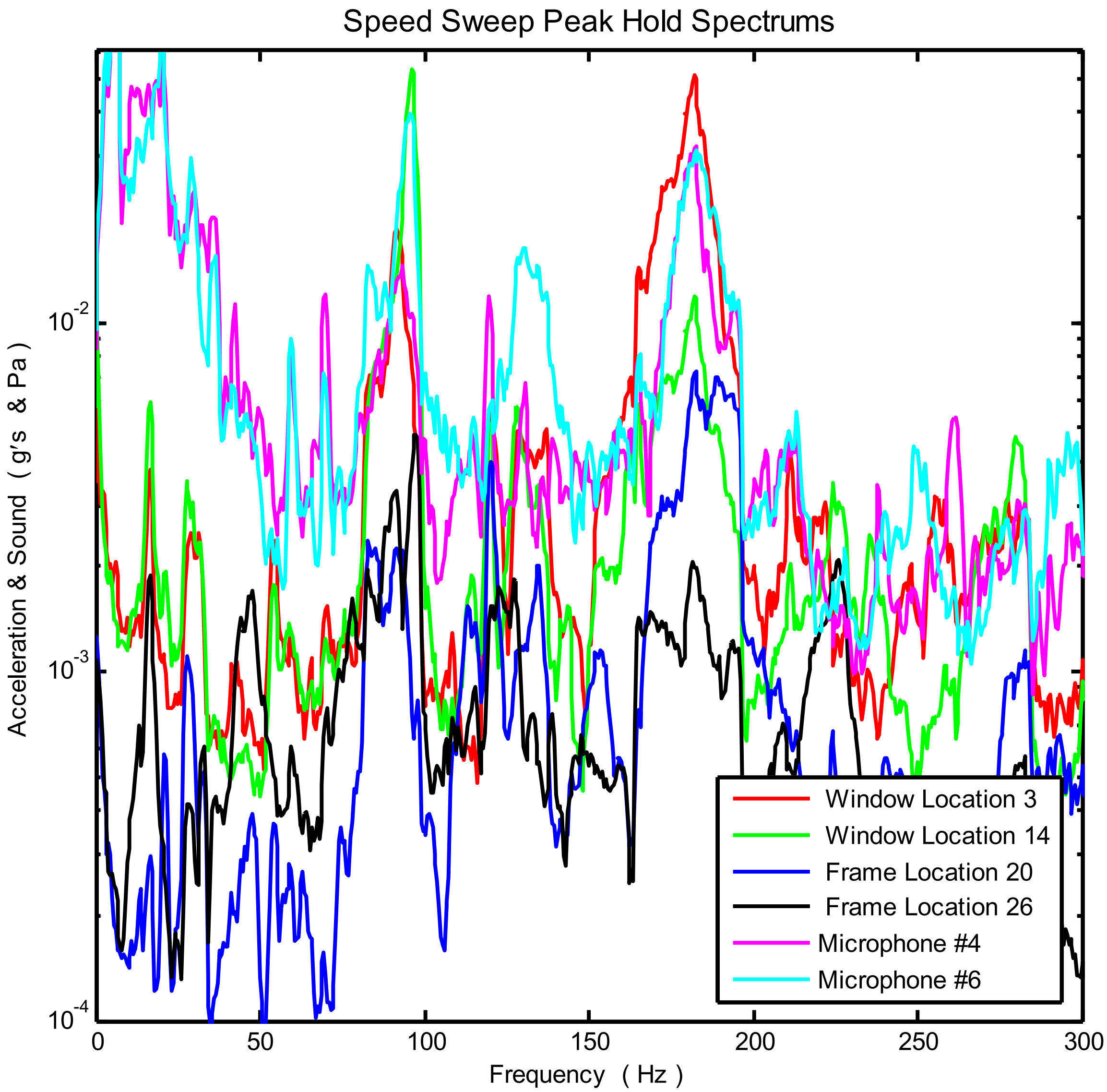
Speed Sweep Results - Window

All of the resulting window peak hold spectrums are plotted below. The following frequencies exhibited possible resonant behaviors: 96 and 182 Hz.



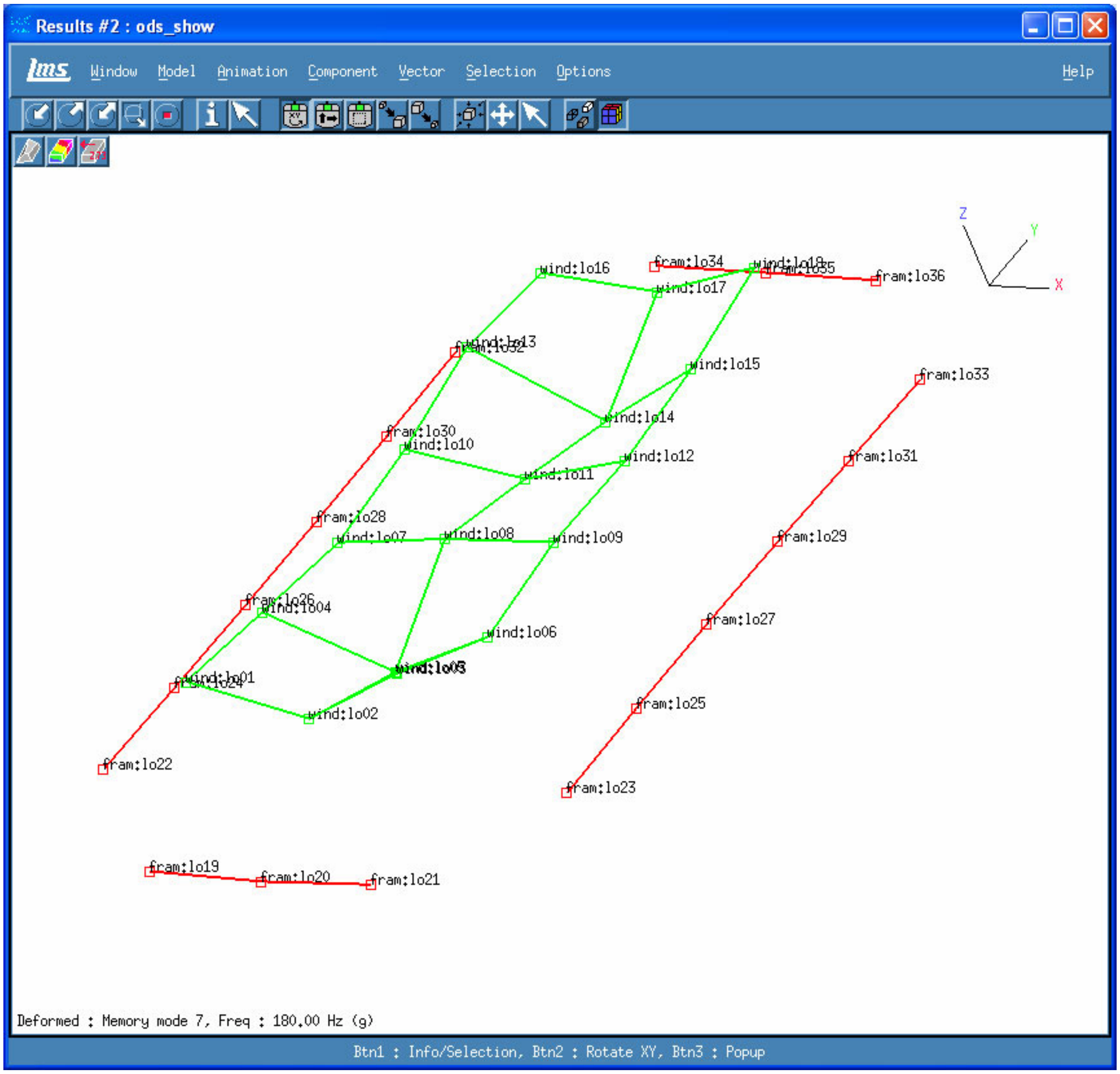
Speed Sweep Results - Summary

The plot below of individual speed sweep peak hold spectrums shows the strong relationship between the window's 96 and 182 Hz resonant behaviors and their associated microphone responses.



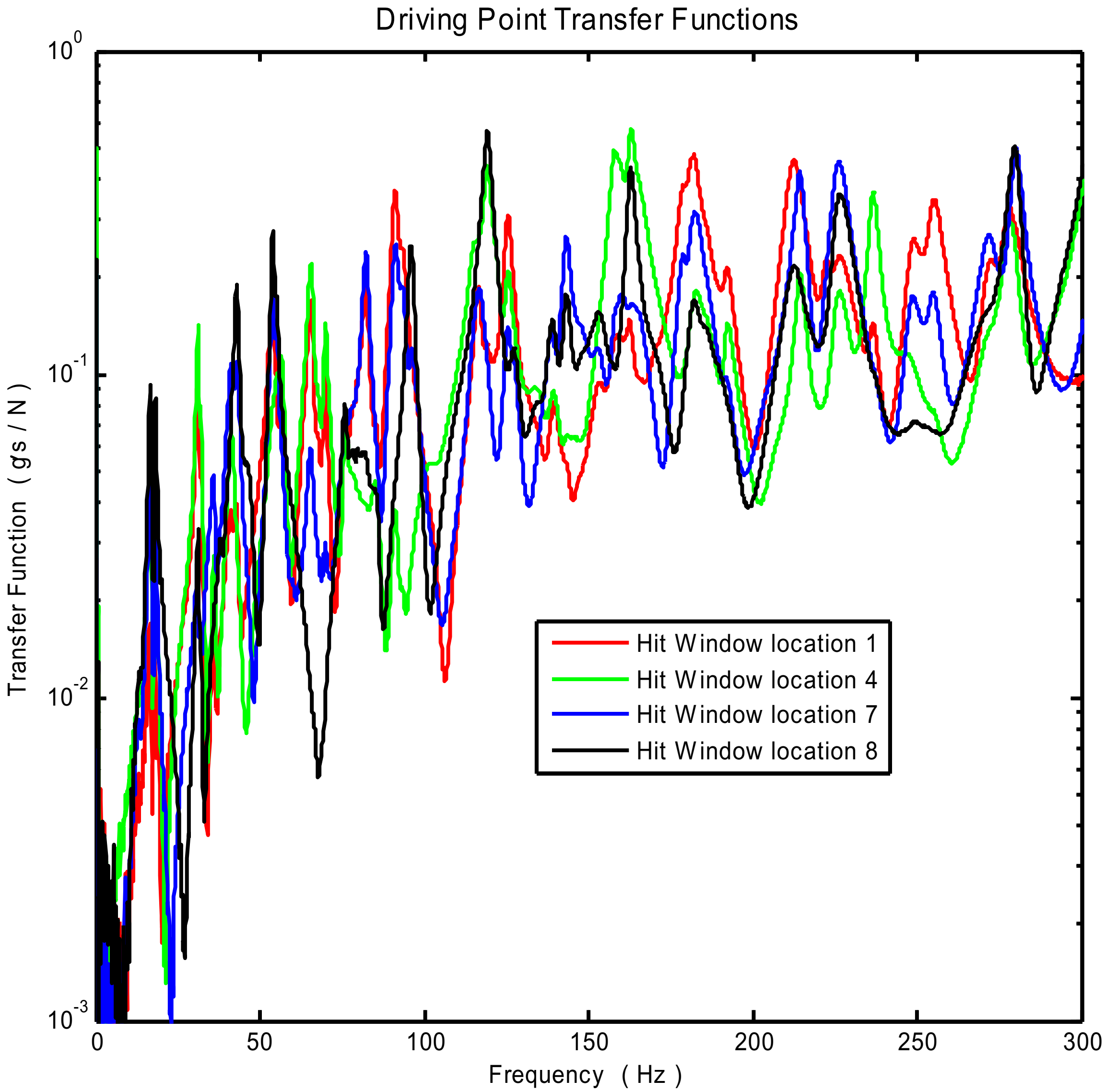
Operating Deflection Shapes

For later model correlation, operating deflection shapes were generated of assorted orders. The 180 Hz motion is shown below.



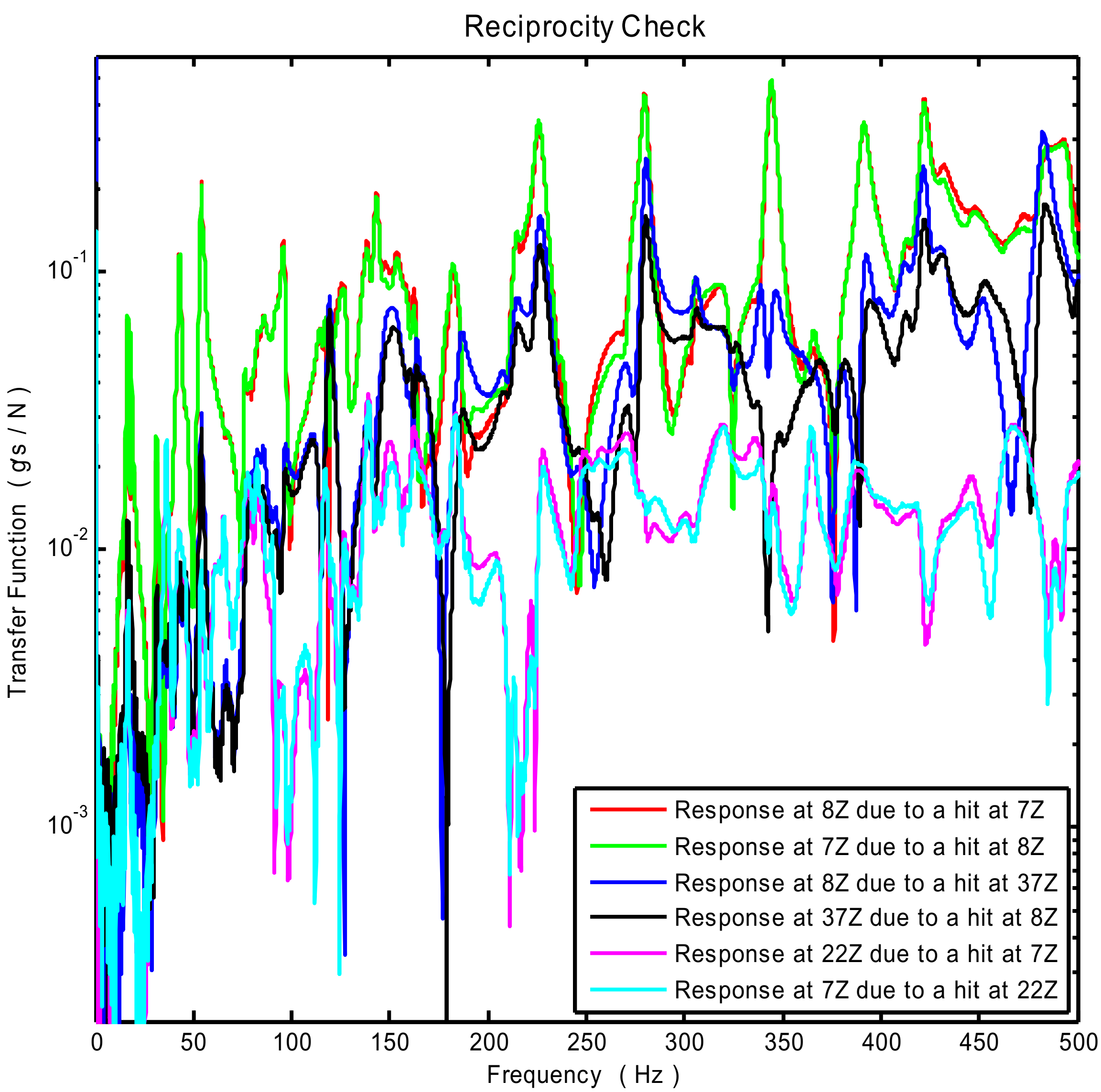
Modal Test – Driving Points

To further support modeling efforts, a modal test was run. As expected, a very large number of resonant frequencies were present. Four of the most active driving points are plotted below.



Modal Test – Reciprocity Check

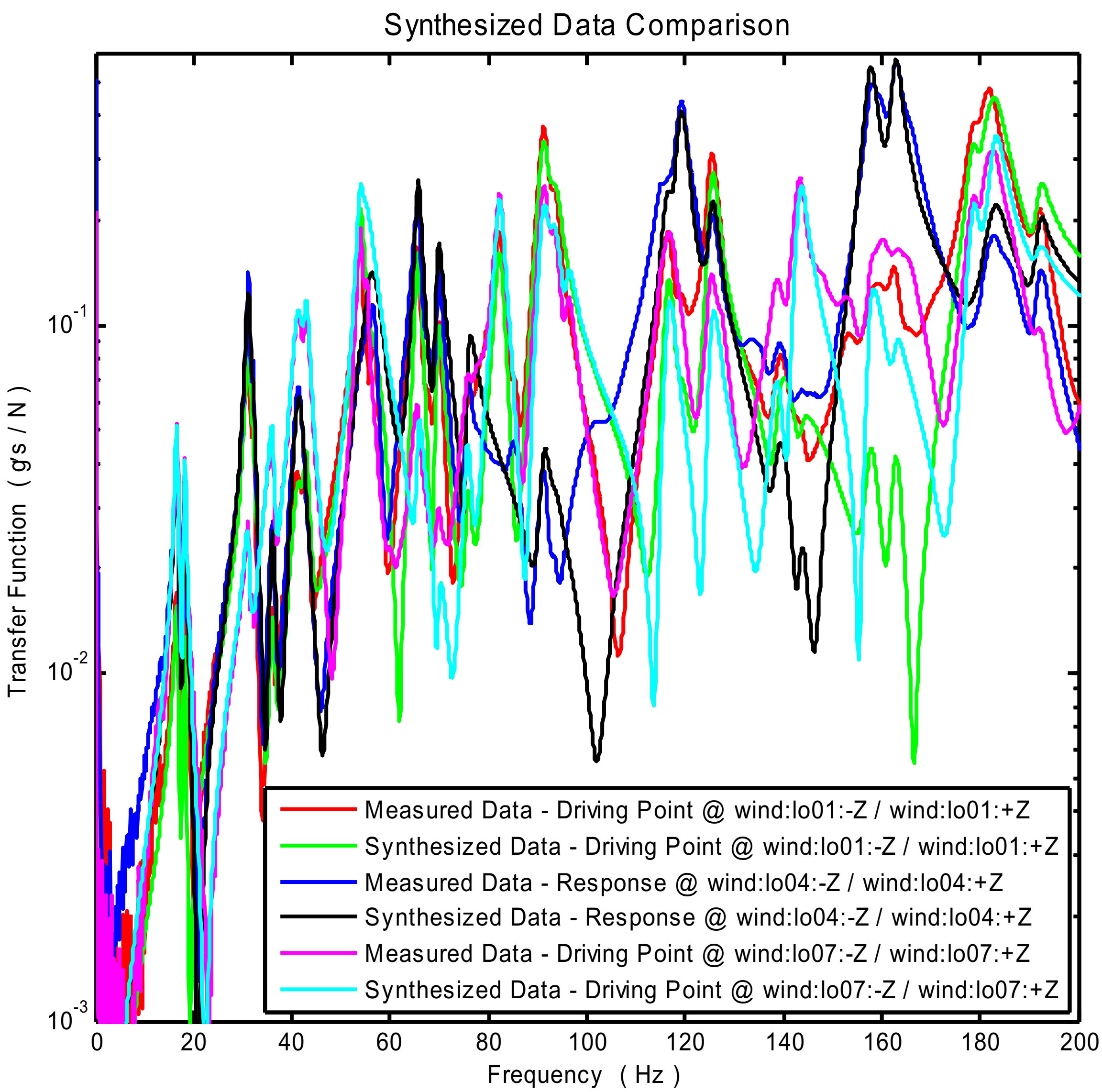
Modal analysis assumes that the tested structure is linear. Of a linear structure, the transfer function of the response at location A in direction B divided by the hit at location C in direction D will be the same as the response at location C in direction D divided by the hit at location A in direction B. This is called a reciprocity check. Reciprocity holds fairly well across the entire frequency range and even across the frame to the window: location 7 is on the window and location 22 is on the frame.



Modal Test – Synthesized Data

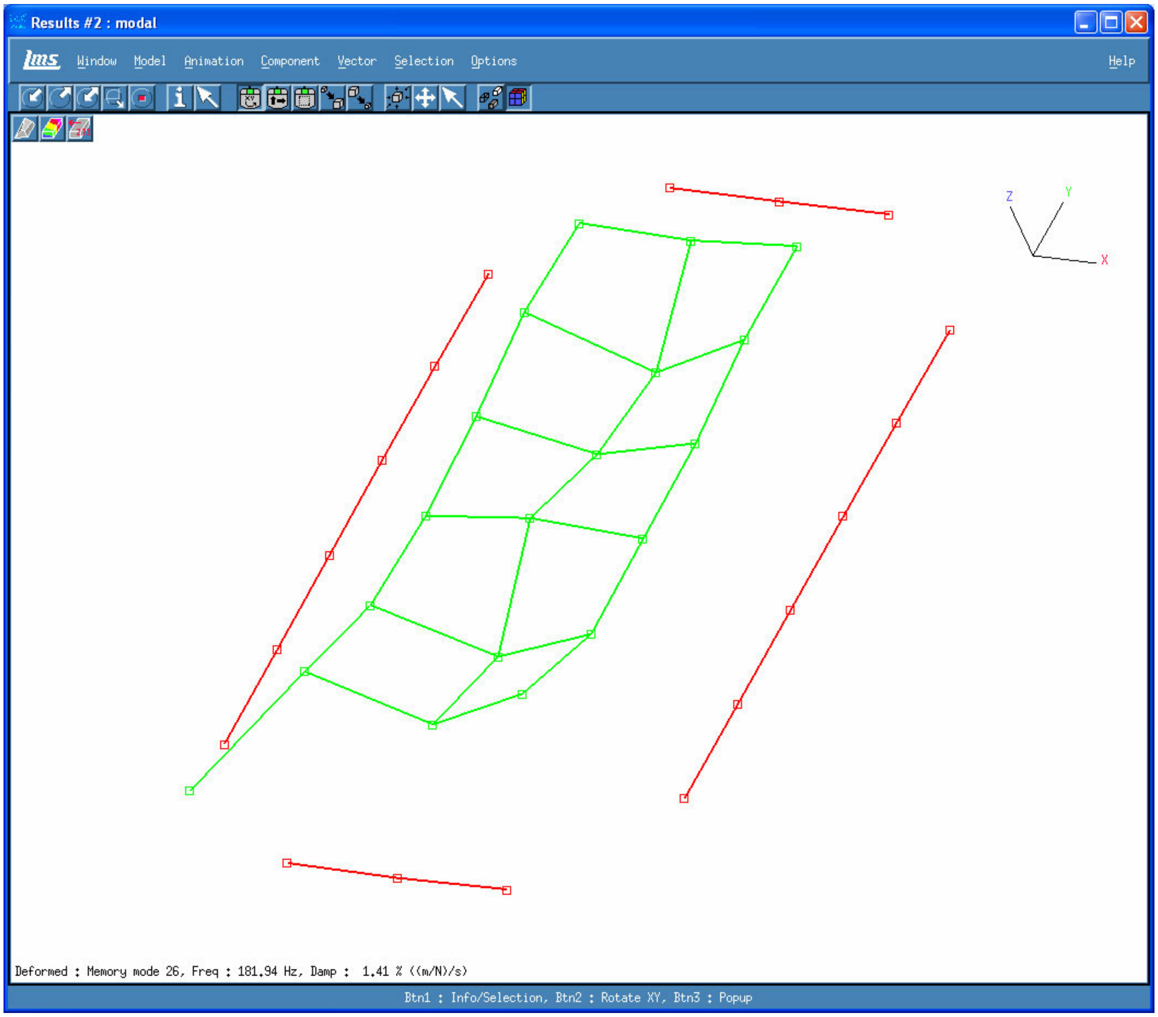
Both single and multi-degree curve fits were tried. The results were pared down to 28 modes.

The synthesized transfer functions correlated fairly well with the measured data, providing an indication that the modal data was valid.



Modal Test – Mode Shape

This is the mode just above 180 Hz, which is assumed to be associated with the excessive noise. This mode shape looks somewhat similar to the 180 Hz operating deflection shape, which was the expected result.



Model Building & Usage

A finite element model was built of the window. The experimental modal test found 28 modes below 200 Hz; the model had 27. Correlation efforts concentrated on matching the frequency and mode shape of the suspected troublesome mode of 181.94 Hz. Reasonable correlation was established using published glass properties and allowing some flexibility at the window's edges - connection to its supporting frame. The flexibility at the window's top and bottom were different from its sides. This was considered a valid approach via discussions with the glass subcontractor.

With the goal in mind of moving resonant frequencies away from 180 Hz, assorted alterations were tried. The final proposal was adding two 2-lb masses, each one near a corner of the window. Per the model, this was expected to move the troublesome resonant frequency from 186 to 177 Hz.

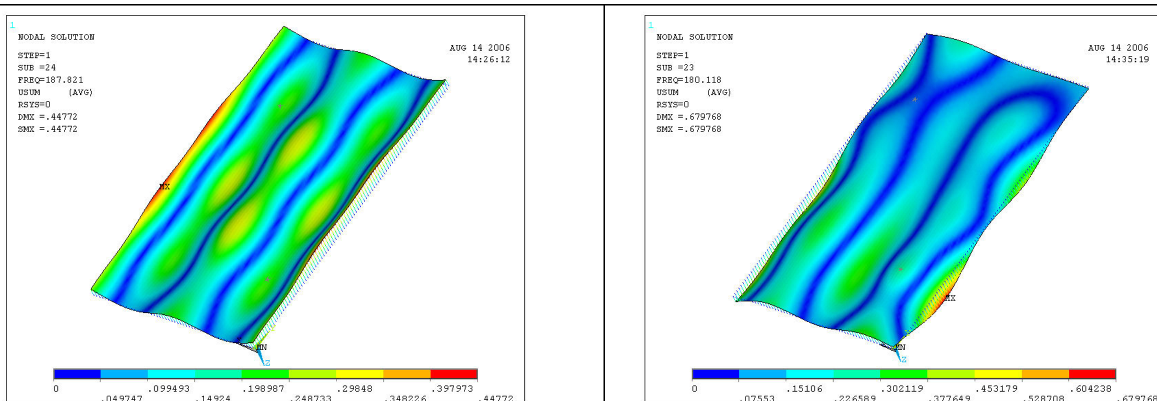


Figure 10. Mode shape of the glass panel before and after treatment

Third Site Visit – Confirming the Proposed Solution

Sound measurements were made in a conference room where there were four windows facing the generator set. This location was chosen because the door could be closed and the effect of all other radiating panels could be negated.

Baseline measurements were made with the generator set running at approximately a 420 kW load, then again with two 2 lb steel weights fastened with beeswax to the inside of each of the four windows. Each steel weight was three inches in diameter and one inch thick. Data showed that the 180 Hz tone was reduced about 15 dB with overall noise reduction in the conference room about 10 dB(A). This effectively eliminated the noise annoyance problem. Figure 11.a shows the sound spectra before and after the treatment and Figure 11.b shows the windows with the massed attached.

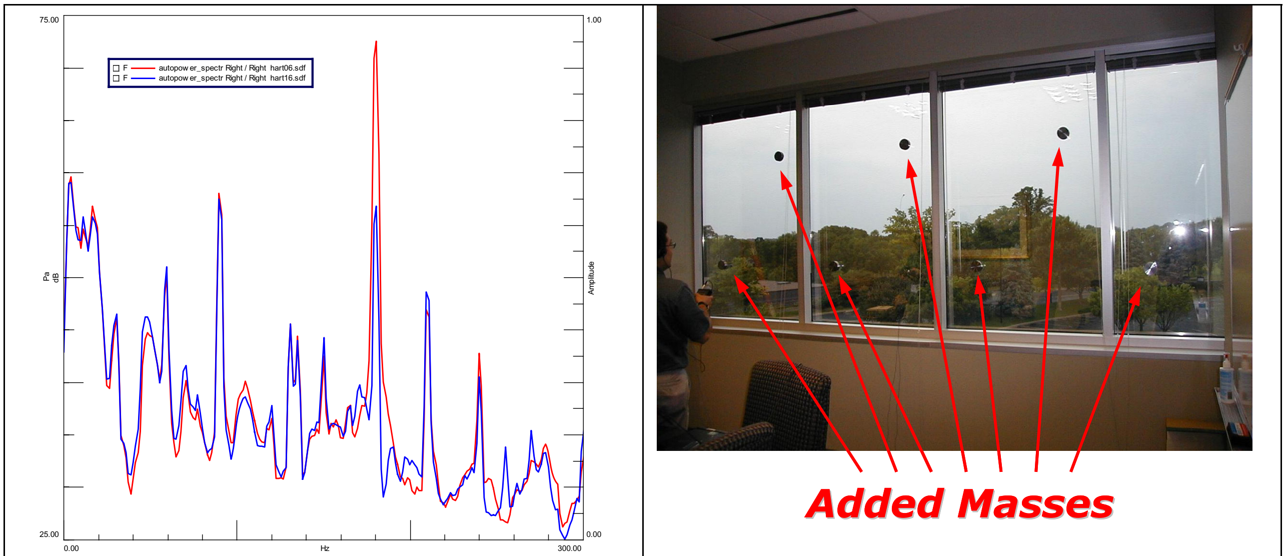


Figure 11. Sound reduction and added masses

Summary

This paper explained the steps taken to understand and ultimately solve a building noise complaint. This turned out to be a case where a dominate frequency of an outside noise source happened to coincide with a structural natural frequency of the building, yielding unacceptable noise levels inside the building.

Experimental modal analysis identified the troublesome resonant behavior. Finite element modeling was used to explore design space and provide a solution. The final recommendation was to treat all of the windows on the side of the building facing the generator set with two 2 lb masses.

Acknowledgements

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