AIM Cryocoolers for Harsh Environments

M. Nussberger, I. Rühlich, M. Mai, C. Rosenhagen, T. Wiedmann, S. Zehner

AIM Infrarot-Module GmbH, Heilbronn, Germany

ABSTRACT

State-of-the-art high performance IR-sensors still require cooling by means of cryocoolers to achieve their electro-optical performance. In many applications such as guided missiles, rifle and gunner sights, fighter aircrafts, helicopters or launch vibrations for space applications, the system including cryocooler has to withstand Harsh Environments. Depending on requirements like heat load, operating temperature, size weight and power constraints (SWaP) as well as exported vibrations different types and sizes of coolers are used.

Several aspects of compressor and coldfinger design like moving magnet driving mechanism, flexure bearing design, transferline or stiffness of coldfinger/dewar will be discussed. Design features to meet such requirements will be presented for different single and dual piston linear compressors. This includes compact single piston cryocoolers for high operating temperature (HOT), low SWaP coolers like SX020 and long life flexure bearing coolers like SF400 pulse tube cryocoolers for space applications. Specific modifications, vibration profiles and testing results are discussed.

INTRODUCTION

In many applications such as guided missiles, rifle and gunner sights, fighter aircrafts, helicopters or launch vibrations for space applications, the system including cryocooler has to withstand Harsh Environments. To fulfill typical requirements in several different types of harsh environment a design inherent solution is needed.

The following sections give an overview on different design features to meet such requirements. This includes moving magnet motors, flexure bearing technology, design of end stops for single piston cooler with passive balancer and design of coldfinger without additional mechanical support [1] [2].

A short overview of different cooler types and qualified profiles is given.

DESIGN FEATURES

Moving Magnet Motors

AIM has designed compressors with Moving Magnet Motors to withstand harsh environments. A principle design is shown in Figure 1. The design allows positioning of the coil winding outside of the helium vessel. This removes a potential source of contamination. Furthermore, it enables the removal of the electrical feedthrough and the flying lead to support a moving coil. The statistical failure rate is therefore reduced [1] [2].

The Magnet Assembly is fully encapsulated under a stainless steel cover. The Piston-Magnet Assembly is further designed to withstand hitting the end stop even under harsh shock and vibration environment.

Cryocoolers 21, edited by R.G. Ross, Jr., J.R. Raab and S.D. Miller

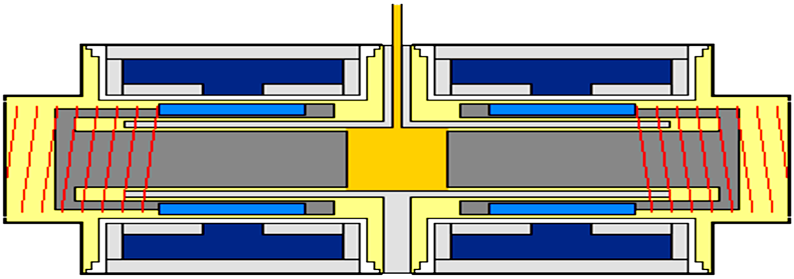

Figure 1. Principle design of AIM moving magnet compressors

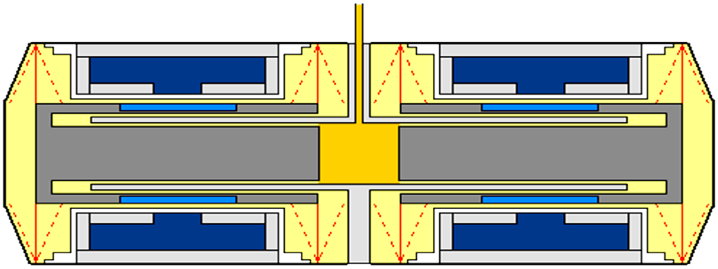

Figure 2. Principle design of AIM flexure bearing moving magnet compressor

The only threaded connection of the entire drive assembly is between Piston and Magnet Assembly. All soft iron components of the coil winding assembly are welded.

Flexure Bearing Technology

To increase MTTF life AIM combined the Moving Magnet Motors with Flexure Bearing Technology to entirely eliminate the piston wear out mechanism [1] [2]. The principle design of an AIM Flexure Bearing Moving Magnet Compressor is shown in Figure 2.

The springs are welded to the Piston-Magnet Assembly and the outer housing. The elongation in radial direction is limited due to the small piston gap. The elongation in axial direction is within the endurance range of the material even when hitting the endstops.

To ensure the mechanical robustness the mechanical structure was designed by FEA. As an example, the FEA of the spring tension at full stroke for a SF100 Flexure Bearing spring is shown in Figure 3.

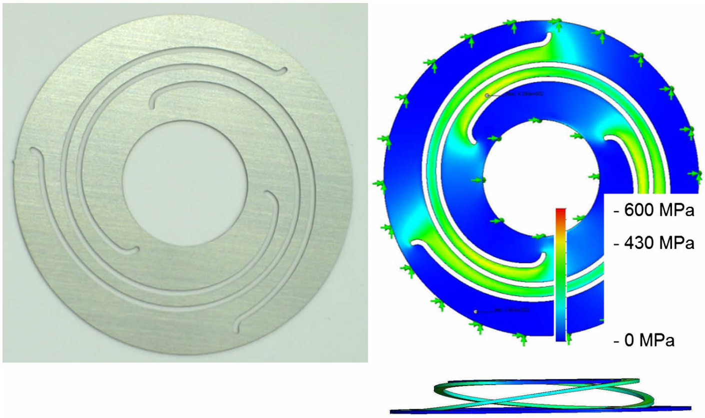

Figure 3. SF100 Flexure Bearing and FEA - spring tension at full stroke

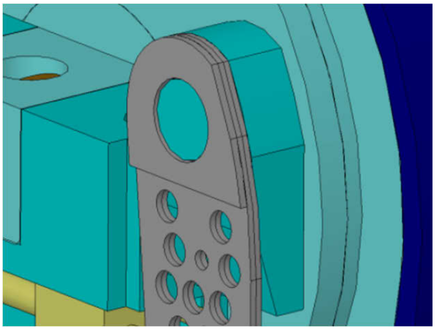

Figure 4. Detail of SX020 Legs

Figure 5. SX020 Compressor with 5mm Coldfinger

Mechanical Characteristics of Single Piston Coolers

In order to achieve low exported vibration there are in general two options: to either use a dual opposed piston compressor or a single piston compressor with passive balancer [4]. A Single Piston Compressor with Moving Magnet Technology without passive balancer is analogous to a dual opposed piston compressor design and is inherently mechanically robust. To meet the goal of high mechanical robustness even with a passive balancer, AIM has designed a harsh environment version of the SX Single Piston Compressors [3].

A key aspect of the design was a robust solution for the compressor legs. The legs are necessary to enable a small movement of the compressor in axial direction. This movement is needed to excite the movement of the passive balancer to thus reduce the exported vibration. An example of the advanced leg design is given in Figure 4. As can be seen a two-layer perforated spring design is used. On top of that, in the welding region, a reinforcement is implemented to achieve mechanical robustness.

Besides the new leg design, another improvement was implemented. In order to limit the possible movement of the compressor in axial direction to prevent over-stroke of the legs, soft endstops were added. Those endstops are shown in Figure 5. As a result, the improved single piston compressor with passive balancer is even able to withstand Gun-Fire-Requirements in the compressor longitudinal axis.

To avoid jumping resonance caused by the implemented soft endstops they must be designed properly. Therefore, the cooler operating frequency (i.e. the resonance frequency of the passive balancer) and the jumping resonance of the compressor assembly when hitting the soft endstops must not be too close to each other.

The result is shown in Figure 6. There can be seen the measurement of the resonance of a SX020 compressor. As can be seen there is a gap between the resonance of the endstops and the damping resonance of the balancer. Because the damping resonance of the balancer equals the driving frequency in

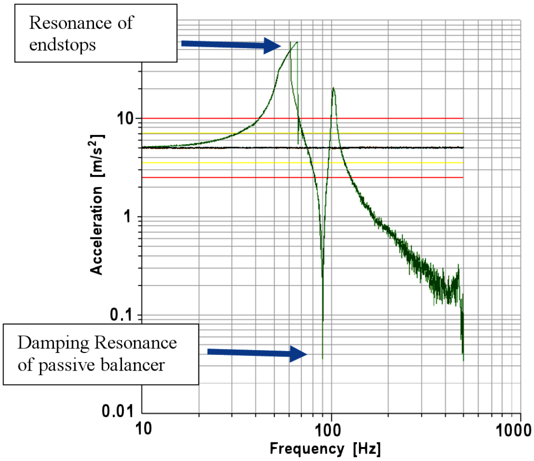

Figure 6. Resonance of SX020 for Harsh Environment

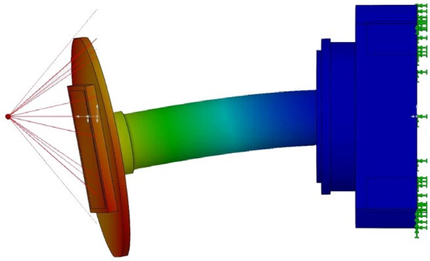

Figure 7. Simulation for 5mm coldfinger

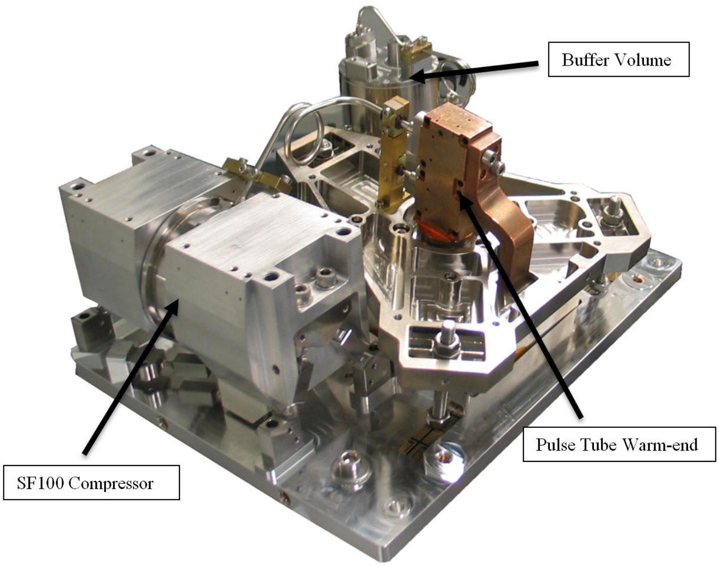

Figure 8. SF100 with Pulse Tube for EnMAP

order to achieve low exported vibrations, the risk of the jumping resonance is avoided through the design inherent solution of a sufficiently large gap between the resonance frequencies.

Stiffness of Coldfinger

The design of coldfinger depends on the weight of the detector and coldshield. The mechanical robustness of the dewar (e.g. bonds) can be more critical than the mechanical robustness of the cooler.

For a given material, the stiffness of the coldfinger depends on its length, diameter, and wall thickness. Achieving higher stiffness is thus opposite to the target of low thermal load. In order to achieve a sufficient robustness, a typical target in coldfinger/dewar design is a first eigenfrequency in excess of 800 to 1200 Hz.

Figure 7 shows a simulation for a compact 5 mm coldfinger with 100 µm wall thickness for usage with the SX020 compressor. The result is a first eigenfrequency of 1050 Hz with 1.85 g for detector including coldshield. Therefore, there is no additional mechanical support needed.

SPACE APPLICATIONS

SF100 German EnMAP Mission

For the German EnMAP Mission, AIM build up a SF100 Flexure Bearing Moving Magnet Compressor with Pulse Tube Coldfinger [5]. The assembly is shown in Figure 8. It consists of the SF100 Compressor, Pulse Tube, and Buffer Volume. The cooler is fully qualified. Like for all other AIM linear coolers, there is also no launch lock needed for SF100 compressor.

Table 1. SF100 EnMAP Qualification Tests

Test	Freq.[Hz]	Level	Rem.
Sinusoidal Vibration Tests	5-21	11mm (0-peak)	no notching
	21-60	20 g (0-peak)	
	60-100	6 g (0-peak)	
Random Vibration Tests	20-110	+3dB/oct.	
	110-700	0.09g²/Hz	$11.12 g_{rms}$
	700-2000	-3dB/oct.	
Shock Tests	**Freq.[Hz]**	**Shock spectrum (Q=10) [g]**	
	30-50	5-10	
	50-100	10-80	
	100-700	80-1000	
	700-1000	1000-2000	
	1000-1500	2000-2800	
	1500-4000	2800-4000	
	4000-5000	4000	

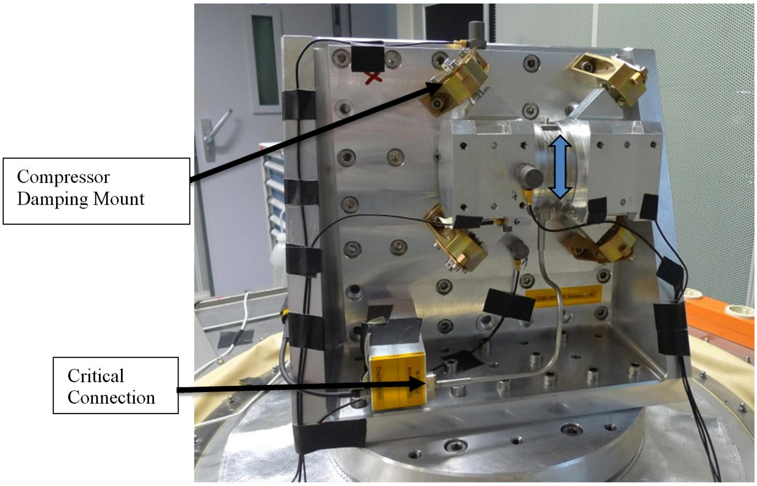

Figure 9. SF400 mounted on Shaker for environmental tests

For qualification, the assembly went through different sinusoidal, random vibration and shock tests. The levels of the different types of tests are shown in Table 1.

SF400 Launch Mechanical Vibration

AIM SF400 Compressor for Space Application was also tested on mechanical vibration. Figure 9 shows a SF400 Compressor with Damping Mount on a Shaker for environmental tests. Within the signed transversal axis, a small movement of the compressor is possible due to the damping mount. It is therefore necessary to tests the critical connection of the transferline for the required vibration profiles. Tests were successfully completed for the requirements shown in Table 2.

VIBRATION ENVIRONMENT

Random Vibration

AIM has several Coolers qualified for Random Vibration Environmental conditions. An overview for selected coolers is given in Figure 10. Included in the figure is the previously mentioned SX020 for harsh environments. The vibration profile is shown and equals 11.7 gRMS in transversal axis and 9.7 gRMS in

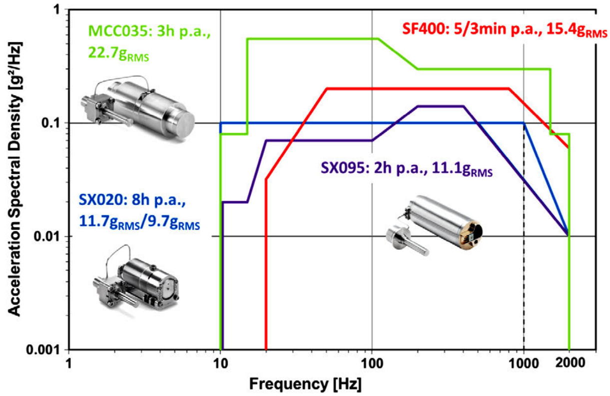

Figure 10. Random Vibration Profiles for selected AIM Coolers

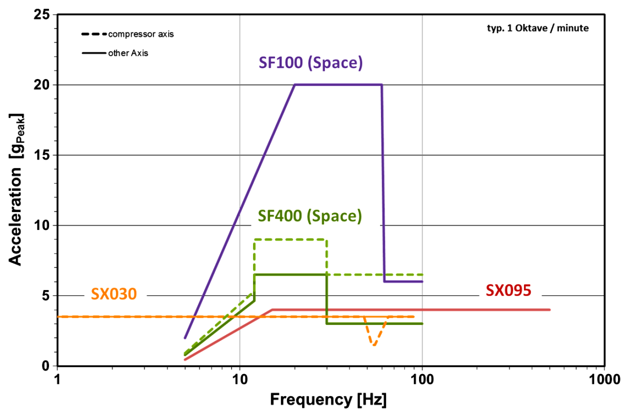

Figure 11. Sine Vibration for selected AIM Coolers

Table 2. SF400 Vibration

Sine Vibration:
±9.2mm @ 5-16 Hz
9.0g @16-50Hz
6.5g @ 50-100Hz

Random Vibration:
0.114 g^2/Hz @ 20-2'000 Hz
15 g_{RMS} flat random

the compressor longitudinal axis. The testing time was 8h per axis. For MCC035 there is a harsh environment profile, which was tested for 3 h per axis. The total amount of the profile equals 22.7 gRMS. The SX095 Cooler was tested for 2 h per axis with a Random Vibration Profile that equals 11.1 gRMS. The last Cooler shown is SF400 with 5 min (qualification test) and 3 min (acceptance test) per axis for Launch Vibration. It equals 15.4 gRMS, which was shown earlier in Table 2.

Sine Vibration

There are Sine Vibration Profiles for different coolers shown in Figure 11. There can be seen two Space Applications of SF100 and SF400. In addition, profiles are included for the SX095 dual piston cooler and a SX030 single piston cooler with passive balancer.

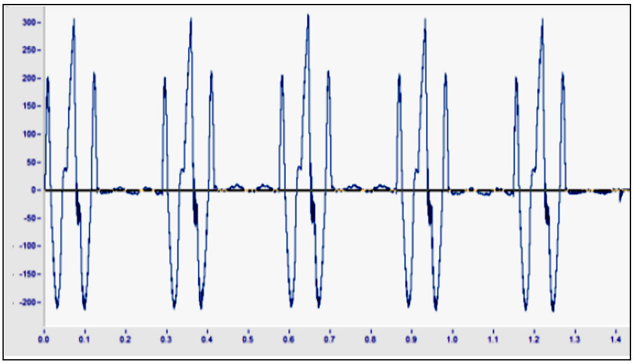

Figure 12. Burst sawtooth 30g / 30ms / 0.83 Hz

Gun-Fire Vibration

In handheld application, requirements often contain Gun-Fire Vibration. AIM has qualified Gun-Fire Requirements even for single piston coolers. The first one is SX030 for AIM rifle sight HuntIR Mk2. The requirement contained Infrantry Maschine Gun with 150 g / 0.5 ms / 14 Hz. The SX030 is fully qualified for this application. The second one is SX020 Gun-Fire Requirement. Gun-Fire Requirements often are represented as burst sawtooth shocks in a row. An example is given in Figure 12 which shows burst sawtooth shocks with 30g / 30ms / 0.83Hz.

The SX020 compressor was successfully tested for 18,000 shocks in total, 6,000 in each axis. The design inherent solution enables it to withstand harsh environments even in the compressor longitudinal axis.

OTHER ENVIRONMENTS

Besides the mechanical robustness against vibration, there are requirements for harsh environments such as rapid change of ambient air pressure or thermal shock in missile applications. A change of ambient air pressure from 100 kPa to 4 kPa in short time or from 71°C to -35°C in less than 2 minutes is typical. Several AIM coolers that were mentioned before are qualified for such environments.

SUMMARY AND CONCLUSION

AIM linear coolers with Moving Magnet Motors and Flexure Bearing design features are suitable for use in harsh environments. This ranges from small single piston coolers for HOT applications like SX020, to larger dual opposed flexure bearing moving magnet compressors like SF400 for space applications.

With improvements like soft endstops and optimized compressor legs, a single piston compressor like SX020 can even be used with a passive balancer in harsh environments. The design inherent solution provides the opportunity to use the compressor even in longitudinal axis.

The flexure bearing moving magnet technology in SF100 and SF400 makes it suitable for launch vibration. Therefore, it can be used even without a launch lock.

REFERENCES

1. M. Mai, I. Ruehlich, C. Rosenhagen, Th. Wiedmann "Development of the Miniature Flexure Bearing Cryocooler SF070," *Cryocoolers 15,* Kluwer Academic/Plenum Publishers, New York (2009), pp. 133-138.

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

3. Rühlich, I., Mai, M., Rosenhagen, C., Withopf, A., "AIM Cryocooler developments for HOT detectors," Proc. SPIE, Vol. 9070 (2014).

4. Nussberger, M., Rühlich, I., Mai, M., Rosenhagen, C., Zehner, S., Wiedmann, T., "Stirling-Kleinkühler für IR und andere Hochleistungssensoren – Stand und Entwicklungstendenzen," *DKV-Tagung 2019,* Ulm, Germany (2019).

5. Mai, M., Rühlich, I., Schreiter, A., Zehner, S., "AIM-Space Cryocooler Programs," *Cryocoolers 16,* ICC Press, Boulder, CO (2011), pp. 133-141.