Characterization Testing of the Thales LPT9310 Pulse Tube Cooler

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ABSTRACT

The Jet Propulsion Laboratory (JPL) has identified the Thales LPT9310 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 5 W at 80 K for 160 W of compressor power. JPL purchased the LPT9310 cooler for thermal and dynamic performance characterization, and has initiated the flight qualification of the existing cooler design to satisfy the near-term JPL needs for this cooler. The cooler has been subjected to random vibration testing and post-vibration thermal cycling. The thermal performance has been characterized as a function of input voltage and as a function of cold tip load and temperature at heat sink temperatures of -20°C, +20°C and +60°C The cooler was also placed on a force dynamometer to measure the self-generated vibration of the cooler as a function of input power, and the orientation dependence of the cooler performance with respect to the gravity vector was also explored. Test results of the thermal and dynamic testing of the Thales LPT9310 cooler will be presented here.

INTRODUCTION

The Thales Cryogenics LPT9310 pulse tube cooler has undergone comprehensive characterization and flight qualification tests at the Jet Propulsion Laboratory (JPL) to determine its suitability for future cost-capped NASA flight missions. The LPT9310 pulse tube cooler is a split cooler configuration with its pulse tube connected with a ~20 cm length helium transfer line. The back-to-back piston design has flexure bearing support springs to ensure non-contacting piston motion. Characterization tests included thermal-vacuum performance testing under various cooler operating parameters and heat rejection temperatures, gravity-orientation performance dependence and exported vibration. The cooler was also subjected to qualification-level random vibration and post-dynamics thermal cycling tests. The cooler was powered with either the Thales XPCDE4865 cooler drive electronics, the Thales CDE7232 cooler drive electronics with vibration control, or the laboratory Chroma 61602 AC power source.

Per the Thales Cryogenics LPT9310/17 Cryocooler Specification[1], the maximum input voltage is 28 Vac during cooldown with parallel connection to the opposed motor coils. Its optimal performance drive frequency is 47 Hz. The cooler is sold without means of structural/thermal interface support for the customer (Fig. 1) so an aluminum clamshell thermal clamp was fabricated to support the cooler throughout all JPL tests (Fig. 2).

Figure 1. The Thales LPT9310 cooler as procured.

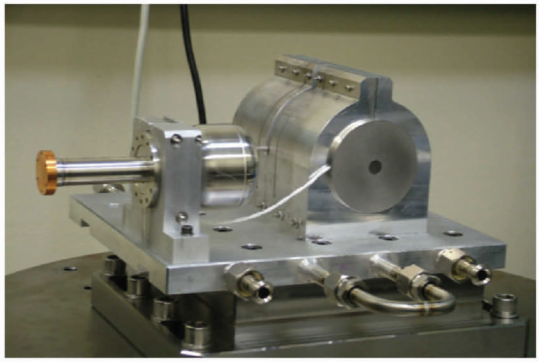

Figure 2. Thales LPT9310 with thermal/structural support clamp.

RANDOM VIBRATION

Setup in ETL

The Thales LPT9310 was subjected to proto-flight random vibration in three axes at the JPL Environmental Test Laboratory. The random vibration testing was conducted to the requirement specified in the Goddard Space Flight Center (GSFC) General Environmental Verification Standard (GEVS).[2] The vibration levels are shown in Table 1, and in Fig. 3. Two control accelerometers and a monitor accelerometer were utilized on the cooler vibration test fixture to control the vibration input. The cooler was instrumented with miniature Dytran Model 3133 tri-axial accelerometers at three locations: the cold finger cold tip, the cold head support clamp and the compressor end cap, as seen in Fig. 4. The cooler was mounted on a fixture adapter plate which in turn was mounted on a small cube fixture for vibration testing. The cooler was subjected to proto-flight launch vibration levels, i.e., power spectral density equal to qualification levels applied for a one minute duration per axis. Overall test levels were 14.1 G_{RMS} in each of the three axes over the frequency band of 20-2000 Hz. No force limiting was invoked for the vibration tests. Random vibration signature runs of two minute durations (0.0001 g^2/Hz and overall 0.45 Grms) were performed before and after random vibration testing in each axis to verify any changes in measured large resonances. Cooler function was verified before and after these dynamic tests, but not between vibration test runs.

Results

Z Axis Vibration Test Results. The cooler was first mounted on top of the cube to shake the cooler in the direction perpendicular to the plane of the cooler. Proto-flight (PF)-level random

Table 1. Random vibration test levels per the GEVS. [2]

Frequency, Hz	FA Level	PF Level
20	0.013 g2/Hz	0.026 g2/Hz
20 - 50	+ 6 dB/octave	+ 6 dB/octave
50 - 800	0.08 g2/Hz	0.16 g2/Hz
800 - 2000	- 6 dB/octave	- 6 dB/octave
2000	0.013 g2/Hz	0.026 g2/Hz
Overall	10.0 grms	14.1 grms

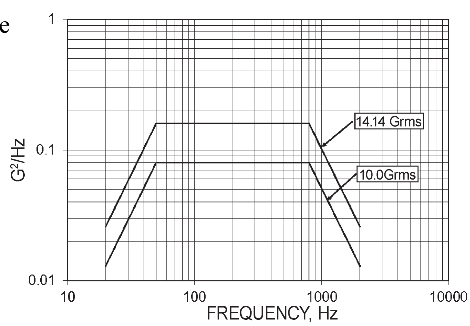

Figure 3. The GEVS proto-flight random vibration test level.

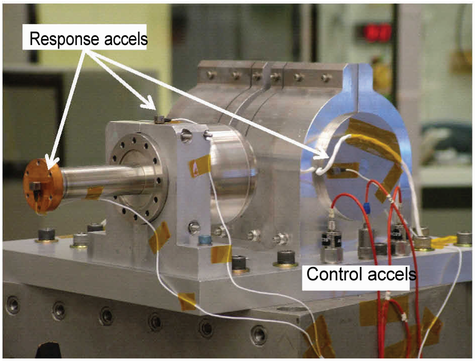

Figure 4. Locations for the three tri-axial response accelerometers.

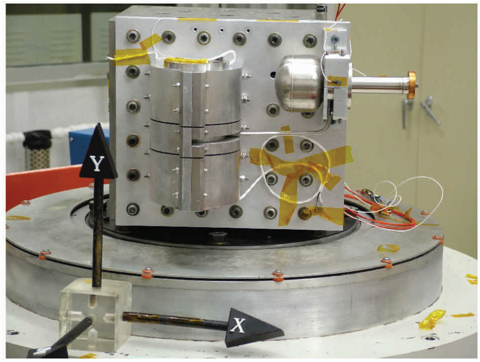

Figure 5. Mounted on cube for compressor axis vibration tests.

vibration testing was originally planned to be performed in the Z axis. However, two attempts of proto-flight level testing in the Z axis were automatically shut down by the shaker control system a few seconds into the test due to excessive chattering detected by the input controller. As a result only Flight Acceptance (FA) level testing was completed in the Z axis (Fig. 6). The in-axis vibration response at the pulse tube bracket was 12.6 Grms; the compressor end cap vibration response reached 42.7 Grms; and the pulse tube cold tip vibration response was 64.6 Grms.

The pre- and post-test 0.0001g^2/Hz signature data show the Thales cooler had a 20 Hz shift around 470 Hz and a more sizable 50 Hz-shift near 750 Hz. No loosening of the cooler clamp fasteners was detected. The frequency shift was likely due to settling of the cooler in the clamp fixture.

Y Axis Vibration Test Results. No excessive chattering of the test article was detected during testing in the Y axis (compressor axis) and the test levels were brought up to the full PF level. At the

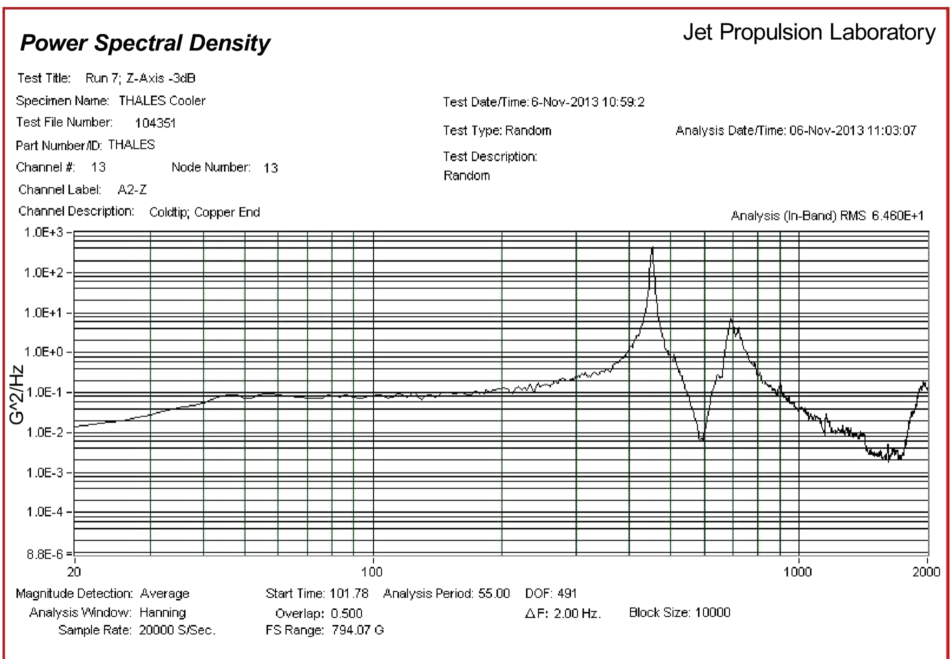

Figure 6. Cold tip vibration response at Flight Acceptance (-3dB) level.

PF level the in-axis compressor end cap vibration response reached 25.7 Grms, the pulse tube bracket vibration response was 29.4 Grms, while the cold tip vibration response reached 147.8 Grms. No noticeable frequency shifts were observed when comparing the pre- and post-vibration tests.

X Axis Vibration Test Results. Significant chattering was again observed in the X axis (pulse tube axis) even at the FA level test, no attempt was made to test at the full proto-flight level where the controller would have probably shut the shaker down. At the FA vibration level the compressor end cap in-line vibration response reached 15.0 Grms, the pulse tube bracket vibration response was 45.6 Grms and the cold tip vibration response was 28.7 Grms. No noticeable frequency shifts were observed between the pre and post signature data.

In summary the Thales LPT9310 cooler successfully passed proto-flight level random vibration testing in the Y axis, and flight acceptance level random vibration testing in the X and Z axes. Post-vibration thermal performance measurements on the cooler indicated no change in performance after exposure to these PF qualification levels of launch vibration. There are plans to build a new thermal/structural clamp for the cooler at which time random vibration tests will be repeated at the proto-flight level.

PROTO-FLIGHT THERMAL TESTS

After dynamics testing, the cooler was returned to the laboratory for thermal vacuum performance testing and thermal cycling tests at typical instrument proto-flight temperatures. The thermal cycling test consisted of six hours of soak at the proto-flight hot and proto-flight cold temperatures, plus three thermal cycles over the hot to cold operating temperatures. Cooler power-ups were conducted at both hot and cold plateaus. Functional load line tests were conducted at specified input voltages at each hot and cold temperature plateau to exercise the cooler and look for performance variations between thermal cycles.

Table 2 shows the operating/nonoperating cooler reject temperatures provided by Thales Cryogenics in their LPT9310 cryocooler specification. Also shown are the typical Allowable Flight Temperatures expected for flight instruments, and the corresponding proto-flight temperatures used in these tests to qualify the cryocooler. Normally the qualification temperature range extends 15°C below and 15°C above the Allowable Flight Temperature range[2]. A thermocouple on the cooler compressor center plate near the transfer line was used as the "skin" temperature. Load lines were taken at compressor input voltages between 16 Vrms and 28 Vrms. Figures 7-9 show the performance sensitivity to reject temperature for the cooler at 20°C, -20°C and at +60°C, respectively.

Over the course of cooler thermal performance testing, the cooler was operated with the Thales XPCDE4865, the Thales CDE7232 or the Chroma 61602 AC supply drive electronics. The Thales XPCDE4865 was tested in the vacuum chamber and kept at ambient temperature with a dedicated heat exchange plate; the other cooler drive electronics were vacuum incompatible and kept outside the chamber when used to drive the cooler.

ORIENTATION DEPENDENCE

The cooler was mounted on to a rotating table to allow cooler operation in any orientation. Figure 10 shows the test configuration for the orientation dependency tests. For coaxial pulse tube coolers such as the LPT9310, the cold tip must be pointed downward to achieve the optimal performance. 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 cold head. There is a well-known performance dependence on orientation for pulse tube coolers[4-6]. However this

Table 2. Cooler skin temperatures for the thermal performance temperatures.

Condition	Thales LPT9310 Specification [1]	Typical Allowable Flight Temperatures	Protoflight Temperatures
Operating	-40°C to +71°C	0°C to +40°C	-20°C to +60°C
Non-Operating	-55°C to +80°C	-15°C to +50°C	-30°C to +70°C

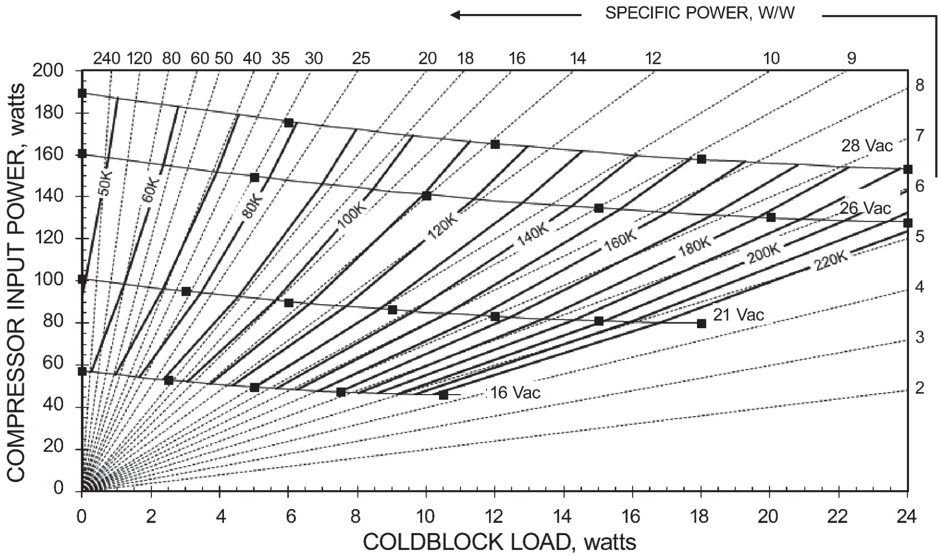

Figure 7. Thales LPT9310 thermal performance at ambient temperature (20°C)

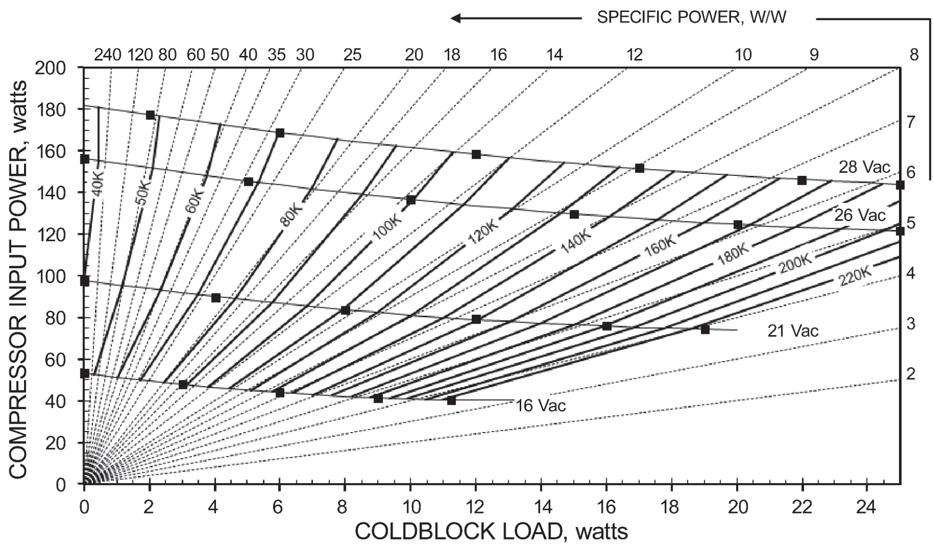

Figure 8. Thales LPT9310 thermal performance at proto-flight cold temperature (-20 oC)

cooler did not perform as other pulse tube coolers nominally performed. Rather than displaying its loss of performance between the adverse angles of 135° and 150° this cooler showed a continual loss in performance up to 180°. These tests confirmed results found by Chris Paine a year earlier[3]. Out of curiosity, orientation effect testing was continued through the entire 360° clocking to check for performance symmetry with respect to the gravity vector. Test results for the orientation dependent no-load performance of the cooler are shown in Fig. 11. The test data displayed for the other hemisphere of orientation angles (180° to 360°) does indeed perform as one would have expected[4-6]. This begs the question of whether there is some asymmetry in the mechanical design that would help suppress the gas convection on one side, and whether it can be added to the other side as well without altering the cooler's thermal performance. To determine if this asymmetrical orientation performance was generic in the Thales pulse tube coolers, a follow-up retest of the gravity depen-

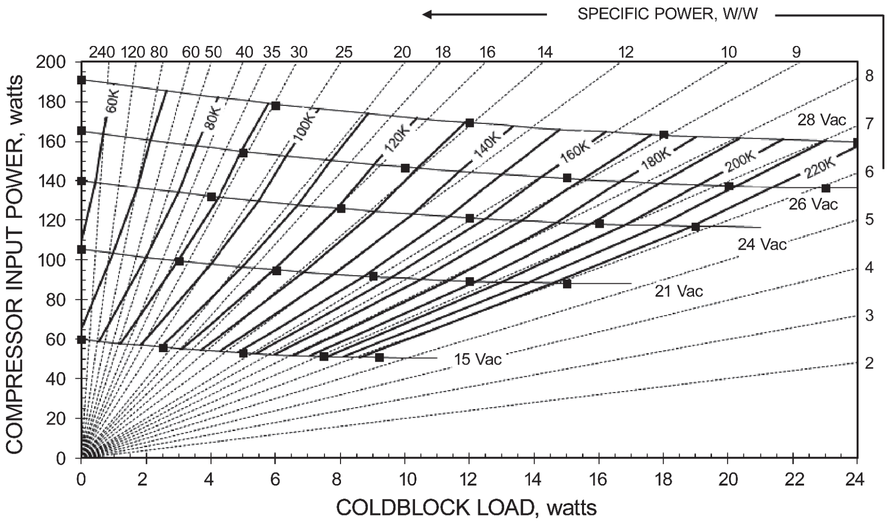

Figure 9. Thales LPT9310 thermal performance at proto-flight hot temperature (60°C)

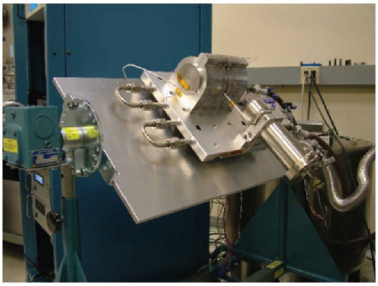

Figure 10. The orientation dependent test setup for the LPT9310 cooler.

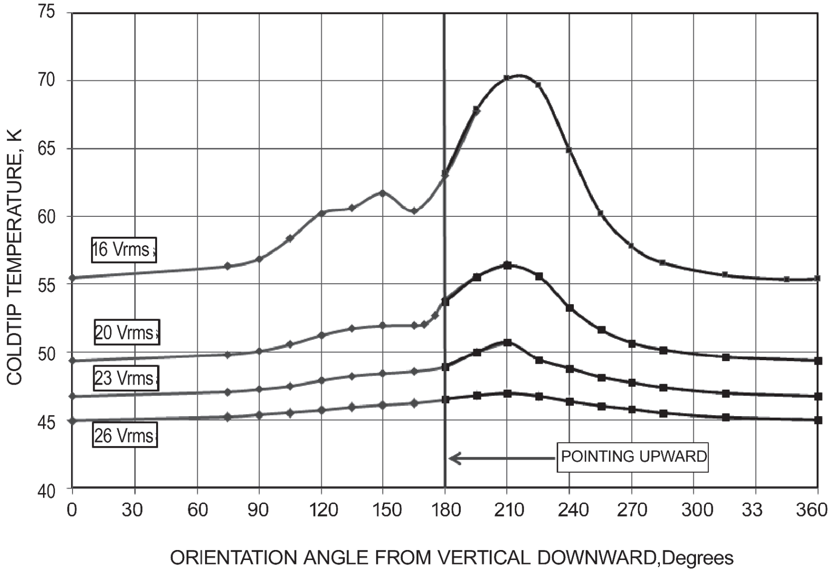

Figure 11. LPT9310 orientation test results through a full 360 degree orientation relative to gravity.

dent performance of the smaller LPT9510 cooler was conducted, with the test results showing complete symmetry about the gravitational vector.

EXPORTED VIBRATION

The exported vibration of the cryocooler was measured in the JPL vibration characterization facility using a Kistler Model 9255 Quartz 3-component dynamometer and a Kistler Model 5017 charge amplifier. Figure 12 shows the cryocooler mounted to the dynamometer and Fig. 13 shows the exported vibration characterization facility. The dynamometer was bolted to a 2275 kg steel seismic mass that was mounted on three Newport model SLM-24A air supports to isolate the cryocooler from ambient vibrations. The Newport air isolators have a 3-5 Hz natural frequency and were incorporated to remove the low frequency building mechanical noise. The resonance of the dynamometer setup was determined using a PCB Piezotronics Model 086C02 impact hammer to be around 1800 Hz corresponding to a very stiff system. A Crystal Instruments Spider80X Dynamic Signal Analyzer was used to acquire the amplified signal from the four three-axis load cells in the dynamometer. Note that the dynamometer was statically calibrated by the manufacturer. In addition, using a small Labworks Inc. inertial shaker, the force measured by the dynamometer was compared to that of a statically calibrated PCB Model 208B load cell and agreed within 10% for frequencies between 40 Hz and 50 Hz and for forces up to 1.5 N in each axis.

The exported vibration of the cryocooler was measured with the cooler at nominal cold operating temperatures for input voltage and drive frequency ranging from 16 Vrms to 26 Vrms and 42 Hz to 52 Hz, respectively. The cooler was driven with the Thales CDE7232 drive electronics that featured an automatic vibration reduction (AVR) function to attenuate the first five harmonics. The amplified force signal in the compressor axis was used as feedback for this function. Figure 14 shows the auto power spectra for the first six harmonics as measured by the Crystal Instruments Engineering Data Management (EDM) software with the cooler driven with 26 Vrms input voltage at various drive frequencies with the AVR function switched off (left), and on (right). It is evident that the AVR function successfully reduced the exported force in the compressor direction at the first five harmonics to less than 20 mN for all drive frequencies for this input voltage. In addition, the exported force in the compressor axis was nearly independent of drive frequency when the AVR function was off.

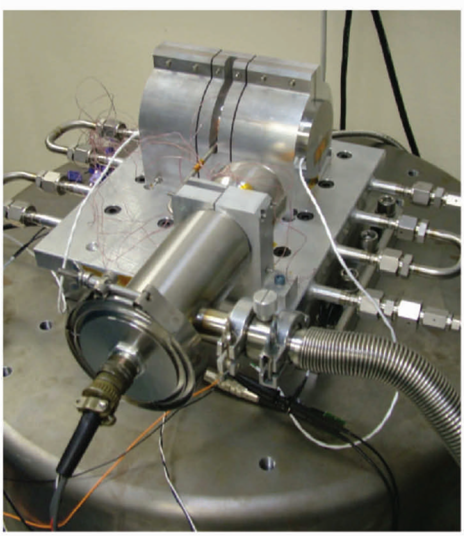

Figure 12. The Thales LPT9310 cooler mounted on the Kistler dynamometer.

Figure 13. Dynamometer test facility.

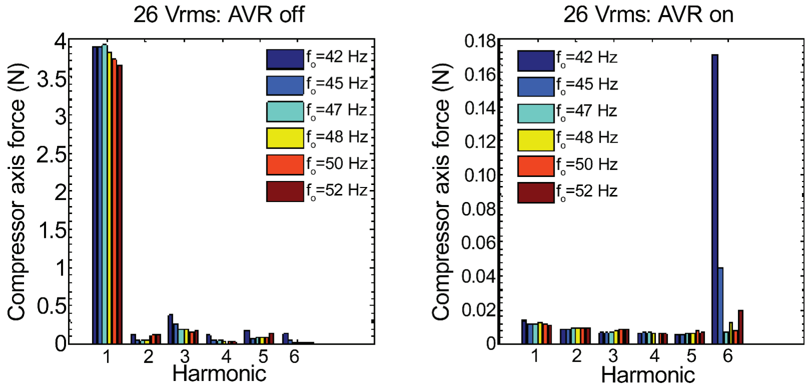

Figure 14. Exported vibration along the compressor axis as a function of drive frequency and at 26 Vrms input voltage using the Thales CDE7232 drive electronics, with AVR switched off (left) and on (right). A flattop window was used to perform the auto power spectrum on force vs. time data collected over approximately three minutes.

The large exported force in the compressor axis may be attributed to the mismatch in electrical resistance of the two motor coils. In fact, a 4-wire measurement made with Hewlett Packard 3457A revealed a 2.48% difference in coil resistance. Future measurements will be made applying separate i^2R power signals to the two motor coils to understand the sensitivity of exported vibration to the relative i^2R power applied to the two motor coils.

Figure 15 shows the exported force in the compressor axis at the first harmonic as a function of compressor input voltage. While the fundamental harmonic vibration level increased with input voltage the higher harmonics did not follow suit.

Figure 16 shows the exported pulse tube (left) and vertical (right) forces (perpendicular to the plane of the cooler) at the 47-Hz drive frequency for various compressor input voltages. The force in both directions increased with increasing compressor input voltage as expected. As expected, the AVR function had no credible effect on the vibration levels in either the pulse tube axis or in the perpendicular axis.

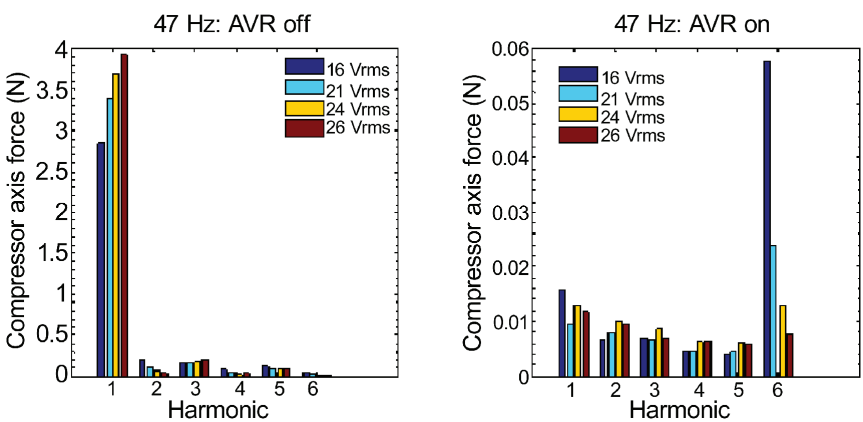

Figure 15. Compressor axis force at the 47 Hz drive frequency as a function of compressor input voltage. The plot on the left shows levels with the Thales CDE7232 AVR turned off, and the plot on the right shows levels with the AVR turned on.

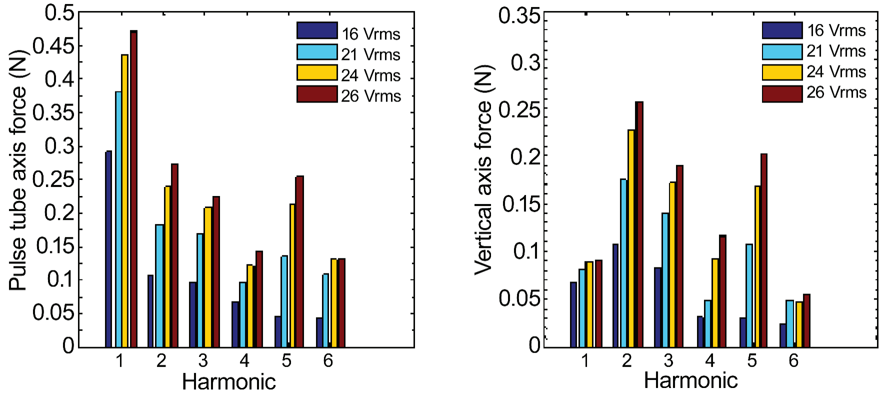

Figure 16. Pulse tube (left) and vertical (right) direction forces as a function of compressor input voltage at the 47-Hz drive frequency.

SUMMARY

The Thales LPT9310 pulse tube cooler has been demonstrated to be a very robust cooler, and having good thermal performance over a wide reject temperature range. The cooler displayed a unique ability to diminish typical convective losses when operating at angles other than pointing downwards. Random vibration tests of the cooler will be repeated at the proto-flight levels after redesign of the thermal/structural clamp for the cooler.

ACKNOWLEDGMENTS

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