Producibility Of Cryocooler Compressors

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ABSTRACT

This paper describes the high yield rate, the quality process, and the high performance uniformity among the 12 space qualified HEC (High Efficiency Cryocooler) compressors that have been fully assembled and tested over a period of 15 months. The number of compressors produced allows initial SPC (Statistical Process Control) results of process capabilities to be assessed. 100% yield in final assembly as well as in sub-assembly processes and tests have been achieved. Acceptance tests include compression tests and high temperature friction tests to assure frictionless non-wearing operation of the compressors over their wide operating temperature range. A summary of the manufacturing experience of producing small clearance frictionless compressors will be presented. The paper also recommends process enhancements and new testing methods and equipment for future manufacturing.

INTRODUCTION

The HEC compressor was developed by Oxford to supply the pressure source for the TRW High Efficiency Cryocooler[1]. The compressor was a linear motor, flexure spring, true clearance seal, frictionless configuration designed for high efficiency and low mass for space applications.

The compressor was productionised by Hymatic, with the aim of making the compressor more rugged, and also introducing a fully controlled assembly and test process more suitable for repeated and consistent quantity production[2]. In a period of 15 months 12 HEC compressors were built and tested at Hymatic, using new assembly and test processes, and have been delivered to TRW.

To ensure high yield, Hymatic has implemented quality control systems at the component manufacturing stage and at the assembly stage of the compressors. The statistical capabilities of the manufacture and test processes are examined and reported in this paper.

QUALITY PLAN

Formulation

Based on the performance specification and test requirement of the compressor, and drawing on Hymatic's experience in manufacturing frictionless cryocoolers, a Failure Mode Analysis was performed on the compressor design. Critical features for each component part and sub-assemblies were identified. In addition to the general drawing dimensions, Key Features were highlighted on the part drawings to focus attention to areas critical to the successful operation of the compressor. Sub-assembly and final test plans were also drawn up to detail the specific measurements required for the success of each assembly operation. 100% inspection of the Key Features was enforced.

Part Quality

Some component parts were machined in-house and some were sub-contracted. The quality strategies for the two routes were different.

For in-house machined parts, the machine operators were responsible for 100% inspection on all the features of the parts. After machining, the Key Features of the parts were re-inspected 100% by independent inspectors and the results recorded to give objective evidence that the parts comply with the drawing requirements.

For sub-contracted parts, the subcontractors were responsible for the quality of the parts and they submitted their inspection reports of the Key Features to Hymatic. At Hymatic, the Goods Inward Inspection department verified that the Key Features inspection reports were complete and performed random re-inspection to audit the sub-contractor's inspection results.

Sub-assembly and Final Assembly Quality

In a batch production environment it was felt unwise to assume that components that passed the Part Quality control procedure were automatically suitable for assembly. Transit and handling damage can and will occur. Features that would affect the quality of the assembly build were re-inspected immediately before assembly. The result was that only correct parts were assembled.

During each sub-assembly stage specific tests were conducted to measure the degree of success of the sub-assembly. The tests performed at each stage of the sub-assembly are summarized below.

The result of these inter-operation tests was that only good sub-assemblies were allowed to proceed onto the next stage.

Finally the assembled compressors were put through the performance tests specified by the customer.

Inter-Operation Tests	**Assembled spring stack**	**Locked spring stack**	**After bonding piston**	**Compressor tested at high temp.**
Alignment	√	√	N/A	N/A
Stroke	√	√	√	N/A
Friction	√	√	√	N/A
Electrical	√	√	√	N/A
Friction at temp.	√	√	√	√

Figure 1. Sub-assembly tests at each assembly stage

PROCESS CAPABILITY

The disciplined data recording procedure and the automatic data logging feature of the test facility provides objective evidence of the capability of the assembly processes. In excess of 800MB of data were collected for the 12 compressors. The capability of critical processes were summarized below. The data shown applies to the compressor pairs and additional test pieces which were tested under similar conditions; some test results were not used because they were tested at conditions before the parameters were finalized:

Production Yield

The production yield of the 12 compressor pairs was 100% at the final test as well as at all the sub-assembly tests. No re-work was necessary at all assembly stages. The quality plan, the vigorous process design and the attention to detail in assembly workmanship have proved to be effective.

Motor Flux Density

Magnetic flux density in the linear motor air gap affects the driving force available to the motor. The higher the flux density the more efficient is the compressor. The magnetic flux attainable is a function of the magnet material, pole piece material, dimensional control of the motor components and the magnetizing machine.

The distribution of the average flux density in the air gap is shown in Fig 2. The average flux density was measured using a fixed separation ganged search coil averaging the flux density over a fixed distance. The mean of the average flux density was 4.46 mWb-Turn or 0.67 Tesla. The percentage variation of the flux density was expected to be less than 4.45% over +/-3 Sigma or 99.7% of the total population.

Spring Alignment

Two sets of flexure springs suspended the piston. Accurate alignment of the springs was required to ensure that the piston moved along its own axis. It was this coaxiality of movement that ensured frictionless compressors. The spring alignment was measured before and after the alignment settings were locked. The distribution of the linearity of the alignment is shown in Fig 3. The data showed that the locking procedure had little effect on the alignment. The mean alignment error was 3 micron. At the +3 sigma limit, the alignment error was expected to be less than 7 microns. The capability of the alignment process compared favorably with the clearance between the piston and cylinder of the compressor.

	Flux in mWb-Turn
Mean =	4.46
Std Dev =	0.0331
+3 Sigma =	4.559
-3 Sigma =	4.361
% Variation over 6 Sigma =	4.45%

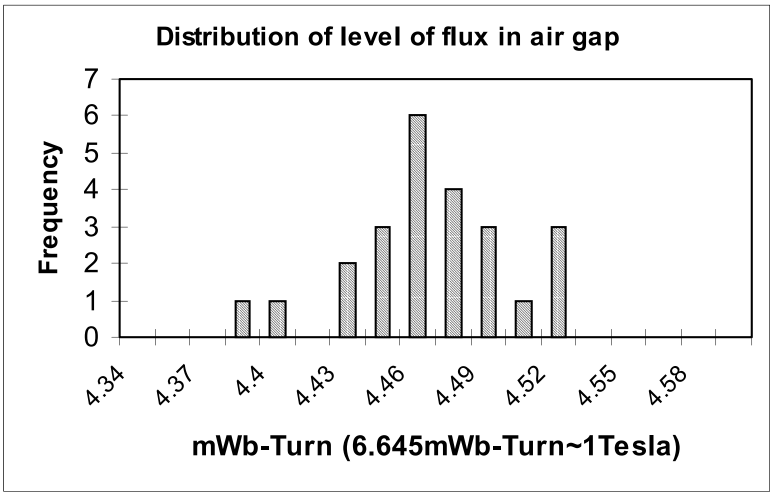


Figure 2. Distribution of flux density in linear motor magnetic gap.

Alignment Error (mm)	Before Locking	After Locking
Mean =	0.00299	0.00302
Std Dev =	0.00118	0.00132
+3 Sigma =	0.00654	0.00697

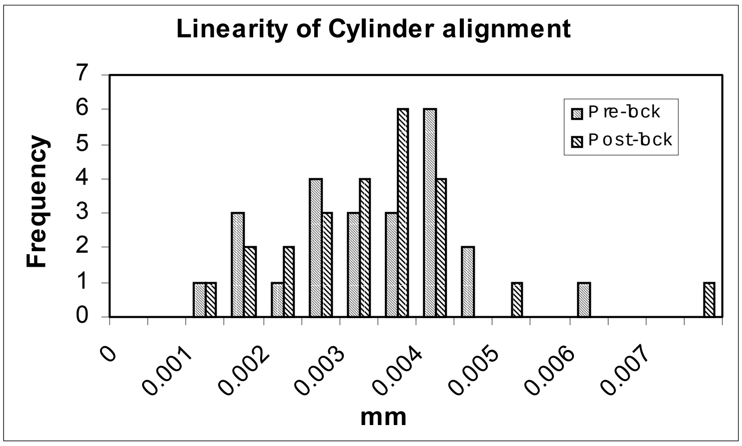


Figure 3. Distribution of spring alignment error before and after locking

Resonant Frequency in Vacuum

Each compressor half was tested for its resonant frequency in vacuum. The result of this test was an indicator of the consistency of the mechanical spring mass system.

The distribution of the resonant frequency is shown in Fig 4. It can be seen from the histogram that there are 2 families of results. This variation was traced to two batches of springs that were used in the 12 compressor pairs. The thickness of the springs within each batch was consistent but the mean thickness values of the two batches were at either end of the tolerance range. The mean resonant frequencies were 37.33 and 38.77Hz for the batch with weak and the batch with strong springs. The corresponding expected variation over +/-3 sigma population was 8.3 and 8.1 Hz. The design of the compressor included a feature to tune the final drive frequency. The small variation of resonant frequency in vacuum was not considered as being significant to the operation of the compressors.

Friction Test At Room Temperature

At different stages of the build (see Fig 1), the integrity of the sub-assemblies was verified by a set of 3 friction tests. The three tests were Stiction Test, Static Friction Test and Ring Down Test. The Stiction Test checked the dynamic friction between the moving parts. The Static Friction Test measured the stick-slip characteristics. The Ring Down Test measured the friction as a function of its damping effect on oscillation of the piston in the cylinder.

Hz	Weak Spring	Strong Spring
Mean =	37.333	38.766
Std Dev =	0.516	0.525
+3 Sigma =	38.879	40.341
-3 Sigma =	35.786	37.190
% Variation over 6 Sigma =	8.3	8.1

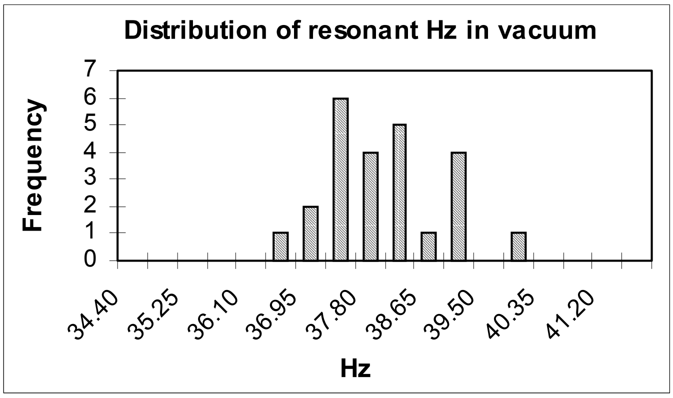
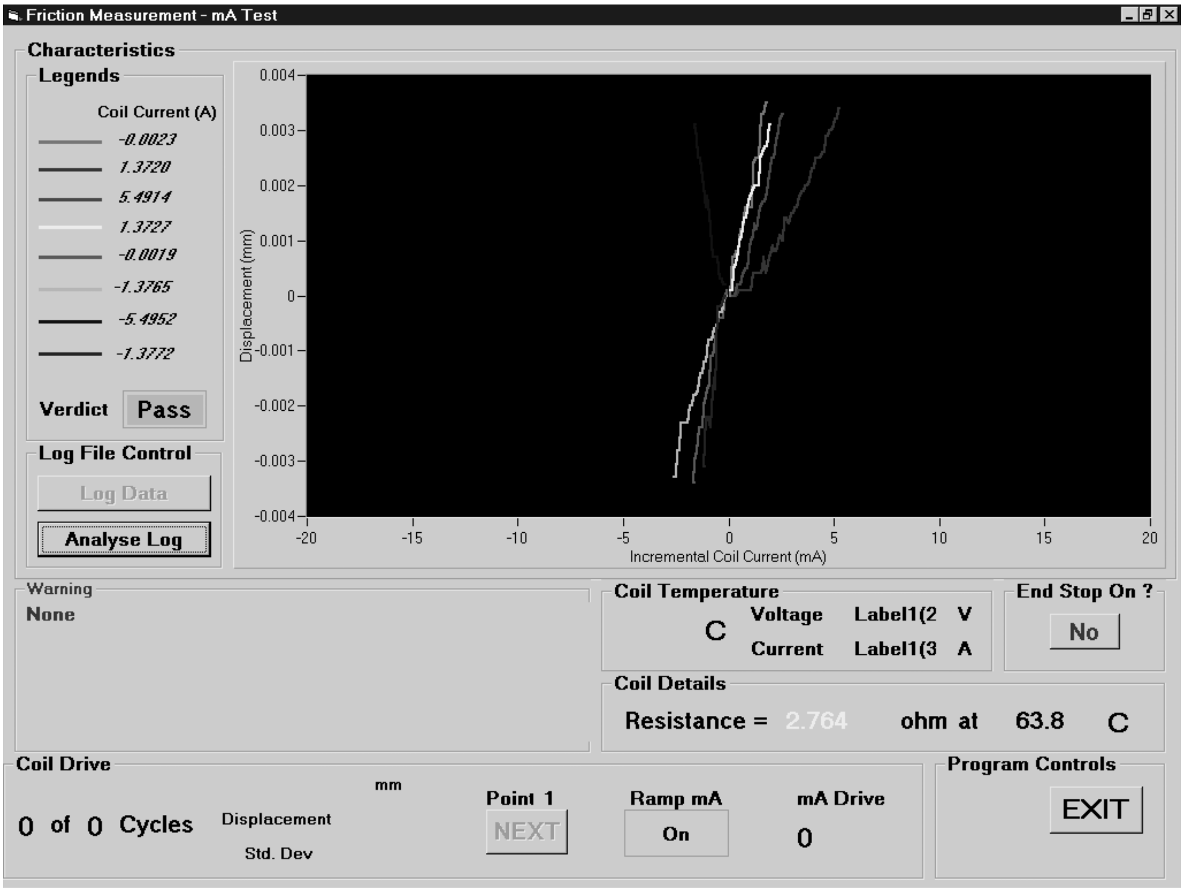


Figure 4. Distribution of resonant frequency of compressor halves



Friction Measurement - mA Test

Verdict Pass

Warning None

Coil Temperature C Voltage Label1(2 V Current Label1(3 A

End Stop On ? No

Resistance = 2.764 ohm at 63.8 C

0 of 0 Cycles

Point 1

Ramp mA On

mA Drive 0

Figure 5. Typical result of Static Friction Test showing the immediacy of movement of the piston on application of a small coil current at 8 positions along the stroke.

All the compressors pass the preset limits of the three friction tests at all stages of the build. No stick-slip was detected at full, quarter and mid stroke positions. A sample result of the Static Friction Test was shown in Fig 5.

Friction Test At High Temperature

To avoid overheating the coil, only the Ring Down Test was used to detect the maximum ambient temperature before friction set in. This temperature was considered an indication of how even was the gap between the piston and the cylinder and it sets the maximum operating temperature limit of the compressor.

The temperature when friction occurred varied from 60ºC to 90ºC. Considering the maximum operating temperature of 50C, there was a healthy minimum margin of 10ºC. However, the large variation was an indication of process variability. Studies were done to correlate the variation with diametrical piston to cylinder clearance and the pressure drop through the clearance as shown in Fig 6 and 7. No correlation was found. Further work is required to identify the factors that limit the capability of the piston and cylinder gapping procedure.

Pressure Swing Of Compressor Half

The peak to peak pressure swing of the compressor halves when discharging into a dead volume was tested at 75% and 90% stroke levels as well as at 10W fixed power. The compressor halves were charged to the final charge pressure of the system and the dead volume was initially tuned to resonate at the system frequency. This test represented the capability of each half to satisfy the functional requirement of the compressor.

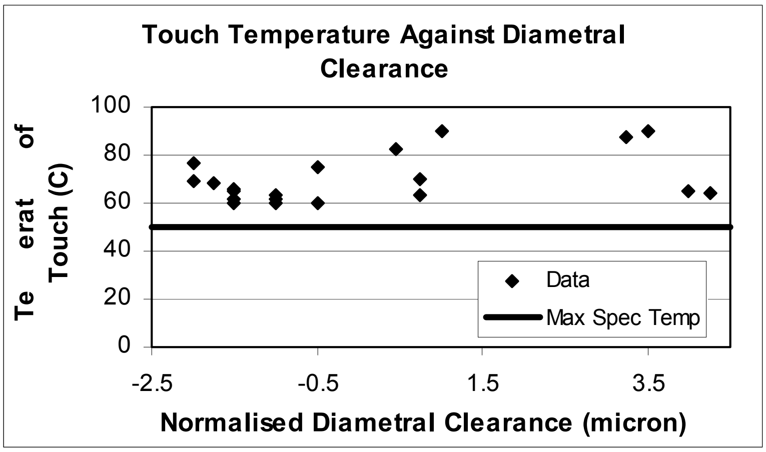


Figure 6. Correlation of temperature at which friction occurs with compressor gap. No correlation evident.

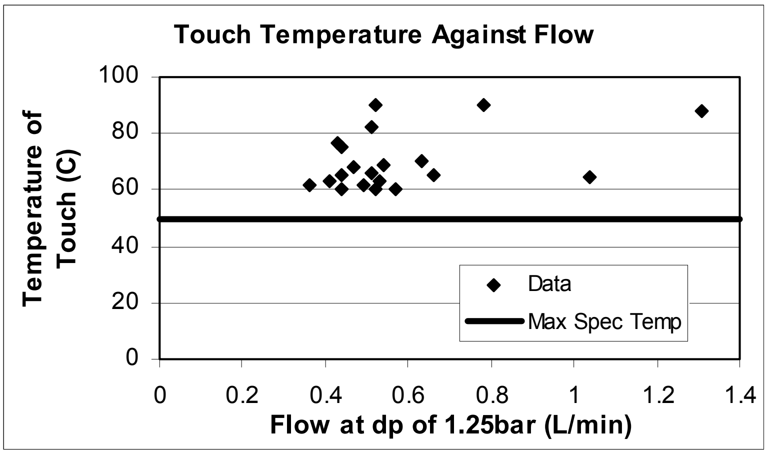


Figure 7. Correlation of temperature at which friction occurs with air flow rate through compressor gap. No correlation was evident.

Fig 8 shows the consistency of the pressure swing obtained. Over +/-3 sigma of the population, less than 11.7 % variation of the 77.01psi mean pressure swing was expected at fixed 10W input power.

Pressure Swing Of Compressor Pair

The test was similar to that of the compressor halves. However, 20W input power and a different representative system test volume were used.

Fig 9 shows the consistency of the pressure swing obtained. Over +/-3 sigma of the population, less than 10.5 % variation of the 72.16psi mean pressure swing was expected at the fixed 20W input power.

MANUFACTURING AND ASSEMBLY EXPERIENCE

The quality audit procedure revealed that not all subcontractors' inspection reports were reliable. It was important not to take data at their face value. Rechecking functional features was key to successful assembly.

Subcontractors needed to be educated on the specific requirements of part features for cryocooler applications. It was through this understanding that the manufacturing personnel improved their part quality. The basic rule of manufacturing engineering to produce the most accurate dimension first and the best finish last must be enforced.

The cleaning and out-gassing procedures for each component must be defined. Particular attention should be paid to blind threaded holes which harbored contamination easily.

Electrical insulation breakdown could be a significant cause of failure if sharp edges adjacent to electrical insulators are not removed. Dragged out fraze and loose metal particles may pierce through thin insulation causing an electrical short

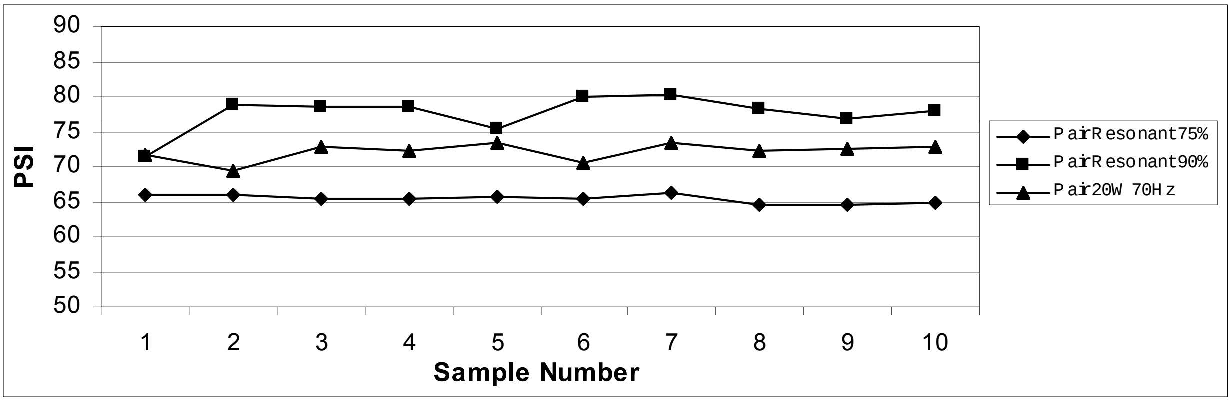


Figure 8. Distribution of peak to peak pressure swing of compressor halves

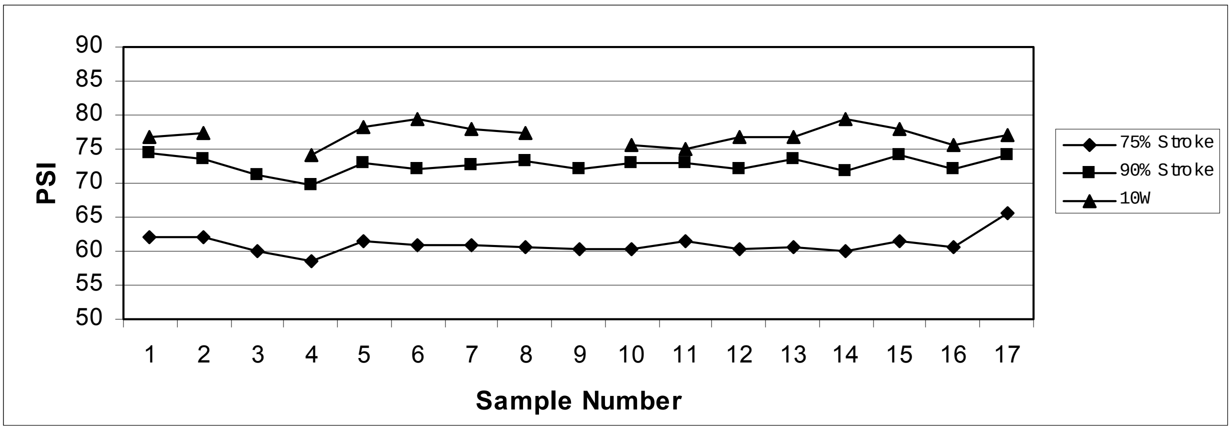


Figure 9. Distribution of peak to peak pressure swing of compressor pairs.

Anaerobic adhesive that is spilt onto an exposed surface must be cleaned off. It would not cure in the presence of air. Epoxy resin was to be preferred.

Automated test and data logging equipment was essential in reducing the test time, improving the test consistency and minimizing human errors.

RECOMMENDED EQUIPMENT

Accuracy of dimensional measurement on piston and cylinder can only be ascertained with the use of non-contact measuring instruments. Frequent calibration and temperature stabilization is needed to overcome thermal drift.

A means of measuring cylindricity, coaxiality and squareness was required to verify the level of success of assembly processes and part quality before final assembly. Hymatic has purchased a Talyrond 265 roundness checking machine and dedicated it for cryocooler manufacturing inside the cleanroom. Significant benefit had been realized with the use of the machine.

CONCLUSION

Statistical evidence confirms that the HEC compressor is a mature and producible design. Through continuous improvement in process design, assembly workmanship, manufacturing equipment and close customer liaison, a batch manufacturing system has been established in Hymatic to produce long life friction free HEC compressors at a consistent quality level to meet the stringent requirement for space application.

ACKNOWLEDGMENT

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