The Reliability Development of Miniature Stirling Cryocoolers

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ABSTRACT

Reliability has always been one of the most important performance measures for miniature tactical Stirling cryocoolers. The paper addresses methods to estimate the reliability of Stirling cryocoolers for products made by RICOR, Thales Cryogenics, and BAE, and estimates their reliability. The reliability growth and development trend of both Chinese and foreign tactical miniature Stirling cryocoolers from 1950s to now are introduced. Finally some acceleration methods of the reliability are introduced.

INTRODUCTION

Miniature Stirling cryocoolers are widely used in many applications, such as vehicle-mounted, airborne and ship-based tactical infrared systems. Their merits are high efficiency, small volume, light weight, fast cool-down, low vibration and wide operating temperature range. With the rapid development of infrared detectors, thermography systems require high performance and reliability of the cryocoolers. Cryocooler manufactures all over the world are trying to improve the reliability of their products. At first, the paper introduces some basic conceptions of reliability and the reliability prediction methods for RICOR, Thales Cryogenics and BAE. Secondly, the reliability growth and development trend of tactical miniature Stirling cryocoolers from 1950s are introduced. Finally, some acceleration methods of the reliability are introduced. The discussion of aerospace Stirling cryocoolers with their high cost and high reliability are beyond the scope of the paper.

BASIC CONCEPT OF THE RELIABILITY OF MINIATURE STIRLING CRYOCOOLER

Basic Conceptions

The technical indexes of reliability include confidence coefficient, failure rate, mean time between failures (MTBF), mean time to failures (MTTF), and availability factor. The basic indexes to measure the reliability of Stirling cryocoolers are MTBF and MTTF. MTBF is for reparable systems while MTTF is for irreparable systems. When it comes to the bathtub curve,. MTBF depicts the failure in the occasional failure zone while MTTF depicts the failure in wear-out region

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Prior to 1983, MTBF was generally used to depict the reliability of cryocoolers, and the failure of cryocoolers was considered to be random failure. With the improvements in the reliability and the accumulation of field data, the failure mechanisms of cryocoolers by contamination and the wear of the assemblies over time, can be attributed to wear failure. MTTF is generally used to depict the reliability of cryocoolers now. Mean Time To First Failure (MTTFF) is also used to estimate the reliability of cryocoolers in recent literatures. MTTFF is equal to MTTF numerically but it emphasizes the non-maintenance property of cryocoolers. The definition is stricter and more applicable to military equipment.

Calculation Methods of Reliability

The exponential distribution, the normal distribution, lognormal distribution and Weibull distribution are commonly used to estimate the life. An exponential distribution is aimed at products that fail because of "random" events instead of a specific failure mechanisms. The failure can be eliminated by means of design, processing control and screening experiment. The Normal distribution is also called Gaussian distribution. It is widely used in many fields such as processing error, measuring error and the parameters of products. The probability density function of the lognormal distribution looks like an asymmetric hill. The failure density near the top is high. The Weibull distribution mainly aims at chain models of overall failure that result from part failure. Part failure includes many types of failures, such as the wear of piston, the fracture of spring, the leakage of weld, etc. Many companies take advantage of the Weibull distribution to estimate the cryocooler life.

Calculation Methods to Evaluate Reliability of Cryocoolers

The leading companies will estimate the reliability of Stirling cryocoolers that have been designed. The estimate method of every company is different.

RICOR. RICOR utilizes the Weibull probability distribution to estimate the overall life of integrated Stirling cryocoolers. The method is based on the life measure of similar cryocoolers. The life estimate method of the K560 cryocooler used by the company is below:

a) It assumes that the shape parameter of the Weibull distribution $\beta \backsimeq 7.5$.

b) It assumes that the scale parameter of the Weibull distribution $\alpha=5780$h.

The estimated life of the K560 is derived from the parameters for the 5430h cryocooler.

Thales Cryogenics. Thales Cryogenics also takes advantage of the Weibull probability distribution to estimate the life of cryocoolers. Thales Cryogenics considers it difficult to acquire the reliability of all the assemblies. When the failure data of an assembly is given, it is defined as MTTF=$\sum$(runtime)/the number of failure. When the failure data of an assembly is missing, it is defined as MTTF=$\sum$(runtime). When it comes to the reliability of RM2/01, Thales Cryogenics estimates the failure time of bearings, seals, the drive controller, gas contamination and piston wear. The proportion of different failures is based on the experience of Thales Cryogenics. The reliability of RM2/01 is acquired at last.

BAE System. BAE System takes advantage of the power time method to estimate the life of their cryocoolers. The overall power/energy consumption of a cryocooler (the product of average input power and overall runtime) is fixed according to this method. The input power that varies along time will be improved in the actual measurement of cryocooler. The overall power consumption will be acquired by means of the integration of the life measure curve. The shortcoming of this method is that it requires the life measure power curve of the cryocooler.

THE RELIABILITY DEVELOPMENT OF FOREIGN STIRLING COOLERS

The reliability of foreign long-life cryocoolers has improved from hundreds of hours in the 1960s to 10,000s of hours nowadays. Chinese long-life cryocoolers have made noticeable progress, and the estimate life reaches 30,000 hours. With the development of tactical infrared

technology, miniature Stirling cryocoolers progress and the reliability has improved. There are three principal stages of development, namely, 1950s-1980s, 1990s and the period after 2000.

1950s-1980s. U.S. developed the earliest tactical Stirling cryocooler in the late 1950s, which was used in infrared camera of an upper air scouting plane. The life was in the hundreds of hours. Philips in Holland developed the earliest linear resonant cryocooler in 1976. Philips developed a split Stirling cryocooler driven by a linear compressor in 1983. The life reached thousands of hours. There were a variety of split cryocoolers driven by oppositely operating dual linear motors and dual pistons to reduce vibration in the developed countries in the late 1980s. The cryocooler had a small volume, a light weight and a life exceeding 3000 hours. It was a high-standard tactical cryocooler. The technology called "integration of detector, dewar and cryocooler assembly (IDDCA)" also appeared in the late 1980s, which reduced the power consumption, the vibration and the wear greatly and extended the working life. RICOR developed the K506 (the predecessor of K508) overall integrated Stirling cryocooler based on this technology. Its life was about 3000 hours.

1990s. In the 1990s, in order to meet the development requirement of a second generation infrared focal plane detector assembly, the U.S. Department of Defense (DOD) established the Standard Advanced Dewar Assembly (SADA). A series of linear Stirling cryocoolers were built to this standard. The main characteristics of the series of cryocoolers were low cost (below $1,000 U.S.), average reliability (MTTF was between 4,000h and 8,000h), fast cool-down time (it cools down to 80K in less than 15 min), and a cooling capacity ranging from 0.15W to 1.75W. The MTTF of the rotating electric cryocoolers at the same time rose to 6,000h~8,000h.

2000. The reliability of both rotating Stirling cryocoolers and linear Stirling cryocoolers improved further in this time period. The reliability of both types of cryocoolers exceeded 20,000 hours. Figure 1 presents the reliability data of typical foreign tactical Stirling cryocoolers.

The Development of Linear Stirling Cryocooler. In the 21st century, the primary development direction of the linear Stirling cryocooler has been the moving-magnet Stirling cryocooler. Both Thales Cryogenics in France and AIM in German emphasize the development of this type of Stirling cryocooler. The two main characteristics of this cryocooler are the moving-magnet linear compressor and the flexure spring support. The reliability of miniature Stirling cryocooler exceeds 20,000 hours owing to these advancements.

At the same time, under the support of the U.S. DOD, DRS improved SADA-based Stirling cryocoolers. The most noticeable improvements is the replacement of coil spring with flexure spring. The reliability of SADA series of cryocooler exceeds 15000 hours owning to these advancements.

Thales Cryogenics introduced a subminiature Stirling cryocooler UP8497 in 2010. The weight of the cryocooler is 600g and the reliability reaches 15000 hours. The reliability of UP8497 has been improved by improving the wear-resistance material of the piston and reducing the weight

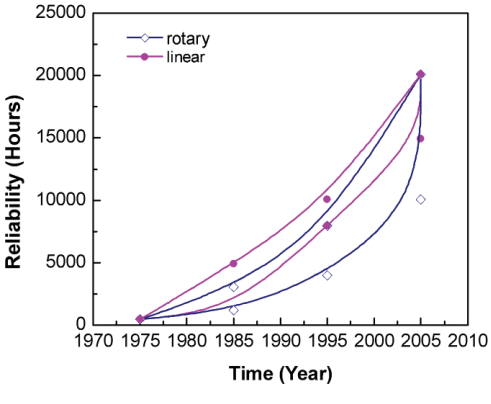

Figure 1. The reliability development of foreign Stirling cryocooler

of the moving coil., The reliability of the moving coil linear Stirling cryocooler reaches 15,000 hours because Thales Cryogenics improved the wear-resistance material of piston. Thales Cryogenics performs a procedure of friction separation at present. Thales Cryogenics expects to work out the best installation position of the cryocooler in thermal imager to reduce the wear rate of the cryocooler piston and improve the reliability of the cryocooler. Thales Cryogenics also improved the controller by the addition of Digital Signal Processing (DSP). The efficiency of improved controller has been improved to greater than 90% from 80%. The cooling capacity of the Thales Cryogenics' linear Stirling cryocooler of has improved to more than 0.3 W. The power consumption of the cryocooler will be reduced and the reliability will be improved owing to the advancement of cryocooler performance.

The Development of Rotary Stirling Cryocooler. It is difficult for the reliability of rotary Stirling cryocooler to exceed 10,000 hours. It is possible for the reliability to exceed 10,000 hours and even 20,000 hours with the introduction of new technology in the design of rotary Stirling cryocooler.

The biggest improvement that Thales Cryogenics has made to the rotary Stirling cryocooler is the adoption of a Super Duplex bearing. The characteristic of the bearing is to shift a part of radial pressure of piston in the axial direction and a double row of ball bearings can bear a larger load. The reliability of rotary Stirling cryocooler by Thales Cryogenics is approximately 10,000 hours.

The Rotary Stirling cryocooler, K508, is a featured product of RICOR of Israel. RICOR increased the reliability of the K508 cryocooler on condition by keeping the appearance and the size of the cryocooler the same. The measures taken by RICOR include improving the bearing and grease, adjusting the distribution of the inner assembly and improving the bearing preload force. The estimated life of K508N reaches 20,000 hours due to these improvement.

The Development of Foreign Stirling Cryocoolers

Figure 1 is based on the data found in Table 1, Table 2 and Table 3. It can be seen that the reliability of cryocoolers has improved greatly since 1990s. Foreign infrared focal plane detectors have been mass-produced since the 1990s because infrared detectors rely greatly on the reliability of cryocoolers. With the development of the third and fourth generation large scale arrays and high resolution infrared detectors, it can be predicted that the reliability of cryocoolers will develop in the following way.

1) High resolution detectors require greater cooling capacity and better adaption to the environment, and require increasingly higher reliability.
2) The introduction of short wave and medium wave infrared detectors with higher working temperature will improve the reliability of cryocoolers greatly.
3) Long life cryocooler will be redefined. It is believed in traditional theory that because of the yawing force effect of the crankshaft and the connection to an electric rotary compressor, long life cryocooler will utilize a linear compressor. The reliability of the RICOR K508N exceeds 20000 hours. As a result, electric rotary cryocoolers of small size, light weight and low power consumption can be of long life. The reliability will improve rapidly.

THE RELIABILITY DEVELOPMENT OF CHINESE STIRLING CRYOCOOLERS

The development of miniature Stirling cryocooler in China started from 1980s. The principle prototype was manufactured in the early 1990s, and the reliability reached hundreds of hours. With the introduction of a foreign cryocooler assembly line by Chinese manufacturers (such as Kunming Institute of Physics and the No. 16 Research Institute of Electronics Department) in the late 1990s to 2000s, the reliability of cryocooler reached 4000 hours. Thermal imagery systems required increasingly high cryocooler reliability after 2000, and the Chinesemanufacturers set out to manufacture tactical miniature Stirling cryocooler with a reliability exceeding 10,000 hours. The massive usage in Chinese infrared detector in engineering after 2010 drove the improvement in cryocooler reliability. The linear Stirling cryocoolers of Kunming Institute of Physics, Shanghai Institute of Technology and Physics and the No. 16 Research Institute of Electronics Department has reached 20,000 hours.

Table 1. The reliability of foreign tactical Stirling cryocooler in the 1980s

Company	Model	MTTF/MTBF	Cooling Capacity 77K@23℃	Weight	type
Signaal (Holland)	U7056	3500h	500mW	1.2kg	linear split of counter pressure
CTI (U.S.)	CM-4	1000 h	1000 mW		Rotation split
	CM-2	1160 h	1000 mW		Rotation integrated
Hughes (U.S.)	7012H	1000 h	1000 mW	1.8kg	linear split of counter pressure
AEG (Germany)	SC025	2000 h	250 mW	1.1kg	Rotation split
CT° (France)	RM2-6I	2000 h	200 mW		Rotation integrated
	LS5-5	2000 h	200 mW		linear split of counterpressure
RICOR (Israel)	K506B	3000 h	300 mW		Rotation integrated
	K526s	1500 h	500 mW	0.9kg	Rotation split
	K523	5000 h	250mW		linear split of counter pressure
Sumitomo (Japan)	SRS2105B	3500 h	500mW		linear split of counter pressure

Table 2. The reliability of foreign tactical Stirling cryocooler in the 1990s

Company	Model	MTTF/MTBF	Cooling Capacity 77K@23℃	Weight	type
RICOR (Israel)	K508	8000h	700mW	450g	Rotation integrated
	K515	4000h	600mW	770g	Rotation split
AIM (Germany)	SL070A	8000h	600mW	940g	Linear dual piston split
Raytheon (U.S.)	7070-260s	4000h	800mW	800g	
L3 (U.S.)	B1000	4000h	1000 mW	1.8kg	
U.S.	LC1056	8000h	800mW	1.1kg	linear split
Thales (Netherlands)	RM2-7i	6000h	300mW	275g	Rotation integrated
	LSF9188	1000h	1850mW	2.4kg	linear split

Table 3. The reliability of foreign tactical Stirling cryocooler in the 2000s

Company	Model	MTTF (hr)	Cooling Capacity 77K@23℃	Weight	type
RICOR (Israel)	K508N	20000	700mW	450g	Overall integrated
	K549	10000	550mW	940g	Rotation split
	K527	30000	130mW	270g	moving magnet linear
AIM (Germany)	SF100A	20000	2000mW	1.6kg	moving magnet linear
Carleton (U.S.)	LC1065	10000	1500mW	1100g	Linear split
Thales (Netherlands)	RM2	10000	400mW	275g	Overall integrated
	LSF9588	20000	650mW	1700kg	moving magnet linear
	UP8497	15000	650mW	600g	moving coil linear
	UP7080	15000	700mW	1550g	moving coil linear

THE ACCELERATED EXPERIMENT OF RELIABILITY

To verify the reliability of cryocooler, massive life tests are required besides the research in single failure mechanisms. Because the life tests of reliability take a long time, the internationally accepted approach is to carry out accelerated life tests to estimate the reliability.

Accelerated life tests increases the stress and make the product fail in short time, but the product failure distribution does not changed. The reliability of cryocoolers in working condition and in storage is estimated. The principles of accelerated life experiment are listed below:

1) The accelerated stress level does not go beyond the designed working capacity of the cryocooler.
2) The typical failure modes found in the accelerated test matches these in the normal life test.

Accelerated life tests fall into the following categories:

1) Temperature cycle. To simulate the working environment, temperature cycling is used to accelerate stress and switch experiment is supplemented. The environment experiment profile of every manufacturer is different.
2) High temperature. The generation of contaminating gas is accelerated and the wear of the piston system is aggravated when the cryocooler keeps working at a high temperature, and the experiment is accelerated. According to the "power-time" function suggested by Miskimins and Kuo, the power consumption is negatively related to the life, and the life of cryocooler will decrease when the power consumption increases. The power consumption increases as the environmental temperature increases. The function can be used to estimate the acceleration effect that high temperature has on the cryocooler life.
3) Increasing the travel of piston. This method is primarily used in linear cryocooler. When the travel of piston is increased, the wear of piston and cylinder is accelerated and the burn-in of the cryocooler is accelerated.

It should be noted that the reliability of cryocooler cannot be shown directly in the accelerated test. It requires an accelerated test with a cryocooler whose reliability is known. A comparison can be made between the cryocooler with the known reliability and the cryocooler under test. The reliability of the cryocooler under test can be estimated from this comparison.

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CONCLUSION

According to the research state of reliability of current Stirling cryocooler, the gap between the reliability of the Chinese cryocooler and the reliability of the foreign cryocooler is being closed. The reliability of the Chinese cryocooler can only be achieved by experimentation and engineering application. The reliability model of the cryocooler and the reliability design are in blank. Because the foreign technology is kept secret and it requires massive experiments to build the growth model of reliability, Chinese institutes need to do a great deal of work about the influence mechanisms of reliability and the acceleration models of reliability. We believe that with further development, the reliability design of Chinese cryocoolers will be put into practice, and new products will be produced.

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