Small Scale Cooler: Extending Space Developed Technology into Adjacent Markets

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ABSTRACT

Honeywell Hymatic in collaboration with Science & Technology Facilities Council (STFC), Rutherford Appleton Laboratory (RAL) have further developed the prototype design of the Small Scale Cooler (SSC) (Figure 1), presented at the Space Cryogenics workshop at ESTEC 2013 [1], to a production ready system capable of serving the original market i.e. space, but in addition serving applications such as EO/IR and radioisotope detection. The aim is to provide a SSC with low mass, cooling power of 0.75W at 77K and with high reliability built upon heritage design language.

This work builds upon the achievements of the initial prototype build by STFC with particular attention being paid to optimizing the overall cooler system efficiency, adapting the design for manufacture at production volume and accommodating differing system integration requirements, whilst maintaining a level of commonality suitable for multiple applications.

Productization activities include full system drawing release, definition of manufacturing and process methodology to assure product quality, development of tooling and assembly equipment, and procedures to build and test coolers.

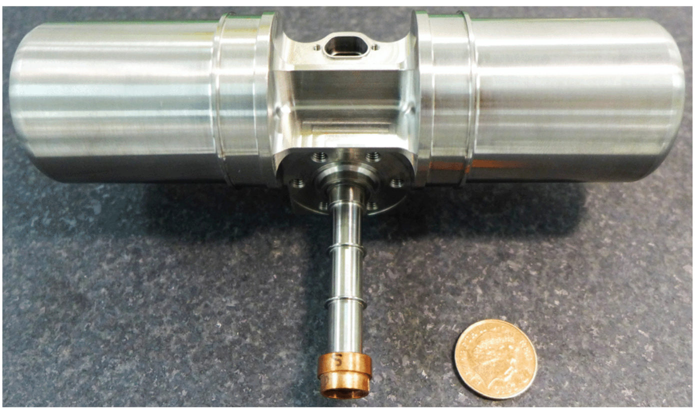

Figure 1. Photograph of the Small Scale Cooler next to a UK one penny coin for scale.

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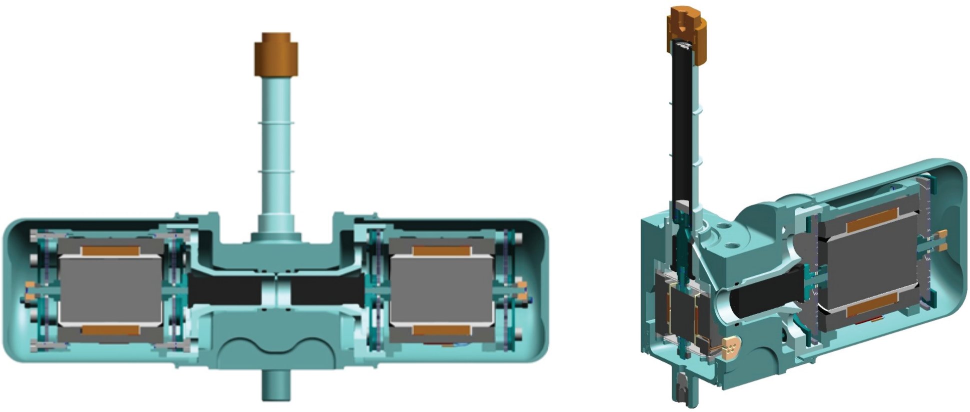

Figure 2. Cross sectional arrangements of the SSC showing the back-to-back compressor design with integral cold-head arrangement. Details of the motor arrangements have been omitted.

INTRODUCTION

Honeywell Hymatic has over 60 years experience in manufacturing JT coolers, Cryocoolers and Space Compressors (as used by Northrop Grumman e.g. the HEC Compressor). In 2013 Honeywell Hymatic signed a license with RAL to industrialize a Small Scale Cooler (SSC) for space and adjacent markets. Hymatic delivered a prototype SSC to an industrial customer for integration to a sensor and performance evaluation. Positive feedback and suggestions on improvements were received as a consequence. Continuous operation in the customers device, >12 months and counting, has resulted in no change in performance. This paper highlights the design characteristics of the SSC and the process of putting the cooler into production. The cross section of the SSC is shown in Figure 2.

DESIGN FEATURES OF THE SSC

The primary design features are as follows:

- Dual opposed compressor design for balancing.
- Displacer mechanism is driven by a small motor to allow for phase adjustment.
- Design based on RAL Space heritage and long life technology such as true clearance frictionless seals and flexure bearings.
- All Titanium welded body design for Helium hermetic gas retention and low mass.
- New moving magnet motor for both the compressor and displacer drive. Axially magnetized magnetic pair configuration obviating the need for inner iron cores.

The design parameters and prototype measured performance are as follows:

- Mass: 620g.
- Size: 152mm X 55mm X 102mm.
- Power Input: 22W.
- Lift: 500mW @ 77K (21°C ambient).
- Closed Loop Temperature Stability: ±5mK 10mins, ±30mK 1hr.

THE NEW MOTOR

The new motor design has advantages and disadvantages over conventional designs that must be considered.

Advantages:

- Lower part count and thus reduced bill of material costs. Lower part costs as a consequence of not having a moving coil former which introduces complexity. Additionally there is no radial magnetized magnet assembly that introduces component and process costs.
- Low magnetic interference with minimal external field.
- Stationary coil with no moving electrical connections.
- Enhanced design flexibility; to adjust frequency and easily scalable.
- Compact.

Disadvantages:

- Eddy current loss needs to be carefully controlled in order to minimize motor losses. This may be done by careful material selection.
- Radial magnetic force requires the careful selection and design of suspension springs with high radial stiffness.

VARIATION OF RADIAL FORCE AND MOTOR CONSTANT WITH RADIAL GAP

The moving magnets are located in an air gap defined by the magnet assembly on the inside, and the yoke on the outside. The magnetic forces are trying to make the moving magnet eccentric radially in the air gap, and these forces are opposed by the mechanical spring forces which are trying to center it. The radial magnetic force decreases with increasing radial gap according to an inverse square law which can be seen in Figure 3. It should be noted that the maximum radial force occurs at the mid-stroke.

From Figure 3 which shows the radial magnetic force at mid stroke when the magnet assembly is displaced eccentrically by a typical assembly clearance of 20 micron, it can be seen that a larger radial gap between the motor and yoke is beneficial as it reduces the magnetic side load. Figure 4 shows that there is a 13% decrease in motor constant when the radial gap is increased from 0.2mm to 1.2mm with a corresponding reduction in radial force by a factor of 10. It is important to consider this during the design of the motor in order to ensure that a true clearance can be maintained between the piston and cylinder.

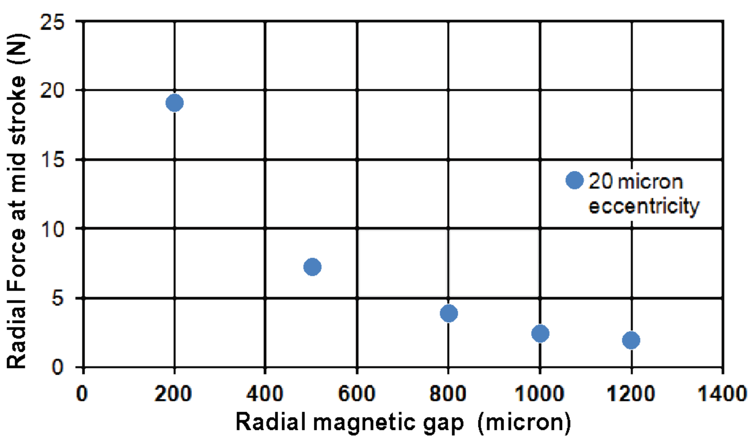

Figure 3. Plot of radial magnetic force vs radial magnetic gap. Data courtesy of RAL.

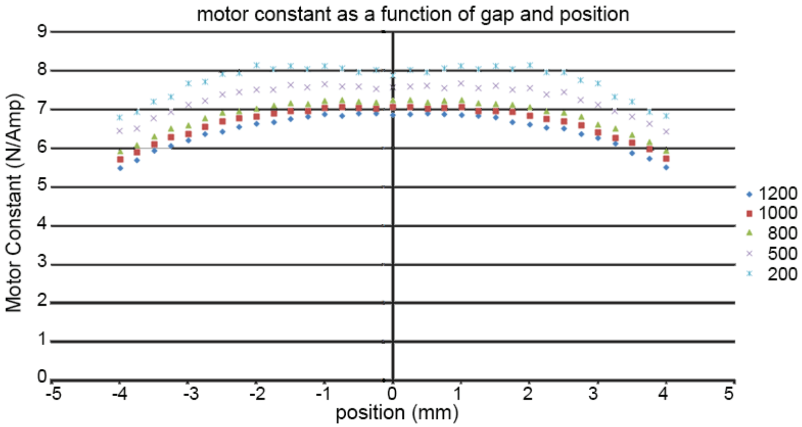

Figure 4. Plot of motor constant as a function of gap and position. Data courtesy of RAL.

Table 1 shows the radial stiffness due to the magnetic forces and the mechanical springs as a function of axial position. The radial stiffness is taken at a radial displacement of 0.22mm which is the radial bump stop position of the magnet assembly. Figure 5 shows the margin between magnetic and mechanical spring rates for the minimum number of springs, which is 2.

Table 1. Radial Spring Rates: Typical Motor Configuration

Axial Displacement (mm)	Radial Spring Rate at 0.22 mm radial offset (N/mm)			Factor of Safety
	Magnetic	Mechanical (2 springs)	Mechanical (6 springs)	
0	127.9	273.70		
3.3	93.1	138.75	416.25	4.47
3.96		111.76		
5		69.23		

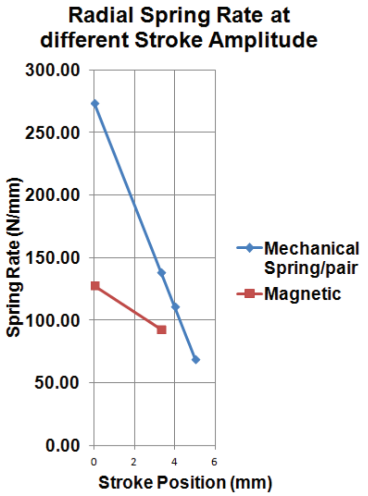

Figure 5. Plot displays how the mechanical radial spring rate has been designed such that it exceeds the magnetic radial spring rate. This is for 2 mechanical springs.

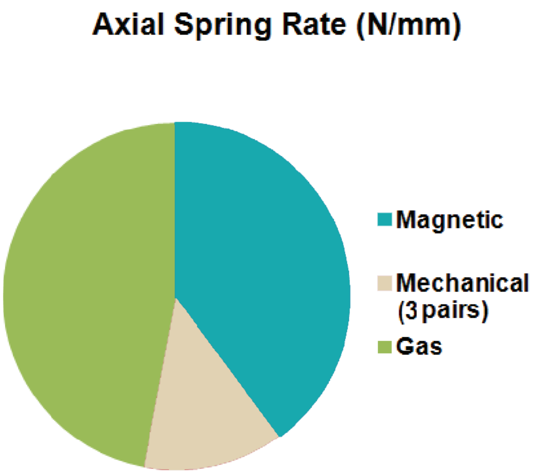

Figure 6. Proportional representation of motor axial spring rates.

AXIAL MAGNETIC SPRING RATE

The axial magnetic spring is a significant contributor to the total axial spring stiffness, the proportions of which can be demonstrated in Table 2 and Figure 6. With minor modifications to the motor configuration the desired spring rate can be varied whilst minimizing the change in motor force. This spring rate can be tailored to be positive, negative or zero as seen in Figure 7. With the contribution of the axial magnetic spring, this design lends itself to high operating frequencies due to the high additional spring rates.

Table 2. Axial Spring Rates: Typical Motor Configuration

Magnetic	N/mm	6.56
Mechanical (6 springs)	N/mm	2.16
Magnetic + mechanical	N/mm	8.72
Gas Spring	N/mm	7.74
Total	N/mm	16.45
Moving Mass	gram	49.23
Natural Frequency	Hz	92.00

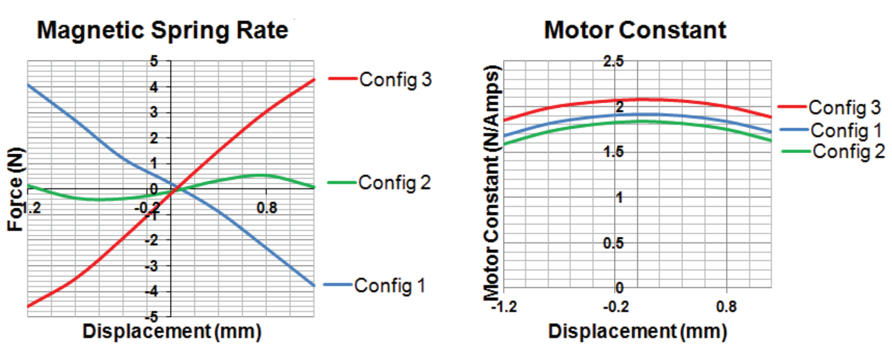

Figure 7. Shows magnetic spring rates for varying motor configurations and their corresponding motor constants. Data courtesy of RAL.

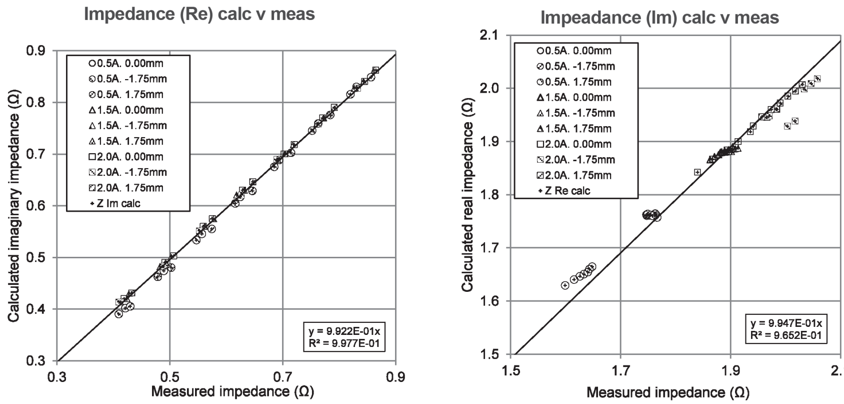

Figure 8. A comparison between measured total impedance and that derived from static analysis which displays a good agreement over a wide range of operating conditions. (f=60Hz-120Hz, I=0.5A-2.0A, x=-1.75mm-+1.75mm). Data courtesy of RAL.

SMALL SCALE COOLER MOTOR LOSS ANALYSIS

RAL developed a series of electrical models to understand the motor losses. The stator core was represented by a parallel inductance and resistance, and the total impedance included the winding resistance. Core losses arose from the 'core resistance' which was a function of geometry and operating conditions. Dynamic losses arose from the magnetic (back emf) damping. Static measurements (motor stalled) at various positions as a function of current and frequency gave the functional form of the core resistance, and also core inductance. Fits to simple functions could be made. Figure 8 shows the comparisons between measured impedance and the static analysis providing a good correlation over varying operating conditions. Dynamic measurements as a function of frequency and stroke included the back emf damping. Back emf damping was verified by free oscillation decay. Static, dynamic and Joule loss contributions could be separated, the results of which can be seen in Figure 9.

As a result the position waveform could be derived from the knowledge of the total impedance under particular operating conditions. This was compared to actual measurements using a laser displacement sensor as seen in Figure 10.

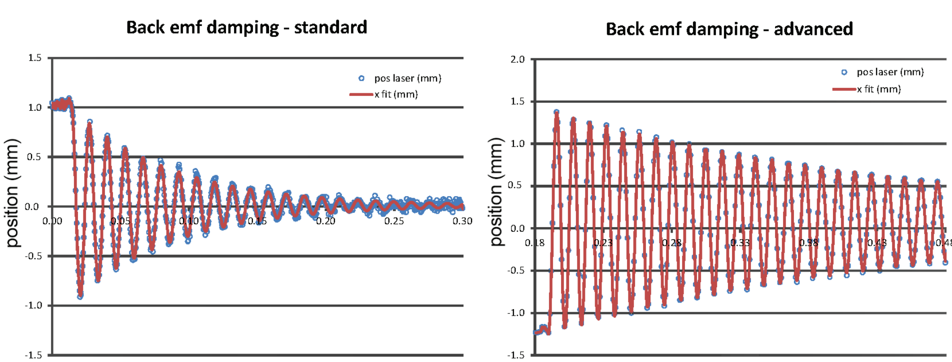

Figure 9. Dynamic measurements for Eddy loss reduction. Standard geometry – damping 1.6Ns/m. Advanced geometry – damping 0.36Ns/m. Data courtesy of RAL.

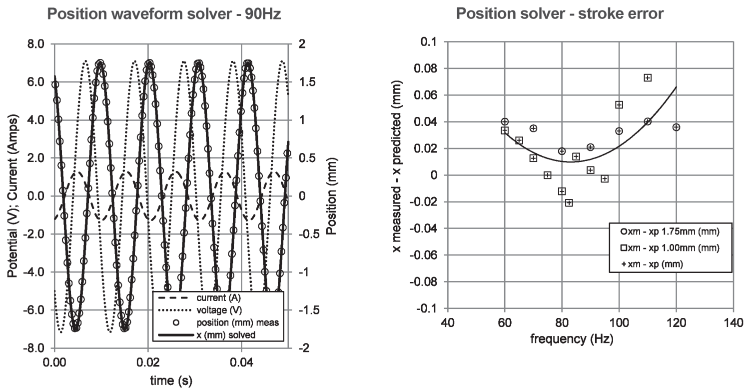

Figure 10. Comparison between measured position using a laser displacement sensor and derived position. Data courtesy of RAL.

PRODUCTIONIZATION PERFORMANCE ENHANCEMENT & PRODUCT RELIABILITY

As a consequence of the RAL development activities for the SSC and customer feedback from performance evaluations of the prototype, the following design modifications were implemented for the production model in order to match the cooler to the requirements of our industrial customer:

- Improved thermal management – modification of the centre plate design and heat sinking.
- Increasing the compressor stroke amplitude to 3.3mm for faster cool down and higher performance capacity.
- Improvements for the cold head phase control to further facilitate faster cool down. This focused on displacer modifications.
- Reduction of eddy current loss by interruption of the eddy current flow path.

The primary aim of these modifications is to drive the performance up to approximately 750mW at 77K (21˚C ambient) from the current performance of 500mW.

Design for reliability has taken lessons learnt from Hymatic heritage products used for space applications (such as the HEC compressors used by Northrop Grumman). Spring design has been taken through FEA stress analysis at over stroke positions as shown in Figure 11, in addition to practical testing whereby the following has been undertaken:

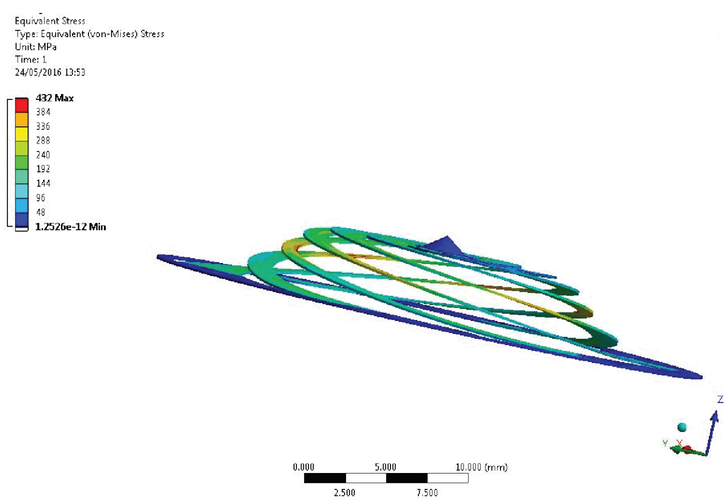

Figure 11. FEA performed on the compressor spring using ANSYS Workbench V16.2.

Compressor Spring Testing:

- 25% over stroke from mechanical stop position.
- 5mm amplitude during test.
- Fatigue testing completed to 800 million cycles.

Displacer Spring Testing:

- 25% over stroke as above.
- 1.8mm amplitude during test.
- Fatigue testing completed to 800 million cycles.

LINEARITY OF PISTON MOVEMENT

Linearity of movement of the piston throughout its stroke has been measured to be less than 8μm; however the following has been noted during assembly:

Sources of error and control:

- Piston movement is controlled by a pair of spring stacks at either end of the motor. The spring mounting faces must be parallel and concentric.
- Unbalanced radial magnetic forces cause piston radial misalignment. The magnetic and spiral spring stiffness must be matched to minimize the radial deflection. The magnet assembly must be centralized in the yoke at the zero force position.

Implementation:

- The manufacturing method for the spring mounting faces controls geometric tolerances and the sequence ensures that this is done at minimal cost.
- Piston linearity of movement is measured in 4 planes to ensure process consistency.
- The magnet is centralized in the yoke using a pair of XY force transducers monitoring forces less than 0.2N.

FLAWLESS LAUNCH, PRODUCT DEVELOPMENT, AND QUALIFICATION

Honeywell Hymatic is currently establishing a production line for the manufacture of approximately 30 SSCs per month. The production line is being established using Honeywell 'Flawless Launch' philosophies:

- Product designed for manufacturing and assembly (producibility). Whereby producibility is seen on an equal footing to technical requirements.
- Zero customer escapes, i.e. no failures of the product at the customer. Zero defect mindset quality culture.
- Early manufacturing and supplier engagement in the product development process.
- Lean manufacturing and de-skilling of operations, mistake proof (Poka-Yoke) tooling, design for Six Sigma (DFSS) methodology.
- Rolling Throughput Yield requirement of 99% for low rate initial production. Rolling Throughput Yield is a combination of First Pass Yield's within the assembly and test of a product.

The main objectives of these initiatives are that of customer satisfaction, competitive advantage, and maintaining ultra high reliability as seen on space products.

Qualification testing is now being planned on the initial production standard units in order to meet the requirements of our customers. This includes high and low temperature operation, temperature cycling at storage conditions (followed by leak and performance checks), performance testing in three orthogonal orientations, random vibration and shock, exported vibration, cool down characterization, cold finger side load deflection tests, and finally drop test survivability (2m onto concrete with the cold finger protected).

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REFERENCES

1. Crook M. "Progress Towards a Small Scale Cooler for Space Applications," *5th European Space Cryogenics Workshop*, Noordwijk, Netherlands (2013).