

# Ball Low-Vibration Cryocooler Assemblies

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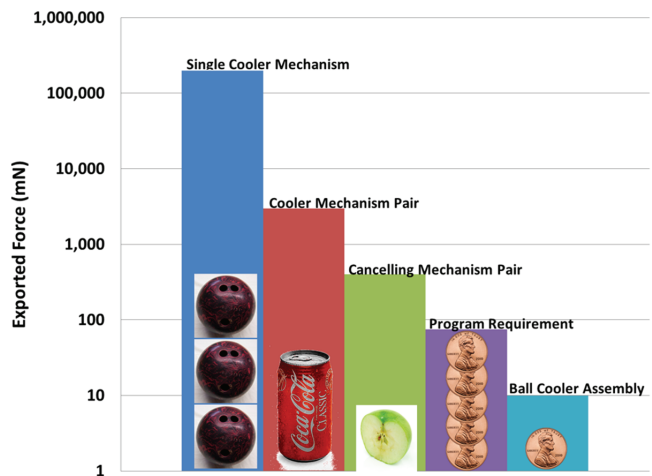
## ABSTRACT

This paper describes the design, development, testing, and performance at Ball Aerospace for a series of Low Vibe CCAs (Cryocooler Assemblies). These CCAs attenuate cooler vibration or EFT (Exported Force and Torque) by several orders of magnitude. They are also modular, stand alone, and provide structural support as well as thermal heat rejection. They have been used to isolate both space cryocoolers (NGAS and Ball units) and tactical cryocoolers (Sunpower) for space and airborne applications. To date, seven CCAs have been built and tested and another six are in build. The CCAs provide passive isolation in all six degrees of freedom. The basic principal of operation is a low frequency isolation platform. However, many of the key and challenging aspects of the system are to minimize the transmission and impact of the parallel peripheral paths around the platform, including cables, thermal links, insulation, and heat rejection. For these parallel paths, we have developed unique solutions that reduce the impact to the platform to negligible levels and reduce the parallel EFT transmission to levels below those transmitted by the base platform. The resulting CCA performance attenuates EFT peaks to less than 20 mN and 20 mN-m in any axis or harmonic and over a range of cooler operating frequencies.

Additionally, we have developed several sizes of testbeds to verify and characterize the combination of Low Vibe CCAs and payloads. These testbeds have resolution levels lower than or in the mN range and span the test article range from 5 lbs. coolers to 400 lbs. instruments. These CCAs have been developed in cooperation with the cooler teammates Ball, NGAS, Sunpower, the thermal link teammate SDL, and the isolator teammate Moog CSA.

## INTRODUCTION AND BACKGROUND

Ball Aerospace has had multiple jitter sensitive programs and applications that require very low levels of cryocooler generated EFT. These applications have required EFT with orders of

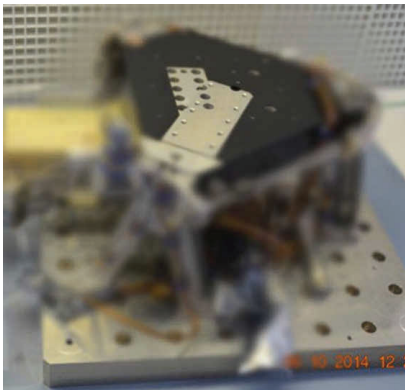


**Figure 1.** Illustration of the challenges and success in reducing cooler EFT

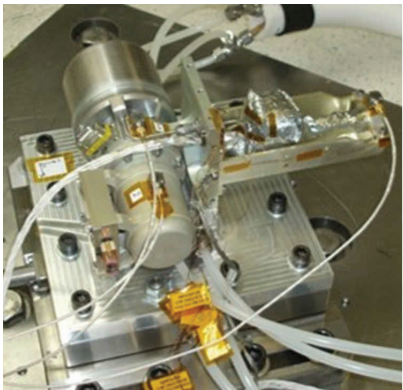
magnitude lower than that produced from already balanced and actively cancelled cryocoolers such as the NGAS HEC (High Efficiency Cooler). In collaboration and partnership with Moog CSA (isolation component), NGAS, Ball, and Sunpower (cryocooler suppliers), and SDL (flexible link supplier), Ball has designed, built, and tested multiple Low Vibration CCAs for space and airborne applications. These CCAs significantly attenuate the already low EFT output from the cryocooler TMUs (Thermomechanical Units) approximately 50 times smaller than the original.

The challenges to this level of EFT performance are illustrated in Figure 1. Not only are the reductions in EFT large, but the measurement of the resulting low levels of EFT is challenging. The coolers themselves often produce EFT so low that it is difficult to sense to the human touch. And, the CCA level performance can be 50 times lower than that of the cooler. Thus, Ball has developed several high-fidelity EFT testbeds for the verification of the TMUs, CCAs, and whole instruments.

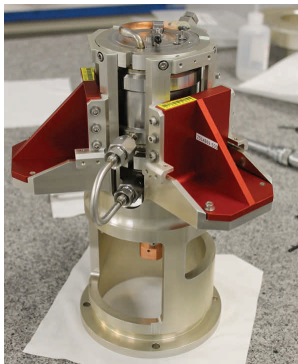
To date, Ball has delivered seven Low Vibe CCAs and has built six more that are entering testing. This includes two variations: the Low Vibe Space CCA (Figure 2) used with the NGAS HEC (Figure 3) and the Low Vibe Airborne CCA (Figure 4) used with the Sunpower GT Cooler (Figure 5). Ball is also developing a Low Cost, Low Vibe Space CCA for use with the Ball SC-235 (Figure 6), the HEC, and the Sunpower MT (Figure 7), and DS30 (Figure 8) coolers.



**Figure 2.** Low Vibe Space CCA using NGAS HEC (areas intentionally blurred for proprietary reasons)



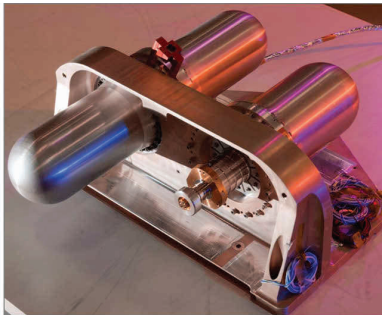
**Figure 3.** NGAS HEC cooler (nominal 2.2 W at 45 K or 14 W at 100 K) in EFT testing at Ball



**Figure 4.** Low Vibe Airborne CCA (with some components intentionally removed for proprietary reasons) with Sunpower GT Cooler



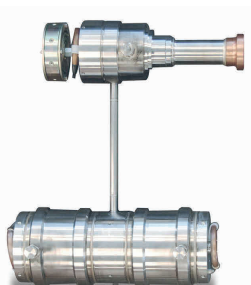
**Figure 5.** Sunpower GT Cooler (nominal 4.5 W at 45 K or 16 W at 77 K)



**Figure 6.** Ball SC-235 (TIRS) cooler (nominal 2.5 W at 35 K and 15 W at 85 K)



**Figure 7.** Sunpower MT Cooler (5 W at 77 K)



**Figure 8.** Sunpower DS 30 Cooler (30 W at 77 K)

**LOW VIBE CCA DESIGN**

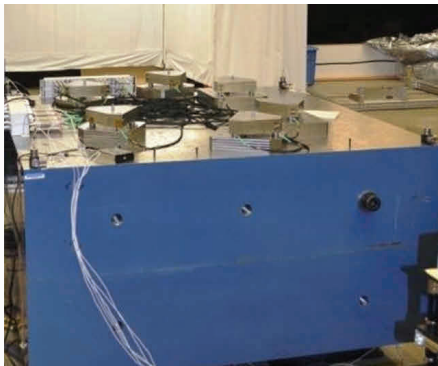
The basic principle of the Low Vibe CCA is to create a low frequency isolation platform. However, the most significant challenges are to control the impact to the platform and the transmission of EFT from parallel paths around the CCA mounting base. These parallel paths include the cables (power and telemetry), cold path heat transport for cryogenic cooling, heat transport connection for removing cooler dissipation, and MLI (Multi-Layer Insulation) around the cold path. Ball has developed custom solutions for each one of these parallel paths which required significant effort to mitigate and characterize. For the cold path heat transport, a unique thermal flexible thermal link was developed with SDL. And a LHP (looped heat pipe) was developed and used for the cooler heat dissipation path. Another challenge area was to mitigate the moments that the cryocooler creates and transmits to other critical components.

**EFT TESTBEDS AND TESTING**

To characterize and verify the low levels of EFT, Ball has developed several testbeds. Ball has a moderate size 2-ton testbed for testing coolers and small instruments (Figure 9) and a large size 15-ton testbed (Figure 10) for testing large (500 lbs. or more) instruments and spacecraft. Additionally, the large testbed has a custom vacuum chamber that allows for EFT testing at cryogenic temperatures and over a range of cooler heat rejection temperatures. These testbeds all have noise floors of less than 0.1 mN. The testbeds have dynamometers capable of measuring EFT in multiple locations. For example, Low Vibe CCA testing typically measures EFT (forces and moments) in 4 locations: CCA Base, thermal link, MLI, and LHP.



**Figure 9.** Ball moderate (2 ton) Eft testbed for coolers and smaller test articles



**Figure 10.** Ball large (15 ton) EFT testbed for test articles up to and in excess of 500 lbs.

To date, Ball has used the testbeds to measure EFT on:

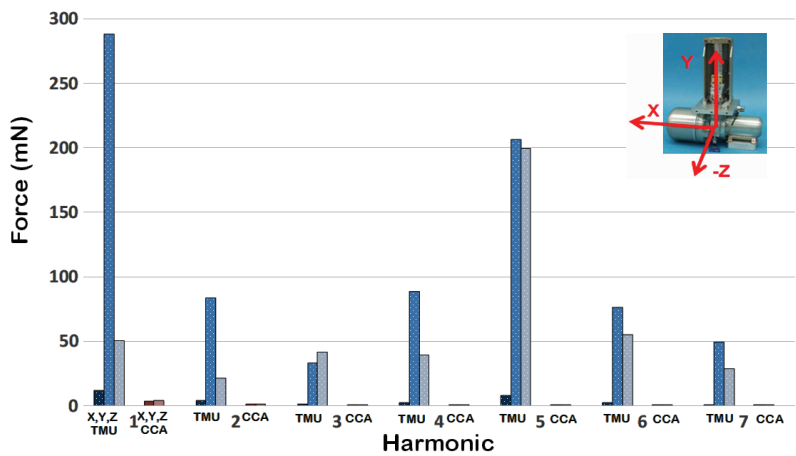
- 1. TMUs over operating frequency ranges of  $\pm 10\%$  of nominal, power levels from 25 to 100%, rejection temperatures from 248 to 325 K, and output frequencies up to 1,000 Hz
- 2. Low Vibe CCAs over operating frequency ranges of  $\pm 10\%$  of nominal, power levels from 25 to 100%, ambient temperatures of 10 to 30 °C, and output frequencies up to 1,000 Hz
- 3. Space Instruments (~400 lbs.) with both coolers and PMAs (Proof Mass Actuators) as EFT sources over operating frequency ranges of  $\pm 10\%$  of nominal, power levels from 25 to 100%, and ambient temperatures of 10 to 30 °C.

**TMU AND CCA TEST RESULTS**

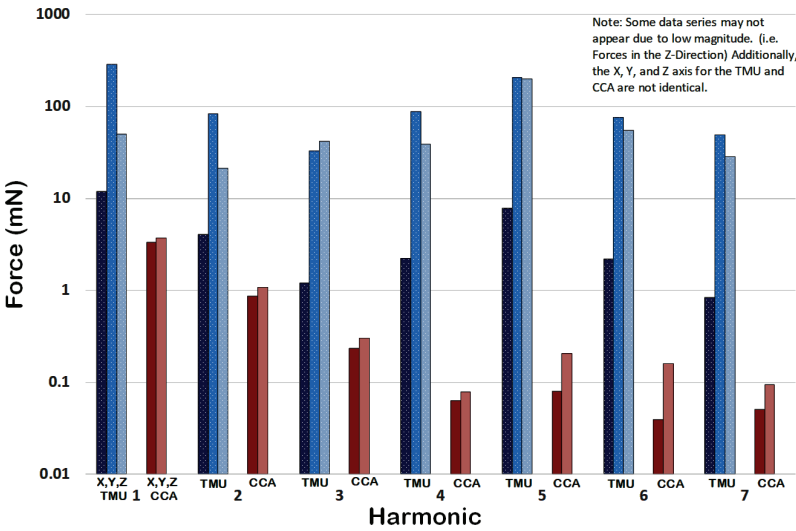
Table 1 presents a top-level summary of the EFT for HEC TMUs, Sunpower GT TMUs (with and without active cancellation), and Low Vibe CCAs with an HEC cooler. The table provides the largest forces and moments for any axis (X,Y,or Z) for nominal and off-nominal cooler operating frequencies and for the fundamental and higher harmonics. Figures 11-13 plot the test data for the HEC TMU and Low Vibe CCA at the nominal 67 Hz operating cooler

**Table 1.** Summary of TMU and CCA EFT

Source	EFT Path	Max EFT Any Axis at Nominal Operation Frequency		Max EFT Any Axis or Operating Frequency	
		Force (mN)	Moment (mN-m)	Force (mN)	Moment (mN-m)
HEC TMU	Fundamental	287.9	57.9	344.5	60.9
	Any Harmonic	287.9	57.9	1928.6	279.8
SP GT Active	Fundamental	19,000	N/A	N/A	N/A
	Any Harmonic	19,000	N/A	N/A	N/A
SP GT Non-Active	Fundamental	28,000	N/A	N/A	N/A
	Any Harmonic	28,000	N/A	N/A	N/A
Low Vibe CCA with HEC	CCA Base (incl. Cable)	5.0	5.5	7.5	6.0
	Thermal Link	17.0	<1.0	19.0	<1.0
	MLI	15.0	<1.0	16.0	<1.0
	LHP	7.0	<1.0	11.0	<1.0



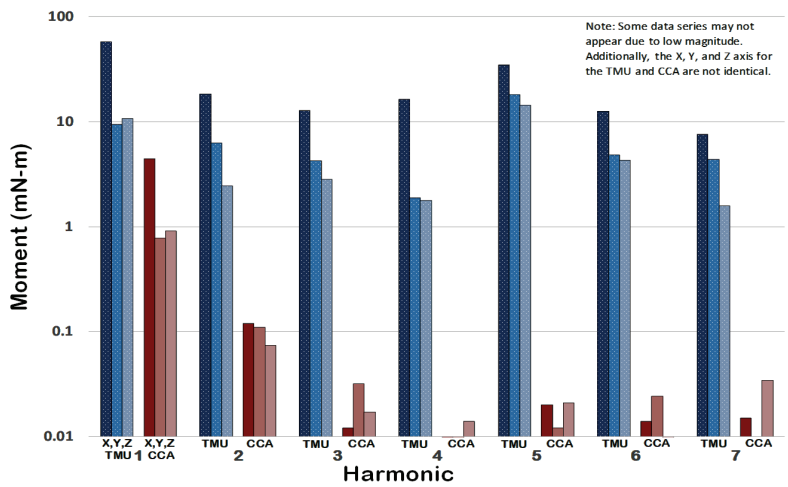
**Figure 11.** X,Y,Z exported force measurements (on linear scale) of HEC TMU and Low Vibe CCA EFT at 67 Hz operating frequency ; X,Y,Z directions noted on insert image.



**Figure 12.** X,Y,Z exported force measurements (on log scale) of HEC TMU and Low Vibe CCA EFT at 67 Hz operating frequency

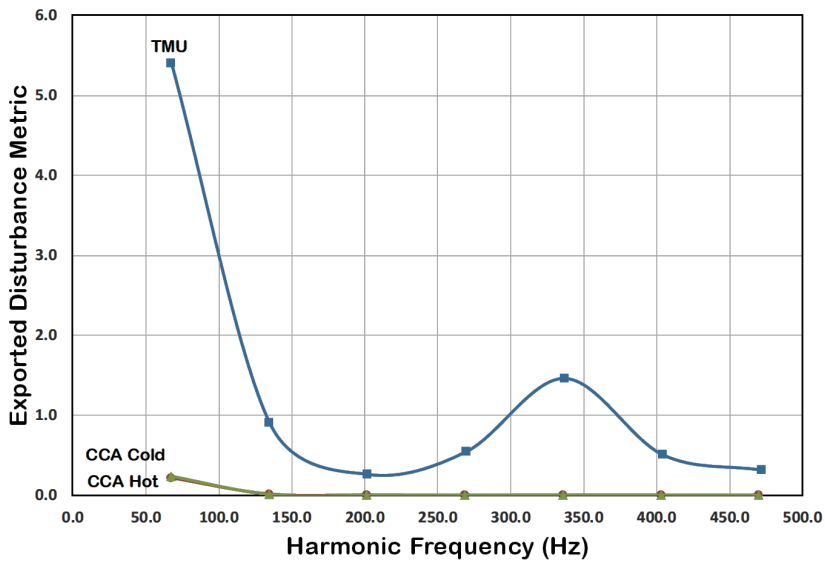
frequency. Figure 11 is on a linear scale to show the magnitude of the EFT reduction and includes the definition of the axes. Of specific interest from Table 1 and the plots are that:

1. At the fundamental operating frequency, the Low Vibe CCA reduced the HEC EFT force by a factor of 50.
2. At higher harmonics, the reduction increased to more than 250 times for off-nominal frequencies that were associated with internal cooler modes.
3. Though small, the parallel path (thermal link, MLI, and LHP) transmissions are larger than through the CCA base
4. The transmitted moments are well controlled, particularly through the parallel transmission paths

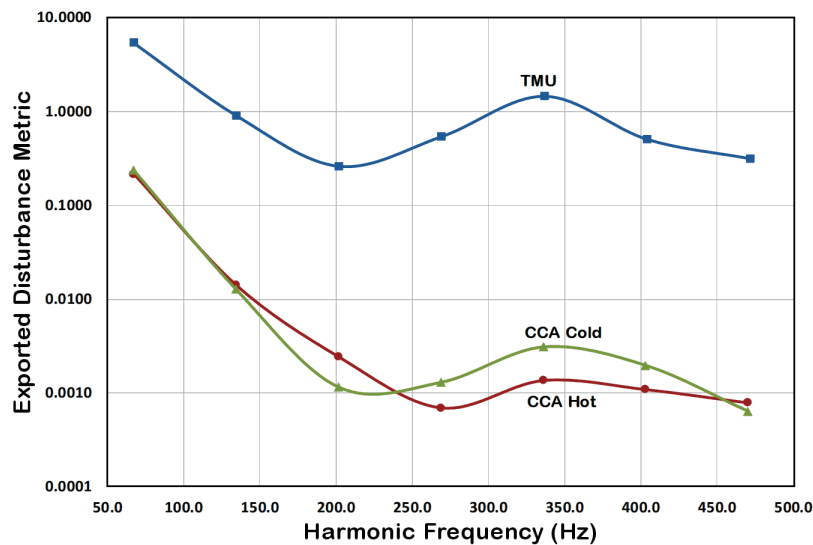


**Figure 13.** X,Y,Z exported moment measurements (on log scale) of HEC TMU and Low Vibe CCA EFT at 67 Hz operating frequency

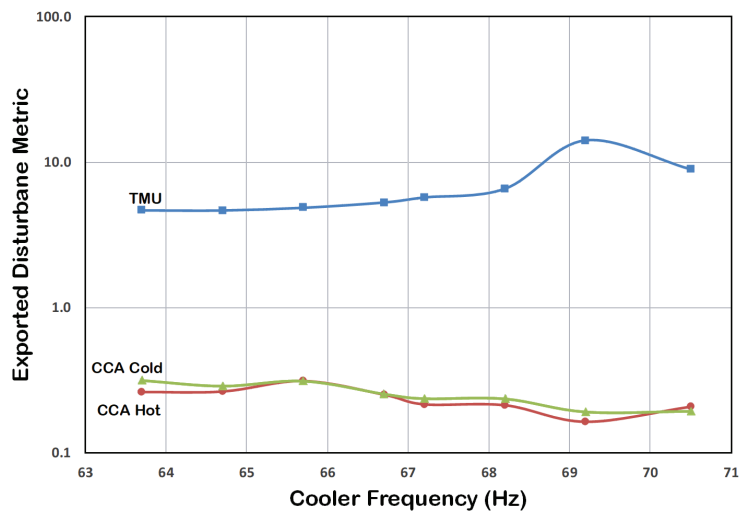
Due to the six axes of forces and moments, approximately 15 harmonics of EFT frequencies, and range of cooler operating frequencies, it is challenging to present and summarize the test data. One of Ball’s customers created an EFT requirements metric that used jitter transmission/sensitivity coefficients for each frequency and can sum together contributions from all the axes and frequencies of both forces and moments into a single ED (Exported Disturbance) metric. This metric is scaled to give a requirement value of approximately 1.0 and is very useful in presenting a summary of the EFT performance. Figure 14 uses this metric to show HEC TMU and Low Vibe CCA (at cold and hot ambient temperatures) Exported Disturbance at individual harmonic frequencies at 67 Hz cooler operating frequency on a linear plot. Figure 15 shows that same information on a log plot. And, Figure 16 uses the summation across all harmonics of the metric to show performance across a range of cooler operating frequencies.



**Figure 14.** HEC TMU and Low Vibe CCA (at cold and hot ambient temperatures) Exported Disturbance metric performance at individual harmonic frequencies at 67 Hz cooler operating frequency on linear plot.



**Figure 15.** HEC TMU and Low Vibe CCA (at cold and hot ambient temperatures) Exported Disturbance metric performance at individual harmonic frequencies at 67 Hz cooler operating frequency on log plot.



**Figure 16.** HEC TMU and Low Vibe CCA (at cold and hot ambient temperatures) Exported Disturbance metric performance summed over all harmonic frequencies over range of cooler operating frequency.

### CONCLUSIONS

In collaboration with NGAS, Moog CSA, SDL, and Sunpower, Ball has developed several low vibration CCAs for multiple cryocoolers for space and airborne applications. These CCAs significantly reduce the already low EFT of the coolers to meet the challenging program jitter requirements.