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Comparative Investigation of Muffler Models

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1. INTRODUCTION

The reduction of automotive noise, both internal and external, has become a paramount issue in the area of car development. Engine developers have answered the demand from the public for improved engine performance by increasing engine efficiency through lowering inlet and outlet valve resistance. As a result, greater amplitudes of noise can propagate through the exhaust system downstream of the exhaust valves. Given the greater legislative emphasis on lowering automotive noise emissions, there are many restrictions imposed on exhaust system manufacturers who must not only attain higher attenuation levels with their products, but they must do so in conjunction with lower flow resistance in order to maintain performance. [2]

In the past, the acoustical design of the exhaust system has been a trial and error process resulting in a design time cycle which is too long to meet the needs of the automotive manufacturers, as well as being cost prohibitive. In an effort to reduce these development costs and overall design time, the development of computer based systems for acoustical modeling have been implemented. [6] Given the powerful software packages that are now available, very reliable prediction of engine noise, including exhaust, can be obtained. Unfortunately, many of these software packages have become so sophisticated that the input criteria has become extremely involved, thus again, increasing both development time as well as amount of skills required to use these design packages.

The purpose of this paper is to investigate the feasability of using simplified theoretical modeling equations as a preliminary step in the design process for exhaust muffler systems. Specifically, the results of a theoretical equation for a simple expansion chamber muffler are compared to the results of a computer model. Further, the results of a relatively simple computer model are then compared to the results of a very complex computer simulation model of a muffler system complete with a modeled internal combustion engine as the source. The muffler dimensions used in this investigation are illustrated in Figure 1.

2. MUFFLER THEORY

The muffler design used in this investigation is a simple single expansion chamber muffler chosen for its simplicity in

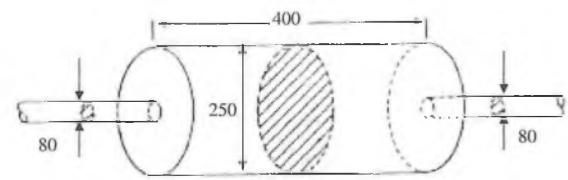

Figure 1: Modeled Muffle Dimensions

establishing theoretical behavior. This type of muffler is classified as a reactive muffler in which its performance is mainly determined from its geometrical shape which initiates an impedance mismatch for the acoustical energy traveling along the duct. "This impedance mismatch results in a reflection of part of the acoustic energy back toward the source of sound", thus preventing some of the energy from being transmitted past the muffler.

The criteria used for measuring the effectiveness of the theoretical model compared to the simple computer model is the realized Transmission Loss (L_{TL}). The calculated transmission loss illustrates the relationship between the sound power of the incident wave at the muffler inlet and the sound power in the transmitted wave at the muffler outlet and is given in the units of decibels (dB). While it is a useful analytical tool, transmission loss measurements can be difficult, but not impossible, to determine experimentally. For a single expansion chamber muffler the transmission loss is given by the periodic equation below. [1]

$$L_{TL} = 10 \log \left[1 + \frac{1}{4} \left(m - \frac{1}{m} \right)^2 \sin^2 kl \right]$$

Here the behavior of the muffler is influenced by the ratio of the cross sectional areas of the chamber and duct (m), the length of the chamber (l) and the wavelength of sound ( ) at the temperature of the gas in the muffler. The general transmission loss of an expansion chamber of dimensions l and m is given in Figure 2. [3] It should be noted that this theoretical representation is in the absence of steady airflow.

Insertion Loss (L_{IL})was used to compare the simple computer model to the results of the complex simulation model complete with a modeled internal combustion engine as the dynamic noise source. Insertion loss is simply the difference, in decibels, between two sound pressure levels meas-

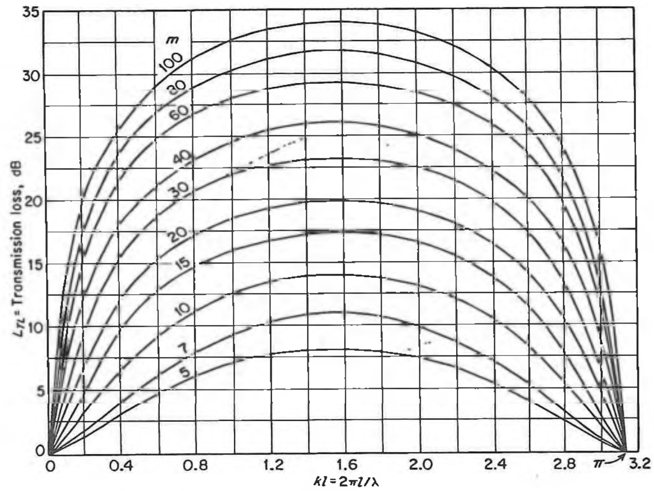

Figure 2: Transmission Loss of Expansion Chamber

ured at the same location before and after the muffler is inserted between the measurement location and the source.

3. COMPUTER MODEL

To model the transmission loss, a computer software package call Ricardo WAVE was used. "WAVE is a computer-aided engineering code developed by Ricardo to analyze the dynamics of pressure waves, mass flows and energy losses in ducts. WAVE provides a fully integrated treatment of time-dependent fluid dynamics and thermodynamics by means of a one-dimensional formulation incorporating a general thermodynamic treatment of various working fluids." [5] The transmission loss is calculated using a computer analog of the Chung-Blaser experimental technique where a two-probe microphone is placed both upstream and downstream of the muffler. A pseudo-white noise generator acts as the dynamic source at the upstream end of the muffler and an anechoic termination is placed at the far downstream location. The transmission loss is then calculated and plotted versus frequency. [4]

To model the insertion loss of the muffler, two computer models were created with WAVE and the results were compared to each other. The simpler model was the same as that used in the transmission loss simulation. Here measurements downstream of the muffler location were made with both the muffler in place and again with the muffler replaced with a straight pipe. These results were then compared to results from a much more complex simulation. Here, the muffler was placed within an entire exhaust system which was attached to a modeled 16 valve 4 cylinder engine complete with combustion. This representation includes realistic temperatures and mass flows.

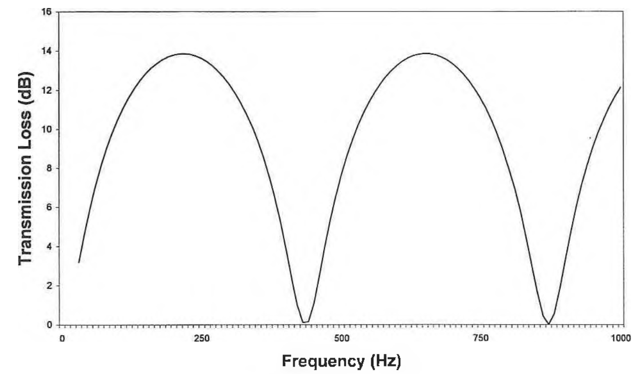

Figure 3: Theoretical Transmission Loss Results

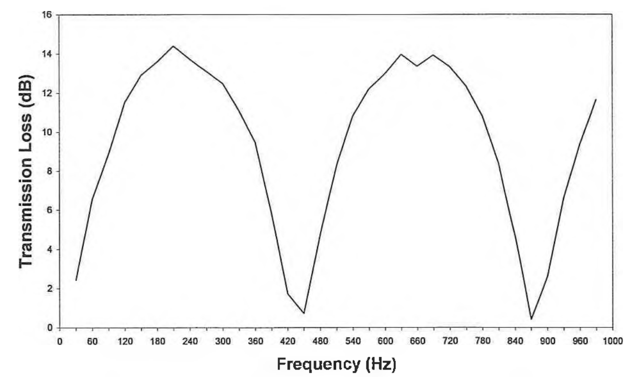

Figure 4: Computational Transmission Loss Results

4. RESULTS OF TRANSMISSION LOSS CALCULATIONS

The theoretical transmission loss results obtained from equation1 discussed earlier are illustrated in Figure 3. For the wavelength at the gas temperature of 300 kelvin and for the specific muffler dimensions chosen, the theoretical equation predicts that the maximum transmission loss of almost 14 dB will first occur at 220 Hz and, thereafter, cyclically repeat with a wavelength of 440 Hz. There is also a significant reduction of transmission loss at 440 Hz which again repeats with the same wavelength of 440 Hz. It should be noted that the literature suggests that these transmission loss results for a single expansion chamber should not be affected by the presence of a superimposed steady flow as long as it does not have a velocity greater than 35 m/s. It has been found that the flow noise can become significant at very high velocities, thus rendering the muffler ineffective.

Examination of the computational results obtained from WAVE and given in Figure 4 show very similar results. The maximum transmission loss again appears at 440 Hz with a periodic curve of wavelength equal to 440 Hz. The computational results give a maximum transmission loss of just over 14 dB. This is only a slight increase over the theoretical results presented above. Smoother representations of the

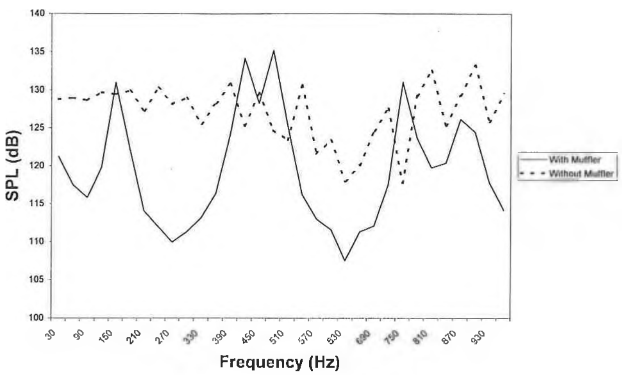

Figure 5: Insertion Loss For Simple Computational Model

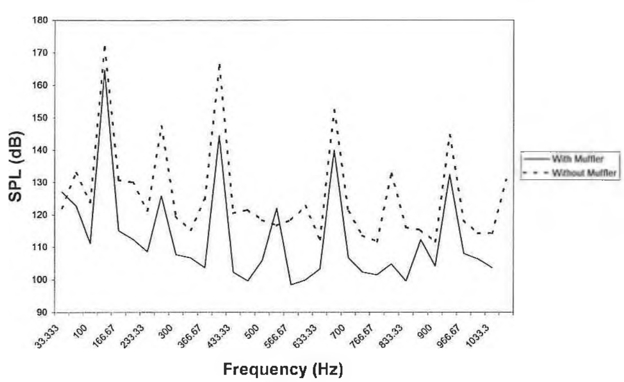

Figure 6: Insertion Loss for Complex Computational Model

computational curve may be possible if the model were subdivided with a greater discretization number. The trade off would be an increase in computational time. The overall character of the curve, however, remains the same with respect to amplitude and frequency.

5. RESULTS OF INSERTION LOSS CALCULATIONS

Figures 5 and 6 illustrate the insertion loss predictions for the simple computational model and the complex simulation respectively. The dotted and solid lines represent the sound pressure levels downstream of the muffler location without and with the muffler inserted.

For the simple model, the sound pressure levels determined at the downstream position from the muffler location are, for the most part, between 10 dB and 20 10 dB lower than the measurements without the muffler in place. The exception to this is at about 170 Hz, 500 Hz and 760 Hz where any insertion loss becomes negligible. For the complex simulation, the effects of the muffler are obvious.

Across the entire frequency spectrum, the noise level is approximately 20 dB less with the inclusion of the muffler over the noise level without the muffler. This represents a significant contribution to the attenuation of the produced sound level by the modeled engine. These results also follow those predicted by the simple simulation.

6. CONCLUSIONS

While not an exhaustive study, this investigation has demonstrated the merits of using the fundamental equations for preliminary design considerations for muffler systems. It has been demonstrated that the transmission loss results from the computational simulation closely resembles those predicted using the theory with a realized maximum transmission loss of 14 dB. It has also been shown that a significant insertion loss can be achieved with the addition of the muffler in both a simple and a complex computational model. The purpose of this investigation was to establish whether there is value in using fundamental approaches for preliminary design considerations in the design of muffler systems. It has been shown that such simple approaches do have merit.

7. REFERENCES

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