A Low Maintenance and Vibration 4 K GM Cryo-Refrigerator with Independent Variable Speed and Valve Timing

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ABSTRACT

Over the course of developing a small scale cryogen-free physical property measurement system (VersaLab™) we have learned a great deal about the strengths and weaknesses of commercially available Gifford-McMahnon (G-M) cryocoolers with regard to our specific application. This has motivated us to develop a novel low vibration G-M cryocooler with a nominal cooling power of 0.25 W at 4.2 K. The system features an independently controlled valve assembly providing dynamic control of the intake and exhaust cycles of the refrigeration gas exchange between the cryocooler and the compressor. Some unique features of the valve assembly design are its significantly lower power consumption and its low frictional forces; which translates into improved durability and component longevity over existent designs. This, combined with the ability to dynamically control the frequency and the motion profile of the displacer and the precise control of the gas flow functions (independently of the displacer mechanics) allows for optimization of the cryocooler performance with regard to cooling power, efficiency, and vibration levels. Additionally, all moving components and seals have been designed for very low wear. Collaborations with other manufacturers and researchers have also provided us with insights into additional optimizations that may be desirable for other cryogenic instruments and platforms.

INTRODUCTION

The VersaLab™ Physical Property Measurement System (PPMS©) provides for a compact, cryogen-free temperature/magnetic field platform (50K -400K and +/- 3 tesla) that can host a variety of integrated measurements for the characterization of the physical properties of materials [1]. These include DC and AC magnetometry, heat capacity, thermal and electronic transport, as well as numerous possibilities for custom experimentation. The VersaLab™ is a completely cryogen-free system that uses less than one "K" type helium gas cylinder per year for sample temperature exchange and has a small 1 square meter footprint for the entire system (cryostat and air-cooled compressor). Since its inception, it became apparent to us that the "orientation-free" operation of G-M refrigerators could be used advantageously to minimize the size of the VersaLab™ cryostat, making it virtually portable. In addition, the availability of commercial G-M cryocoolers; with a smaller physical size and reduced cooling power (nominally 0.1 W at 4.2 K), perfectly balance the size and weight requirements for a portable system while still maintaining an adequate cooling budget to operate the cryostat's cryogenic sub-systems (i.e. superconducting magnet, sample chamber and cryopump). Figure 1 highlights the cooling strategy adopted in the VersaLab™ cryostat: the second stage of the cryocooler (Figure 1 (a)) provides cooling to operate a small 3T Niobium-Titanium (NbTi) conduction cooled superconducting solenoid, while the first stage (Figure 1 (b)) services a variable temperature sample environment from 50 K to 400 K. The reduced power consumption of the helium compressor; when used in conjunction with these compact cryocoolers make it an obvious choice for designing a cryostat that would meet most common physics and materials science undergraduate laboratory space and power requirements while maintaining the maximum flexibility in performance.

Subsequently it became apparent that commercially available G-M cryocoolers systems of this type were essentially a scaled-down and economical version of their larger and more powerful industrial grade coolers that typically deliver 1.0 to 1.5 W at 4.2 K. In practice, this heritage has proven to be problematic in achieving critically important requirements (of sensitive measurement instrumentation) such as high temperature stability, low vibration, low-power consumption, and long life. In general, G-M cryocoolers have earned their nickname "thumper" due to the incoming rush of gas that slams down through the displacers and consequently pushes on the drive rod. This combination of forces exercises a backlash in the mechanical linkages connecting the motor, scotch yoke, and displacers to create a characteristic thump or clack. The mechanical impulse is rich in harmonics, creating a comb of noise peaks roughly 1 Hz apart in the vibration spectrum. In the past, the valves that control the helium gas inlet and exhaust functions are actuated by cams mounted on a rotating crank that leave little opportunity for adjustment and timing. These adjustments may be employed in strategies to reduce the forces on the displacers and/or optimize the cooling provided in each cycle. Since the forces in the scaled-down version of the G-M cryocoolers are substantially lower than their larger counterparts we felt that a greater reduction of vibrations could be possible if the gas flow, linkages and bearings could be made to operate more smoothly and in concert with one another.

In this paper, we describe a novel "instrument" grade G-M cryocooler driven by a variable speed "energy smart" compressor [2, 3] that is specifically designed for the VersaLab™ and similar laboratory apparatus where energy efficiency, long life and low vibrations are of interest. Notable features of the cryocooler are the independent computer control of the displacer movement and a specially designed "spool" valve adapted for dynamic control of the intake and exhaust flow of the helium within the cryocooler. The valve is adapted for resilient and durable operation over an extended period of time. We show that this enhanced control can be used to beneficially optimize the cryocooler performance with regard to cooling power, efficiency, and vibration levels.

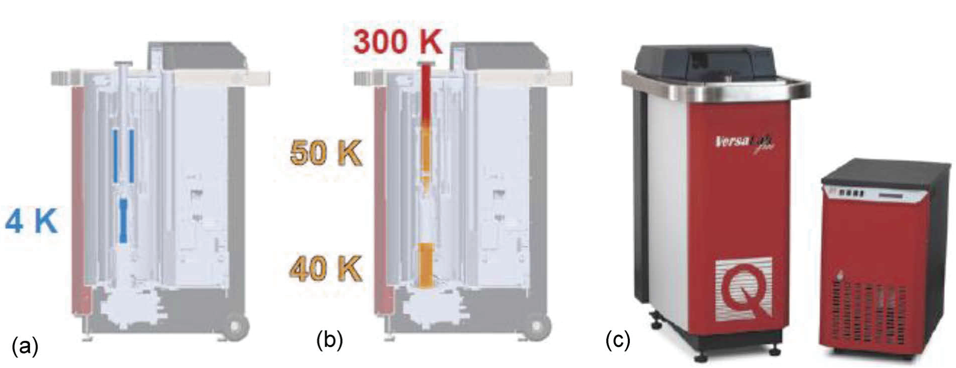

Figure 1. (a) A 3 T superconducting magnet is cooled by the 4 K stage using solid conduction cooling through high conductivity copper, (b) a thermal switch connects the sample chamber to the 40 K stage and cools the bottom of the sample chamber down to 50 K, (c) the complete system is shown with the small variable speed compressor for the G-M cryo-refrigerator.

The variable speed compressor can; by varying the scroll capsule speed, significantly reduce the overall power consumption for the system and deliver cooling power on "demand" according to the dynamic requirements (i.e., heat loads) within the system. For instance, when first cooling down the VersaLab™, the compressor and cryocooler will run at high speed to deliver maximum cooling power to the first and second stage. Then; once the system is cold and measuring a sample at a fixed temperature and magnetic field, the compressor and cryocooler will run at "low" speed to deliver minimal cooling power to the stages as required by the parasitic heat loads in the system. This saves wear on both head and compressor while reducing power consumption.

CRYOCOOLER SYSTEM DESCRIPTION

Figure 2 shows the physical configuration of the GA-1 cryocooler and details of the internal construction of the 2.5 kW class HAC900S variable speed compressor. The GA-1 is a two stage cryocooler that uses the G-M refrigeration cycle. The first and second stage cylinder dimensions are approximately 46 mm and 20 mm in diameter and 129 mm and 115 mm in length respectively. The displacers are driven by a synchronous 5-phase motor that is controlled by a computer controlled Pulse Width Modulated (PWM) circuit that feeds a half-bridge driver for each phase of the motor. The "spool" valve includes a linear armature driven by an induction motor, whose position and speed can be tracked and changed using microprocessor-based electronics. The valve assembly provides key benefits over previous designs. For instance, the armature is "floating" within a shuttle valve cylinder, which reduces the frictional contribution to power consumption, working lifetime and vibration. In general, the valve consumes a mere 0.1 W as opposed to the more conventional rotary valves that require about 20 W to operate. The 1st stage flange provides a cooling power of 4 W at 40 K and the 2nd stage flange provides a 0.25 W cooling capacity at 4.2 K. The displacers are constructed of phenolic and stainless steel, respectively, and filled with optimized amounts of phosphor bronze screens, lead and rare-earth materials.

Figure 2 (b) shows the details of the HAC900S. This compressor is air-cooled and runs on a 200-240 VAC 50/60 Hz power. Power consumption ranges from 800 W to 2 kW (~0.65 P.F.) depending on the capsule speed and the supply/return helium pressures. A commercially available inverter drives the compressor scroll capsule and a specially designed 5-phase inverter drives the cryocooler motor. Since the capsule motor is started slowly by the inverter, there is essentially

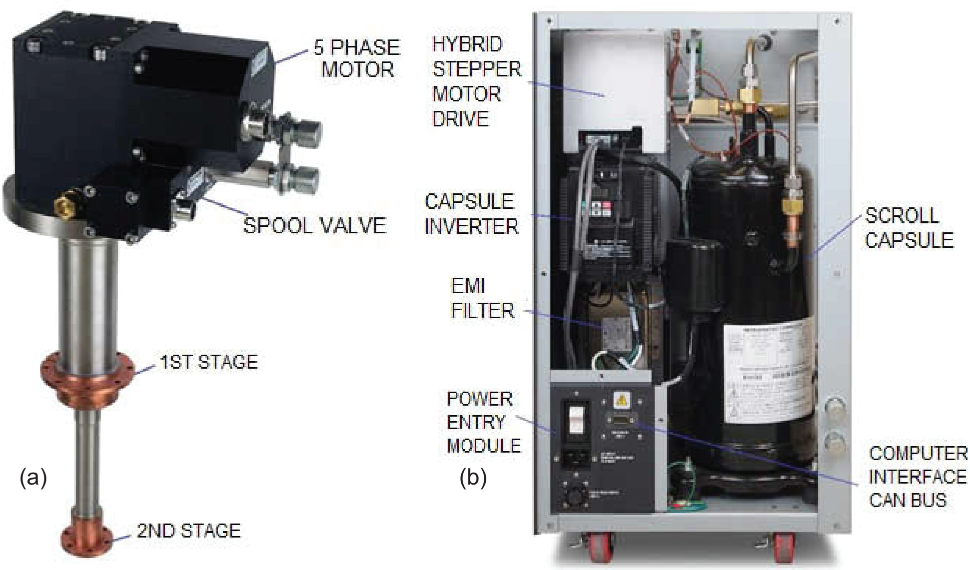

Figure 2. (a) The GA-1 cryo-refrigerator and, (b) details of the HAC900S variable speed compressor.

no surge-current or mechanical shudder at power-on. Ambient air is drawn into the front section where is cools the oil-coalescing filter and charcoal adsorber before being forced over the radiator coils, capsule, and inverters. Air exhaust, hose fittings, and electrical connectors are all at the rear panel. This configuration provides optimal cooling for the components that remove oil and vapor from the helium. Other features of the HAC900S compressor are all-stainless construction, oversized charcoal adsorber, electronic pressure, temperature, and oil-level sensors, and sophisticated firmware to control the state-engine and detect/report subtle fault conditions. The compressor has a full-featured Control Area Network (CAN/CANOpen) bus interface so that it integrates fully with the other modules in our instrument. We have also provided the hardware for an RS-232 interface to support OEM applications and a Software Development Kit (SDK), which enables third party programs to control compressor speed and query the HAC900S for diagnostic data.

Convenient speed control is the great side-benefit of this electronic drive system. We have found that the GA-1 cryocooler motor can be dynamically operated with input frequencies between 30 Hz and 70 Hz to achieve different system goals. At the low-frequency end, we can implement a "stand-by" mode that will extend the product lifetime and reduce power consumption. The system can be operational again after only a few minutes rather than many hours. At the high-frequency end, we can roughly double the cooling capacity of the head for transient high-load conditions such as rapid cooling of the sample-chamber in our VersaLab™ instrument. To properly accommodate such changes to the head speed, the compressor itself must be able to adjust its gas output over a range of at least 2:1.

Independent Refrigeration Cycle Control

Figure 3 depicts the principle of operation of the independent refrigeration cycle control. The displacers are driven with a reciprocating drive rod by use of a scotch yoke. The exact position of the displacer stroke and valve are independently operated by electric motors and tracked by two separate encoders. In practice, the displacer position provides for a "clock" signal of the refrigerator cycle providing a reference signal to be used by programmed electronics for the valve control. Figure 4 shows a typical oscilloscope waveform of the displacer and valve positions in a typical refrigeration/heat cycle. The electronics dynamically control the inlet/exhaust timing, dwell and

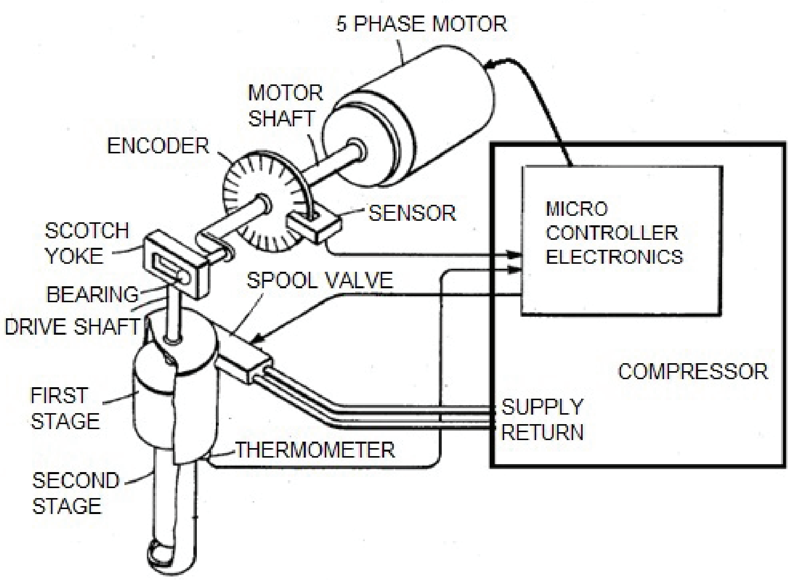

Figure 3. Control systems for the independent refrigeration cycle.

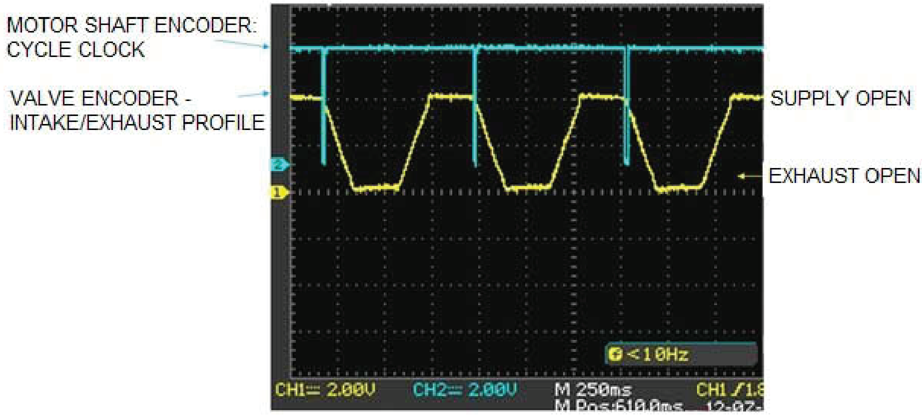

Figure 4. Independent control of the refrigeration/heat cycle.

flow areas relative to predetermined positions of the displacer. Unlike previous mechanisms, the valve can supply high pressure helium gas from the compressor to the cylinder and exhaust the helium gas back to the low pressure side of the compressor "on the fly" and in a very precise way, depending on the cooling requirements of the VersaLab™. This capability enables the system to be optimized with respect to cooling power and with added precision. Pressure changes within the cryocooler can be managed such that common problems including noise and losses due to fluid-friction are minimized. Such a valve, not being dependent on displacer mechanics, may also prove to be useful with modern pulse-tube cryocoolers.

EXPERIMENTAL RESULTS

Agile Temperature Control

The dynamic control of valve timing using a microprocessor allows for the GA-1 cryocooler to provide cooling and warming of the first and seconds stages in a "on-demand" basis. This form of temperature control is attained without the use of external heaters. In practice, this is accomplished by reversing the phase of the intake and exhaust functions during the refrigeration cycle. This feature is particularly desirable if a fast cycle of the cryocooler system is required for the regeneration of the cryo-pump at 77 K and subsequent cool down. Previously this might require the entire cryocooler system to the shut down for a several hour warm up. In our system, the cycle can be achieved in 30-40 minutes. Figure 5 shows data warming and cooling curves attained by varying the Phase Delay (PD) at a high speed. With no heat load, it takes 70 minutes for the first stage to reach 40 K and about 60 minutes for the second stage to achieve temperatures slightly below 2.5 K. From the base temperature, heating of the first and second stages can be simply achieved by varying the phase delay of the intake and exhaust functions during the refrigeration cycle. The data shows that different warming rates can be achieved by solely changing the phase delay at a fixed speed.

Load Maps

The performance of the GA-1 cryocooler driven by the HAC900S compressor was characterized by a number of conventional load maps with heat inputs up to 4 W applied to the first stage and loads up 0.2 W applied to the second stage. Figure 6 reveals the rich load map landscape obtained using different compressor and cryocooler input power frequencies. The data is taken at different cold head and capsule speeds. Of interest in this data is the exquisite control of the first and second stage cooling capacities as a function of the input frequency power for the capsule and cold head. During the "High" cooling mode the first stage cooling of the refrigerator is optimized to its lowest temperature. This mode of operation is particularly important in a liquefaction system where the gas to be liquefied needs to precooled before it can be liquefied at the second stage. The

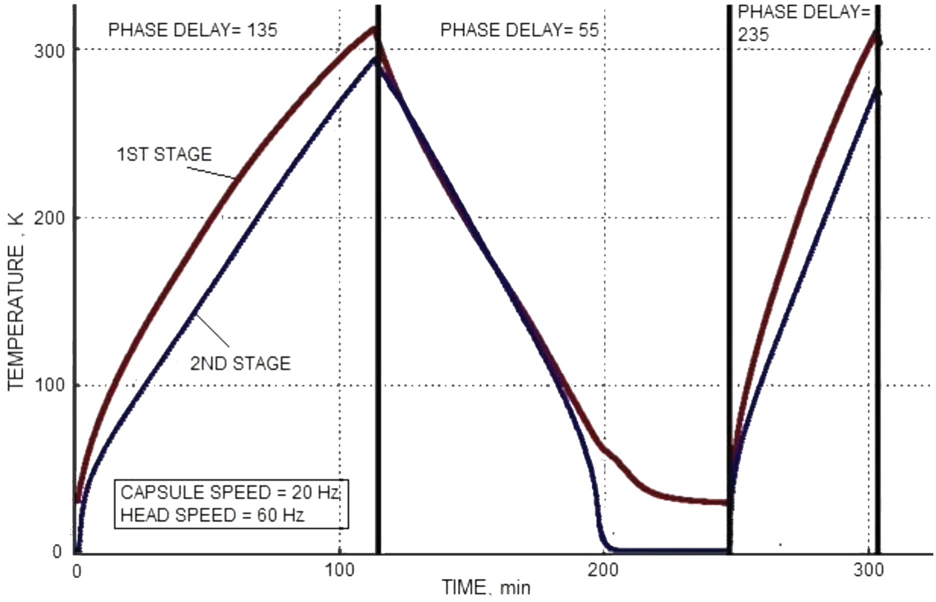

Figure 5. Warming and cooling curves.

"Low" cooling mode on the other hand maintains low temperatures at the second stage but reduces the cooling power at the first stage. This mode can be used for reducing power consumption, when the system is in "Stand-by" or idle.

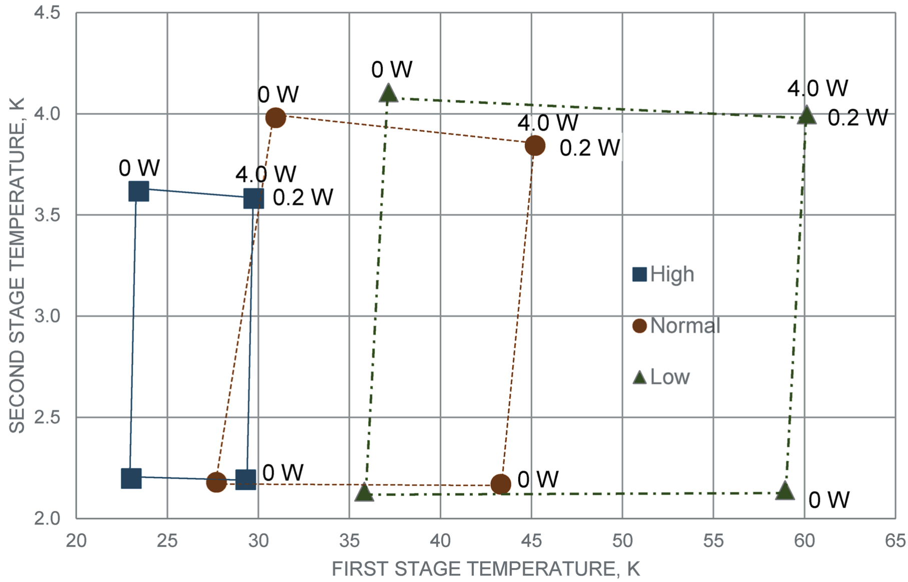

Figure 6. Cooling load maps of the two stage cold head with the HAC900S compressor.

Power Draw

Variation of the power draw versus input frequency is shown in Figure 7. The measurements were performed using a 3-phase Fluke 437 digital meter at three capsule speeds 30 Hz, 18 Hz and 13 Hz. The data shows that the power draw is dependent on the compressor capsule speed and to a lesser degree on the differential pressure (Supply – Return Pressure) of the compressor. At 30 Hz the average power consumption is approximately 2 kW, while at 13 Hz is closer to 1 KW. For a given speed during cool down was about 0.3 MPa larger than the differential pressure once the system was cold at its base temperature leading to a power reduction of typically 0.5 kW. In the VersaLab™ these lower speeds are attained when the magnetic field from the superconducting magnet is zero, and the temperature is stable. This idle state provides the user with substantial power savings over the course of even one year.

Vibration Spectrum

The vibrations of the G-M cryocooler were measured and compared to a commercial off-the-shelf unit of the same size (see Figure 8). To ensure accurate measurements of the vibration spectra, the cryocooler was isolated from external vibrational sources and care was taken to eliminate any dampening effects that the fixture itself might cause during the measurement. We accomplished this by forming a "crack" resistant concrete block weighing approximately 250 lbs standing on four high crush vibration dampening feet. Within the block is a cylindrical hole that accommodates the outer vacuum jacket; employed in load map experiments, without contacting the inner walls of the concrete. To further isolate the cryocooler from vibrations in the floor we bolted it to an aluminum plate through the four screws that normally hold the vacuum jacket. This plate rests on top of the concrete block separated with four Iso-damp grommets. The geophone used is the Geospace GS-11D 4.5Hz [4] and it is securely attached to the cryocooler at the top cover plate. This fixture secures the geophone by use of a Delrin® cap that is bolted to an aluminum base with four screws that are finger tightened to inhibit its ability to move within the fixture but without compressing the housing of the geophone. It is then bolted to the cryocooler using two of the screws holes that are used to hold the top plate. The geophone is wired to a 100x preamp through a shielded twisted pair cable

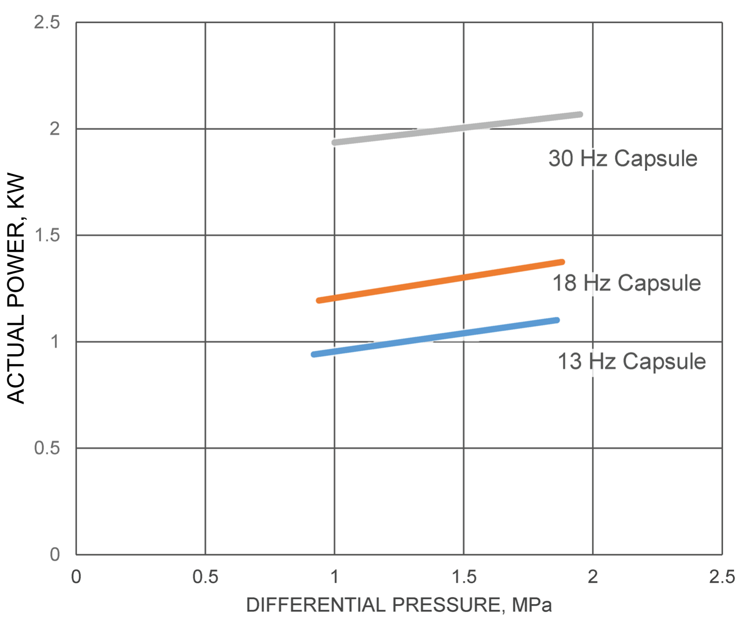

Figure 7. Power draw measurements of the GA-1 and HAC900S compressor.

and from the preamp to the spectrum analyzer with a standard BNC cable. The spectrum analyzer measurements are taken with a HP3561A in 200 Hz sections from 0-1kHz at 10 RMS; resulting in a bandwidth of 0.5Hz. The calculation to convert from dbV (from the spectrum analyzer) to meters of displacement is a transfer function that mimics a critically dampened spring and was verified at multiple frequencies as well as frequencies below its natural frequency to confirm our low frequency measurements (at 2 and 3 Hz). With the cryocoolers being driven at a 60 Hz motor input frequency, the vibration spectra indicate that the GA-1 has a lower vibration spectrum by at least one order of magnitude up to 1 KHz (gray curve). Experiments currently in progress, further indicate that the vibrations will continue to decrease at lower speeds.

Wear and Refurbishment

In general, the official recommended interval between head refurbishments is 10,000 hours for most commercially available G-M cryocoolers. This is only 14 months and refurbishing costs are typically several thousand dollars. This is one of the reasons, we operate the cooler in our VersaLab™ at reduced drive levels. It has been our experience that these heads typically run substantially longer than this period, even at standard drive levels. Unless down-time must be avoided at all costs, it is generally acceptable to run a head until it either begins making disturbing noises or fails to provide adequate cooling power.

We have looked at the typical wear patterns of several G-M cryocoolers and found several common themes. The greatest wear usually happens in the head, not in the displacer seals.

The plastic bushing on the motor eccentric (that drives the scotch yoke) shows the highest wear of all parts and this directly creates a loud clacking noise in the head (see previous comments about linkage slop). The next major wear items are the slide-bushings that constrain the scotch yoke to move vertically. As these wear, the drive rod moves transversely and tears up the gas seal that is riding on it.

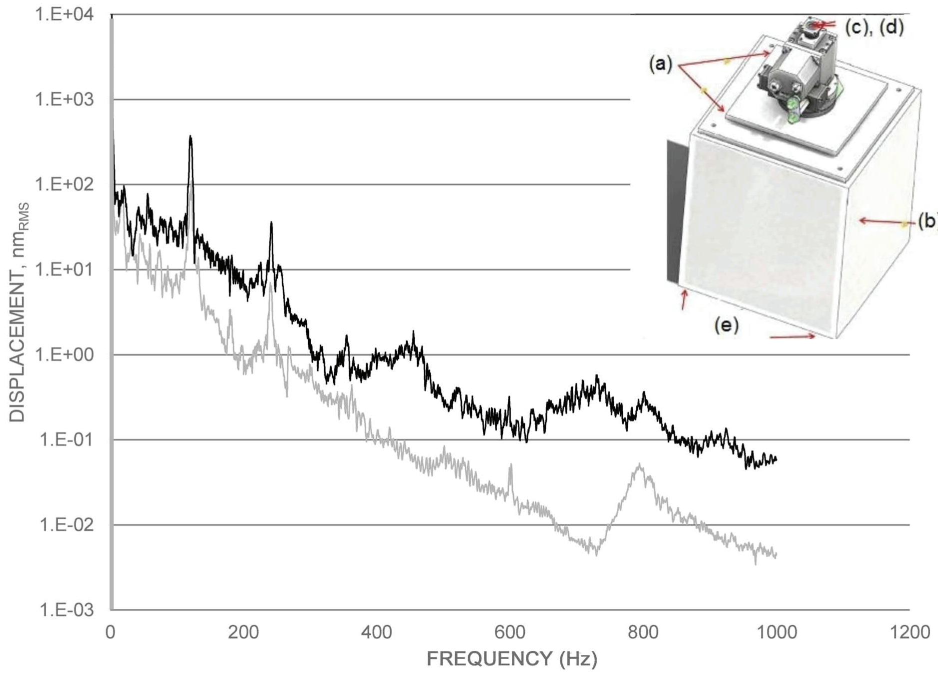

Figure 8. Vertical vibration spectra for the GA-1 cryo-refrigerator (Grey) and an "off the shelf" commercial cryo-refrigerator (Black). (Inset) Vibration test rig comprising of: (a) Iso-damp grommets, (b) Concrete block, (c) Geophone GS-11D, (d) HP3561A Spectrum Analyzer and, (e) Vibration isolation feet.

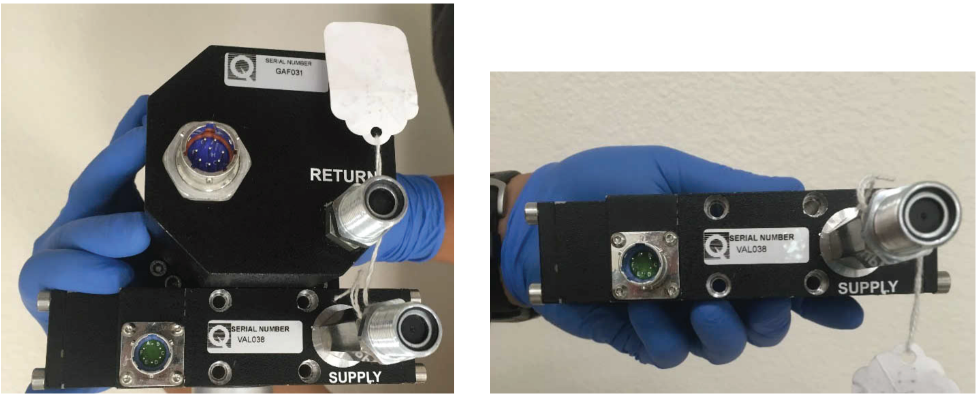

Figure 9. Replacement of the valve mechanism in GA-1 is accomplished by simply venting the system and unbolting four bolts.

In the GA-1 all the gas seals have been designed to provide a minimal amount of friction during operation. In addition, one of the benefits of an independent valve assembly, which is not mechanically linked to the displacer motion, is the ease of servicing the unit. Figure 9 shows the removal of the GA-1 spool valve by venting the cryocooler and unbolting four bolts that mate the valve to the main housing.

CONCLUSION

In this paper, we described a novel cryocooler and "smart energy" compressor system that dynamically controls the intake and exhaust functions of the refrigeration cycle. This enhanced control allows for optimizing the operation of the cryocooler system with respect to vibrations, cooling power, efficiency and service life.

ACKNOWLEDGMENT

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