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AN ANALYSIS OF THE HERMETIC RECIPROCATING COMPRESSOR ACOUSTIC SYSTEM

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ABSTRACT

The purpose of this paper is to understand the reciprocating compressor's acoustic system through a simplified model that is composed of a simple expansion muffler and a square room. Many designers should deal with between muffler and shell design when there is a problem of cavity noise, especially in household refrigerator. Therefore, there should be an analysis how the acoustic system works.

In the case of shell redesign, the amount of oil and shell temperature range should be considered to select a safe region between two rotational harmonic frequencies. A case study is shown for a full compressor FEM model to predict the cavity resonance frequencies, and the results from full FEM model and from experiment are compared. Also, some effective ways for the cavity resonance noise are suggested for several cases.

INTRODUCTION

The acoustic system of a general hermetic reciprocating compressor is composed of shell cavity and muffler volume. Generally, the shell cavity means the volume except muffler, mechanical parts, and remained oil from the total hermetic enclosure.

The reason why the major concerns are focused on the cavity resonance noise in the hermetic reciprocating compressor is the high radiation efficiency in comparison with the other noises when the compressor is installed in a refrigerator. In most cases, the first three cavity modes cause the noise problem.

Since the operation temperature of refrigerators varies, the shell cavity resonance frequencies change with the temperature. Fig.1 shows how a cavity resonance frequency moves with shell temperature range from 40°C to 70°C(R134a). As it is shown in the figure, the noise level of 468Hz(8^{th} rotational harmonic) moves from 32dBA to 43dBA. In the case of Fig.1(a) the cavity mode is about 24Hz away from 8^{th} rotational harmonic and Fig.1(b) shows the full resonance between cavity mode and 8^{th} rotational harmonic frequency.

The remained oil amount in shell can be another factor of shell cavity resonance frequencies. Fig.2 shows the experimental results with the change of remained oil amount at constant shell temperature 50°C. The dramatic frequency change region(150~170cc) is around the contact region of the motor end coil and oil surface.

Some studies describe on suction mufflers to reduce the cavity resonance noise[1]. The main idea of the studies is to put the outlet(acoustic point of view) of the suction muffler on the nodal plane of the cavity resonance mode causing high noise level. However, as it is seen in Fig.3, there are three cavity resonance modes having possible resonance with rotational harmonic frequencies. Since the nodal lines(plane) of the cavity modes are rotated about 90 degree one another in three-dimension, it is impossible to put the muffler inlet to nodal plane of all three cavity modes. On the other hand, some other studies on mufflers have reported on the source reduction of cavity resonance noise through new muffler designs[2], [3].

In this paper a focus on how the hermetic reciprocating compressor's acoustic system works and how the muffler and shell cavity are related through a simplified model. Also, what is the effective way to reduce shell cavity noise in various situations.

NUMERICAL ANALYSIS ON SIMPLIFIED MODEL

The transmission loss(TL) is used for a general muffler estimation, which is defined as follows;

$$TL = 20\log\left|\frac{Pi^{+2} A_i}{Po^{+2} A_o}\right| \quad (1)$$

where Pi^+ and Po^+ are incident pressure components at the inlet and outlet of muffler, A_i and A_o are the areas at the inlet and outlet. The TL curve of simple expansion muffler is shown in Fig.4 where the anti-resonance frequency is tuned around 500 Hz for the cavity resonance frequencies. For the calculation of TL, anechoic termination condition is applied at the outlet, and only incident wave components at inlet and outlet are considered for Eq.(1).

A square room for a cavity is shown in Fig.5. The cavity resonance frequencies of the square room are determined by considering the possible cavity resonance frequencies of an actual reciprocating compressor. The first three resonance frequencies are simply calculated as follows;

$$\text{Freq.(Hz)} = c/(2L) \quad (2)$$

where c is the speed of sound and L is the length of the geometry. The frequencies chosen for the calculation are 401Hz, 466Hz, and 486hz, which are checked through SYSNOISE as in fig.5.

The simplified muffler and cavity connected system is composed of the muffler in Fig.4 and the cavity in Fig.5 as shown in Fig.6. The outlet location of the muffler is moved from ① to ④ as in Fig.6 to see if positioning muffler outlet at the nodal line is effective. The outlet position of ① is the center of the bottom left quarter where no nodal lines cross. The outlet positions of ② and ③ are on the height (401Hz)and side(466Hz) direction cavity nodal line. The position of ④ is the nodal point both for height and side direction cavity. The muffler outlet is not positioned at the nodal line of front/back(486Hz) direction cavity in any of the four cases. Since the resonance frequency of the direction is close to the anti-resonance frequency of muffler, we can examine how the muffler works from 480 to 500 Hz range.

For the calculation of the cavity and muffler connected system, SYSNOISE(FEM) is used. The boundary condition around the square cavity surface is all fixed. The rigid body motion at the inlet for all frequency range (white noise) is applied. The incident wave component at the inlet (P_i^+) and at the outlet (P_o^+) of muffler can be derived as follows;

$$P_i^+ = (P_i + \rho C)/2 \quad (3)$$

$$P_O^+ = (P_o + \rho C V^+)/2 \quad (4)$$

where pressure, ρ is density, c is speed of sound , and V^+ is incident velocity component.

The transmission loss(TL) of the muffler in the simplified acoustic system in the frequency range 380Hz to 500Hz is shown in Fig.7. The muffler at position ① does not properly work for cavity resonance since the TL value is low around the cavity resonance frequencies, which means the source of the cavity resonance can never be reduced through the muffler and its outlet position ①. However, positioning outlet to nodal line is very effective. In the case of ④, only front direction cavity effect(486Hz) is shown because its outlet is at the cross point of height and side direction cavity resonance. In order to check again the TL curve, frequency response at the surfaces of cavity's top, back, side, and muffler outlet is calculated as in Fig.8. It shows the same results as in Fig.7 by different expressions. The position ① shows all three cavity modes, but other three position shows only two modes(b, c) or one mode(d). From the simulation results in Fig.7 and Fig.8, we found that the positioning muffler outlet to the nodal line can be an effective way to reduce cavity resonance, but reducing the source of the cavity resonance using pure muffler characteristics is almost impossible.

The problem of the positioning muffler outlet to the nodal line is from the complicated geometry of hermetic reciprocating compressor. There is no all three nodal line cross-section point from the geometry. Another possible way to reduce the cavity is to put a resonator inside the muffler, but it is very hard to tune the frequency of a resonator in the oil and refrigerant mixed surroundings. The possible application of resonator is described in [4] and [5].

A CASE STUDY

For a hermetic reciprocating compressor having high noise level at 400 Hz and 500 Hz(1/3 octave band) in the shell temperature range 38 °C to 70 °C, we applied the muffler outlet position on the nodal line of the height direction cavity. For the front/back and the side direction cavity resonance, we should redesign the shell since there is no robust design point for mufflers and resonators.

For the design of compressor shell in the point of low cavity resonance noise, it is necessary to have the exact information on the amount of oil inside the shell in the operating condition and on the cavity resonance frequency moving range as the shell temperature changes. Also, a safe frequency region where the cavity resonance frequencies are positioned should be considered. The amount of oil in the operating condition can be deduced by comparing the cavity resonance frequencies in the operating condition at a temperature and the oil volume change experiment in air with no compressor running. The exact level of oil in the operating condition do a key role for FEM analysis. The frequencies in the air can be converted by multiplying the ratio of refrigerant's and air's speed of sound. In the case of the shell temperature change, the cavity frequencies move about 7Hz up as the temperature moves 10 °C up. Therefore, the moving range of cavity resonance frequencies is about 22Hz in 38 °C to 70 °C temperature condition. From our experiences, the cavity mode should be about 15Hz away from the rotational harmonic frequencies. The Fig.9 shows the safe region in the shell temperature range. To put the two 22Hz moving cavity frequencies into safe region by the new design of a shell, a fine tuning of FEM model is required.

Fig.12 shows the full cavity model for FEM analysis. The front/bank direction cavity mode is 490 Hz and the side direction cavity mode is 485Hz from the analysis.(R134a at 38 °C). The experiment is carried out in the air to a plastic prototype shell, and the results are shown in Fig.10 and Fig.11in which the frequencies are converted into the same condition of the FEM analysis. The front/bank and side direction cavity modes are 491Hz and 484Hz which are within the 1% error range. Since the safe region of 8th harmonic should be started from 483Hz to 492Hz at 38 °C, the results are satisfied.

CONCLUSIONS

Some important rules are observed through the simplified system ;

1. In the design stage of compressor acoustic system, the outlet of suction muffler should put on the cross point of two cavity modes' nodal line. The remained one cavity mode should be on the safe region between two harmonic frequencies.
2. In the trouble shooting stage for low frequency noise, try to put the suction muffler outlet to the nodal line. If it is impossible to put on the nodal line because of the geometry problem, the shell should be redesigned.
3. The precise information on the shell temperature range and amount of oil in operating condition should be prepared before redesigning the shell.
4. It is impossible to reduce the source of cavity by using pure muffler. However, the effects of resonator are not verified in this paper.

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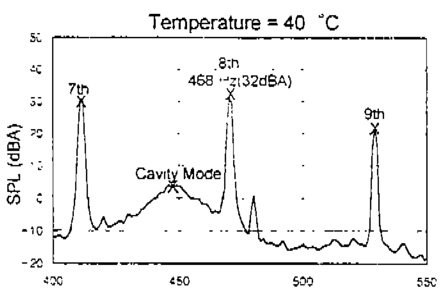
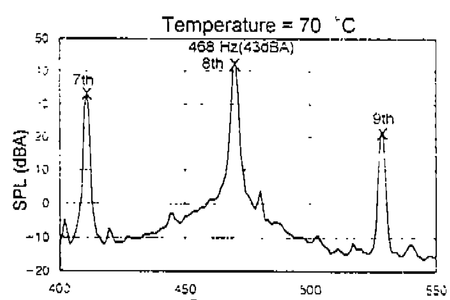


(a) Cavity resonance mode away from 8th



(b) Cavity mode resonance with 8th

Fig1. Cavity resonance shifting with temperature

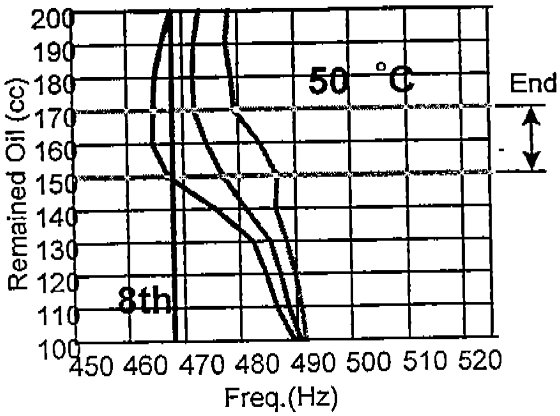
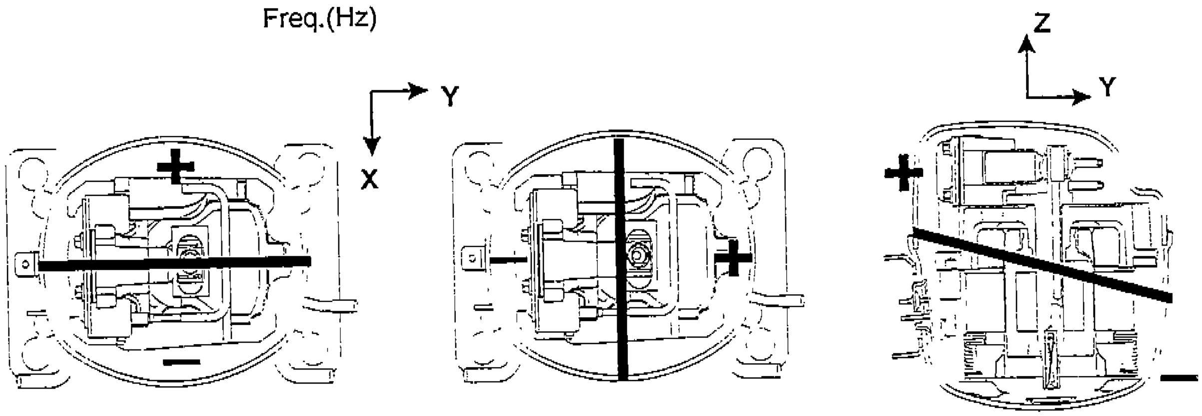


Fig.2 Typical cavity resonance frequency shifting with remained oil volume variation at constant temperature 50 °C (R134a)



(a) Front(X) direc. cavity mode (b) Side(Y) direc. cavity mode (c) Height(Z) direc. cavity mode

Fig3. First Three Cavity Modes in Reciprocating Compressor

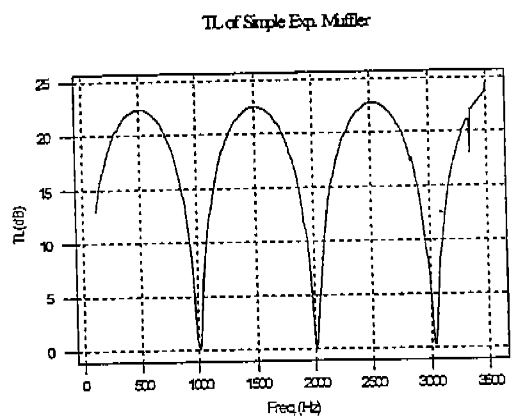


Fig.4 TL of simple expansion muffler (area ratio m=25)

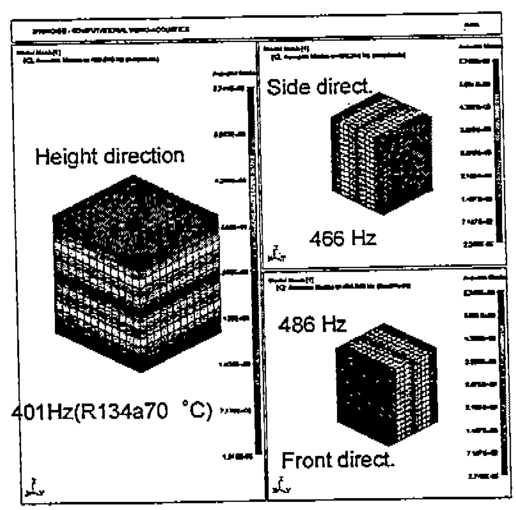


Fig.5 A cavity with the dimension of 182.8mm X 212.5mm X 175.3mm

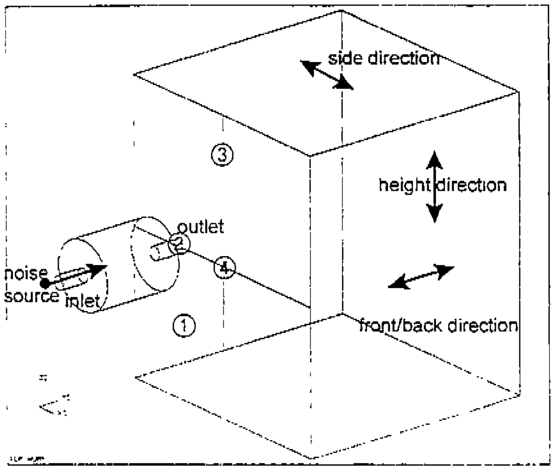


Fig.6 Simplied muffler-cavity connected system

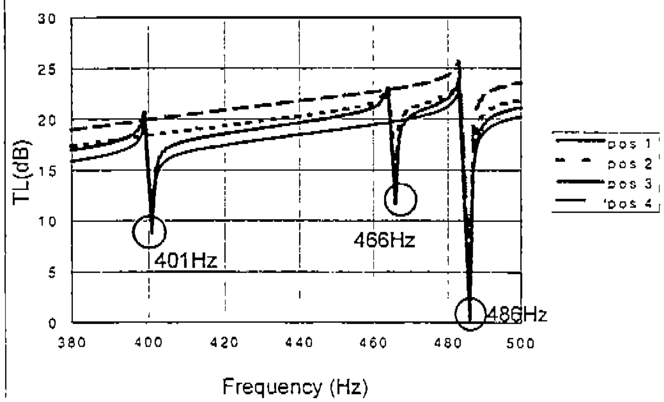
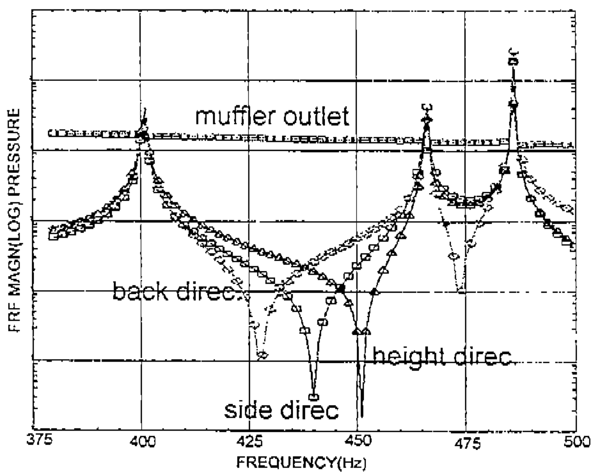
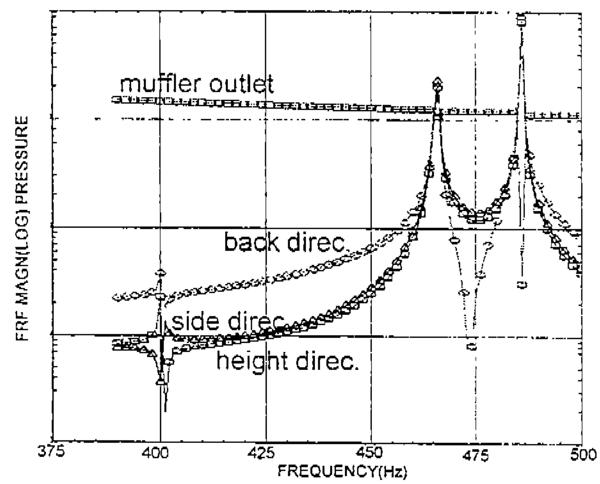


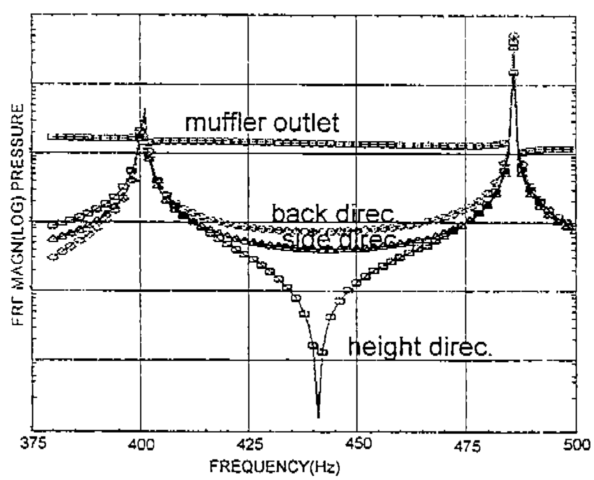
Fig7. Transmission Loss at the outlet positions notified in Fig6.(b) (Frequency range 380 to 500, material :R134a 70 °C)



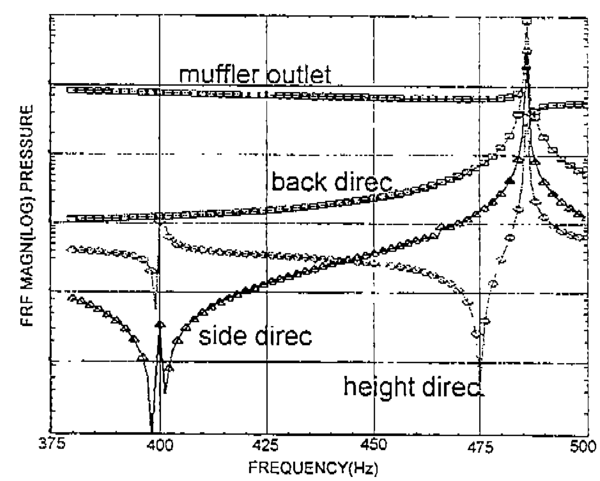
(a) Muffler outlet position at ①



(b) Muffler outlet position at ②



(c) Muffler outlet position at ③



(d) Muffler outlet position at ④

Fig.8 Frequency Response using SYSNOISE(R134a 70 °C)

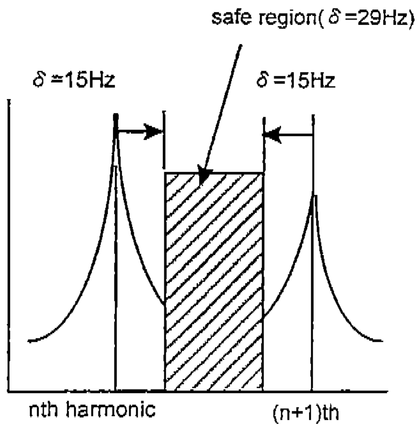


Fig.9 Safe region for cavity resonance

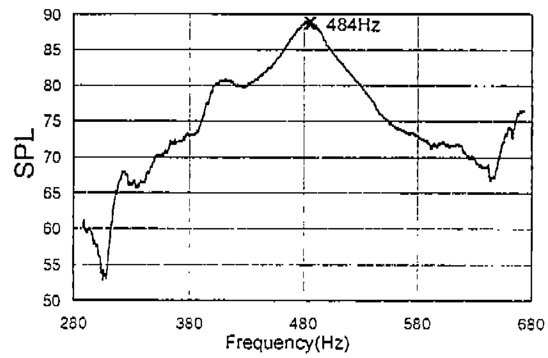


Fig10 Experimental result of side direction cavity mode(R134a 17 °C)

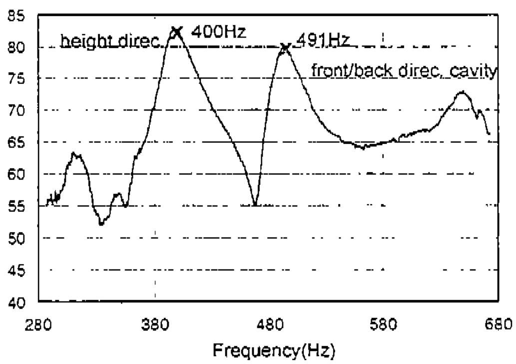


Fig.11 Experimental result of height and front/ back direction cavity mode(Ra134a 17 °C)

Fig.12 Full compressor model for cavity resonance frequency calculation