Investigation Of A High Frequency Sound Quality Concern In A Refrigerator And Resulting Compressor Design Study

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ABSTRACT

The noise of a residential refrigerator exhibited some undesirable high frequency tones. The tones did not affect the overall A-weighted sound power level of the unit, but they represented a sound quality concern for the refrigerator manufacturer. This paper describes the analytical and experimental techniques that were applied to troubleshoot and solve the problem. An analytical model of the compressor discharge muffler was built, validated with test data, and used to identify the best countermeasures.

INTRODUCTION

A residential refrigerator exhibited some undesirable high frequency tones. The level of these tones was too low to affect the overall A-weighted sound power level of the unit, however they were a sound quality concern for the refrigerator manufacturer. Furthermore, the compressor itself met its sound power level targets, but this did not prevent the occurrence of these objectionable high frequency tones. Compressor manufacturers often qualify their products by measuring sound power levels yet even a quiet compressor may, when installed in the unit, excite local resonances and produce unexpected and annoying noise components. This paper describes analytical and experimental techniques that were applied by the compressor manufacturer to troubleshoot and solve the problem in a refrigerator.

IDENTIFYING THE SOUND QUALITY CONCERN

The refrigerator exhibiting the problem was placed in a semi-anechoic chamber and two binaural heads were placed in front and in back of the unit. Since, according to the complaint, the annoying tones were particularly evident at the beginning of the refrigeration cycle, it was decided first to record a few complete cycles to verify when the problem occurred. For this purpose, a digital ADAT recorder was used to record the signals picked up by the microphones in the binaural head during a few refrigeration cycles. Each cycle was approximately 45 minutes long, with the compressor on for 20 minutes. The recordings were first reviewed by a small number of engineers in order to identify the occurrence of the problem and then they were analyzed for narrow band frequencies. Figure 1 shows a waterfall of FFT spectra with the frequency of the sound quality concern highlighted. The objectionable noise was due to a few tones distributed in a fairly narrow band around 2350 Hz. The identification of the sound quality concern was accomplished by filtering out the frequencies of interest with real-time digital filters in a commercially available sound quality software package.

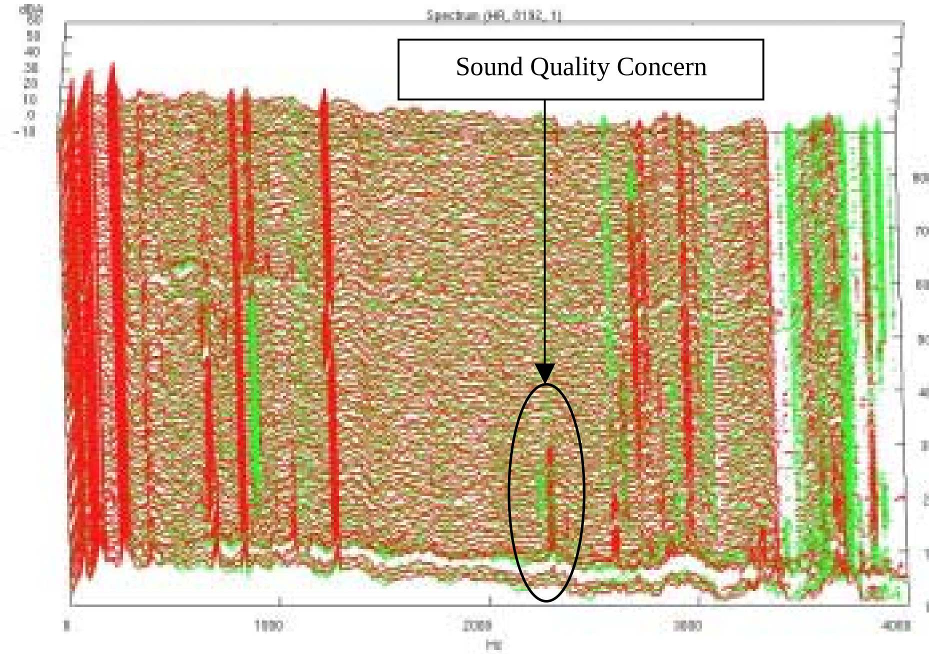

Figure 1. 3-D Waterfall of Refrigerator Sound

DIAGNOSING THE PROBLEM

The refrigerator and the compressor were then instrumented with accelerometers at various locations (compressor shell, refrigerator bottom pan, suction and discharge lines), with pressure transducers to measure the dynamic suction and discharge pressure and with microphones in the proximity of the compressor and in front of the refrigerator. The refrigerator was again allowed to cycle and the time histories from all twelve channels were recorded to disk. Since the frequency of the problem had been identified to be 2350 Hz, all data were sampled at 12.5 kHz to allow for an analysis bandwidth of 0-5000 Hz.

The acceleration signal on the compressor shell was bandpassed using a digital FIR filter to obtain a tachometer for the compressor pump. This signal was then used as a phase reference for all other signals during analysis in the frequency and order domain. Frequency and order slices in the 2000 to 3000 Hz range were then extracted for all channels and compared to each other in order to identify the possible cause of the 2350 Hz tones. Figure 2 shows a waterfall of FFT spectra of the discharge pulsation in the 2150 to 2500 Hz band. Five relatively constant frequency compressor harmonics are shown along with three time varying resonances. Figure 3 shows frequency slices versus time around the four dominant orders in this region of the discharge pulse. It is clear that when a harmonic of the compressor matches one of the three resonance frequencies, an amplification results. For the most significant tone at 2352 Hz, Figure 4 compares the time slices of the discharge pulse to the sound in back of the refrigerator. The strong similarity and a high degree of correlation between the discharge pulse and the noise between 2200 and 2400 Hz clearly suggested that the resonances in the discharge system at these frequencies were the cause of the sound quality concern.

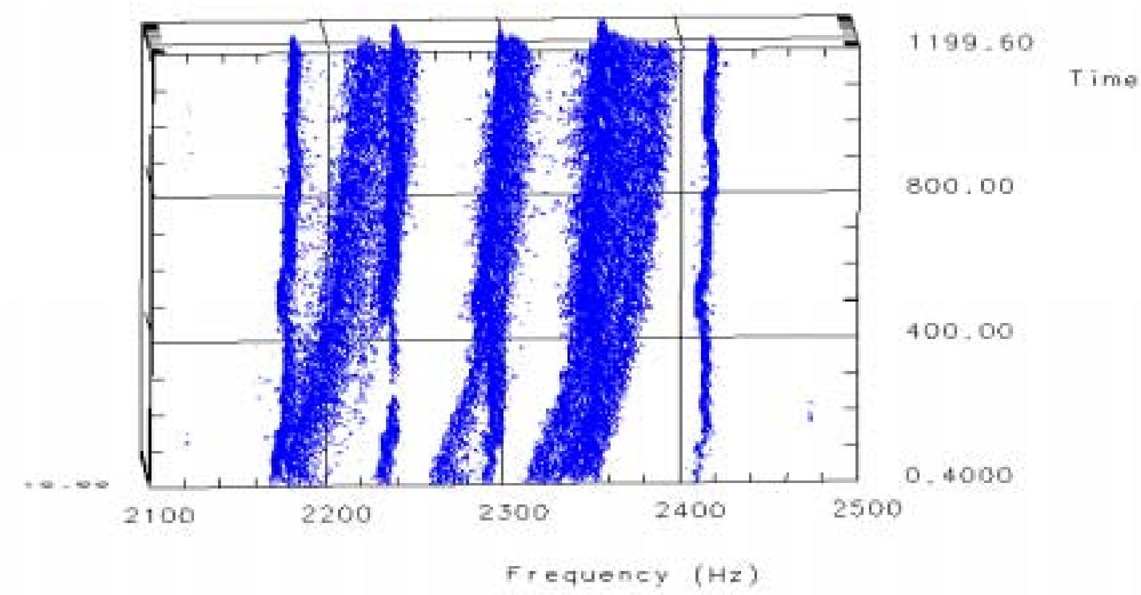

Figure 2. 3-D Waterfall of Discharge Pulse during Compressor On Cycle

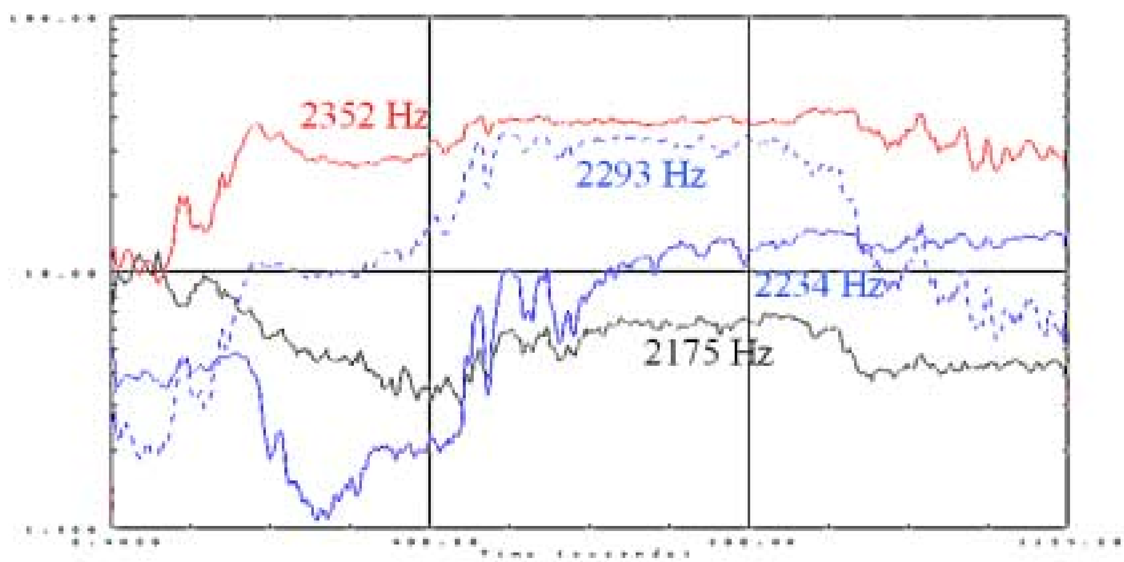

Figure 3. Frequency Slices of Discharge Pulse over One Refrigerator On Cycle

In order to verify this conclusion, the discharge system of a compressor (from the cylinder head to the final discharge line) was mounted on a speaker test bench. A sine sweep signal from 100 to 10000 Hz, representing a 50 to 5000 Hz range in the refrigerant, was fed to the speaker and the frequency response function between the microphone in the cylinder head and a microphone downstream from the discharge muffler was measured. The measured frequency response function (FRF) is shown in Figure 5. It clearly shows peaks in the frequency region of interest, confirming the presence of a resonance in the discharge system.

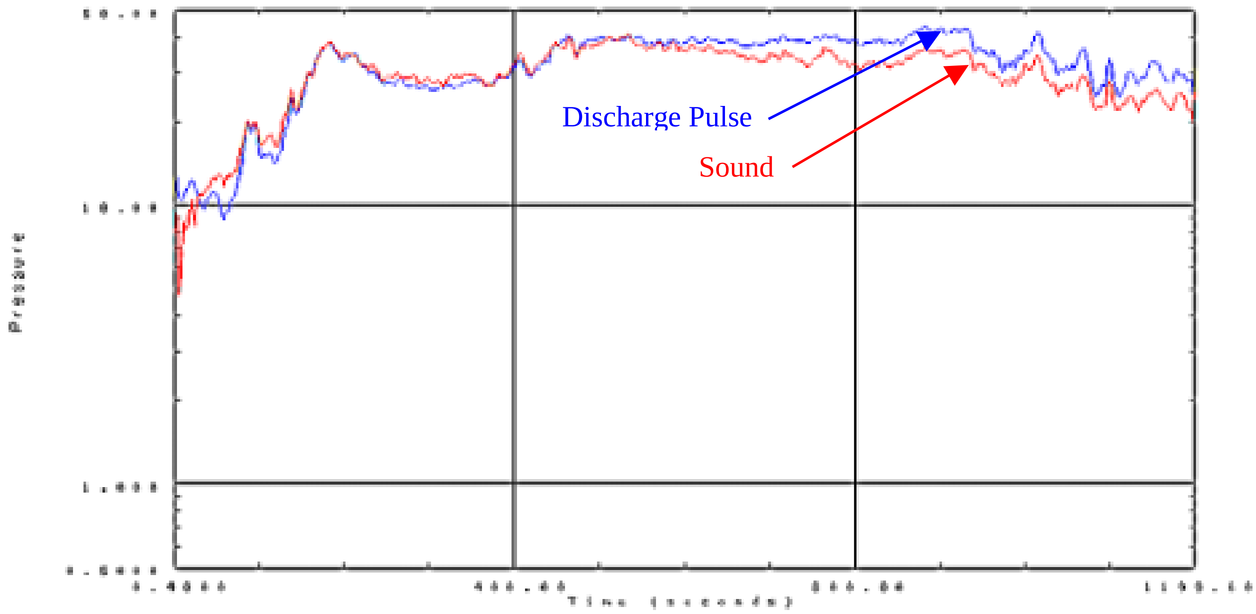

Figure 4. Frequency Slices of the Discharge Pulse and Sound at 2352 Hz Compared

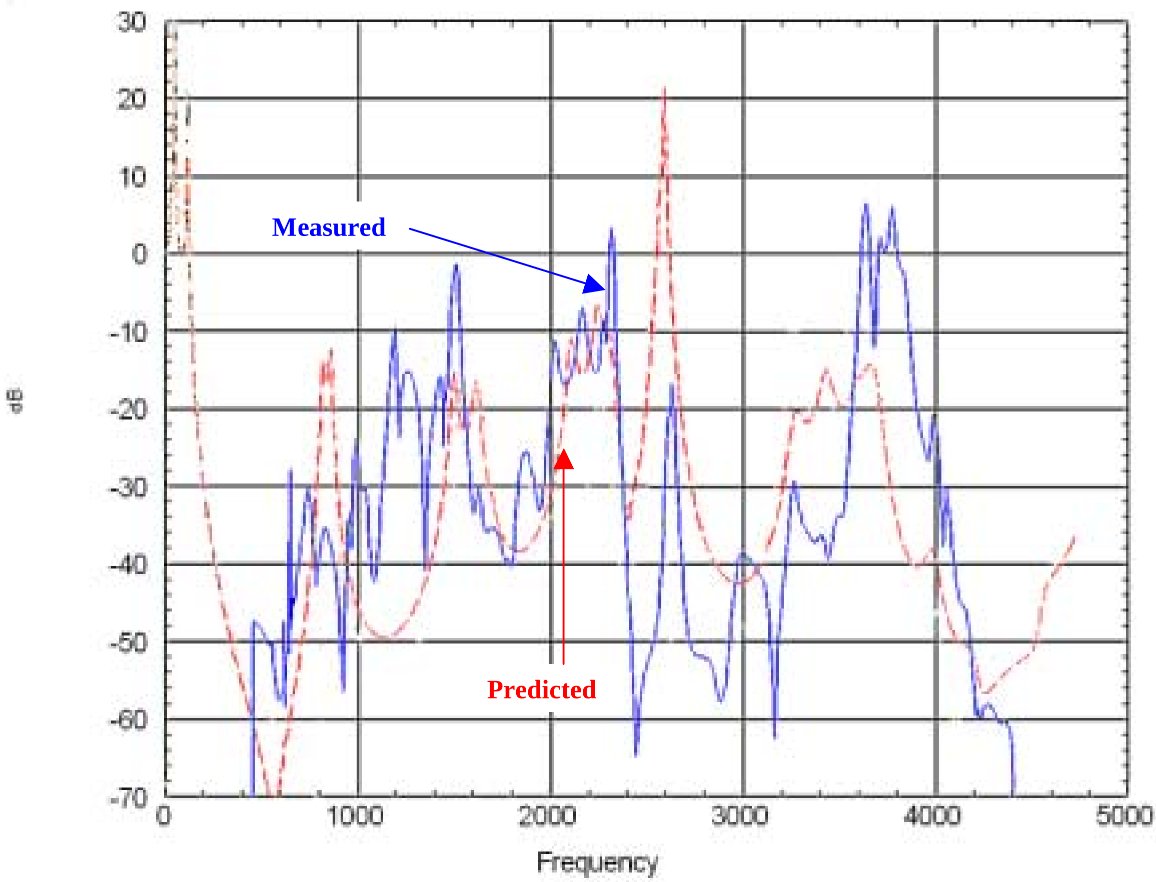

Figure 5. Measured and Predicted Frequency Response of the Discharge Muffler

FINDING A SOLUTION

An acoustic finite element model of the discharge system that was tested on the speaker test bench was then built and correlated to the results shown in Figure 5. The model was forced with a unit impulse volumetric acceleration at the discharge port. The model predicts the pressure at any point in the system and a predicted frequency response function can be calculated between any pair of locations. The predicted FRF was compared to the FRF measured on the speaker test bench and the model was adjusted until good agreement was achieved in the frequency range of interest. Once the model was correlated, it was used to simulate different design changes and to evaluate their effectiveness in the frequency range of concern.

Table 1 lists the modes predicted up through the frequency range of concern. As can be seen, in the 2200-2600 Hz region, all modes are associated with the two circular chambers of the discharge system and to the interconnecting tube. Figure 6 shows a contour plot of the discharge muffler mode at 2292 Hz, which is associated with the first chamber. Figure 7 shows the similar mode associated with the second chamber.

Table 1. Discharge Muffler Resonance Modes from Model

Mode	Frequency	Description
21	75.3	Muffler Helmholtz
32	187	Discharge Plenum to Muffler Helmholtz
43	816	Tube half wave
54	958	Helmholtz within Discharge Plenum
65	1620	Tube full wave
6	1738	Discharge passage half wave
7	2244	Muffler chamber Diameter resonance
8	2269	Muffler chamber Diameter resonance
9	2270	Muffler chamber Diameter resonance
10	2292	Muffler chamber Diameter resonance
11	2442	Discharge chamber half wave
12	2447	Tube 3 half waves
13	2561	Muffler chamber length
14	2592	Muffler chamber length
15	3267	Tube 2 full waves

Several design iterations were run. A couple of prototypes were then built which incorporated two of the more effective design changes and deemed feasible from a manufacturing standpoint. The prototypes were first tested on the speaker test bench, then assembled in two compressors and tested again with a line frequency sweep. Both prototypes exhibited much less objectionable noise in the 2350 Hz range. The comparison between the best of the two prototypes and the baseline discharge system is shown in Figure 8.

CONCLUSION

Use of multi-channel data acquisition along with sound quality techniques is very useful in diagnosing sound problems. Sound quality methods, especially real-time filtering, are essential in determining the frequency range of many sound concerns. Multi-channel data acquisition allows variations in time to be used as an aid in identifying root causes for the sound problem. Finally, the insight provided by analytical models aids in both identifying the cause and possible solutions to sound concerns.

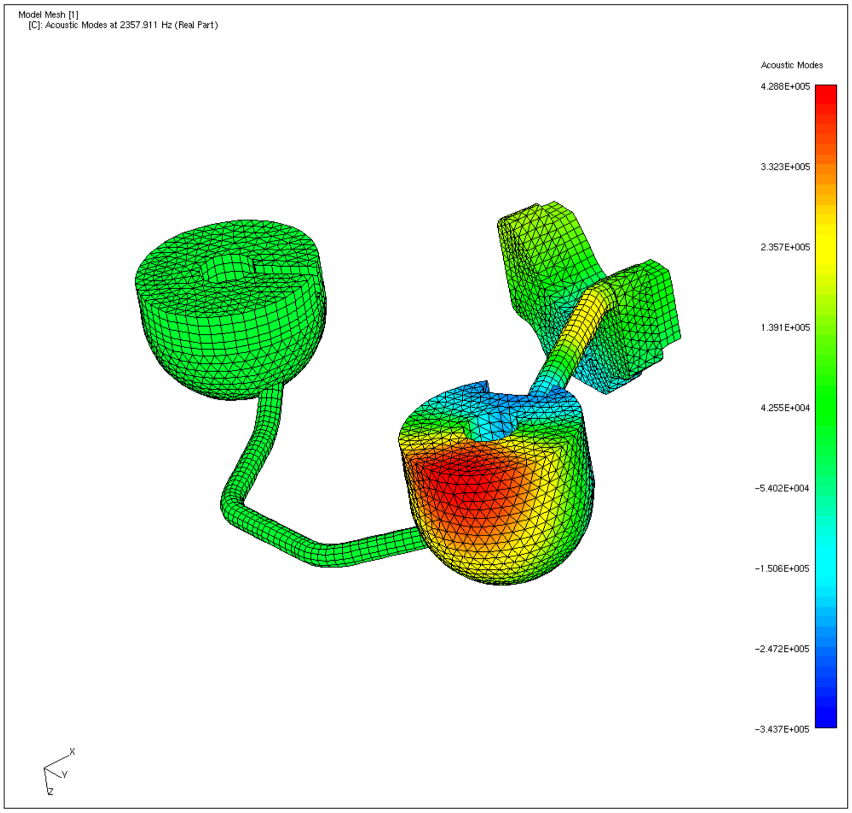

Figure 6. Acoustic Resonance of First Discharge Chamber

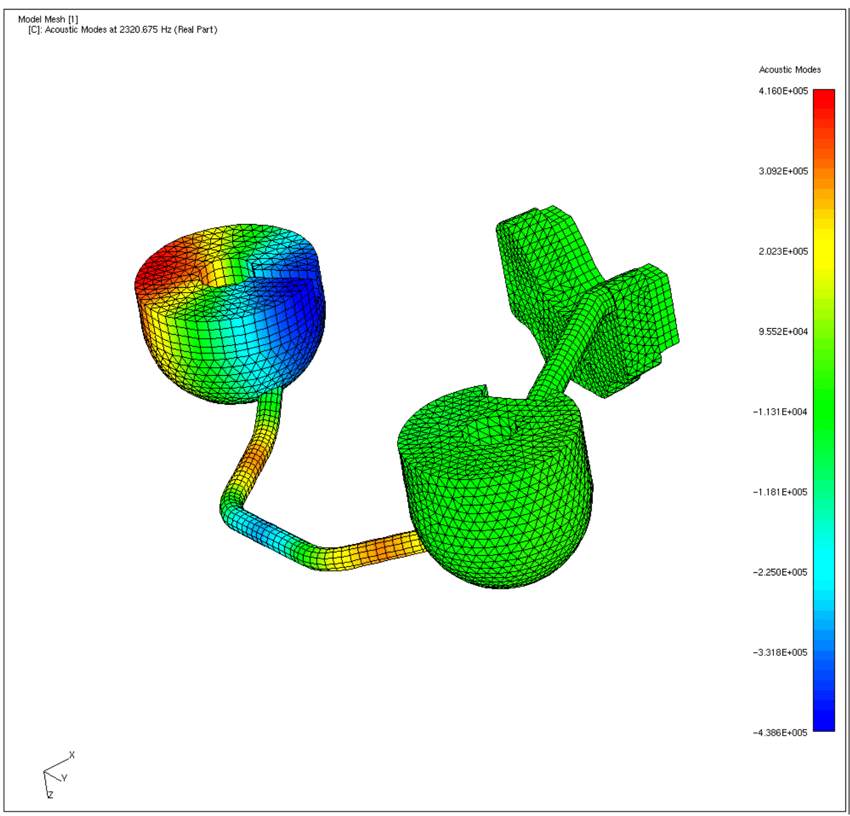

Figure 7. Acoustic Resonance of the Second Discharge Chamber

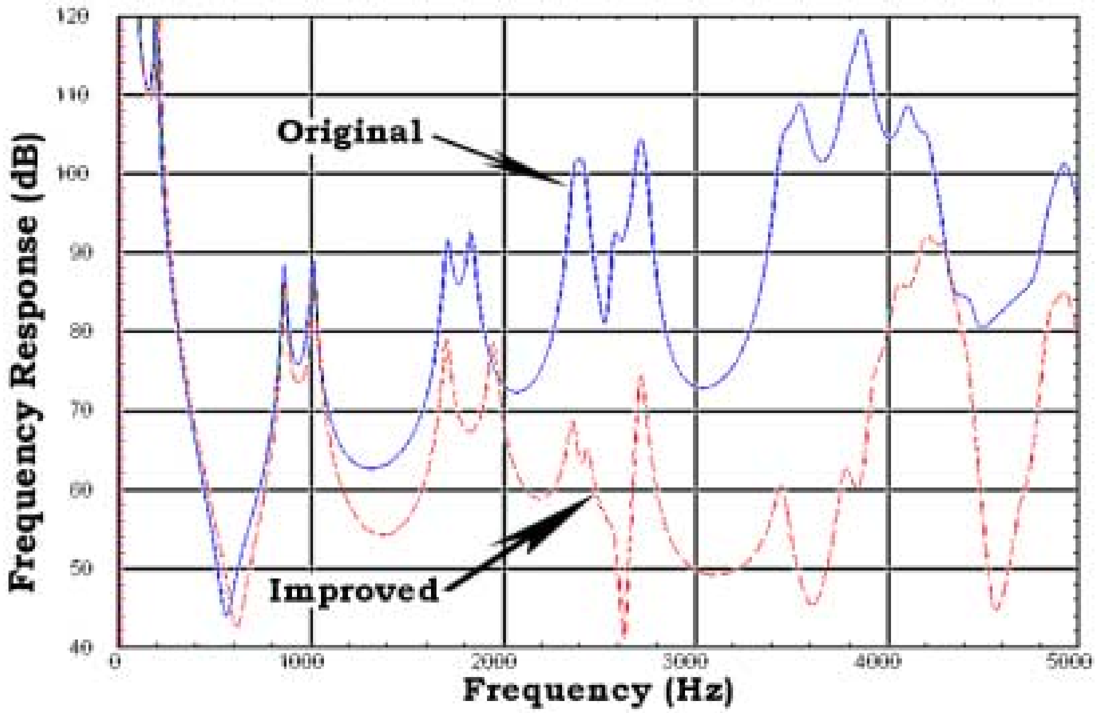

Figure 8. Comparison of Analytical Muffler Frequency Response Functions