Integrated Testing of the Thales LPT9510 Pulse Tube Cooler and the Iris LCCE Electronics

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Abstract. The Jet Propulsion Laboratory (JPL) has identified the Thales LPT9510 pulse tube cryocooler as a candidate low cost cryocooler to provide active cooling on future cost-capped scientific missions. The commercially available cooler can provide refrigeration in excess of 2 W at 100K for 60W of power. JPL purchased the LPT9510 cooler for thermal and dynamic performance characterization, and has initiated the flight qualification of the existing cooler design to satisfy near-term JPL needs for this cooler. The LPT9510 has been thermally tested over the heat reject temperature range of 0C to +40C during characterization testing. The cooler was placed on a force dynamometer to measure the self-generated vibration of the cooler. Iris Technology has provided JPL with a brass board version of the Low Cost Cryocooler Electronics (LCCE) to drive the Thales cooler during characterization testing. The LCCE provides precision closed-loop temperature control and embodies extensive protection circuitry for handling and operational robustness; other features such as exported vibration mitigation and low frequency input current filtering are envisioned as options that future flight versions may or may not include based upon the mission requirements. JPL has also chosen to partner with Iris Technology for the development of electronics suitable for future flight applications. Iris Technology is building a set of radiation-hard, flight-design electronics to deliver to the Air Force Research Laboratory (AFRL) as a deliverable under a Phase 2 Small Business Innovative Research (SBIR) contract. (C/N FA9453-11-C-0178) Test results of the thermal, dynamic and EMC testing of the integrated Thales LPT9510 cooler and Iris LCCE electronics is presented here.

Keywords: Thales, pulse tube, cryocooler, orientation dependence, exported vibration
PACS: 07.20.Mc

INTRODUCTION

The trend at NASA continues to be the release of Announcements of Opportunity for lower and lower cost space missions. Earth Ventures Instrument (EVI) missions are a case in point. The EVI missions are severely cost-capped, yet at the same time require the instruments and the mission to have multi-year lifetimes, thus forcing the hardware selection process towards the more costly choices. To propose an instrument that requires cryogenic cooling of its detectors can create quite a challenge if traditional space borne cryocooler systems are the only option. Current space borne cryocooler systems, while having proven themselves in flight for their exceptional reliability and their robustness against degradation, cost many millions of dollars and are not affordable for the new paradigm of low cost science instruments. As an alternative, the Jet Propulsion Laboratory (JPL) is looking at tactical cooler designs that have incorporated flexure bearings, and ideally the non-moving pulse tube coldheads as the next generation flight cryocoolers to cover these low cost missions. The Thales Cryogenics linear pulse tube coolers, with their 10^{+}-year lifetime predictions [1] have been identified as ideal candidates and will serve as the initial coolers to qualify for flight. While Thales does provide miniature commercial drive electronics for the LPT9510 and LPT9310 cryocoolers, it does not provide flight electronics to drive these cryocoolers. Iris Technology, on the other hand, has been developing a set of low cost, radiation-hard drive electronics under an Air Force Phase II SBIR that are suitable for driving a variety of cryocoolers, including the NGAS micro pulse-tube cooler, the Thales pulse tube coolers, AIM and Ricor Stirling coolers, and a simulated Creare reverse turbo Brayton compressor [2].

JPL has procured the Thales Cryogenics LPT9510, the LPT9310 and the LPT9710 pulse-tube cryocoolers for comprehensive performance testing to understand the cryocooler model advantages and disadvantages. Iris Technology and Air Force Research Laboratory (AFRL) have graciously provided a brass board version of the LCCE to JPL to drive the Thales LPT9510 cooler. This research is in support of the overall long-term objective of qualifying low cost tactical pulse tube cryocoolers with flight qualified electronics for future JPL space borne instruments. Testing has commenced with the LPT9510 pulse tube cooler and test results are provided in this paper.

THALES LPT9510 PULSE TUBE COOLER

A representative Thales LPT9510 cryocooler is shown in FIGURE 1a. Built for tactical applications, where the customer had its own standard interface requirements, this cooler lacks the needed built-in structural and thermal interface to facilitate interfacing with a flight instrument. For laboratory tests, an aluminum thermal clamp was fabricated and installed around the compressor and coldhead to function as the structural and the thermal interface to the heat exchanger (FIGURE 1b). This added 896g to the overall cooler mass, and would be in excess of the additional mass that a cooler containing the structural/thermal interface would have. Per the Thales LPT9510 specification, the maximum input voltage during cool down is 12 Vac, with a maximum input current of 6 A [3]. The nominal drive frequency is 45 Hz (operation at 40 Hz provides almost as good of performance as 45 Hz, but the performance was degraded at higher input currents/powers when operated at 50 Hz.) The permissible "skin" temperature range for the cooler is 0^{o}C to $+50^{o}$C when operating, and -55^{o}C to $+90^{o}$C when non-operating or in storage.

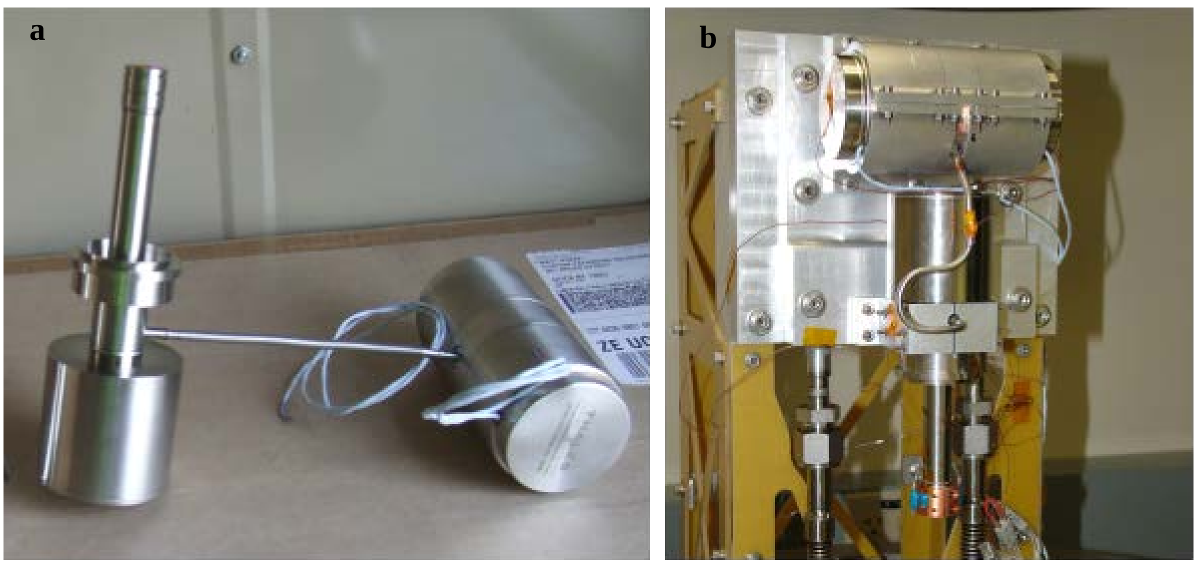

FIGURE1. The Thales LPT9510 pulse-tube cryocooler as delivered from Thales (a) and with integrated JPL thermal clamp and heat sink (b).

IRIS LOW COST CRYOCOOLER ELECTRONICS

The Low Cost Cryocooler Electronics (LCCE) has been developed by Iris Technology under an Air Force Phase II Small Business Innovative Research (SBIR) contract to provide a compact, robust and highly reliable electronics solution for a wide range of cryocoolers of interest for cost-constrained spaceborne infrared payloads. The LCCE is a space-qualified, radiation-hard (>300 krad total ionizing dose, TID) electronics package that provides a wide range of capabilities, including:

- Constant power or constant temperature mode;
- Programmable frequency and operational set points;
- Programmable temperature control coefficients;
- Extensive telemetry stream including two temperatures, input power, and output voltages;
- RS422 command and control interface to support mode, set point and command coefficient updates from the ground station;
- Over voltage and current in-rush protections;
- Firmware reconfigurable motor drives for linear or recirculating cryocooler drive.

These capabilities are provided in a package that is about $1/10^{th}$ the cost of traditional space borne cryocooler electronics. This has been accomplished primarily through designing out complexity that is not required for many applications and achieving tremendous reduction in radiation-hard parts cost and software complexity as a result.

The LCCE, shown in FIGURE 2, is compact and lightweight. The mass is 750g with overall dimensions of 12.6 x 14.2 x 3.1 (cm). It has been designed to survive "typical" launch shock and random vibration loads with considerable margin. The LCCE has been shown analytically to have >7X margin relative to both 20g shock and 17grms random vibration. The rated operational temperature range is -50C to +65C at 100W output power. During recent testing at Iris, the LCCE was successfully operated at 168W output in the laboratory environment; additional testing is planned to establish the safe operational capacity, which appears to be well in excess of 100W.

FIGURE2. The Iris Technology Low Cost Cooler Electronics (LCCE).

Advanced capabilities, such as input current ripple attenuation and exported vibration mitigation, are presently under development on a recently-awarded NASA SBIR Program. Working together with NASA, Iris is investigating methods to incorporate these additional capabilities with only minimal impact on the LCCE cost and size.

JPL is using the brassboard version of the LCCE which is not vacuum compatible and is thus operated in ambient air. It was tested at input voltages between 22Vdc and 35Vdc and up to input powers of 70 W with case temperatures reaching no more than 37^{o}C (TBR).

CHARACTERIZATION TESTS

Thermal Performance

The aluminum clam-shell support clamps at the cooler compressor and cold head were fabricated to provide both the thermal and structural interface between the cooler and the heat sink (see FIGURE 1b). The inner surfaces of the clamps were machined to provide interference fits with the cooler, thus eliminating the need for an interstitial material to help remove the waste heat from the cooler. The cooler was installed in a vacuum chamber, with the chiller recirculating lines running to the heat sink plate on which the cooler was mounted. Thermocouples were attached at various locations on the cooler, its structural clamps and the heat sink plate to monitor temperatures. The clamshell support clamp design limited access to compressor body for temperature sensing so the compressor "skin" temperature was monitored with a thermocouple mounted on the compressor adjacent to the helium transfer line.

Two different sized copper coldtip heater blocks (87 grams and 37 grams) were used alternately to provide the thermal load to the cooler. This gave the opportunity to test the optimal PI control settings of the LCCE under different cooler operating conditions. Redundant diodes were mounted to each heater block, along with a resistive heater and an in-line protective thermal cutoff for the applied heater power. Testing of the LPT9510 was performed by measuring load lines of coldtip temperature vs. applied thermal load as a function of compressor AC input voltage, drive frequency and reject temperature.

The cooler was driven using both the Iris LCCE and the laboratory rack electronics Chroma AC Model 61002 power supply. There was no noticeable difference in cooler performance using either electronics. True rms power meters inserted in the cooler drive power circuit before and after LCCE permitted the LCCE electronics efficiency and the Vrms input to the compressor to be measured. The measured LCCE efficiency is in the 88% range.

Thermal performance test results are shown in FIGURES 3-5. The data presented has had the i^2R line losses subtracted off. FIGURE 3 shows the performance dependency on the cooler input voltage when operating at a drive frequency of 45 Hz and at a 20^{o}C heat reject temperature. FIGURE 4 shows the dependency of the cooler thermal performance with respect to drive frequency when operating the cooler at a 10Vrms input voltage and at a 20^{o}C skin temperature. The data clearly suggests that the optimal drive frequency is somewhere between 40 Hz and 45 Hz. FIGURE 5 shows the thermal performance dependency on heat rejection (skin) temperature of 0^{o}C and 20^{o}C. A 20^{o}C difference in skin temperature results in a 200-mW change in refrigeration capacity at all input powers

(10^{o}C difference in coldtip temperature for low input powers, reducing to about a 5^{o}C difference at the higher input powers).

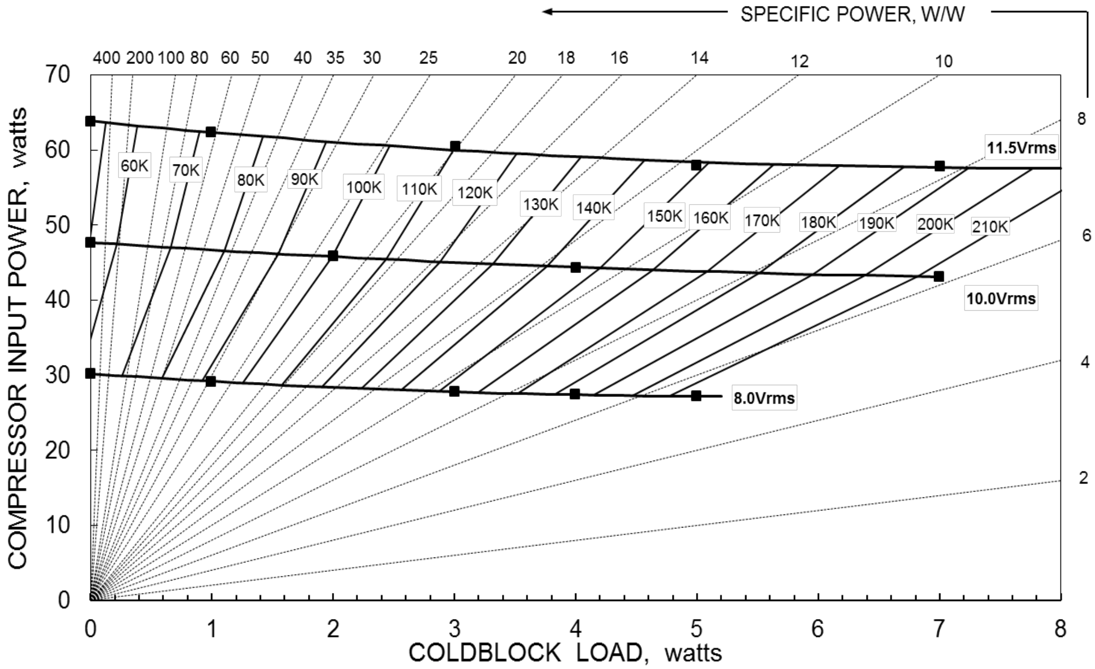

FIGURE3. Cooler thermal performance as a function of input voltage.

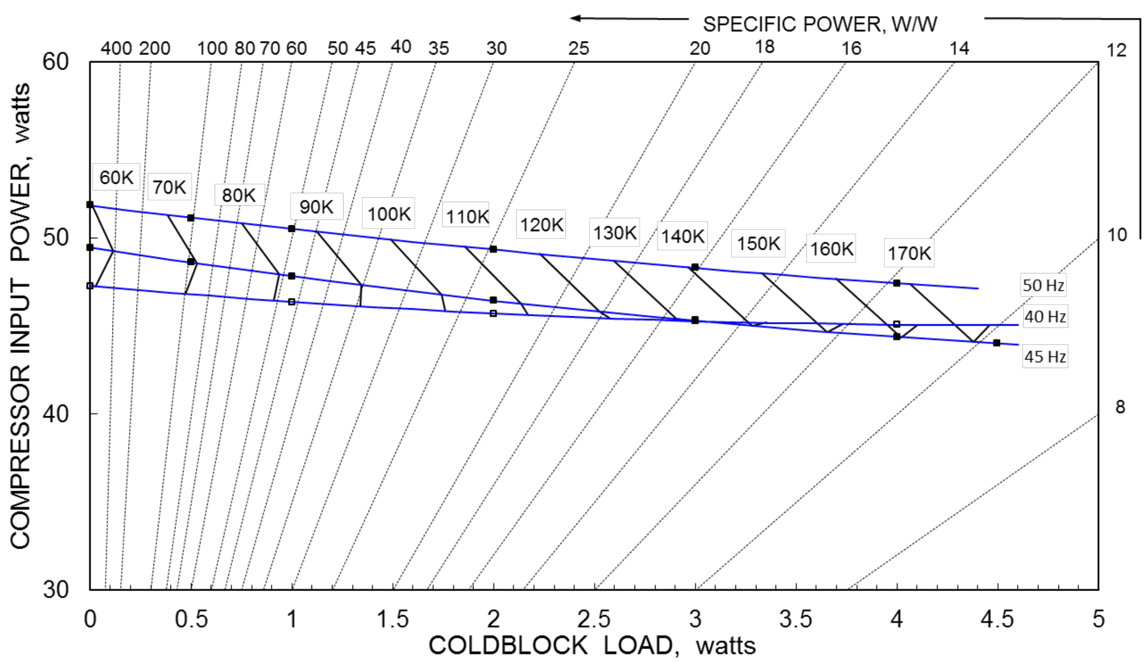

FIGURE4. Cooler performance for 10 Vac input voltage as a function of drive frequency.

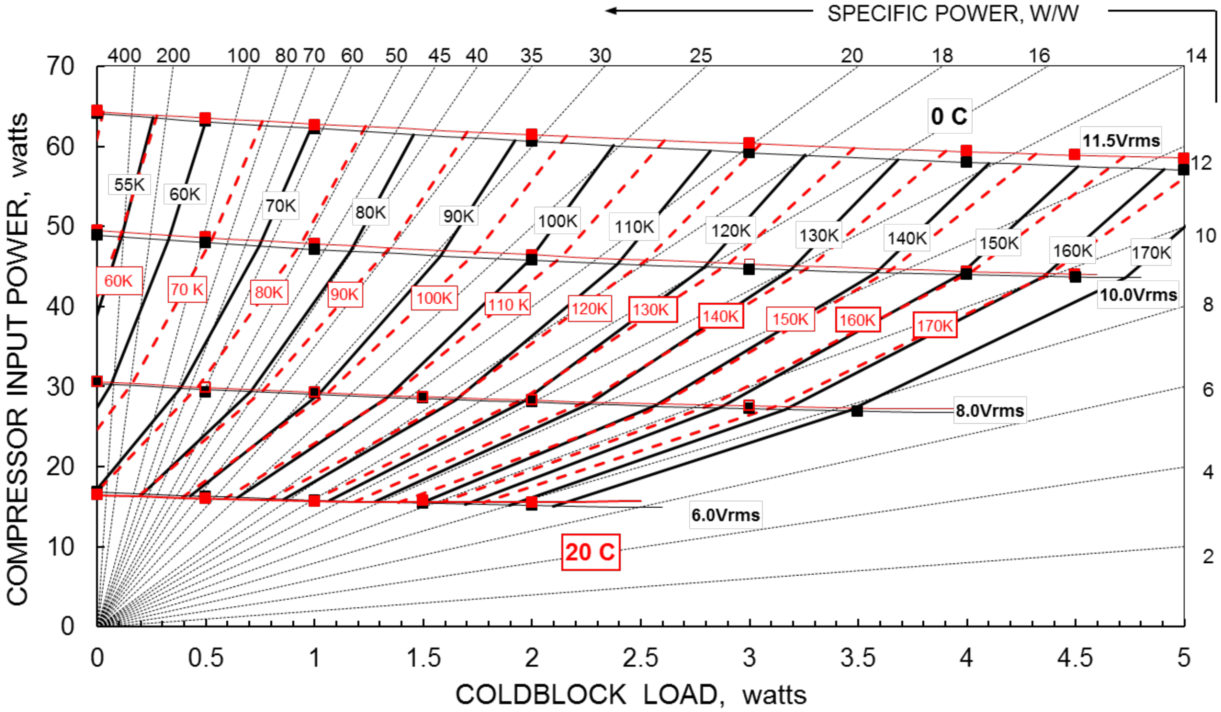

FIGURE 5. Cooler thermal performance comparisons for 20°C and 0°C compressor skin temperature. The 20°C heat sink isotherms are shown as dashed lines and their temperature values are boxed.

Orientation Dependence

There is a well-known performance dependence on orientation for pulse tube coolers [4-6]. For coaxial pulse tube coolers such as the LPT9510, the cold tip must be pointed downward to get the optimal performance out of the cooler which is representative of the expected on-orbit performance. FIGURE 6 shows the test configuration for the orientation dependency tests. The cooler is mounted on to a rotating table to allow operating the cooler in any orientation. A chiller provides coolant to the heat exchanger to keep the compressor body near 20°C, and a small turbo-molecular pump maintains a good vacuum on the pulse tube coldhead. FIGURE 7 shows the no-load temperature of the cooler as a function of the orientation angle for several different input voltages. At low input powers the effect is large (there is insufficient mixing of the gas in the pulse tube). At high input voltages the effect becomes much reduced. A series of tests were run to see how operating the cooler in different orientations affects the available refrigeration capacity. FIGURE 8 compares the performance of the cooler for two cases where the cooler was operated in the optimal coldtip down condition (0° orientation) and when operated at the nearly worst condition (135° orientation). At high input powers and low coldtip temperatures the difference in refrigeration capacity is roughly 500mW, decreasing in significance as the coldtip temperature increases. At low input powers the loss in refrigeration capacity is greater overall, 600-700mW, with the performance degradation remaining reasonably constant with coldtip operating temperature.

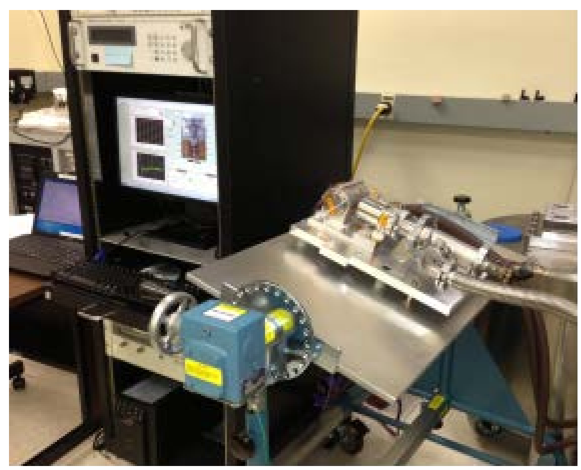

FIGURE6. Thales 9510 pulse-tube cyrocooler and heat sink mounted to tilt table for orientation performance testing.

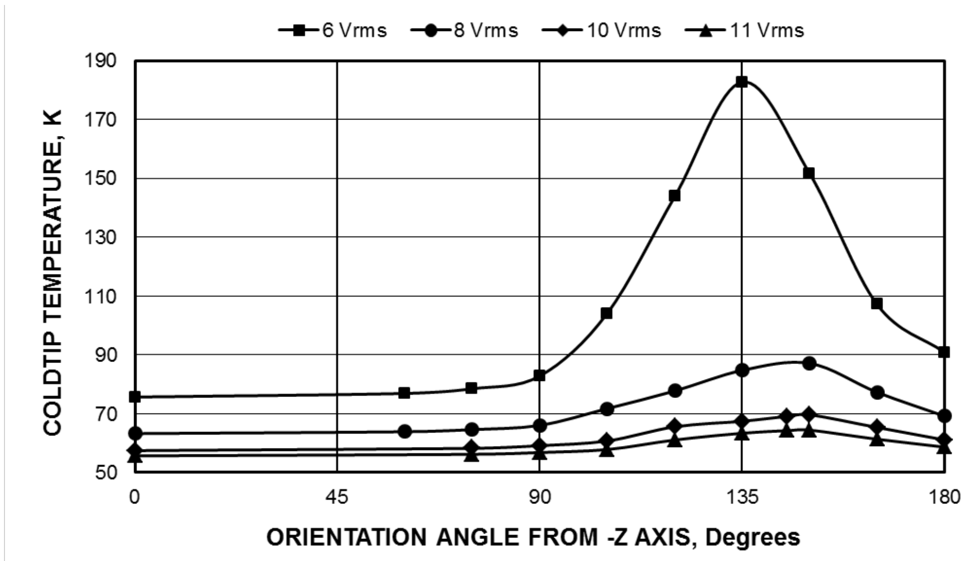

FIGURE 7. The no-load coldtip temperature as a function of orientation angles.

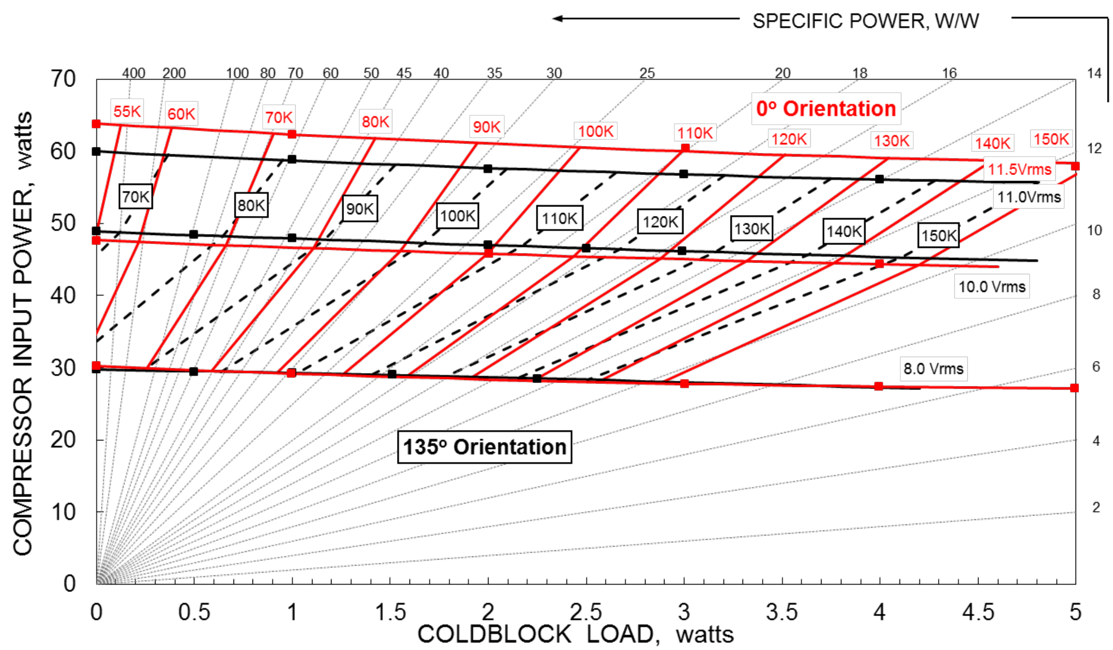

FIGURE 8. Thermal performance comparisons for the cooler pulse tube pointed at orientation angles of 0^{o} and 135^{o}.

Exported Vibration

Measurements of the cryocooler exported vibration was conducted in the JPL vibration characterization facility using a Kistler Model 9255 force table and the Kistler Model 5017 charge amplifier. The four 3-axis force transducers within the dynamometer are able to discern vibration levels to better than 10mN. The Kistler table is mounted on a 2275 kg steel seismic mass. The characterization facility and Kistler table are shown in FIGURE 9. To isolate the Kistler table from the environmental noise sources, the seismic mass was mounted on three cylindrical legs with 2.5cm of E.A.R. visco-elastic damping material to eliminate the building ambient vibrations which were observed around 45 Hz. The resulting overall table resonance with the cooler was around 700 Hz, resulting in a very stiff system. The Kistler table and electronics output were compared to vibration results measured with a calibrated load cell and a small (1 kg output) inertial shaker as a sanity check. To eliminate the effect of the dynamometer and fixture structure affecting the vibration levels, additional masses are mounted to the cooler with either damping material or with putty to move the fixture-related resonance (frequency goes as the root of the mass). If the measured vibration levels do not change with the added affixed mass then we know the fixture is not contributing to the moving mass vibrational levels of the cooler. A Crystal Instruments Spider80 Dynamic Signal Analyzer was used to analyze and process the Kistler load cell output from the Kistler charge amplifier. The resulting FFT analysis is then converted by the analyzer in to prepared report formats.

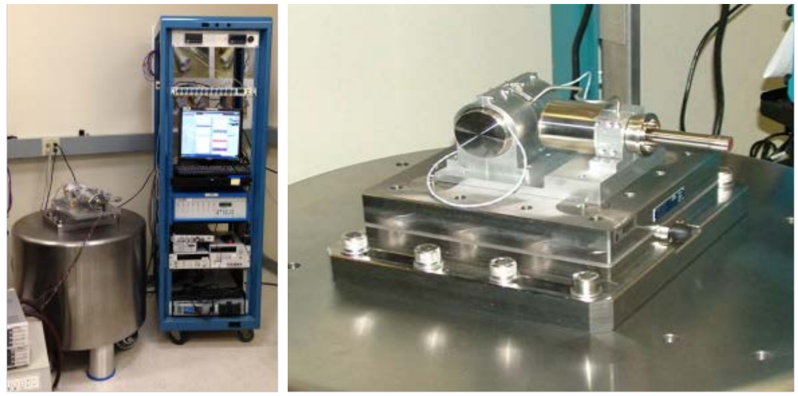

FIGURE9. The JPL exported vibration facility (left) and Kistler 9255 force table (right).

During exported vibration measurements the cooler was operated at the nominal cold operating temperatures over a variety of input voltages, and was driven at 42 Hz to differentiate the cooler drive frequency harmonics from the 60-Hz AC line frequency harmonic noise. The vacuum pump and recirculating chiller lines were disconnected from the cooler during data gathering so as to eliminate their influence on the test measurements. FIGURES 10 and 11 show the exported vibration for the cooler in the compressor and pulse tube axes, respectively, when operating the cooler at an 11.4 Vrms and an input of 62watts. As can be seen from the harmonic force levels from the compressor (FIG.10) and from the pulse tube (FIG. 11), the cooler exported vibration appears to be very clean; meaning there are only a few harmonics observed and these harmonics are of relatively low force levels. The back-to-back compressor pistons cancel most of the compressor exported vibration. As there are no moving parts in the pulse tube to generate vibration, the residual vibration in the pulse tube direction is due to the pressure pulse acting on the pulse tube. This results in an elongation of the pulse tube. FIGURE 11 shows the exported vibration at the drive frequency as a function of cooler input voltage for the compressor, pulse tube and third orthogonal axis. Note that there is a significant (50% change) variation in compressor vibration level over the range of input voltages tested, but for the pulse tube axis only a slight increase is observed (change in gas density of input voltages tested, but for the pulse tube axis only a slight increase is observed (change in gas density and pressure ratio).

One of the concerns of using these coolers for flight optical instruments is that the residual vibration level of the tactical coolers could render them unusable. While the cooler tested had very low harmonics, it is not certain if this is an anomaly or the general state of this cooler model. Therefore vibration control will be incorporated in the LCCE electronics in future to have it available as needed. There was no provision in the current brassboard Iris LCCE electronics or in the Chroma AC power source for testing the multi-harmonic vibration cancellation.

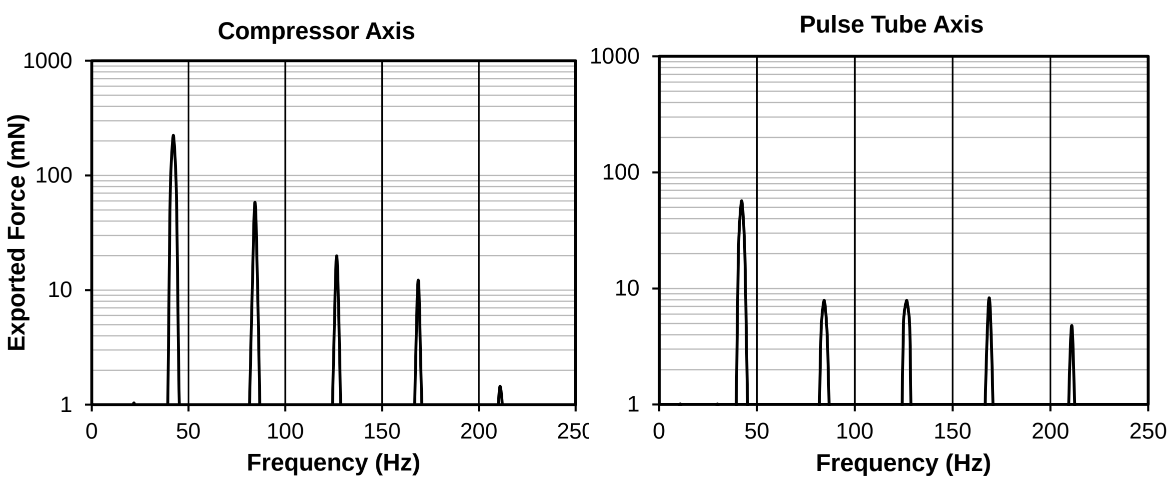

FIGURE 10. Harmonic vibration levels in the compressor (left) and pulse-tube (right) axis.

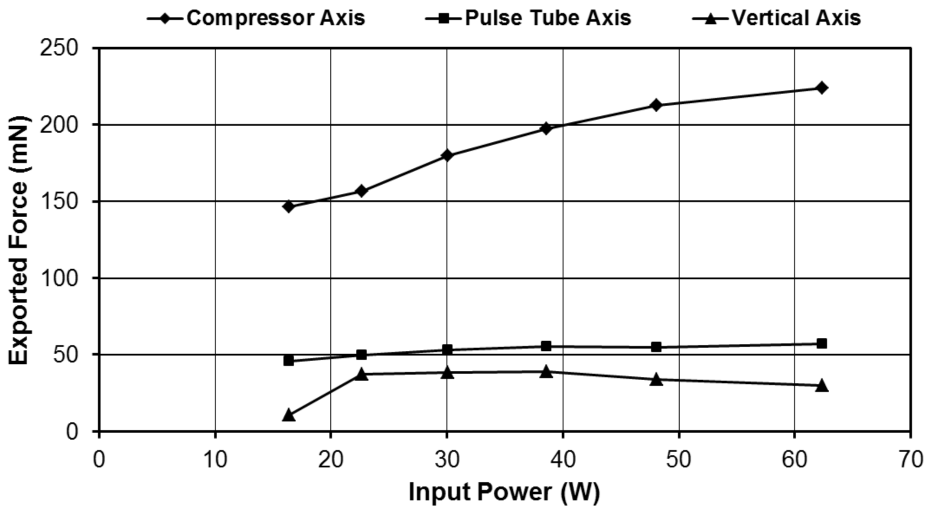

FIGURE 11. Compilation of drive frequency vibration levels in each of the three axes.

SUMMARY

The Thales LPT9510 pulse tube cooler and the Iris Technology cooler drive electronics look like an ideal cryocooler system for the NASA low cost mission sets that require multi-year life mechanical coolers for detector cooling. The Thales LPT9510 has proven to be a good performing cooler, with many of the attributes needed for flight. Incorporation of the current ripple filtering and the vibration control capability into the LCCE drive electronics will provide the added versatility for the LCCE to work not only with the Thales coolers, but with many different cryocoolers for flight applications.

ACKNOWLEDGMENTS

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the NASA JPL Earth Science Directorate through an agreement with the National Aeronautics and Space Administration.

We would like to acknowledge Iris Technology for providing the LCCE brass board to us for our extended use. We are sad to report that Michael Haley, the Iris LCCE Program Manager, passed away during the performance of this research. He will be missed personally and professionally by all who knew him

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