한국동력기계공학회지 제21권 제5호 pp. 5-12 2017년 10월 ISSN 1226-7813(Print) ISSN 2384-1354(Online)
Journal of the Korean Society for Power System Engineering http://dx.doi.org/10.9726/kspse.2017.21.5.005
Vol. 21, No. 5, pp. 5-12, October 2017

Performance Evaluation of a Crank-driven Compressor and Linear Compressor for a Household Refrigerator

Minchan Park*, Yoongho Jung*, Jaeyeol Lee**, Jaekeun Lee*** and Youngchull Ahn****†

(Received 13 March 2017, Revision received 10 October 2017, Accepted 10 October 2017)

Abstract: With the difficulties in increasing the efficiency of conventional crank-driven compressors due to mechanical loss, compressor manufacturers have investigated new kinds of compressor such as a free piston compressor mechanism. This study investigates the energy efficiency of two different types of compressor for a household refrigerator. One is the conventional crank-driven compressor, and the other one is a linear compressor. The energy efficiencies of these compressors are evaluated. Experimental results show that the linear compressor has 10% lower power consumption than the brushless direct-current (BLDC) reciprocating compressor. The linear compressor demonstrates excellent energy efficiency by reducing the friction loss. Furthermore, a motor efficiency exceeding 90% is achieved by using a linear oscillating mechanism with a moving magnet. Additionally, the compressor stroke to piston diameter ratio of the oscillating piston in the linear compressor can be adjusted in order to modulate the cooling capacity of the compressor for improved system efficiency.

Key Words : Linear Compressor, Reciprocating Compressor, Power Consumption, Motor Efficiency, Moving Magnet

1. Introduction

A compressor is an essential component of a refrigeration system. It circulates refrigerant through the system in a continuous cycle, and accomplishes the required heat lift and rejection through phase change of the refrigerant. The need for efficient compressors has induced the development of a linear compressor. The recent worldwide awareness of the global environment and conservation has focused attention on energy saving in household appliances, particularly the development of high efficiency compressors, because most of the total electric energy in a house is consumed by a refrigerator and an air conditioner, in which the compressor consumes most of the electric energy[1,2).

The reciprocating compressor commonly used in a household refrigerator has many limitations to increase energy efficiency due to the crank mechanism. Therefore, compressor manufacturers have focused on developing new kinds of compressor mechanism, such as the free piston mechanism[3)]. This mechanism has some advantages in tribological aspects over the conventional reciprocating compressor because it does not

****† Youngchull Ahn(corresponding author) : Department of Architectual Engineering, Pusan National University.
E-mail : ycahn@pusan.ac.kr, Tel : 051-510-2492
*Minchan park, Yoongho Jung : School of Mechanical Engineering, Pusan National University.
**Jaeyeol Lee : LG Electronics, Gaeumjeong-dong, Changwon City, Gyeongnam.
***Jaekeun Lee : EcoEnergy Research Institute, Busan Techno Park.

generate any side force on the piston. A linear compressor is a piston-type compressor in which the piston is driven directly by a linear motor, rather than by a rotary motor coupled to a conversion mechanism, as in a conventional, reciprocating compressor. Linear motors are simple devices in which axial forces are generated by currents in a magnetic field[4]. Because all the driving forces in the linear compressor act along the direction of linear motion, there is no sideways thrust on the piston. This design substantially reduces bearing loads and allows the use of gas bearing or low viscosity oil. Additional information on the origin and development of linear compressors has been presented other previous studies[5].

Compressors with wide capacity modulation characteristics are essential for the energy efficient and smart refrigerators. To satisfy this need, the inverter driving operation of a compressor has been widely developed. The typical compressor is a reciprocating compressor with a brushless direct-current (BLDC) inverter for a household refrigerator. By changing the operating frequency, the BLDC inverter reciprocating compressor is operated with a cooling capacity range of 40~110%. On the other hand, the linear compressor is modulated by controlling the stroke. The characteristics of the mechanical part, the motor, and the compression efficiency with respect to capacity modulation are totally different from those of the BLDC reciprocating compressor.

In this study, a compressor calorimeter is used to investigate the energy efficiencies of two different types of compressor for a household refrigerator a conventional crank-driven compressor, which is a positive-displacement compressor that has the piston driven by a crankshaft to discharge gas at high pressure, and a linear compressor which has no crank mechanism and its piston is oscillated by a linear motor and helical coil spring.

2. Experimental Setup

2.1 Test system

Fig. 1 shows the schematic diagram of the experimental apparatus to measure the coefficient of performance (COP) of a refrigeration system. The system is designed to have a secondary refrigerant calorimeter presented in the standards of ASHRAE 23 and ISO 917[6,7]. This equipment consists of a controller, a compressor-power meter, a calori-power meter, a control switch, a suction pressure gauge at the inlet of the evaporator, a discharge pressure gauge at the outlet of the condenser, thermocouples, and an expansion valve. Additionally, an inverter control system and a linear variable differential transformer are equipped to not only convert the operating frequency to the natural frequency at system resonance, but also to control the top dead center (TDC) location and the stroke of the piston. An oscilloscope and a powermeter are used to measure the location of the stroke and the phase between the current and the back electromagnetic force.

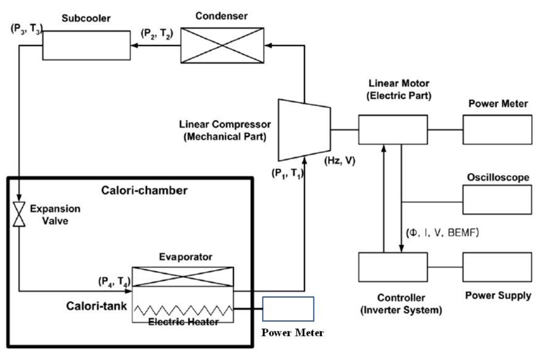


Fig. 1 Schematic diagram of the experimental apparatus for evaluating the performance of compressors by measuring the COP of the refrigeration system

In this system, the evaporator absorbs the heat from the secondary refrigerant, which obtains the energy from the electric heater in the calori-tank. In the steady state, the cooling capacity of the evaporator is the same with the input power to the electric heater. Therefore, the input power of the electric heater in the calori-tank is measured to obtain the cooling capacity. The uncertainties for W, Q and COP depend on measuring values of the input power of the compressor and the electric heater. In this system which was used in the previous study[8], the uncertainties of W and Q are 0.01% and 1%, respectively. In addition, the uncertainty of COP can be calculated as 1%, including errors.

2.2 Linear compressor

A linear compressor has two major practical limitations, which restrict its implementation in practical systems. Both the resonant frequency and stroke are sensitive to changes in geometry and operating conditions. The linear oscillating compressor consists of a moving mass(piston), resonant springs and a linear motor. In the mechanical system, resonant springs, a moving mass, a damper, pressure load and motor force comprise a basic compression system. If the supporting springs are used to reduce the vibration of the compressor body, second oscillation of the compressor body should be considered. Therefore, a two-degree-of-freedom model with spring-mass-damping system under periodic motor force can be obtained. Here, the damper, which means mechanically dissipated loss, may be classified by the viscous damping loss of a piston and a cylinder, wind loss and magnet shuttle loss[9].

Fig. 2 shows the structure of the linear compressor affected by gas pressure force and the electromagnetic force of the linear motor in the refrigeration system. It is composed of a mechanical spring, a piston, refrigerant suction and discharge parts, and a linear motor. The stroke of the piston driven by the linear motor is moved from the top dead center(TDC) to the bottom dead center(BDC) and controlled around the TDC. According to the controlled position of TDC, the location of the piston can have a positive value (+) or a negative value (-) due to the free piston mechanism of the linear compressor. This affects the efficiency and the cooling capacity, which are related to the system resonance[8].

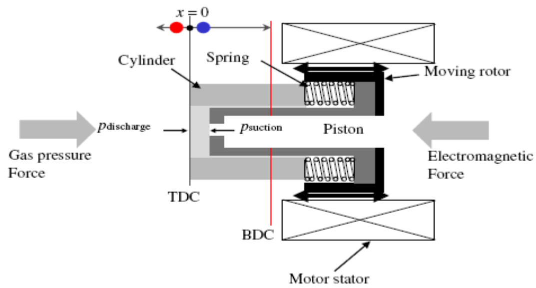


Fig. 2 Schematic diagram of the linear compressor affected by the gas pressure force and electromagnetic force

Therefore, the efficiency of the compressor itself is very important and the capacity modulation is also important for the energy saving. Even if a capacity variable compressor has the same efficiency, the capacity variable compressor may consume less energy than the capacity invariable compressor owing to the capacity modulation effect. The efficiency of the refrigerator is not only related to the capacity of the compressor, but also proportional to the compressor efficiency. The small capacity of the compressor reduces the difference between condenser pressure and evaporator pressure in the refrigerator. While the load to the compressor decreases, the cooling capacity does not decrease as much as the load because of the increasing density of suction refrigerant. Therefore, the efficiency of the refrigerator can be increased by up to 12%, even though the efficiency of a compressor does not change. The smaller the cooling capacity becomes, the greater the capacity modulation effect that is acquired and the minimal cooling capacity for keeping temperature is about 50%. The efficiency of the refrigerator is dependent on the cooling capacity of the cycle and the efficiency of the compressor. The capacity modulated efficiency and the efficiency of the compressor are important for predicting the efficiency of the refrigerator[10]. The efficiency of the compressor is shown as Eq. (1):

$$\eta_{compressor} = \eta_{motor} \times \eta_{mechanical} \times \eta_{compression} \quad (1)$$

Where $\eta_{compressor}$, η_{motor}, $\eta_{mechanical}$, $\eta_{compression}$ are the efficiency of the compressor, the motor, the mechanical part, and the compression, respectively. Each term of Eq. (1) is measured at several cooling capacity modulation. The motor and the mechanical efficiencies are calculated from the losses of the copper, the iron and the friction at each cooling capacity.

3. Results and Discussion

3.1 Linear compressor

A linear oscillating motor is grossly classified with moving magnet type, moving iron type and moving coil type according to their moving part configuration. Usually, the commercialized moving coil type motor with very small side force is using the portable refrigerator, but it is only limited to the small compressor because of the coil reliability. Although the moving iron type linear motor can be produced inexpensively, the friction loss by the large side force of motor and the large motor size are weak points.

Among the three types of linear motor, the moving magnet type linear oscillating motor with Nd magnet for the motor efficiency and size has been developed by referring to the previous study[11]. To minimize the motor losses, the core is laminated in the radial direction and the energy efficiency of the developed linear motor can exceed 90%. Such a motor has the following differences and advantages compared with the conventional rotary induction motor.

Fig. 3 compares the linear and rotary induction motors in terms of energy efficiency as a function of velocity changes. Velocity ratio is defined as the ratio of the maximum velocity to the modulation velocity of systems. While the rotary induction motor needs a large starting torque, the linear motor has very low starting torque. Therefore, the linear compressor starts softly even under a very low input voltage. Additionally, even under a high pressure load, the linear compressor can be started without any problems. The efficiency variation of the linear motor according to the velocity ratio is less sensitive than the rotary induction motor. Therefore, the linear motor has advantages for capacity modulation. The Redlich type linear oscillating motor has much less copper loss than a normal induction motor used for conventional reciprocating compressor, because it does not have unnecessary end-coil and rotor bar, which cause high copper losses.

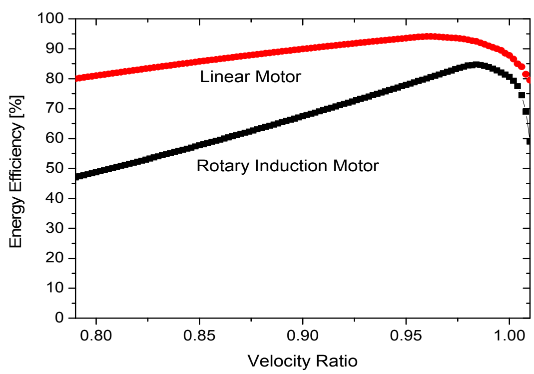


Fig. 3 Energy efficiency variations of the linear and rotary induction motors as a function of velocity changes

3.2 Side force of resonant spring and friction loss

The linear oscillating compressor has a free piston mechanism, with no crank and crank shaft. The piston attached on the moving magnet assembly moves linearly as the magnets of linear motor move. This absence of any crank mechanism can give the linear compressor a friction loss of less than half that of the reciprocating compressor. A helical compression coil spring is selected as a resonant spring for cost effectiveness and high reliability. When the spring is compressed in the linear compressor, it has a side force that is perpendicular to the compression direction.

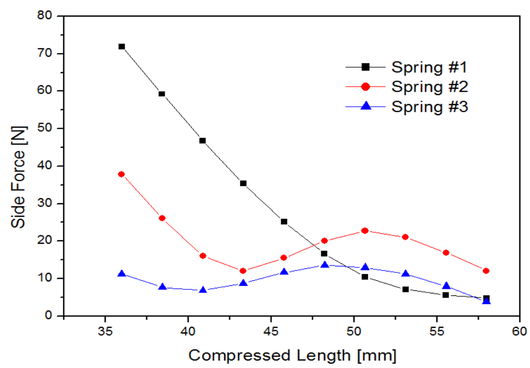
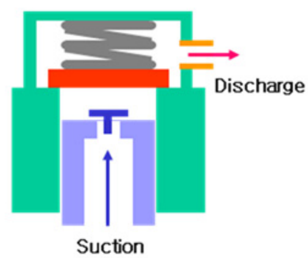


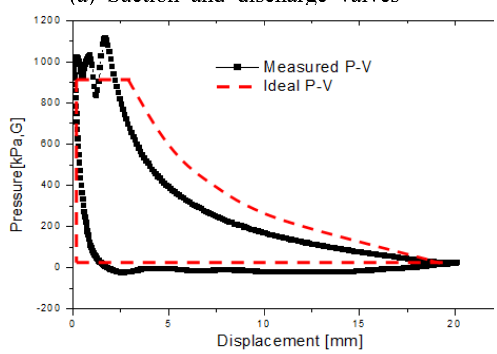
Fig. 4 Comparison of side force generation for three types of resonant compression coil spring changes

Therefore, resonant springs must be designed to reduce the side force of the spring to the minimum to reduce friction loss and prevent the wear problem between the piston and the cylinder. Fig. 4 shows the side force variations of three types of coil spring. The commonly used coil spring #1 shows very large side forces at the beginning of compression, and even the modified coil springs #2 and #3 have quite improved characteristics. The coil spring #3 shows very low side forces through the entire compression process. For high energy efficiency, the friction loss has to be minimized. In the linear oscillating compressor, the viscous damping loss can be calculated theoretically by assuming Newtonian fluid and Couette flow as a reciprocating compressor. In addition, the friction loss by viscous damping in the linear compressor can be calculated quantitatively by only measuring the velocity in the free damped oscillation.

3.3 Valve mechanism



(a) Suction and discharge valves



(b) P-V diagram

Fig. 5 Schematic diagram of the suction and discharge valve system and P-V diagram measured

Fig. 5(a) shows the schematic diagram of the suction and discharge valve system. A disk valve and a coil spring are used in the valve system. This kind of valve system can minimize over-compression loss because it has a much larger flow area than conventional reed valves. Moreover, the top clearance between the piston and the discharge valve becomes nearly zero, because the spring can absorb impact. Therefore, it is possible to minimize the re-expansion loss of the compressor and enhance the compression efficiency. In addition, the linear compressor has a larger cooling capacity per unit volume than a conventional reciprocating compressor, so the size of the linear compressor can be reduced. A suction valve is placed on the piston and the suction flow path is inside the piston. Thus, the flow resistance and suction heating loss are much less than those of conventional reciprocating compressors. With this arrangement, as shown in Fig. 5(a), it is possible to use direct suction and minimize the heat exchange between the suction and the discharge gases. Fig. 5(b) represents the experimental and theoretical PV diagrams of the linear compressor, which exhibits relatively good agreement because of its low losses.

3.4 Cooling capacity modulation

Fig. 6 shows the energy efficiency ratio (EER) as a function of the compressor stroke to piston diameter ratio and the cooling capacity ratio in the linear compressor. The stroke to diameter ratio is changed from 0.28 to 0.56 and the vertical axis represents the normalized EER. It is the ratio of EER of each case to the EER of 0.56 of stroke to diameter ratio which has the smallest EER values. The EER increases with decreasing compressor stroke to piston diameter ratio due to the increasing mechanical efficiency. The efficiency of the linear compressor is closely connected with the efficiencies of the motor and the mechanical parts. The natural frequency of the linear compressor is one of the important operating parameters, and it is a function of the piston diameter, compressor stroke, mass of the moving part, and charging pressure of working fluid. For the same volume in the linear compressor, the mechanical efficiency increases with the increasing of piston diameter and with decreasing compressor stroke. As the compressor stroke decreases, the motor efficiency decreases according to the increased input current of the motor.

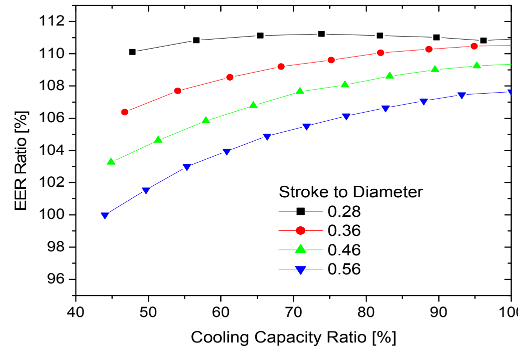
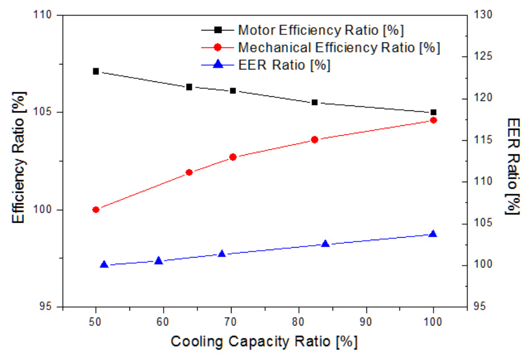
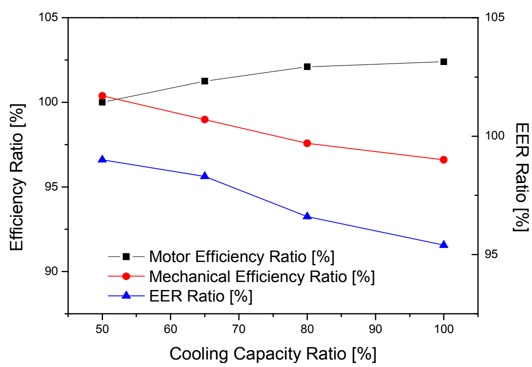


Fig. 6 EER ratio as a function of compressor stroke to piston diameter ratio and cooling capacity ratio



(a) Small bore and large stroke (stroke to dia. ratio: 0.56)



(b) Large bore and small stroke (stroke to dia. ratio: 0.32)

Fig. 7 Motor and mechanical efficiency ratios and EER ratio as a function of cooling capacity ratio

Fig. 7 shows the general patterns of the mechanical efficiency and the motor efficiency according to the capacity control of the linear compressor. All the efficiency data are normalized by the mechanical efficiency value at 50% of cooling capacity ratio, and the EER data are also normalized by the value of 50% of the cooling capacity ratio. When the cooling capacity ratio is decreased, the motor efficiency increases and the mechanical efficiency decreases. The total efficiency of the linear compressor is proportional to the product of the mechanical efficiency and the motor efficiency. The compression efficiency is almost the same for the each capacity modulation and the slopes of the motor and the mechanical efficiencies are almost identical. Then, the total efficiency of the linear compressor reaches its maximal value at the cross point of the mechanical efficiency curve and the motor efficiency curve. The total efficiency of the compressor shown in Fig. 7(a) has the maximal efficiency around the 100% cooling capacity ratio; however, the total efficiency shown in Fig. 7(b) reaches its maximal efficiency around the 50% cooling capacity ratio when the piston bore is increased and the stroke is decreased. Considering these characteristics between the stroke to diameter ratio and the maximal total efficiency, a new type of linear compressor with modified resonant springs has been developed.

Fig. 8 shows the efficiencies of the new type of linear compressor, the conventional linear compressor, and the BLDC reciprocating compressor as a function of cooling capacity ratio. The new linear compressor used in this study is designed not only to increase the efficiency of the overall range by improving several of the components, such as the bearing and valve systems, but also to maximize the efficiency at the 50% cooling capacity. The EER ratio is expressed as the ratio of the EER values to the value of 50% of the cooling capacity ratio of the previous linear compressor. The EER ratio of the new linear compressor is slightly decreased with increasing cooling capacity ratio, but remains almost constant, whereas that of the previous linear compressor shows an increasing tendency. The BLDC reciprocating compressor shows a rapid decreasing tendency. Based on the 90% of cooling capacity ratio, the new type linear compressor is 20% and 8% more efficient than the BLDC reciprocating and conventional linear compressors, respectively. In addition, it is 10% and 15% more efficient than the BLDC reciprocating and conventional linear compressors at the 50% of cooling capacity ratio, respectively. The new linear compressor exhibits superior performances throughout the entire tested range and it is expected to reduce the energy consumption and to be cost effective.

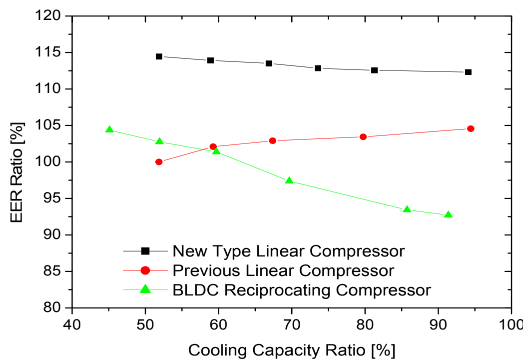


Fig. 8 Comparison of the changes of the EER ratio for the three types of compressor

4. Conclusions

This study investigated the energy efficiency of two different types of compressor for used in household refrigerators such as the conventional crank-driven compressor and the linear compressor. For high energy efficiency, a new linear compressor was designed using the Redlich type linear motor, low friction loss by free piston mechanism, new valve system, and capacity modulation by the compressor stroke to piston diameter ratio control. This new linear compressor was designed not only to increase the efficiency of the overall range by the improving several of the components, such as bearing and valve systems, but also to maximize the efficiency at the 50% cooling capacity. The new linear compressor exhibited a power consumption reduction of about 10% compared with the BLDC reciprocating compressor. At the full cooling capacity, the efficiency of the new linear compressor was 20% and 8% more efficient than that of the BLDC reciprocating and conventional linear compressors, respectively. In addition, the efficiency of the new linear compressor was about 10% and 15% more efficient than that of the BLDC reciprocating and conventional linear compressors, respectively, at the 50% cooling capacity.

References

1. J. I. Yoon, C. H. Son, S. K. Heo, M. J. Jeon, and T. Y. Jeon, 2016, "Performance Analysis of a Seawater Ice Machine Applied Two-stage Vapor Compression Refrigeration System for Various Refrigerants", Journal of the Korean Society for Power System Engineering, Vol. 20, pp. 85-90.
2. J. I. Yoon, K. H. Choi, C. H. Son, and H. Jo, 2014, "Performance Comparison of Two-stage Compression Refrigeration System Using R404A", Journal of the Korean Society for Power System Engineering, Vol. 18, pp. 57-62.
3. R. Z. Unger, 1998, "Linear Compressor for Clean and Specialty Gases", Int. Comp. Eng. Conf. at Purdue University, USA.
4. R. Redlich, R. Z. Unger, and N. R. Walt, 1996, "Linear Compressor: Motor Configuration, Modulation and System", Int. Comp. Eng. Conf. at Purdue University, USA.
5. R. Z. Unger and N. R. Walt, 1996, "Linear Compressor for Non-CFC Refrigeration", IATC 46, Purdue University, USA.
6. ASHRAE 23: Methods of Testing for Rating Positive Displacement Refrigerant Compressors and Condensing Units.
7. ISO 917. 1989, Testing of Refrigerant Compressors, pp. 1-8.
8. H. Kim, C. G. Roh, J. K. Kim, J. M. Shin, Y. J. Hwang and J. K. Lee, 2009, "An Experimental and Numerical Study on Dynamic Characteristic of Linear Compressor in Refrigeration System", Int. J. Refrigeration, Vol. 32, pp. 1536-1543.
9. K. Park, E. Hong, K. Choi and W. Jung, 2004, "Linear Compressor Without Position Controller", Int. Comp. Eng. Conf. at Purdue University, USA.
10. B. Craig R., G. Eckhard A. and G. Suresh V., 2013, "Linear Compressors for Electronics Cooling: Energy Recovery and its Benefits", Int. J. Refrigeration, Vol. 36, pp. 2007-2013.
11. R. Redlich, 1995, "A Summary of Twenty Years Experience with Linear Motors and Alternators", Distributed at Linear Drives for Industry Applications, Nagasaki, Japan.