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Acoustics of Suction Mufflers with Multiple Chambers

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ABSTRACT

In recent years there has been a growing focus on reducing the suction noise from hermetic household compressors. One approach is to reduce the transmitted sound power through the suction muffler at particular frequencies. In order to better control the acoustic performance of the muffler, a large variety of muffler designs have emerged. Most notably is the appearance of mufflers with two or more chambers which are often connected in series.

In this study, the acoustic effects of introducing multiple chambers in series are investigated by use of boundary element and transfer matrix methods. General conclusions are given on the acoustic performance of mufflers with identical and different chambers in series.

1. INTRODUCTION

During the design process of suction mufflers the design engineer is often confronted with the problem of confining the muffler within an enclosure of limited size. This limitation can conflict with some of the design criteria, for instance, those of high acoustic attenuation for all dominating resonances and source frequencies. This work solely focuses on the acoustic performance of multi-chamber mufflers with axisymmetry and it is motivated by the observation that a high number of chambers can improve the overall acoustic performance. Furthermore, only non-dissipative configurations with multiple chambers in series are considered.

At Danfoss, the acoustic performance of new muffler designs is assessed by use of experimental methods and the boundary element (BE) method (Ciskowski and Brebbia, 1991). However, in order to make the investigation as general as possible, a large variety of muffler geometries need to be considered. Experimental and BE methods are tedious and time consuming, and hence they are unsuitable for such an investigation. However, one-dimensional methods, which assume plane wave propagation, offer a good alternative to the aforementioned methods. The transfer matrix (TM) method is well suited for mufflers with axisymmetry and multiple chambers in series. For a thorough and detailed introduction to this theory, the reader is referred to the book by Munjal (1987). In this study, the insertion loss (IL) and transmission loss (TL) are used as acoustic performance parameters.

The organization of this paper is as follows: in Section 2 the acoustic performance of mufflers with identical chambers is investigated by use of the BE method. The insights made in Section 2 will serve to better comprehend the observations in the latter sections. In Section 3 the TM method is used to calculate the performance of randomly parameterized muffler geometries. In these calculations, the total volume of the mufflers is kept constant i.e. independent on the number of chambers. The reported performance parameters are the average values of an ensemble of randomly generated geometries.

2. MUFFLERS WITH IDENTICAL CHAMBERS IN SERIES

Figure 1(a) shows the cross sectional view of the parent muffler element from which the mufflers are constructed. The elements are axisymmetric and the symmetry axis is indicated by the horizontal dotted line. The muffler element has an extended inlet and outlet of length L_1 and L_3, respectively. The total length of the element is $L_{elem} = L_1 + L_2 + L_3$. The multi-chamber mufflers are generated by joining the elements along the symmetry axis; see Figure 1(b). Throughout this paper, the diameters of the expansion chamber and inlet and outlet tubes are invariant. For the IL calculations, a constant velocity source is assumed and the muffler is allowed to radiate into free space. In this section a multi-domain direct BE method is used (COMET/Acoustics, 2005).

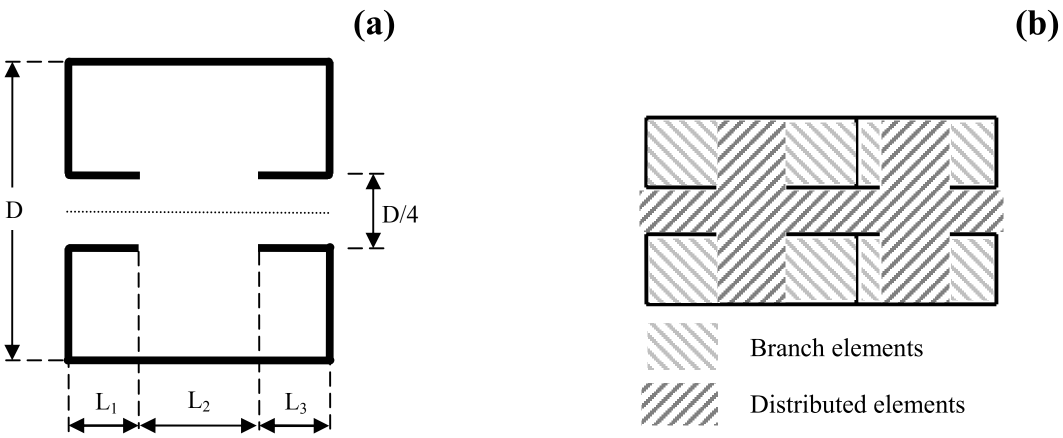

Figure 1: Cross-sectional view of the muffler element: (a) parent element and (b) combination of two elements and their sub-division into branch and distributed elements.

Figure 2 shows the IL of three mufflers with N identical chambers with relative dimensions: $D = L_{elem}$ and $L_1 = L_3 = L_2/2 = L_{elem}/4$. In this case the total length (and volume) of the muffler increases proportional with the number of chambers. It is seen, that at low wave numbers the IL is dominated by troughs, which correspond to an increased power transmission relative to that of the source without the muffler. Inspection of the IL reveals that the number of troughs equals the number of chambers. The increased power transmission is due to resonances of the Helmholtz type. For all mufflers, the lowest resonance is characterized by having a global maximum of the particle velocity in the inlet tube. In addition, the chambers have high pressure magnitudes relative to that in the inlet tube. The next resonances are various combinations of high particle velocities in the internal tubes and high pressures in the chambers i.e. they can be regarded as internal resonances. Around the highest Helmholtz resonance, the IL curves start to increase and a local maximum is reached at essentially identical wave numbers. Most notably, however, is the observation that an increase in the number of chambers is accompanied by an overall increase of the IL.

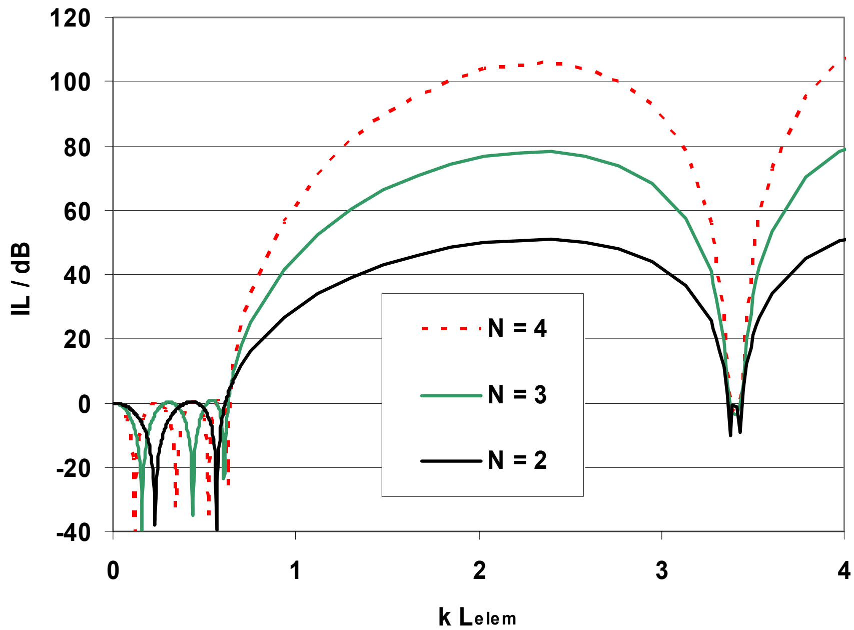

Figure 2: Insertion loss of mufflers with N identical chambers: N=2, 3 and 4. Each muffler chamber has length L_{elem}.

In the above example, the total length was allowed to increase with the number of chambers. Another example would be to consider multi-chamber mufflers with identical total length L and consequently the size of the chambers will decrease with an increasing number of chambers. Figure 3 shows such an example, where the muffler has N chambers and total length L. The remaining design parameters are given by: D = L/2, $L_1 = L_3 = L/16$ and $L_2 = L\ (1/N - 1/8)$. When comparing the IL curves (N = 2 and 3) in Figure 2 and 3, it is seen that the IL behaves differently. In Figure 3 some of the resonances nearly coincide. As already mentioned, the lowest resonance only involves the inlet tube and the total volume of the muffler and hence no significant changes in the position of the troughs are expected. Moreover, the 2nd resonance of N = 2 and 3 also coincide. This observation can, in principle, be generalized to the nth resonance for mufflers with N = n, n+1, etc. At higher wave numbers it is seen that the attenuation tends to increase with an increasing number of chambers.

In the case, where a high attenuation is desirable at low wave numbers, it is important to note that the attenuation is forced down in the vicinity of the troughs. Consequently, the presences of many chambers make it difficult to obtain high attenuation at low wave numbers. This can for instance be a problem around the first couple of acoustic resonances of the compressor cavity.

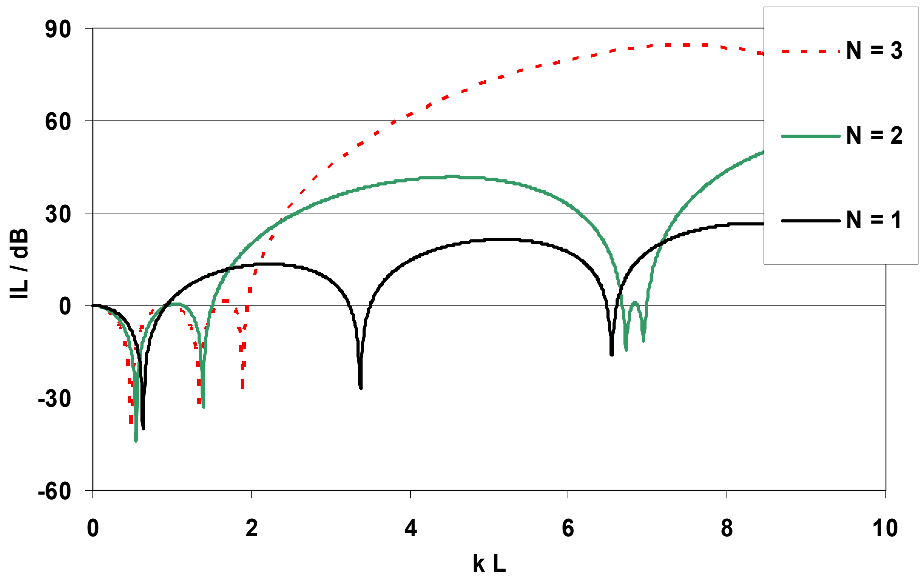

Figure 3: Insertion loss of mufflers with N chambers: N = 1, 2 and 3. All mufflers have a total length L.

3. MUFFLERS WITH DIFFERENT CHAMBERS IN SERIES

In this section the assumption of identical chambers is relaxed and the acoustic calculations are performed by use of the TM method.

3.1 Transfer matrix method

The TM method is implemented according to the theory presented by Munjal (1987). The model is formulated in terms of branch and distributed elements; Figure 2(b) indicates the sub-division into these elements. The TM method has been tested against the BE method and it was found that end corrections of the extended tubes were very important in order to obtain a good correspondence at the Helmholtz resonances. Furthermore, an end correction of the branch elements was needed. In this case, the end correction was chosen to be a frequency independent 2nd order Taylor series in L_1 or L_3. The radiation impedance at the end of the inlet tube is that seen by an opening on an infinite flange. High attenuation phenomena are found in the situation where resonances occur in the branches. Around these resonances, the IL and TL of the TM method has a poor resemblance with those obtained by use of the BE method. Figure 4 shows the IL for a two-chamber muffler similar to that displayed in Figure 1(b). The branch resonance manifests itself by a sharp peak in the IL. In Figure 4, two TM calculations are shown: one where the reflection coefficient R is unity at the termination of the branch and one where it is less than unity. The two curves are nearly identical except for the disappearance of the peak with R < 1.

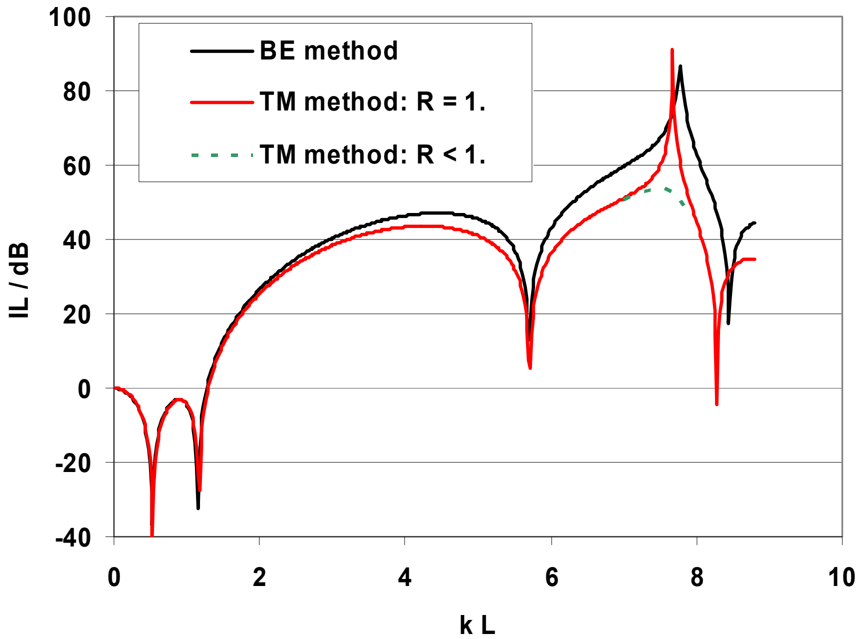

Figure 4: Insertion loss of a two-chamber muffler using the BE and TM methods.

3.3 Muffler performance calculations on randomly parameterized geometries

The randomly parameterized muffler geometries are generated in the following parameter space: (a) $1/3 \leq \mathrm{Min}(L_{elem})/\mathrm{Max}(L_{elem}) \leq 1$ and (b) $1/3 \leq (L_2 / L_{elem}) \leq 1$, where $\mathrm{Min}(L_{elem})$ and $\mathrm{Max}(L_{elem})$ denotes the minimum and maximum length of the chambers, respectively. The lengths of the chambers and the corresponding lengths of the extended tubes are generated by random numbers with a uniform distribution. For each of the geometries, the IL and TL are calculated (on a dB scale) and the average of the ensemble of geometries is calculated. At this point it should be noted, that peaks have been removed by introducing absorption at the termination of the branch. The removal, which has been discussed in the previous section, is performed so that the peaks do not dominate the ensemble average. The primary interest of this investigation is to analyze the overall behavior of the performance parameters and hence it should not be dependent on some sort of mathematical singularity. Experiments on our mufflers indicate that such peaks are considerably broadened by absorption.

Figure 5 and 6 show the average values of the IL and TL, respectively. The values are obtained from 10^3 random geometries and the number of chambers are N = 1 to 5. In Figure 5, it is seen that at high wave numbers the IL increases with an increasing number of chambers. However, the relative increase seems to decrease for every added chamber. The IL for N = 4 is only slightly below that of N = 5. At very low wave numbers, all IL are nearly identical, this indicates that significant interference effects are absent below a certain cut-on wave number. The single chamber muffler has the lowest cut-on wave number and it increases with an increasing number of chambers. In the wave number region between these two trends, the IL is highest for single-chamber mufflers and is lowered when increasing the number of chambers. This effect can be explained by the observations made from Figure 3, namely, that the wave number position of the troughs tend to increase with an increasing in number of chambers. This effect will, in turn, decrease the IL in the vicinity of the troughs. For the TL the same sort of observations can be made. There is, however, a very important exception at high wave numbers: the TL increases by almost the same amount (in dB) for each added chamber. This means that the design engineer might reach different conclusions when employing either IL or TL. However, the IL is the only parameter which is based on the transmission of sound power, and therefore the design engineer should use the IL for the final analysis.

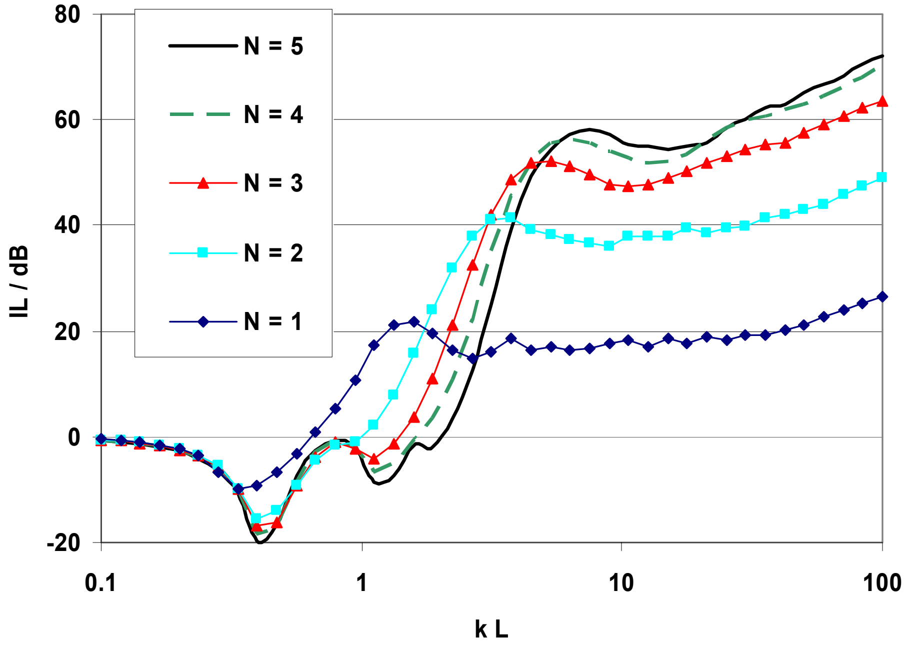

Figure 5: Averaged insertion loss of randomly parameterized muffler geometries with N = 1 to 5 chambers.

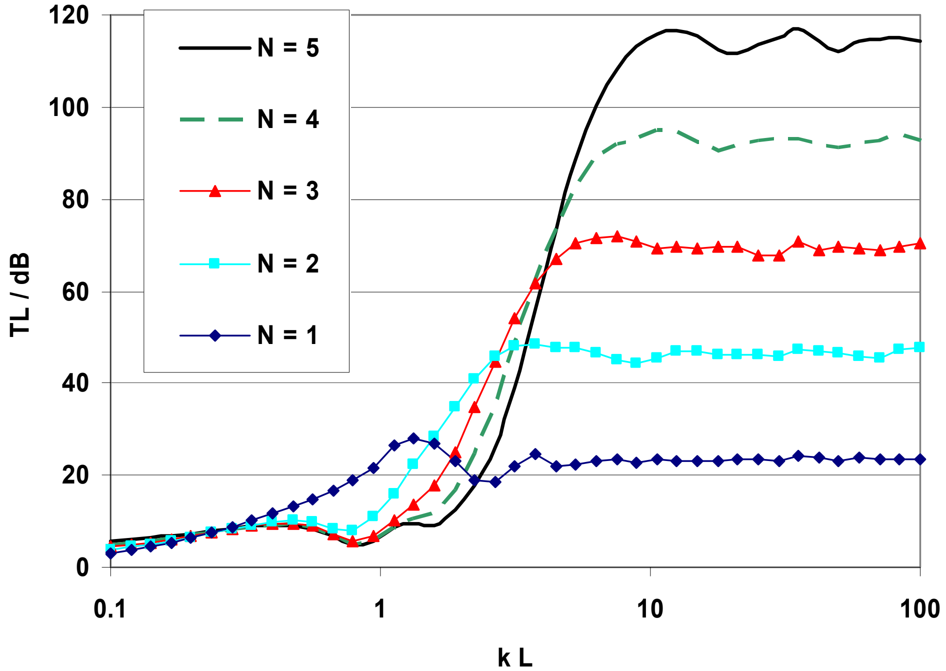

Figure 6: Averaged transmission loss of randomly parameterized muffler geometries with N = 1 to 5 chambers.

5. DISCUSSION

In this study only plane waves in the TM method has been assumed. The cut-on of higher-order modes have not been considered. In the situation in which the boundary conditions are axisymmetric the cut-on of the first radial mode would appear at k L = 38. Therefore, some reservation on the validity of the results in the high wave number region is justified. In addition to this, there is a poor resemblance between BE and TM methods around the sharp peaks of the IL; see Figure 3.

6. CONCLUSIONS

In Section 3 of this paper, the acoustic performance of axisymmetric multi-chamber mufflers with identical total volumes has been investigated. When increasing the number of chambers, the following behavior has been observed:

- At low wave numbers: the IL and TL are nearly equal below a certain cut-on wave number. The lowest cut-on wave number is seen for the single chamber muffler.
- At high wave numbers: the IL and TL are increasing and the IL tends to converge to a maximum obtainable value.
- At medium wave numbers: the IL and TL are decreasing, which is caused by Helmholtz type resonances.

NOMENCLATURE

BE	boundary element	N	number of chambers
IL	insertion loss	TL	transmission loss
k	wave number	TM	transfer matrix

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