XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6−11, 2009, Lisbon, Portugal

INVESTIGATIONS OF NEW SILICON LOAD CELLS WITH THIN-FILM STRAIN GAUGES

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Abstract − This paper discusses the usability of load cells (LCs) made of single crystalline silicon (Si) mechanical springs with sputtered-on thin-film strain gauges (SGs) as sensors for force and weighing measurements. Experimental investigations of the characteristic line in a temperature range from -10 °C to 40 °C concerning reproducibility, hysteresis and linearity are presented. The results offer the usability of the Si LC in the range of precision measurement if temperature behaviour of sensitivity and linearity are compensated.

Keywords: silicon, load cell, strain gauge

1. INTRODUCTION

In legal metrology, LCs made of metallic mechanical springs with glued foil SGs are used almost exclusively for weighing instruments with less than 10000 verification intervals (v) [1]. For a higher number of verification intervals the electromagnetic force compensation technology with a resolution of a few million steps is normally used.

A new SG LC has been developed to extend the range of application up to precision measurements. The new LC consists of a mechanical spring made of single crystalline Si (Si Spring) and thin-film SGs applied by using sputtering deposition technology.

Experimental investigations of Si Springs confirm the expected low mechanical after effects of the Si Springs [2]. In addition, thin-film technologies like sputtering deposition reduce time-dependent effects during strain transmission from the mechanical spring to the SGs compared to glued foil SGs [3]. Due to these reasons, the Si LC will offer low time dependent effects and a high reproducibility of the measurement signal.

A high reproducibility of the measurement signal is, furthermore, the basic condition to improve the LC properties by digital compensation. By means of mechatronic systems, environmental influence factors such as temperature or humidity – but also nonlinearity – can be compensated in principle. For a useful compensation these influencing factors have to be known very well and the reproducibility of the measurement signal has to be sufficiently high. However, the compensation of time-dependent effects such as creep or hysteresis is very complex and thus difficult up to now. Analytical compensation models have to consider the whole load history of the sensor. Furthermore the characterisation of time-depending effects is very complicated due to their dependence on other factors such as temperature and humidity.

This paper deals with investigations of Si LCs with sputtered-on SGs concerning the characteristic line in a temperature range from -10 °C to 40 °C. Reversibility, hysteresis and linearity of the LC signal are analysed according to the standard EN ISO 376 (ISO 376) [4]. To discuss the range of applications in the field of weighing instruments the measurement data are compensated concerning temperature behaviour and linearity. The compensated measurement data are evaluated according to International OIML Recommendation 60 (R 60) [5] which is normally used to test LCs for weighing instruments in legal metrology.

By operating the new Si LC within a mechatronic weighing system and by compensating for non time-dependent effects like temperature behaviour and linearity, the resolution is expected to be increasable above 10000 v up to the range of precision measurement.

2. SILICON LOAD CELL

The Si LC is designed as a double-bending beam with a nominal load of 6 kg (Fig. 1). The length amounts to 150 mm, the height to 30 mm and the width to 20 mm. The thickness of the thin places is about 1 mm.

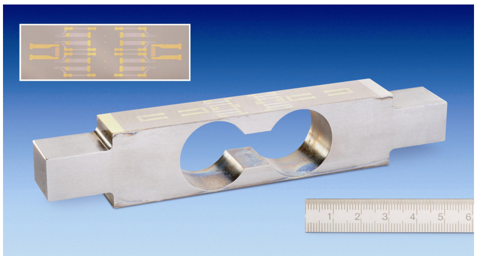

Fig. 1. Picture of a silicon load cell with thin-film strain gauges.

Besides the well-known advantages of this geometry such as the wide independence of force introduction, aspects of manufacturing caused by the processing of Si and the application of thin-film SGs by the sputtering technology, are mainly decisive for this geometry [6].

The thin-film SGs were applied on the upper surface of the Si Spring in the area of the thin places of the LC body by using the sputtering technology. The material of the SGs is NiCr and the thickness of the SGs amounts to 250 nm. The small application area of one SG with only 0.8 mm times 1.8 mm leads to a higher sensitivity compared to glued SGs with greater application areas. After the alignment of each SG concerning similar resistance values the SGs were connected to full-bridges. The measurement signal of the supplied full-bridge is the output signal of the LC and is discussed in the following.

3. EXPERIMENTAL SETUP

To investigate the characteristic line of the Si LCs in the temperature range from -10 °C to 40 °C the experimental setup shown in Fig. 2 is used.

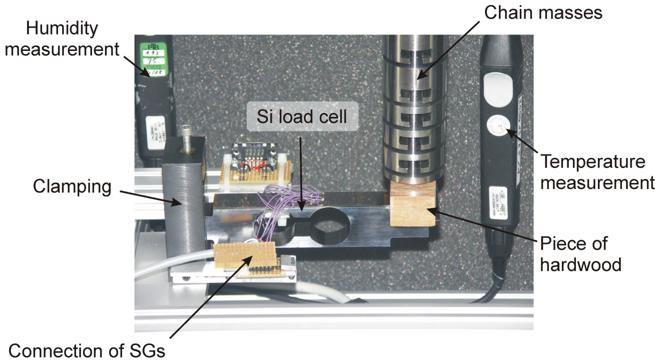

Fig. 2. Experimental setup for load dependent measurements.

The LCs are clamped on the clamping step to fix them within the experimental setup. For thermal isolation the force is introduced via a piece of hardwood. The force is generated by chain masses which are dropped on the hardwood. Humidity and temperature are recorded during the whole measurement.

The whole setup is mounted in a temperature controlled chamber and additionally isolated thermally. The maximum difference in temperature during one measurement cycle amounts to 50 mK.

The loads are applied automatically on the LC step-by-step via chain masses. Through the use of nine chain masses the maximum load amounts to 2500 g. Every load step is applied for about one minute.

The LC signals are analysed by a precision operation amplifier with a resolution of $2.5 \cdot 10^6$ steps within the measurement range of ±2.5 mV/V. The excitation voltage of the full bridges amounts to 10 V.

The investigations are carried out on four Si LCs of the same geometry at the temperatures -10 °C, 20 °C and 40 °C.

4. RESULTS

4.1. Evaluation according to EN ISO 376

The evaluation of the measurement data is performed according to ISO 376, normally used to calibrate and classify force transducers, to discuss the reproducibility, the hysteresis and the linearity of the Si LCs. For classification in the ISO 376, four classes are defined from class 2 with the lowest requirements via classes 1 and 0.5 to class 00 with the highest requirements.

Table 1. Relative errors of reproducibility, reversibility and interpolation for classification according to EN ISO 376.

Relative error in 10^{-5} of	Class 00	Class 0.5	Class 1	Class 2
reproducibility b'	±25	±50	±100	±200
reversibility u	±70	±150	±300	±500
interpolation f_c	±25	±50	±100	±200

Table 1 shows the requirements of each class for the errors of reproducibility, reversibility and interpolation. The relative reproducibility error b' has to be within $\pm 25 \cdot 10^{-5}$ to achieve class 00. The relative reversibility error u is used to characterise the hysteresis and has to be within $\pm 70 \cdot 10^{-5}$ to attain the best class. The relative interpolation error f_c describes the difference of the measurement data to a linear smoothing function and is used to characterise the linearity of the load cells. The relative interpolation error has to be within $\pm 25 \cdot 10^{-5}$ to achieve class 00.

Figure 3 shows the relative reproducibility error b' as a function of the load for different Si LCs at a temperature of 20 °C. The rising values of the curves for small loads are induced by the relative evaluation of the values.

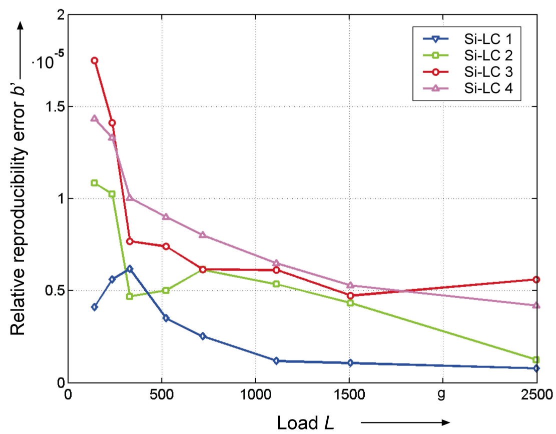

Fig. 3. Relative reproducibility error b' as a function of the load L for different Si LCs at a temperature of 20 °C.

The relative reproducibility error is better than $\pm 2 \cdot 10^{-5}$ for all Si LCs. The best LC in the test reaches a relative reproducibility error better than $\pm 0.7 \cdot 10^{-5}$. This means the requirements of the best class 00 are exceeded by more than one magnitude for all tested LCs. At the other temperatures the values of the reproducibility error are very similar to the values at 20 °C. Due to this excellent reproducibility, the basic condition to improve the properties of the Si LCs by digital compensation is satisfied.

To discuss the hysteresis of the Si LCs, the relative reversibility error u is shown in Fig. 4 as a function of the load for different Si LCs at a temperature of 20 °C. The Si LCs numbers 2 and 4 reach relative reversibility errors of $u < 3 \cdot 10^{-5}$. The Si LCs numbers 1 and 3 show higher reversibility errors. The difference between the Si LCs is assumed to be caused by a variation of the thin film process.

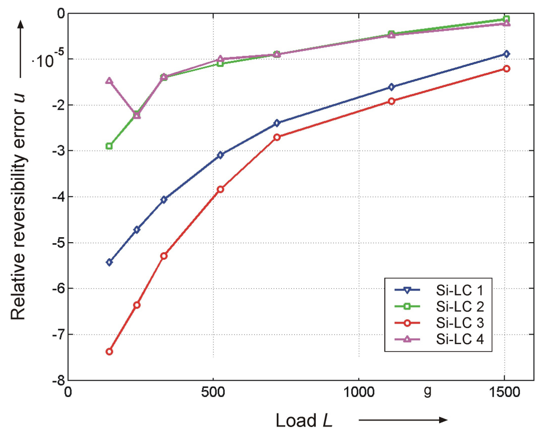

Fig. 4. Relative reversibility error u as a function of the load L for different Si LCs at a temperature of 20 °C.

All Si LCs keep within a relative reversibility error of $\pm 8 \cdot 10^{-5}$. This means the Si LCs exceed the requirement of $\pm 70 \cdot 10^{-5}$ defined in ISO 376 for the best class 00 by about one magnitude. At the temperatures -10 °C and 40 °C the behaviour of the Si LCs concerning reversibility error is very similar. Due to these results, a complex compensation of hysteresis effects is not necessary for the use of Si LCs in force transducers or weighing instruments.

In Fig. 5 the relative interpolation error f_c as a function of the load is shown for different Si LCs at 20 °C.

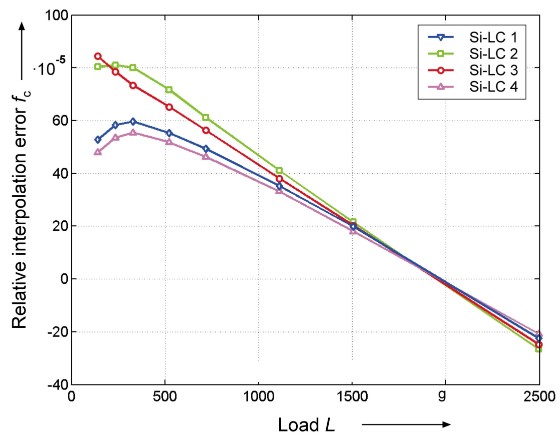

Fig. 5. Relative interpolation error f_c as a function of the load L for different Si LCs at a temperature of 20 °C.

The relative interpolation errors of the Si LCs amount to $\pm 90 \cdot 10^{-5}$. With them the Si LCs show nonlinearities in the range of conventional SG LCs and reach the class 1. The relative interpolation errors at -10 °C and 20 °C are also located within $\pm 90 \cdot 10^{-5}$.

Due to these results, the linearity is one important factor limiting the range of application of the Si LCs. The non-linearity has to be compensated to use Si LCs for precision measurements. Due to the excellent reproducibility, the compensation of non-linearity is comparatively simple by the use of digital systems.

4.2. Evaluation of the compensated measurement data according to OIML R 60

The investigations result in an excellent reproducibility of the measurement signal and low hysteresis. Linearity as well as the dependence of the sensitivity on temperature, which is not discussed in this paper, are the limiting factors.

In the following, the measurement data are subsequently compensated digitally for temperature behaviour of sensitivity and for non-linearity by using a linear model.

The compensated data are evaluated according to R 60 to evaluate the field of application for Si LCs in the field of weighing instruments.

R 60 classifies LCs concerning the number n of verification intervals ν which are the smallest graduation for applications admissible for verification. The bases for classification are several tests. For every test the error has to be lower than a maximum permissible error (*mpe*) calculated by the given number n of verification intervals ν.

Subsequently the LC error E_{LC} as well as the repeatability error E_{Rep} of the Si LCs within the temperature range of -10 °C to 40 °C is discussed.

Fig. 6 shows the LC error E_{LC} and the maximum permissible error as a function of the load for Si LC number 4 at the temperatures -10 °C, 20 °C and 40 °C. The errors are plotted in units of ν for a number of 50.000 verification intervals. With it ν corresponds to 50 mg. The *mpe* is shown for accuracy class B50 with 50.000 ν.

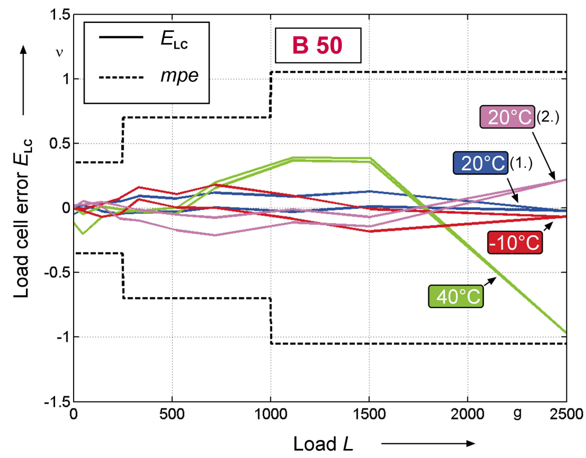

Fig. 6. LC error E_{LC} of the Si LC 4 in units of ν as a function of the load L for different temperatures; accuracy class B50.

The evaluation offers that the LC error E_{LC} of the Si LC keeps to the *mpe* of accuracy class B50 with 50.000 verification intervals in the temperature range from -10 °C to 40 °C.

In Fig. 7 the repeatability error E_{Rep} and the mpe are plotted as a function of the load for Si LC number 4 at the temperatures -10 °C, 20 °C and 40 °C. As in Fig. 6, the errors are plotted in units of ν for a number of 50.000 verification intervals and the *mpe* is shown for accuracy class B50.

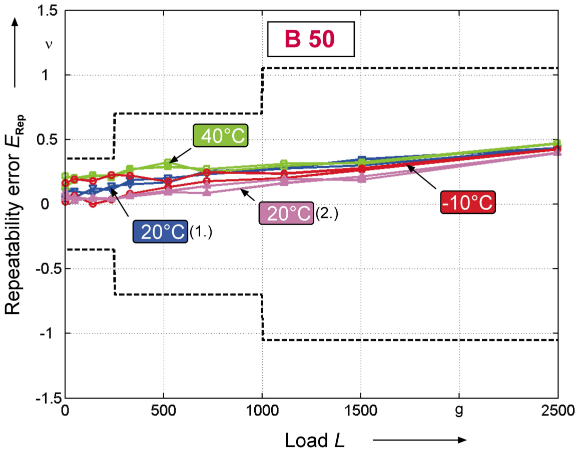

Fig. 7. Repeatability error E_{Rep} of the Si LC 4 in units of ν as a function of the load L for different temperatures; accuracy class B50.

The repeatability error E_{Rep} clearly keeps to the *mpe* of accuracy class B50 with 50.000 verification intervals in the whole temperature range. The Si LC number 4 would even keep to the mpe of accuracy class B80 with a number of 80.000 ν.

The evaluation of the LC error and the repeatability error according to R 60 shows that Si LCs reach a number of $n = 50.000$ verification intervals in the accuracy class B. With this, the number of verification intervals is more than a factor of 5 higher compared to conventional SG LCs. Furthermore, the repeatability error shows the potential to increase the number of verification intervals up to 80.000 by improved digital compensation.

In contrast to conventional SG LCs which do not exceed a number of 10.000 ν the Si LCs could be used for precision measurements which are normally the field of the electromagnetic force compensation technology.

5. CONCLUSION

Experimental investigations are performed on load cells made of single crystalline silicon and sputtered-on thin-film strain gauges to evaluate the characteristic line of the LCs in the temperature range from -10 °C to 40 °C.

The investigations result in a high reproducibility and a low hysteresis which are about one magnitude better than for conventional strain gauge load cells. The linearity is comparable to conventional strain gauge load cells and limits the range of use of the Si LCs. The influence of temperature on reproducibility, hysteresis and linearity are negligible in the range from -10 °C to 40 °C.

By digital compensation of non-linearity and temperature-dependent sensitivity, the LC error and the repeatability error of the Si LCs reach accuracy class B50 with 50.000 verification intervals. This means the Si LCs could to be used for precision measurements which are normally the field of the electromagnetic force compensation technology. Beyond, in spite of the electromagnetic force compensation technology, the Si LCs are not limited to low and medium loads and thus they are suitable to be used as transfer standards.

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