21st Century Cryocooler Electronics

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ABSTRACT

Significant progress has been made in the development of Cryocooler Control Electronics (CCE) to support the unique capabilities of the Raytheon Stirling / Pulse Tube Two-Stage (HC-RSP2). Design capabilities of the advanced CCE feature a two stage temperature control and active line filtering to reduce the conducted emissions by >30 dB at >90% efficiency.. The CCE will drive a cryocooler capable of lifting 2.6 W at 35 K and 16.2 W at 85 K with 513 W of cryocooler input power. The cryocooler was demonstrated during thermal vacuum testing with lab electronics. The result will be a complete Electro-Optic cooling system with one main 300 kRad total ionizing dose (TID) capable electronics box and one cryocooler, greatly reducing system complexity and improving operational performance.

INTRODUCTION

A great deal of ground work has been done on the Cryocooler Control Electronics (CCE) in order to support the unique capabilities of the Raytheon Stirling/Pulse Tube Two-Stage (RSP2) Cryocooler. In this paper, we will discuss two aspects of the new CCE design, the two stage temperature control and the active line filter.

Raytheon is developing the RSP2 and its associated electronics in response to identified United States Government (USG) needs for two-stage cryocoolers, primarily to provide simultaneous optics and focal plane cooling for space-borne infrared sensors.[1] The current effort for the CCE design is targeting the “High Capacity” (HC)-RSP2 which is designed for 35 K / 85 K; measured capacity is 2.6 W and 16.2 W, respectively. Raytheon is taking a modular approach that will allow customized scaling for other power levels with minimal nonrecurring engineering to optimize for these different levels.

Two-Stage Temperature Control

The full benefit of the Raytheon RSP2 cryocooler is not realized without a method for controlling the temperature at both stages. Obviously, it is most desirable to be able to command the temperature of the two stages independently, rather than have them track each other. Fortunately, the ability of the RSP2 to shift heat-lift capacity from one stage to the other by varying the expander piston (EP) phase angle relative to the compressor pistons allows independent control to be achieved within a limited range. Figure 1 shows the stages of development necessary to accomplish this type of control.

Temperature control on previous Raytheon single-stage Stirling coolers was accomplished by modulating the compressor stroke via a PID control law while holding the expander stroke con-

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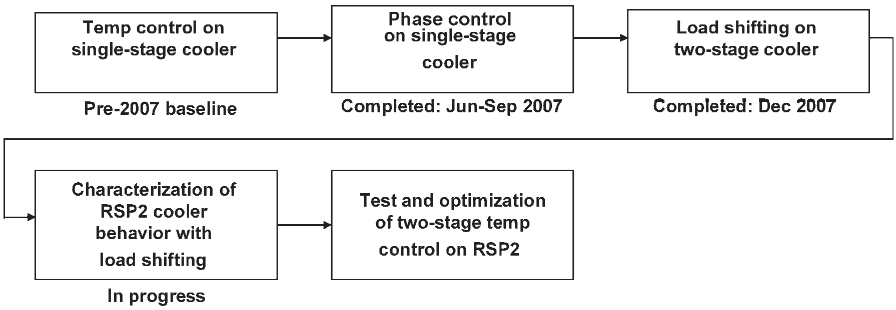

Figure 1. Road map for developing two-stage temperature control for RSP2 cooler

stant. It was recognized that expander piston phase was one other parameter that could be used to control the temperature, although this control method was never explored because it would reduce cooling efficiency.

However, as described in previous RSP2 papers[2,3,4,5,6,7], controlling the temperature by varying the EP phase of a RSP2 type machine does not incur the penalty of reduced efficiency because the heat lift capacity is shifted from one stage to the other according to the phase angle. While holding the other motor drive parameters constant and within the EP phase control range, as the EP phase is increased, the Stirling stage's heat lift is reduced and the pulse tube stage's heat lift is increased. This is shown in Figure 2 from test data taken on the MC-RSP2 in December 2007.

Compressor stroke has a direct effect on the cooling capacity of both stages, as does the EP phase. Thus there are two approaches to this control method: 1) control the Stirling stage's temperature with compressor stroke, and control the pulse tube's temperature using EP phase, and 2) control the Stirling stage's temperature with EP phase, and control the pulse tube's temperature using compressor stroke. Both methods will be evaluated.

Figure 3 plots the total power dissipated in the compressor versus the TD phase angle, and shows that the total power is affected very little by the load shifting.

Testing of the two-stage temperature control was interrupted shortly after the characterization of the MC-RSP2 with our legacy drive electronics began for an internally-requested test. Coding of the algorithm is complete and ready to be tested using the HC-RSP2 cooler as soon as its drive electronics are ready. The software can easily switch between the two control methods so that both can be evaluated under a variety of conditions to determine which works best.

The challenging part of integrating the two-stage temperature control with exported vibration control will be in keeping the residual fundamental vibrations low. Any time the expander phase or amplitude changes relative to the compressor, the balancer motion needs to be adjusted accordingly

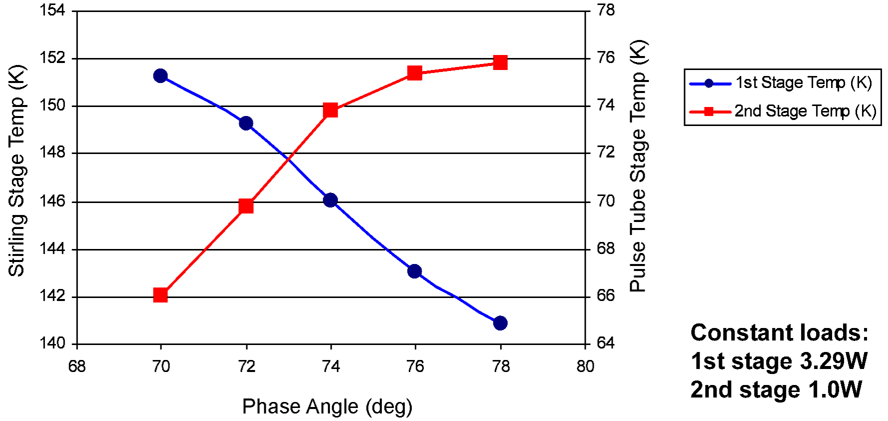

Figure 2. Load shifting on MC-RSP2 using phase control software on Raytheon CTCE electronics

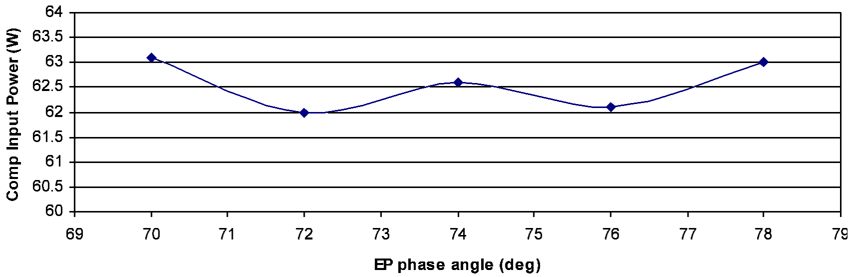

Figure 3. MC-RSP2 Compressor input power versus Phase Angle

to cancel the new resultant force exported by the expander. For small adjustments, the Raytheon Adaptive Feed-Forward (AFF) vibration control is expected to provide sufficient control. For larger adjustments, a method of deciding when the balancer drive parameters need to be adjusted has been developed instead of allowing AFF to modify the feed-forward signal. The method monitors the amount of fundamental content in the AFF feed-forward signal and starts to adjust the balancer drive when this feed-forward fundamental component gets too large.

Active Line Filter

Cryogenic IR space sensors with active coolers draw high ripple current from the spacecraft power bus. This can excessively destabilize voltage and degrade the performance of other systems on the power bus. An active line filter (ALF) has been developed to control the load current drawn from a DC electric power bus, such that very low load current ripple is reflected back to the power bus. Without either an ALF or large and heavy passive filtering, other electronics boxes could not be supplied on the same power bus as the CCE, unless they included heavy filtering at their inputs. The ALF will be a modular piece of the complete CCE to allow for adjustment to accommodate different power levels and efficiency. The following data is from tests of the lower power breadboard ALF. The higher power design to support the HC-RSP2 cryocooler has been completed. This design will be built and tested in 2008.

As shown in Figure 4, the current ripple is reduced from 10 A peak-to-peak variations to a nearly constant current with < 0.3 A peak-to-peak ripple. This results in a very small voltage ripple as shown in Figure 5.

Figure 6 shows the basic design that was built up as a breadboard and tested. The active filter regulates input current to a fixed DC level set by the Error Amplifier (EA) output. The very low bandwidth output voltage regulation control loop does not respond to output voltage ripple. The EA provides slowly changing DC levels.

Figure 7 shows the next-iteration design of the ALF which incorporates output load feed-forward. Input voltage feed-forward and output load feed-forward are added to provide very fast response to input voltage transients and output load transients. These signals are added in order to

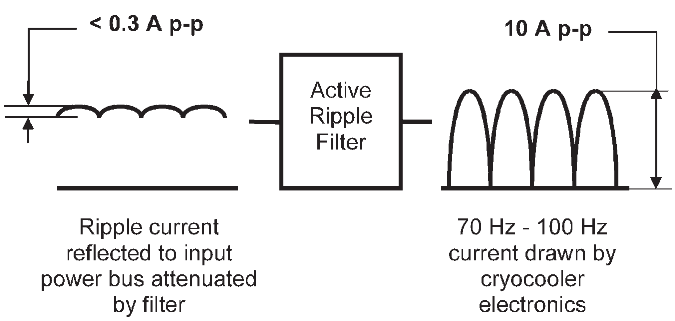

Figure 4. Input current ripple reduced by Active Ripple Filter

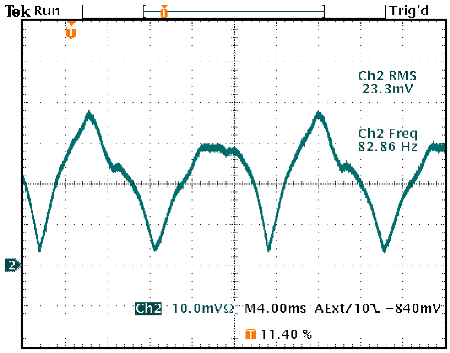

Figure 5. Measured input voltage ripple minimized due to reduced current ripple

maintain output voltage regulation. The output load feed-forward signal will be provided internally in the CCE.

As illustrated in Figure 8, by maintaining low ripple on the input current, the output current ripple becomes an output voltage ripple. The rest of the CCE circuitry needs to tolerate and adjust for this output voltage ripple. The amount of voltage ripple can be adjusted as required by designing in additional capacitors to provide the required energy for the output current ripple.

The ALF was built and tested in order to prove the concept and evaluate its performance. The 'Proof of Concept' breadboard, as seen in Figure 9, was configured as a 200 Watts continuous current boost converter. The ALF demonstrated > 30 dB of attenuation at >93% efficiency over most of the load range.

The ALF for the CCE that will drive the HC-RSP2 cryocooler is designed to be directly connected to the spacecraft 48 volt bus and will provide the necessary output voltage. Results are expected to be in line with the lower power 'Proof of Concept' breadboard.

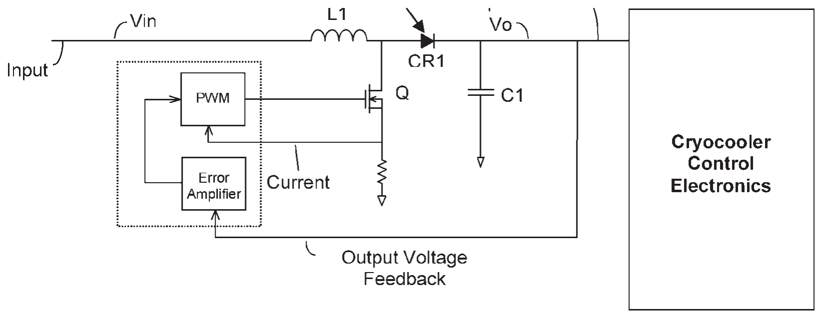

Figure 6. Active Line Filter Base Design

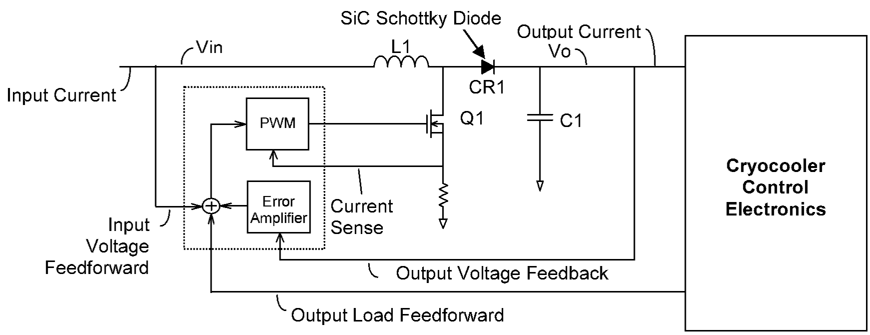

Figure 7. Enhanced Active Line Filter Design

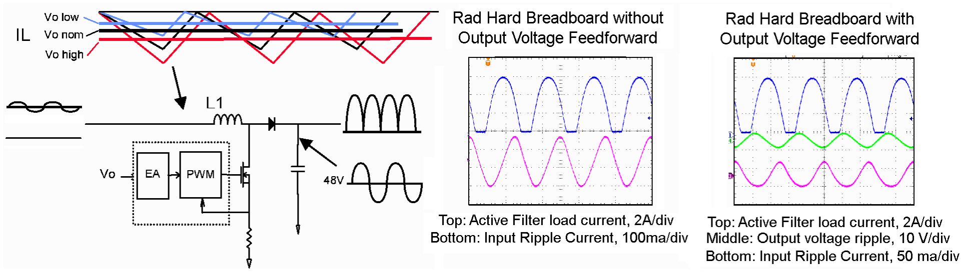

Figure 8. Output voltage modulation

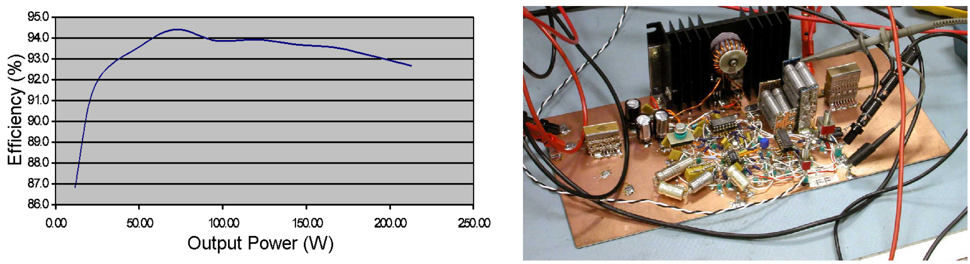

Figure 9. Active Line Filter 'Proof of Concept' breadboard

CONCLUSION

The basic operations of a two stage temperature control and an active line filter have been demonstrated. These are two of the essential building blocks that have been demonstrated in order to support the unique capabilities of the RSP2 cryocooler and eliminate additional required external electronics as the new CCE will be connected directly to a spacecraft bus. Having concluded the viability of both these concepts, they will be incorporated into a new overall CCE design concept. Testing of the new CCE design is expected in 2008.

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