

# Flight Qualification Testing of the Thales LPT9510 Pulse Tube Cooler

**D.L. Johnson, I.M. McKinley, J.I. Rodriguez**

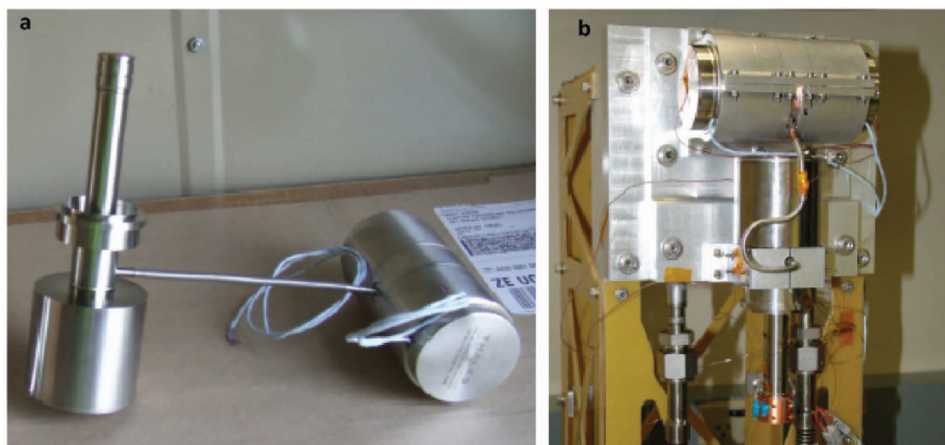
Jet Propulsion Laboratory, California Institute of Technology  
Pasadena, CA 91109

## ABSTRACT

The Jet Propulsion Laboratory (JPL) has continued the qualification of the Thales LPT9510 pulse tube cryocooler as a candidate low cost cryocooler for 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 completed random vibration dynamics tests and the post-dynamics thermal cycling tests for the flight qualification of the existing cooler design to satisfy near-term JPL needs for this cooler. The cooler was subjected to protoflight dynamics levels in all 3 axes to the 0.16 g<sup>2</sup>/Hz level. The LPT9510 cooler was then thermally cycled three times over the heat reject temperature range of -15°C to +55°C to demonstrate its survival of the dynamics testing. Thermal performance characterization measurements were made at several input voltages at the -15°C, +20°C and +55°C reject temperatures. Finally, the cooler was placed on the dynamometer to measure the exported vibration using the Thales CDE7232 cooler drive electronics with its automatic vibration reduction capability. Test results of the Thales LPT9510 cooler dynamics, thermal and exported vibration testing are presented here.

## INTRODUCTION

The Jet Propulsion Laboratory (JPL) continues to identify and make available reliable, low cost cryocoolers to budget-conscious (cost-capped) space missions. JPL is looking at tactical cooler designs that have incorporated flexure bearings, and preferably non-moving pulse tube coldheads as the next generation flight cryocoolers to cover these low cost missions. The Thales Cryogenics line of linear pulse tube coolers, with their >10-year lifetime predictions<sup>1</sup>, have been identified by JPL as ideal candidates to serve as the initial coolers for flight qualification. In continuing the characterization and qualification process for the Thales LPT9510 cryocooler, JPL conducted protoflight-level random vibration and thermal cycling performance testing to demonstrate the cooler is at the Test Readiness Level (TRL) 6, implying it has passed the necessary environmental tests and is now a viable candidate for space flight. Additional exported vibration tests have also been conducted on the cooler to correct testing errors found in test results reported earlier<sup>2</sup>, and to compare vibration cancellation techniques made with the Thales CDE7232 laboratory drive electronics. 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. Initial performance testing of the Thales LPT9510 cooler was presented in an earlier paper<sup>2</sup>.



**Figure 1.** The Thales LPT9510 pulse tube cryocooler. Left: as purchased. Right: after attaching thermal/structural support clamps.

A representative Thales LPT9510 cryocooler, as delivered by the vendor, is shown in left-hand photograph in Fig. 1. The transfer line geometry and the coldhead orientation relative to the compressor are customer-defined. Thales leaves to the customer the means to structurally support and thermally interface the cooler. For JPL laboratory tests, an aluminum thermal clamp was fabricated and installed around the compressor and coldhead to function as the structural and the thermally conductive interface to the heat exchanger (Fig. 1 right). This clamp added 896 g to the overall cooler mass which is acceptable for all ground testing but heavier than desired for a flight application. Per the Thales Cryogenics LPT9510 pulse tube cryocooler specification, the maximum input voltage during cool down is 12 Vac, with a maximum input current of 6 A<sup>3</sup>. The nominal drive frequency is 45 Hz. The permissible “skin” temperature range for the cooler is 0°C to +70°C when operating, and -55°C to +90°C when non-operating or in storage.

The cooler has been performance tested at JPL using the Thales HPCDE2465 cooler drive electronics, the Thales CDE-7232 drive electronics, the Chroma Model 61602 AC source, and with a brassboard set of Low Cost Cryocooler Electronics (LCCE) from Iris Technology<sup>4</sup>.

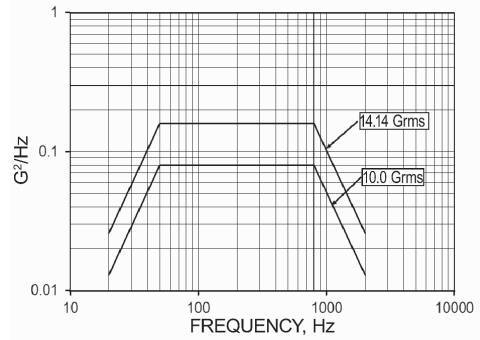
## LAUNCH VIBRATION TESTING

### Test Setup Description

The Thales LPT9510 was subjected to protoflight random vibration in three axes at JPL. The random vibration testing was conducted to the requirement specified in the Goddard Space Flight Center (GSFC) General Environmental Verification Standard (GEVS)<sup>5</sup>. The vibration levels are shown in Table 1, and in Fig. 2. The cooler was instrumented with miniature Dytran Model 3133 triaxial response accelerometers at three locations as shown in Fig. 3 to measure the vibration response: the endcap of the compressor, the coldtip of the pulse tube and the support clamp holding the pulse tube coldhead. The cooler was attached to a fixture adapter plate which in turn was mounted to one of several faces of the small cube fixture on the vertical shaker (Fig. 4). Two control accelerometers and a monitor accelerometer were utilized on the cooler vibration test fixture to control the vibration input from the shaker. No mass was added to simulate an attached flexible thermal strap other than the 1-gram triaxial accelerometer bonded to the pulsetube coldtip. A two minute low level random survey (0.0001 g<sup>2</sup>/Hz and an overall 0.45 Grms from 20 Hz to 2000 Hz) was conducted before and after random vibration testing in each axis to look for frequency shifts in the large resonances.

**Table 1.** Random vibration test levels per the GEVS.<sup>5</sup>

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



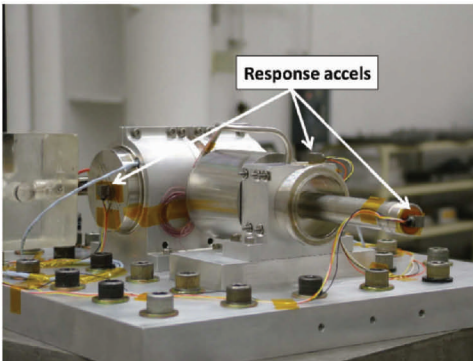
**Figure 2.** The GEVS protoflight random vibration test level.

**Results**

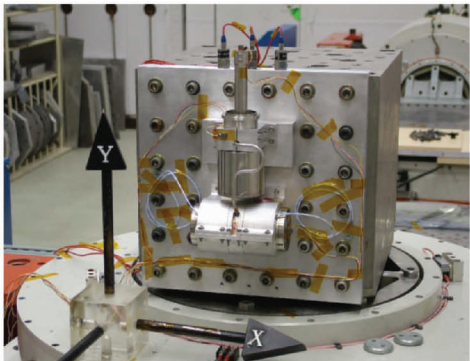
The cooler was subjected to protoflight launch vibration levels, i.e., power spectral density equal to qualification levels, applied over the frequency band of 20-2000 Hz for a duration of one minute per axis.  $G_{RMS}$  levels were 14.1  $G_{RMS}$  in each of the three axes.

**Z Axis Vibration Test Results.** The Thales Cooler Z axis PF random vibration acceleration test input is shown in Fig. 5. This was the first axis tested. The compressor end plate response reached 16.7 Grms, the pulse tube bracket vibration response reached 17.2 Grms, while the coldtip response was 117.8 Grms. The pre- and post-test signature data did show the coldtip had a 10 Hz shift in the first mode and a sizable 70 Hz shift in the second mode. Some settling of the cooler in the test fixture may have occurred, as the pulse tube coldhead bracket was found to have loosened during the PF level test. The bracket was re-torqued and the random survey run was repeated. The two primary peaks shifted back up to within an acceptable 5% of their original peak frequency. The cooler clamp fixture screws were subsequently re-torqued between each test to ensure no further resonance shifts were encountered. All-thread rod was used to fasten the two clamp sides together, and these were not hardened screws that could take large torques on the nuts.

**Y Axis Vibration Test Results.** Vibration in the pulse tube axis was performed next. The pulse tube bracket vibration response was 43.3Grms. The pulse tube cold tip response was 31.3 Grms in the direction of the pulse tube length. Vibration response on the compressor end cap reached 25.4 Grms. The pre- and post-test signature data showed that the cold finger second mode response



**Figure 3.** Dynamics test setup and location of three triaxial accelerometers to measure the vibration response.



**Figure 4.** The cooler is shown mounted on the vertical shaker to perform the random vibration tests along the pulse tube (Y) axis.

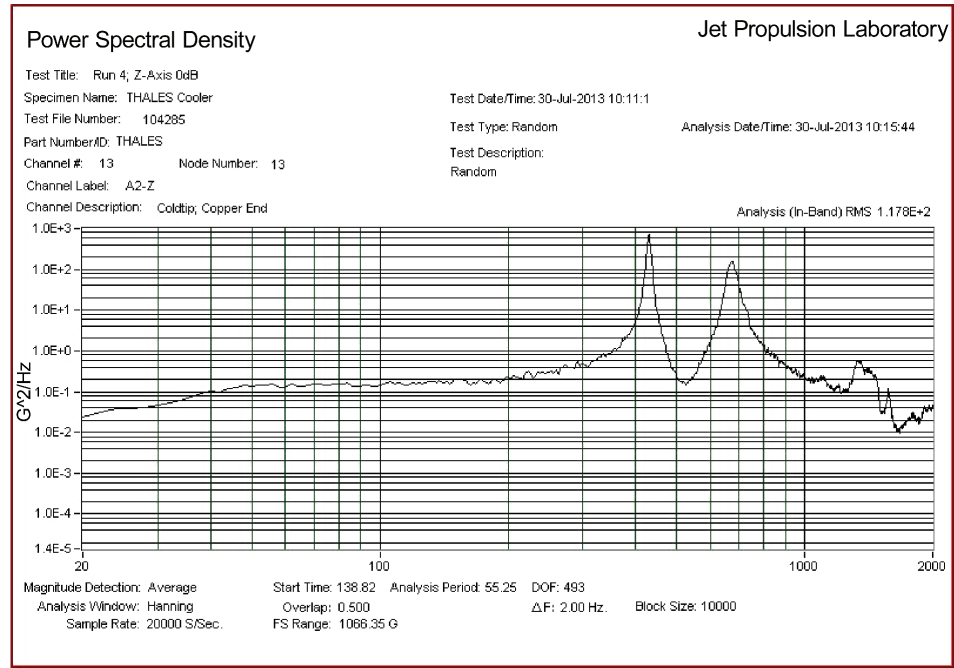


Figure 5. Coldtip vibration response at the full protoflight qualification level.

shifted from 850 Hz to 820Hz. Peak response at 1700 Hz was lessened with a minor frequency shift. Both peak frequency shifts were within 5%.

**X-Axis Vibration Test Results.** The cooler interface plate was next rotated 90° on the vertical cube for testing the cooler along the compressor axis. For the compressor axis vibration tests, the pulse tube bracket vibration response was 14.7 Grms; the compressor end cap response reached 27.5 Grms; while the pulse tube coldtip vibration response was highest at 147.4 Grms. The pre- and post- test signature data showed that the cooler had no frequency shifts even though the pulse tube coldtip response in the X axis was 25% higher than in the Z axis. Consensus of the JPL dynamicists indicated that the Z axis frequency shift in the pulse tube were almost certainly due to fixture bracket loosening. Post-vibration thermal testing at protoflight temperature level verified this to be true. The thermal results are discussed in the next section.

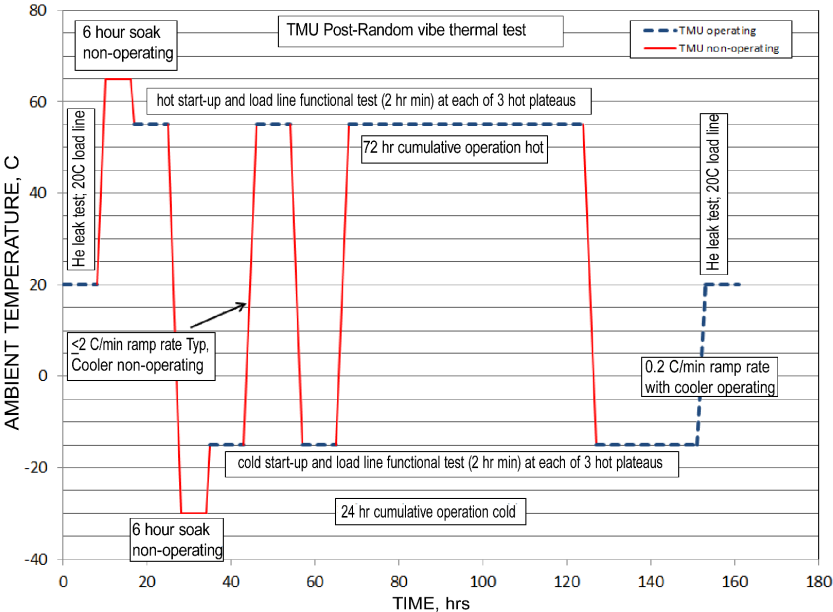
PROTOFLIGHT THERMAL PERFORMANCE TESTS

After dynamics testing, the cooler was returned to the laboratory for thermal vacuum performance testing and thermal cycling tests at typical instrument-level protoflight temperatures. Table 2 shows the operating/non-operating cooler reject temperatures provided by Thales Cryogenics in their LPT9510 cryocooler specification. Also shown are the typical Allowable Flight Temperatures and the corresponding Protoflight temperatures used to qualify the cryocooler. A thermocouple placed on the cooler compressor center plate near the transfer line served to measure the compressor “skin” temperature; this also served as the reject temperature. The thermal cycling test (see Fig. 6 for test plan) consisted of six hours of soak at the protoflight hot and proto-flight cold temperatures for the non-operating cooler, plus three thermal cycles over the hot to cold operating temperatures. Cooler power-ups were conducted at both hot and cold plateaus, even though in all cases the cooler electronics were kept external to the vacuum chamber. Functional tests consisting of load line(s) at constant input voltage were conducted at each hot and cold temperature plateau. Figures 7-9 show the cooler performance sensitivity to reject temperatures of -15°C, 20°C and 55°C. Load

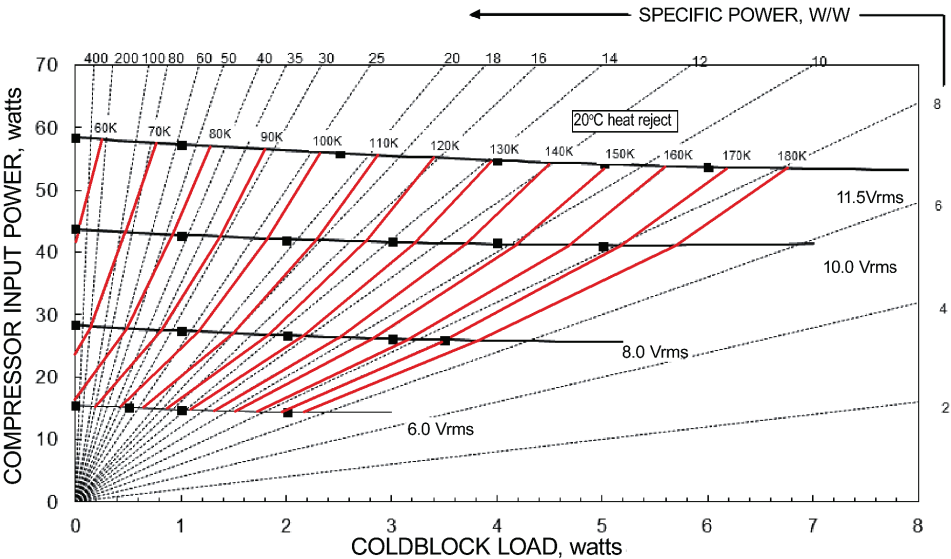
**Table 2:** Cooler skin temperatures for the thermal performance temperatures.

Condition	Thales LPT9510 Specification <sup>3</sup>	Allowable Flight Temperatures	Protoflight Temperatures
Operating	0°C to +70°C	0°C to +40°C	-15°C to +55°C
Non-Operating	-55°C to +90°C	-15°C to +50°C	-30°C to +70°C

lines were taken at input voltages of 6, 8, 10 and 11.5 Vrms input to the compressor at each of these temperatures.



**Figure 6.** Protoflight thermal cycling test profile.



**Figure 7.** Thermal performance at ambient temperature (20°C)

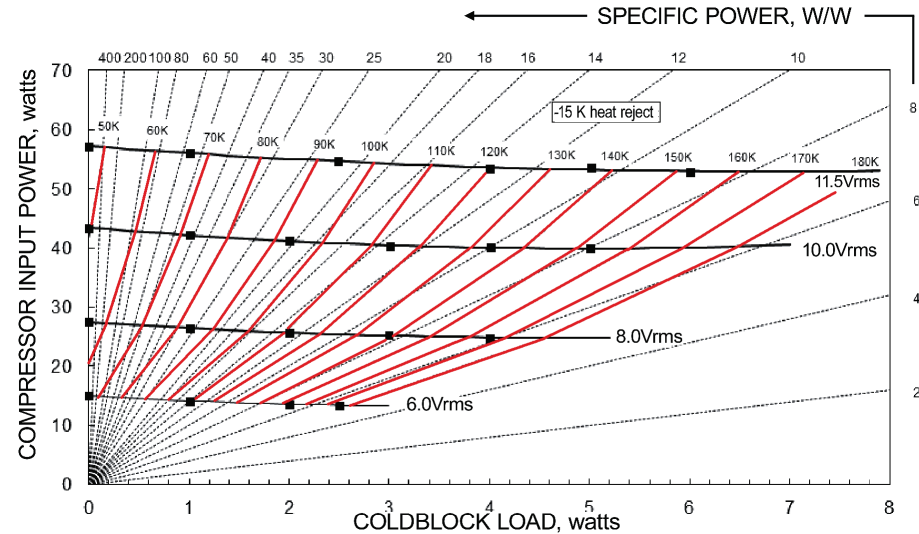


Figure 8. Thermal performance at Protoflight cold temperature (-15°C).

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 10 shows the characterization facility and the cryocooler mounted to the dynamometer. The dynamometer was mounted to a 2275 kg steel seismic mass that rested upon three Newport Model SLM-24A air supports to isolate the dynamometer from environmental (building) ambient vibrations. The resonance of this system was measured to be around 1800 Hz using a PCB Piezotronics Model 086C02 impact hammer. A Crystal Instruments Spider80 Dynamic Signal Analyzer was used to acquire the amplified force signal from the four tri-axial load cells in the dynamometer. These load cells were statically calibrated by the manufacturer and agreed with the force measured by an independently calibrated PCB Model 208B load cell. The force of a single

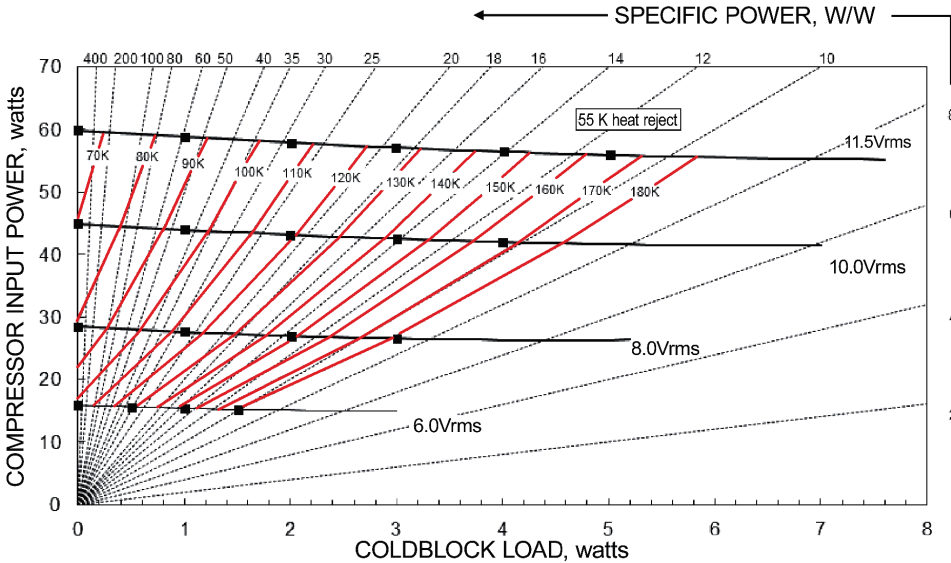
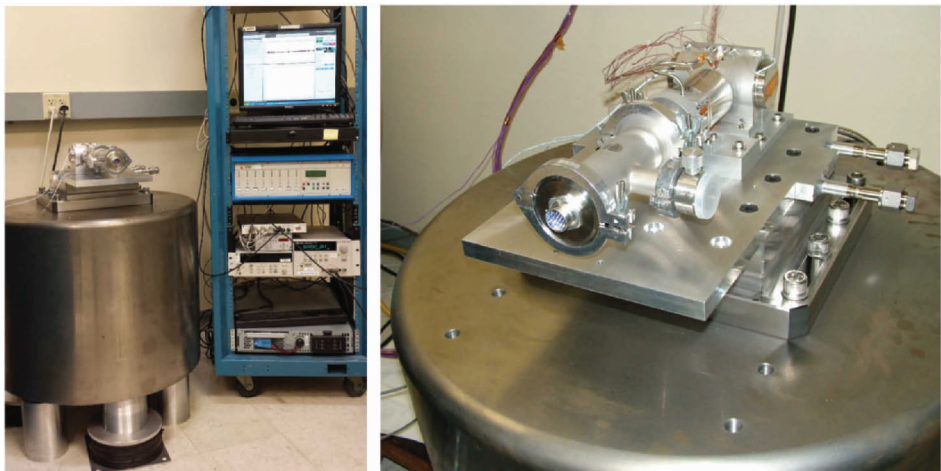


Figure 9. Thermal performance at Protoflight hot temperature (+55°C).

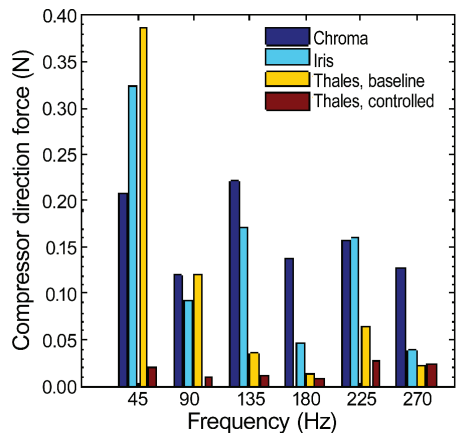




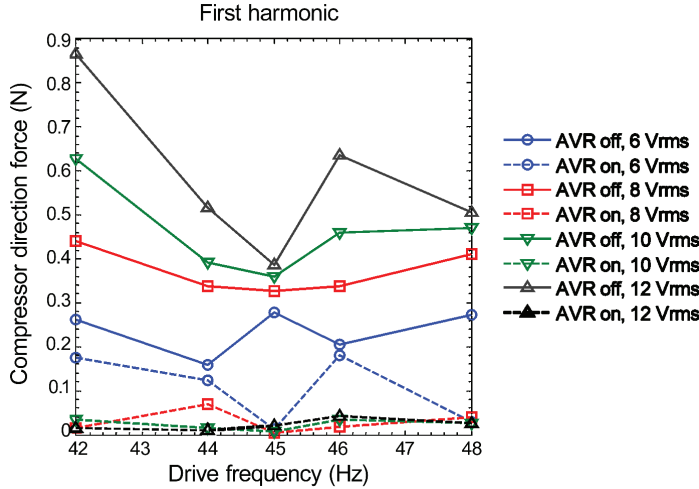
**Figure 10.** The JPL exported vibration facility (left) and Kistler 9255B force table (right).

axis inertial shaker measured by both methods agreed within 10% for frequencies between 40 Hz and 50 Hz and forces up to 1.5 N in all directions.

The exported vibration of the cooler was measured at nominal cold operating temperatures for drive frequency and input voltage ranging from 42 Hz to 48 Hz and 6 Vrms to 12 Vrms, respectively. The vacuum pump and recirculating chiller lines were disconnected from the cryocooler during force measurement. Each measurement lasted approximately three minutes. In addition, the cooler was driven with three different drive electronics, namely the Thales CDE7232, the Chroma Model 61602 AC power supply, and the Iris Technology brassboard LCCE. The automatic vibration reduction (AVR) function featured on the Thales CDE7232 drive electronics was used to reduce the exported forces in the compressor axis for the first five harmonics. The amplified force signal was used as feedback for this function. Figure 11 shows the magnitude of the auto power spectra (APS) as measured by the Crystal Instruments data management software, with the cooler driven by the different drive electronics at 45 Hz with 12 Vrms corresponding to  $75.5 \pm 2.5$  Watts. A flattop window was chosen to accurately determine the magnitude of the peaks. Figure 11 illustrates that the exported force is largely dependent on the purity of the drive electronics signal. Also, it is evident that the Thales AVR function successfully reduced the exported force in the compressor



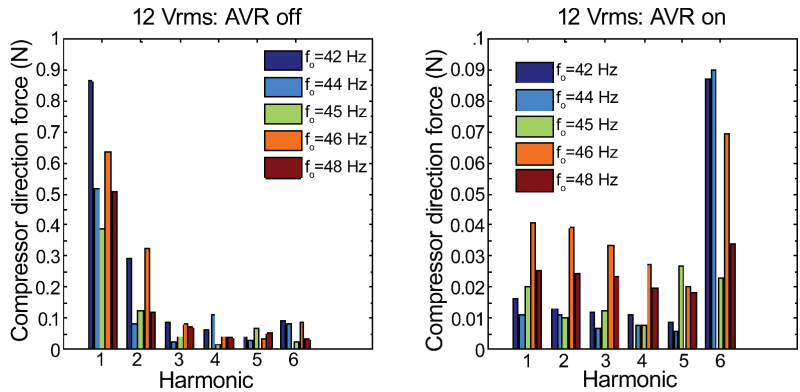
**Figure 11.** The first six harmonics of the compressor axis forces for various electronics driving the cooler at 12 Vrms ( $75.5 \pm 2.5$  W) and at 45 Hz.



**Figure 12.** First harmonic of the compressor axis force as a function of drive frequency for various input voltages with the AVR off (solid) and AVR on (dashed).

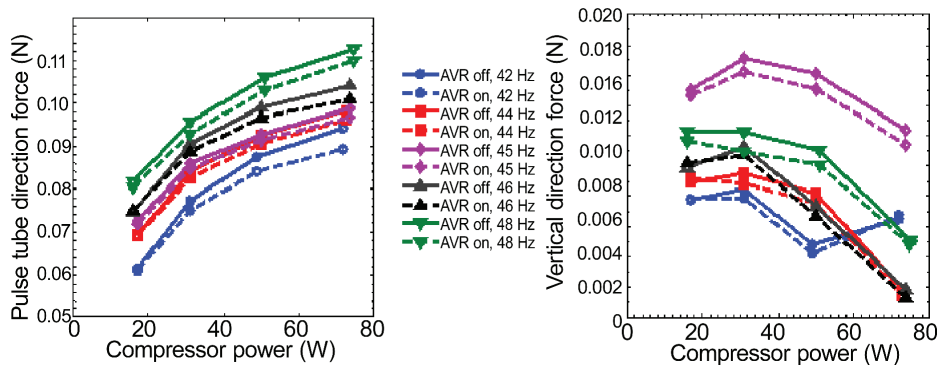
direction at the drive frequency through the fifth harmonic. Finally, it is noted that the force measurements made in the present study do not agree with those previously reported<sup>2</sup>. This is due to the fact that, in the previous study, the authors reported the average of the fast Fourier transform (FFT) as measured by the Crystal Instruments software. The FFT average consisted of both magnitude and phase information that caused the magnitude of the peaks to decrease (or even zero out) over time when not triggered correctly. This issue came to light early in this present study, and was avoided by collecting data using the auto power spectra (APS) because it contains no phase information and is truly an average of the magnitude of the peaks.

Figure 12 shows the first harmonic compressor direction force as a function of drive frequency for the cooler driven with the Thales electronics with various input voltages and with the AVR function switched on and off. It is evident that, for a given frequency, the force increased with increasing compressor power. In addition, the AVR function successfully reduced the exported force below 200 mN for all input voltages and drive frequencies tested, and was observed to work most effectively at the higher input voltages. Figure 13 shows the first six harmonics of the compressor direction force for various drive frequencies with 12 Vrms input corresponding to  $73.5 \pm 1.5$  W with the AVR function switched off (left) and on (right). Drive frequencies of 42 Hz and 46 Hz



**Figure 13.** Exported vibration at the first six harmonics for various drive frequencies. The cooler is being driven at 12 Vrms with the Thales CDE7232 drive electronics; the AVR controlling the first five harmonics. Left: vibe cancellation (AVR) off. Right: Vibe cancellation (AVR) on.





**Figure 14.** First harmonic exported vibration as a function of drive frequency and compressor input power in the pulse tube direction (left) and in the perpendicular direction to the plane of the cooler (right).

produced the largest exported forces with the AVR function switched off. In addition, the AVR function was able to reduce the force of the first five harmonics to less than 45 mN for all drive frequencies at the higher input voltages.

Figure 14 shows the first harmonic pulse tube (left) and vertical (right) direction (perpendicular to the plane of the cooler) forces as a function of compressor power for various drive frequencies, and with the AVR function switched on and off. The pulse tube and vertical direction forces were less than 115mN and 18 mN in all cases, respectively. In addition, the pulse tube direction force increased with increasing compressor power and drive frequency. On the other hand, the vertical direction force decreased with increasing power. Finally, for a given frequency and compressor power, the AVR function only slightly reduced the forces in both the pulse tube and vertical directions. This indicates that the cooler mounting couples the compressor direction with the pulse tube and vertical directions.

SUMMARY

The Thales LPT9510 pulse tube cooler successfully completed Protoflight random vibration testing and thermal cycling testing to raise its TRL level 6. Additional exported vibration testing was conducted to start looking at vibration cancellation techniques and capabilities. In doing so JPL found it was incorrectly collecting FFT data, and improved its exported vibration data collection using the auto power spectra. The Thales 7232 drive electronics was able to reduce the exported vibration at the first five harmonics by more than an order of magnitude for all but the lowest of cooler input powers. Exported vibration levels were reduced to less 45 mN for all but the lowest compressor input voltages.

ACKNOWLEDGMENT

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 and thank Iris Technology for providing the LCCE brass board to us for our extended use.

The cooler was powered with the Thales CDE7232 drive electronics. The solid lines represent data taken with the AVR function off; the dashed lines with the AVR function on.

REFERENCES

1. van de Groep, W., van der Weijden, H., van Leeuwen, R., Benschop, T., Cauquil, J.M., Griot, R., "Update on MTF figures for linear and rotary coolers of Thales Cryogenics", *SPIE Infrared Technology and Applications XXXVIII*, Vol. 8353 (2012), pp. 83531S-1 to S-15.

2. Johnson, D.L., Rodriguez, J.I., Carroll, B.A. Bustamante, J.G., Kirkconnell, C.S., Luong, T.T., Murphy, J.B. and Haley, M.F., "Integrated Testing of the Thales LPT9510 Pulse Tube Cooler and the Iris LCCE Electronics," *Adv. in Cryogenic Engineering*, Vol 59B, American Institute of Physics, NY, 2014, pp. 1806-1813.
3. *Cryogenic Cooler LPT 9510/01 Specification, Thales Cryogenics, July 21, 2006.*
4. Freeman, J.J. Murphy, J.B. and Kirkconnell, C.S., "Experimental demonstration of cryocooler electronics with multiple mechanical cryocooler types," *Proc. of SPIE*, Vol. 8353 (2012), pp. 83531W-1 to W-7.
5. GSFC-STD-7000, "General Environmental Verification Standard (GEVS) For GSFC Flight Programs and Projects," NASA Goddard Space Flight Center, Greenbelt, MD, April 2005.