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ABSTRACT

The authors have developed a high efficiency, low noise swing compressor with a concentrated winding motor in order to meet energy saving and noise reduction demands for refrigeration and air conditioning equipment.

In order to reduce the noise, the authors conducted a magnetic field analysis and a modal analysis. The results of those analyses showed that the noise was caused by the resonance between the magnetic force of the radial direction components of a concentrated winding motor and the natural frequency of first bending mode of the rotor-crankshaft.
Furthermore, it was found that inhibiting the eccentricity between the rotor rotation axis and the stator core is effective in reducing the magnetic force.

An experiment was conducted to verify the results of the analyses and a reduction in the noise of the compressor was confirmed.

1. INTRODUCTION

There is a growing demand from both the market and from society for increasingly efficient refrigeration and air conditioning equipment that will result in energy savings, from the standpoint of reducing the costs associated with electricity as well as for the prevention of global warming. At the same time, the market also places great importance on noise reduction, from the perspective of residential comfort. It is no exaggeration to say that these fundamental features of refrigeration and air conditioning equipment, namely high efficiency and low noise, are dependent upon the characteristics of the compressor, the key component in such equipment.
By employing a highly efficient proprietary swing compressor mechanism and a concentrated winding motor in a compressor, the authors have increased the efficiency of the compressor. Furthermore, by investigating the cause of the noise through both magnetic field analysis and modal analysis and by verifying the results through an experiment, the authors have succeeded in reducing the compressor noise.
In this paper the authors use analyses and an experiment to investigate the characteristics of the swing compressor with the concentrated winding motor and the cause of the noise in that compressor and then describe in detail how the noise was reduced.

2. FEATURES OF THE HIGH EFFICIENCY SWING COMPRESSOR

2.1 Structure of the compressor

Figure 1 shows a cross-sectional drawing of the swing compressor with the concentrated winding motor. This compressor is made highly efficient by the fact that it employs a swing compressor mechanism and a concentrated winding motor. The swing compressor unit is fixed in the lower part of the housing by spot welding. The stator is shrink fit in the center of the housing. The rotor is shrink fit to the crankshaft and the crankshaft is supported by the journal bearings of the compressor unit.

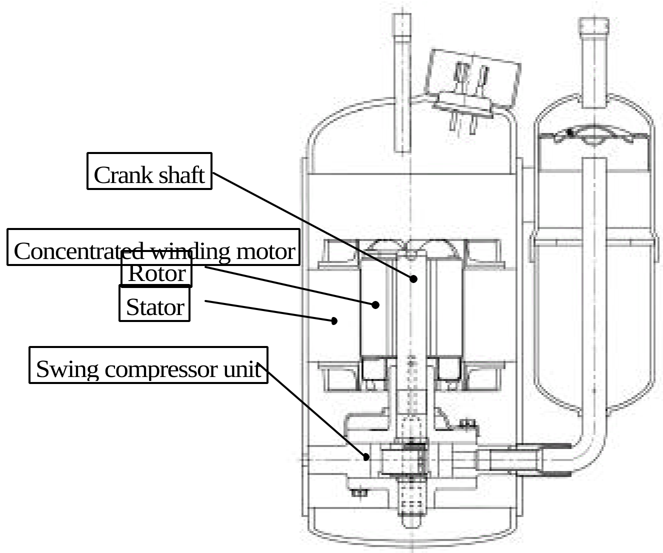


Fig.1 Cross-sectional drawing of the swing compressor

2.2 Features of the swing compressor mechanism

Figure 2 shows a swing compressor mechanism and a rotary compressor mechanism. In the swing compressor mechanism the vane and the roller of the rotary compressor mechanism have been combined and rotation of the piston is made possible through swing bushes. The efficiency of this mechanism in terms of mechanics and volume has been increased since there is no longer any sliding loss nor is there any leakage between the tip of the vane and the roller.

Furthermore, a change has been made in the mechanism in that the differential pressure that is exerted on the vane dividing the suction chamber from the compression chamber was previously supported on one side but is now supported on both sides. As a result, the reaction force on the side of the vane has decreased and the mechanical efficiency has increased. Table 1 shows estimated values of mechanical loss in the swing compressor mechanism and the rotary compressor mechanism. As indicated in Table 1, the mechanical loss is improved by approximately 5% in the swing compressor mechanism as compared to the rotary compressor mechanism. The volume efficiency is even further increased at low operating speeds where there is much leakage gas between the tip of the vane and the roller.

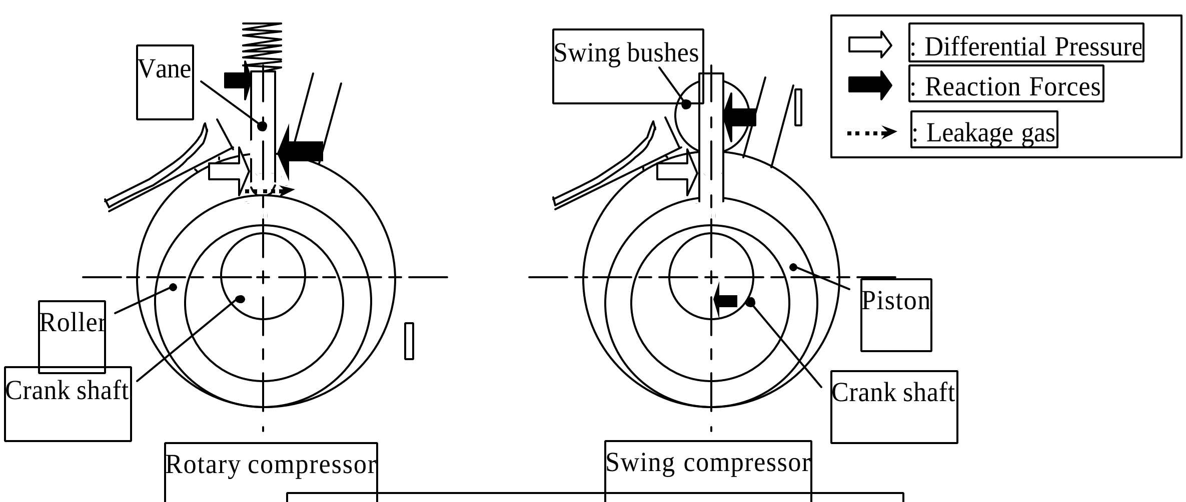


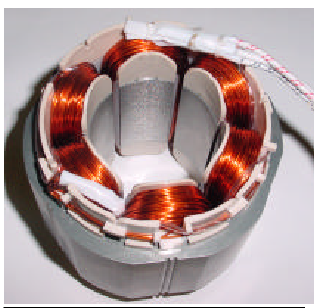
Fig.2 Mechanism of swing and rotary compressors

Table.1 Comparison of mechanical loss in swing and rotary compressors

Lubrication parts	Swing	Rotary
Main/sub bearing	24.1%	24.0%
Crank-pin bearing	34.5%	31.7%
Vane and roller	---	12.5%
Vane side	24.0%	26.5%
Outside of swing bush	6.6%	---
Crank thurust etc.	6.0%	5.3%
Total loss	95.3%	100%

2.3 Concentrated winding motor

Figure 3 shows the stators of the concentrated winding motor and the distributed winding motor. The concentrated winding motor shown in this figure is a 4-pole 6-slot Interior Permanent Magnetic (IPM) synchronous motor. The distributed winding motor is a 4-pole 24-slot IPM synchronous motor. The concentrated winding, in which the winding is placed directly on each tooth, can reduce the length of the coil windings and decrease the number of slots below that of the distributed winding. This reduction in length produces the effect of reducing the copper loss. Therefore, the efficiency of the concentrated winding motor can improve greatly. However, the following fault is mentioned.



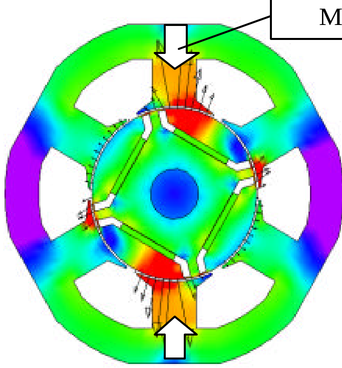
Concentrated winding motor

Distributed winding motor

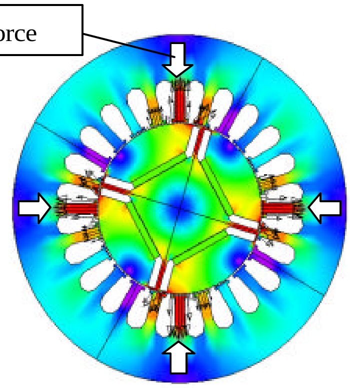
Fig.3 Stators

The results of the magnetic field analysis on the concentrated winding motor and the distributed winding motor are shown in Figure 4. These are the results found when using the two-dimensional finite element analysis to investigate the distribution of the magnetic force acting on the motor while it is in operation. This figure shows that there are two locations where the maximum magnetic force builds up in the concentrated winding motor and four locations where it builds up in the distributed winding motor. There are fewer locations where running torque occurs in the concentrated winding motor than in the distributed winding motor and as a result it has more magnetic force than the distributed motor.

Magnetic force



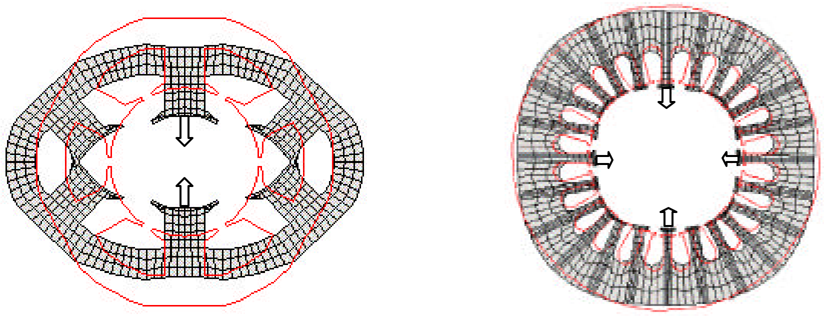
Concentrated winding motor



Distributed winding motor

Fig.4 Results of magnetic field analysis

As shown in Figure 5, when the two-dimensional structural finite element analysis was used to investigate the deformation of the stator resulting from the magnetic force, for the reason shown above, it was found that there was a greater amount of displacement in the concentrated winding motor than in the distributed winding motor. This indicates that there is a possibility noise will increase in the concentrated winding motor.



Concentrated winding motor   Distributed winding motor

Fig.5 Deformation by magnetic force

3. NOISE ANALYSIS

Due to the fact that this compressor is controlled by an inverter and is used at a wide range of speeds from low to high, it must have low noise at all operating speeds. Measurement of the compressor noise at each operating speed confirmed a noise projection in the 315 Hz band at an operating speed of around 78s-1, as shown in Figure 6.

The noise in the 315 Hz band is projected at 15 dB or louder than the noise at either of the adjacent frequency bands. It is necessary to reduce the noise projection, since it is unpleasant and adversely affects the comfort level of a residential space.

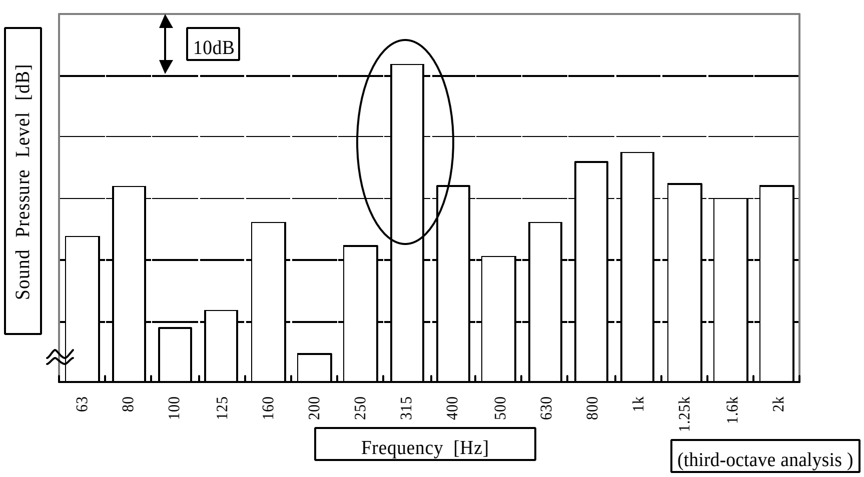


Fig.6 Noise power level (Operating speed of 78s-1)

In order to know the effect of order component of the operating speed, the change in noise at a frequency of four times the operating speed was investigated. As a result, it was found that the noise level reaches its maximum at around the operating speed of 78s-1, as shown in Figure 7. Thus, it is thought that there is a site in the compressor that has a natural frequency mode of around four times the operating speed of 78s-1, in other words of around 312 Hz.

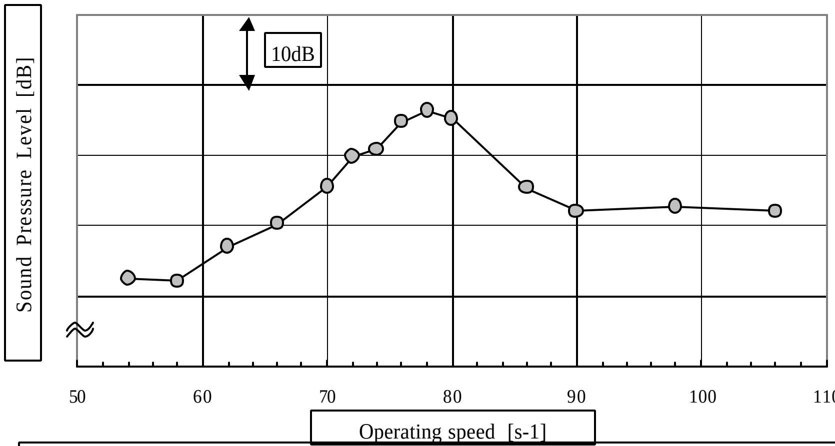


Fig.7 Change in noise at a frequency of four times the operating speed

4. INVESTIGATION OF THE CAUSES OF NOISE THROUGH ANALYSIS

4.1 Identification of the resonating body through modal analysis

In order to identify the site having a natural frequency mode of around 312 Hz, the three-dimensional finite element analysis was used and a modal analysis was conducted on an assembled compressor. As a result, it was found that the natural frequency of first bending mode of the rotor-crankshaft was around 312 Hz. As shown in Figure 8, this frequency mode causes a great deal of vibration to the rotor portion in the radial direction. It is therefore thought that this frequency mode is subject to the effects of the magnetic force that occurs in the radial direction components between the rotor and the stator.

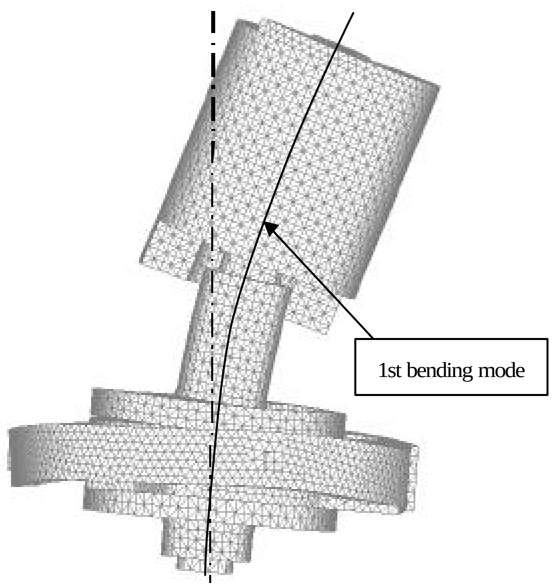


Fig.8 Vibration mode of rotor-crankshaft

4.2 Identification of the cause of increased the magnetic force through magnetic field analysis

From the modal analysis, it was found that in order to reduce the noise projection in the 315 Hz band it was necessary to understand the characteristics of the magnetic force. Thus, a magnetic field analysis was conducted in order to investigate how the magnetic force occurs at a frequency of four times the operating speed. The results showed that the magnetic force increases in one direction while it decreases in the other due to the eccentricity between the rotor rotation axis and the stator core, as shown in Figure 9.

In this way, when the eccentricity causes the magnetic force to be asymmetric, an excitation occurs (hereinafter called "imbalanced magnetic force") that vibrates the rotor in the radial direction as a result of the imbalance in the magnetic force of the radial direction components.

Figure 10 shows the relationship between the imbalanced magnetic force and the amount of eccentricity.

A synthesis of the above-described results shows that the resonance is very likely caused by the imbalanced magnetic force and the natural frequency of first bending mode of the rotor-crankshaft. Therefore, it is thought that inhibiting the eccentricity between the rotor rotation axis and the stator core and reducing the imbalanced magnetic force should be effective in reducing the noise.

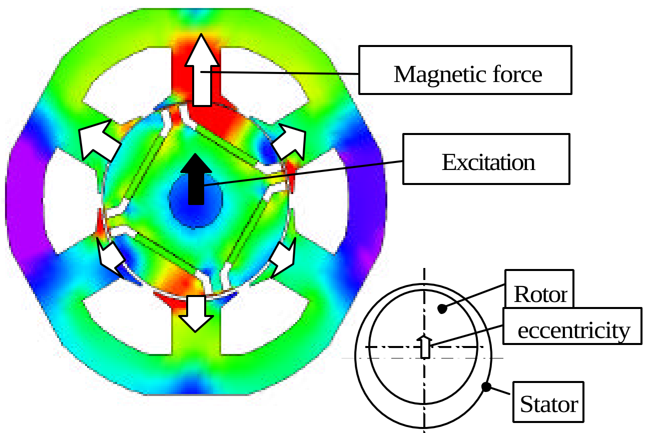


Fig.9 Results of magnetic field analysis

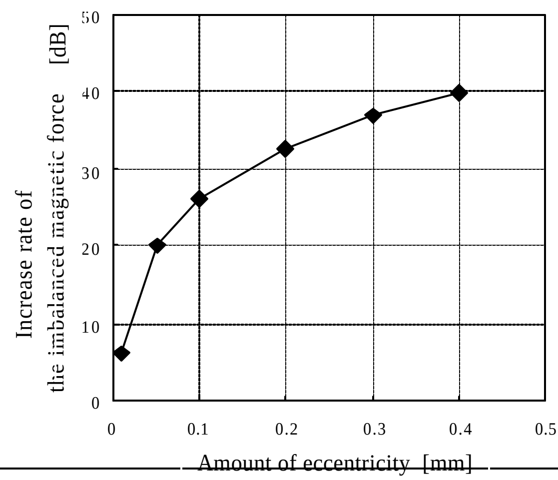


Fig.10 Relationship between the imbalanced magnetic force and the amount of eccentricity

5. VERIFICATION OF ANALYSIS RESULTS THROUGH EXPERIMENTATION

The results of the modal analysis and the magnetic field analysis were verified through an experiment.

In order to verify the results of the modal analysis the noise of the compressor was measured by changing the crankshaft materials, bearing shapes, and other components. As a result, there was a good match between the natural frequency of first bending mode of the rotor-crankshaft from the modal analysis and the frequency of the peak noise at a frequency of four times the operating speed, as shown in Table 2.

Table.2 Results of the modal analysis and the experiment.

	The natural frequency of first bending mode of the rotor-crankshaft from the modal analysis	The frequency of the peak noise at a frequency of four times the operating speed from the experiment	
	[Hz]	[Hz]	(The operating speed [s-1])
Original	307	312	(78)
Changed	420	420	(105)

In order to verify the results of the magnetic field analysis, the noise of the compressor was measured while inhibiting the amount of eccentricity of the shaft. As a result, the projection of noise in the 315 Hz band was greatly reduced, as shown in Figure 11.

These experiments confirmed that the noise resulted from the resonance that was occurring between the imbalanced magnetic force and the natural frequency of first bending mode of the rotor-crankshaft.

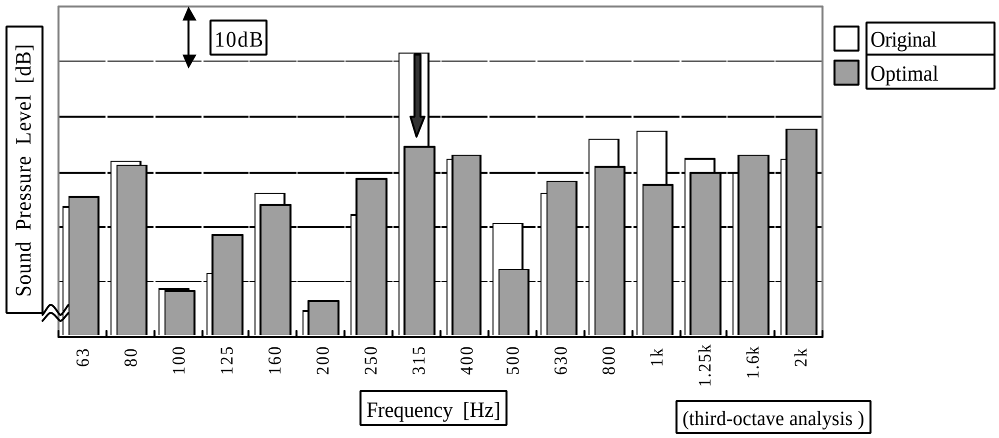


Fig.11 Comparison of noise power level

6. CONCLUSION

In order to reduce the noise of a swing compressor with a concentrated winding motor, a magnetic field analysis, a modal analysis, and an experiment were conducted. The results are summarized below.

(1) The noise projected in the 315 Hz band that was confirmed around the operating speed of 78s-1 was caused by the resonance between the magnetic force of the radial direction components and the natural frequency of first bending mode of the rotor-crankshaft.

(2) When eccentricity causes the magnetic force to be asymmetric, an excitation occurs that vibrates the rotor in the radial direction due to the imbalance in the magnetic force of the radial direction components.

(3) Inhibiting the eccentricity between the rotor rotation axis and the stator core is effective in reducing the magnetic force when the frequency is four times the operating speed.

(4) The results of the modal analysis and the magnetic field analysis were consistent with the results of the experiment.

The development of a swing compressor with a concentrated winding motor that is highly efficient and has low noise was made possible through the above-described efforts.

7. REFERENCES

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