Development of a Compressor for a Miniature Pulse Tube Cryocooler of 2.5 W at 65 K

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ABSTRACT

The Fuji Electric group has developed crucial technologies with high reliability for Stirling cryocoolers targeted for space missions. For commercial applications, a miniature pulse tube cryocooler with a heat lift of 2 W to 3 W at 70 K using 100 W electric power input has developed and is being marketed.

A moving magnet motor has been introduced to the driving system in order to achieve better compactness and higher efficiency in place of the moving coil in a conventional system that had about 65% efficiency. The compressor performs a total compression work of 75 W with 90% efficiency and has a life longer than 50,000 hours. One intended application is the cooling of a high temperature superconductive (HTS) device for a wireless telecommunication system.

We began by designing a motor structure and running experiments on basic elements because a moving magnet system is a new technology to Fuji. At first the magnetic circuit for element tests was evaluated by a basic equation and computed by general-purpose FEM software. The results from the element tests and calculated data were used for the next design. For bearing support magnets, we considered various approaches. This paper describes the development status of the compressor, including the motor design and the primary test results.

INTRODUCTION

Recently, wireless communication has rapidly become widespread. This has brought about a shortage in the regions of electromagnetic wave frequency and caused a need to find measures to meet the situation. It is well known that one of these measures is the application of a superconducting filtering system. The system for a receiver is already in practical use, but one for a transmitter remains unexploited. Therefore, a project to develop a superconducting filtering system for a transmitter was begun in December 2005 and is scheduled to be completed in March 2008. It is funded by a Japanese government institution, the Ministry of Public Management, Home Affairs, Posts and Telecommunications. A cryocooler for that system requires compactness, high frequency and a long lifetime. The requirements are better performance than that provided by any previously developed cryocooler.[1,2]

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MOTOR DESIGN

Design Concept

The target specifications for the compressor being developed are shown in Table 1. This target was too high for a conventional moving coil motor to achieve, especially at an efficiency of 90%.

We started by developing a moving magnet linear motor which was more compact and had the potential for higher efficiency. To create higher performance motor and be able to increase the generative force, a moving part needs to combine a permanent magnet and two side magnets, as shown in Figure 1. The moving part becomes stable at the center of each leg of an outer yoke in this magnetic configuration because each magnetic circuit between a main magnet and one side magnet makes a loop through each leg of the outer yoke. If the moving part becomes displaced from a stable state to the left or right side, magnetic potential energy is stored. In other words, a force is caused in the opposite direction than that generated by the exciting current.

Our company had very little knowledge and skill with a moving magnet linear motor. In the first phase, we manufactured an element test model and developed experimental data for the purpose of verifying a basic principle and to understand the effects of the side magnet configuration.

Basic Equation

Fleming's left-hand rule consists of defining an equivalent current for a generative force. Using an equivalent current of a permanent magnet, generative force is described as following.

$$F = B_g \cdot 2I_M \cdot L \tag{1}$$

where, B_g is the magnetic flux density of the air gap between an outer yoke and an inner yoke, and L is the average peripheral length of a permanent magnet. This equation differs from a general BIL equation in that an equivalent current is twice what it would indicate. This is because the equivalent current exists on two sides of a magnet. The equivalent current I_M is defined in the following equation:

$$I_M = H_{CB} \times L_M = \frac{1}{\mu_0}\frac{B_r}{\mu_r} L_M \tag{2}$$

where H_{CB} is the magnetic coercive force, L_M is the magnetization direction thickness, B_r is the remanent magnetic flux density, μ_r is the recoil relative permeability of a permanent magnet, and μ_0 is the permeability of the vacuum.

By the way, all that is required is that B_g or I_M is increased to bring about an increase in F without increasing the size of the motor, as is clear from Eq. (1). If you want to increase B_g, you have to supply more current, but that leads to a decreased efficiency in the motor. There are two methods to increase I_M. One is to use a stronger magnet, and the other is to add two side magnets to a main magnet, which means that the number of hypothetical coils is increased. This method shows that an equivalent current is twice as great, as is shown below:

$$F = B_g \cdot 4I_M \cdot L = 4\left(B_g \cdot \frac{1}{\mu_0}\frac{B_r}{\mu_r} L_M \cdot L\right) \tag{3}$$

Table 1. Target Specifications.

Type	Opposite Piston
Output Power	75W
Motor Efficiency	90%
Dimension	Less thanφ 88×195mm
Lifetime	Over 50,000hr

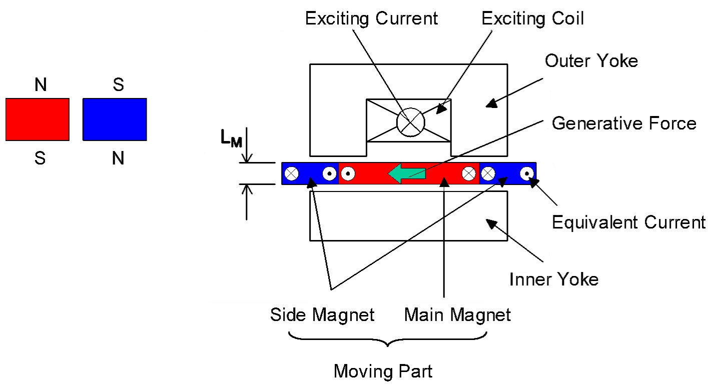

Figure 1. Pattern Diagrams of a Moving Magnet.

PRIMARY SIMULATION RESULT

In this section, we show only the behavior of a magnetic flux at a neutral position as the primary results. The other results are described in the following sections. A magnetic flux density and a line of flux without current are shown in Figure 2 and Figure 3, and then with an applied current of 1.6 A in Figure 4 and Figure 5. This simulation used the general purpose analysis software, ANSYS 9.0, and a 2-D axisymmetric electromagnetic field analysis.

Without supplying current to an exciting coil, the magnetic flux is looped between a magnet and the leg of an outer yoke. These loops of the flux create an axially stable state. Namely, the center position of the moving part is automatically determined when there are side magnets. This provides a great advantage compared with a single magnet configuration.

With an appled current of 1.6 A, the magnetic flux flows through a whole outer yoke and causes a concentration of the flux at the bottom side of each leg of the outer yoke. The force is generated in the direction which is relaxed by an imbalance of the energy, that is, the upper side.

ELEMENT EXPERIMENT

Experimental Setup

A cross section of the experimental element model is shown in Figure 6. And an outline of the experimental setup to measure generated force is shown in Figure 7.

To examine the effectiveness of the side magnets, the moving part is prepared in four distinct configurations, which are different according to the lengths of the side magnets. An outer yoke

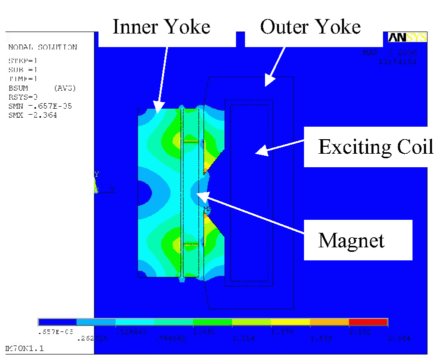

Figure 2. Magnetic Flux Density without Current in a Neutral Position.

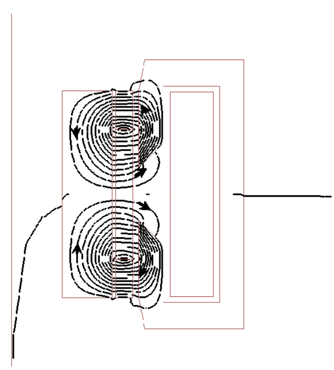

Figure 3. Lines of Magnetic Flux without Current in a Neutral Position.

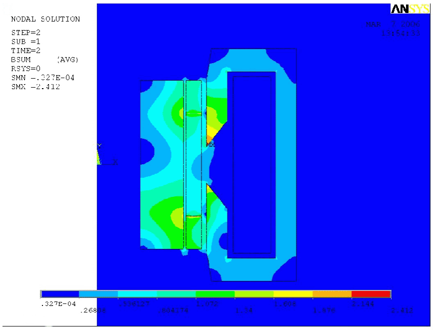

Figure 4. Magnetic Flux Density with Current of 1.6A in a Neutral Position.

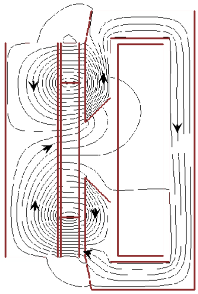

Figure 5. Lines of Magnetic Flux with Current of 1.6A in a Neutral Position.

consists of eight segmented steel blocks, which are arranged in a radial pattern.

The inner yoke and the outer yoke are fixed on a supporting flange that is made of stainless steel. A main magnet as a moving part is a ring geometric neodymium magnet, and two side magnets have reverse poles relative to the main magnet. A magnet holder containing a set of magnets is connected to a mock piston which rolls on a slider. Because this element model shows the measurements in a static manner, the moving part has no supporting structures, for example, flexure bearings.

The generated force is estimated by a force gauge attached to the head of a mock piston. The piston displacement from a neutral position is determined by a laser displacement meter.

Result and Discussion

In this test, we measured the restoring force by magnets without current and a net thrust with three current conditions.

First, the restoring force, which represents different side magnet lengths, is shown in Figure 8. When a moving part has no side magnet, the restoring force in an experiment as well as in a simulation is about 0 N. With side magnets, the restoring force shows increases monotonically as the displacement increases. But this does not mean that the longest side magnet has the strongest restoring force, in fact, the side magnet length of 8.5 mm has the strongest restoring force under a 3.7 mm displacement. In this case, the value of the simulation is a little larger than the experimental one, but both values show an approximately equal trend. The difference between the experiment and the simulation is about 10 % under a 2 mm displacement, and 15 % or so at a 4 mm displacement.

Second, the relation of generated force to supplied current in the neutral position is shown in Figure 9. We can see the true increased effect of side magnets without a restoring force. The greater the length of the side magnets, the greater is the generative force. The generative force of the side magnet at a length of 10 mm is 1.6 times greater than at a length of 0 mm. The computational value is also equal to the experimental value.

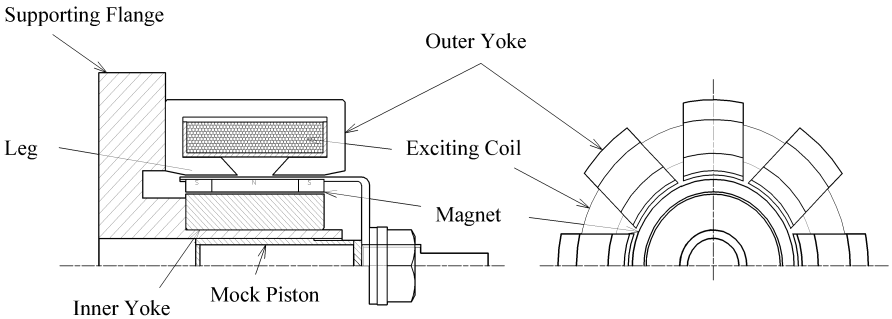

Figure 6. Cross Section of the Element Experimental Model.

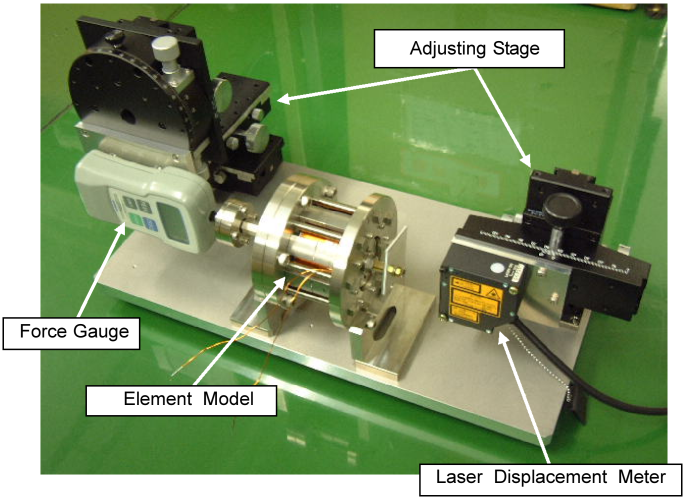

Figure 7. The Experimental Setup to Measure Generative Force.

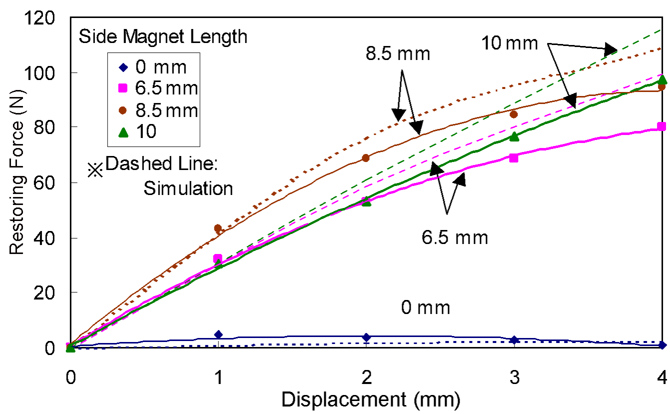

Figure 8. Restoring Force without Current.

Finally, the generative forces of the side magnet at lengths of 0 mm and 10 mm are each shown in Figure 10 and Figure 11. Without side magnets, the generative force decreases as the displacement increases. The experimental and simulated curves decrease in the same way, but the difference gets larger with an increasing displacement, up to 10 %.

When there are side magnets, the generative force obviously decreases steeply in comparison with no side magnets. This means that the restoring force cancels the net generative force. With an input of 1.6A, this motor is able to displace only 3 mm even with no load.

From these results, we found that a total design which includes a gas spring, a mechanical spring and a magnetic spring (for restoring force) is important when using side magnets.

CONCLUSION

The results of measuring the restoring force and the generative force are as follows:

- The increased effect of the generative force when there are side magnets of 10 mm is 1.6 times greater than without magnets.
- The restoring force with side magnets differs according to their length, with a length of 8.5 mm creating the greatest force. The results of both the experiment and the simulation are in good agreement.

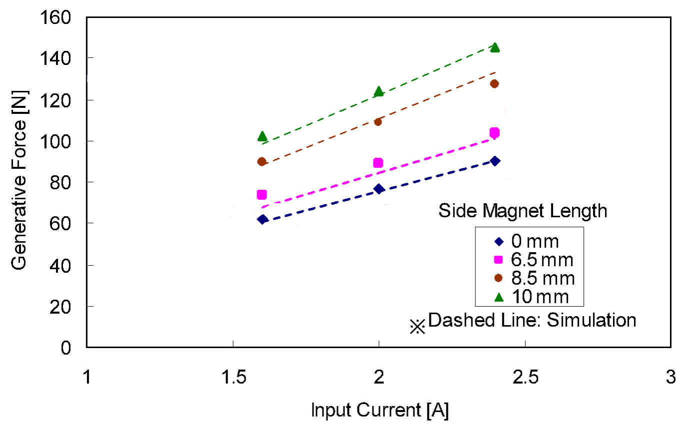

Figure 9. Generative Force at Neutral Position

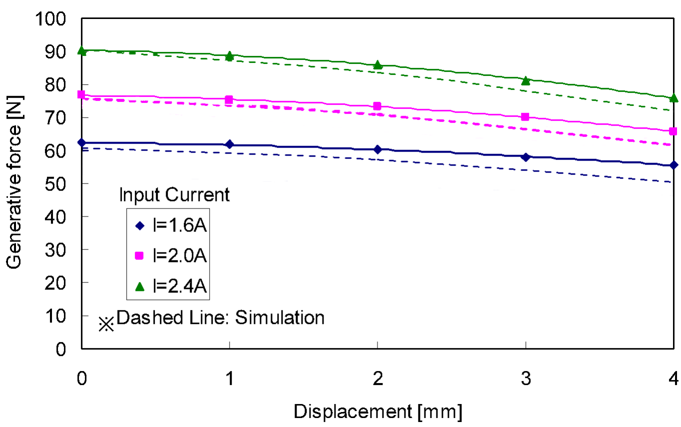

Figure 10. Generative Force without Side Magnet

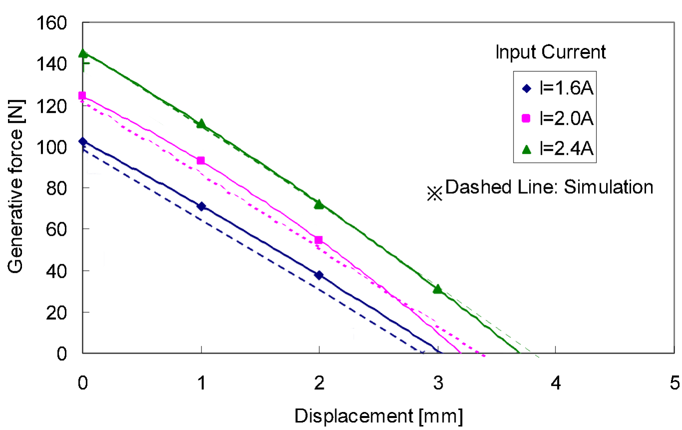

Figure 11. Generative Force with Side Magnet Length of 10mm.

- The generative force decreases slowly without side magnets, but the generative force with side magnets decreases steeply until it is cancelled by the restoring force. There is a limit to the piston stroke.

ACKNOWLEDGMENT

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