High-availability single-stage Stirling coolers with high power density

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Abstract. Recent developments at Thales Cryogenics have been aimed at improving the performances of 100 W and 200 W input power class flexure bearing Stirling coolers. The aim of these developments has been twofold: To enable multi-year operation with a vanishingly small failure probability (high availability) and to extend the usable range down to below 42 K (low temperature). As the starting point for development, the LSF9589 and LSF9340/LSF9350 cooler ranges were selected. By performing these upgrades, the usability range of the cryocoolers is extended. Multiple upgrades will be shown such as tuning for low-temperature operations and material upgrades. Test results will be presented and potential future improvements will be discussed. The work performed was done for a variety of customers, with applications including nitrogen recondensers for zero boil-off dewars, high temperature superconducting filters, and low temperature longwave infrared detectors.

1. Introduction
Thales Cryogenics produces a large range of cryogenic coolers for various applications. These coolers are based on the Stirling or the pulse-tube principle. Different applications impose different requirements on the coolers that are used. In this paper, we will present some modifications that were done on linear Stirling coolers to make them better suitable for the intended use.

In the title of this paper, the term High-Availability is used as a description of the reliability of a cooler. Availability is related to the reliability of the cooler. Reliability analysis is often based on Weibull statistics [1]. Here the mean time to failure (MTTF) is used as a figure of merit for the life time and reliability of the cooler. MTTF is the amount of time after which 63 % of a population will have failed. For systems requiring 24/7 operation without interruption or disturbance, using ‘Availability’ as a figure of merit is more appropriate. Availability represents the probability that a system will function according to specification for a set amount of time. It is the inverse of the failure rate.

Flexure bearing compressors are known for their extremely long lifetime [1]. When combined with pulse-tube cold fingers, the lifetime is virtually infinite. Stirling coolers can also benefit from the high reliability of flexure bearing compressors. If a cooler type is to be chosen for a particular application, a trade-off has to be made. Pulse-tubes have near infinite life and extremely low induced vibrations, whereas the advantage of the Stirling cooler is a higher efficiency and a higher power density. If the advantages of the Stirling coolers can be combined with the lifetime expectations of pulse-tube coolers, the resulting product would be a high-power, high availability cooler.
In this paper, we present recent developments on two of our Stirling cooler families. These developments are aimed at improving the performance of the coolers in their intended applications. One such application is the cooling of high-temperature superconducting filter electronics. Such an application requires continuous operation (24/7) over a long period of time. In Figure 1 an example is shown, where a Thales LSF9589 cryocooler is used to cool a superconducting filter and low-noise amplifier (LNA). These systems can be used in commercial applications such as mobile communication as well as scientific astronomy applications. The advantage of this HTS technology used in this application is not just the well-defined, sharp filter cut-off typical for HTS designs, but also the superior noise performance at relatively high cryogenic temperatures, typically 77 K [2]. For large-scale astronomy projects such as the Square Kilometer Array (SKA), this will give a significant benefit in power consumption compared to traditional LNA systems requiring multi-stage 10 K coolers, combined with a maintenance free operation over long periods of time. Stirling coolers are preferred for these applications because of the advantages in power consumption and power density.

Figure 1: Cryogenically cooled superconducting RF filter (picture courtesy of Toshiba).

The improvements that were done on the cooler and the subsequent lifetime results will be presented in the next chapter.

Another development that will be presented is the extension of the usable temperature range of our 20 mm Stirling cooler (LSF9340). This was done for an infrared application where long wavelength, low energy photons were to be detected, combined with high-speed spectroscopy. By reducing the no-load temperature, the IR sensor could be cooled to 45 K. A Stirling cooler was selected here for the power density, and because of the improvement, a single-stage cooler could be used.

2. Lifetime and reliability upgrades on the LSF9589 cooler

For applications as described in the introduction, where high-temperature superconducting electronics are used in practical systems, long lifetime and high availability of the coolers is crucial. These applications require 24/7 cooler operation for multiple years without significant failure probability. For these applications, the LSF9589 linear Stirling cooler was selected. This cooler uses a flexure-bearing compressor, and has a typical cooling power of 2.8 W at 80 K and 80 W input power, room temperature ambient. The design goal for availability for this application was higher than 98% after 5 years of continuous use, which would not be met with the existing cooler design.

An extensive overview of cooler failure modes was presented by Ross et. al. in 2001 [3]. It can already be concluded before-hand that the dominant failure mechanisms for a Stirling-type cooler with a flexure bearing compressor should be found in the cold finger. The compressor with flexure-bearing technology has an MTTF that far exceeds that of the cold finger, which can be seen in the lifetime estimates of the pulse-tube coolers [4]. The failure modes not related to the compressor according to Ross are:

- Excessive internal cooler contamination
- Hermetic seal or feedthrough leaks
- Expander structural failure
- Expander blow-by due to long-term wear
- Expander alignment (binding)

All but the blow-by due to long-term wear are considered to be random failures. The impact of these failure modes is mitigated by design, production procedures, or handling instructions. By ensuring the cooler design with sufficient margin of safety, the chance of any such failure occurring is minimal.

The main failure mode of the cold finger is thus the blow-by along the expander. This is not a random failure, as it is wear-out related. There is a correlation between wear and time. In a first order approximation, this can be described by Archard’s law, \( V_w = k_w F s \), with \( V_w \) the wear volume, \( k_w \) the wear coefficient, \( F \) the normal force, and \( s \) the distance travelled. This equation states that the wear volume depends on the properties of the wearing materials, the load which acts on the bearing, and the time the bearing is used.

Under the assumption that the bearing material already has the lowest possible wear coefficient, no improvement can be found here. Also, the distance travelled cannot easily be influenced. The motion of the displacer is given by the thermodynamic performance. Obvious changes to system design parameters - such as drive frequency - will not yield much improvement either, as a reduction in frequency typically means that the amplitude will increase, and vice versa. So the obvious way to further reduce the wear volume is to reduce the load on the bearing.

In case of flexure bearings, this is ensured by the positional accuracy of the flexures. The flexures enforce a purely axial motion, and with correct alignment this means that the bearing load is zero. In miniature Stirling cold fingers without flexures, this is not the case. Moving displacers are usually supported by a wire spring which has a finite radial stiffness. As a consequence there will be a load on the displacer bearing.

We have investigated the sources of the normal force that acts on the displacer bearing. These summarize to:
- Gravity,
- Non-axial reaction forces of displacer suspension.

The effect of gravity is obviously orientation dependent. When the cold finger is oriented in the vertical direction, the load on the bearing due gravity to will be negligible. Non-axial forces are a combination of a few aspects. Without going into all the details, they are combination of misalignment in the bearing, tolerances and positional accuracy, and a-symmetry in the spring.

A study was conducted to quantify these effects. Tolerance-stack analyses were combined with finite element modelling. It was found that by optimizing geometry the radial forces could be greatly reduced. It was also found that some uncertainty remained in the analysis. Therefore the radial forces on the bearings were measured directly in a dedicated test setup (Figure 2).

In the test setup, the displacer suspension is mounted between a stationary and a moving part. On the stationary part a three-axis force load cell is placed. On the moving part, a precise axial motion can be applied by a flexure-supported guidance. Furthermore, a low-friction thrust bearing allows a small rotation, a degree of freedom that is also present in practice.

Manipulators on the setup allow the misalignment to be changed. In Figure 3, the measured forces for a worst-case setting are shown as an example. It can be seen that the radial forces are approximately 5% of the axial forces (the two radial force components should be vector-added). With this setup, the implications of the design and tolerances of the bearing suspension could be easily validated without lengthy tribological or lifetime testing. Using it as a design validation tool, a displacer suspension with minimal radial force was designed. It was found that a reduction of more than a factor 5 was realized, directly decreasing the bearing load and thus increasing the availability of the cooler.
Figure 2: Bearing force measurement setup (right).

Figure 3: Raw measurement of forces in three directions. Solid markers are the axial spring force, open markers two perpendicular radial directions. The forces are normalized to the maximum axial force, in this worst-case situation the radial forces.

The update was incorporated in a new definition of the LSF9589 cooler. Two of the coolers are shown in Figure 4. The cooler was qualified in 2017 and subsequently placed in lifetime testing, both in the lifetime test lab at Thales and also in a field test at the customer. Test results are shown in Figure 5. All four coolers are running continuously under conditions comparable to the environmental conditions of the application. At regular intervals the coolers are taken out of the lifetime test setup and a full performance measurement is conducted. The cooling power at maximum input power is plotted in Figure 5; it can be seen that the performance has remained constant over the last two years, and the performance remains well above the required specification level.
Figure 4: Two of the LSF9589 coolers.

Figure 5: Results of running lifetime tests, cooling power at 77 K tip temperature and 80 W input power is measured at regular intervals during the lifetime tests.

An additional cooler is placed in lifetime test at the customer. This unit includes a cryogenic payload consisting of 6 LNA units with 12 RF IO interfaces. The system is running outdoors in a high ambient temperature and humidity. The setup has been running for two years continuously without degradation.

Lifetime tests will continue to be conducted. Based on the results so far it can be concluded that the lifetime is indeed extended and that the design goal of 5 years continuous operation can indeed be met. This brings the availability of this Stirling cooler in the same order of magnitude as a pulse-tube cooler.
3. Extending the operating temperature window of the LSF9340/50 cooler family

Another optimization was recently done on the LSF9340/50 linear Stirling cooler range. This cooler range consists of a flexure-bearing compressor together with a 20 mm Stirling cold finger. The LSF9340 is the standard version, the LSF9350 is the cold finger intended for use in dewars of the integrated detector-cooler assembly (IDCA) type. The coolers were developed for 77 K tip temperatures in civil and tactical applications. In detector-cooler combinations of the IDCA type, the inner wall of the dewar acts as the outer wall of the cold finger, thus minimizing the axial heat conduction.

It is the cooler family with the largest cooling power in the range if linear Stirling coolers at Thales. Therefore, this cooler type was selected for an application where a relatively large amount of cooling power was required at a significantly lower tip temperature of 42 K. The ambient temperature and heat sink characteristics yielded a typical skin temperature of 55 °C.

At this low tip temperature, the thermodynamic balance changes. A larger amount of heat needs to be transferred in the regenerator each cycle. Also, the specific heat capacity of the stainless steel regenerator is lower which potentially leads to additional losses. Increasing losses means that the efficiency of the cooler reduces, and less cooling power is generated. Finally, because of the influence of temperature on gas dynamics, the driving force on the displacer also changes.

The optimization of a cooler is a trade-off between the individual loss mechanisms. The optimum setting means that that the sum of all losses is minimal. Boundary conditions determine the location of the optimum. If a condition such as the cold-end temperature is changed, the optimum will be different. Furthermore, the motion dynamics of the displacer should be balanced between maximum cooling power and efficiency; both the displacer amplitude and the phase difference between displacer motion are affected.

In this project, it was chosen not to completely redesign the regenerator, cold finger, and cooler. It was decided to optimize the performance without changing the hardware of the cooler, so by only changing operating characteristics; fill pressure and operating frequency.

In an empirical approach, the performance was mapped at different tip temperatures, fill pressure, and operating frequencies. Care was taken to correct for variable losses of the measurement equipment. The self-loss of the measurement equipment was determined by means of a calibrated boil-off measurement using liquid nitrogen and thermal modelling for lower temperatures [5].

The results are shown in Figure 6 and Figure 7 below. In Figure 6, the cooling power versus drive frequency is shown. The electrical input power is fixed at 150 W, the skin temperature at 55 °C. Each cooling power graph shows a maximum at a certain frequency. This maximum is determined by two aspects, one is the ‘tuning’ of the displacer; in case of a free-displacer Stirling cold finger the stiffness of the displacer spring and thus the resonance frequency of the displacer have an optimum. This optimum is where the thermodynamic efficiency is at its maximum. The second aspect is the efficiency of the compressor, or the ratio between mechanical (pV) output power and electrical input power. This efficiency depends on frequency as well. The combination of thermodynamic efficiency and compressor efficiency is the overall cooler efficiency.

It can be seen that the measurement at 77 K tip temperature shows an optimum at 50 Hz. This is the condition for which the cooler was originally optimized. When the same configuration is tested at 42 K, it can be seen that the optimum cooling power is reached at 48 Hz. Upon analysis of the compressor performance, it was shown that the compressor resonance conditions were not fully met. In order to reduce the compressor resonance, the fill pressure was reduced, and an optimum was found at 22 bar fill pressure. At this pressure the optimum drive frequency further reduced to 47 Hz.

With this optimized configuration, the cooling power was measured as a function of the input power. These results are shown in Figure 7. At the maximum input power of 170 W, the cooling power at 42 K increased by 400 mW, which is more than 20 %.
Figure 6: Cooling power versus drive frequency for 150 W input power and 55 °C skin temperature. Solid line is the reference performance at and optimized for 77 K. The dashed lines are the different settings for a 42 K tip temperature.

Figure 7: Cooling power versus input power. Tip temperature is 42 K, ambient temperature is 55 °C. The solid line is the newly optimized configuration, the dashed line is the old configuration optimized for 77 K. At maximum input power the cooling power is approximately 400mW, or 20 % higher.

With a minimal design effort, the performance of the cooler was thus optimized significantly. The advantage of not changing the hardware is flexibility. The same hardware configuration can be used and adapted for different conditions. Customers with the capability of handling IDCA-systems have the possibility to use different fill pressures, otherwise this can be changed during production. A different drive frequency is easily changed by adapting the settings of the cooler drive electronics.

When hardware changes are considered, further optimization can be done. The first choice would be to optimize the regenerator matrix for lower temperatures. This would include a change to the
regenerator matrix. A smaller wire diameter would lead to a better heat transfer and a higher fill factor could increase heat capacity. The trade-off between these two effects and a subsequently increased pressure drop would have to be considered. Also, a different material in the regenerator, such as high-heat capacity material coated gauzes could be used. Such a redesign would however mean a significant design and requalification effort.

4. Conclusions
In this paper, we presented two modifications to existing products in the portfolio of Thales Cryogenics. Both modifications give the possibility of using these products in application where they would otherwise not be suitable.

After analysis of the potential failure modes in the cold finger, an improvement was made that increased the lifetime of the cooler. The intended application, the cooling of low-noise amplifiers and high-temperature superconducting filters in RF applications require significant lifetimes. The improved cooler was requalified and ongoing lifetime tests both under lab and field conditions indicate that the required lifetime can indeed be met. This brings the availability of the Stirling cooler to the same level as pulse-tubes.

Another improvement that was done extended the usable cold end temperature of the cooler. In a long-wave infrared application, a sensor needed cooling at 42 K. By optimizing the operating conditions of the cooler, the efficiency and maximum cooling power were improved by more than 20%, without making any modifications to the cooler hardware.

5. References
[1] Van de Groep, W et al, 2012, Update on MTTF figures for linear and rotary coolers of Thales Cryogenics, Proceedings of SPIE Volume 8353.
[2] Kayano, H et al, 2018, Cryogenic Receiver with Superconducting Filter, Proceedings of 2018 IEEE International Symposium on Radio-Frequency Integration Technology, to be published.
[3] Ross, R, 2001, Cryocooler Reliability and Redundancy Considerations for Long-Life Space Missions, Cryocoolers 11, pp. 637-648.
[4] Willems, D, Arts, R, Douwen, J, 2015, State-of-the art cryocooler solutions for HPGe detectors, Canberra website, http://www.canberra.com/literature/detectors/tech_papers/CP5-plus_C48083.pdf.
[5] Willems D, Garcia S, Arts R, Ligtenberg K and Vasse C, 2019, Theoretical and experimental analysis of Dewar thermal properties, Proceedings of SPIE Volume 11002.