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REFRIGERANT MUFFLER ANALYSIS

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INTRODUCTION

Most refrigeration systems require mufflers to reduce noise due to gas pulsations in compressor suction and discharge lines. In the past, the design and analysis of refrigerant mufflers has been largely by cut-and-try methods, due to the complexity of the numerical calculations necessary for even relatively simple muffler configurations. As in other areas of design, the widespread availability of digital computers has made practical the use of more comprehensive design and analysis methods. The purpose of this paper is to describe one such method which yields information of value to the designer, and to describe also transmission loss measurements made in air which were used to validate the computer model.

The usual purpose of muffler analysis is to obtain a plot of transmission loss as a function of frequency. The designer does not need extremely precise information of this sort, but he does need to know the locations in frequency at which the muffler amplifies rather than attenuates, and he needs to know the approximate attenuation which is attained in the muffler stop bands. Further, it is of great value to be able to relate singularities in the muffler response to specific elements of the muffler.

A variety of methods have recently been developed to obtain this information. A few of these are described in References 1 through 5. Methods which have been used range from highly simplified models using lumped circuit theory to sophisticated methods which provide numerical solutions to the wave equation. The lumped circuit methods, at the one extreme, are open to the objection that they are limited to low frequencies only, and that they fail to account for finite wavelength effects which are of much practical importance. The more elaborate computations, on the other hand, require much time on a powerful computer and often yield considerably more information than can be utilized by the practical muffler designer.

The method to be described here is intermediate in complexity and accuracy to the extremes mentioned above. Based on the prior work of Miller and Hatten[1], it utilizes a modular approach to enable rapid assembly of a computer program to analyze most refrigerant muffler configurations. The muffler and associated tubing are broken down into sections, each of which can be represented by a matrix relating input and output quantities. Matrix elements are functions of the physical parameters of the section. Only a very limited number of different section matrices are required. After the matrices have been defined, multiplication of the matrices by a computer gives the muffler transfer function, from which other desired quantities can be obtained.

In this paper, a general discussion of muffler section types will first be given, followed by application to a particular configuration. Next, the measurement method will be described and results of computation and measurement compared. Finally, some advantages and disadvantages of the method will be outlined.

COMPUTER PROGRAM

Almost any reactive muffler having one input and one output port can be modeled by using four different network elements. These are a transmission line section, a shunt element, a lumped capacitance, and a termination. Other elements can, of course, be conceived but have not yet been needed.

Figure 1-A is the representation of a transmission line section. This would be used to model a muffler element having approximately constant cross sectional area. The area can be of any shape, but the largest transverse dimension must be less than one half wavelength at the highest frequency of interest. If the cross section changes slowly, it may be possible to represent the section as two or more separate parts. This network element is used to represent tubes, for example, and also holes in baffles. These holes, even in thin baffles, have a finite effective length. The important parameters of the section are the area, length, velocity of sound, and density of refrigerant.

Figure 1-B shows the electrical analog, a transmission line. Here, $\hat{U}$, is the acoustical volume current into the section and $\hat{P}$ is the alternating

component of pressure at the input. As shown in Figure 1-C, these quantities are complex, having both real (subscript R) and imaginary parts (subscript I).

The relationship between input and output quantities can be written in electrical network form as shown in Figure 2-A. The complex constants $\hat{A}$, $\hat{B}$, $\hat{C}$, $\hat{D}$ for a lossless transmission line are evaluated by assuming two waves on the line, with one wave traveling in the forward direction and one in the backward direction. The result of this evaluation is shown in Figure 2-B, with an additional intervening step omitted. The omitted step separated the two equations with complex coefficients and variables into four equations having only real coefficients and variables. This step is necessary because the computer language used, BASIC, does not allow use of complex numbers. Figure 2-B also gives the definitions of two intermediate functions, I and J, used for convenience in computation. Finally, Figure 2-C gives the matrix formulation of the equations. The input quantities, separated into real and imaginary parts, form a matrix with one column and four rows as do the output quantities. The coefficient matrix is 4x4, with elements which are functions of cross sectional area and length of the muffler section and of refrigerant density and velocity of sound in the refrigerant. Any consistent set of units can be used.

The matrix representation for a shunt section is shown in Figure 3. This is derived by requiring continuity of pressure and volume current at the junction point and treating the shunt as a section of transmission line with shorted termination. That is, the closed end has volume current set to zero.

The lumped circuit representation for a capacitance is shown on Figure 4. This is used primarily for representing the head volume. Geometry is usually complex and therefore, it is necessary to use a highly simplified model. A lumped capacitance has been found to be a reasonable model.

Finally, the column matrix used for a resistive termination is shown on Figure 5. This is a good approximation for a muffler which is connected to a long length of tubing, as a discharge muffler on a refrigerant compressor often is. Other terminations have been used, however, and any desired one can be programmed in. One useful termination sometimes found in practice in suction mufflers is a hole in a plate. The first two terms of the infinite series solution for an orifice were used in one analysis of this type with good results. For any termination, the procedure is to assume a real unit output pressure and to calculate the resulting output volume current, U, which may then be either real or complex.

A computer program to analyze a particular muffler is assembled by first dividing the muffler into sections, each of which can be represented by one of the four matrices described above. Each matrix is assigned an identifying letter and number. The data describing each section is then read into the program using the identifying number as a subscript and a beginning frequency assigned. Thus, the length of the 6th section is L6. Next, the elements of each matrix are defined, using the identifying letter together with row and column number, as, for example, A(1,1) for the element in the first row and first column of the A matrix. After this process is completed, the program is directed to multiply each matrix by the preceeding one, beginning with the termination matrix. When this is completed, the result is a 4x1 matrix. The first element in this matrix is the real part of the input pressure and the second element is the imaginary part. Thus, since a unit real output pressure was assumed, the transmission loss is obtained by calculating ten times the logarithm to the base 10 of the sum of the squares of the two input pressure components. This process is then repeated for each frequency of interest.

An example will perhaps make this somewhat more understandable. Figure 6 is the schematic of a typical refrigerant muffler. The cylinder head volume is connected to the muffler by a short tube. The muffler itself has two expansion chamber sections separated by a thin baffle having several holes. The downstream side of the muffler feeds into a long tube. Position 7 is arbitrarily chosen as the output point. For purposes of calculation, the muffler termination impedance is chosen to be purely resistive, of magnitude equal to the characteristic impedance of the tube.

As shown on Figure 6, each section of the muffler is assigned a letter and a number and the type of section determined. Section 1 is modeled as a lumped capacitance and hence, the elements A(i,j) of matrix A are those for the lumped capacitance on Figure 4. The dimensions of this section are L1 and S1 and refrigerant properties are C1 and ρ1.

Section 2 through 6 are all transmission line sections and the elements of matrices B, C, D, E, and F are defined by Figure 2-C. Lengths are L2 through L6, and so for other parameters. Section 7 is the termination and its elements are as shown on Figure 5. This particular muffler does not include a shunt section.

In the actual program, it is first necessary to provide dimensions for all matrices. Next, the velocity of sound in each section, lengths, areas, and density of refrigerant are read in. The intermediate functions I and J are defined for each section. The program then asks for the frequency at which the computation is to start, the ending frequency, and the frequency increment size. For the starting frequency, the program then computes the I and J functions and the elements for all matrices. Then the matrix multiplications are done.

For the example shown here, the first multiplication is that of the G or termination matrix by the F matrix. The program is written in BASIC language which provides a single statement for matrix multiplication. The 4x1 matrix resulting from the first multiplication is then multiplied by the E matrix and so on. It is necessary to specify in the program names for the intermediate natrices. Thus, the matrix formed by the product of G by F might be designated matrix P. Matrix P would then be multiplied by Matrix E and the product designated Q.

After all multiplications are completed, the transmission loss for that frequency is computed and stored. The starting frequency is then incremented by the specified amount and the calculations repeated. This continues until the desired stopping frequency is reached and the data is printed out.

It has been found desirable to use relatively large frequency steps for the first calculations. After results of calculations are printed out, it is usually found necessary to repeat calculations in selected frequency ranges using smaller frequency steps to detail attenuation in the vicinity of transmission loss singularities such as resonances.

Results of computations for this example will be discussed after the measurement arrangement is described.

MEASUREMENT ARRANGEMENT

It was considered highly desirable that the computer model be validated by comparison with experimental data. Measurements were made in air, since measurements in an operating refrigerant system present considerable experimental difficulties. Even measurements in air require considerable care if reproducible data is to be obtained.

Some factors which must be considered in muffler measurements are the establishment of realistic source and terminating impedances, avoidance of vibration and flanking paths, and elimination of electrical distortion products. Means to avoid these problems are shown on Figure 7, which shows the equipment arrangement used for measurements.

An oscillator is used to feed a power amplifier which in turn is connected to a horn driver unit. The driving frequency is measured with an electronic counter. The horn driver unit is enclosed in a soundproof enclosure to prevent flanking paths for acoustic energy from the horn driver directly to the output microphone, bypassing the muffler.

Energy from the driver is fed into the cylinder head volume by means of a capillary tube filled with fine wires. This provides an approximately constant acoustical current drive into the closed head volume. Sound pressure level in the head is measured with a 1/4 inch condenser microphone.

The muffler is placed on a soft foam pad to prevent transmission of room vibration into the measurement system. A long (about 50 feet) copper tube with the open end filled with loose cotton serves as the anechoic termination. Output sound pressure is measured with a second 1/4 inch microphone fitted into the output line so as to provide as little acoustical mismatch as possible.

Outputs of the microphone are amplified and connected through a switch to a tuned narrow band voltmeter. Use of a sharply tuned filter on the output is necessary to reject extraneous noise and harmonics of the driving frequency. Without this precaution, highly incorrect results can be obtained due to amplification of harmonics of the driving frequency by muffler resonances.

Measurements are performed by successively tuning the oscillator in small frequency increments through the range of interest and recording the sound pressure level in decibels at each microphone. The difference between input and output is the transmission loss. The voltmeter must be tuned to the driving oscillator frequency for each measurement. As for the computed transmission loss curves, frequency increments can be large in regions not near resonances but near resonances, the increments are made smaller.

Figure 8 shows a comparison between measured and calculated results. For this figure, the frequencies measured in air have been scaled by the ratio of the velocity of sound in refrigerant at operating conditions to the velocity in air. This factor usually ranges between 0.5 and 0.6.

The dashed line in Figure 7 is the transmission loss measured in air and the solid line, the calculated curve. Note that positive attenuation is plotted downward. Thus, regions where the muffler amplifies are above the zero line. What is desired for good noise suppression is that the attenuation be positive (downward) and as large as possible. The negative (upward) peaks need to be located as far from harmonics of the running speed as possible.

It will be noted that agreement between the two curves is good. One difference which can be seen is that peaks in the calculated curve are sharp, while measured peaks are rounded. This is because effects of dissipation are not included in the computer program. Dissipation could be included but for the purpose for which the analysis is intended, the increased complexity was not believed warranted.

It is possible to correlate the singularities in the transmission loss curves with the element or elements which cause them. Each tube will, for example, contribute a peak at each frequency at which it is a multiple of one half wavelength long. One way to connect elements with singularities is to vary the length of a section and observe the effect on the transmission loss.

Better agreement between computed and measured response curves can be obtained by adjusting the effective lengths and areas of sections. Some judgment is required because muffler sections often have rounded ends and thus, it is not clear what the effective length is. A dimension which requires considerable care is the effective length of tube assigned to represent holes in a thin baffle. Adequate theory is available for a baffle with only one hole, but the effective length decreases as the number of holes increases.

CONCLUSION

The method of muffler analysis outlined here has proved to be of considerable value in providing guidelines for muffler design. It has some advantages as well as disadvantages and it would be well to discuss some of these.

One limitation is that the method assumes plane wave propagation and hence, the upper frequency range is limited to about 1.22 c/d for a tube feeding into the center of a cavity and about 0.59 c/d for a tube feeding off center into a cavity. Here, c is the velocity of sound and d is the cavity diameter. For R22 at typical discharge conditions and for a muffler 3 inches in diameter, the upper limits are about 3,200 hertz and 1,600 hertz, respectively. For smaller mufflers, the limits are higher. The program is still useful above those limits, but other effects not predicted by the computation will occur causing significant effects on the transmission loss.

The effects of flow and of dissipation are not included. These could be added if desired but the additional complication has not been felt justifiable. A more important disadvantage is that interactions between compressor and muffler are not accounted for.

In contrast to the disadvantages, it is very easy and straightforward task to assemble a program to analyze almost any single input-single output muffler. The programs are very flexible and cost little to run. Different refrigerant properties can be used in each section of the muffler, if desired, and any source and load impedance can be used. It can be modified to analyze mufflers for multicylinder compressors but some different methods must be used. It yields results which are sufficiently accurate and detailed for design purposes and it is easy to see results of varying muffler parameters.

Additional data, such as pressure at input or output of any section and muffler input impedance can easily be read out.

In summary, it has been found that this approximate method of muffler analysis is a good compromise between simple methods which provide insufficient output data and more sophisticated methods which are difficult to use, expensive to run, and may provide more output data than a muffler designer can utilize.

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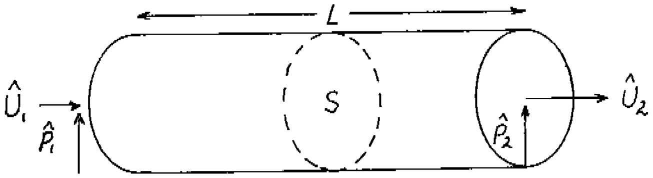
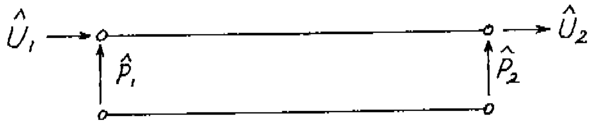


TUBE SECTION
1-A



TRANSMISSION LINE
1-B

$$\hat{P}_1 = P_{1R} + j P_{1I} \qquad \hat{P}_2 = P_{2R} + j P_{2I}$$
$$\hat{U}_1 = U_{1R} + j U_{1I} \qquad \hat{U}_2 = U_{2R} + j U_{2I}$$

COMPLEX VARIABLES
1-C

TRANSMISSION LINE SECTION
FIGURE I

$$\hat{P}_1 = \hat{A}\hat{P}_2 + \hat{B}\hat{U}_2$$
$$\hat{U}_1 = \hat{C}\hat{P}_2 + \hat{D}\hat{U}_2$$

GENERAL NETWORK EQUATIONS IN COMPLEX FORM

2-A

DEFINE : $I = 2\pi FL/c$

$J = \rho c/S$

ρ = GAS DENSITY

C = VELOCITY OF SOUND

F = FREQUENCY (HERTZ)

S = CROSS SECTION AREA

L = SECTION LENGTH

$$P_{1A} = P_{2R}\,COS(I) - U_{2I}\,J\,SIN(I)$$
$$P_{1I} = P_{2I}\,COS(I) + U_{2R}\,J\,SIN(I)$$
$$U_{1R} = -(P_{2I}/J)\,SIN(I) + U_{2R}\,COS(I)$$
$$U_{1I} = (P_{2R}/J)\,SIN(I) + U_{2I}\,COS(I)$$

NETWORK EQUATIONS IN REAL FORM

2-B

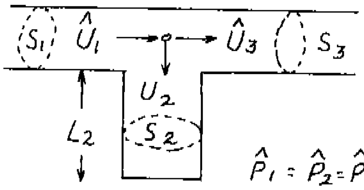
$$\begin{bmatrix} P_{1R} \\ P_{1I} \\ U_{1R} \\ U_{1I} \end{bmatrix} = \begin{bmatrix} COS(I) & 0 & 0 & -JSIN(I) \\ 0 & COS(I) & JSIN(I) & 0 \\ 0 & -(\frac{1}{J})SIN(I) & COS(I) & 0 \\ (\frac{1}{J})SIN(I) & 0 & 0 & COS(I) \end{bmatrix} \begin{bmatrix} P_{2R} \\ P_{2I} \\ U_{2R} \\ U_{2I} \end{bmatrix}$$

MATRIX FORM

2-C

DEVELOPMENT OF MATRIX EQUATIONS

FIGURE 2

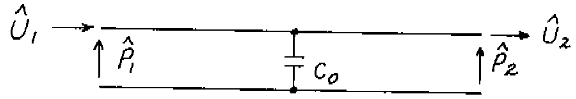


$$\hat{P}_1 = \hat{P}_2 = \hat{P}_3$$
$$\hat{U}_1 = \hat{U}_2 + \hat{U}_3$$

$$\begin{bmatrix} P_{1R} \\ P_{1I} \\ U_{1R} \\ U_{1I} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -(\frac{1}{J_2})TAN(I_2) & 1 & 0 \\ (\frac{1}{J_2})TAN(I_2) & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} P_{3R} \\ P_{3I} \\ U_{3R} \\ U_{3I} \end{bmatrix}$$

SHUNT SECTION

FIGURE 3



$C_0 = V/(\rho c)^2$

V = VOLUME = LS

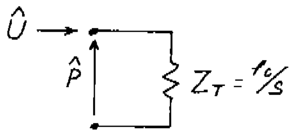
$\omega = 2\pi F$

$$P_{1R} = P_{2R} \qquad P_{1I} = P_{2I}$$
$$U_{1R} = U_{2R} - \omega C_0 P_{1I}$$
$$U_{1I} = U_{2I} + \omega C_0 P_{1R}$$

$$\begin{bmatrix} P_{1R} \\ P_{1I} \\ U_{1R} \\ U_{1I} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -\omega FC_0 & 1 & 0 \\ \omega FC_0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} P_{2R} \\ P_{2I} \\ U_{2R} \\ U_{2I} \end{bmatrix}$$

LUMPED CAPACITANCE MATRIX

FIGURE 4



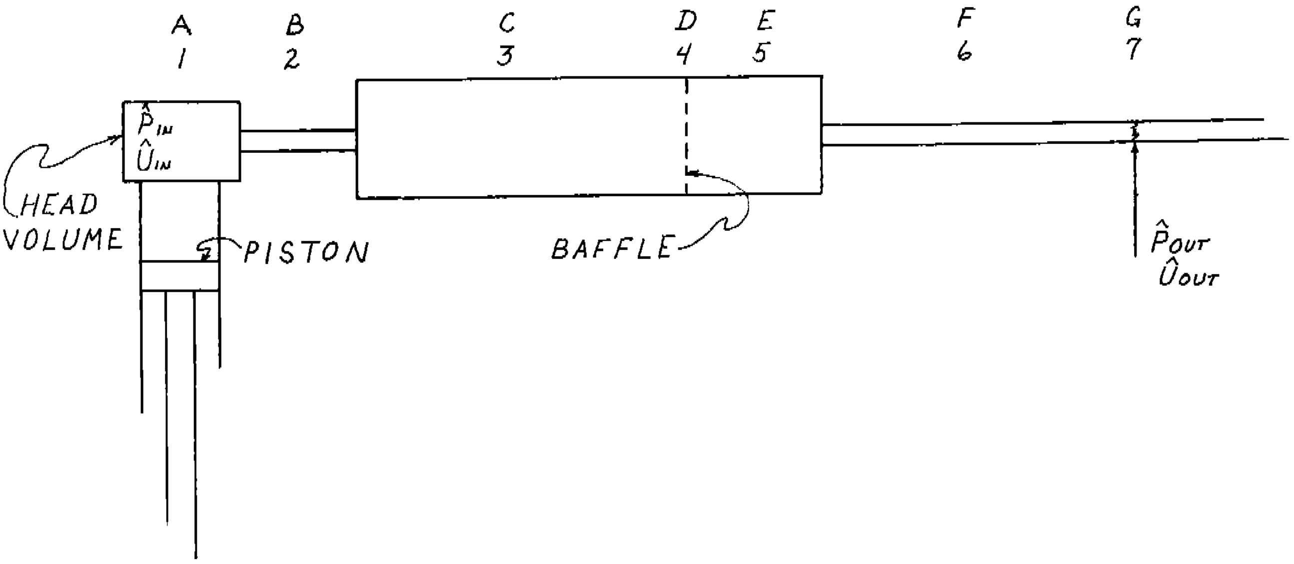
LINE TERMINATED IN CHARACTERISTIC IMPEDANCE

$U_R = P_R\,(S/\rho c)$
$U_I = P_I\,(S/\rho c)$

CHOOSE $\hat{P} = 1 + J0$

$$\begin{bmatrix} P_R \\ P_I \\ U_R \\ U_I \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ S/\rho c \\ 0 \end{bmatrix}$$

TERMINATION MATRIX FIG. 5

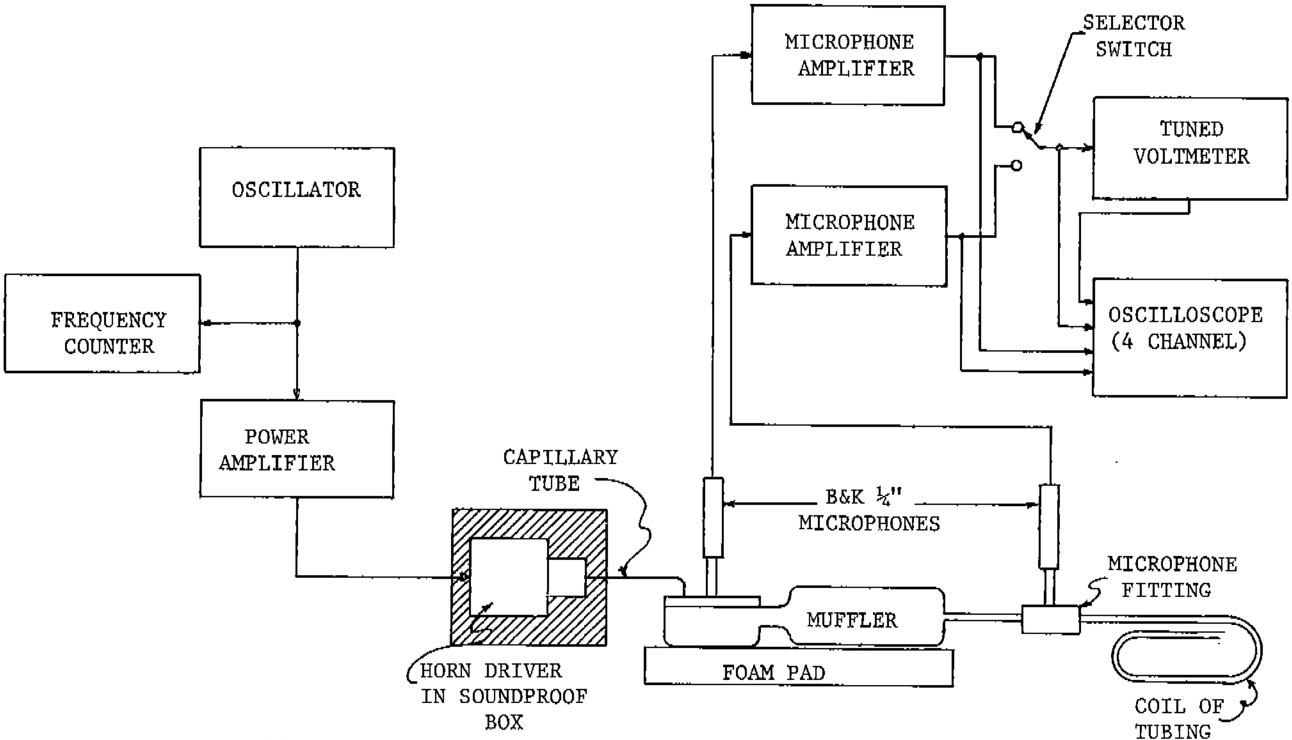


SECTION NO.	1	2	3	4	5	6	7
LETTER	A	B	C	D	E	F	G
TYPE	LUMPED CAP	TRANSMISSION LINE	TRANSMISSION LINE	TRANSMISSION LINE	TRANSMISSION LINE	TRANSMISSION LINE	TERMINATION

$$\begin{bmatrix} P_{INR} \\ P_{INI} \\ U_{INR} \\ U_{INI} \end{bmatrix} = \begin{bmatrix} A \end{bmatrix} \begin{bmatrix} B \end{bmatrix} \begin{bmatrix} C \end{bmatrix} \begin{bmatrix} D \end{bmatrix} \begin{bmatrix} E \end{bmatrix} \begin{bmatrix} F \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ S7/\rho_7 c_7 \\ 0 \end{bmatrix}$$

TYPICAL MUFFLER AND COMPUTER MODEL

FIGURE 6



MUFFLER MEASUREMENT ARRANGEMENT
FIGURE 7

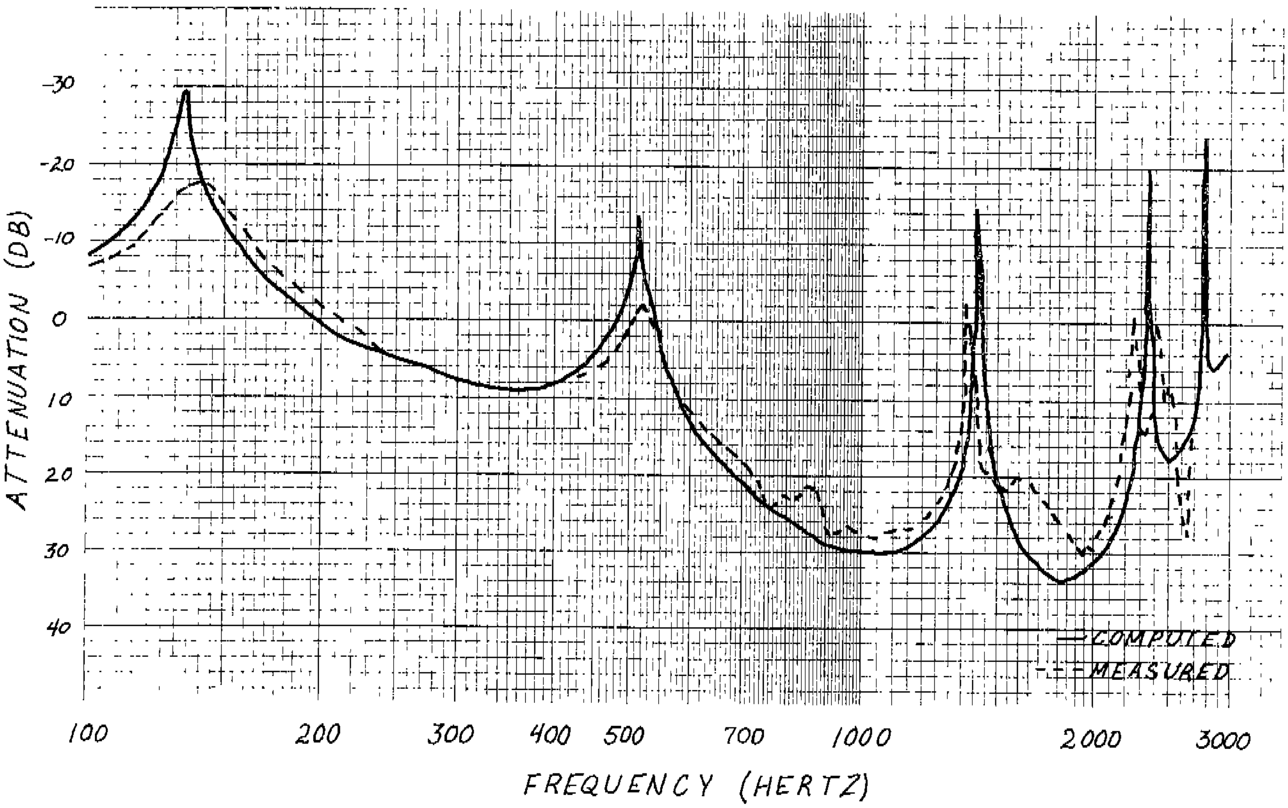


FIGURE 8