DEVELOPMENT OF A NOISE-FREE POSITION ENCODING DEVICE FOR SPACEFLIGHT USE

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ABSTRACT

Conventional potentiometers both rotary and linear are commonly used in mechanisms for space flight applications. Potentiometers offer simplicity, low power consumption and relatively low price for the resolutions they offer; however, they frequently exhibit "noise" and "drop-outs" in signals after a few thousand revolutions. Having any type of signal "drop-out" noise could become mission critical. The generated noise is mainly caused by wear particles lodging themselves in-between the wiper contact and the resistive or conductive tracks. This phenomenon is common to all types of conventional sliding contact potentiometers.

This paper addresses a rolling contact encoding device developed jointly by H&K GmbH and Moog Inc. USA. The device is based on a proven and patented membrane potentiometer technology design by H&K used in industrial, medical and aerospace applications. For the commercial device to be used for space, special development was needed to address the materials and processes, hard vacuum, noise-free operation for extended life and linearity better than 0.25%.

This paper summarizes the design, development, qualification and life testing of this device. The device trademarked as "Moog QuieSense™" noise-free potentiometer has undergone extensive development testing under different conditions and has proven the noise-free operation for over one million revolutions.

1. INTRODUCTION

Conventional conductive plastic potentiometers both rotary and linear have been used widely in space-flight applications. These devices offer simple analog position knowledge, very low power consumption and temperature compensation, but due to the sliding contact nature of the device they have limited life and prone to frequently exhibited "noise" and "drop-outs" in signals after a few thousand revolutions, caused by debris and polymer formation.

A detailed trade study was conducted for alternative position encoding technologies that would address the finite life and signal integrity issues. The trade studies included resistive potentiometers, capacitive, inductive and optical sensors. Inductive sensor studies included resolvers, Inductosyn and Hall-Effect devices. The optical sensor studies included conventional optical encoders and diffractive optic-based systems. The study concluded that all alternative position encoding technologies would require onboard and external electronics. Adding new electronics is a very expensive proposition, as most satellite manufacturers have already proven heritage electronic systems that would require a redesign and re-qualification.

Since the exhibited "noise" and "drop-outs" in signals is a direct artifact of the wear introduced by the sliding nature of conventional potentiometers, a membrane potentiometer technology was chosen as a potential offering all the features of the conventional potentiometers with the added benefit of a rolling contact resulting in longer life and noise-free operation.

Products and specifications of several manufacturers of these type devices were tested and studied. The first unit of a membrane potentiometer technology was procured from a US supplier.

The unit was produced using fiberglass foils. The testing was done in ambient pressure environmental chamber. No computer generated linearity tests were performed on this unit configuration. Resolution of the potentiometer signal was not checked lower than 1.5 degree increments which were easily reached. Testing was limited to first determining if unit was noise free for a number of revolutions at ambient, hot and cold temperatures. Strip chart recordings indicated that linearity was not that good based on looking at the straightness of the trace and some large jumps from one single motor step to another. The commercial POM wiper in a spring-loaded screw housing was used. This could have possibly explained the jumps in trace voltage.

The unit was tested in ambient pressure at 8 pulses/sec and temperatures of 23C, +80C and -40C for 110,000 revolutions total. No noise was detected although the line shape changed at times.

A micro-hole was drilled to act as a vent hole in potentiometer to allow use in vacuum. Test article was

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cycled in vacuum at +80C and -40C for 24,326 revolutions total at 8 pulses/sec. No noise was detected although the line shape changed at times as explained previously. No mechanical breakdown on the external surface of the foil was observed.

Use of this manufacturer was deleted from the development program because it was not pressure balanced for operation in vacuum. Since the entire sensor was build from non-metallic materials it was prone to permanent set (memory) when left at a given position for a long time.

Hoffman and Krippner's **SENSOFOIL® Hybrid** (Patent Pending) technology was selected to replace the current potentiometers for the following reasons:

1. Vacuum compatible (pressure compensated)
2. Wide temperature range operation
3. The upper collector foil is additionally protected by a highly flexible metal bond.
4. Dents are avoided during longer periods of inactivity and the temperature range is from -40 °C to +125°C. No memory (Figure 1)

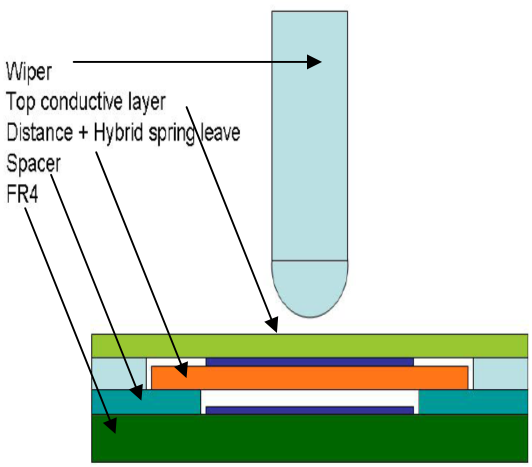

Figure 1. Composition of Hybrid **SENSOFOIL®**

2. PRINCIPLE OF OPERATION

SENSOFOIL® membrane potentiometers are used as voltage dividers and consist of several layers, which are separated by so-called 'spacers'. These layers are connected to each other through pressure generated by either mechanical or magnetic means to create a contact (Figure 2). The contact can be made either by using a mechanical wiper through the use of a magnet instead of a wiper.

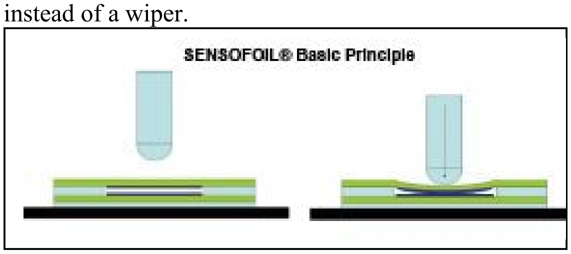

Figure 2. Principle of Operation

SENSOFOIL® membrane potentiometers are the perfect linear position sensors. They work similar to conventional, mechanical potentiometers, but are only 0.7 - 2.2 mm thick and perfectly suited for limited installation space. SENSOFOIL® membrane potentiometers are already successfully used in the medical and laboratory industry, aerospace, automation, consumer electronics as well as machine building industry.

3. DEVELOPMENT

The overall project goal was to design and specify a membrane potentiometer, tailored to the specific needs of spaceflight use. The product was to be able to meet or exceed the performance specifications of conventional conductive plastic potentiometers currently used on Moog actuators. As a minimum the product was to meet the following:

Must be able to operate in a vacuum
Must be able to operate for more than 100,000 revolutions without creating the slightest noise

Mechanical Travel:	360 degree bi-directional
Electrical Travel:	340 degree minimum, 360 degrees max.
Total Resistance:	10,000 Ohms +/- 10%
Insulation Resistance:	100 MOhm min. at 100 VDC between all wires
Absolute Linearity:	+/- 0.25%
Output Smoothness:	0.035% or better
Voltage gradient:	2.5 mV/degree min. with 1.0 V applied
Life:	>100,000 revolutions
Temperature, non-Op.	-75C to +120C
Temperature, Operating:	-50C to 110C
Shelf Life:	10 years
Applied Voltage:	2.25-10VDC
Operating Wiper Speed:	0 to 25 RPM (TBD)

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3.1 Development Steps of Moog QuieSense^{TM} Potentiometer

The overall development was conducted in the following three individual development steps:

3.1.1 Advanced Technology Development

1. Moog and H&K to jointly set-up of the requirement document, development of theoretical approach, and material selection.

2. To conduct pre-examination and testing to verify various solution concepts

3. To perform development and testing of the determined solution

4. To design a single track rotary membrane potentiometer to operate with the following limited technical specifications:

Operating Temperature	Ambient
Resistance tolerance	+/-30%
Linearity	<4%
Output smoothness	undefined
Voltage gradient	undefined

Samples were provided to MOOG for validating performance in vacuum

5. Moog designed the wiper and the sliding contact
6. Prototype production units were tested at MOOG with POM (Delrin), 440C stainless steel, rolling ruby ball and Vespel sliding elements.
7. Ambient condition tests were conducted at H&K in parallel to thermal vacuum testing at Moog on the prototype units.

Development testing at Moog started using the H&K rotary potentiometer with their existing commercial materials and manufacturing processes (non-Kapton). No computer generated linearity tests were performed on this unit configuration. Resolution of the potentiometer signal was not checked lower than 1.5 degree increments which were easily reached. The tests were limited to first determining if the unit was noise free for a number of revolutions at 23C under vacuum. Strip chart recordings indicated that linearity was not very good based on visual straightness of the traces. The commercial POM wiper in a spring-loaded screw housing was used. The test rate was increased to 100 pulses/sec in an attempt to decrease the test time.

At 30,000 to 70,000 revolutions at ambient temperature under vacuum, noise spikes were appearing near .75 volts in a few places. Linearity continued to be poor. At 182,000 revolutions spikes were appearing again and continued randomly. The EDU test at Moog was terminated at approximately 207,000 revolutions. The commercial unit although exhibited some random noise and poor linearity, but results was promising as compared to conventional potentiometer performance.

H&K in parallel conducted ambient condition tests on the EDU unit. Figure 3, 4 and 5 depicts the typical performance results of the prototype EDU unit at H&K after 800,000 cycles.

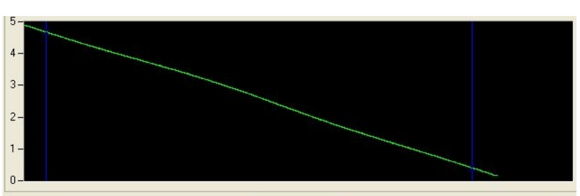

Figure 3. EDU Performance
No signal "drop-out"

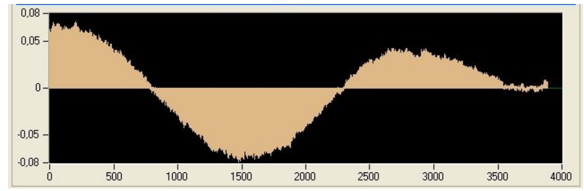

Figure 4. EDU Linearity < +/- 0.08 percent

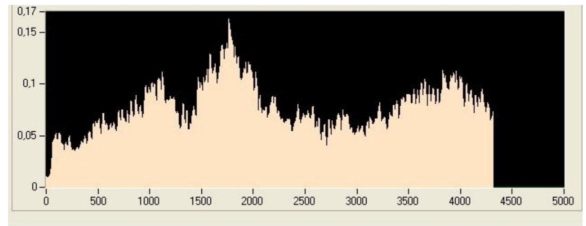

Figure 5. Contact Resistance
Min. 9 Ohms, Max. 163 Ohms

The tests were conducted on the X-Y programmable universal positioning machine using standard POM (Delrin) spring loaded plunger.

The test setup is depicted on Figure 6.

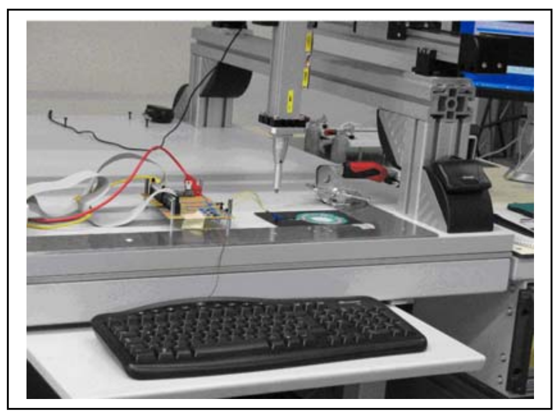

Figure 5. Universal X-Y Positioner

The results were captured by using custom-made software, a typical screen-shot of which is shown in Figure 6. The software automatically calculates the linearity and also displays the contact resistance. Monitoring contact resistance ensures the health of the potentiometer. It is shown that as long as the resistance stays below 300 ohms the potentiometer would not have any "drop-out" noise. Results indicated that even after 800,000 cycles the contact resistance stayed below 163 ohms.

It was demonstrated that the technology could be used at environments as high as 105C. Figure 7 shows the potentiometer article on the hot plate held at 105C during test.

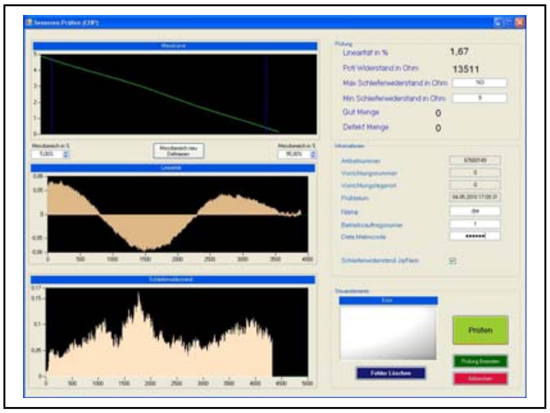

Figure 6. Screen Shot

At the conclusion of this phase the following decisions were made after a detailed design review between Moog and H&K:

Finalize the potentiometer outline dimension.
It was decided to use Kapton as material of choice for the membrane
No adhesive under the track area
Increase operating temperature over standard design and linearity.
The original spring-loaded POM wiper had too much looseness to insure good repeatability and low hysteresis. It was decided for Moog to design and furnish a new wiper arm contact assembly.

The subsequent testing at Moog and H&K were conducted using 440C stainless steel balls.

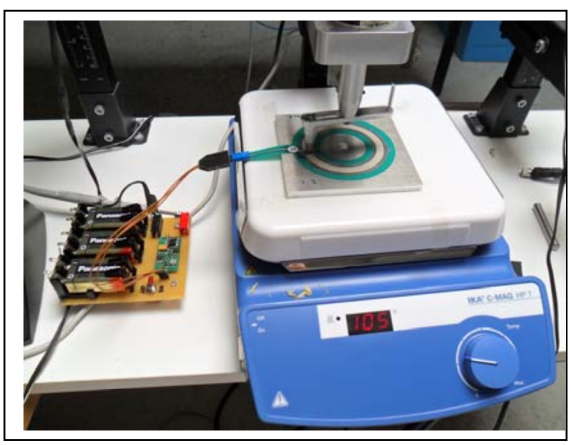

Figure 7. Test article at 105C

3.1.2 Preliminary Design and Validation

During the second phase of the development the following steps were taken.

1. Testing and validation of the different approaches, recommendation for selecting a technology
2. Static testing to determine the best possible solution
3. Dynamic testing
4. Kapton foil with no adhesive under track area samples were provided to MOOG for validating the $5*10^{-5}$ Torr Vacuum
5. Further development of the approved version
6. Design improvements
7. Sample production and documentation
8. Test
9. Results evaluation

The new BeCu wiper with 440C stainless steel ball was used and initially thought to be the answer for a good wiper. Bray grease was added to the wiper track area prior to operating. Test was run at 16 pulses/sec.

After approximately 567,720 revolutions the test was terminated. The Kapton showed some wear but potentiometer traces indicated the it could continue to be operational for more revolutions. Unit was disassembled for examination.

Examination of the steel ball showed a wear pattern with 2 parallel lines on either side of the ball in the direction of the wiper arm travel. The Kapton foil surface showed a wear pattern with divots connected by a linear scrape between each divot. This was caused by the oscillating motion of the 1.5 degree stepping of the wiper arm. Testing was terminated on this unit due to expected changes in design for the next version. Improvements to linearity and elimination of adhesive backing were expected.

Another wiper design was tried in an attempt to create a rolling wiper. This incorporated a Ruby ball with a pin in the rotating center. The BeCu wiper arm force of 5 N and the smooth surface of the Kapton prevented the ruby from rolling. This design was abandoned.

To achieve linearity better than 0.25 percent, a Kapton on FR4 Printed Circuit board construction was selected as the choice candidate for construction technology for QuieSense™ potentiometer. H&K was reaching its in-house capability to produce better linearity on a plastic film base using the resistive ink without trimming. To produce linearity of better than 1 % required a base made from FR4 and trimming of the resistive track by a computer-controlled router. The unit is shown in Fig. 8.

A computer controlled linearity test was performed on the FR4 board construction unit with BeCu/steel ball wiper. A full-scale best-fit linearity of .8330 % was measured on the unit.

Figure 8. Kapton on FR4 PC Board

A BeCu wiper arm was fabricated to hold the stock POM wiper and another BeCu wiper arm had a pressed in .125 inch Vespel ball in place of the steel ball.

The POM wiper was run with 5 N force at 100 pps to speed up test time to accumulate full revolutions reversing direction every 24 hrs. At random times during the test the step rate was slowed to 8 pps to perform strip chart tests and look for noise. The unit was noise free up to 436,800 full revolutions.
At 436,800 revolutions the test was halted to perform a computerized linearity test. The measured linearity was -.7798% / +.8407%. The test was resumed at 100 pps and continued noise-free stopping at 533,760 revolutions.

At this time it was decided to switch to a Vespel wiper. Although POM (Delrin) is an accepted non-metallic material for spaceflight use, its maximum allowable temperature rating was considered not suitable as a wiper material for Moog actuator product line.

The POM wiper was replaced with a Vespel SP1 ball at 5.5 force. Bray 601 grease was applied to the sliding element surface. Tested Linearity was at -.7662% to +.8447%.

Changed the step rate to 16 pps and reversing direction of motion every 24 hrs. The test was ran an additional 155,040 revolutions for a total of 688,800 noise-free revolutions on this element.

The test was terminated in expectation of new version potentiometer with improved trimmed linearity. No "dropouts" or noise were noted.

3.13 Design and Validation

1. Definition and design of close-to-production potentiometers
2. Preparation of production design criteria
3. Development of test program and software
4. Static and dynamic testing
5. Validation
6. Qualification and Life testing
7. Documentation

4. QUALIFICATION TEST

A qualification FR4 board trimmed potentiometer with Kapton membrane was subjected to qualification testing at extreme hot, cold and ambient temperatures and vacuum condition.

Concurrent to Moog testing, other samples were tested at H&K directly mounted onto a stepper motor rotor. The tests were run at low pulse rates so that the stepper motor oscillations were directly imparted to the wiper (Figure 9 & 10).

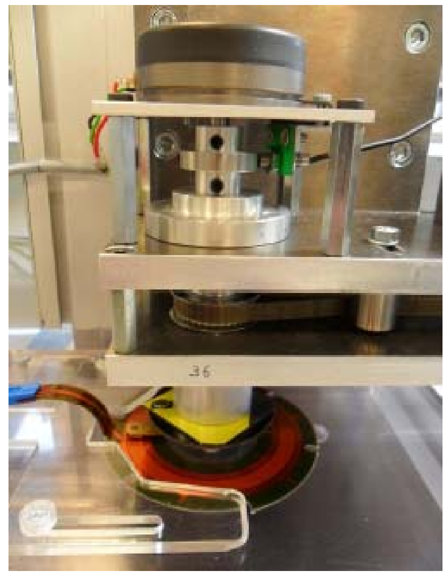

Figure 9. Test Setup at H&K

The qualification testing of the final version was conducted over a 60 degree segment of the element to decrease calendar time. The step rate was set at 16 pps, reversing direction every 60 degrees. The test was performed under vacuum.

The test was conducted by fixturing a standard Moog Type-3 rotary actuator unit (Figure 11) with the potentiometer, Serial No. 16E (FR4 with new Vespel wiper @ 5.5N pressure, Bray601 grease). The linearity was checked at -.1227% to +.1277%.

The unit was first run for an initial 506 sweeps of 60 degrees at ambient pressure and temperature. No noise or dropouts were noted. The subsequent tests were run by installing the unit in thermal vacuum chamber. Cycling was programmed for a 60 degree sweep from 2.5 volts to 3.38 volts with a 5 volt supply. The cycling started at1 x 10^{-5} Torr, at 23C, no "dropouts" or noise were noted.

Completed 725,676 sweeps total; 167,000 cycles at ambient +23C, followed by 211,378 sweeps at +105°C and 347,298 sweeps at -40°C. No drop outs or noise were noted. Following is the summary of linearity measurements pre and post-qualification:

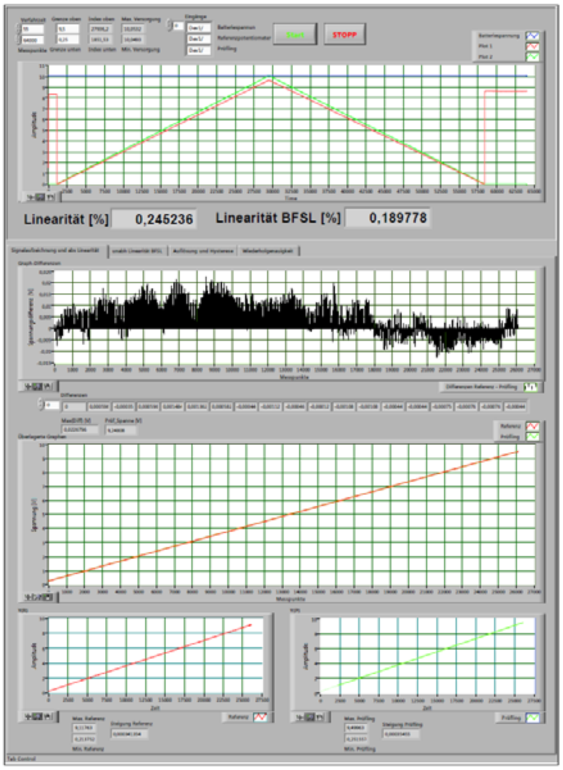

Figure 10. Screen Shot H&K Test

Pre qualification test at room ambient using reference encoder: -0.123% / + 0.128%
Post qualification test at room ambient using reference encoder: -0.127% / + 0.165%

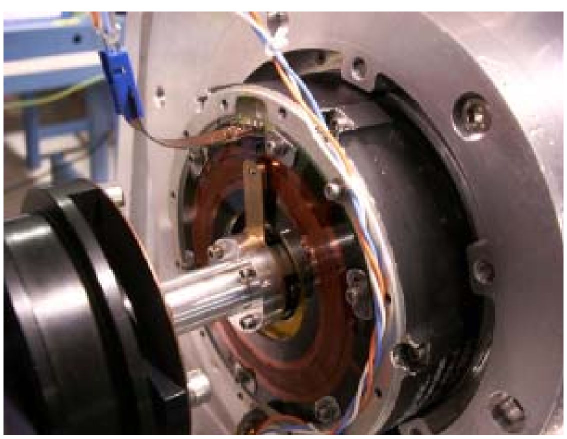

Figure 11. Test Setup at Moog

Vacuum at 23 C using motor step angle reference: -0.153% / +0.152% (Figure 12)

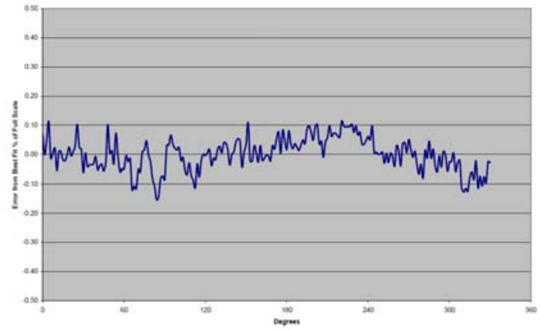

Figure 12. Best Fit Linearity at +23C and vacuum

Vacuum at 105C using motor step angle reference: -0.147% / +0.148% (Figure 13)

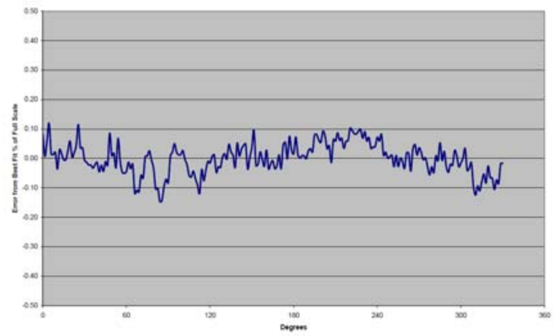

Figure 13. Best Fit Linearity +105C, 1x10-5 Torr Vacuum

Vacuum at -40C using motor step angle reference: -0.212% / +0.196% (Figure 14)

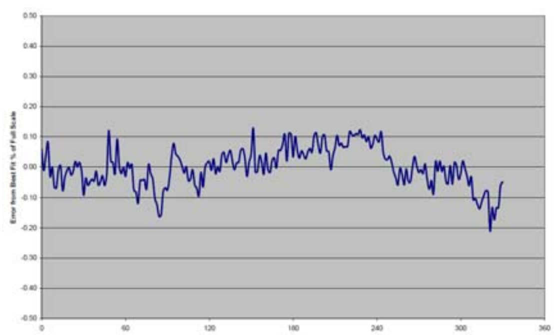

Figure 14. Best Fit Linearity -40C, 1x10-5 Torr Vacuum

5. MATERIALS and PROCESSES

All the materials and processes used in the construction of the QuieSense™ potentiometer has been carefully selected to meet the space flight outgassing requirements of TML < 1% and CVCM < 0.1%.

Sample of every material has bee n sent to an independent chemical laboratory for testing.

6. EXTENDED LIFE TEST

Currently the unit is being subjected to a more extended life testing installed on a Moog standard Type3 rotary actuator. The extended qualification and life testing will extend until the motor input shaft accumulates more than one million revolutions.

The extended life testing will expose the two QuieSense™ qualification potentiometers; one potentiometer referred to as fine attached directly on the stepper motor rotor shaft, and the other referred to as coarse coupled to the actuator output shaft. The test units will be exposed to various predetermined environments enveloping most spaceflight requirements.

The potentiometer performance will be monitored before, during and after exposure to dynamic and thermal environments.

These environments included variations in:

- Temperature (-60 to 115°C non-operating and - 50 to 105°C operating) during thermally controlled space vacuum simulation
- Pressure ambient pressure to $1x10^{-5}$Torr. vacuum
- Sine vibration
- Random vibration in three axes (23.6 GRMS)
- Shock

The results of the life test will be presented at the symposium.

7. CONCLUSIONS

It was demonstrated that the QuieSense™ potentiometer technology offers noise-free output signal for over a million revolutions

Standard SENSOFOIL® potentiometers can achieve an absolute linearity of around 1%

QuieSense™ noise-free potentiometers are trimmed to achieve a linearity of better than 0.25%. It was demonstrated that the worst linearity achieved during qualification testing was 0.212% at cold.

Since the wiper slides on the external Kapton surface, any wear does not affect the performance characteristics of the potentiometer.

Tests conducted with several wiper contact materials demonstrated that although POM is an excellent choice for commercial use; due to its limited high temperature performance, Vespel is a better choice for space-flight environment.