Development of the Miniature Flexure Bearing Cryocooler SF070

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ABSTRACT

Enhancement of reliability is still a major goal for the development of today's tactical cryocoolers. For linear coolers, the introduction of the Flexure Bearing technology enables Mean Time To Failure (MTTF) of 20,000 hrs. or more. This results in a significant reduction to the total cost of ownership for the IR devices. Recently, AIM has introduced the flexure bearing cooler SF100 in the one watt class with a full Flexure Bearing suspension on both ends of the driving mechanism and a Moving Magnet driving mechanism. This solution meets performance data, environmental specifications and even form factor requirements of the current standard linear coolers. The transfer of the above-mentioned technologies to the entire range of linear coolers at AIM is in progress. Typically, such transfer to devices with smaller form factors is more demanding compared to devices with less stringent form factor requirements. The paper reports on the development of a compact ¾W Flexure Bearing Moving Magnet cooler, designated the SF070. This paper gives an overview of the design considerations, in order to achieve highest compactness and presents performance data of the cryocooler when being operated with a 8 mm Stirling cold finger in sleeve design. The cooler is characterized for ambient temperatures ranging from -40°C to 71°C with cold tip temperatures from 67 K to 90 K.

MOVING MAGNET AND FLEXURE BEARING - NEW DESIGN, NEW RULES

The state of the art compressors for linear Stirling coolers are designed with moving coils. Moving coils are well known and their performance is easy to predict owing to the fact that all losses can be accounted for with simple formulas. The lifetime of these compressors is limited by the outgassing of organic materials out of the coils into the helium vessel. Encapsulating the coil is possible, but contributes to increased complexity of the compressor because of the needed electrical feed-through. Also the connection wires need to oscillate together with the moving coils. All these issues can be avoided by using moving magnets. The coils can be placed outside the helium vessel. Therefore there is no contamination coming from the coils and there is no need for a helium-tight electrical feed-through.

Another life limiting factor for linear compressors is the wear-out of the piston coating. The state of the art solution for this is the use of full flexure bearing support on both sides of the driving mechanism, which is well known from space cryocoolers. Standard linear coolers with spiral springs need free space for the piston stroke on both sides of the reciprocator. In contrast for flexure bearings it is necessary to have the piston stroke on both sides of both flexure bearings free. Therefore,

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the minimum necessary void volume in a flexure bearing compressor is doubled compared to a standard compressor without flexure bearings.

There are a lot of advantages which argue for the flexure bearing and the moving magnet design, however, this technology brings with it new issues which have to be solved in order to achieve an optimal compressor.

Iron losses

Iron losses occur due to the changing magnetic fields in electrically conductive materials and also depend upon the rate of this change. The eddy current losses even depends on the square of the frequency. In the standard linear coolers the magnets and thereby their fields are stationary, only the coils and the coil carrier see a notable changing magnetic field. As the name implies, in the moving magnet design the magnets and thereby their induced electromagnetic fields are in motion with respect to the compressor as a unit. Therefore, there are some differing design rules for an optimized compressor with moving magnets. All parts that move relative to the magnetic fields (or in this case that are stationary in the compressor and within the moving fields) should be made of electrically low or nonconductive materials. The volume of the remaining conductive materials should be reduced and/or moved away from the impact zone of the fields as much as possible. In addition to reducing the frequency and lowering the volume of conductive materials, iron losses can also be lowered by reducing the length traveled in the field; here that translates to limiting the piston stroke.

Figure 1 shows the measured iron losses of the SF100 (one side of compressor) depending on the stroke of the piston for two different stator yoke materials having different electromagnetic properties.

To have a specified cooling capacity a specified pV-power is needed. There are two possibilities to reduce the piston stroke: increase the piston diameter or run at a higher frequency. Will an increased piston diameter ultimately lead to an increased compressor efficiency?

To answer this question, the resonance conditions of the spring mass system has to be investigated. The spring consists of two parts. The mechanical spring, in the form of a spiral spring in the AIM moving coil cooler without flexure bearings SL070 and two Flexure-Bearing springs in the new SF070, and the gas spring. By increasing the diameter of the piston the gas spring stiffness will also be increased. To be in resonance it is therefore necessary to either reduce the mechanical spring rate or to increase the mass of the reciprocator. Another typical method to bring the spring-mass system into resonance is to adjust the helium pressure. A lower working gas pressure will decrease the resonance frequency, but will also increase the iron losses because now to maintain the same

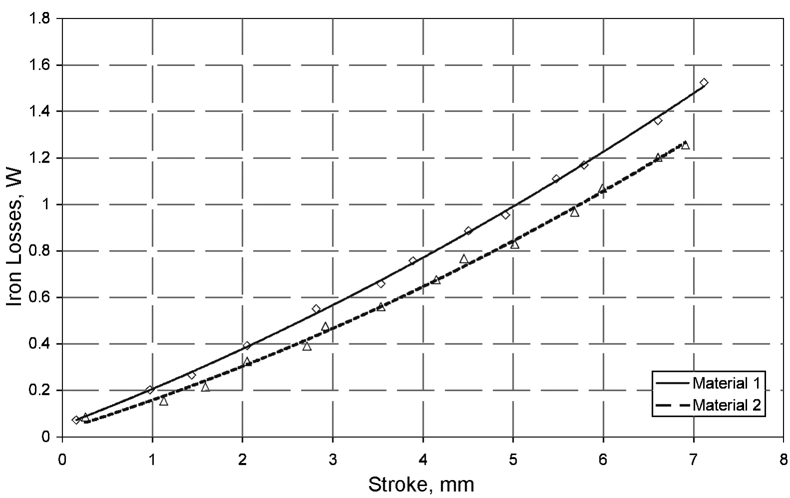

Figure 1: Iron losses for different soft iron materials (measured values taken from SF100)

pV-power the stroke must be increased. It is also possible to work at higher operating frequencies. The idea of adjusting the operating frequency deserves closer attention.

To do this we need to examine more closely the origins of iron losses. Iron losses are caused by two effects. First there are the hysteresis losses, P_H. They are directly proportional to the operating frequency, f:

$$P_H = f \cdot W_H \tag{1}$$

where W_H is the material specific work for one hysteresis loop.

The second part, the losses caused by eddy currents, $P_{E,}$ are proportional to the square of the operating frequency:

$$P_E = \frac{U^2}{R} \tag{2}$$

with the induced voltage

$$U \sim f \tag{3}$$

To increase the operating frequency does not really solve the problem because it will also lead to an increase in the iron losses. If we take care of the resonance condition it would seem to be possible to reduce the iron losses by increasing the piston diameter. But will this be sufficient to build an optimal compressor? Nevertheless, it is important to reduce the iron losses by using materials with the highest possible electrical resistance and also to minimize the volume of these materials.

Copper losses

A second major loss mechanism of a linear motor is copper losses. As discussed before it would seem to be beneficial to minimize the piston stroke in order to reduce the iron losses. But looking at the fundamental physical regarding copper losses reveals the problem. The pV-power, P_{PV} can be calculated as follows:

$$P_{PV} = f \cdot F \cdot s \tag{4}$$

Without changing the frequency a reduced piston stroke leads to higher needed forces. The force *F* of an electromagnetic drive is given by the following equation:

$$F = B \cdot I \cdot n \tag{5}$$

where *B* is the field strength, *I* is the current, and *n* is he number of turns in the winding.

For a moving magnet system a higher B-field will increase the iron losses. Secondly the achievement of a constant force over the full stroke length is more demanding. Matsumoto[1] describes the influence of additional magnets on the force of the compressor drive. The generative force was increased by 1.6 times. Also described is the impact of the additional magnets on the restoring force without current. This may be a problem if the compressor has to work regardless of direction. The pistons of an upright compressor will sag from their resting positions. The lower piston will sag in the direction of the compressor back, the upper one in the direction of the compression space. This results in different forces acting simultaneously; one reason for vibration output.

The best solution is to increase the number of windings in the coils. But this needs a lot of space. To double the force without increasing the copper losses it is necessary to quadruple the coil cross-sectional area.

Induction loses

When using a compressor drive with coils having a large cross-sectional area induction becomes more important. To estimate the influence on the compressor performance it is necessary to take a look at the underlying physics. Following Faraday's Law of Induction,

$$U_L = n \cdot \frac{d\Phi}{dt} \tag{6}$$

where Φ is the magnetic flux through the circuit, and

$$\frac{d\Phi}{dt} = \omega \cdot \hat{\Phi} \cdot \cos(\omega t) \tag{7}$$

and

$$\cos(\omega t) = \sin(\omega t + 90°) \tag{8}$$

The induced voltage in the coil depends on the number of windings and the rate of change of the magnetic flux (Φ). In principle, both will be increased by larger coils. The equivalent network of the coil and it's influence on the power factor is shown in Figure 2.

The calculation of the power factor of a complex coil and soft iron system such as that found in a linear compressor is challenging as there is no closed solution available. But in a moving magnet drive there is additionally the influence of the B-field of the magnet. To calculate the impedance of this coil a finite element analysis is now needed.

Figure 3 shows the measured power factors of a SL070 (moving coil) and a SF070 (moving magnet) cooler during operation at room temperature and a cold tip temperature of 77 K. As expected from theory the maximum power factor under resonance conditions is constant in the relevant range of operating frequencies for the moving coil driving mechanism in the SL070 compressor. On the other side the maximum reachable power factor of the moving magnet compressor will decrease with higher frequencies under resonance. At higher frequencies the influence of the induced voltage in the coils will be increased.

MINIATURE FLEXURE BEARING CRYOCOOLER SF070

Based on the design rules described above AIM has developed two miniature Flexure Bearing Compressors for use in long life applications. The first development was the SF100, a compressor with the same interface as the standard One Watt Linear (OWL) cooler SL100. More details are given in the work by Rühlich, et.al.[2]

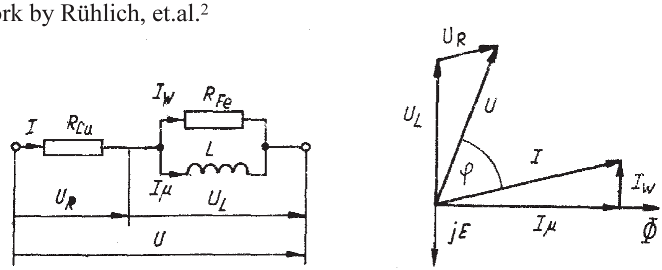

Figure 2: Equivalent network and vector diagram of a coil

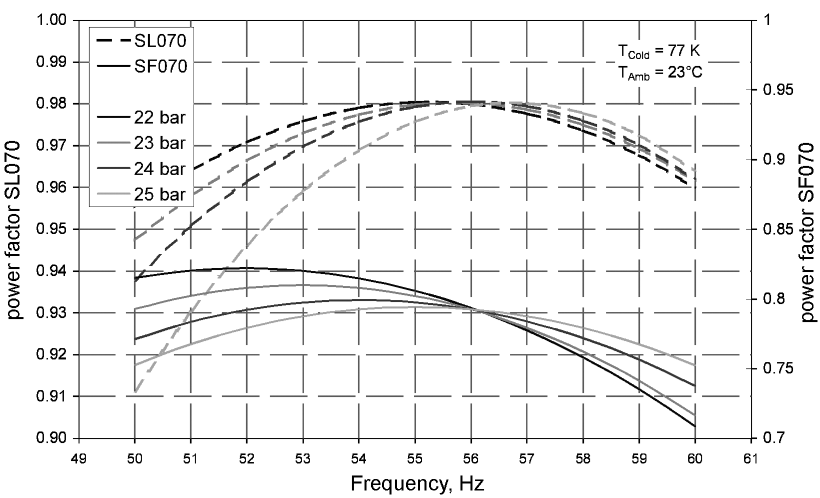

Figure 3: Power factor of SL070 and SF070 depending on frequency and gas pressure

Figure 4: SF070 with 8 mm sleeve coldfinger

The second compressor of the AIM Flexure Bearing series is the SF070 shown in Figure 4. It is the long life version of the standard linear compressor SL070. The dimensions of the new flexure bearing compressors compared to their moving coil counterparts are shown in Table 1. Even though the additional space was necessary for the piston stroke, it was possible to reach the same external dimensions for the SF series as for SL series. The SF070 is even shorter than the SL070.

To reach the same performance data as the SL070 (see Figure 5) it was necessary to reduce the iron losses by using painstakingly chosen materials and to decrease the volume of the magnets. It also was necessary to increase the coil volume to reduce the copper losses.

Due to the reduction of the magnet volume it was also possible to reduce the volume of the soft iron. The extent of the change of the volume for the different parts is given in Table 1.

Table 1: Design parameter of the SF series compared to the SL series

		SL100	SF100	SL070	SF070
Diameter [mm]		60.45	60.45	44.4	44.4
Length [mm]		122	122	128.5	113
Mass [kg]		1.72	1.68	0.992	0.857
Volume relative to SL compressor	**Copper [%]**	100%	547%	100%	467%
	Magnet [%]	100%	20%	100%	21%
	Iron [%]	100%	48%	100%	54%

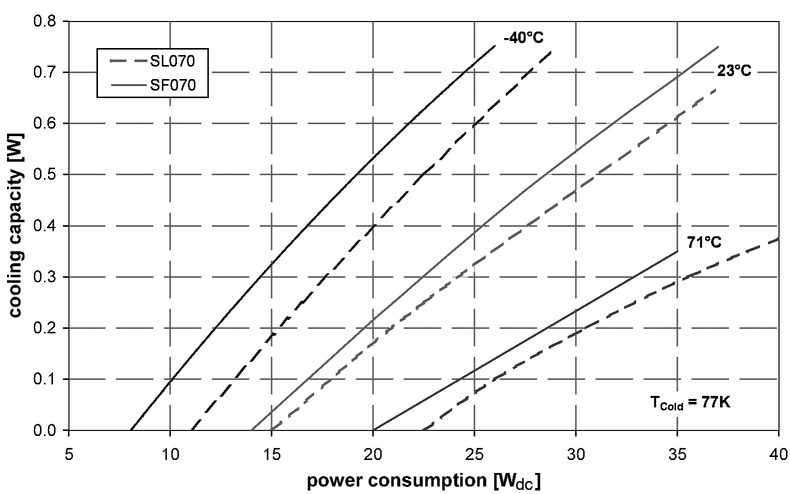

Figure 5: Performance data of the SF070 compared with the SL070

CONCLUSION

The new generation of linear coolers are designed with full Flexure Bearing suspension on both ends of the driving mechanism and a Moving Magnet driving mechanism. Different design rules are effective, as compared to the standard linear compressors with moving coils and spiral springs for this type of compressor, . To design an efficient and compact compressor, it is necessary to take care about the moving magnet specific losses. As shown in this paper, the maximum reachable power factor and the iron losses depend upon the operating frequency. For very high frequencies as described by Radebaugh[3], special design rules known from the high frequency technology need to be applied.

AIM has designed a new Flexure Bearing compressor series. First was the SF100, second the miniature compressor SF070. One design goal for the development of the SF070 was to reach at least the performance data of the SL070 without increasing the outer dimensions. The development leads to a compressor with the same diameter and even with a decreased length. Despite the drawbacks of a reduced power factor together with additional iron losses, as compared to the SL070, the overall motor efficiency is increased.

REFERENCES

1. Matsumoto, N., Yasukawa, Y., Ohshima, K., Takeuchi, T., Yoshizawa, K., Matsushita, T., Mizoguchi, Y., Ikura., A., “Development of a Compressor for a Miniature Pulse Tube Cryocooler of 2.5 W at 65K,” *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 327-333.

2. Rühlich, I., Mai, M., Wiedmann, Th., Rosenhagen, C., “Flexure Bearing Compressor in the One Watt Linear (OWL) Envelope ,” Proc. SPIE, Vol. 6542, pp. 654221-1 to -7, 2007.

3. Radebaugh, R., O’Gallagher, A., “Regenerator operation at very high frequencies for microcryocooler,” *Adv. in Cryogenic Engineering*, Vol. 51, Amer. Institute of Physics, Melville, NY (2006), pp. 1919-1928.