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Title of paper	Development of the LSF 95xx 2nd generation flexure bearing coolers.
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ABSTRACT

Thales Cryogenics has been working on high reliability cryocoolers since 1997. During this period two cooler series have been developed, the LSF91xx series for cooling powers up to 3W at 80K and the LSF93xx series for cooling powers up to 8W at 80K.

As a result of several design improvements, it was possible to decrease the length and mass of our flexure-bearing coolers. These improvements have been applied in the new LSF95xx series. With the length and mass reduction, the LSF95xx complies with the SADA II specification with respect to envelope and mass. Based on this, being the first manufacturer offering a full flexure-bearing supported cooler that fits within the SADA II envelope, Thales Cryogenics has been selected in several new (military) programs with their LSF coolers.

By using a moving magnet configuration in all our flexure-bearing coolers, the risk with respect to contamination problems due to out-gassing have been diminished because the coils are not part of the helium circuit. Furthermore, all connections in the LSF95xx are laser-welded, which means that there is no additional locking required inside the cooler. By using a different magnet design, no magnet segments have to be glued together, which decreases the risk of out-gassing and increases the robustness even more.

This paper describes the trade-offs that have been considered in the design phase, and gives a detailed overview of the test results, the status of the qualification program and the resulting specification of the LSF95xx cooler series.

INTRODUCTION

The first generation of Thales' LSF91xx flexure bearing compressors was introduced in 1999. The flexure supported moving magnet concept is generally recognized as the most robust and reliable implementation of a stirling compressor. By making this concept available in volume production, Thales set a first and important step to introduce stirling and stirling-type pulse tube cryocoolers into civil and industrial markets. Further, interest was raised in the space community, as the design and fabrication methods turned out to be suitable for making space-worthy coolers for a fraction of the cost generally associated with space cryogenics.

From the world of military infrared systems, it was soon recognized that the significant increase in MTTF (as compared to conventional cryocoolers) gives a large potential in reducing cost-of-use and increasing maintenance intervals. Space constraints, as well as agreed standards such as the SADA envelope, limited the applicability of the LSF91xx series cryocoolers in military applications.

In 4 years of production of the LSF91xx, and in the design of compressors for a number of space programs, Thales has obtained extensive experience in building and designing flexure compressors. It was therefore decided to design a moving magnet flexure cooler fitting in the SADA envelope, using the cold finger of an existing Thales contact-seal SADAII cooler.

The compressor design is now used as the basis of the LSF95xx series of cryocoolers. The series contains the LSF9599 with a ½" SADA compatible cold finger, and the LSF9597 with an ¼" IDCA cold finger interfacing with the same dewar as Thales' rotary monobloc coolers. Furthermore, a number of slip-on coolers such as the LSF9580, LSF9587, LSF9588 and LSF9589 are available.

DESIGN

Magnetic circuit design

A mass reduction study was conducted on the LSF93xx compressor in order to use it in the LSF9330 for the Cryosystem space application. In this study, it was found that it is advantageous to replace the 16 magnet segments used in the motor by a single magnetized ring. For the mass and size reduction of the LSF95xx, it was decided to use the same approach. The magnetized ring is more robust than separate magnet segments, thus making the design even more suitable for applications where the cooler is subjected to severe shock and vibration. Furthermore, the segmented design may have trapped gas volumes in the gaps between the segments, thus requiring great care in cleaning and drying of the compressor in production. The magnetized ring is a single piece, thus the design further reduces potential outgassing into the helium space.

The biggest advantage, however, is the fact that the design enables a reduction in moving mass for the same magnetic flux in the motor.

Flexure support design

In the 1st generation LSF91xx, the pistons are supported at both ends by flexure packs, giving the axial and radial stiffness required to support the piston even under high transverse loads. Each flexure pack consists of two flexures (thus 8 flexures per compressor).

Using a combination of FEM calculations and extensive fatigue tests [1], Thales has continued to refine their Algor® based FEM flexure optimization tool. A new spring steel material is found that has a 10% higher fatigue threshold than the old spring steel. Combined with the lower moving mass, this material made it possible to design flexures that can support the loads in a single-flexure arrangement.

Thus, in the LSF95xx, each piston is supported by one flexure at each end. Consequently, the compressor contains 4 flexures only and the length has reduced from 165mm to 122mm.
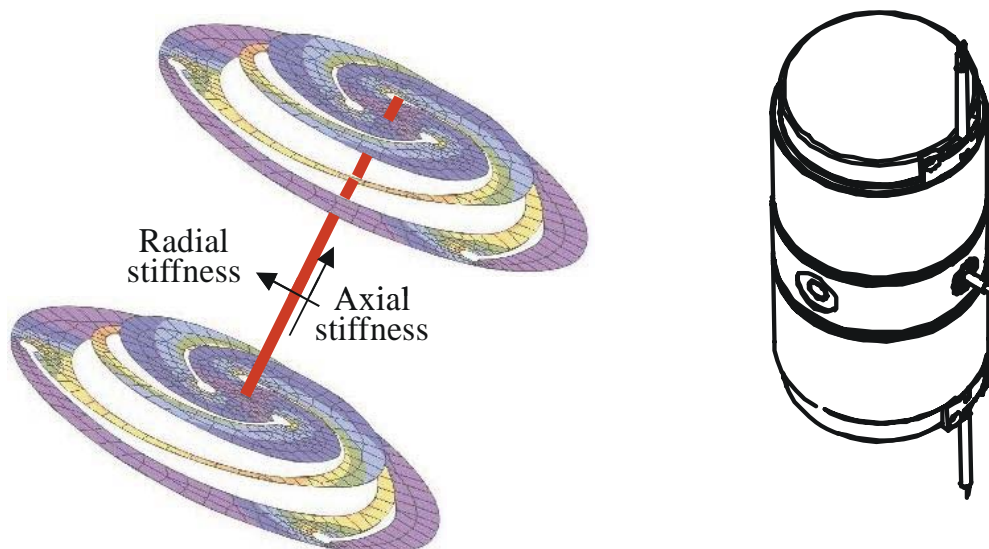

Radial stiffness
Axial stiffness

Figure 1: single flexure arrangement (1 flexure per piston side) and LSF95xx outline

Compressor housing design

Having gained experience from the severe safety constraints in civil and space applications, the housing of the compressor is optimized to reduce stresses in the housing material. For general applications, the optimized housing is made of AISI 304L (yield strength = 170 N/mm^2) and laser welded. This provides a

robust housing with a burst pressure well above the required 2 times the maximum design pressure. For applications requiring compliance with MIL-Std-1522, the housing can be made of AISI 321 (yield strength = 205 N/mm^2) and electron-beam welded.

Modularity

In parallel to the approach chosen for the LSF91xx series, the compressor is designed as much as possible in a modular concept. Adaptation to the various Thales' cold fingers is possible with the exchange of a minimum number of parts. This makes it possible to build even small series of coolers for economically acceptable costs.

SPECIFICATION AND PERFORMANCES

In the design of the LSF95xx, special care is taken to make sure that the weight and size reduction did not impact compressor efficiency. Therefore, the performance specifications of the LSF95xx series are identical to that of the LSF91xx series. A summary of the performances of the LSF95xx compressor with existing Thales cold fingers is given in table 1.

As many heat-sink designs clamp around the center part of the compressor, the fact that the LSF95xx has the same diameter as the LSF91xx means that the two designs are to a large extend interchangeable.

Dynamic impedance

For integration of a cooler in a system, the dynamic impedance $Z=U^2/P$ of the cooler often is important. For a cooler drive electronics giving a fixed voltage, a too high dynamic impedance would imply that there is not enough power going into the cooler. With a too low dynamic impedance, the high power drawn by the cooler may cause problems in the system power supply or in the thermal budgets. For interchangeability, the dynamic impedance of the LSF95xx is designed to be equal to that of the LSF91xx. As the dynamic impedance is influenced by many variables such as system damping, piston resonance conditions, friction, piston stroke and coil impedance, this proved to be an important constraint in the design process.

COOLER TYPE	UNIT	LSF9580	LSF9597	LSF9588	LSF9589	LSF9599
coldfinger/ approx dewar bore	mm	5	1/4"	10	13	1/2" SADA
Dimensions compressor (diam x L)	mm	60x122	60x122	60x122	60x122	60x122
Cooling power @ 80 K, 23C	mW	600	650	1600	2800	1500
Input power	W	40	40	60	100	60
Typical cooldown time to 80 K	min	9' @850J	8'@850J	7' @850J	5'@850J	13'@1440J
IDCA or Slip on		Slip on	IDCA*	Slip on	Slip on	IDCA*
MTTF	hours	>20.000	>20.000	>20.000	>20.000	>20.000
Mass	< kg	1.7	1.7	1.8	1.9	1.8

Table 1: LSF95xx performance summary

QUALIFICATION

As the cold fingers and the performance of the LSF95xx series are identical to the LSF91xx series, it was not necessary to re-qualify the coolers for their performance in combination with the various dewars and applications of our customers.

Since the magnet circuit, moving mass, piston mounting and flexure material have changed, a delta-qualification is performed on radiated magnetic field, induced vibration and acoustic noise, shock and vibration, and flexure fatigue / lifetime. The results of this qualification program are described in the next paragraphs.

Electromagnetic interference

Electromagnetic interference is measured according to MIL-STD-461 D as specified. The results are given in Figure 2.

Induced vibration

Induced vibration is measured on 2 prototype compressors driving ¼" IDCA cold fingers. Axial forces are below 1.7 N_{rms}, and radial forces below 0.35 $N_{rms.}$ A typical vibration spectrum, where the compressor is operated near full stroke, is depicted in Figure 3.
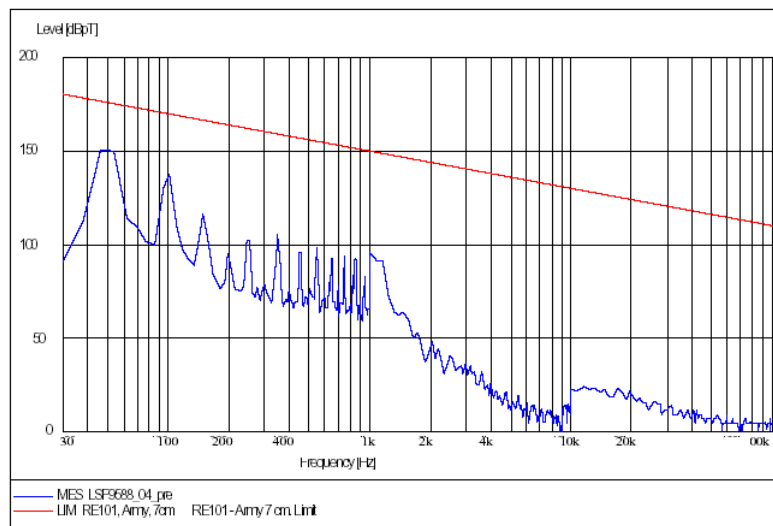

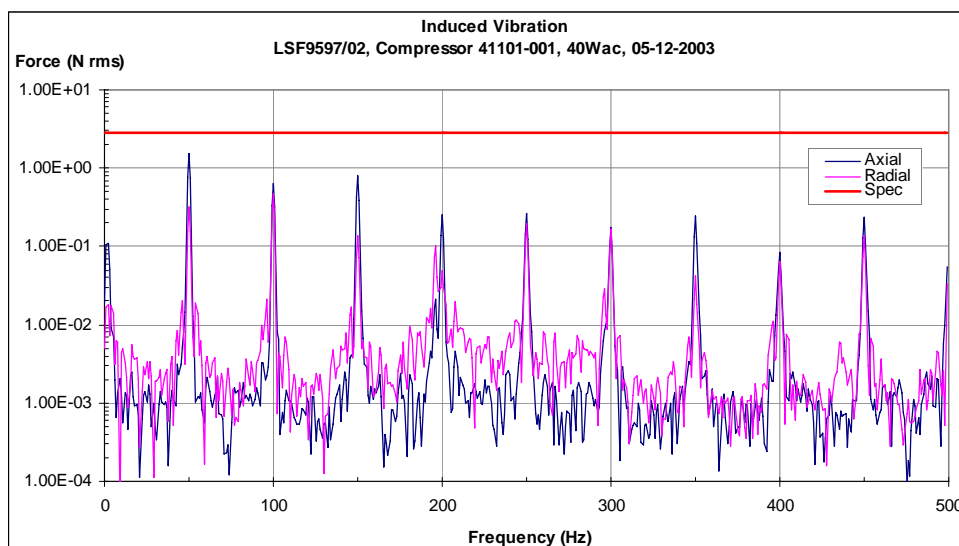Figure 2 : Magnetic interference of LSF95xx

Figure 3: Typical vibration spectrum of an LSF9597

f (Hz)	Sound power (dB)		Sound pressure @5m (dB)	
	LSF9588	LSF9597	LSF9588	LSF9597
63	x	X	x	x
125	10.0	3.9	-15.2	-21.1
250	12.5	12.2	-12.3	-12.9
500	21.1	21.5	-4.4	-3.5
1000	15.0	15.1	-10.1	-10.1
2000	19.5	13.5	-5.6	-11.5
4000	22.0	13.3	-3.1	-11.7
8000	25.2	34.0	-0.2	8.9
Overall (dB (A))	**34.5**	**34.8**	**9.5**	**9.8**

Table 2: Sound power (0 dB=1 x 10-12 W) and sound pressure (0 dB = 2 x 10-5 Pa) measurements

Acoustic noise

Sound power measurements are performed in a reverberant room. From the sound power measurements, the resulting sound pressure at 5 meters distance is extrapolated assuming that at this distance, the cooler may be modelled as a monopole (point) source. It is found that at 5 meters distance, in most frequency bands the sound pressure is below the threshold of human hearing of 20 μPa.

Shock and Vibration

In order to verify the robustness of the new flexure design, a shock and vibration test program is performed. A number of coolers are successfully tested in Thales' Environmental Test Lab (ETL).

For repetitive shock testing, the coolers are subjected to 2000 shocks of 20g, 6ms, in each direction, thus a total of 6000 shocks with the cooler non-operating. The resistance to shocks while operating is tested by subjecting the cooler to 3 shocks of 100g, 11 ms, in each axis.

Random vibration testing consists of a 12.2 g_{rms} random pattern in the frequency range of 20-2000 Hz. This test is performed in 2 directions, for 3 hours in each direction.

Finally, each qualification cooler is subjected to a sinusoidal vibration test, where the frequency range of 5-2000 Hz is swept through 10 times at 1 octave per minute, in 2 directions. The level ramps up to 1 g peak from 14-23 Hz, and then ramps up further to 5 g peak from 52-2000 Hz.

Flexure fatigue and lifetime testing

In the design phase of the flexures, FEM calculations and fatigue tests were performed in parallel. A large number of flexures, mounted exactly as they are in the compressor, are tested for more than 10^7 cycles (Wöhler fatigue curve) to support the FEM fatigue calculations. In the compressor design, the actual stroke of the pistons is limited so that the flexures stay 35% below their fatigue limit.

Apart from the mounting method of the flexures, the flexure material and the design of the magnet circuit, the LSF95xx is conceptually identical to the LSF91xx. The reliability of the flexure mounting is proven in the fatigue tests, as well as in the shock and vibration tests. The magnetic circuit of the LSF95xx is even less susceptible to outgassing than the moving magnet design used in the LSF91xx. Thus, the lifetime results of the LSF91xx can be extrapolated to the LSF95xx. An overview of running lifetime tests is given in Table 3. A number of LSF95xx coolers will be added to the lifetime test setup in the coming period.

Cooler	#	remarks

type	operating hours	
LSF9188	39255	Of which 400 hours in centrifuge (up to 10 g)
LSF9180	35044	
LSF9180	16273	Stopped for destructive analysis
LSF9110	28262	Pulse tube cold finger
LSF9320	17622	
LSF9320	26053	
LSF9188	25187	
LSF9188	25206	
LSF9330	19242	
LSF9330	19475	
total	251619	

Table 3 : overview of lifetime tests on LSF9xxx coolers

MTTF calculation (based on LSF91xx)

The calculation procedure as described below is used to determine MTTF figures of long lifetime cryocoolers. First, a FMECA (Failure Mode effect critical analysis) analysis is performed based on the available experience in cryogenic coolers. The output of the FMECA is a list of identified critical parts or functions in the cooler from the MTTF point of view.

For the parts subject to wear, we assume that the failure rate is constant (random failure). The tests results of lifetime tests already performed on similar parts are then considered. From these results, we determine the MTTF of the part or function with MTTF=Σ(running hours)/(number of failures). When no failures are observed, we take MTTF=Σ(running hours).

For the calculation of the MTTF of the complete cooler, we again assume that the failure rate is constant (random failure). This simplification can be justified by the considerations that all the different components inside the cooler follow different distributions. As a consequence, the system behaves in an unpredictable way (random failure) with a constant failure rate. This is supported by experience figures.

Therefore, we calculate the MTTF of the cooler as MTTF = $1/\lambda$ with λ being the summation of the failure rate of each component over the number of components in the cooler for which a λ_i is defined. Using the list of failure mechanisms as reported by Ross [2] and filling it with figures from Thales experience, Table 4 gives the resulting figures for the reliability and MTTF.

Note that the resulting MTTF of 27601 hours is changing every day, as the lifetime coolers that are reported in Table 3 are all still operating.

CONCLUSIONS AND FUTURE WORK

The development of the LSF 95xx 2nd generation of flexure bearing compressors has led to a 35% reduction in mass and a 33% reduction in compressor volume. All other cooler performance characteristics have either improved or stayed the same.

The shorter compressor design has slightly less margin with respect to hitting of the end stops. This implies that under axial acceleration, the input power to the cooler during cool down may have to be limited. A test campaign will be started soon to establish the allowable values.

	Conventional coolers[1]	**Thales LSF 9199**	

FAILURE MECHANISM	Stirling + balancer w/ back to back compressor	LSF 9199 stirling	*MTTF*	= 1/MTTF
Excessive Internal Cooler Contamination	3	1	226581	4.41E-06
Hermetic Seal or Feed through Leak	2.5	0.5	226581	4.41E-06
Comp. Flexure Breakage (fatigue)	0.1	0.1	226581	4.41E-06
Comp. Motor Wiring Isolation Breakdown	1	0.2	226581	4.41E-06
Comp. Piston Alignment Failure	0.2	0.2	226581	4.41E-06
Comp. Piston Blowby due to Seal Wear	1	1	226581	4.41E-06
Comp. Piston Position Sensor Failure	1	0		
Expander Structural Failure (launch)	0.2	0.2		
Expander Blowby (wear)	3	3	205135	4.87E-06
Expander Motor Wiring Isolation Breakdown	0.5	0		
Expander Spindle Alignment Failure	0.2	0.2	205135	4.87E-06
Expander / Balancer Position Sensor Failure	1	0		
Total failure probability (%)	**13.7**	**6.4**	***Total MTTF***	**27601.23**

Table 4: Thales 9199 reliability and MTTF calculation

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1. Benschop A.A.J, Mullié J, Meijers M. "High reliability coolers at Thales Cryogenics", *Proceedings of SPIE*, (2000), pp. 385-393.

2. R.G. Ross, jr., 'Cryocooler reliability and Redundancy Considerations for Long-Life Space Missions', Cryocoolers 11, (2001) pp. 637-648