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AN APPROACH TO EVALUATE THE ACOUSTICAL CHARACTERISTIC OF SILENCERS USED IN HERMETIC COMPRESSORS FOR HOUSEHOLD REFRIGERATION

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1. ABSTRACT

One of the causes of the acoustic excitation of the housing of the hermetic compressor for household refrigeration is the periodic variation of the pressure of the gas which is contained by the compressor shell. This is mainly due to the opening and closing movement of the suction valve which generates a pressure field on the internal surface of the housing. For this reason efficient silencers must be used to achieve the maximum attenuation of the amplitude of the pressure wave which propagates itself through the suction line of the compressor.

In this paper you will find the main results obtained in setting up an efficient and reliable mathematical model to evaluate the acoustical characteristics of silencers in order to properly design the mufflers of hermetic compressors.

2. INTRODUCTION

When describing the acoustic features of a silencer, three different methods of investigation can be adopted [1]:

1. The Transmission Loss (*TL*)
2. The Insertion Loss (*IL*)
3. The Level Difference (*LD*)

The Transmission Loss is the difference between the levels of the input and output power of a silencer connected to an anechoic termination.

$$TL = 10 * \log \left| \frac{S_i A_i^2}{S_o A_o^2} \right| \quad (1)$$

where A_i and A_o are the pressure values of the sole input wave in the inlet and outlet sections (S_i , S_o) respectively. The insertion Loss is defined as the difference between the acoustic power radiated without a silencer and that with the silencer:

$$IL = 10 \log \frac{W_1}{W_2}$$

where subscripts 1 and 2 denote the system without silencer and with the silencer respectively. It requires prior knowledge or measurement of the internal impedance of the source.

The Level Difference is the pressure level difference between a point at the inlet and a point at the outlet of the silencer.

$$LD = 20 \log |p_i / p_o|$$

where p_i and p_o indicate the r.m.s. pressure at the inlet and outlet respectively.

In the first part of the paper the mathematical framework of the transmission loss numerical computing procedure is briefly summarized. It is essentially based on the four pole parameter representation. Afterwards the experimental technique of the two microphones method is extensively explained together with the experimental setup used to carry out the transmission loss determination test. A case study is finally described in the last part of the paper.

3. THE NUMERICAL APPROACH

From a theoretical point of view a silencer acts as an acoustic filter and the two physical quantities, pressure and velocity, at the inlet and outlet are related by the following transfer matrix

$$\begin{Bmatrix} p_i \\ v_i \end{Bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{Bmatrix} p_o \\ v_o \end{Bmatrix} \quad (2)$$

where the four parameters T_{ij} can be easily evaluated numerically imposing the boundary conditions of a closed ended pipe ($v_o = 0$) and then those of an open ended pipe ($p_o = 0$).

$$T_{11} = \frac{p_i}{p_o} \Big|_{v_o=0} \quad T_{12} = \frac{p_i}{v_o} \Big|_{p_o=0} \quad T_{21} = \frac{v_i}{p_o} \Big|_{v_o=0} \quad T_{22} = \frac{v_i}{v_o} \Big|_{p_o=0}$$

Pressure and velocity at the inlet (i) of the silencer can be written as the sum of an incident wave, pressure A , and of a reflected wave, pressure B :

$$p_i = A_i + B_i \quad (3)$$

$$v_i = \frac{A_i - B_i}{Y} \quad (4)$$

where Y is the impedance associated with a progressive wave.

At the outlet (o) the same relations are valid except that B_o can be set to zero when using an anechoic termination:

$$p_o = A_o + B_o = A_o$$

$$v_o = \frac{p_o}{Y} = \frac{A_o}{Y}$$

(3) and (4) are used to solve the pressure value on the inlet duct of the incident wave:

$$A_i = \frac{p_i + Y * v_i}{2}$$

Which, when substituting the value of p_i and v_i obtained from (2) and dividing by A_o , gives:

$$\frac{A_i}{A_o} = \frac{1}{2} [T_{11} + T_{12}/Y + T_{21}Y + T_{22}] \quad (5)$$

substituting (5) into (1):

$$TL = 20 * \log \left[\left(\frac{S_i}{S_o} \right)^{\frac{1}{2}} \frac{1}{2} \left(T_{11} + \frac{T_{12}}{\rho c} + T_{21} \rho c + T_{22} \right) \right] \quad (6)$$

where $\rho c = Y$ and c is the speed of the sound in the gas with density ρ .

This final formula allows the numerical evaluation of the Transmission Loss of a silencer having different inlet and outlet sections using a simulation code [3] employing the boundary elements technique BEM in the variational formulation [4].

On the other hand - experimentally - expression (1) or its equivalent formulation (1.a) is used and the equivalence is guaranteed by the hypothesis of an anechoic termination which must be physically realized during the experiment.

In the BEM method, the acoustic characteristics of the domain of interest are defined and the boundary is modelled with shell type elements. Two different approaches can therefore be utilized, the collocation and variational methods. These two approaches both use the same integration method [3] for the calculation of the sound pressure in the domain of

interest, but they differ in their method of calculation of the integration parameters. The collocation approach calculates the pressure and speed on all the mesh nodes and integrates these values; the variational method calculates, for each node of the mesh, the pressure and velocity difference through the surface which defines the domain and utilizes these values for the integration. The open tube conditions have been modeled by imposing zero pressure on the output nodes.

4. THE EXPERIMENTAL APPROACH

From an experimental view-point it is easier to determine the characteristics of a muffler for a hermetic compressor by determining its LD index [4]. The frequency values by which this index is at a minimum indicate that the input pressure is the same as, or even less than, the output pressure, i.e. that the sound wave has not undergone attenuations. The aforesaid can be verified when the frequency values are around the natural frequencies of the silencer.

Discarding the effect of the load to the source generated by the silencer and the temperature gradient, the IL index is equal to the LD index.

Concerning the Transmission Loss the two microphone method can be used for any silencer when the outlet duct is provided by an efficient anechoic termination.

When applying this technique three microphones are needed and the basic formula which gives the final result is the following relation [1]:

$$TL = 10 \log \frac{S_{AA}(f_i)}{S_{33}(f_i)} \quad i = 1 \dots N \quad (1.a)$$

where S_{AA} , S_{33} are the autospectral densities of the incident sound wave of the inlet duct and of the outlet duct, N is a previously determined integer from the Discrete Fourier Transform. A schematic of the experimental apparatus is shown in figure 1, where at points 1, 2 and 3 microphones are positioned to measure the sound pressure of the acoustic wave propagating along the duct.

The discrete function $S_{33}(f_i)$, which is determined experimentally, is limited by the ground noise value and has no zeroes. On the other hand, $S_{AA}(f_i)$ has to be evaluated by solving the system of equations:

$$\{Y\} = [M]\{X\}$$

where:

$\{X\}$ is the four dimensional vector of unknowns S_{AA} , S_{BB} , C_{AB} and Q_{AB}

S_{AA} is the autospectral density of the incident wave,

S_{BB} is the autospectral density of the reflected wave,

C_{AB} and Q_{AB} are the real and imaginary part of the cross-spectral density between the incident wave and the reflected wave,

$\{Y\}$ is the four dimensional vector of the measured quantities S_{11} , S_{22} , C_{12} , and Q_{12} , at microphones 1 and 2 of the inlet duct,

$[M]$ is a 4x4 matrix which in the absence of gas flow has the simple following form, when the origin of the reference system is set at the point of discontinuity of the acoustic impedance and the z coordinate axis is oriented along the direction of the duct from the inlet to the outlet:

$$\begin{Bmatrix} S_{11} \\ S_{22} \\ C_{12} \\ Q_{12} \end{Bmatrix} = \begin{bmatrix} 1 & 1 & 2 \cos(kz_1) & 2 \sin(2kz_1) \\ 1 & 1 & 2 \cos(2kz_2) & 2 \sin(2kz_2) \\ \cos k(z_1 - z_2) & \cos k(z_1 - z_2) & 2 \cos k(z_1 + z_2) & 2 \sin k(z_1 + z_2) \\ \sin k(z_1 - z_2) & -\sin k(z_1 - z_2) & 0 & 0 \end{bmatrix} \begin{Bmatrix} S_{AA} \\ S_{BB} \\ C_{AB} \\ Q_{AB} \end{Bmatrix}$$

where k is the wave number and z_1 and z_2 are the coordinates of the microphones measured from the origin. This matrix is obtained from the equations that give the spectral densities at points 1 and 2 using the spectral functions of the incident and reflected sound wave propagating along the duct. The solution for every frequency of the foregoing algebraic system gives the value of S_{AA} .

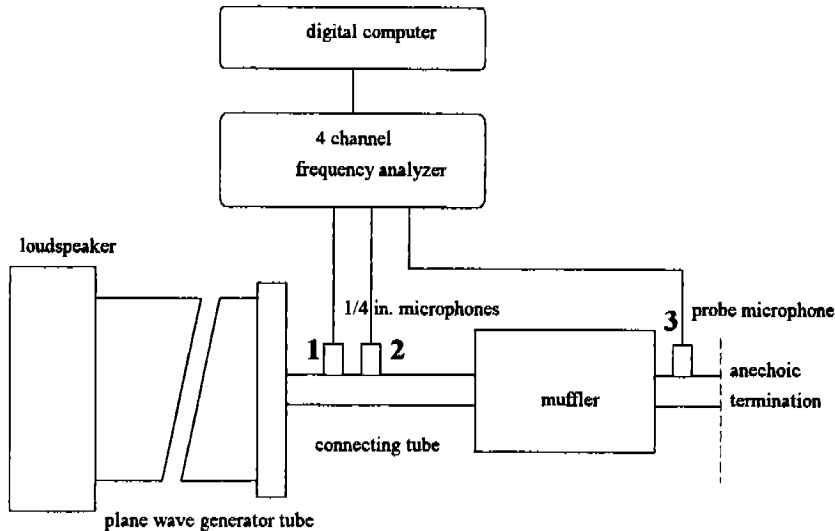


Figure 1. Experimental setup schematic

In order to carry out the experimental tests to determine S_{11} , S_{22} , C_{12} , and Q_{12} the silencer to be tested was connected to a plane wave generator tube having a length of 1270 mm and a diameter of 50 mm as shown in figure 1. The input and output pressures have been measured using 1/4 in. microphones, phase matched, and a four channel narrow band frequency analyser.

The pressure curves have been determined by generating a random frequency sound wave of constant amplitude and measuring, in a stationary condition, the sound pressure in the inlet and outlet ducts of the silencer under test. Experiments were carried out at ambient temperature (24° C) with no air flowing through the tube. TL curves can be reckoned for a different gas from air knowing the speed of sound ratio. The introduction of the connecting tube (length 25.5 mm and internal diameter 6 mm, figure 1) to match different diameters of the inlet duct of the silencer caused sensible perturbation in the autospectral density of the incident wave S_{AA} . To prevent this error happening, the transfer function of the connecting tube for the sole incident wave was measured and used to correct S_{AA} . Figure 2 shows the comparison among numerical, analytical [5] and experimental results for a cylindrical silencer [4] used as a standard sample. As can be seen, the results are in good agreement, especially for the frequencies of TL curve minimum values.

5. A CASE STUDY

How to design effective silencers is well documented in the literature [5] so it seems an easy task to design a silencer for hermetic compressors. Unfortunately, the big difficulty with small compressors is that the silencer must also be small and yet effective. Small size silencers, with an external shape well fitted to the compressor geometry, must be designed to be effective and efficient. Often the only degree of freedom that is left is the internal part of the silencer that must be carefully designed to optimize its performance. In the following a case study is described of an actual plastic muffler that has been developed in our laboratories for R134a compressors to be produced in Verdichter Oe (Austrian factory). The plastic muffler originally designed with an external shape consistent with the compressor geometry is shown in figure 3. It has neither internal ducts, nor sectors. It is a pure expansion silencer. Figure 4 shows the comparison of its numerical and experimental TL curves. The graph shows that performance is sufficiently good but the TL has a steep decrease around 3150 Hz (1600 Hz in R134a). The insertion of a resistive duct at the outlet of the silencer generates a decrease of the highest peak with an increase of the TL at high frequency as shown in figure 5. Finally a sector is inserted. Such sector has a special shape and is fixed in a previously optimized position of the cavity of the muffler. The

comparison between numerical and experimental results is shown in figure 6. As can be seen, the sector introduces resonances that cause a TL decrease at low frequency compensated by an increase of the TL through a wide range frequency. Throughout each step a very good agreement between theory and test, both numerical and experimental, was achieved. This fact allowed a better understanding of the influence of the various geometrical parts of a muffler and a greater confidence in the numerical method employed.

6. CONCLUSION

This paper tries to summarize what has been done in the attempt to optimize the acoustic performance of plastic mufflers for small hermetic compressors. Numerical and experimental methods have been devised to cope with the task, they proved to be reliable and in a good agreement with theory. This will allow their use in the more difficult future task of modelling mufflers in the presence of flowing gas.

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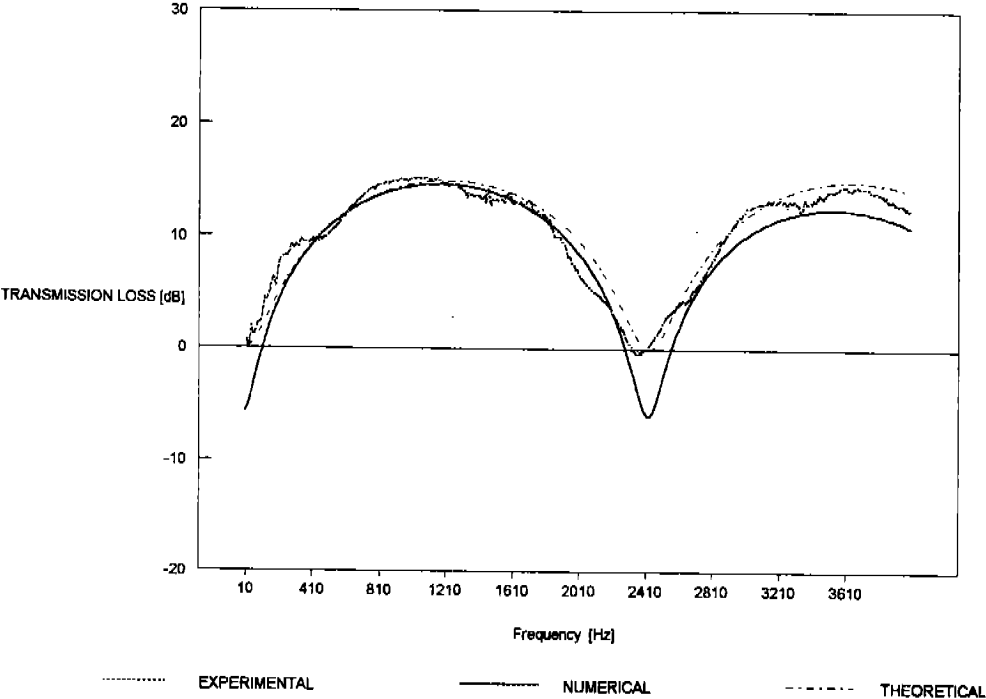


Figure 2. TL curves for cylindrical standard shape silencer

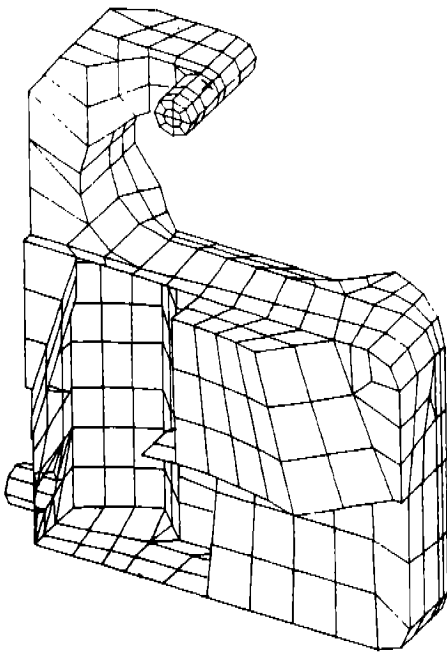


Figure 3. Pure expansion silencer BEM.

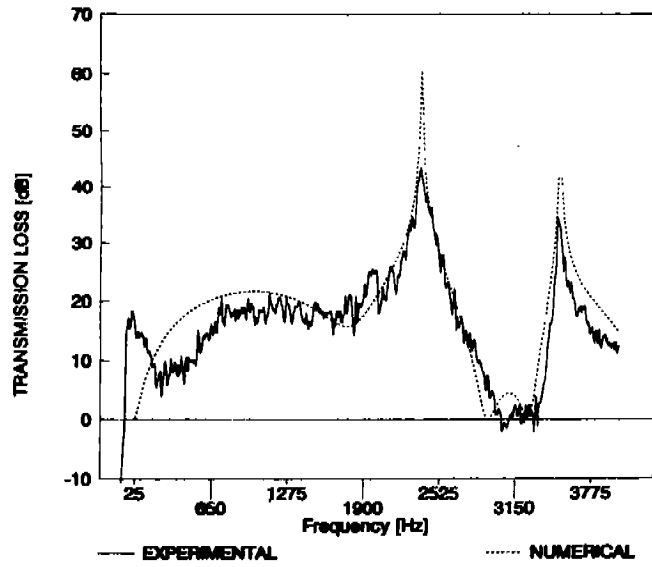


Figure 4. TL curves of the pure expansion silencer.

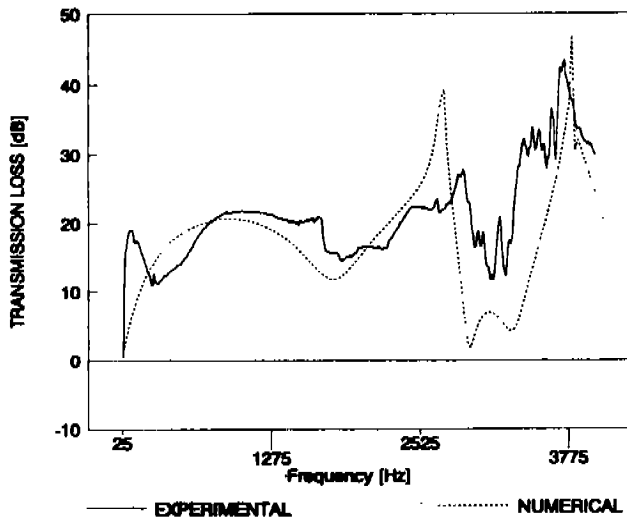


Figure 5. TL curves of the silencer with inlet duct.

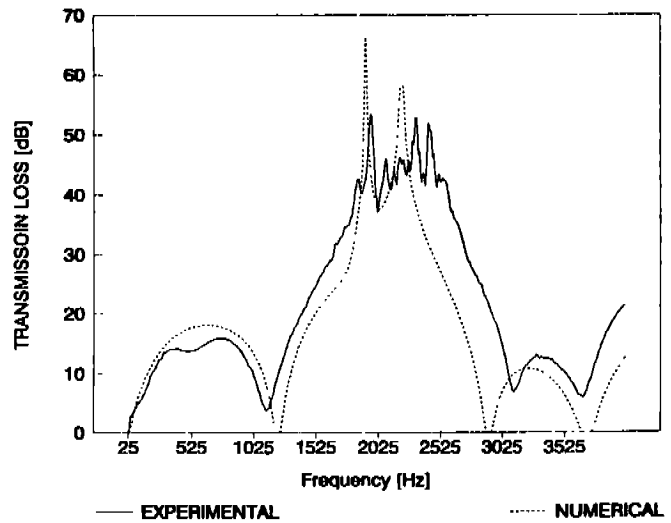


Figure 6. TL curves of the silencer with inlet duct and sector.