Design of a structural strain measurement system based on slotted photomicrosensors

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Abstract

Structural deformation in manufacturing machines, either due to thermal or finite stiffness effects, can affect their performance. Measurement of strain of a structural member is common for many safety critical systems but is not used very often for precision machinery to enable correction of resulting errors. This may be due in part to the temperature sensitivity of strain gauges or the complexity of installing many sensors to characterise complex bending of large structures often found on machines. This paper describes the design of a new strain sensing system based on a low-cost displacement sensing technique employing off-the-shelf slotted photomicrosensors and connecting rods to facilitate long range measurement. A small framework of a series of sensors is simulated with detailed analysis of the design. Finally, some preliminary validation results are presented which show sub-micron resolution and repeatability.

1 Introduction

Structural deformation in machinery either due to thermal or finite stiffness effects, can affect their performance. Measurement of strain of a structural member is common for many safety critical systems but is not used very often for precision machinery to enable correction of resulting errors. This may be due in part to the accuracy of some strain gauges, the complexity of installing a large number of sensors to characterise complex bending often found on machines and the associated costs. An example where this has been applied is by Biral [2] where a series of fibre optic sensor shave been arranged on a large milling machine structure. A significant challenge of optical methods is the cost of spectrometry.

Strain gauges have significant cost advantages and can be applied to flat or curved surfaces, but they are not direct measurement of the overall distortion effect. A review of high resolution sensors that could be used to create strain measurement systems is provided by Fleming [3].

In this paper, a new sensor is design around a slotted photomicrosensor (PMS) arrangement described in [1] which provides differential output that compensates for some of the uncertainty contributors. Figure 1 shows the principal of operation. When the shutter (sometimes called a shield) moves, two sensors allow more light transmission while two allow less. This new design uses a slightly different make and model, a Kingbright KRB011 (<£1 GBP). This has a very small aperture giving 90% change in output for less than 100 µm of movement of the shield (referred to as the shutter in this article).

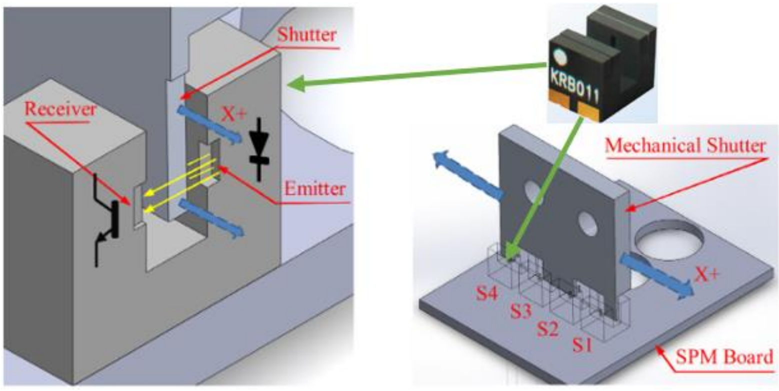

Figure 1. (a) Cross section view of a single sensor and shutter and (b) schematic of the overall system [1].

Equation 1 represents the differential output proportional to displacement of the shutter with output voltages of all the sensors.

$$V_{out} = \frac{\left[\frac{(v_1 - v_2)}{2} + \frac{(v_3 - v_4)}{2}\right]}{2} \qquad (1)$$

Where, v_1 to v_4 are the sensor voltages and V_{out} represents the average differential voltage. This method cancels out source voltage drift and potentially differential thermal expansion. Potdar [1] reported a sensitivity of 0.1648 V/µm, a resolution (noise floor) of 21 nm and an accuracy of ±1% of full-scale range of 20 µm.

To exploit the advantages of this sensor to detect displacement as part of a structural strain measurement system, a sensor housing and framework have been created with uncertainty and cost consideration to exploit the key benefits.

2 Design analysis

The key aims for the design of the displacement sensor based on the operating principal and application are:

1. Frictionless motion for sub-micron bi-directional movement (section 2.1).
2. Single degree-of-freedom motion to reduce cross talk (section 2.1).
3. Minimise thermal influence (section 2.3.1).
4. Simple manufacture and assembly (section 2.1).
5. Easy installation as a retrofit system and sensor replacement (section 2.2).

Transmissive slotted PMS and low sample rate Analog to Digital Converters (ADCs) are ultra-low cost these days, so restrictions on manufacture in point 4 will influence the design. In this case, a plastic 3D printed solution was adopted, eliminating complex machining of small features and simplifying assembly. The design therefore tries to exploit this method and considers issues such as overhangs, low accuracy, anisotropic properties and poor surface finish.

Before examining the detail in the design for the various requirements, an overview is provided here to aid in the visualisation and operation of the sensor module going forward. Firstly, Figure 2 shows the two main components that make up the sensor housing, with all parts being 3D printable without support structures. The principal of operation of the assembly and setup as a strain sensing framework are shown in Figure 7 and Figure 8 respectively. The PMS circuit board sits in the static part as indicated in Figure 2 (a).

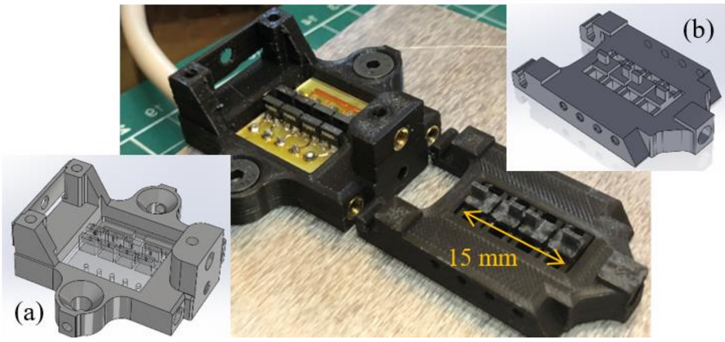

Figure 2. Three main components of the sensor housing (a) static part (with location of PMS circuit board indicated), (b) moving part,

2.1 Flexure system

In order to eliminate friction in the mechanism, a flexure system was employed for relative movement between the two parts of the sensor. A disadvantage of the flexure system is the addition of mechanical stiffness therefore the rigidity needs to be as low as possible to minimise forces in the joining mechanism (Figure 8). Figure 3 (a) shows horizontal and Figure 3 (b) vertical flexure elements to constrain the five unwanted degrees of freedom. See Figure 7 for the deflected shape. Figure 3 (b) inset shows the flexure is push fit with three line contact to constrain vertically, reduce stiffness and eliminate bi-directional hysteresis.

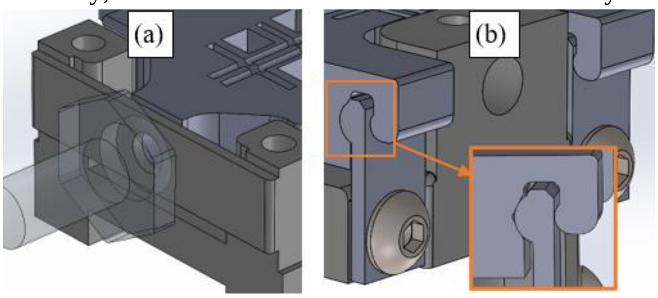

Figure 3. Horizontal (a) and dual vertical (b) flexures for one degree-of-freedom motion

2.2 Sensor adjustment post installation

There is significant challenge during assembly to set all 4 sensors close to the middle of their range to maximise the linear regions in the outputs. The KRB011 are soldered onto the circuit board using a fixture to achieve good uniformity. However, it is not sufficiently accurate when combined with the 3D printed housing to get the same voltage output at the nominal position. Individual adjustment is required with very fine control given that the sensitivity of the sensor is so high. Figure 4 shows the four narrow detector slits partially covered by the shutter fingers, all which need individual adjustment. Figure 5 shows M2 grub screws used to push against a taper on a dual flexure to create axial motion of each shutter. The simulation result in Figure 6 shows the single degree of freedom adjustment.

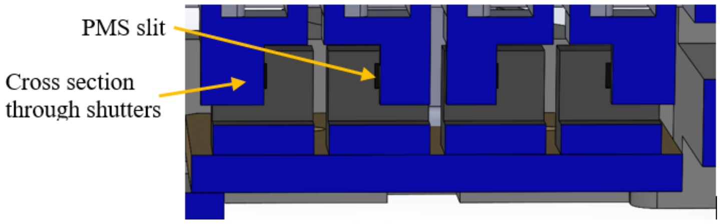

Figure 4.Assembly cross-section showing shutter partial coverage of detector slit

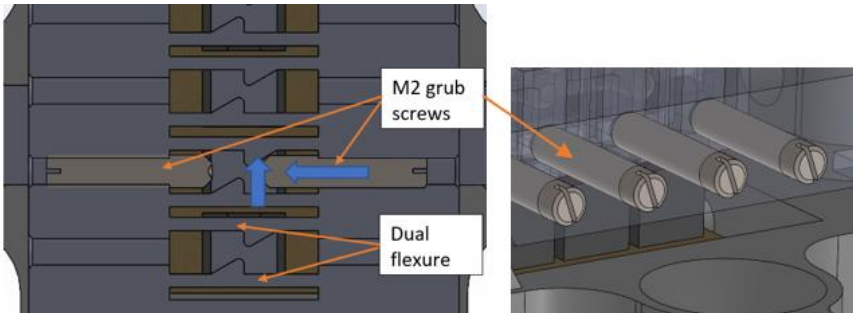

Figure 5. Shutter adjustment mechanism

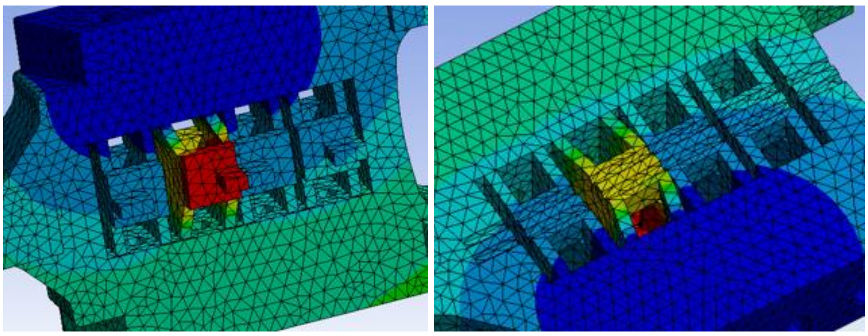

Figure 6. Simulation of the resulting motion of the shutter when adjusted

2.3 Sensor simulation

Preliminary validation of the sensor node design is through Finite Element Analysis (FEA). Firstly, the static stiffness was determined using a 1N force applied axially to the moving part of the assembly. The front flexure thickness has already been reduced to the minimum thickness possible using a typical 3D printer nozzle size of 0.4 mm. A Deflection of 5.9 µm equates to a stiffness of 0.17 N/µm. The variation in displacement of the face of each shutter was 0.3 µm cause by tension/compression in the housing, a linear constant that is easily calibrated.

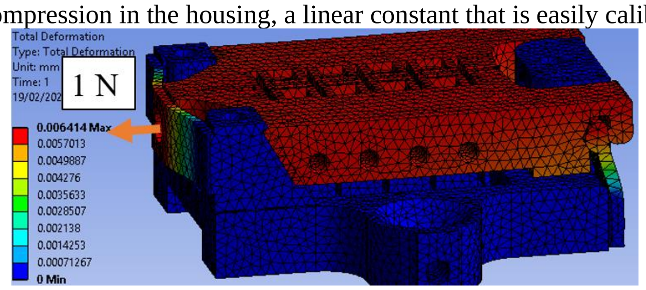

Figure 7. Deflection of the sensor with 1N axial force applied

2.3.1 Multi-sensor strain setup

The joining members provide flexibility over the range of structure being monitored but are also most susceptible to thermal error given that environmental temperature variability may be high in embedded machine monitoring applications. Invar, Uni-directional CFRP and Zerodur bars are all relatively thermally stable options but increase in cost with performance. Figure 8 shows a test setup using 200mm long 10mm square section Zerodur bars, using which loses just 30% of the strain due to the sensor flexure forces. Again, for different rod materials, the stiffness will be calibrated. Residual thermal error includes uncertainty in expansion coefficient and temperature measurement accuracy. At 10 % uncertainty applied to invar (1.2ppm) and 0.1 °C (PT100) respectively, a basic estimate gives (0.1x1.2)x0.1x0.2 = 0.0024 µm for 200mm bar.

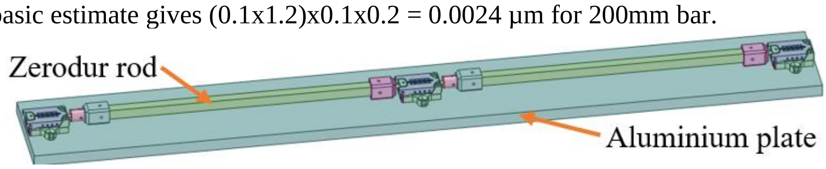

Figure 8. Setup of sensor modules to measure strain of a metal beam.

Although the sensor module is small, 3D printed plastics can have high thermal expansion coefficient resulting in a differential between the moving shutter part and the circuit board assembly. FEA was used to simulate this effect using an average convective coefficient of 6 W/m/°C and a sink temperature changing from 20 °C to 45 °C in ~~5~~ five steps of 5 °C. The expansion of the plate between modules was 200 µm, while the sensors measured 100 µm, an error of 40 µm after accounting for 30% rod tension loss. Using the differential between the inside and outside PMS pairs, which relates to the thermal error, a linear correction can be made which leaves a residual error below 2µm, much of which is a transient issue with the step change in the simulated ambient conditions.

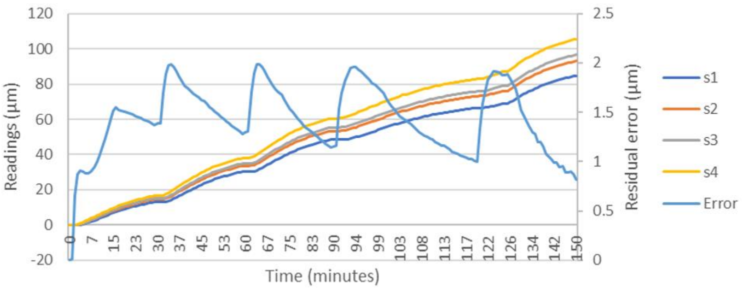

Figure 9. Residual thermal error after differential thermal error correction

2.4 Prototype result

The prototype shown in Figure 2 was assembled and preliminary repeatability tests completed using a Thorlabs closed-loop controlled Piezo actuator. Five bi-directional, 20 µm displacements were recorded, indicating an average standard deviation of 11.4 mV for 6 different displacements (bi-directional), equating to 0.047 µm using a sensitivity 0.1648 V/µm [1].

3 Conclusion

A new sensor design has been created that exploits ultra-low-cost (<£1 GBP) slotted PMS to create a displacement sensor that can be configured in a framework for measuring structural distortion. A 3D printable design has been used to reduce manufacturing cost of an intricate flexure design. Simulation results show the low stiffness to reduce compression/tension losses in the connection rods to 30%. Differential thermal error can be corrected using the sensor reading. A prototype has been built using standard PLA material and preliminary functional tests completed. The standard deviation from 5 bi-directional displacement tests using a Piezo actuator is 0.047 µm. Further work is planned to fully evaluate the long-term accuracy, including the latest low cost ADCs.

Acknowledgement

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