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RAYTHEON DUAL-USE CRYOCOOLER SYSTEM DEVELOPMENT

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ABSTRACT

The Dual-Use Cryocooler system, consisting of a single-stage pulse tube thermo-mechanical unit (TMU) in combination with a modified, high reliability set of tactical cryocooler electronics, has been designed to fill the gap that exists between present low-cost tactical and high-cost space cryocooler products. The TMU portion of the system contains a significantly smaller number of parts than typical space cryocoolers while maintaining all of the long-life features that allow those machines to operate continuously and reliably for 10+ years. This reduction in mechanical complexity positively impacts both unit cost and required build time. The drive electronics have been developed in parallel, and include such features as dual independent motor drives, output waveform shaping, and a variety of TMU / electronics protection algorithms.

The fabrication and test cycles for the brassboard system have been completed, and insights gained from these exercises are presented in this paper. Initial design trades and present design status for the TMU and drive electronics are both presented, as well as a comparison of expected versus measured performance. Lastly, an overview of the steps required to bring this system design to flight-readiness will be given.

KEYWORDS: Cryocooler, tactical cryocooler, space cryocooler, pulse tube, Stirling, cryocooler electronics

SYSTEM DESCRIPTION

As described previously [1], the DUC system is intended for long-life tactical and low-cost space applications that will require the extreme high reliability typical of a space

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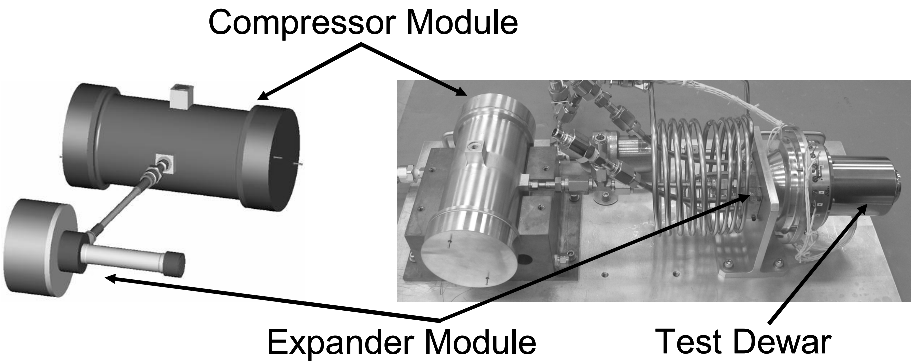

Figure 1. Dual-Use Cryocooler solid model (left) and photograph (right). Solid model illustrates a flight-packaged version with integral inertance tube and surge volume. Photograph illustrates the DUC test configuration with a coiled inertance tube and separate surge volume.

cryocooler system but will not require “cutting edge” thermodynamic efficiency, sub-50 K temperatures or extremely low exported vibration. Potential applications include domestic and foreign civil space, the DD(X) cruiser, the Joint Strike Fighter, and future Operationally Responsive Space payloads.

FIGURE 1 contains a rendering of the DUC thermo-mechanical unit (TMU) as well as a photograph of the brassboard unit. The DUC TMU is a single-stage pulse tube design with separate compressor and expander modules. Though both Stirling and pulse-tube designs were considered, the pulse-tube architecture was chosen for its inherent lack of cold-head moving parts, a feature which is beneficial in terms of both complexity and uncompensated exported vibration performance. Initial design concepts for the DUC TMU included a typical u-tube type coldhead, however the DUC expander module was ultimately designed around a concentric pulse-tube that minimizes mass and package size while maximizing structural robustness. Lastly, an experimental drop-in regenerator was chosen for the DUC system such that time spent packing regenerator screens is largely eliminated.

As with many space compressor modules, the DUC compressor was designed with dual-opposed linear motors such that the fundamental-frequency motor forces are inherently balanced. While the compressor does contain clearance gap seals and flexure-borne moving mechanisms usually typical of space cryocooler systems, piston position measurement was excluded in order to minimize package size and electronics complexity. Flexure stress levels are limited to safe values by strict adherence to known safe-power profiles and the inclusion of hardstop surfaces. Taken as a whole, the DUC compressor module contains roughly half the parts count of a typical Raytheon space compressor module while also implementing a number of features that significantly ease the build process.

TABLE 1 describes the top-level design parameters for the DUC TMU. The nominal operational point was chosen as 1.5W of heat lift at a cold tip temperature of 67K for approximately 84W of electrical input power, though the DUC system is adaptable to both higher and lower-power design points. TMU lifetime is expected to exceed 50,000 hours, and exported vibration forces are expected to be below 0.500 Newtons per module at the fundamental drive frequency. All thermodynamic and electromechanical modeling / design exercises were completed at Raytheon Space and Airborne Systems.

Table 1. Top-level design parameters for the Dual-Use Cryocooler

Specification	Value
Nominal Cold Tip Temperature	67K
Nominal Capacity	1.5W
Nominal Input Power	84W
Fundamental Exported Vibration	< 0.5Nrms
Lifetime	>50,000 hours
Env. Temperature	-40C to +60C

A study of potential electronics packages revealed that a great deal of functionality including temperature control, cool-down rate control and various protection algorithms are available for a relatively small cost in the form of existing tactical cryocooler drive electronics. Typical space cryocooler electronics packages are orders of magnitude higher in both cost and complexity, much of which can be attributed to the implementation of high performance vibration-reduction algorithms. The applications for which the DUC system is designed do not require extremely low exported vibration levels, eliminating the need for excessive electronics complexity. The DUC drive electronics were therefore derived from a set of Raytheon high-reliability tactical cryocooler electronics. The heritage electronics package, already containing a very flexible digital control section, has been modified to include dual independent motor drives that allow for active balancing of the fundamental-frequency motor forces. A comprehensive reliability analysis of the electronics has been performed, and component / circuit changes necessary to guarantee high reliability have been made. Additionally, the package and circuitry have been analyzed for radiation susceptibility, paving the way for a 300krad, single event effect (SEE) resistant, single event latch-up (SEL) immune implementation.

THERMO-MECHANICAL UNIT DEVELOPMENT

Build

The fabrication and build processes for the DUC TMU occurred in a very short amount of time, with the compressor module being put together in less than a week as opposed to the typical timeframe of three weeks or more for past space compressor designs. In quantity, assembly time is expected to be one day for this design. Alignment and checkout procedures proceeded without incident and were completed within the one-week timeframe. The expander module, designed with a novel drop-in regenerator, a simplified braze / weld schedule, and commonly-available materials, was inherently simple to fabricate and build as well. Prior to assembly of the first expander, a coupon was created and destructively tested in order to evaluate the weld and braze operations. The brassboard module was produced after successful completion of the coupon and was successfully taken through necessary proof pressure testing.

Initial Test

The DUC compressor and expander modules were subjected to a variety of tests in order to evaluate the functionality of each as an isolated component. Compressor electromechanical performance, evaluated while integrated to the TMU level, was found to correlate well with both the thermodynamic and electromagnetic design models. Specifically, the power efficiency was generally observed to be within several percent of the predicted values across a wide variety of operating conditions. The compressor resonant frequency was assessed as a method of evaluating both the dynamic mechanical and pneumatic performance, and the observed value of 59Hz fell within ~1Hz of the predicted value. This close agreement indicates that the inertial, spring, and pressure forces acting on the compressor pistons are all as-expected.

In addition to the above testing, a series of cases were run involving operation of the compressor module at very high power over a wide variety of rejection temperatures. This series of tests was performed to verify the temperature insensitivity of the compressor clearance seals as well as the ability of the motors to withstand increased operating temperatures while dissipating large amounts of power. The compressor was run at housing temperatures ranging from 268K through 328K with input powers from 52W to 147W. At no temperature or power was the compressor found to exhibit reduced performance indicative of rubbing piston / cylinder seals, and compressor efficiency was found to vary by a maximum of 15% (relative to peak efficiency) over the 60K range of operating temperatures.

Expander module testing principally involved evaluation of the concentric cold head design and the experimental drop-in regenerator. To this end, a series of load curves were generated, including high-power no-load points. The expander module exhibited a lack of performance throughout the temperature range, with a measured no-load temperature approximately 18K above the predicted value of 48K. A variety of potential causes were investigated, however two pieces of information helped to significantly narrow the search. First, measured pressure ratios at the transfer line were much higher than predicted by the model. Second, an analysis of several warm-up curves indicated that thermal parasitics were 2-3 times higher than anticipated and could not be attributed to convective phenomena within the pulse tube.

Though several causes were considered, it was ultimately determined that the drop-in regenerator was likely the source of both the increased pressure drop and the excessive thermal parasitic. Post-test analysis of similarly-constructed regenerators supported this conclusion, and it was determined that a second expander module would be constructed using a traditional packed-screen regenerator.

Secondary Test

The second version of the DUC expander module was constructed and integrated with the DUC compressor module. A similar set of tests were run and the performance of the new expander module, containing a traditional packed-screen regenerator, was found to be greatly improved. Several load lines were generated at a variety of cold-tip temperatures and compressor strokes, and the load line of most interest, taken at ~88% of maximum compressor stroke, is illustrated in FIGURE 2 below.

Table 2. A comparison of test and model performance data. Note that the model consistently under predicts both input power and transfer line pressure ratio.

Cold Tip Temperature (K):	Input Power (W):		Pressure Ratio:	
	Model:	Test:	Model:	Test:
67	96.9	122.8	1.19	1.23
82	95.3	121.7	1.20	1.23
97	94.2	121.0	1.20	1.24
112	92.8	119.0	1.21	1.24
127	91.5	118.3	1.21	1.24
142	90.5	117.1	1.21	1.24

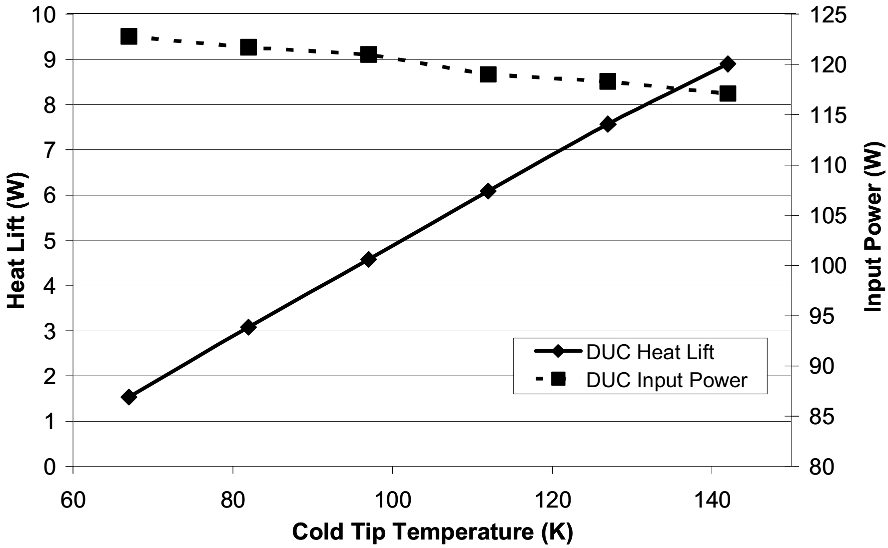

Figure 2. Measured DUC load curve and input power. Test data represents the performance of the second expander module with a packed-screen regenerator.

The DUC TMU is capable of providing the originally-specified 1.5W of heat lift at 67K and can also be run at higher temperatures and heat loads (such as 5W at 100K or 9W at 140K). Indicative of greatly reduced thermal parasitics, the no-load temperature of ~53K was found to be within several Kelvin of the model prediction, a large improvement over the 18K discrepancy exhibited by the original expander module. Though the heat-lift specification was met, the DUC cryocooler does require significantly higher input power than was predicted by the model. TABLE 2 contains a comparison of observed and predicted input powers and pressure ratios for several test cases.

Approximately 8W of the input power discrepancy can be associated with a slight compressor motor imbalance, however that effect alone is not sufficient to explain the remaining bulk of the discrepancy. An examination of the pressure ratio data indicates that the DUC expander is significantly more resistive to flow than model predictions (though not as resistive as the original implementation using the drop-in regenerator), an issue that is related directly to the increase in required input power. The likely location of the flow restriction is at the expander inlet, notionally illustrated in FIGURE 3. The present design forces the incoming gas to flow around two 90 degree bends in very close proximity to one another.

Table 3. A comparison of various math model configurations to observed test data.

	Test:	Baseline Math Model:	Math Model with Inlet Restriction:	Math Model + Inlet Restriction + 5% Inertance Tube Diameter Change:
Transfer Line Pressure Ratio:	1.23	1.19	1.23	1.23
Surge Volume Pressure Amplitude (Pa 0-peak):	3.31E+04	3.67E+04	3.64E+04	3.24E+04
Input Power (W):	128	97	122	118
Heat Lift (W):	1.54	1.98	1.91	1.54

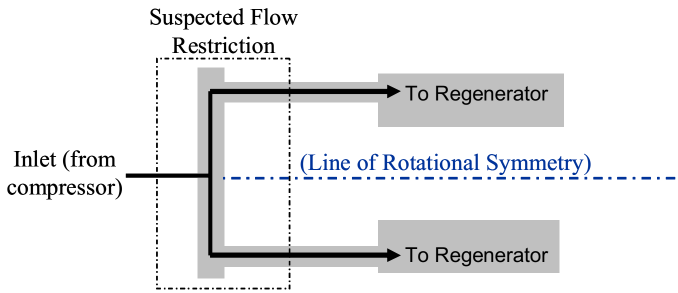

Figure 3. Notional illustration of the DUC expander inlet flow passages. Note that the figure is an illustrative cross section of a rotationally symmetric system.

The DUC thermodynamic model has been exercised in order to investigate the effects of increased flow restriction on overall performance, and it has been found that a flow restriction at the inlet of the expander module is sufficient to explain both the increased pressure drop as well as the increased input power. TABLE 3 contains a comparison of the predicted and measured performance taking into account several thermodynamic model configurations

The predicted performance parameters fall into sync with the observed test values when small changes in the inertance tube diameters are modeled in combination with an expander inlet flow restriction. Prior to the build of additional DUC systems, the flow passages of interest will be examined and reanalyzed such that this issue can be addressed.

DUC DRIVE ELECTRONICS DEVELOPMENT

The DUC electronics were primarily developed by the Raytheon Tactical Cryocooler group and are largely based on the tactical Low Cost Cryocooler Electronics (LCCE) package. The LCCE is a feature-rich set of tactical electronics with a very flexible digital control section, making it an ideal starting point for the DUC electronics. The heritage electronics already contained features such as closed-loop temperature control, selectable operational frequency, cooldown rate control, output "wave shaping" and various protection circuits and algorithms. The majority of the initial development work therefore focused on implementation of dual-independent motor drive circuits, a feature not found in the heritage electronics. Additionally, reliability and radiation studies were performed in parallel with the circuit modification. A brassboard version of the electronics was fabricated and tested extensively with resistive and tactical Stirling cryocooler loads, then transported to the Raytheon El Segundo facility and integrated with the brassboard DUC cryocooler.

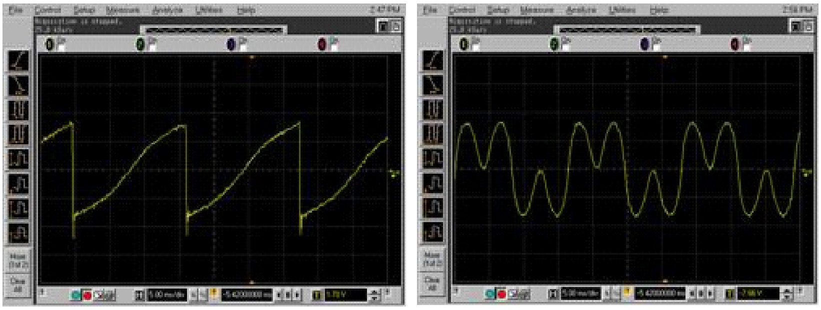

Figure 4. Captured DUC electronics output waveforms. Wave shaping is implemented digitally and a wide variety of arbitrary waveforms can be generated.

The brassboard system functioned as expected, with the dual motors drives, output wave shaping, and closed-loop temperature control features all being successfully demonstrated. The motor drives of the brassboard DUC electronics were not optimized for the expected loads; however, they were able to reach efficiencies in the 80-85% range during testing. Efficiency is expected to increase in production implementations. FIGURE 4 contains a screenshot of several output waveforms produced by the brassboard DUC electronics, illustrating the ability of the output wave shaping functionality. This feature will likely be utilized in future implementations as a type of first-order active vibration cancellation.

After successful completion of the brassboard electronics testing, a more complete design exercise was undertaken with the goal of producing a high-reliability (HiRel) version of the DUC electronics. Unlike the brassboard electronics, the HiRel DUC electronics makes exclusive use of Military Grade components. Various circuit changes have been implemented to accommodate these parts, and the HiRel PWB layouts have been optimized for more efficient packaging. Additionally, the HiRel version of the electronics has been designed such that relatively minor changes will provide for radiation hardness. Through straightforward component swaps and minor package changes, the HiRel electronics can be brought up to 300krad, single event effect (SEE) resistant, single event latch-up (SEL) immune radiation hardness levels. The availability of radiation-hardened electronics for a very low cost as compared to typical space cryocooler electronics is unique to the DUC system and will provide future applications, particularly those in Space, with a cryocooler option that is presently not available.

The HiRel electronics testing with a tactical Stirling cryocooler was completed in June 2007, and testing with the DUC is planned for July 2007. An article describing the test results is presently anticipated for release in 2008.

DUC PATH FORWARD

The prototype DUC TMU has performed extremely well in terms of mechanical / thermal stability, heat lift capacity, and ease of assembly. The increased power draw is related in a straightforward way to excessive pressure drop at the inlet of the expander module, and future implementations of the DUC TMU will feature a redesigned inlet structure that is much less restrictive. Though the compressor module performed very well with no issues, several areas of improvement have been identified in the time since the original design was completed. These principally concern a reinforcement of several internal fastener features as well as a light-weighting of the motor cores.

Testing of the prototype DUC TMU is largely complete, and the fundamental low-cost, long life design concepts have been proven to be viable. Transition to a production program will necessarily involve the build and environmental test of a qualification model, although the inherent simplicity of the design renders this a much less complex task than for past Raytheon space cryocooler designs. The DUC drive electronics have completed multiple design evolutions in a short period of time and are ready for integration into a flight-ready / production package. Additionally, a radiation-hardened version of the electronics can readily be produced to support space applications as required.

DUC SYSTEM SUMMARY

The DUC system represents a new, viable option for payloads requiring a highly reliable, low-cost cryocooler system. No other systems available at the DUC price point will be able to provide a list of features comparable to the DUC system, including extremely long TMU lifetime and the availability of radiation-hardened drive electronics.

ACKNOWLEDGEMENTS

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REFERENCES

1. C. S. Kirkconnell and B. A. Ross, “Raytheon Dual-Use Long Life Cryocooler,” Proc. of the SPIE, vol. 5783, pp. 169-177, 2005.