Development of High Speed Inverter Rotary Compressor for the Air-conditioning System

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Abstract. In order to meet the various operating loads of an air-conditioning system, an inverter compressor with a wide operational range is necessary. One of the ways to achieve a wide operation range is to drive a small capacity compressor at high speed. Moreover, it is possible to maximize the efficiency in part-load operation condition close to actual operating conditions and to reduce the cost by compact design of a small capacity compressor. In addition, the shortage of maximum capacity, due to the small rated capacity, is covered through high speed operation. However, in general, if the compressor operates at high speed, problems occur such as reduced efficiency due to friction, increased noise, increased amount of oil discharge and decreased durability of the main components. In order to solve these problems the following have been investigated: optimized dimension parameters of the compression chamber, enhanced shaft design and the structure for the reduction of oil discharge and noise at high speed operation. Finally the high speed inverter rotary compressor with high efficiency and more compact size has been developed as compared with the conventional rotary compressor.

Keywords: Rotary compressor, High-speed, Oil discharge, High efficiency

1. Introduction
In recent years, energy saving in the residential and industrial area has become a big issue in the world. In particular, the demand for energy-saving residential air conditioning systems, including heating and cooling, is increasing. The inverter rotary compressor has a key role in energy savings and reliability as the critical component accounts for 85% of the power consumption of air conditioning. In response to the various operational loads in a residential air conditioning system, Inverter technology to control the capacity by varying the rotation speed is important. Through inverter technology, we have developed a high speed inverter rotary compressor capable of controlling up to 150rps (rotor speed). In this development, we confirmed the problems of the rotary compressor at high speed operating conditions and maximized the efficiency in the operating conditions of the air conditioner through CAE analysis and experimental approaches. Also, it is possible to lower material costs through reducing the shell diameter from Φ112mm to Φ101mm.
In this paper, the way to choose component specifications are introduced and the CAE(Computer Aided Engineering) / CFD(Computational Fluid Dynamics) analyses are performed for its reliability of developing a high speed rotary compressor.[1-4]

2. Overview of high speed rotary compressor

We have developed a rotary compressor with a displacement volume of 13.0cm$^3$, which is employed in a residential air conditioner. R410A and PVE oil are used as a refrigerant and lubrication oil. Figure 1 shows the structure of rotary compressor. The compressor consists of a cylinder, a reciprocating vane, roller, crankshaft with eccentric parts, main and sub bearings and brushless DC motor with rotor and stator. The lubrication oil in the sump is fed by the centrifugal force of the propeller, which is installed in the hollow hole of crankshaft. The compressor has two compression chambers which are operated alternately with a phase difference of 180 degree. The compression load generated by the compression chambers is supported by main and sub bearings positioned in the upper and lower parts of the compression chambers.

In a residential air conditioner, the high load occurs at the highest outdoor temperature in summer and at the lowest outdoor temperature in winter. In that case, the compressor must provide large capacity to fulfill the high load. In terms of a compact design compressor, it is necessary to achieve high speed operation with the high load.

In this paper, the optimized compression part design, the brushless DC motor design, the shaft reinforcement structure and oil discharge reduction structure to complete the high speed rotary compressor are introduced.

![Figure 1 Structure of rotary compressor](image)

3. OVERVIEW OF HIGH SPEED ROTARY COMPRESSOR

3.1. Optimization of cylinder dimension

To enhance efficiency at high speed operating conditions, we focused on reducing the leakage loss in the compression chambers and friction loss on the lubrication parts such as bearings. Figure 2 shows the design limitations of rotary compressor based on the cylinder inner diameter and height as the main specifications. The area A is suggested the optimized design area limited by geometry of compression chamber and reliability of main parts. These limitations are decided through
implementation analyses and confirmation tests. As a result of adopting a lower cylinder height, the volumetric efficiency of developed model is improved by reducing the leakage loss from the radial clearance between the cylinder and roller.

Figure 2 Design limitations of rotary compressor specifications

3.2. Reduction of crankshaft deformation and sliding surface pressure

The load acting on the crankshaft is composed of the sum of gas forces acting on the roller, vane force pushing the roller and centrifugal force of eccentric part (crank pin). The load deforms the parts at high speed operation under overload condition and is the maximum in the vicinity of crank angle when the discharge valve is opened. If a rotary compressor is operated with very high speed, the load is distributed in all areas by increasing the centrifugal force of eccentric part of crankshaft and its durability decreases by the high load acting on the sliding part.

Figure 3 shows the analytical result of crankshaft deformation between conventional and developed models. ANSYS was used for CAE analysis on the crankshaft deformation. From the analytical results, the shaft deformation was reduced by about 40% as compared to a conventional crankshaft at high speed. We confirmed that the maximum stress is located at the upper part of the crank pin. In order to verify the decrease of shaft deformation, we conducted an experiment on the basis of reliability standard and the result met with the criteria. Figure 4 shows the specifications for reducing shaft deformation. When we design the crankshaft considering the change to minimize crankshaft deformation, we should also consider the insertion of roller and middle plate. The shorter crank pin length is advantageous for shaft deformation and a certain length is required for a minimum of design in the assembly state. The pump part can be assembled by this bending length when the middle plate passes through the eccentric part. In other words, a middle plate can be assembled when this calculated bending length is less than the period overlapped between the eccentric part and middle plate.
Figure 3 Comparison of crankshaft deformation at high speed

Figure 4 Specifications for reduction of shaft deformation

Design guide: \[ H \geq L \geq H - \sqrt{D^2 - \varepsilon^2} \]
3.3. Optimization of Discharge Valve

When the pressure in the compression chamber is higher than the pressure outside the cylinder, the discharge valve is opened and then compressed gas is discharged through discharge port. The delayed opening of the valve influences the increase of over-compression during discharge process. When the rotary compressor operates in high speed, the over-compression becomes larger than normal speed. So the valve reliability problems can occur due to larger impact stress and velocity of discharge valve. For that reason, valve design is very important for reliability of compressor. The discharge valve design was determined by CAE analysis and experiments for specifically configured conditions of valve thickness and width, and $L_{mb}$ to consider the operating and geometric conditions. $L_{mb}$ is seated area of discharge valve at main bearing and it is key factor of valve reliability. Figure 5 shows the discharge valve structure and specifications. We performed the test with various valve specifications and compared them with the simulation results of valve stiffness.

|           | Thickness [mm] | Width [mm] | $L_{mb}$ [mm] | Stiffness [N/m] |
|-----------|----------------|------------|---------------|-----------------|
| Present   | 0.305          | 3.2        | 10            | 1413            |
| Spec 1    | 0.254          | 3.2        | 10            | 816             |
| Spec 2    | 0.254          | 5.0        | 7.6           | 850             |
| Spec 3    | 0.254          | 5.0        | 6.5           | 682             |

Figure 5 Discharge valve structure and specifications

Figure 6 Simulation result of discharge valve
Figure 6 shows the effective stress and impact velocity of discharge valve according to the specifications. In the case of present and spec.1 with same valve width, if the discharge valve thickness becomes thin, the noise of the compressor increases and the reliability of compressor worsens due to increased stress and velocity. In spec.2 and spec.3, the effective stress of the discharge valve is reduced by about 27%. The spec.2 was slightly smaller impact velocity than spec.3. We selected spec.2 as the optimum design for reliability, noise and efficiency of the compressor.

3.4. Reduction of oil circulation ratio (OCR)

In order to keep a stable oil level in the compressor, it is necessary to optimize the circulation path of discharged oil. Most of the oil discharged with the refrigerant gas from the discharge muffler goes through the air gap between the motor stator and rotor and is separated by the centrifugal force caused by the rotation of the rotor. The oil moving to the upper space of the compressor is separated and dropped from the gas by the density difference. The separated oil is moved to the oil sump at the bottom of the compressor through the stator outer peripheral space. If the compressor operates at high speed, the oil circulation ratio (OCR : The amount of oil contained in the gas) increases due to lower separation capacity by high flow velocity. If the OCR increases, the reliability of the compressor worsens as the oil level decreases. Thus, even at the highest speed, OCR must be maintained at an appropriate level. In addition, if the OCR increases, the amount of oil withdrawn together with the refrigerant increases. For that reason, volumetric efficiency is decreased. In this study, we confirmed the flow pattern inside the compressor through a CFD analysis to improve the oil separation structure in the conventional compressor. Figure 7 shows the specifications for the reduction of OCR. The distance between the end of the discharge pipe and crankshaft was investigated from 5 to 10mm. The upper length and lower length of case were changed to decrease pressure difference between upper and lower spaces based on the motor as well.

Figure 7 Design improvement of reduction of oil circulation ratio

Figure 8 shows the one example of CFD analysis result to understand the flow pattern inside the compressor and the experimental result of OCR according to the operating condition before and after changing the oil reduction specification. Finally, OCR could be reduced from 2.8 to 0.6wt% at 150 rps.
3.5. High speed brushless DC motor

Generally, the bridge of the rotor shows the weakness at high speed rotation. Thus, we reinforced the bridge to avoid rotor rib damage and prevent the escape of permanent magnet through CAE analysis. Figure 9 shows the bridge stress of conventional and developed models. The bridge stress is reduced from 314MPa to 79MPa with changing the rotor shape, and we acquired enough marginal safety ratio(Yield stress/Max. stress) in spite of high speed operation.

| Stress at 150rps | Conventional model | Developed model |
|------------------|--------------------|-----------------|
| Max [MPa]        | 314                | 79              |

Figure 8 Oil circulation ratio experimental result

![Oil circulation ratio experimental result](image)

![Maximum stress and safety ratio of bridge](image)
3.6. Noise reduction at high speed

As the noise and vibration characteristics of the inverter rotary compressor are changed in accordance with operating conditions, the countermeasures of those are important to develop an the compressor. Especially, noise control at high speed operation is one of the most important factors because it plays an important role in technology competitiveness.

The increasing noise level at high speed is not related to a resonance but an excitation force and transfer path of the compressor. So, the study of noise characteristics and design optimization should be carried out for the related component parts. First, in this study, noise level is measured by using microphone. Then, frequency spectrum analysis is carried out to measure the signal to find the countermeasures of the noise problem. Finally, motor design and welding method are modified to improve the excitation force and the transfer path of the system, respectively.

The motor design which generates electromagnetic force is modified using computational simulation to reduce the noise level. Table 1 shows the comparison of motor specifications between conventional and developed motor. According to the simulation result, the excitation force of the developed motor decreased while motor efficiency is equivalent to the conventional design. In order to verify the computational analysis, the vibrations of conventional and developed models are measured.

|                      | Conventional model | Developed model |
|----------------------|-------------------|-----------------|
| Motor Stack [mm]     | 55                | 45              |
| Coil Diameter [mm]   | Φ0.95             | Φ0.85           |
| Turn No.             | 51                | 65              |
| Slot fill factor [%] | 80.3/81           | 82.4/83         |
| Resistance [Ω]       | 0.828             | 1.078           |

Table 1. Specifications for developed motor

(a) Vibration measurement position with accelerometer (b) 1/3 Octave band at 130rps

Figure 10. Comparison of vibration level between conventional and developed motors
Figure 10 shows the vibration measurement position and the experiment result using accelerometer. Radial vibration is measured at the half of motor stack height (hm) and 1/3 octave band frequency spectra of conventional and developed models are compared. As a result, the vibration level of the developed model is reduced by about 50%. Especially, 3–6 kHz frequency range is most effective because high order harmonic components of electromagnetic force are reduced. Since vibration of structure is the cause of noise radiation, reduction of vibration implies an improvement of noise level. Additionally, welding position of case and pump part was investigated to improve the vibration transfer path. In general, 3 points of main bearing are welded to the compressor case to support a pump part. However, the thickness of main bearing was too thin and the combined structure was too unstable to hold up the pump part. Thus, design modification was carried out by computational simulation and 3 points of sub bearing are additionally welded.

Figure 11. Comparison of noise level between conventional and developed model
Figure 11 shows the noise reduction after design modification as compared with the conventional design. A microphone to measure the noise is placed at a distance of 30cm from the half the compressors body height and a noise signal is obtained after 15 seconds of stationary condition. Figure 11(a) is the color map of noise level with respect to operating speed. Both 1.25~1.6 kHz and 3~6 kHz frequency ranges are reduced due to the improvement of motor design and welding method, respectively. In order to check noise reduction at high speed, 1/3 octave band frequency spectra of conventional and developed designs are compared at 130rps operating condition as shown in Figure 11(b) Noise level in the 1.25~1.6 kHz frequency range is reduced by about 10dB and that of the 3~6 kHz frequency range is reduced by about 3dBA. Total noise level is reduced by about 3dBA.

4. Conclusion
This paper described the technology to solve the problems in the high speed operation of the compressor. For the better reliability and higher efficiency, the cylinder dimensions were compactly optimized to reduce the leakage loss from the radial clearance between the cylinder and rolling piston. The new crankshaft design concept of wide range application was confirmed and verified by CAE analysis and the experiment. The design guideline was also determined to assure the sufficient rigidity of the crankshaft. And blushless DC motor shape is modified for high speed operation and it is verified through rigorous testing. As a results, the high speed(150rps) inverter rotary compressor was developed with high efficiency and reliability for the air-conditioning system.

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