SPACE COOLER DEVELOPMENTS AT THALES CRYOGENICS TO FIGHT TRIBOLOGICAL FAILURE PHENOMENA

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ABSTRACT

The use of active instrument cooling in space leads to very stringent requirements for the cryocoolers which are selected. Besides performance, requirements regarding life time and vibrational behavior (level of induced vibrations) are very often decisive for the cooler selection. In Stirling cryocoolers the underlying cooling process is based on expansion and compression cycles of a working gas driven by a compressor. The piston movements inevitably lead to a certain level of induced vibrations and to wear, should there be contact between piston and cylinder. When pulse tube technology cannot be used for reasons of required cooler efficiency, moving parts in the cold finger can also give rise to wear related phenomena. Thales Cryogenics B.V. (TCBV) has developed solutions to mitigate the risk of contact between the moving parts in its space cryocoolers reducing the risk of wear and lowering the levels of induced vibrations which will be discussed in this paper.

1. INTRODUCTION

For various space programs, TCBV delivers the Large Pulse-Tube Cooler Compressor Assembly (LPTC CPA). For this CPA the induced vibration behaviour is a critical characteristic for the higher level cryocooler system. TCBV has performed a study in 2016 into the main causes of these induced vibrations and the corresponding impact on CPA level. This study has been performed in the frame of an ESA GSTP (GSTP 6-2 AO, Impact Analysis of Piston Alignment on Key Compressor Performance Characteristics). The goal of this study was to gain an understanding of the underlying root causes and to come to recommendations for the CPA design in order to make it less susceptible to integration and test influences with respect to induced vibrations. A number of recommendations regarding alignment have been put forward to be introduced in the manufacturing process of the CPA for the Meteosat Third Generation (MTG) and IASI program. This improved alignment is also used in the compressor for the 30-50 K Two stage Pulse-Tube project (see Figure 10) that TCBV is doing together with its partners Absolut System and CEA (ESA TRP refer 4000109933/14/NL/RA) and in the 15 K compressor. In chapter 2 details of the GSTP study will be presented.

The LPTC CPA is a full space grade ECSS compressor. On the other end of the spectrum are the low cost cryocoolers based on off-the-shelf equipment upgraded for space applications. When due to performance reasons a pulse tube with excellent lifetime properties cannot be used and a Stirling cold finger is preferred, actions are necessary to enhance the lifetime. The use of flexure bearings is a known route in this respect. For compressors the use of flexures enabling in-axis motion of the pistons while at the same time providing radial stiffness has proven to be a major step forward in the prevention of wall-piston contact and wear. The Thales LSF series cryocoolers is based on this principle. As early as 2004 TCBV has investigated the same principle in Stirling cold fingers in developing the coolers for Cryosystem [3] which have been running in life time tests accumulating more than 90000 hours since. Based on this design TCBV has developed a low cost space cooler with a flexure bearing cold finger (LSF 9199/30) which has been selected for several space programs. Performance results of this cooler will be presented in chapter 3.

2. LPTC COMPRESSOR

LPTC CPA Description

The TCBV LPTC CPA is based on the compressor that was originally developed under a ESA TRP program N°18433 and modified later on for the French National CSO program. The current version of the LPTC CPA that was selected for the MTG and IASI program is based on this CSO design with only minor interface modifications. The basic design of the CPA for the three programs is therefore identical when considering motor design and internals despite the different requirement regimes. For the CSO program, flight models (FM) have been delivered while for MTG and IASI EM systems have been delivered and FM manufacturing has started recently.

The basic function of the CPA is to generate a pressure wave to the Cold Finger Assembly (CFA). It does so by converting electrical power into a reciprocal motion of two opposed pistons in a cylinder. The results of the reciprocal motion of the pistons is an alternating compression and expansion of the working gas (helium), see Figure 1.

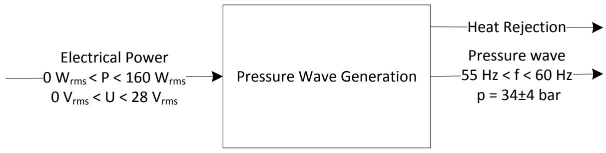

Figure 1: CPA Basic Function

The CPA (Figure 2) together with the Cooler Drive Electronics (CDE) and the CFA make up the cryocooler unit (CCU) (Figure 3).

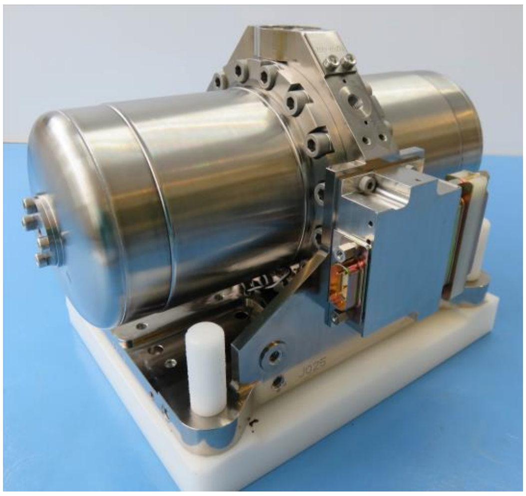

Figure 2: Current compressor Assembly (CPA)

The design of the CPA is such that the movements of the dual opposed pistons cancel out vibrations to a large extent. To make maximum use of this benefit, during the design phase it was chosen to have motors which can be mounted and dismounted on the centre part by using bolts and C-seals. This allows to optimize the CPA for induced vibrations by manufacturing motors in a batch and selecting a pair with optimum induced vibration behaviour by a matching effort.

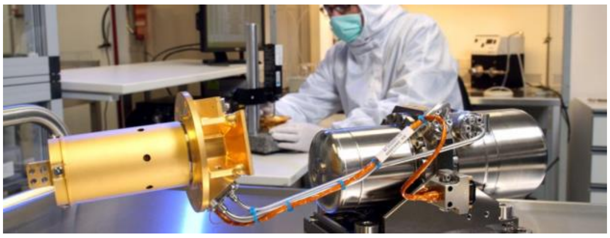

Figure 3: ALAT CCU [Courtesy: ALAT website]

The moving part of the linear motor – consisting of the piston, piston flange, and magnet assembly – is suspended between two flexure bearing packs on each end of the motor, see Figure 4. These flexure packs ensure the positioning and alignment of the piston in the cylinder. The two flexure bearings give a definite stiffness in axial direction and a near-infinite stiffness in the radial direction. That allows a purely axial, contactless, motion of the piston.

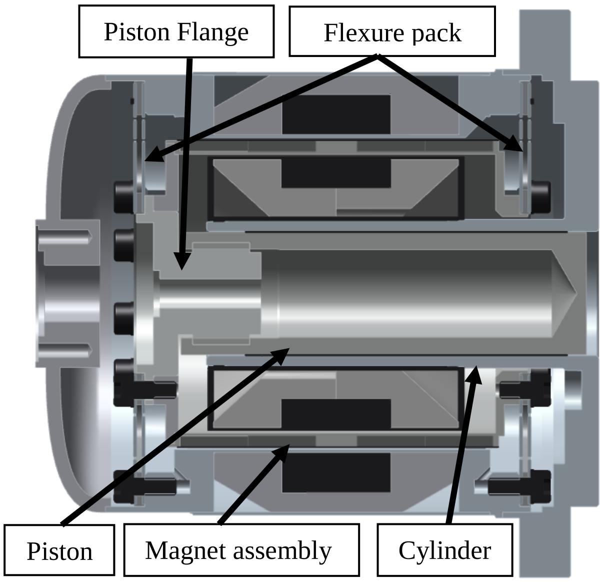

Figure 4: CPA Motor cross-section

The alignment of the piston in the cylinder is done by a micro precision machined alignment profile on the piston liner which centers the piston with respect to the motor cylinder, when the piston is positioned into the motor. The alignment profile is designed in such a way, that after the piston is aligned and fixated, it can wear away during run-in and early operation of the CPA, so that ideally the piston runs in contactless motion afterwards.

The LPTC CPA is a tightly toleranced and aligned system, which allows for minimal contact between the piston and motor cylinder. However one of its main disadvantages is that it is still a system which for the positioning of the cylinder relies on some initial contact between piston liner and cylinder. As a result of this, some wear, friction and induced vibrations are inherently present in the CPA in case a small deviation of the achieved alignment is present.

Recently, the original design choice for the LPTC CPA has been put to discussion in the MTG program. This is linked to the observation of high sensitivity of the design to changes in friction and levels of induced vibrations as a result of assembly steps or thermal and environmental stress during MAIT. Furthermore a sensitivity to orientation with respect to gravity has been noticed. To mitigate these effects TCBV has performed a study related to CPA induced vibrations and its sensitivities, which is further discussed in the next section.

CPA Induced Vibrations Study

The study TCBV has performed on the existing LPTC design was based on the following steps:

Step 1: Identify main influence factors for induced vibrations within the CPA;
Step 2: Quantify their contribution to the overall CPA induced vibrations by means of analyses or tests;
Step 3: Define a set of recommendations for improvement, which can be either process or design related.

Axial vibrations can be reduced by electronic active vibration reduction (AVR). Thus transversal vibrations are the main concern since they cannot be reduced by AVR.

Step 1 - Identify:
In order to determine the different factors with respect to the LPTC CPA induced vibrations six main influence factors were identified:

- Misalignment of the piston w.r.t cylinder;
- Misalignment of various parts of the magnet circuit;
- Over-constraintness of the suspension mechanism (flexure packs);
- Relative misalignment of the two motors;
- Gas dynamics induced vibrations;
- Differences between motor characteristics.

For each of these factors, Ishikawa (fishbone) diagrams were generated to identify the underlying factors with respect to design, process, workmanship, etc. which can contribute to the above mentioned six main influence factors.

A set of tests and analyses was identified to determine the impact of the various influence factors.

This was done by:

- Analysis of heritage measurement data;
- Detailed analysis of the design by means of finite element and tolerance analysis;
- Tests on breadboard level;
- Tests on CPA level.

Friction and ring down[1] test results at different temperatures, at different working pressures (CPA filling pressure) and at different CPA orientations have been analysed. Furthermore friction and ring down test results have been analysed before and after important assembly steps, such as welding or after mounting the motors on the centre part by using a C-seal.

Finite Element Analyses (FEA) were performed to analyse magnetic circuit sensitivity, analyse impact of flexure pack over-constraintness, analyse flexure pack rotation during stroke (piston movement), and perform modal analysis to analyse structural modes and the measured higher harmonics of the CPA. In addition a detailed tolerance stack analysis was performed in order to determine impact on motor concentricity as a result of the worst case stacked tolerance of the underlying individual piece parts.

Concerning the flexure pack, breadboard measurements on part and subassembly level were performed to verify the impact of the over-constraintness as determined by analysis. Other tests on breadboard level were done to determine the impact on concentricity as result of bonding steps during assembly such as welding processes and curing of glue.

Tests on CPA level consisted mainly of induced vibrations[2] measurements and determining the impact of misalignment between the two motors with respect to CPA induced vibrations behaviour. The first tested configuration was placing shims on one side between the motor and the centre part in order to place the connecting motor flange under a slight angle with respect to the centre part interface plane. The second configuration was placing one motor slightly out of center of the centre part interface plane, so that the piston axes of both motors are slightly off-set from each other.

Step 2 - Quantify:
From the various friction ring down test results analyses the main finding was that at low temperature the CPA shows an increase in friction, which confirms the susceptibility of the CPA with respect to friction and corresponding vibrations as result of thermal environmental stress.

On the other hand at high temperature no significant changes in friction behaviour were observed. This can clearly be seen from the difference in measured ringdowns at -30°C and +60°C. The nominal specification is minimal 10 ringdowns, which is achieved at the high temperature, but not at the cold temperature, see Figure 5 and Figure 6.

The tests on CPA level with intentionally misaligned motors did not lead to any major findings. In order to observe significant impact, misalignments larger than the worst case tolerance were necessary.

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[1] Friction and ring down tests are used to determine the friction between the CPA piston and cylinder in which it moves in a qualitative and quantitative manner.

[2] Induced vibrations for the LPTC CPA are measured on a customer furnished device called "Kistler table". During this measurement the exported or induced vibrations of the CPA are measured with the CPA in horizontal orientation in X-, Y-, Z-direction. The vibrations are measured as forces for the first harmonic (H0) and the seven following higher harmonics.

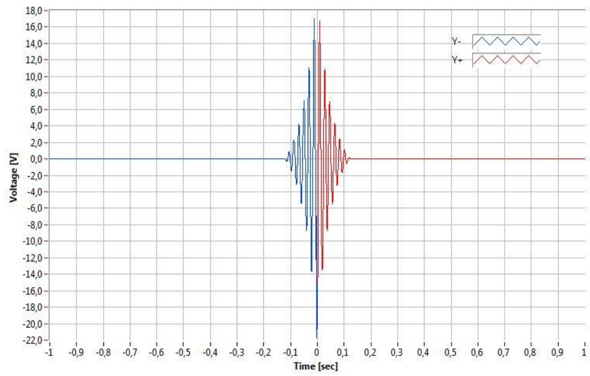


Figure 5 : Ringdown -30 ℃. Left : 6 Right : 6

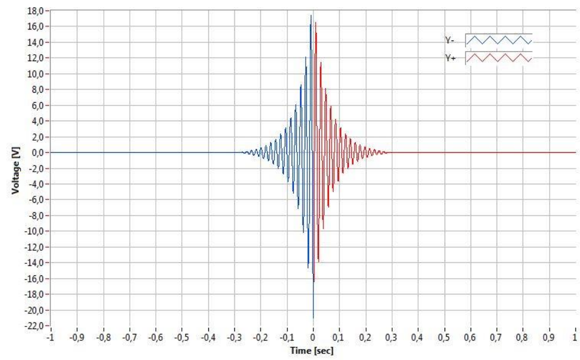


Figure 6 : Ringdown 60 ℃. Left : 11 Right : 12

An analysis that provided major insights in the induced vibration sensitivity of the CPA was the tolerance stack analysis. This analysis showed that a significant worst case stacked tolerance of 0.13 mm at location of the end plate flexure pack can occur as a result of the individual tolerances on the motor piece parts; the summation of these tolerances obtained by stacking the individual tolerance values according to the logic as indicated by the red arrows in Figure 7. At the location of this stacked tolerance the piston flange and piston are connected to the motor moving mass. So in case the worst case stacked tolerance in the order of tenths of millimeters materializes, it will have a direct impact on the alignment of the piston in the cylinder since piston alignment accuracy is in the order of micrometers. This impact can therefore lead to increased friction and induced vibrations on CPA level.
In case that this stacked worst case tolerance can be reduced the impact on the piston alignment can be significantly reduced.

Furthermore from this analysis it was concluded that the piston which is aligned with the micro precision machined alignment profile (Figure 8), could be integrated in the cylinder under a slight angle instead of centered all along its axis in the cylinder. After alignment the alignment profile is designed such to wear away during run-in and early CPA operation. However in the case of the piston under an angle, the alignment profile might only wear away on two opposing sides on the piston instead, see Figure 8.

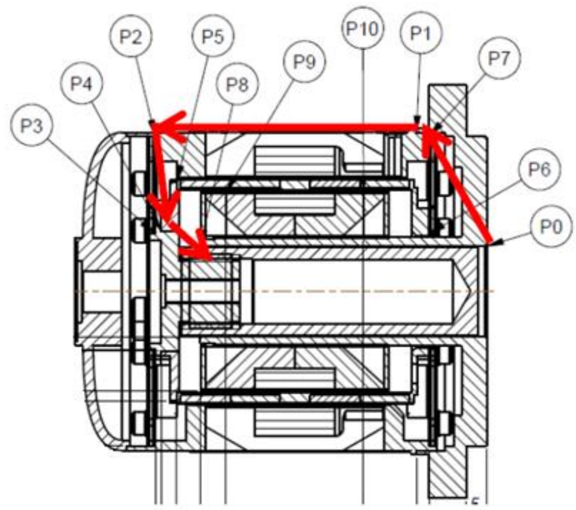
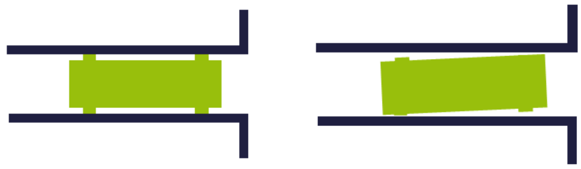


Figure 7: Tolerance stack analysis logic



Piston with aligned in cylinder

Piston under angle worn away at two sides

Figure 8: Schematic of motor cylinder with piston alignment profile

It was found that there is a significant influence of the welding on the concentricity of the LPTC CPA motor.
This non-concentricity of the motor can be avoided by reducing the non-symmetric weld overlap of the structural EB welds of the motor. By reducing the overlap of the weld, the influence of the weld on motor concentricity was reduced by a factor of 4, meaning that a correction on motor non-concentricity could be achieved.

Adhesive bonding breadboard sample tests showed that curing of the glue can have an impact on the concentricity of the parts which are bonded together. By varying the temperatures at which the glue cures different results could be achieved. By curing a glue at 50 °C or 100 °C, concentricity displacements of 0.02 mm and 0.03 mm respectively were observed. Furthermore from additional tests it was shown that approximately half of these concentricity displacements was caused by the glue curing and other half by handling between gluing and curing.

<u>Step 3 – Recommendations:</u>
The main points for improvement were related to the

fact that:

- The current piston alignment method from a design point of view is very susceptible for friction as a result of MAIT influences;
- The concentricity of the motor can be improved by improved weld processes, glue processes and improved assembly tooling;
- Piston alignment can be improved by reducing the worst case stacked tolerance.

To study the influence of the factors above, it was decided to build a LPTC CPA engineering model which includes an improved contactless piston alignment method. Explanation on this alignment method and the test results are provided in the next section.

Contactless Piston Alignment CPA EM Test Results

The alignment method presently used in the LPTC compressor is based on a micro precision machined alignment profile on the piston surface, which is designed to wear away during CPA run-in and early operation. In the optimised piston alignment method the alignment is performed with removable spacers, which can be removed before burn-in instead of an integral alignment profile. The spacer is positioned between the piston and cylinder wall at a few locations, see the schematic representation in Figure 9. In this way the piston is centered in the motor cylinder in a similar manner as with the alignment profile on the piston surface. Once the piston is bonded to the piston flange and thus fixated, the spacers are removed, which leaves a well aligned piston, which really moves contactless with respect to the cylinder wall, see Figure 9.
Friction and thus wear effects are significantly reduced with a higher robustness against manufacturing steps and environmental stresses. This is caused by the fact that in the contactless alignment method a constant gap exists after alignment, whereas in the original configuration this gap was highly dependent on the wear pattern of the alignment profile on the piston surface.

An engineering model LPTC CPA, equipped with the contactless piston alignment method was built to validate the different improvements and to prove robustness of this contactless piston alignment method against environmental stresses and to characterize its performance on LPTC CPA level.

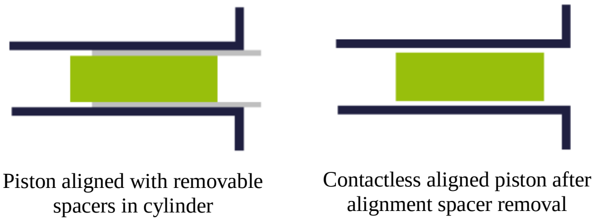


Figure 9: Schematic of motor cylinder with contactless alignment piston.

The model was subjected to a test campaign, which tested performance characteristics, such as pressure wave, friction ring down and induced vibration, followed by mechanical and thermal environmental testing. Afterwards the performance measurements were repeated.

Figure 10: 30/50K CryoCooler Unit

From the test results it is concluded that the contactless alignment method meets the MTG performance criteria, and the performance results are in line with earlier results obtained with a new alignment 'proof of principle' model.

The same method of alignment is used for the compressor of the 30-50K program. In this ESA TRP program (refer 4000109933/14/NL/RA) a Two stage Pulse-Tube cooler is developed together with partners Absolut System and CEA (ESA TRP refer 4000109933/14/NL/RA), see Figure 10. Here similar improved behaviour is observed with regards to friction and induced vibration results.

The contactless alignment engineering model shows the required robustness against the MTG environmental specifications. Thermal tests have been performed at qualification levels (4 thermal vacuum cycles from -50°C to +91°C). Both sine and random vibration test have been performed in ProtoFlight Model (PFM) approach (qualification levels at respectively acceptance sweep level and acceptance duration level).
Furthermore there is no impact on the performance of the improved alignment CPA due to the environmental vibration tests and the thermal vacuum cycling tests. This is illustrated by Figure 11, Figure 12 and Figure 13. Figure 11 shows the pressure wave pre and post environmental testing. The pressure wave is the main output to be generated by the CPA and therefore one of the main performance parameters of the CPA to monitor its health. It can be seen that the results clearly overlay each other and do not show significant differences.

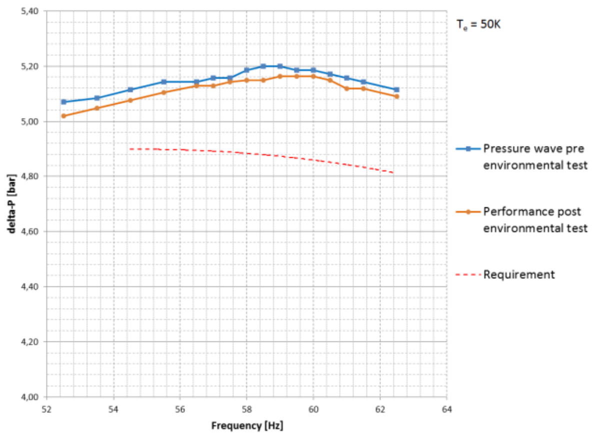
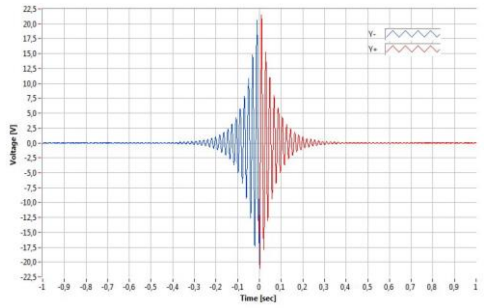
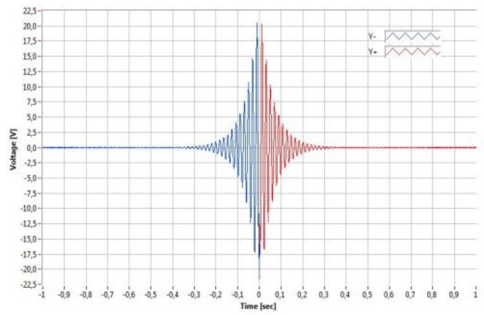


Figure 11: Pressure wave measurement pre and post environmental test

In addition the measured induced vibration test results and ring down test results show that the contactless piston alignment engineering model is not affected by the environmental tests performed during the test campaign. Both the ring down and induced vibration measurements are direct indicators for the piston alignment of the CPA and the presence of sliding contact. When comparing the ring down measurement results and induced vibration in piston axis measurements pre- and post environmental tests in Figure 12 and Figure 13, it is observed that no significant differences have occurred.

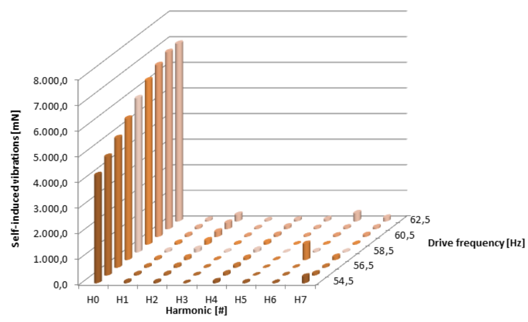


Y-Axes Ring-down at 20°C pre environmental test;
Left : 12 Right : 12.

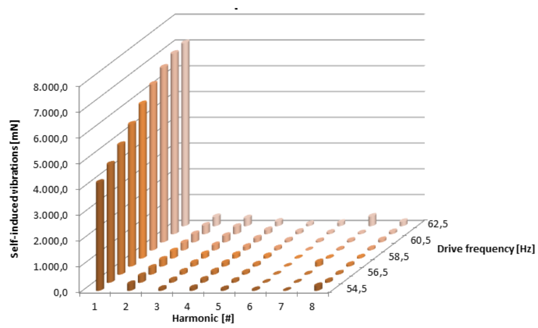


Y-Axes Ring-down at 20 °C post environmental test;
Left : 12 Right : 12.

Figure 12: Ring down measurement pre and post environmental test



Induced vibrations pre environmental test;



Induced vibrations post environmental test;

Figure 13: Induced vibrations measurement in piston axis at 160Wpre and post environmental test. [3]

Design and Process Improvements for LPTC CPA

Based on the EM test results and the findings as discussed in the step 2 section, recommendations to improve manufacturing processes and the CPA design have been proposed. These recommendations do not impact form, fit, function of the CPA and are currently under qualification to be implemented in the LPTC CPA for both the MTG and IASI programs.

Another significant improvement that is made on the CPA is the reduction of the worst case stacked tolerance at the location of the end plate flexure pack which directly connects to the piston flange and piston. This is done by improving the concentricity of motor itself and by improving the concentricity of flexure pack subassembly. The motor concentricity itself is improved by applying the optimized weld processes which allow for adjustable weld overlap in order to control motor concentricity. The flexure pack concentricity is improved by improvement of tooling for flexure pack assembly and post machining.

A third major improvement is that due to the different

[3] Piston axis induced vibrations for the contactless piston alignment engineering model are relatively high between 4 and 8 N over the entire frequency range. The reason for this is that the motors on this CPA were not matched from a larger motor pool as is done for flight manufacturing in order to optimize induced vibration performance.

parts geometry it is now possible to measure the concentricity of the piston flange with respect to the motor cylinder along the motion axis of the piston. This enables a measurement to verify the impact of the worst case stacked tolerance at the end plate flexure pack and determine its impact on the motion axis of the piston with respect to the motor cylinder thus determining initial piston alignment. Corrective measures can be taken at this point by simply removing the piston assembly and re-installing these parts. With the old alignment method such a measurement is not possible.

So to summarize, by implementing these measures the LPTC CPA will become less susceptible for initial wear, friction, and induced vibration effects, but also during the MAIT and its lifetime.

3. LSF9199/30 COOLER

The LSF9199/30 cryocooler is developed as an efficient low cost Stirling cryocooler for space applications building on civil heritage. For the space market additional qualification testing and inspection steps during manufacturing are added. One of the key life time enhancing design alterations compared to conventional civil siblings of this type of cryocooler is the use of flexures in the Stirling cold finger.

The LSF9199/30 is designed as a cost efficient cooler for GEO-synchronous space applications with a design which on the one side meets high performance requirements and on the other side approaches the high reliability over lifetime of a pulse-tube solution.

Product Development and Key Design Decisions

The compressor which was selected for the LSF 9199/30 cooler is based on the Linear Stirling Flexure (LSF) compressor series. This compressor is known for its reliability and is an available of the shelf product for both civil and military applications.

The requirement specification and design objectives resulted in the conclusion that a pulse-tube cooler was not a feasible option so a Stirling cold finger cooler was required.
To cope with the reliability over lifetime requirement a convential Stirling cold finger could not be used. It was decided to use a flexure-bearing cold finger as previously developed for the Cryosystem program [3], see Figure 14. This LSF9330 type cooler has been running in life time tests since over 10 years. and has successfully accumulated more than 90000 hours.

A cold finger with a flexure bearing will provide both axial and radial stiffness, avoiding contact between the displacer and cold finger wall. It therefore enables compliance to the requested lifetime. The induced vibration design requirements can be met with this design. An active or passive balancer could even further improve the vibrational behaviour. In Figure 15 a photo of the LSF9199/30 flexure-bearing cold finger is provided.

Figure 14: LSF9330 Originally developed for the Cryosystem Program.

For both the compressor and cold finger, the selected materials are screened to assess compliance to the space environmental requirements.

Figure 15: LSF9199/30 Flexure cold finger.

Furthermore a dedicated qualification test campaign against the design requirements was performed with the LSF9199/30. Additional inspections and tests were added to the cooler manufacturing and test phase to increase screening reliability.

FM product description

The LSF9199/30 cryocooler is shown in Figure 16. As it has a pneumatically-driven free displacer, the efficiency of the cryocooler is high without the need for expensive, high-grade material combinations. Furthermore, the SADA-compatible displacer design allows infrared detector manufacturers to adopt a similar COTS-to-space approach for the detector-dewar assembly.

Figure 16: LSF9199/30 Cryocooler

The LSF9199/30 meets the key requirements which were defined for this development. The main corresponding characteristics are provided below:

- Cooling power is graphically presented in Figure 17 for both the 150 K and 50 K case;
- The total mass of the Cryogenic Cooler is max. 2.5 kg;
- Induced vibrations is:
  - Compressor ≤ 2.2 Nrms;
  - Cold finger at 50 K ≤ 6.0 Nrms at 30 °C steady state;
  - Cold finger at 150 K ≤ 3.9 Nrms at 55 °C steady state;

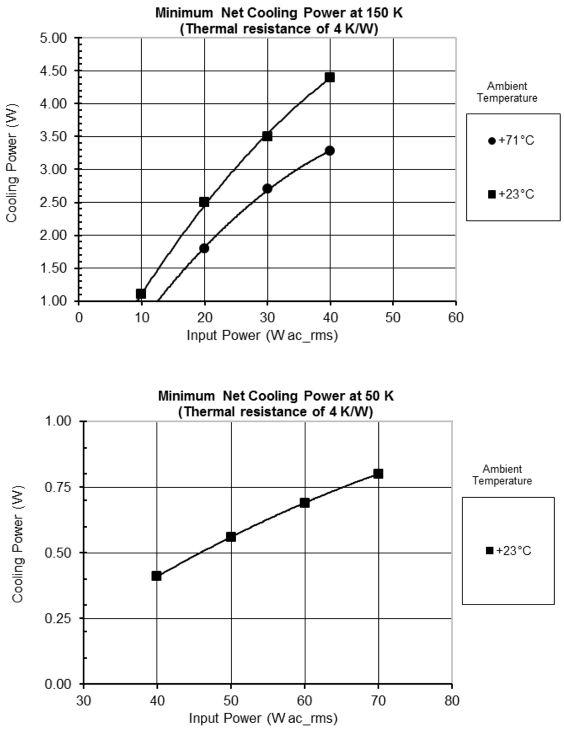


Figure 17: LSF9199/30 performance curves.

In [1] and [2] it is explained that a cooler such as the LSF9199/30 which operates by means of a linear moving flexure supported mass in the cold finger is expected to achieve reliability performance similar to that of a pulse-tube cooler. This is illustrated by life time test results at TCBV where flexure-bearing free displacer LSF 9330 coolers have been running successfully in life time testing for more than 10 years. In addition it is discussed in [2] that exported vibration can be further reduced by applying active vibration reduction.

It can be concluded that the LSF9199/30 is an off-the-shelf solution upgraded with state of the art solutions to overcome the tribological challenges in the standard design and make it worthy for space.

4. CONCLUSIONS

The design criticalities of the existing LPTC CPA regarding friction and vibrational behaviour have been investigated in the course of a GSTP study. Based on this study design changes without impact on form-fit-function and MAIT improvements have been proposed which are currently under qualification in the MTG and IASI program.

TCBV has developed a low cost Stirling cryocooler for GEO-synchronous space applications based on civil and military heritage. For applications where a fully space qualified pulse-tube cryocooler is not feasible this LSF 9199/30 cooler with a flexure cold finger is a viable alternative.

TCBV has successfully developed several state of the art solutions for space applications to overcome wear related issues, in order to meet stringent customer product requirements related to induced vibrations, lifetime and reliability.

Acknowledgement

The LPTC CPA study has been performed in the frame of a GSTP (GSTP 6-2 AO, Impact Analysis of Piston Alignment on Key Compressor Performance Characteristics). The support from ESA and NSO in this GSTP study is highly appreciated.

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