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BOUNDARY ELEMENT ANALYSIS OF THE MUFFLER FOR THE NOISE REDUCTION OF THE COMPRESSORS

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ABSTRACT

Mufflers have been an important element in engineering practice, which reduce various kinds of noises because of its general capability of application. Many kinds of methods are applied to analyze their characteristics and to expect their performances.

Some of the methods, conventionally, are based on the plane wave assumption for its simplicity. The shortcoming of this approach is its limitation of analysis ranges and parameters related with analysis and response.

This research employs boundary element method for the analysis of mufflers, which considers 3 dimensional scattering effects. This method can be used more appropriately for the analysis of mufflers because its analysis ability for higher frequency range which can be decided by the element size of the model.

And, experimental analysis using reciprocity theorem is conducted to verify the analysis results.

1. INTRODUCTION

Electrical efficiency like EER (Energy efficiency ratio) has been the most important factor for the development of the refrigerator for the past decade. But, present preferences of consumers toward noiseless products have made noise and vibration more important factor for any kind of electricity. Furthermore, consideration of noise and vibration is more crucial to the refrigerator manufacturer because refrigerators are located indoor and turn on all the day.

Noise can be categorized with structure-borne noise and air-borne noise, the first one is propagated by the vibrating structures like diaphragm of the speaker, and the second one is related with the resonance of the hermetic cavity or flow.

Compressors are predominant source of noise and vibration because of the severe compression process. Sources of the noise and vibration inside the compressor compose such a diverse categories like impact of valves, pulsating flowing of the compressed refrigerant, mechanical resonance and electrical excitation that it is very difficult to classify specific sources according to the measured noise.

Even though sources of noise and vibrations are generated by such a diverse reason, noise generated by a compressor cannot be propagated without exciting the shell of the compressor because the compressor is hermetic type.

One of those excitations to the shell is generated at the suction process in which the refrigerant is flowed into the cylinder because high-speed collision of the suction valve is inevitable to compress the refrigerant [1-3].

Sound wave generated by the impact of valves excites the cavity of refrigerant and then, the resonances of the cavity make the shell vibrates. Therefore, suction muffler is essential for the reduction of the noise and vibration of the compressor.

Along with reduction of noise, efficient suction rate should be considered at the design of the muffler because the shape of muffler is deeply related with flow of refrigerant and total efficiency of the system.

Transfer matrix method based on the plane wave sound propagation theory has been used most frequently because of its simplicity of use and clarity of theory. But, this approach has limitations to problems of complex geometry and frequency range of its analysis. Finite element analysis and boundary element analysis approaches are, recently, conducted to avoid those limitations.

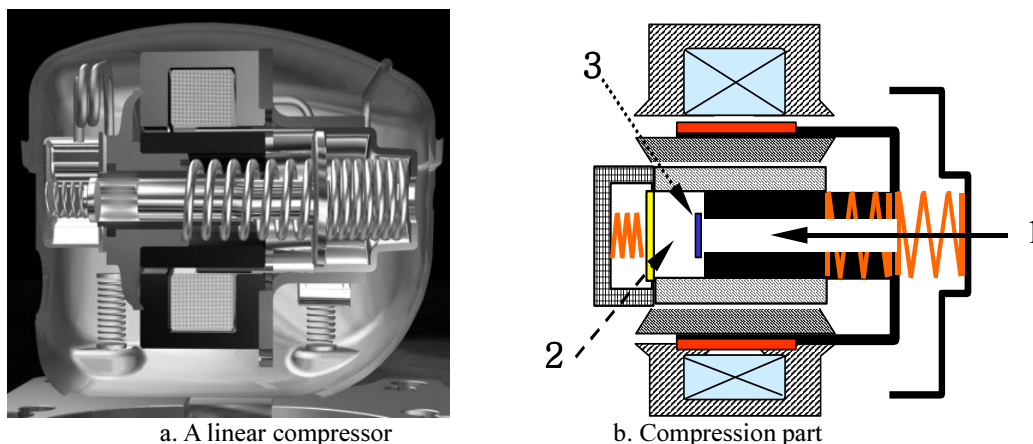
This research use boundary element analysis to predict the performance of the suction muffler and the results of the analysis is validated with experiments based on the acoustic reciprocity theory.

2. ANALYSIS OF THE MUFFLER

Various kind of noise source generated by equipment, such as fans, blowers, and internal combustion engines is controlled through the use of mufflers. Many researchers studied muffler to improve the understanding of it. Theory of the exhaust type mufflers can be applied to the intake type because both types of mufflers are developed using the same principles and design methods [4].

Schematic diagram of given system, the linear compressor, fig.1 (a) shows inner parts of the linear compressor and fig.1 (b) represents the compression part and flow direction.

Sound wave generated by the impact of suction valve is propagated through the suction muffler and excites the cavity which is filled with refrigerant. And, resonances of the cavity are one of the main sources of the noise from the compressor.



a. A linear compressor

1. Flow direction 2.Cylinder 3. Suction valve

Fig. 1 Schematic diagram of the compressor

The most frequently used performance criteria are the insertion loss (IL), noise reduction (NR), and transmission loss (TL). All three use a sound pressure level difference as a performance indicator.

Transmission loss (TL) of noise generated by the impact of valves during the suction process can be formulated as eq.(1) with parameters of the simple geometry of muffler based on the plane wave approach [5],

$$TL = 10 \log[1 + 1/4(M - 1/M)^2 \sin^2(kl)] \quad (1)$$

where M; ratio of cross sectional area, l ; element length

Figure 2 shows the example of TL diagram according to Eq. (1).

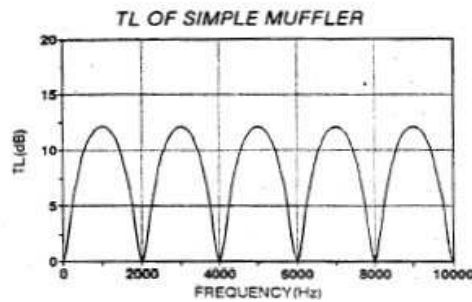


Fig.2 Calculation of TL by plane wave theory

Regardless of the inherent advantages of the plane wave approach such as simplicity in modeling and clarity of the basic theory, this method is not suitable for the problems of complex geometry and, furthermore, analysis result of high frequency reason is not confident.

Finite element analysis method has been studied for the replacement of the transfer matrix for the complex geometry and for enlargement of the analysis range. Even though, FEM provides confident results for room acoustics problem such as separated cavities, difficulties still arise for the problems at which enclosures are connected with free boundary by openings.

3. BOUNDARY ELEMENT ANALYSIS

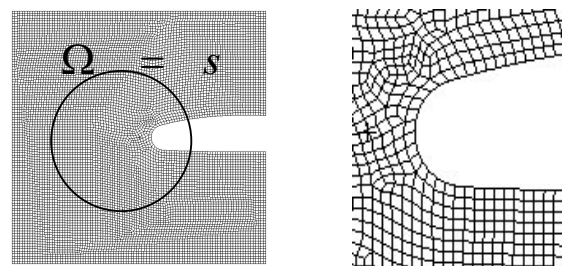
The main feature of the boundary element method is that the governing equations are reduced to contain only surface integrals, and all the volume integrals are removed from the equations by mathematical manipulation as follows^[6]

$$\int_S (\varphi \frac{\partial \psi}{\partial \mathbf{n}} - \psi \frac{\partial \varphi}{\partial \mathbf{n}}) dS = \int_V (\varphi \nabla^2 \psi - \psi \nabla^2 \varphi) dV \tag{2}$$

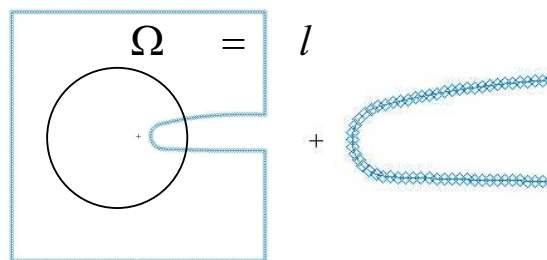
where ∇^2 : laplacian operator, \mathbf{n} : normal vector

This transformation of domain of calculation decreases the order of the problem as well as the element numbers which are important factor for the computer computation.

Fig.3 gives examples of the FEM and BEM modeling for the simple 2-dimensional problems.



a. Finite element modeling



b. Boundary element modeling

Fig. 3 Finite and boundary element modeling

Table.1 compares the element numbers of the two methods.

Table. 1 Number of the nodes and elements

Method	Element	Node
BEM	481	487
FEM	9484	9725

Along with the reduction of problem, boundary element analysis can avoid the difficulty about the free boundary having openings with the environment if indirect boundary element analysis is applied.

4. ACOUSTIC RECIPROcity

There are some international standards to measure the performance of a muffler or a silencer^[5]. One of them, two microphone method is the most popular methods to measure the performance criteria such as the insertion loss (IL) and transmission loss (TL).

For this method, sound level difference should be measured at the both entrances against the outside acoustic source as shown in fig.4.

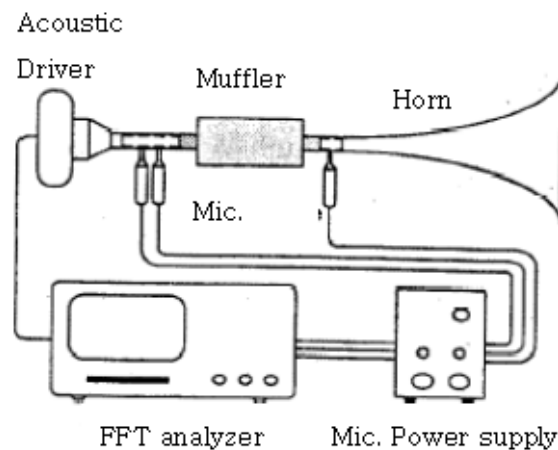


Fig. 4 Experimental setup

The criteria for the performance of a muffler can be measured easily in an operation test. But there are some situations that the performance should be predicted before integrating the muffler element into the whole system. Further more, it is very difficult to distinguish acoustic characteristics of the muffler from the radiated noise because in operating condition it is difficult to define source and transmission paths.

For this reason, most of the method employ white noise source outside the muffler element.

But, mufflers of domestic refrigerator compressors have compact shape and the source of valve impact is located at the inside of the muffler structure. In this case, experimental setup like fig. 4 is impossible to apply because of the small dimension of the structure.

In this research, acoustic characteristics of the muffler are measured with the experiment based on the acoustic reciprocity theorem to avoid such a difficulty in conventional experiment.

Assuming two velocity potential Φ_1 and Φ_2 related with sound pressure, $p = -j\omega\rho_0\Phi$, particle velocity, $\bar{u} = \nabla\Phi$, eq.(1) gives an other form^[7]

$$\int_S (\Phi_1 \nabla \Phi_2 - \Phi_2 \nabla \Phi_1) \cdot \hat{n} dS = \int_V (\Phi_1 \nabla^2 \Phi_2 - \Phi_2 \nabla^2 \Phi_1) dv \tag{3}$$

where \hat{n} : unit outward normal to S.

The relation between acoustic source and field point can be given from eq.(3)

$$\int_S (p_1 \bar{u}_2 \cdot \hat{n} - p_2 \bar{u}_1 \cdot \hat{n}) dS = 0 \tag{4}$$

Eq.(4), one of the principle of acoustic reciprocity, states that if the locations of a small source and field point are interchanged in an unchanging environment, the received signal will remain the same.

Fig. 5 shows an example of the experimental results regarding the acoustic reciprocity. The problem constitutes source point in a box having one small opening and field point outside the box. And, the source point and field point are interchanged.

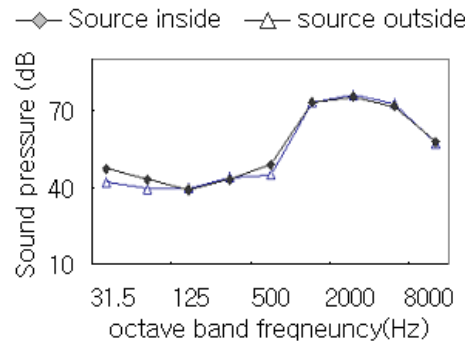


Fig. 5 Acoustical reciprocity test

5. VALIDATION WITH EXPERIMENT

Analysis method of transfer matrix and experimental method of two microphone can be easily applied for measurement of insertion loss (IL) or transmission loss (TL) of many kind of mufflers. But, when mufflers of complex geometry are connected with complex geometrical boundary condition and source condition, employment of those methods are difficult to employ such as in the given problem.

Thus, this research conducted sound pressure measurement experiment based on the acoustical reciprocity.

In the given muffler structure, the main source is located inside the muffler itself where it is impossible to locate the acoustic source such as horn speakers.

Thus, using very thin probe microphone source points is replaced with field point. And, white noise source is generated outside the muffler and excite the acoustic field.

Fig.6 represents boundary element analysis and experimental results of the suction muffler using reciprocity theorem.

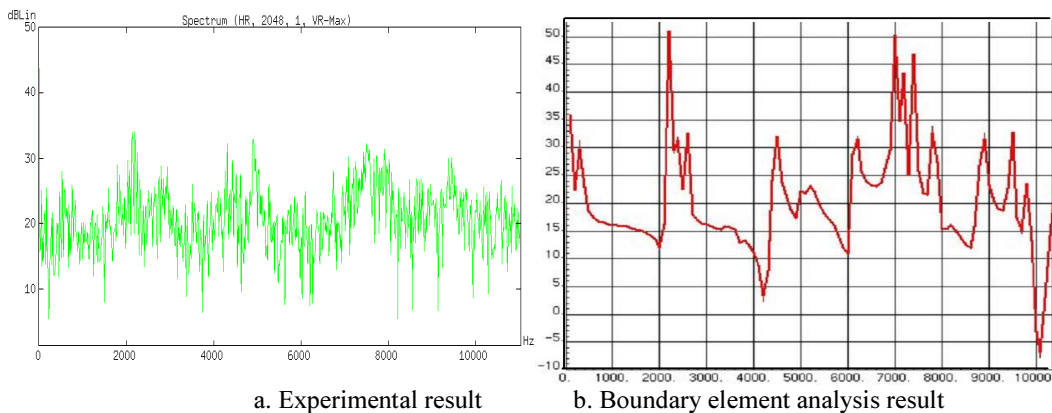


Fig. 6 Experimental result and BEA

6. CONCLUSIONS

Boundary element analysis is applied for prediction of the acoustic characteristics and performance of the domestic refrigerator compressors. The result of the BEM analysis is validated with experiment based on the acoustic reciprocity theorem.

For the problems with complex geometry, 3 Dimension boundary element analyses provide a confident analysis results up to high frequency reason. And, for the muffler which has its sources in itself, experiment using acoustic reciprocity theorem is conducted to disclose its acoustic characteristics and performance. Proposed experimental setup is an efficient method and can be the replacement of two microphone methods for the problem of given conditions.

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