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## Noise Reduction in Two-Cylinder Rotary Compressor

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### ABSTRACT

We have developed two-cylinder rotary compressor with BLDC motor, hereafter referred to as TBR Compressor, to address the growing concerns over the environment pollution and the energy efficiency. TBR compressor was designed to use R410A refrigerant, so that the damage of ozone layer can be minimized. The concentrated winding BLDC motor was chosen to achieve high efficiency by reducing the power consumption. However, the noise was a big concern over the course of development.

This study was designed to investigate the sources of the noise and how to reduce them. The major noise sources of TBR compressor are divided into 4 big categories, which are investigated by CAE simulation and experimental methods. The modifications are applied to reduce the sound pressure level of each noise sources.

### 1. INTRODUCTION

The strong regulations for environmental protection and energy saving have enforced many compressor makers worldwide to develop the eco-friendly and highly efficient compressor.

One of the approaches to minimize the damage of ozone layer is using R410A refrigerant, despite of the high global warming potential (GWP). However, R410A refrigerant has bigger pressure difference between the suction and discharge comparing to that of R22 refrigerant, which causes big vibration problems. To reduce the vibration of compressor, the two-cylinder pump unit that has 180° phase differences has been generally adopted.

In addition, in order to save energy, motors with variable speeds, such as BLDC motors, have been used to cover the wide ranges in operation related to the load laid on the air-conditioner unit. There are two kinds of BLDC motors. One is a concentrated winding motor and the other is a distributed winding motor. Considering the performance, noise level, control, cost and mass productivity, an adequate motor has been selected for each compressor by makers. Generally the concentrated winding motor shows good performance and can be manufactured easily. But the noise level of concentrated winding motor is very high comparing to that of the distributed winding motor. TBR compressor we have developed uses the 4-pole 6-slot IPM motors as concentrated winding motors.

In this study, we investigated the noise sources in 4 categories and how to reduce the noise. Two of them are related to the motors and the others are related to the natural mode of some parts of the compressors mode. Especially when the harmonic peaks originated from motors resonate with natural modes of some parts, the noise level increases very drastically. CAE simulations, SYSNOISE for acoustic analysis and I-DEAS for structure analysis, and experimental tests have been carried out to demonstrate the noise sources and method to reduce them.

As a result, we were able to reduce the sound pressure level of TBR compressor approximately by 6dB.

### 2. NOISE SPECTRUM ANALYSIS

Fig.1 shows the cross-section of the TBR compressor which runs in a range from minimum 20Hz to maximum 100Hz. Fig.2 shows general noise spectrum of TBR compressor with its operating speed of 70Hz.

The characteristics of noise spectrum can be divided into 4 categories, which are A, B, C and D categories. Table 1 shows that the A, C parts are the harmonics of operating speed and B, D parts are the natural modes of some structures of a compressor. Especially when C part resonates with B or D parts, the noise increases so drastically. It is important to understand the cause of these noises and how to reduce them.

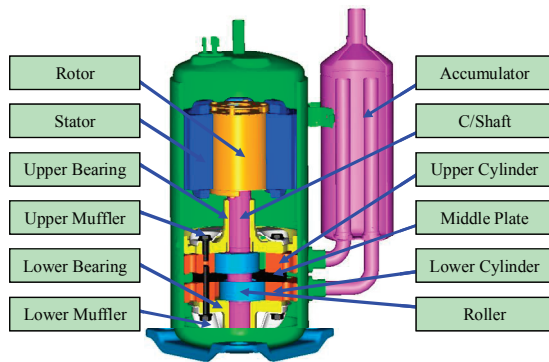


Fig. 1 Cross-Section of TBR Compressor

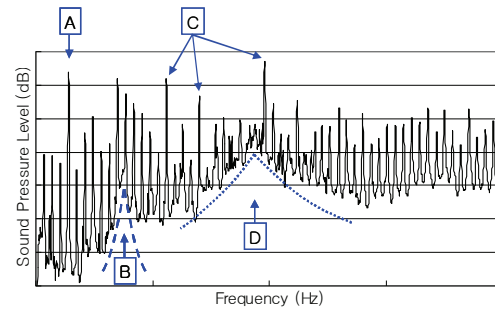


Fig. 2 Noise Spectrum of TBR (Operating speed 70Hz)

Table 1 : Category of Noise Sources

Category	Frequency	Characteristics
A	4-th	Maximum at 70Hz running
B	800Hz	Resonate with each harmonic peaks
C	16-th, 20-th, 28-th	Harmonic peaks of running frequency
D	1.9kHz	Resonate with “C”

### 3. NOISE ANALYSIS OF “A”

#### 3.1 Noise Source Identification of “A”

“A” is the 4-th harmonic peak of operating frequency, the peak level of 4-th harmonics fluctuates up and down with the varying operating frequency. MORIMOTO(2004) showed very well that this noise problem is originated from 4-pole of motor and rotor-c/shaft. When the eccentricity between stator and rotor axis occurs, the unbalanced magnetic force is generated between stator and rotor. The unbalanced magnetic force which depends on the amount of the eccentricity is 4 times of operating frequency and it resonates with the natural frequency of rotor-c/shaft.

Fig.3 shows the first bending mode of rotor-c/shaft solved by finite element methods, the natural frequency is 277Hz. Fig.4 shows that the 4-th harmonic peaks reaches to the maximum at around the operating speed of 70Hz, in which 4-th harmonic frequency is 280Hz. The peak levels of 4-th harmonic changes in proportion to the amount of the eccentricity at each operating speed. So minimizing the eccentricity between stator and rotor axis is one of most effective ways of reducing the 4-th harmonic noise peak. In addition, it would be recommended to change the natural frequency of rotor-c/shaft from 277Hz to above 400Hz to avoid the resonance between unbalanced magnetic force and rotor-c/shaft in the operating ranges.

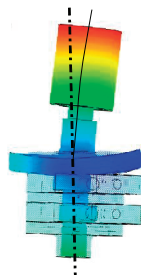


Fig. 3 First Bending Mode of Rotor-C/Shaft

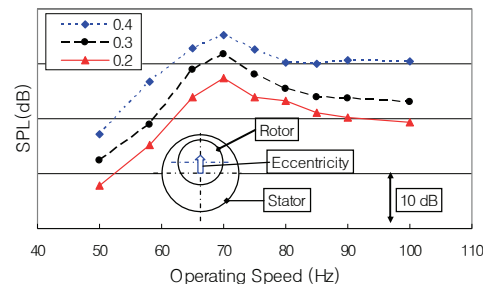


Fig. 4 The 4-th harmonic peak by changing the eccentricity of Rotor-Stator

### 3.2 Reduction of “A”

The modifications of upper bearing and other components that we adapted to change the natural frequency of rotor-c/shaft resulted in the increase of natural frequency from 277Hz to 355Hz with finite element analysis, which shifted the max peak point of 4-th harmonic from 70Hz to 90Hz in operating frequency. Fig.5 shows that the 4-th harmonic is the maximum at 90Hz of operating frequency with the modification, which means that the natural frequency of rotor-c/shaft moves to around 360Hz. But in this trial, we were unable to change the natural frequency of rotor-c/shaft above 400Hz, so that the 4-th harmonic peak noise increased at around 90Hz running. We continuously tried to increase the natural frequency to above 400Hz to avoid the resonance between unbalanced forces and rotor-c/shaft in normal operating range.

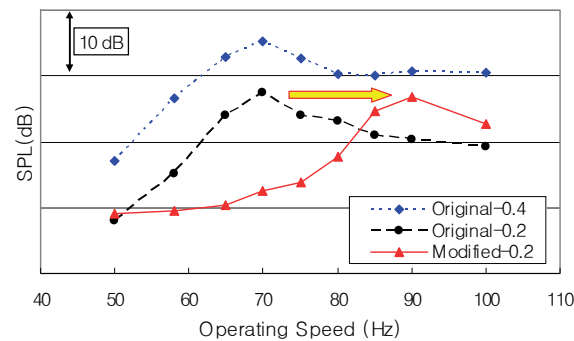


Fig. 5 The 4-th harmonic peak with modifications

## 4. NOISE ANALYSIS OF “B”

### 4.1 Noise Source Identification of “B”

The frequency of noise source “B” in the noise spectrum is almost 800Hz band at this model. When the noise source “B” met the harmonic peaks of fundamental frequency, sound pressure level rose up very sharply. Investigating the noise source “B” is one of main objectives in this study.

The impact hammer test is conducted on the rotor-pump unit at the free-free condition as shown in Fig.6. Fig.7 shows the resultant frequency response function with noise spectrum. The first natural frequency of the rotor-pump unit is at around 800Hz, which is the same in the noise spectrum. In the finite element analysis, the natural frequency of rotor-pump unit is also 824Hz at the free-free condition as shown in table 2.

Table 2 : Natural Frequency of Pump Unit

	Experimental Result	Modal Analysis Result
Pump Unit	800 Hz	824 Hz

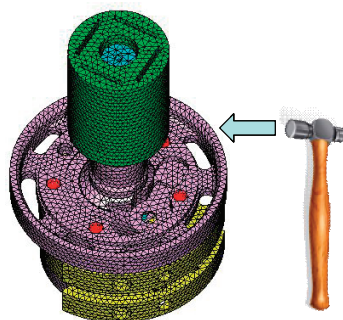


Fig. 6 Impact Hammer Test of Rotor-Pump Unit

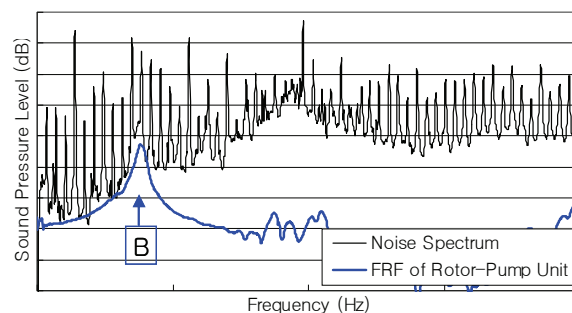


Fig. 7 Comparison of Noise and FRF

## 4.2 Reduction of “B”

To reduce noise, the natural frequency of rotor-pump unit should be moved to higher frequency or removed. But it is not easy to change the natural frequency of rotor-pump unit. So the boundary condition of rotor-pump unit was changed, which includes fixing the rotor-pump unit to the outer shell more tightly.

## 5. NOISE ANALYSIS OF “C”

### 5.1 Noise Source Identification of “C”

Noise source “C” is the 16-th, 20-th and 28-th harmonic peaks of the operating frequency. Fig.8 shows that BLDC motor without pump unit installed in housing has an accelerometer attached to the motor to get the vibration data. The load is put on the motor, and vibration spectrum shows the same increase in 16-th, 20-th and 28-th harmonic peaks as shown in Fig.9 It indicates that 16-th, 20-th and 28-th harmonic peaks come from the motor itself, not from the pump unit or other parts.

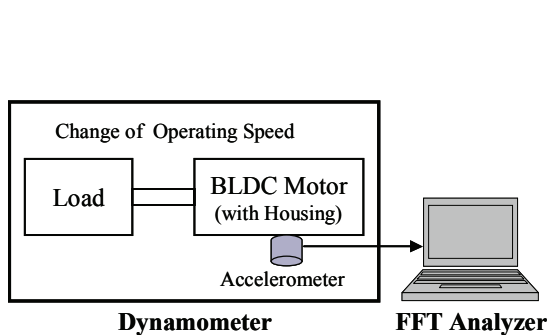


Fig. 8 Vibration Test of BLDC Motor

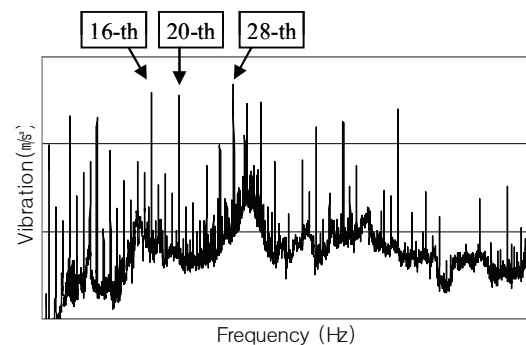


Fig. 9 Vibration Spectrum (Operating Speed 70Hz)

### 5.2 Reduction of “C”

The design of motor core is important in reducing 16-th, 20-th and 28-th harmonics. We developed new type of motor core to verify the reduction of harmonic peaks.

Fig.10, Fig.11, Fig.12 shows that the 16-th, 20-th, and 28-th harmonic peak were reduced with an improved motor core.

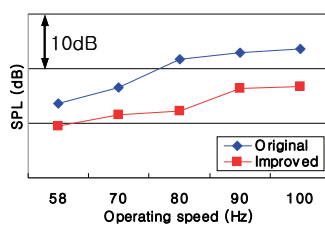


Fig. 10 Noise of 16-th

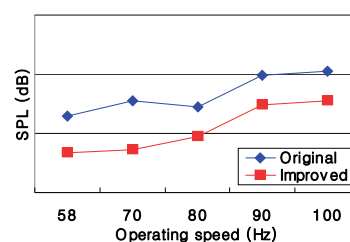


Fig. 11 Noise of 20-th

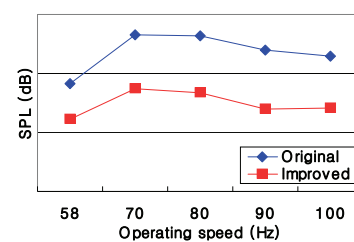


Fig. 12 Noise of 28-th

## 6. NOISE ANALYSIS OF “D”

### 6.1 Noise Source Identification of “D”

Noise source “D” is almost 1.9kHz frequency band, which resonates with 20-th, 28-th harmonic peaks.

The impact hammer test is conducted on the stator alone and the stator with shell. The frequency response function is shown in Fig.13. And the natural mode of stator is shown in Fig.14. Table 3 shows that the first natural frequency of stator is at around 1.9kHz, which is the same band in noise spectrum.

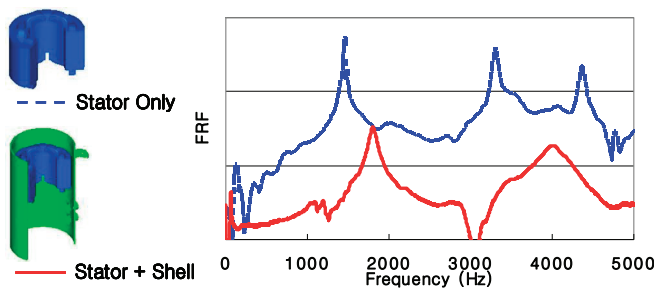


Fig. 13 FRF of stator

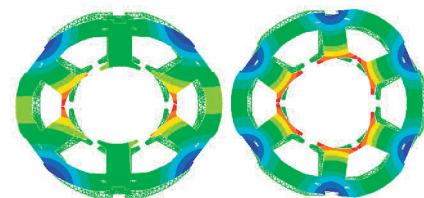


Fig. 14 1<sup>st</sup>, 2<sup>nd</sup> Natural mode of stator

Table 3 : Natural Frequency of Stator

	Experimental Result		Modal Analysis Result	
	1st	2nd	1st	2nd
Stator Only	1460 Hz	3312 Hz	1520 Hz	3435 Hz
Stator + Shell	1830 Hz	4046 Hz	1916 Hz	4168 Hz

### 6.2 Reduction of “D”

Reducing the 1.9kHz noise is difficult. One method is to modify the shape of stator core by increasing the width of yoke and tooth. But this may cause the reduction of slot cavity and coil turns, which lower the efficiency of compressor. Considering that one of main purposes of using the concentrated winding motors is to achieve high efficiency, it is not recommended. The other method is to increase the thickness of outer shell, which results in the increase of the cost of material, it is not recommended, either.

Although the natural mode of stator core in concentrated winding motors is inevitable, the shape of stator core needs to be optimized to the extent that the efficiency does not decrease.

## 7. CONTROL FOR BLDC MOTORS

The last important aspect to reduce the noise is how to control the BLDC motors. The noise spectrum is different by the types of input current signal which are rectangular wave and sine wave. The drive unit for rectangular wave is cheaper than that of sine wave, but contains many high frequency factors by Fourier series and some torque fluctuation in it. On the other hand, sine wave control shows almost zero torque fluctuation and no high orders, but the cost of drive unit is high. Usually sine wave control shows low noise level comparing to that of rectangular wave. The way of current control in TBR compressor was changed to sine wave from rectangular wave. This change reduced the additional motor noise at high frequency band, especially harmonic peaks in 16-th, 20-th, 28-th and the natural mode of stator. Fig.15 shows 2 kinds of current control, which are original and improved ones.

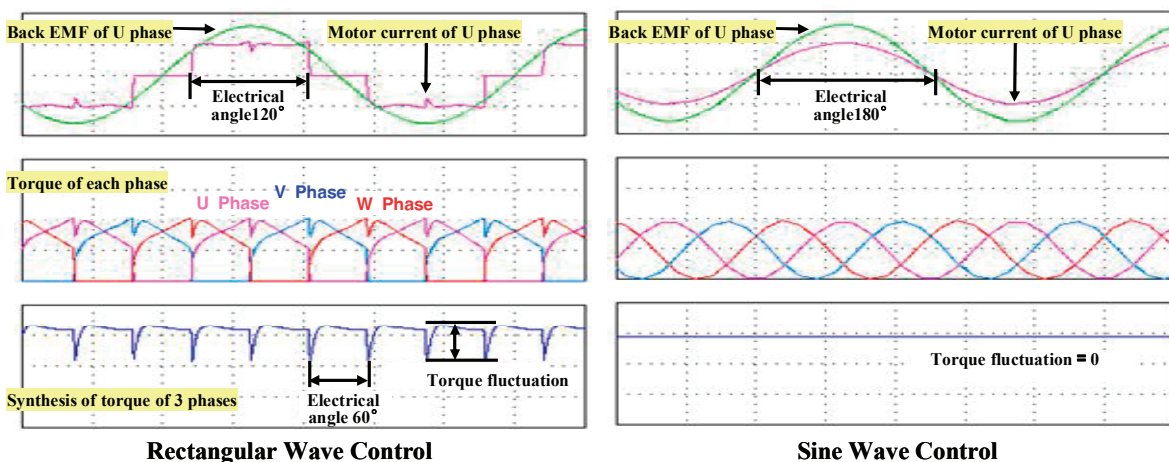


Fig. 15 Rectangular Wave & Sine Wave Controls

## 8. CONCLUSIONS

In this study, the noise sources of TBR compressor using a concentrated winding motor were investigated and reduced to improve the sound quality of TBR compressor with experimental tests and analysis methods. The sound pressure level of TBR compressor was decreased nearly by 6dB, as described in Fig.16.

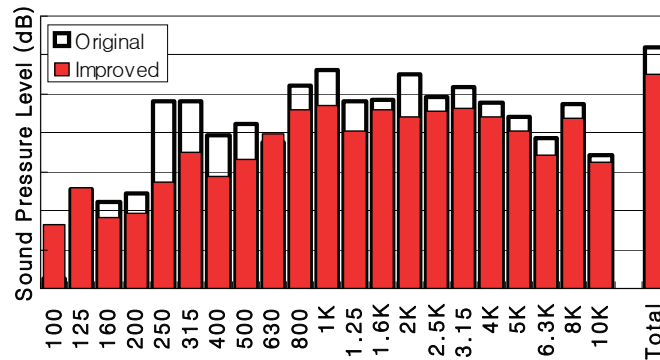


Fig. 16 Sound Pressure Level of TBR at 70Hz running

## REFERENCES

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