# Square Wave Test for Characterization of Compressor Piston Blowby

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## ABSTRACT

Modern cryocooler linear compressors commonly use clearance seals as the primary sealing mechanism between the piston and cylinder. Such clearance seals are just very narrow non-contacting radial gaps on the order of 5 to 10 microns (0.0002"-0.0004") that limit the gas flow past the piston to a tolerable level. Such clearances are quite demanding to produce and are extremely difficult to measure accurately, even when the piece parts are available before final assembly. One means of testing the gaps is via a blowby test –conducted prior to compressor completion–where the flowrate of gas through the assembled clearance seal is measured as a function of differential pressure applied across the piston. For narrow clearance-seal type gaps, the gas flowrate is proportional to the cube of the gap radial distance, so the blowby test can be a sensitive measure of the initial clearance seal dimensions in a compressor.

Because piston blowby is often an important factor in cryocooler efficiency, and increased blowby can be an important indicator of possible life limiting piston/cylinder wear, having an independent means of accessing blowby in an operational cooler is very desirable. Unfortunately, once a compressor is assembled and sealed into a working cooler, the direct measurement of piston blowby is no longer possible. However, indirect means of qualitatively assessing blowby are possible. One means is the square wave test described in this paper. This test involves driving the compressor pistons with a low-frequency square-wave voltage while simultaneously measuring the piston stroke response over time.

## INTRODUCTION

Most modern pulse tube and Stirling cryocoolers utilize linear clearance-seal compressors involving two pistons working into a common compression volume as illustrated in Fig. 1. With such compressors

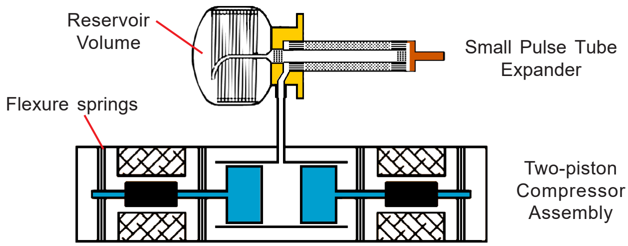


**Figure 1.** Schematic of small pulse tube cryocooler.

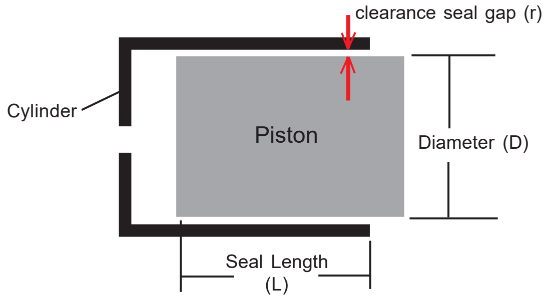


**Figure 2.** Definition of piston and gap parameters.

the piston blowby is basically the sum of the blowby contribution from each piston. This blowby decreases the cryocooler efficiency by directly reducing the peak pressure obtained and represents a work component that directly subtracts from the PV work produced by the compressor. Previous researchers have analyzed the key ingredients of cryocooler compressor efficiency and highlighted the importance of efficiency loss due to blowby.[1,2,3] From the work of Bailey, et al.[1], the total power loss associated with compressing the gas volume can be thought of as being made up of two components: the compression loss and the seal loss due to leakage through the clearance seal. From their studies, as they confirmed using detailed CFD modeling, the leakage flows that occur through clearance seals were found to be entirely within the laminar flow regime over the whole range of operating conditions (strokes and frequencies).

Given the laminar nature of the flow, the instantaneous mass flow rate *dm/dt* through the clearance seal is given as a function of the time-varying pressure difference across the seal $\Delta p$ by the equation:

$$\frac{dm}{dt} = \frac{\pi D \rho_m r^3}{12 \mu L} \Delta p(t) \tag{1}$$

where, as shown in Fig. 2, D is the piston diameter, $\rho_m$ is the mean gas density, $\mu$ the mean viscosity, $r$ is the effective radial clearance of the seal, and $L$ the seal length, which can be a function of piston position, and hence time. In contrast, the swept volume ($\Delta$V) is defined by $\pi D^2 S/4$, where S is the stroke length. If we take the leakage flow rate and ratio it to the swept volume as a measure of the total gas being pumped by the compressor, we get:

$$\dot{m} / \Delta V \propto 1/DLS \tag{2}$$

Equation 2, together with the observation that the clearance gap (r) is pretty much the same for most coolers due to manufacturing limitations, suggests that the seal leakage is likely to be much more important for small coolers where D, L and S are all small in comparison to a larger cooler. This greatly increases the importance of managing and measuring the clearance seals of small coolers.

In response to this importance, the focus of the work described in this paper was on developing a means of characterizing the relative clearance seal leakage of small linear pulse tube compressors after final assembly and sealing. As a confirmation of the effectiveness of the developed approach, a number of seal blowby characterization tests were conducted using various Lockheed Martin micro pulse tube coolers,[4,5,6,7] an example of which is shown in Figure 3.

**Figure 3.** Lockheed Martin micro pulse tube cryocooler

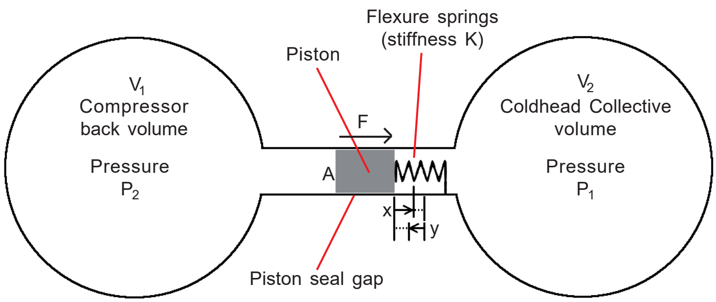


**Figure 4.** Simplified model of pulse tube compressor.

## THE SQUARE WAVE TEST PROCEDURE

Given a sealed cryocooler assembly with no internal instrumentation except piston position sensors, the challenge is to achieve an independent measure of the gas blowby. The approach described here involves using the time-constant of piston position decay following a square-wave applied force to the piston...the applied force being introduced via a square-wave applied current or voltage to the compressor drive coils.

From a modeling perspective, the test procedure involves the application of a square wave current into a linear compressor with a piston separating two volumes of gas. For a typical two-piston compressor, the two pistons just act in parallel, and thus are treated in this discussion as just a single piston between the two gas volumes. One volume, V1, is the combined back volume of the compressor; the second volume, V2, is the combined volume of the cold head and transfer line, plus the inertance tube and reservoir volume.

An applied square wave current is essentially a square wave applied force, with the force defined by the compressor motor's magnet circuit. Two other forces acting on the piston are 1) the net pressure force (P1 -P2) times the area (A) of the piston, and 2) the restoring mechanical spring force associated with the flexure springs supporting the piston. These are illustrated earlier in Fig. 1 and schematically in Fig. 4.

When the positive square wave current is first applied, there is an instantaneous force (F) applied to the piston. With no immediate leakage, the piston moves over to a point X where F equals the sum of the spring force and pressure force. The spring force is defined by the stiffness of the flexure springs ($F_s$=kx), and the gas force is defined by pressure differential $F_p=(\Delta P_1-\Delta P_2)\cdot A$.

Thus:

$$F = (\Delta P_1-\Delta P_2)\cdot A + Kx \qquad \text{or} \qquad x = [F- (\Delta P_1-\Delta P_2)\cdot A]/K \tag{3}$$

$\Delta P_1$ and $\Delta P_2$, initially zero, change by the compression and expansion caused by the delta volume change of volumes $V_1$ and $V_2$ caused by piston motion (x) and the area of the piston (A). Now with time, the differential gas pressure leaks through the piston clearance seal resulting in the net pressure force ($P_1$- $P_2$) going to zero with a time constant associated with the size of the piston gap leakage. During this time the piston motion X increases to the point where the F = kx, (i.e. x = F/k); we define this as point y =0.

### Piston Return Stroke

When the squarewave current is now returned to zero, we jump to a new instantaneous equilibrium with:

$$0 = (\Delta P_1-\Delta P_2)\cdot A + Ky \qquad \text{or} \qquad y = [(\Delta P_2-\Delta P_1)\cdot A]/K \tag{4}$$

where (y) is the instantaneous return stroke and $\Delta P_1$ and $\Delta P_2$ are again defined by the compression/ expansion caused by the piston motion (y) and the area of the piston (A).

Now with time, the differential gas pressure leaks through the piston clearance seal resulting in the net pressure force ($P_1$-$P_2$) going to zero with a time constant associated with the size of the piston gap leakage.

## SQUAREWAVE TESTING OF LOCKHEED MICRO PT CRYOCOOLERS

To test the efficacy of the proposed square wave test, three different Lockheed Microcoolers that exhibited various levels of blowby during component-level testing were electrically integrated with the

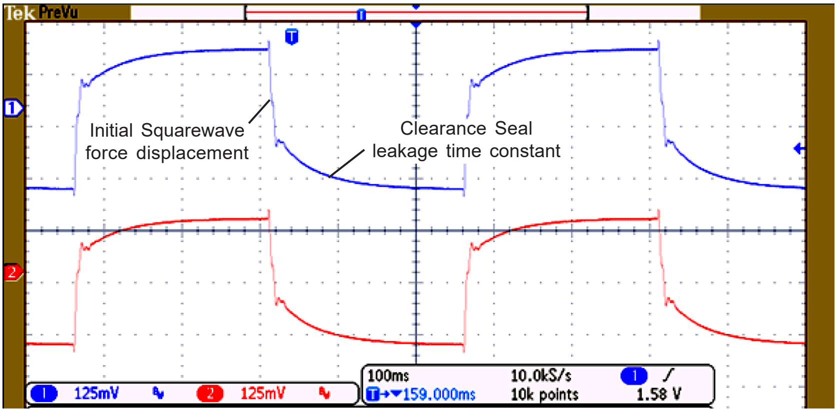


**Figure 5.** Typical Lockheed compressor piston motion response to a square-wave voltage drive.

necessary square wave drive electronics. These were fully welded coolers (compressors plus their PT expanders), thus preventing the use of component-level DC blowby flow testing at this point.

The test setup included a digital oscilloscope for viewing and recording the compressor position-sensor signal as a function of time, and a variable frequency function generator to drive the cooler's dual piston power amplifiers with a squarewave voltage signal. The drive frequency and voltage level were selected experimentally so as to yield an easily observed piston motion decay trace. Figure 5 displays a typical trace taken with a 2-Hz squarewave drive voltage into the compressor amplifier with a piston motion level of about 50 % of full stroke. This is very far away from (much lower than) the cooler's drive resonant frequency of around 130 Hz.

In the recorded traces in Fig. 5, one sees a brief oscillatory transient (~160 Hz) in response to the initial square wave input, followed next by the logarithmic decay of the pressure through the clearance seal. Without a comparison, the decay curve in Fig. 5 is merely indicative of the gradual pressure decay associated with gas leakage through the clearance seal of this cooler. However, a change in this time-constant of decay would be indicative of changed blowby and could be a valuable measurement during, for example, a cooler life test or long-life operation of the cooler.

## Intercooler Comparison

To understand the ability of the method to discriminate unit-to-unit variabilities in compressor clearance seals, the test setup was next used to gather comparison data between coolers (EM and FM2) with suspected differences in their blowby characteristics. As shown in Fig. 6, the square wave test pointed to a clear difference in the blowby decays of the two coolers...FM2 being better (lower blowby indicated by a longer decay time). In an additional test, a new FM3 cooler with exceptionally low blowby in component-level testing was measured.

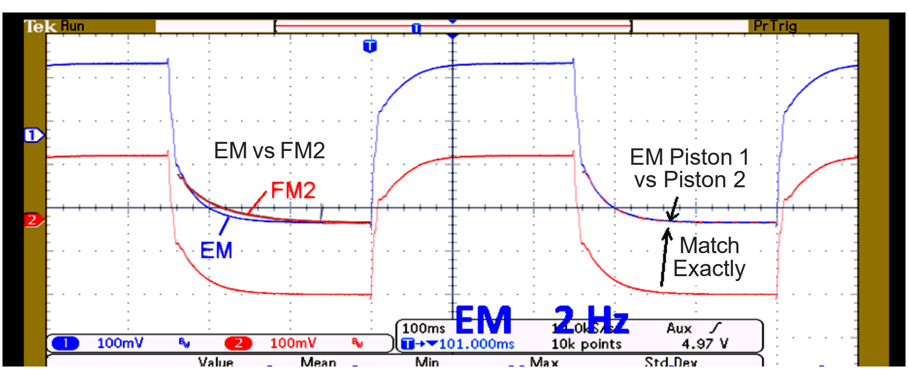


**Figure 6.** Typical Lockheed compressor piston motion response to a square-wave voltage drive.

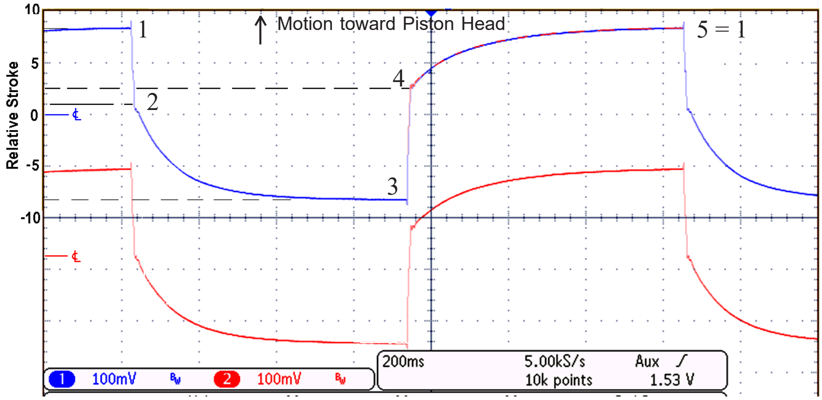


**Figure 7.** Compressor piston motion response of Lockheed cooler FM3 to 0.7 Hz square-wave voltage drive; numbers denote key curve inflection points.

As shown in Fig. 7, the square-wave data for FM3 indicate dramatically reduced blowby compared to both the EM and FM2 coolers...so much better that the squarewave drive frequency had to be slowed down to 0.7 Hz to provide sufficient time for the longer decay time-constant to fully display.

## SQUARE WAVE FORCE-DISPLACEMENT RESPONSE PLOT

To better understand a cryocooler's squarewave response plot, such as that shown in Fig. 7, it is useful to replot the data in the form of a nondimensional force versus displacement plot. This plot format allows the spring constant of the flexure springs and compressed gas to be explicitly displayed together with any net DC pressures that might develop within the compressor and any offsets that might develop to piston motion centering.

Examining the plot shown in Fig. 7, we note the following:

- Point #1 is after dynamic gas pressure has bled off, so it is at zero dynamic gas pressure and maximum positive flexure stroke.
- Point #2 is immediately after the applied force reversal, where the applied force is balanced by maximum dynamic gas pressure plus an intermediate flexure spring force
- Point #3 is again after the dynamic gas pressure has bled off, so it is at zero dynamic gas pressure and maximum negative flexure spring stroke (maximum negative spring force).
- Point #4 is again after the applied force reversal, where the applied force is balanced by maximum dynamic gas pressure plus an intermediate flexure spring force.
- At all points between points 2 and 3 and between points 4 and 1, the total of spring force + dynamic gas force + any net DC pressure force must equal the constant force applied by the square wave. For convenience, we describe the total force reacting a positive square wave input as a positive "reaction" force.
- Between points 1 & 2 and points 3 & 4, the piston is rapidly accelerating and is in a non-equilibrium state with respect to the applied squarewave forces.

### Force Displacement Curve Generation

Referring to the relative force deflection plot in Fig. 8, we start by extracting the flexure spring constants from Fig. 7 by noting that the maximum flexure spring forces (Relative force = +/- 1) occur at the stroke displacements corresponding to points 1 and 3 (i.e., relative oscilloscope strokes of +/- 8). Using a linear spring constant, which is relatively accurate for these Lockheed flexures, we can plot a straight line between the points 1 and 3 as shown in Fig. 8. This represents the total flexure spring force plus any net DC gas pressure force that might exist due to differential pumping (unequal flow) during compressor operation; in Fig. 8, this DC force offset is zero, as the true center position of the pistons during the test corresponds well with the zero-force intercept of the spring-constant curves.

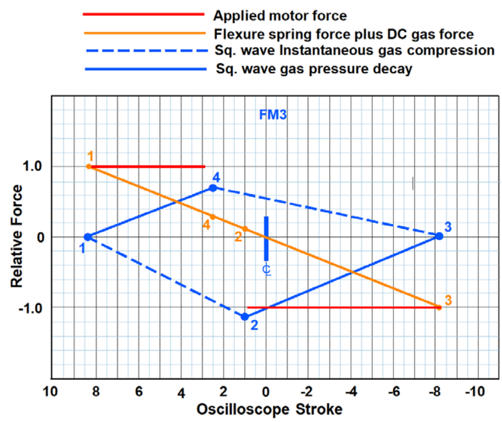


**Figure 8.** Squarewave force-displacement response plot for Lockheed cryocooler FM3.

Next, one can plot the dynamic gas pressure versus stroke curves by first noting that the dynamic gas pressure is zero at the maximum stroke points 1 and 3 and minimum/maximum at points 2 and 4. The strokes corresponding to points 2 and 4 are extracted from the recorded oscilloscope stroke plot (Fig. 7). Points 2 and 4 on the force-displacement plot (Fig. 8) are then located at these strokes using the gas force necessary when summed with the flexure force to react the total applied squarewave force (total to relative forces of +/- 1.0).

Examining the pressure/stroke plot helps explain the oscilloscope plot and provides further insight into the clearance seal operation. In Fig. 7, the short length of the 1-2 drop after the input force (square wave) reversal implies that the pressure built up very rapidly to halt the piston motion with minimal stroke. This relatively fast pressure buildup from 1 to 2 is seen in Fig. 8, in contrast to the more modest reverse pressure buildup from 3 to 4. From the oscilloscope notes in Fig. 7, we see that this 1 to 2 compression took place when the piston was in the forward stroke end of the cylinder for this cooler.

Looking next at the taller 3-4 rise (larger stroke from 3 to 4) after the input force (square wave) reversal, we associate this with a more gradual pressure buildup with stroke, i.e. a more leaky piston in this direction. We note that this compression takes place when the piston is in the back stroke end of the cylinder for this cooler.

In looking again at the oscilloscope plot (Fig. 7), it is clear that the 2-3 bleed-down is with the piston in the back (leakier) position, whereas the 4-1 bleed-down occurs with the piston in the front (better sealing) position. For FM3 it is seen that the bleeddown time-constant is definitely longer for the 4-1 section, which agrees with the step-length differences and 4-1 pressure buildup slope in the force-displacement plot.

This modest change in blowby with piston position is not unexpected with FM3, as it has a very tight clearance seal as noted by comparing its pressure-decay time-constant with that of FM2 and noting the time-scale differences in the plots; FM3 is using a 0.7 Hz square wave as opposed to a 2 Hz square wave for FM2. Given the cubic dependency of blowby flowrate on the clearance gap, it is not surprising that the much smaller gap cooler shows a greater variation in blowby flow along the length of the cylinder due to typical manufacturing variabilities.

## SUMMARY AND CONCLUSIONS

Because compressor piston blowby can be an important factor in cryocooler efficiency, and increased blowby can be an important indicator of possible life limiting piston/cylinder wear, having an independent means of accessing blowby in an operational cooler is very desirable. This development effort, executed in support of Lockheed microcoolers for the JPL Psyche Project, has identified a squarewave test as a potentially very useful tool for characterizing fully assembled coolers at any point in their life cycle. The described squarewave test has now been adopted as a standard test to confirm the stability of blowby attributes of Lockheed Martin microcoolers during their qualification test sequence.

## ACKNOWLEDGMENTS

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## REFERENCES

1. Bailey, P.B., Dadd, M.W., Reed, J.S., Stone, C.R., "Gas Spring Losses in Linear Clearance-Seal Compressors," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 345-352.
2. P. Bradley, M. Lewis, R. Radebaugh, et al., "Evaluation of Total Pressure Oscillator Losses," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 353-360.
3. S. Jacob, R. Karunanithi, J. Kranthi Kumar, et al., "Evaluation of Mechanical Losses in a Linear Motor Pressure Wave Generator," *Advances in Cryogenic Engineering*, AIP Conf. Proc. 1434, American Institute of Physics (2012), pp. 1226-1233.
4. Olson, J., "CubeSat-Sized Space Microcryocooler," 33rd Annual AIAA/USU Conference on Small Satellites (2019). https://digitalcommons.usu.edu/smallsat/2019/all2019/120/
5. McKinley, I., Johnson, D., and Rodriguez, J., "Characterization Testing of Lockheed Martin Standard Micro Pulse Tube Cryocooler," *Cryocoolers 19*, ICC Press, Boulder, Colorado (2016), pp. 75-84.
6. McKinley, I., Hummel, C., Johnson, D., and Rodriguez, J., "Characterization testing of Lockheed Martin high-power micro pulse tube cryocooler," *Advances in Cryogenic Engineering*, IOP Conf. Series: Materials Science and Engineering 278 (2017) 012008 doi:10.1088/1757-899X/278/1/-12008.
7. McKinley, I.M., Mok, M.A., Johnson, D.L., and Rodriguez, J.I., "Characterization Testing of Lockheed Martin Micro 1-2 Cryocoolers Optimized for 220 K Environment," *Cryocoolers 20*, ICC Press, Boulder, Colorado (2018), pp. 71-80.
8. McKinley, I.M., Mok, M.A., and Rodriguez, J.I., "Characterization Testing of Space-Flight Lockheed Martin Micro 1-2 Cryocooler for the Mapping Imaging Spectrometer for Europa," *Cryocoolers 21*, ICC Press, Boulder, Colorado (2021), pp. 135-142.