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Jinkook Kim
LG Electronics Inc.

Kyoungjun Park
LG Electronics Inc.

Kyeongho Kim
LG Electronics Inc.

Youngju Bae
LG Electronics Inc.

DESIGN OF LATCHING SYSTEM OF CAPACITY MODULATION COMPRESSOR FOR REFRIGERATION

Jin Kook KIM[1]*, Kyoung Jun PARK[2], Kyeong Ho KIM[3], Young Ju BAE[4]

[1]*DAC Research Lab., LG Electronics Inc.,
Changwon, Republic of Korea
(Phone: +82-55-260-3863, Fax: +82-55-268-4702, E-mail: jinkook99@lge.com)

[2]DAC Research Lab., LG Electronics Inc.,
Changwon, Republic of Korea
(Phone: +82-55-260-3863, Fax: +82-55-268-4702, E-mail: kjunpark@lge.com)

[3]DAC Research Lab., LG Electronics Inc.,
Changwon, Republic of Korea
(Phone: +82-55-260-3863, Fax: +82-55-268-4702, E-mail: khkim0351@lge.com)

[4]DAC Research Lab., LG Electronics Inc.,
Changwon, Republic of Korea
(Phone: +82-55-260-3862, Fax: +82-55-268-4702, E-mail: yjbae@lge.com)

ABSTRACT

The demand of energy saving products is on the rise because of the environmental controls and people's increased awareness of the global-warming issue. The energy consumption of a refrigerator depends on not only the efficiency of compressor itself, but also the capacity modulation. A new variable capacity reciprocating compressor, named TCM, will be introduced. This mechanically provides a Two-step Capacity Modulation without using any electronic frequency modulation. In the TCM compressor, the capacity modulation is achieved by changing the dead volume of cylinder through the control of sleeve eccentricity, obtained from the alternation of the rotational direction of a crankshaft in both the clockwise and counter-clockwise direction. A new latching system including a key, a spring, and an eccentric sleeve was applied in the TCM compressor for the capacity modulation. In this paper, the structural reliability of the new latching system was investigated for the TCM compressor.

1. INTRODUCTION

The demand for energy saving goods is on the rise because of consumer's awareness of the global warming issues and environmental control becoming more stringent since the Kyoto protocol in 1997. Recently, capacity modulation technology is widely used in the industry due to the improved efficiency of systems such as a refrigerator or an air-conditioner, and should be accompanied by the development of a variable capacity compressor. Developing the capacity control compressor is one of the interesting issues in compressor industries. To date, an inverter system using frequency modulation is the most advanced technology. However, the cost of the inverter system is too high to be applied to every refrigerator and air-conditioner. Therefore a mechanically capacity modulation compressor is currently one of the intermediate steps that many compressor designers are developing.

A reciprocating compressor, in which cooling capacity is controlled with two cylinders by the alternation of rotation of shaft, has already been produced for an air-conditioning system (Powers, 1999). A rotary compressor, in which cooling capacity is modulated by operating a by-pass valve inside cylinder, has also been manufactured (Yamamura, 1979 and Oh *et al.*, 2004). In a refrigerator, the reciprocating compressor (TCM) controls cooling capacity with one

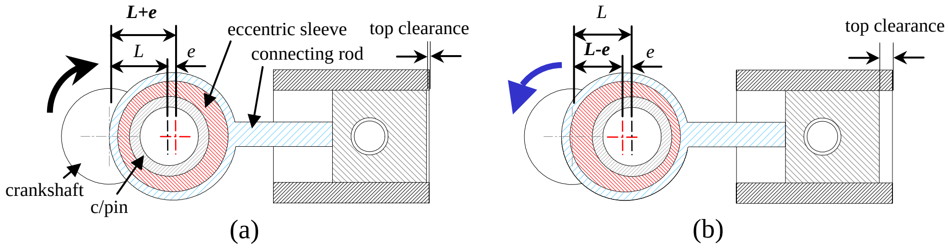

Figure 1 Principle of capacity modulation according to the rotation direction of motor: (a) at full capacity mode; (b) at partial capacity mode.

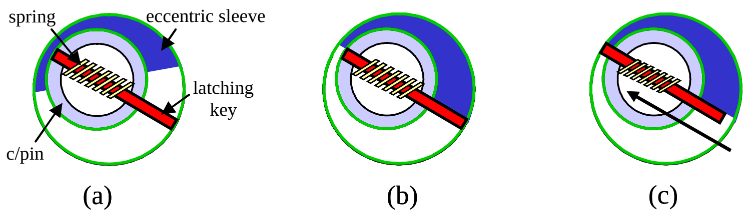

Figure 2 Three steps for mode change: (a) preparation; (b) positioning; (c) holding.

cylinder by both forward and reverse direction of motor (Bae *et al*., 2004). A new latching system is needed for mechanical capacity control with one cylinder in TCM compressor. In this paper, the structural reliability of the new latching system used in the TCM compressor will be investigated.

2. PRINCIPLE OF CAPACITY MODULATION

The capacity of the TCM compressor is modulated by changing the dead volume of the cylinder through controlling the eccentricity of a sleeve. This was obtained by alternating the rotational direction of a crankshaft in both a clockwise and a counterclockwise direction, as shown in Figure 1, in which L and e represent the eccentricity between pin and crankshaft axes and the eccentricity between c/pin and eccentric sleeve axes. In the clockwise and counterclockwise direction, the total eccentricities are the summation of L and e, and the difference between them, respectively. Therefore, the difference of top clearance is $2e$ between both modes, which makes it possible to mechanically modulate the two step capacity of a single cylinder compressor such as full and partial capacities. The modulation ratio depends on the eccentricity between crankshaft pin (c/pin) and eccentric sleeve axes. A new latching system including a latching key, a spring and an eccentric sleeve was applied for the mode change between both cooling capacities.

Consequently, mode change is obtained from following three steps, as shown in Figure 2. In the first step, a latching key is prepared to rotate for the full or partial capacity mode. In the second step, the key is positioned at the one end of the sleeve. In the last step, the key moves to the other end of the sleeve and holds it at both ends because the centrifugal force applied to the key is larger than the spring force. When the key contacts only one side of the sleeve, it occasionally prevents the sleeve and the c/pin coming into contact during the compression process. Therefore, the sleeve has to be restrained at the both ends by the key to prevent unstable latching.

Figure 3 shows energy saving effect on a refrigeration system with respect to capacity of a compressor. The system efficiency was calculated to be 10% higher at the 50% of cooling capacity when the compressor efficiency was same at the whole range of capacity.

3. STRUCTURAL RELIABILITY DESIGN

3.1 Impact Velocity

Impact force is applied to the latching system when a compressor starts or stops operating. Therefore, collision and

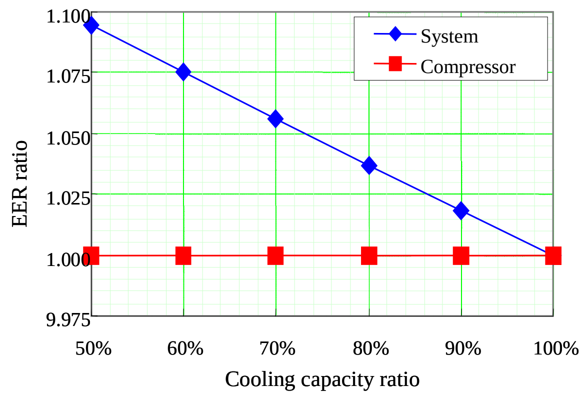

Figure 3 System efficiency with respect to cooling capacity ratio.

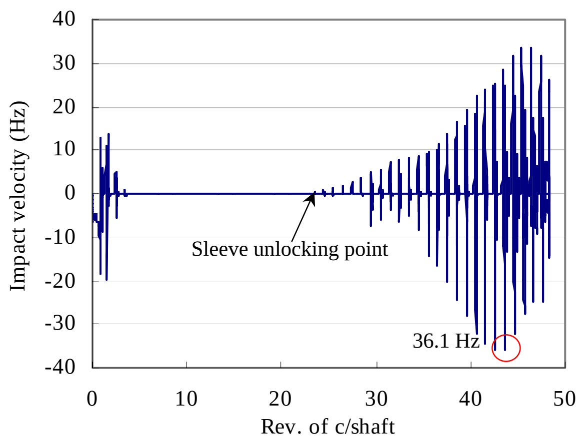

Figure 4 Impact velocity between latching key and eccentric sleeve with respect to the revolution of c/shaft.

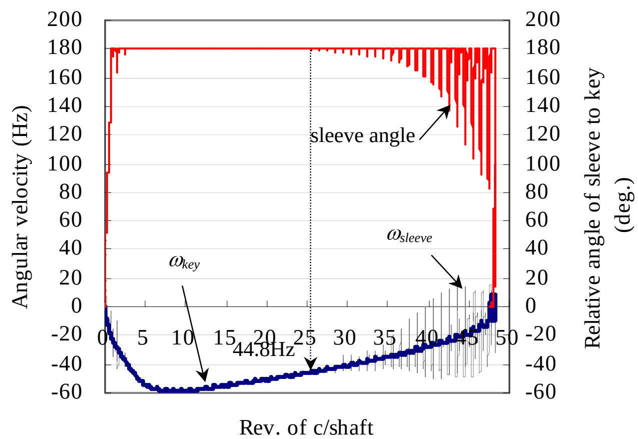

Figure 5 The angular velocity of key and sleeve and the relative angle of sleeve to key with respect to the revolution of c/shaft.

structural analyses are needed to guarantee the structural reliability of the latching system at the latching key, the c/pin of crankshaft, and the eccentric sleeve. Impact angular velocity is the relative velocity between a key and a sleeve calculated as follows:

$$\omega_{impact} = \omega_{key} - \omega_{sleeve} \tag{1}$$

The maximum impact angular velocity was calculated as 36.1 Hz, as shown in Figure 4, when the compressor is stopped operating in a partial capacity mode. Accordingly, the eccentric sleeve was initially unlocked at the c/shaft velocity of 44.8 Hz in relationship to the decrease in motor speed as shown in Figure 5. The real impact angular velocity was 38.0 Hz as measured by a high speed camera. There was only 5% error between the calculated and experimental angular velocities. When the compressor starts operating, the impact velocity was calculated as about 20 Hz in both modes. Also there was no impact when the compressor stopped operating in a full capacity mode.

3.2 Impact Force

Impact force between a key and a sleeve was calculated using an explicit time integration method. Deformation of both the key and the sleeve was considered, as shown in Figure 6, on impact. It was assumed that the sleeve was a perfectly elastic body and the key was also a perfectly elastic cantilever, fixed to the crank pin of a rigid body, and that sleeve and key could rotate around the center of a crank pin. The impact velocity was expressed by the following equation:

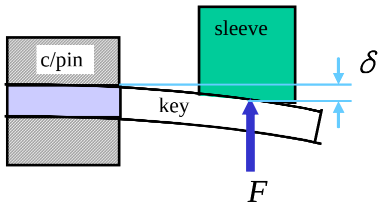

Figure 6 Impact modeling considering the deformation of key and sleeve.

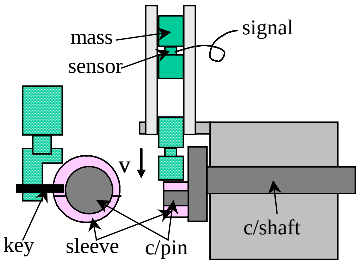

Figure 7 Schematic diagram of experimental set-up for measuring impact force.

$$v_{impact} = r\left(\omega_{key} - \omega_{sleeve}\right) - F\Delta t / m \quad (2)$$

$$F = k\delta \quad (3)$$

Impact force was obtained when the impact speed of sleeve was 15 Hz, through controlling the height of a mass using the experimental set-up shown in Figure 7. The experimental impact force was 98.2 N with a key length of 3.5 mm as shown in Figure 8. The impact force was calculated by Equations (2)-(3) and modified with a correction factor of 1.53 on the basis of experimental data at a key length of 3.5 mm allowing for the above hypothesis. The real key length was insufficient to be used in the experimental testing of the impact force. Subsequently, the real impact force and key stress were obtained by using the correction factor with a real maximum impact velocity of 38 Hz as referred to above.

Figure 9 shows that the maximum impact force was 610 N and the sleeve speed was twice the impact velocity due to the perfect elastic properties of the key and sleeve. Key and sleeve stresses can be obtained from the calculated impact force, using a commercial finite element analysis program, in order to design a more efficient latching system. This analysis showed that the key and sleeve were likely to fail due to an excess stress, which were respectively calculated as 630 and 710 MPa.

3.3 Fatigue test

An impact fatigue test was conducted on the experimental latching system, which was operated in both modes to establish the mode change reliability of the TCM compressor. The impact fatigue machine had five impact hammers, which were simultaneously controlled by an electric motor and a controller. Five latching systems were installed in the machine and exposed to an impact force by each hammer. Impact speed was adjusted by controlling the frequency of the electric motor. Impact force was adjusted by controlling the height of impact mass as shown in Figure 9.

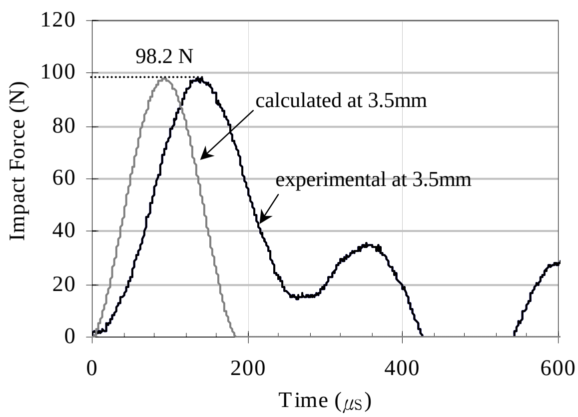

Figure 8 Experimental and calculated impact force data.

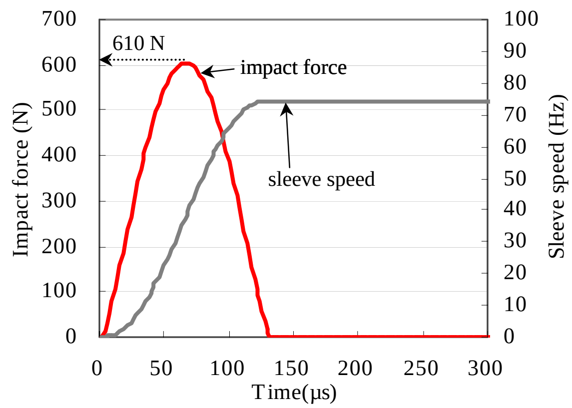

Figure 9 Calculated impact force and sleeve speed.

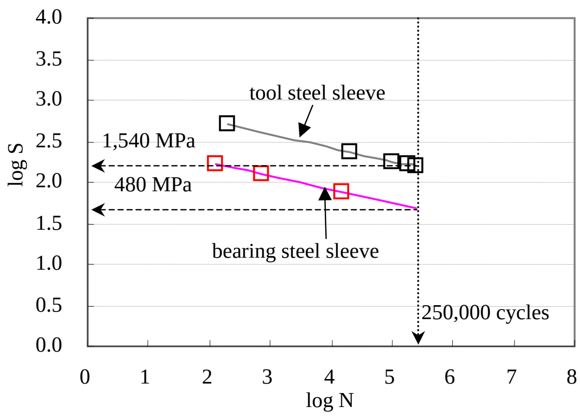

Figure 10 S-N curve of latching system.

The S-N curve shown in Figure 10 was obtained at the time of the first specimen failure during fatigue tests. Failure of all fatigue specimens occurred in the sleeve and not in the key. These failures may be due to the fact that the mechanical strength of the key material is stronger than that of the sleeve. When the fatigue life of mode change in a TCM compressor is over 250,000 cycles, the fatigue strength of a bearing steel sleeve is expected to be 480 MPa from the experimental three point data. The fatigue strength was shown to be lower than the maximum stress of a sleeve calculated above. However, the fatigue strength of a tool steel sleeve was 1,540 MPa. Therefore, the tool steel appears to be a better option for the design of an efficient latching system.

4. CONCLUSION

In this paper, the structural reliability of a new latching system was investigated in the use of a TCM compressor, which provides a two-step capacity modulation mechanically, without using any electronic frequency modulation. Impact velocity between a key and a sleeve was calculated from the difference of angular velocities. The maximum impact velocity was 36.1 Hz when the compressor is stopped operating in a partial capacity mode. There was only a 5% error between calculated velocity and the experimentally obtained one using a high speed camera. From the impact test, it was found that the maximum stresses of a key and a sleeve were 630 MPa and 710 MPa, respectively. Also it was found that a stronger material should be selected for designing an eccentric sleeve because the fatigue strength of a bearing steel sleeve was smaller than the maximum stress applied.

NOMENCLATURE

e	eccentricity between pin and eccentric sleeve	(mm)
F	impact force	(N)
k	spring constant of the system of key and sleeve	(kgf/cm)
L	eccentricity between pin and crankshaft axes	(mm)
r	distance between the center of c/pin and impact point	(mm)
v	velocity	(m/s)
Δt	time derivative	(s)
δ	deflection of the system of key and sleeve	(mm)
ω	angular velocity	(rad/s)

Subscripts

impact	impact between key and sleeve
key	latching key
sleeve	eccentric sleeve

REFERENCES

Bae, Y. J., Kim, J. B., Roh, C. G., Sim, J. S., Kang, D. S., Seo, M. Y., Kim, H., Park, K. J., Kim, K. J., Kim, H. H., 2004, Dual Capacity Compressor, *US patent*, No. 6,755,624.

Oh, S. K., Chang, P. S., Choi, J. K., Lee, I. J., 2004, Design of a Variable Capacity Rotary Compressor Using By-Pass Method, *Proc. 17th Int. Compressor Eng. Conf. at Purdue*, C036.

Powers, J. C., 1999, TS compressors Advance Heat Pump System Operation beyond 'Stop' and 'Go', *The Air Conditioning, Heating and Refrigeration NEWS April 5*.

Yamamura, T., 1979, Air-conditioner, *Japan patent*, No. 54-45638.

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