Design and Development of a Miniaturized Double Latching Solenoid Valve for the Sample Analysis at Mars Instrument Suite

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Abstract

The development of the in-house Miniaturized Double Latching Solenoid Valve, or Microvalve, for the Gas Processing System (GPS) of the Sample Analysis at Mars (SAM) instrument suite is described. The Microvalve is a double latching solenoid valve that actuates a pintle shaft axially to hermetically seal an orifice. The key requirements and the design innovations implemented to meet them are described.

Introduction

This paper outlines requirements, design and development activities of the SAM Microvalves. The SAM instrument suite will be an integral part of the Mars Science Laboratory rover, and the Microvalves will control the gas flow within the SAM instrument suite.

There are 44 in-house Microvalves in SAM, as well as several Microvalves supplied by the sole outside provider of this technology. The decision to develop and build in-house Microvalves was primarily based on past delivery performance of the outside vendor coupled with the high number of valves needed for this mission. Additionally, improvements in mass and reliability were goals of this design effort.

Background

NASA's Goddard Space Flight Center has used Microvalves on several missions in the past (e.g. Galileo, Cassini/Huygens), but never in the quantity required for SAM. Over the past several decades, only one vendor has been able to meet the difficult requirements for the Microvalve, but this vendor has had difficulties meeting delivery schedules. Due to the large number of valves required for SAM, the decision was made to develop an in-house design.

The effort began as an Internal Research and Development project in 2004, and is currently in the flight qualification phase.

Driving Requirements

The primary requirement for the Microvalve is the leak rate. The valve is required to have a helium leak rate across the valve seat and through the outer case of less than $1x10^{-10}$ atm.cc/sec. This drove the design of the pintletip as well as the use of bellows to isolate the gas flow. Also, the materials for the components in the gas flow must be chemically inert so they do not influence the scientific measurements.

Another key requirement was that the valves must be able to survive the qualification temperature range of -60°C to +225°C, and be capable of operation from -40°C to +195°C. This requirement further limited material selection.

In order to reduce mass over current technology, the valves were designed to be welded into their respective manifolds as opposed to a bolted configuration. This requirement drove the design of the "floating" pintletip, as well as the use of an explosion welded Inconel to Titanium bellows housings.

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Since there are a several Microvalves supplied by an outside vendor used on SAM, there was a requirement that the in-house Microvalve operate of the same drive circuitry. This requirement drove the design of the solenoid, as well as the position sensor.

Microvalve Design Overview

A Microvalve is a double latching solenoid valve that actuates a pintle axially to hermetically seal an orifice to control gas flow. A permanent magnet latches the valve in either the open position or closed position with the power off, and a solenoid is energize to change the state of the valve.

In order to achieve the required leak rate, a diamond turned Vespel pintletip is pressed into a lapped and polished titanium valveseat when the valve is closed. The load is applied to the pintletip via a pintle shaft. The load on the pintle shaft is generated by a stack of disc springs that are compressed by an armature. The armature compresses the disc springs when it is magnetically latched in the closed position by a permanent magnet. The amount the disc springs are compressed is controlled by adjusting the gap under the armature that is present at the moment the pintletip first contacts the valveseat. This gap will be closed by the magnetic force of the permanent magnet. The adjustability is discussed in a later section.

A bellows is used to isolate the sample gases and obtain the outer case of leak rate of less than $1x10^{-10}$ atm.cc/sec. The bellows are made of SS321 and are electron beam welded at each end to Inconel 718. The bellows were designed to have a low spring rate because the force generated by the bellows when the valve is in the open state acts against the magnetic latching force that holds the valve open.

To control the magnetic flux path (see Figure 4), alternating rings of Inconel and Hiperco are brazed together and then machined on a lathe to allow for a sliding fit with the armature. The brazing compound used was selected to be below the annealing temperature of Hiperco so the brazing process would not degrade the performance of the assembly.

To reduce friction, both the brazed assembly and the armature are coated with Dicronite, a modified tungsten disulfide dry lubricant. Additionally, the armature and the pintle shaft are nickel coated to prevent similar metals from having a sliding contact surface.

Specifics of the pintletip design, the solenoid design, and the adjustability feature are discussed in more detail in later sections.

<u>Valve Specifications</u>
Mass: 20 grams
Height: 35.5 mm (26.5 mm above manifold surface)
Diameter: 14.73 mm
Power: 18 volts (Since the valve operates on a pulse from a capacitor, voltage is the constraint)
Helium Leak Rate (valveseat): $< 1x10^{-10}$ atm.cc/sec (instantaneous), $2x10^{-9}$ atm.cc/sec (steady state)
Helium Leak Rate (case): $< 1x10^{-11}$ atm.cc/sec
Operational Temperature Range: -60°C to +220°C
All materials in gas flow are chemically inert
Valve Orifice (diameter): 1.778 mm
Pintle Travel: 0.762 mm
Actuation Time: < 1 millisecond

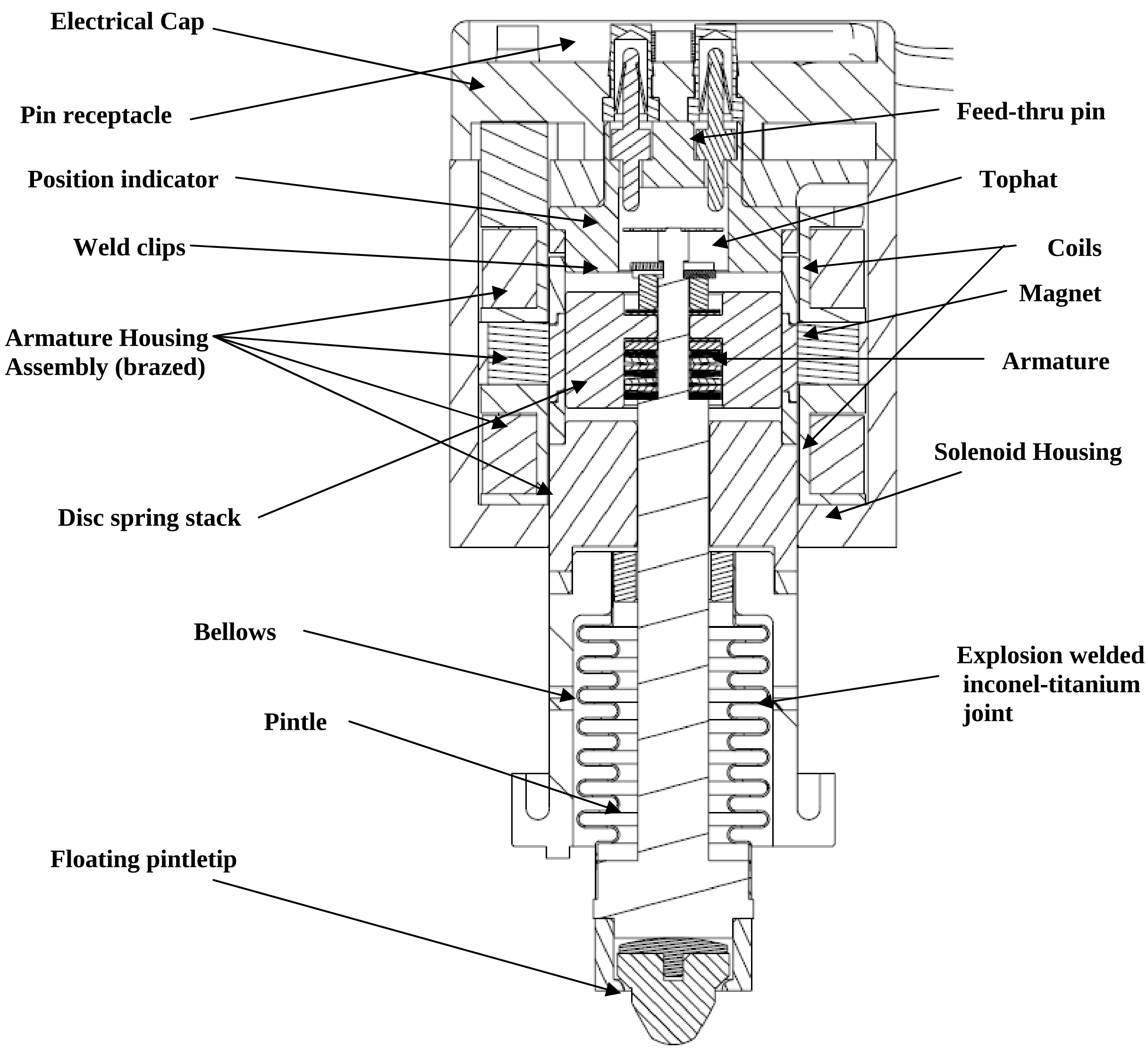

Figure 1 - Microvalve Cross Section

Floating Pintletip

The pintletip for the Microvalve is made from Vespel 22 due to the inert nature of the material, as well as the high operational temperature of Vespel. The part is fabricated on a lathe to the rough dimensions, and then finished on a diamond turning machine to impart a curved surfaced upon the 60-degree cone as shown in Figure 2 (the outside line represents the rough cut part, with the inside line representing the finished, diamond turned part). By creating a curved surface, the pintle tip will "self seat" when pressed into the cone shaped valveseat like a ball in a cone.

Through experimentation it was determined that a radius of curvature of 0.381 cm (0.15 in) was ideal. After the pintletip is diamond turned, it is hand polished with an extremely fine polishing cloth. Each pintletip is screened to ensure the required leak rate can be achieved. It should be noted that the leak rate of less than $1x10^{-10}$ atm.cc/sec is the instantaneous leak rate, and that the Vespel will permeate helium at a leak rate of about $2x10^{-9}$ atm.cc/sec when subjected to helium for an extended period of time (between 5 to 30 minutes).

In order to facilitate the “self seating” action, the pintletip is free to rotate about all three axis, and free to translate in two directions, with the only constraint being the movement along the axis of travel (the Z-axis as shown in Figure 3). The pintletip “floats” in the pintle collar, which is welded to the pintle shaft. The backer plate applies the load from the pintle shaft when the valve is closed, and the plate itself has a curved surface to allow for rotation as the pintle seats itself into the valveseat. The “floating” feature also allows for some misalignment between the axis of the pintle shaft and the axis of the conical valveseat. This is critical since the valveseat is part of the manifold, and the valve is welded into the manifold, which limits alignment capabilities.

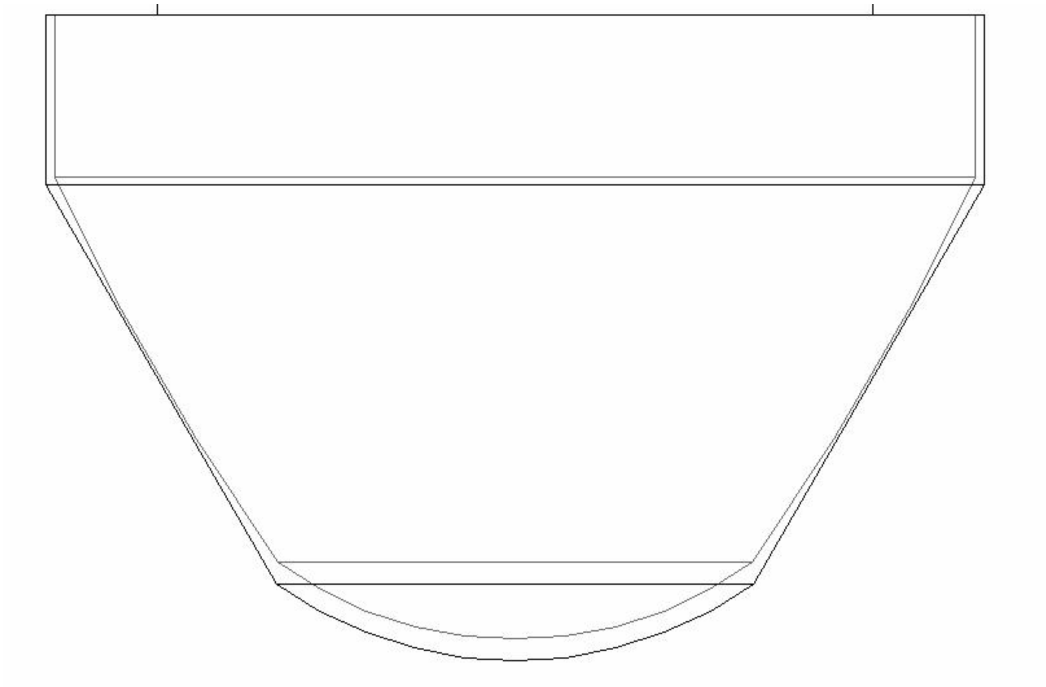

Figure 2 - Pintletip Profile

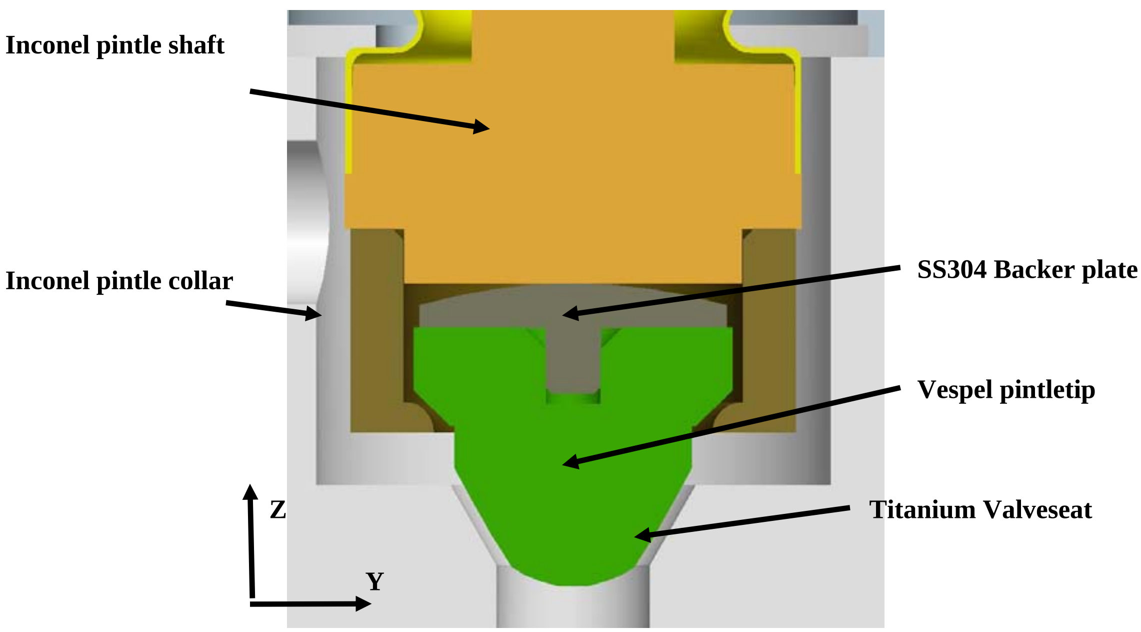

Figure 3 - Floating Pintletip Cross Section

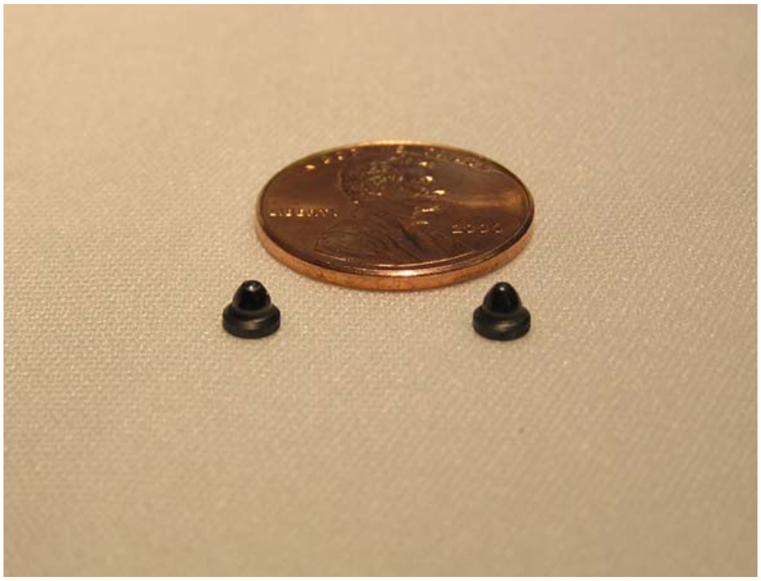

Figure 4 - Sample Pintle Tips

Solenoid Design

The solenoid consists of two coils wound with H-APTZ magnet wire, a radially magnetized Samarium Cobalt magnet, and a Hiperco 50A housing (see Figure 5). The flux path shown in Figure 4 is for the valve in the closed position. The magnet allows for the valve to remain either open or closed with no power supplied to the solenoid. The solenoid is energized by the discharge of a capacitor, and the valve changes state in less than 1 millisecond.

One of the key features of the in-house design is that the solenoid is removable. The ability to replace a solenoid without replacing the whole valve allows for increased reliability in the welded design. If a solenoid were to fail during acceptance testing or any pre-launch operations, the faulty solenoid could be easily swapped out for a new one without machining the valve out of the manifold.

To increase the durability of the coils in the solenoid they are encapsulated with Duralco 4460.

The bobbins that the coils are wound around are ultrasonically machined out of Magnesia partially stabilized Zirconia. This process allows for tolerance control within 0.0254 mm (.001 in) since the ceramic material is machined in the hardened, not green state. The material is very strong, has an extremely high dielectric strength, and has a compatible CTE for the required temperature range.

The wires for each coil are terminated at copper pins by laser welding. The pins are supplied bonded into glass barrels with Kovar sleeves, and these assemblies are bonded into the towers on the ceramic top bobbin.

Another feature of the solenoid design is that the coils can be run either in parallel for redundancy, or in series to reduce the require size of the capacitor to change the valve state. The only change necessary to switch the mode of operation is a change in the wiring of the electrical cap that interfaces with the wiring harness to the drive circuitry. For SAM, the coils are run in series.

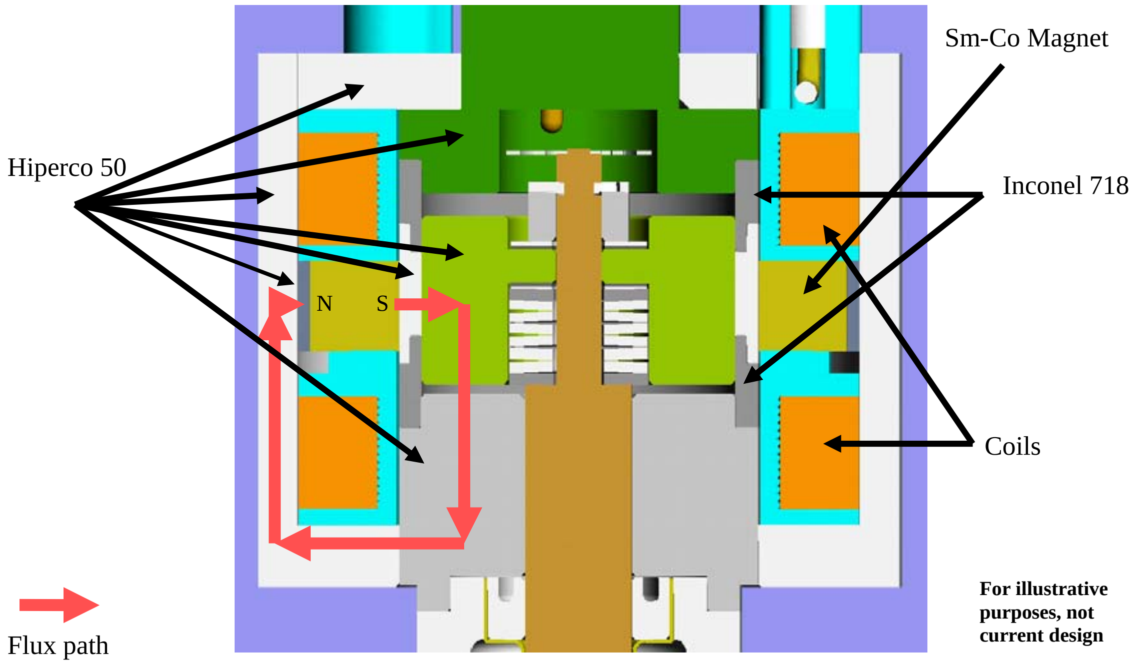

Figure 5 - Solenoid Cross Section

Adjustability for Tolerance Stack-up

Since the components of the Microvalve are small, the tolerances of standard machining become more obvious as a percentage of overall dimensions. For example, on the pintle backer plate shown in Figure 3, the shaft that aligns the part to the pintle tip is only 0.4064 mm (0.016 in) in diameter. The standard tolerance of ±0.127 mm (0.005 in) would be over 50% of the overall dimension! While tolerances in the range of 0.00254 mm to 0.0127 mm (0.0001 in to 0.0005 in) are achievable, they come at a cost. In order to achieve meet the design intent and keep cost relatively low, most tolerances were set to 0.0254 mm to 0.0508 mm (0.001 in to 0.002 in).

The downside is that those tolerances still result in variation from valve to valve during assembly. For the disc springs to apply the correct load to the pintle shaft when the valve is closed the amount the disc springs are compressed must be controlled to within 0.0254 mm (0.001 in). Therefore there has to be adjustability to control the amount of compression. Figure 5 shows how adjustment shims are used to increase or decrease the gap. Each stack of disc springs is calibrated so that the amount of compression required for a desired force is known within 0.0127 mm (0.0005 in).

The measurements shown below are taken during assembly, and the adjustments are made for each valve. After the adjustments are made, weld clips (not shown in Figure 6) are tack welded into place, and the valve is actuated and leak checked to verify the performance. Once verify, the weld clips are permanently welded into place and the tophat is welded onto the valve.

Position Sensor

The Microvalve is designed to have a resistance based position sensor (shown in Figure 1). A flexure contacts a pin when the valve is in the open state and creates a path to ground though the valve case. This design was selected because of the requirement that the valve use the same electronics as current technology. That meant that there was only one wire to use, and that position sensing circuit was based on a resistance measurement.

- h_{gap} controls the amount the disc springs compress
- By measuring h_{arm}, d_{cavity}, and d_{arm} you can determine h_{gap}
- h_{gap} can be controlled by moving the shims (SS304) from on top to below the armature and vice versa

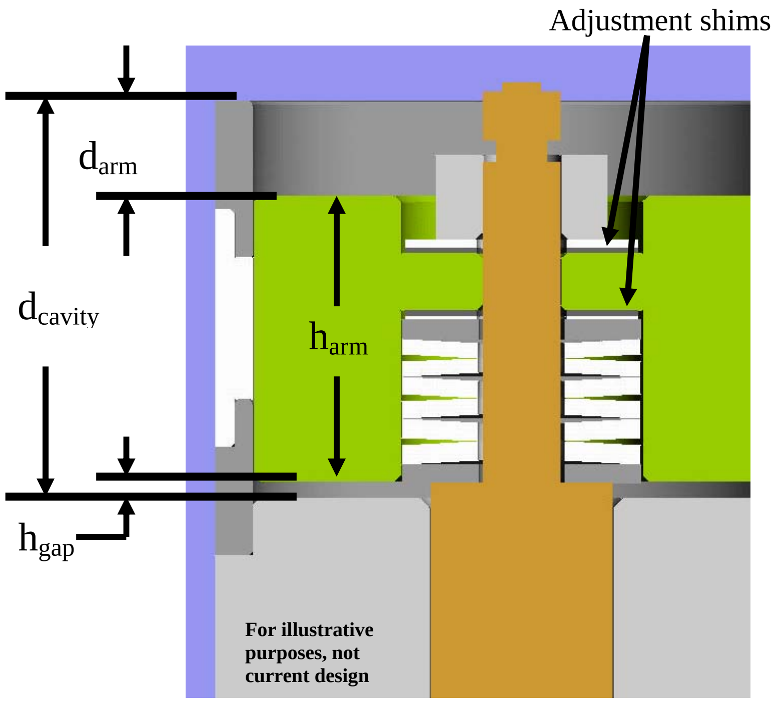

Figure 6 - Disc Spring Compression Adjustability

However, a recent failure with several of the flexures themselves has caused this feature to be removed from the current design used on SAM. The project was not depending on position knowledge for any of the command sequences, and would only use the knowledge for diagnostics. Therefore, due to the extremely tight schedule for SAM, the decision to remove the flexure was reached easily.

It is known that the flexures yielded during actuation, but the exact cause is not yet known. The flexures are designed to see 0.0762 mm (0.003 in) of deflection when the valve is open. Life tests were performed on the flexures where they were deflected 0.127 mm (.005 in) for 10,000 cycles followed by an additional 1,250 cycles at 0.1778 mm (0.007 in) of deflection with no yielding or decrease in reactionary load (~.22 N @ .1778 mm deflection).

One possible cause could be an overshoot of the pintle shaft during the opening of the valve where the flexure would see excessive deflection before settling to the static position. However, preliminary testing indicated there is less than 0.0254 mm (0.001 in) of overshoot, which would not explain the yielding.

Another issue to be investigated is that the valve actuates in less than 1 millisecond, and the shock event may be affecting the flexure. The rate of deflection during the life test performed was so slow it could be considered quasi-static.

Due to the schedule for SAM, this means that there will be no position indicator. However, alternate methods for determining position with just one wire are currently being investigated for future use. One method would be to measure the change in inductance of the top coil that would result from the movement of the armature. Another method would look at the back EMF present when the valve is commanded to close and see if it differs depending on the current state of the valve. For example, is the back EMF higher when you command a valve closed that is already closed than it is if was open?

Testing

The first batch of four (4) Qualification Valves has successfully completed both the vibration and thermal vacuum portion of the qualification test program.

The vibration test consisted of a pre low level sine sweep, a 14.1-grms GEVS specification random vibration, a 60-g sine burst, and a post low level sine sweep.

The thermal vacuum test was run as follows:

- Eight cycles from -60°C to + 225°C at a hard vacuum; the valves were cycled 5 times at each extreme and leak testing
- Eight cycles from -60°C to + 225°C in a CO_2 atmosphere at 10 kPa (100 mBar); the valves were cycled 5 times at each extreme and leak testing

The failure with the position sensor was discovered during the TV testing, so the life test was not run on this batch of valves.

A second batch is about to begin its qualification testing as soon as possible. This batch will undergo the full suite of tests, including life testing. The random vibration levels will be higher since the test levels have been updated by the project, but the increased energy is at frequencies low enough not to be a concern.

Additionally, a multitude of component testing was performed over the last two years, including, but not limited to: thermal cycling of the solenoids followed by high pot testing, life testing of the bellows, pressure testing of the bellows, life testing of the disc springs, thermal cycling followed by strength testing of the brazed joints, strength testing of weld samples for all welded joints.

Conclusion

The Microvalve has gone from a research and development effort to a flight design in the past three and a half years. The first 19 flight valves have already been welded into flight manifolds, and the remaining 25 will be assembled over the next two months. The qualification program has been successful to this point, and additional testing will begin as soon as possible. The failure of the position sensor was a disappointment, but the project considered the loss acceptable. More work needs to be done to either fix the current position sensor design or come up with a new method of position knowledge for future use of the Microvalve.

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Figure 7 - Flight Microvalves Welded into a Flight Manifold