Industrialization of a Small Scale Cryocooler

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RAL - Martin Crook, Geoffrey Gilley, Stuart Brown
Introduction

• Honeywell Hymatic have over 60 years experience in manufacturing JT coolers, Cryocoolers and Space Compressors (as used by Northrop Grumman e.g. HEC Compressor).
  - Sold mainly into Infrared detector applications but also other uses such as Germanium detectors
• In 2013 Honeywell Hymatic signed a license with RAL to industrialize a Small Scale Cooler (SSC) for Space and adjacent markets.
  - Based off customer enquiries for a long life micro cooler that matched this design
• Hymatic delivered a prototype SSC to an industrial customer for integration to a sensor and performance evaluation. Positive feedback and suggestion on improvements were received.
• Continuous operation in customer’s device, >12 months and counting with no change in performance reported.
• This presentation highlights some design considerations of the SSC and the process of putting the cooler into production.
Honeywell Aerospace – Redditch
Mechanical OEM – Complemented by Heritage R&O

JT Mini Coolers
• ASRAAM
• IRIS-T
• Sidewinder
• Javelin
• NSM/JSM
• HISAR

Guided weapon IR cooling devices
• Cooling of Thermal Imaging systems
• Cooling system storage >20 yrs
• Can cool to <100K (-173°C) in 2s
• Temperatures down to 60K (-208°C)
• Uses very high pressure consumable gas

Stored Energy Systems
• Taurus
• NSM / JSM
• Stormshadow
• ASRAAM
• LR TRIGAT
• HISAR

Typically single use
• 3,000 to 10,000psi storage pressures
• Wide capacity range, 0.02 to 2 litres.
• Rechargeable or Sealed for life (shelf life >20 years)
• Mil qualifications including bullet attack and fuel fire
• High purity, super cleanliness and leak tightness for a variety of gases, Air, Argon, Nitrogen, Helium etc

Stirling Cycle Coolers
• Space Compressors
• Gamma Ray Detectors

Closed cycle coolers
• Homeland Defence applications
• Employs Stirling Cycle to convert electrical energy to cryogenic cooling.
• Achieves cryogenic temperatures in the range 75 to 130K (-200ºC to –140ºC)
• Long life & high reliability differentiation

Fighting Vehicle Support
• TOGS
• PASU
• GP-TIRF
• CSU Test Set
• RA’s -T,U & V class Submarine

Multi stage compressors charging from atmospheric pressure to 5000psi at 0.25 cfm
• Self contained air cleaning equipment to pure air standard DEF STAN 58-96 Issue 1.
• Trident, Trafalgar and Upholder class submarine equipment.
• In field standard automated test facility
• Full in-field service support for all heritage equipment
Stirling Cycle Coolers / Compressor

Salient Design Features:
- Linear electric motor and cold head – MOVING COIL DESIGN
- Moving elements mounted in flexure bearings utilising clearance seals
- Very tight tolerance machining & assembly (<0.0001”)
- Horizontally opposed motors to null vibration effects depending on application
- Helium filled hermetically sealed pressure vessel ~300psi

Typical Metrics
- >100,000 hours (~11 years) running achieved on durability test demonstrator (NAX025 cooler)
- No degradation in cooling power / performance over operational life
- Typically 60 - 150K cold finger requirement
- 0.4 - 4 watt heat lift at operating temperature typical

Heritage
- NG & Oxford University – Design
- HH - productionisation of space compressor
- 18 systems currently in orbit > 100 years combined operation
- JAMI, GOSAT, AIRS - in orbit
- MIRI, GOES, ABI - future launch
- ESA - Design study for future European platforms
Design Features of the SSC

• Dual opposed compressor design.
• Driven Displacer.
• Based on RAL Space heritage and long life technology.
• True clearance frictionless seals.
• All Ti welded body design for Helium retention and low mass.
• New moving magnet motor for both Compressor and Displacer drive. Axially magnetised magnet pair configuration obviating the need for inner iron core.

Prototype Measured Performance
Mass: 620g
Size: 152mm X 55mm X 102mm
Power: 22W
Lift: 500mW @77K (21°C ambient)
Stability: ±5mK 10mins, ±30mK 1hr
The new moving magnet motor

**Advantages:**
- Lower part count.
- Lower part cost –
  - No expensive moving Coil Former.
  - No expensive radially magnetised magnet assembly.
- Compact.
- Low magnetic interference.
- Stationary coil, no moving electrical connections.
- High reliability design (RAL heritage).
- Enhanced design flexibility..... to adjust frequency, easily scalable.

**Disadvantages:**
- Eddy current loss required to be controlled. Material selections!
- Radial magnetic force needs suspension springs with high radial stiffness.
## Typical Motor Configuration – Radial Forces

<table>
<thead>
<tr>
<th>Radial Spring Rates</th>
<th>Motor name - Fred</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Radial Spring Rate at 0.22 radial offset - at axial stroke amplitude (mm):</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>127.90</td>
</tr>
<tr>
<td>3.3</td>
<td>93.10</td>
</tr>
<tr>
<td>Mechanical Radial Stiffness at 0.22 radial offset - at axial stroke amplitude (mm):</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>273.70 per pair</td>
</tr>
<tr>
<td>3.3</td>
<td>138.75 per pair</td>
</tr>
<tr>
<td>3.96</td>
<td>111.76 per pair</td>
</tr>
<tr>
<td>5</td>
<td>69.23 per pair</td>
</tr>
<tr>
<td>No. Of pair of spring -n</td>
<td>3.00</td>
</tr>
<tr>
<td>Total mechanical spring radial stiffness at 3.3mm stroke</td>
<td>416.25 per n pair</td>
</tr>
<tr>
<td>Factor of Safety (FOS) for Radial Spring Stiffness</td>
<td>4.47</td>
</tr>
</tbody>
</table>

All rates in N/mm
Typical Configuration – Axial Spring Rate

<table>
<thead>
<tr>
<th>Axial Spring Rates</th>
<th>Motor name - Fred</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Axial Spring Stiffness</td>
<td>6.56</td>
</tr>
<tr>
<td>Total mechanical axial spring stiffness</td>
<td>2.16 per N pair</td>
</tr>
<tr>
<td>Total Mech + Magnetic Spring Rate</td>
<td>8.72</td>
</tr>
<tr>
<td>Gas Spring Rate</td>
<td>7.74</td>
</tr>
<tr>
<td>Total Spring Rate</td>
<td>16.45</td>
</tr>
<tr>
<td>Moving mass</td>
<td>49.23</td>
</tr>
<tr>
<td>Natural Frequency</td>
<td>92.00</td>
</tr>
</tbody>
</table>

All rates in N/mm

- The axial magnetic spring rate is a significant contributor to the total axial spring stiffness.
- Minor modifications to the motor configurations can give the desired spring rate whilst minimising the change in motor force.
- The spring rate can be tailored to be positive, negative or zero.

Magnetic spring enables high operating frequency.

Axial Spring Rate

- Magnetic
- Mechanical (3 pairs)
- Gas
Productionization – Performance Enhancement

Basing on RAL development achievement and customer feedback, the following design modifications were implemented in the production model of SSC to match the cooler to the requirement of Industrial customer:

• Improved thermal management – centre plate design changes.
• Increased Compressor Stroke to 3.3mm for faster cool down/higher capacity.
• Improvement on Cold Head phase control for faster cool down – displacer modifications.
• Reduction of Eddy Current loss – interruption of eddy current flow path.

- Intention is to increase performance from 500mW to 750mW (or higher) at 77K cold tip temperature
Productionization – Product reliability

• Compressor Spring Testing:
  - 25% over stroke from mechanical stop position.
  - 5mm test stroke amplitude.
  - Fatigue Testing completed 800 million cycles.

• Displacer Spring Test:
  - 25% over stroke as above.
  - 1.8mm test stroke amplitude.
  - Fatigue Testing completed 800 million cycles.

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Productionization – Linearity of Piston movement

• Sources of error and control:
  – Piston movement controlled by a pair of spring stacks. Spring mounting faces must be parallel and concentric.
  – Unbalanced radial magnetic forces cause Piston radial misalignment. Match the magnetic and spiral spring stiffness to minimise the radial deflection and centralise magnet in yoke at zero force.

• Implementation
  – Magnet centralized in Yoke using a pair of XY force transducers to less than 0.2N.
  – Control manufacturing method to ensure geometric tolerances of spring mounting faces at minimal cost.
  – Measure Piston linearity of movement in 4 planes.
Productionization – Progress Status

• Compressor Alignment:
  - Modular design aligned in 2 stages. Stage 1 geometric alignment, stage 2 for magnetic zero force alignment using xy force transducers.
  - Approx 100 minutes to build and align a compressor module. Opportunities to reduce this time with tooling refinement and operator learning.
  - Final refinements needed to fixtures in order to de-skill the process to assist production staff assembly.
Productionization – Progress Status

• Cold Head Assembly:
  - Displacer motor assembly successful
  - Displacer filter cartridge assembly successful
  - Final progress hampered by shaft miss-alignment:
    ▪ Analysis to focus on magnet side loading.
    ▪ De-coupling the motor alignment from the displacer alignment.

• 1\textsuperscript{st} Cold Head module ready for integration to compressor modules for first test, as shown.
Planned Qualification Tests

• High and low temperature operation.
• Temperature cycle at storage conditions followed by leak check and performance check.
• Performance test in 3 orthogonal orientations.
• Random vibration test.
• Shock Testing.
• Exported vibration characterisation.
• Cool down drive characterisation.
• Cold Finger side load test.
• Drop test survivability – 2m onto concrete (with Cold Finger protected).