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Design and validation of a thermo-mechanical Self-Calibrating displacement sensor for embedded applications

Thomas Furness[1†], Simon Flectcher[1], Andrew Longstaff[1]
[1]*The University of Huddersfield, Queensgate, Huddersfield, HD75ES*

t.furness@hud.ac.uk

Abstract
Structural deformation due to thermal expansion or finite stiffness effects is prevalent in most manufacturing machinery. Structural monitoring can be achieved using direct measurement of displacement or strain. Such sensors require periodic calibration to maintain traceability, and this may be impractical for an embedded solution inside the structure of a machine. [1-2] discuss a novel low-cost design of sensor capable of long-range strain measurement to monitor these effects. The current design of these stain sensors has shown to have sub-micron resolution and repeatability once calibrated but follow up calibration of these sensor has the potential to be difficult and problematic.
This paper presents a new design of the displacement sensor that incorporates an in-situ self-calibration function negating the potential future need to disassemble and remove the sensor assembly from the machine it is monitoring. This paper reviews the design and preliminary FEA analysis of the thermal actuator mechanism that can provide self-calibration, whilst maintaining the sensors primary functionality. Initial bench tests results are also presented.
The system utilises a system of slave/master displaceable caddies, which allows the sensor head to be displaced when subjected to an external force in normal operation but can also be independently manipulated thought its measurement range by the thermal expansion of a calibrated aluminium slug. This initial validation has shown that this system can allow for the recalibration of the sensor in-situ, currently with an uncertainty in the order of 1.3µm. By calibrating the thermal expansion of the slug and accurately monitoring the inputted temperature, by way of PT100, this uncertainty can be decreased.

Keywords: Calibration, strain measurement, structural measurement, photomicrosensor

1. Introduction

Structural deformation is a fundamental factor in most manufacturing machinery. Thermal expansion, finite stiffness effects, and inertial deformation can affect a machine's structural geometry, which in turn can lead to reductions in machine performance. The monitoring of these effects is well documented [3] [4], and the works of *Potdar et al* [1], and *Fletcher et al* [2], focuses specifically on a low cost, long range, strain measurement framework which forms the basis for this work. The sensor utilises two differential pairs of Kingbright KRB011 slotted photomicrosensors (PMS), and an arrangement of shutters connected to an external fixture. This arrangement is shown in Figure 1.

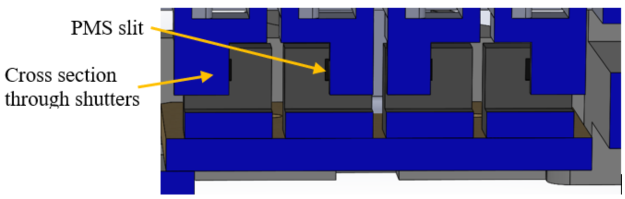

Figure 1: PMS and shutter arrangement (courtesy of *Fletcher et al [2])*

When the fixture, and by connection the shutters, experience an external force they are displaced, restricting or increasing the amount of light the PMS emit.
According to *Fletcher et al* [2], the differential output from the four individual PMS sensors is proportional to the displacement using the equation:

$$V_{out} = \frac{[\frac{(v_1 - v_2)}{2} + \frac{(v_3 - v_4)}{2}}{2}$$

This output method can cancel out input voltage drift and differential thermal expansion. That, coupled with the mechanical design of the whole sensor package, can provide frictionless bi-directional movement, and gives this sensor package a repeatability of 0.047µm, and high sensitivity of 0.165V/µm.
However, whilst this sensor framework has shown to have viable characteristics once calibrated, future periodic calibration is required to maintain traceability throughout the sensor's lifetime.
Whilst the calibration process for this sensor is straight forward, disassembly of the sensor framework is required. This in turn requires access to the framework, that can be problematic if that framework is installed in some of the more hard-to-reach areas on complex manufacturing machinery such as machine tools. For example, under the guarding and inside castings. If this was the case, then for the calibration process to take place the machine in question would need to be removed from production and stripped down is allow access. This machine down time in turn will lead to a loss in revenue for that machine.
This work looks at a new design of the PMS strain measurement framework incorporating a self-calibration function that would allow for periodic in-situ calibration of the system.

2. Thermo-mechanical Calibration

The basic calibration cycle for this sensor framework is to displace the caddy (which houses the shutters) through the sensors measurement range (20µm) whilst observing V_{out}. For this self-calibration design, this movement needs to be independent of any external forces that may be acting on the sensor. To induce this movement, one idea was to integrate a piezo-ceramic actuator with closed loop capacitance feedback, into the carriage housing. This would have easily allowed the

20µm stoke of the sensor to be achieved very accurately and with a high resolution using a intergrated capacitance feedback loop.
However, the integration of an actuator such as this, along with the voltage drive amplifier, would have added many thousands of pounds to what is otherwise a very affordable sensor at £50 per framework section [5].
Whilst the actuator in this design was unsuitable due to cost, the mechanical design of this new self-calibrating sensor was sound, by utilising a combination of two displacement caddies, 1/ that displaces when subjected to an external force (master) and 2/ one that displaces only when the calibration cycle is being performed (slave). This arrangement is shown in Figure 2.

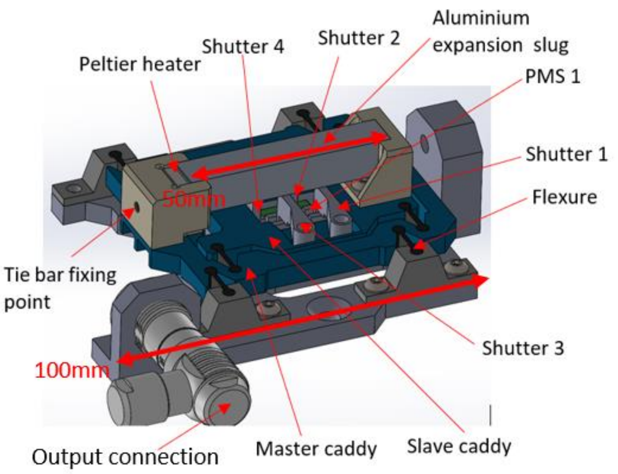

Figure 2: Arrangement of new self-calibration strain sensor

The chosen alternative for actuation was controlled thermal expansion. Many available metals have high thermal expansion coefficients and there are temperature sensors with very low uncertainty. Considering a platinum resistance thermometer, a conservative uncertainty value of +/-0.1 °C would result in a length uncertainty of just 0.12 µm for an aluminium (exp coeff 22.4µm/m/k [6]) slug of length 0.05m. This work evaluates the feasibility of the design for the next stage of defining long term uncertainty for traceability.

As can be seen in figure 2, the slave caddy housing the shutters is mounted inside the master caddy, with the two connected together by an aluminium bar/slug. Under normal operation when a tie bar is fixed to the sensor the master caddy will be displaced when subjected to an external force, moving the shutters. During the simulated calibration cycle the Peltier heater raises the temperature of the aluminium slug to an average of 41.44°C, inducing thermal expansion equivalent to the sensor measuring range. This expansion displaces the slave caddy moving the shutters in the same manner as observed during normal operation. The design seen in figure 2 was subjected to a series of FEA simulations to ensure that this new design can maintain the same characteristics under normal operation and that the added features can perform this calibration cycle.

3. FEA simulations

To determine the mechanical characteristics of this design the CAD model in figure 2 was imported into ANSYS, and as series of structural and thermo-structural simulations were performed. Figure 3 shows the meshed simulation model with the initial boundary conditions. The mounting holes of the sensor have been fixed, with 0.025N applied to the end of the tie bar. Note most holes have been removed to allow for a more consistent mesh. As the sensor had a stiffness value of 879.8 µm/N, 0.025N was chosen as the displacement force that should be required to displace sensor by the necessary 20 µm.

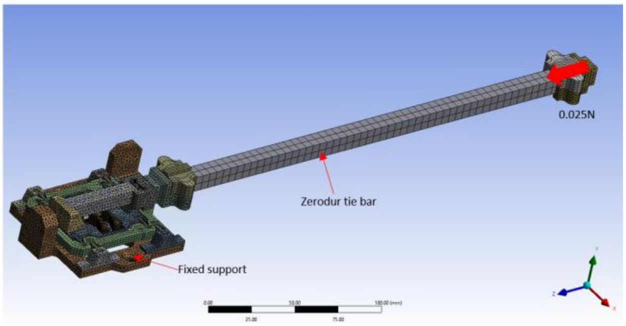

Figure 3: Meshed ANSYS model showing the initial boundary conditions

The results of subjecting the sensor to 0.025N are shown in figure 4. The applied force shifts both master and salve caddies as expected with a maximum magnitude of 21.9µm. This slightly exceeds the sensor's actual measurement range. The individual displacement values for the shutters are shown in table 1 which indicate a maximum range of 0.2µm. It is important that the calibration cycle does not adversely affect the uniformity of these readings.

The next simulation preformed was a steady state thermo-mechanical simulation, simulating the calibration cycle.

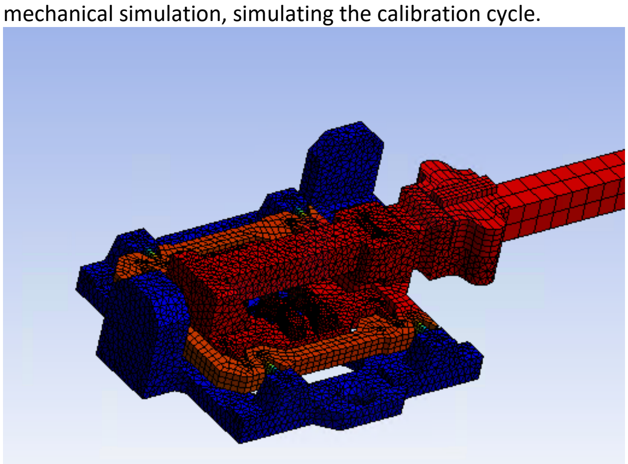

Figure 4: Deformation results for sensor being subjected to 0.025N

Table 1: Individual shutter displacement results

Shutter	Displacement (mm)
1	0.021004
2	0.020963
3	0.020863
4	0.020784

For the thermomechanical simulations, the 0.025N constraint was removed and replaced with a thermal input of 42°C on one end of the aluminium slug, replicating the Peltier heater. Additionally, a convection coefficient of 6W/m²/C was applied to the entire model simulating the heat loss to the environment and the initial ambient temperature was set at 20°C.
In this steady state simulation, the above boundary conditions resulted in an average temperature for the aluminium slug of 41.44°C. The temperature gradient for the aluminium slug in shown in figure 5.
This temperature increase in the slug (temperature distribution across the model is shown in figure 6), resulted in a thermal expansion of 22.1µm (shown in figure 7). The corresponding shutter displacement values are shown in table 2.

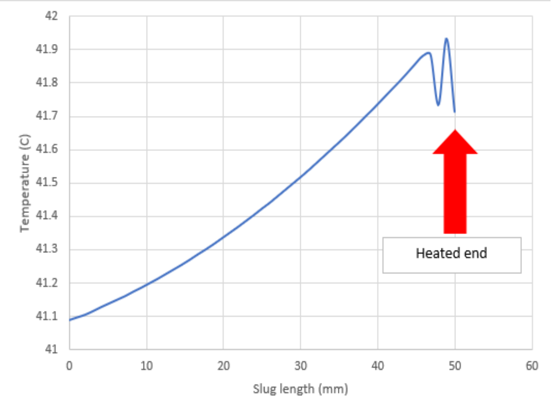

Figure 5: Temperature gradient for aluminium slug

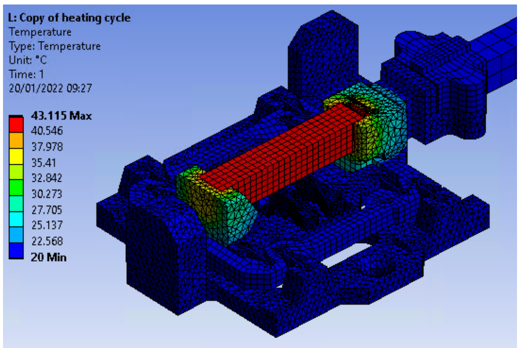

Figure 6: Temperature distribution @ T=43°C

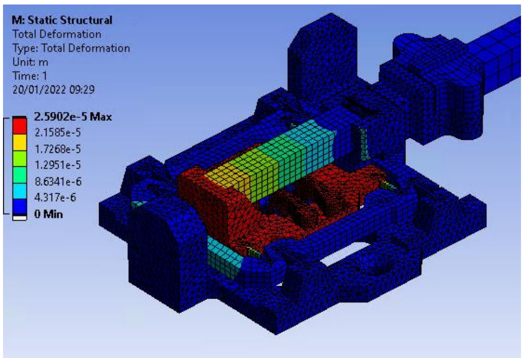

Figure 7: corresponding thermal expansion

Table 2: induvial shutter displacement results during calibration cycle

Shutter	Displacement (mm)	Difference from normal Op (table 1) (mm)
1	0.0222	0.0012
2	0.0225	0.00153
3	0.0227	0.00184
4	0.0231	0.00232

Table 2 shows that the range across each sensor is 0.1 µm which is less than the static force results referenced in table 1. The average difference between the sets of results is 1.7µm. This shows that in principle this thermo-mechatronic self-calibration system can displace the shutters independently of any external forces. However, it does highlight a potential systematic error between the normal operation and calibration cycle.

Practical experimentation is required to validate these simulations, and to ensure repeatability both in the calibration displacement and the corresponding voltage output.

4. Practical Validation

Following the FEA simulations the design shown in figure 2 was assembled. A FLIR A600 series thermal camera was used to perform the thermal monitoring of the Peltier heater, the aluminium slug, and several positions around the body of the sensor. Whilst using a thermal camera did reduce the accuracy of the temperature measurement, at this stage it was more prevalent so that several areas of the sensor could be monitored as previously mentioned. To facilitate the thermal camera being able to monitor the aluminium slug's temperature, masking tape was applied to the viewed face to increase the surface's emissivity (masking tape has an emissivity value of 0.92 [7]). The sensors displacement was monitored by the use of a Renishaw XL-80 laser interferometer with the retroreflector mounted directly on the moving part of the sensor. This set up is shown in figure 8.

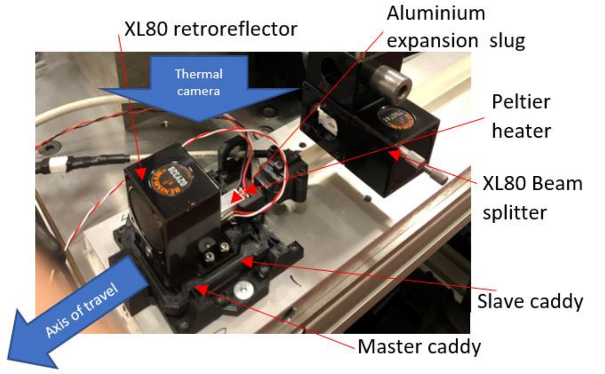

Figure 8: experimental set up

The aluminium slug was heated until it stabilised at 42°C (figure 9). This was achieved by passing 1.15A through the Peltier heater. With the temperature stabilised, the final output voltage and displacement results were recorded. This process was repeated five times.

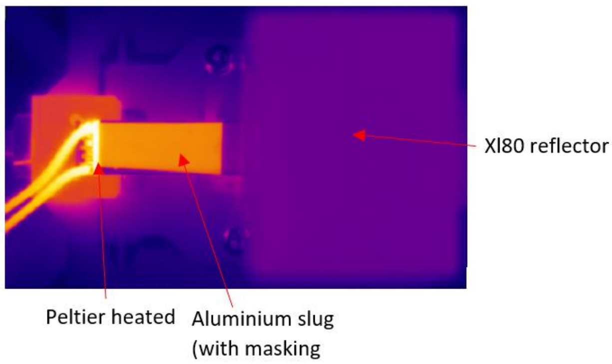

Figure 9: thermal image of heating cycle

To allow for homogenisation both in heating and cooling each calibration cycle took around two hours to complete. Figure 10 shows how the output voltage varied with respect to aluminium slug temperature.

Each calibration cycle resulted in an output voltage of 1.8V with a standard deviation between the output voltage of all five runs being 0.04V. When comparing the calculated thermal expansion of the aluminium slug based on the recorded temperature, with the actual displacement observed by the XL80, the standard deviation was as low as 0.37µm, but with a max error of 1.3µm. These results are shown in table 3. The calculated thermal expansion is shown as D_c (using 22.4e^{-6}m/m°C. for the coefficient of thermal expansion, and an original length of 50mm), and the actual thermal expansion is shown as D_a.

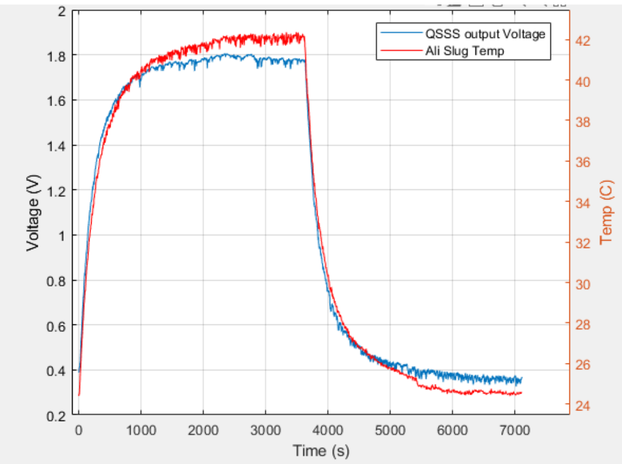

Figure 10: voltage output due to aluminium slug temperature increase

Table 3: displacement results

	T start (C)	T heat end (c)	T Change (c)	D_c (µm)	D_a (µm)	Difference (µm)
Run1	24.2	42.3	18.1	20.905	20.8	0.528
Run2	23.9	42.2	18.3	20.469	21.8	1.304
Run3	24.4	42.0	17.6	19.712	20.5	0.788
Run4	24.1	42.1	18	20.16	20.3	0.14
Run5	24.4	42.3	17.9	20.048	20.8	0.752

Within this preliminary design validation there is high uncertainty associated by the use of a thermal camera to record temperature. There is also uncertainty with the displacement results from the XL80 as there was unwanted heat transfer into the retroreflector. Monitoring the temperature in a more direct way, by using a traceable such as a PT100 platinum resistance probe would reduce some of these uncertainties and possible reduce the observed maximum error. It would also be more practical for industrial use.

5. Conclusions and future work

This work has shown and primarily validated the design of a self-calibrating PMS strain sensor. From simulation it has been shown that the incorporation of this self-calibrating feature has a small effect with regards to the displacement magnitude but as has been shown in the practical validation this heating cycle is repeatably. Therefore, it is expected that this systematic error can be removed by a pre-calibration of the self-calibration system leaving only the residual errors.

As said above the practical validation has shown that this new system when active can induce a repeatable voltage output, and that self-calibrating mechatronics is in itself repeatability and comparable when monitored by an external reference to within 2µm. For future use in industrial applications the thermal camera will be replaced by a PT100. Once calibrated this probe will reduce the uncertainty related with the temperature measurement. That coupled with the calibration of the aluminium's thermal expansion will allow for traceable measurement, reduce the current uncertainty, and allow for the recalibration of the entire sensor framework without the need to disassemble that framework once it has been installed.

The next stage of this investigation is to install a series of these self-calibrating PMS strain sensors into a single framework (figure 11) that can be installed onto a working machining centre. This coupled with the installation of the PT100 sensors will allow for a comprehensive uncertainty evaluation.

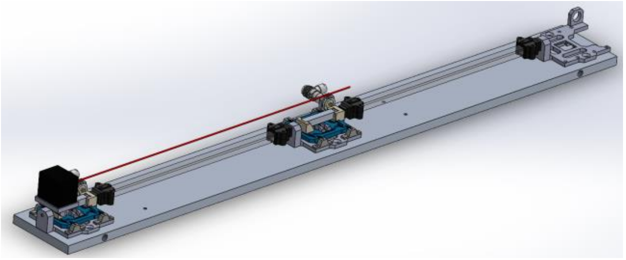
Figure 11: proposed Self-Cal PMS strain sensor framework

6. Acknowledgments

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7. References

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