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Investigations of load cells made of single-crystalline silicon with sputrered-on strain gauges

S. Mäuselein[1], O. Mack[1], R. Schwartz[1], G. Jäger[2]

[1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany,
Sascha.Maeuselein@ptb.de
[2]Technische Universität, Ilmenau, Germany

Abstract:

This paper presents first results of experimental investigations performed with mechanical springs made of single-crystalline silicon (S-Spring) for load cells (LCs) with sputtered-on thin film strain gauges. The investigations are carried out on a specially manufactured S-Spring load cell (S-Spring-LC) with a nominal load of 6 kg and geometry parameters which are optimized by numerical simulations.

This paper deals with load depending deformation measurements of the S-Spring to verify the expected low mechanical after effects. For the first time the investigations are carried out with a Fizeau interferometer, which delivers 3-D topology data of surfaces.

This interferometer actually used at PTB features the grand adventure to determine the deformation of a complete surface of a load cell under load within a short time interval and one single measurement.

The measurements reveal information about the fraction of deflection generated by tilting effects of the force introduction and which fraction is generated by deformations of the S-Spring. The investigations point out that tilting of the force introduction is not negligible but can be compensated analytically. Only with analytical compensation of tilting effects mechanical after effects of the S-Spring can be determined by recording a multiplicity of 3-D topology data within 30 minutes. As a result the S-Spring investigated shows mechanical after effects which value is about a factor of 100 lower in comparison to conventional metallic material LCs and therewith confirm values given in literature for mechanical after effects of silicon [1].

Keywords: silicon, load cells, force sensors, mechanical after effects

1. Introduction

For load cells (LS) made of single-cristalline mechanical springs (S-Spring-LCs) with applied thin film metal strain gauges a high reproducibility is expected [7]. Therewith these LCs are predestined for mechatronic systems to compensate electronically non-linearities and enviromental factors of influence e.g. temperature or time depending effects [2] and are subject of actual investigations at PTB.

One of the requirements for the expected high reproducebility of S-Spring-LCs are low time depending effects e.g. mechanical after effects of the spring material. Theoretically single-cristalline silicon (Si) used as spring material deforms purely elastic and shows nearly no mechanical after effects and therewith fullfills the basic requirements [1], [5], [6]. This paper deals with experimental investigations of the deformation of S-Springs and an experimental assumption of time depending mechanical after effects.

The investigations are carried out with a double bending beam S-Spring. The nominal load of the S-Spring amounts 6 kg. The geometry of the S-Spring is optimised numerically and described by suitable geometry parameters.

Due to the expected low mechanical after effects of the S-Spring in comparison to conventional mechanical springs, tipping effects of the force introduction are not negligible for the assumption of mechanical after effects.

For this reason a Fizeau interferometer is used to carry out experimental investigations on the S-Spring. The interferometer delivers 3-D topology data of surfaces by analysing the interferogram with a camera. This enables both investigations of misalignments and tipping effects of the whole S-Spring within the experimental setup, as well as the calculation of the deformation of the S-Spring under load.

As shown in this paper only by consideration of misalignments and tipping effects within the experimental setup an assumption of mechanical after effects of S-Springs is possible.

2. Mechanical Spring Made of Silicon

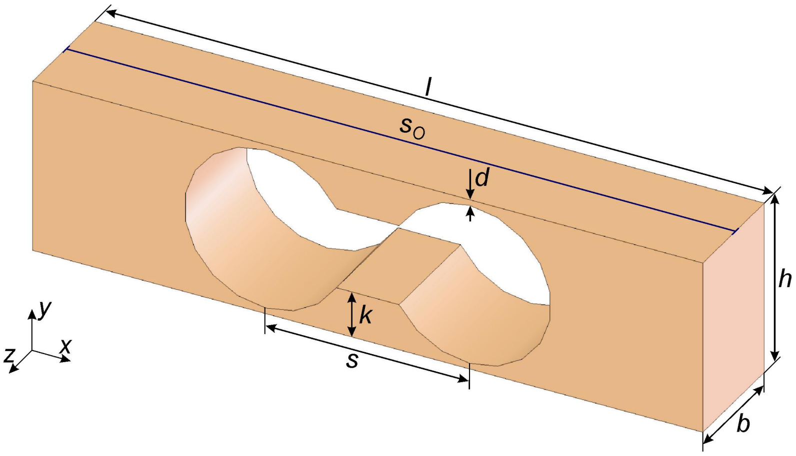
2.1 Geometry

The geometry of the S-Spring is chosen with regard to the nominal load, the requirements of the thin film application and the requirements resulting from the material properties of Si.

The S-Spring is design as double-bending beam. Next to the well known advantages of this geometry aspects of manufacturing caused by the processing of Si and the application of thin film strain gauges by the sputtering technology are mainly deciding.

Figure 1 shows the model of numerical simulations and the optimized geometry parameters of the double bending beam S-Spring [7]. The line s_O is used for later investigations of the strain behaviour.

As already known the parallel guidance and the thin places of the upper and lower bending beam lead to areas of extension and compression under load on the upper and lower surface. For S-Springs only the deformation on one surface is measured. This simplified the manufacturing processes of S-Springs essentially as shown in the following section.



l = 115 mm
h = 30 mm
b = 20 mm
d = 1 mm
s = 35 mm
k = 8 mm

Figure 1 Model of the mechanical spring in double bending beam geometry and values of the optimised geometry parameters.

2.2 Manufacturing

Undoped single crystalline Si rods with a defined orientation due to the anisotropic material behaviour of Si are the feedstock of S-Springs. As a result of numerical investigations [7] the orientation of Si within the S-Spring influences the measurement properties of the S-Spring and has to be taken into account.

For the mechanical manufacturing of S-Springs special tools for processing with diamond grinding heads are required due to the brittle material behaviour of Si. After mechanical processing the surfaces of the S-Spring have unavoidable micro cracks which promote the fracture of the S-Spring under load. To remove these cracks the surface of the S-Spring has to be etched in a subsequent step. But also with etching the surface quality does not fulfil the requirements necessary for sputter on thin film strain gauges and demand additional time-consuming polishing processes.

The complex sputter process of the thin film strain gauges as well as the time-consuming polishing process has to be performed on one single surface if the double bending beam geometry as shown in figure 1 is chosen.

Figure 2 shows the picture of a S-Spring made of single crystalline Si and manufactured at PTB by the mechanical process described above.

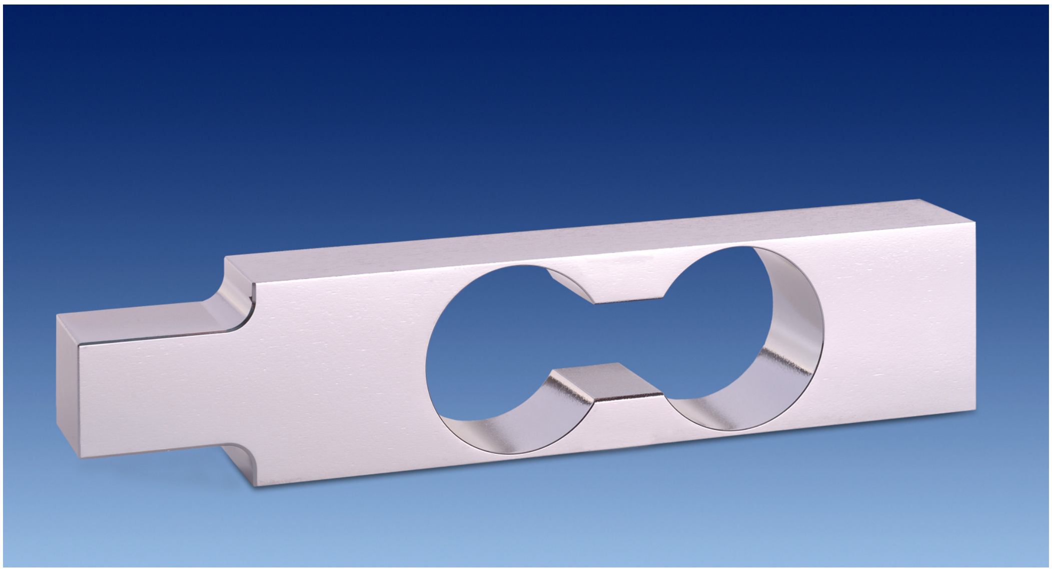


Figure 2 Mechanical spring made of single crystalline silicon

2.3 Numerical Results of Deflections Under Load

In the following the results of numerical simulations carried out on the model of a S-Spring-LC with the geometry parameters shown in figure 1 are discussed. Figure 3 shows the deformation s_y in y-direction at the middle of the upper surface along the line s_O (cf. figure 1) and under a load of 60 N. This load corresponds with the nominal load of the S-Spring of 6 kg.

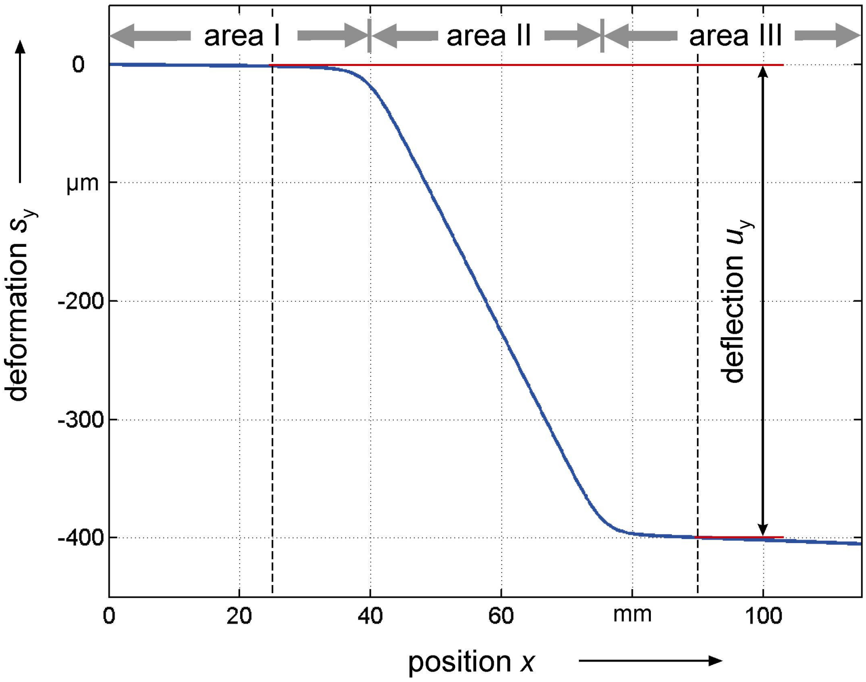


Fig 3 Deformation s_y at the surface of the mechanical spring under load as function of the position x.

As expected the investigations point out three areas of characteristic deformation, which are separated by the thin places.

At the thin places the mechanical strain concentrates and causes the deformation behaviour of the S-Spring under load. As a result the surfaces of the areas before (area I) and behind (area III) the thin places move nearly in parallel. As quantum for the deformation of the S-Spring under load the deflection between the surface of area I and area III is used.

In the following for all analysis the deflection u_y of the S-Spring is defined as the difference of the deformation at the points x = 90 mm on the surface of area III and x = 25 mm on the surface of area I (marked with dashed lines in figure 3).

The simulations point out a linear dependence of the deflection u_y on the acting force. The maximum deflection for a simulated force of 6.12 kg amounts u_y = -398.3 µm. Related to an acting mass the deflection sensitivity results to s_u = 65.1 nm/g.

3. Experimental Setup

To perform experimental deformation measurements on a S-Spring for the first time a Fizeau interferometer available at PTB is used. This interferometer delivers position depending height information data of a surface topology within a short time interval. For this purpose the interferometer analyses the interferogram with a camera and delivers 3-D topology data of the surface. Such a topology measurement only takes about 10 seconds for a cyclical surface up to a diameter of 100 mm. The maximum educible difference in height on the surface is about 50 µm.

A schematic arrangement of the experimental setup with the interferometer and the S-Spring is shown in figure 4.

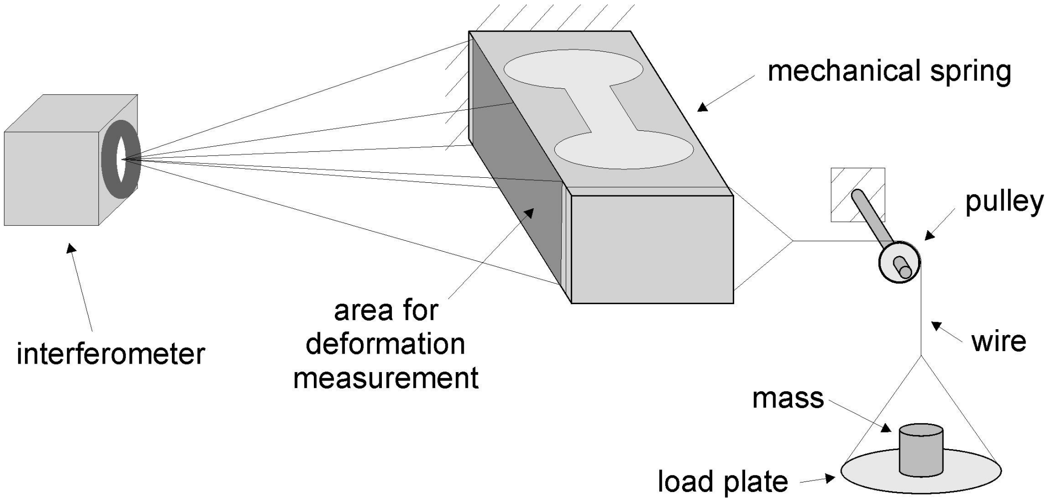


Figure 4 Schematic arrangement of the experimental setup to measure the deformation of the mechanical spring under load.

The fix mounted Fizeau interferometer has path of rays with horizontal adjustment. This requires a rotated mounting of die S-Spring by 90 degrees as shown in figure 4 to achieve a perpendicular arrangement of the surface investigated to the laser beam.

The force introduction is realized by putting weights on a load plate and switching the weight force via a wire and a pulley with low friction to the S-Spring.

To reduce the influence of vibrations the Fizeau interferometer and the experimental setup are mounted on a vibration isolated table. The measurements are performed in an air-conditioned laboratory by a temperature of 20 °C and a relative humidity of 55 %.

Figure 5 illustrates the experimental setup.

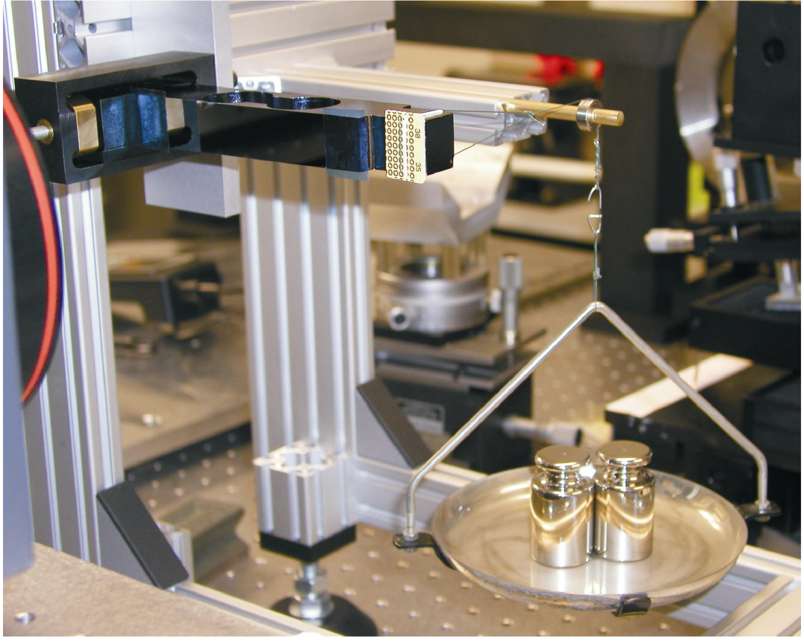


Figure 5 Picture of the experimental setup

For measuring the deformation of the S-Spring the 3-D topology data allows to correct for elongations of the experimental setup caused by temperature drifts, e.g.. This could be also achieved by using a differential two point interferometer which two laser beams touch at the beginning and at the end of the S-Spring.

Using a differential two point interferometer it is not possible to assume the mechanical after effects with the required accuracy as shown in the following.

3.1 3-D Topology Surface Data of a S-Spring Under Load

This section deals with the results of deformation measurements of the S-Spring under load. Because the measuring range of the interferometer is limited to a maximum spring deformation of about 50 µm, it is not possible to load the S-Spring with the nominal load of 6 kg because this would lead to a maximum deformation of 400 µm. This is why the S-Spring is only partial loaded in the following.

Experimental results of the investigations carried out with the Fizeau interferometer on the surface of a S-Spring are shown in figure 6. The surface deformations in µm as function of the positions *x* and *y* in mm for the unloaded S-Spring and two different loads of 50g and 300g are pointed out. Additionally the mass of the load plate of 186 g has to be taken into account to obtain the total load acting on the S-Spring.

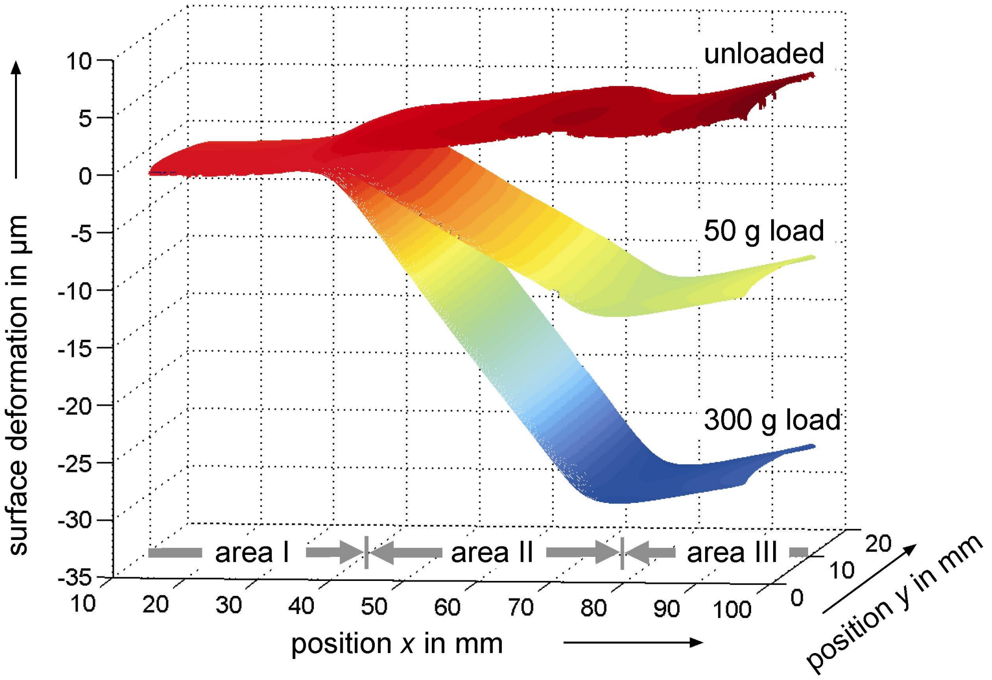


Figure 6 Surface deformation of the mechanical spring as function of the positions *x* and *y* for different load steps

The experimental investigations of the S-Spring under load verify the results of previous numerical investigations in principle. Three areas with different deformations which are separated by the thin places can be detected as expected.

The experimentally determined deflection sensitivity s_u defined in chapter 2.3 amounts 65.2 nm/g and is consistent with the result of numerical investigations of s_u = 65.1 nm/g. The deformation to determine the deflection is analysed along the middle line s_O on the surface of the S-Spring (cf. Figure 1) by averaging the data in *y*-direction over 10 pixels – which corresponds to a distance of about 1 mm.

The data of the unloaded S-Spring indicate the undeformed topology of the S-Spring. The investigations point out that the area between the thin places (area II) is raised a few µm related to the area before (area I) and behind (area III) the thin places. Furthermore, a difference in parallelism between the area I before and area III behind the thin places can be seen. These results are caused by manufacturing processes and show the initial topology of the unloaded S-Spring, which has to be considered by subsequent analysis.

3.2 Arrangement Error and Tipping Effects of the Clamping

A tilted position of the S-Spring to the laser beam of the interferometer leads to an error in the measurement of deflection. A tilted position can be caused by an arrangement error due to a not exactly perpendicular mounting of the S-Spring to the laser beam as well as by tipping effects of the clamping under load.

To discuss these two effects the surface angle α between a line perpendicular to the laser beam and the surface line s_O of the S-Spring is analysed. Therefore linear smoothing functions in the range of 5 mm along the *x*-direction are calculated and the linear coefficients of these functions are converted to a surface angle α as a function of the position *x*. Figure 7 shows the surface angle α as function of the position *x* for the unloaded S-Spring (blue line) and the S-Spring under a load of 300 g (red line).

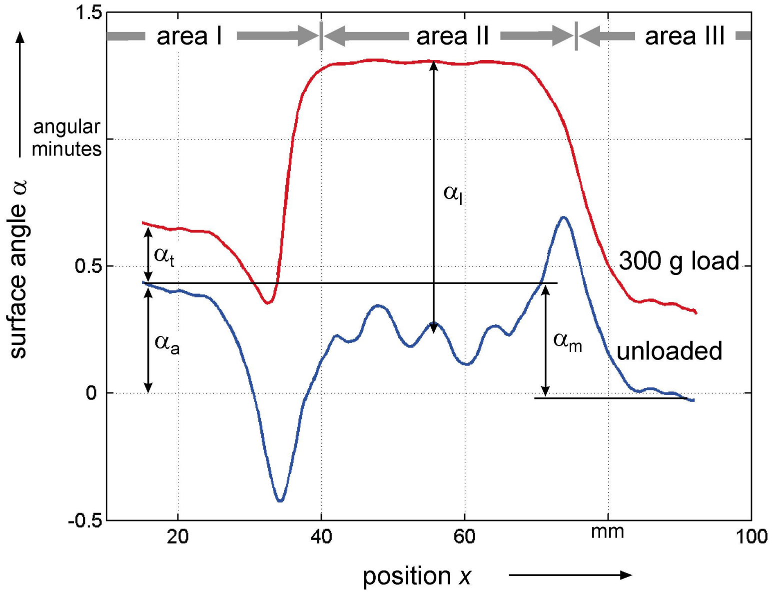


Figure 7 Surface angle α of the mechanical spring as function of the position *x* for different load steps

As discussed due to the manufacturing process the surface of the S-Spring is not exactly plane which results in differing angles α along the position *x* for the unloaded S-Spring. The difference between the angle at the beginning of the unloaded S-Spring (area I, *x* = 17 mm) and the ending of the unloaded S-Spring (area III, *x* = 95 mm) amounts α_m = 0.45′ and is a quantum for the parallelism of the initial topology of the unloaded S-Spring.

The angle α_a = 0.4′ at the beginning of the S-Spring characterises a misalignment of the complete arrangement concerning the laser beam.

Both α_m and α_a leads to errors in the measurement of the deflection but can be corrected easily by subtracting the deflection value for the unloaded S-Spring from all deflection values determined under load.

In the following the results of the angle $\boldsymbol{a}$. of a S-Spring under load are discussed. For a S-Spring under a load of 300 g the surface angles in area II increase from 0.25′ to 1.25′ as expected which results in a difference of $\boldsymbol{a}_{\mathrm{l}} = 1'$. Furthermore at the beginning of the S-Spring $\boldsymbol{a}$ increases about $\boldsymbol{a}_{\mathrm{t}} = 0.25'$. The angle $\boldsymbol{a}_{\mathrm{t}}$ could not be explained by the deformation of the S-Spring. This leads to the assumption that the whole S-Spring is tipped under load caused by deformation and tipping of the clamping in the experimental setup.

If this assumption is right the angle at the beginning of the S-Spring labelled $\boldsymbol{a}_{\mathrm{b}}$ as well as the angle at the end labelled $\boldsymbol{a}_{\mathrm{e}}$ should increase linear with the load.

To discuss the tipping of the S-Spring under load $\boldsymbol{a}$ is calculated for the beginning $\boldsymbol{a}_{\mathrm{b}}$ and for the end $\boldsymbol{a}_{\mathrm{e}}$ of the S-Spring. In figure 8 these surface angles are plotted with the statistical expanded confidence belt as function of the load.

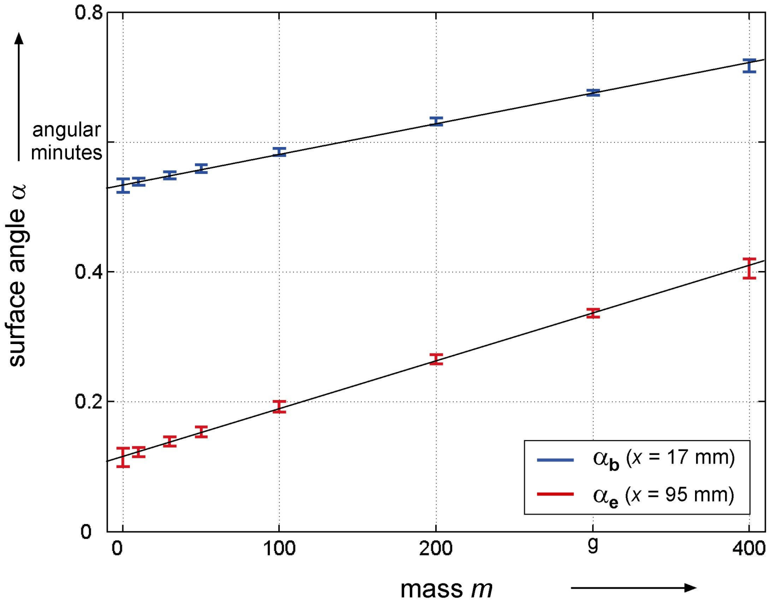


Figure 8 Surface angles $\boldsymbol{a}_{\mathrm{b}}$ at the beginning and $\boldsymbol{a}_{\mathrm{e}}$ at the ending of the mechanical spring as function of the mass m

Both $\boldsymbol{a}_{\mathrm{b}}$ and $\boldsymbol{a}_{\mathrm{e}}$ show a linear and repeatable dependence on the mass, which is illustrated by two linear smoothing functions, and described by the linear coefficients of $7.7 \cdot 10^{-3}$ °/kg for $\boldsymbol{a}_{\mathrm{b}}$ and $12.1 \cdot 10^{-3}$ °/kg for $\boldsymbol{a}_{\mathrm{e}}$. A reason for the difference of these coefficients could be the not exact manufacturing of the thin places which leads to a displacement of the parallel guidance. This is why the surface angle $\boldsymbol{a}_{\mathrm{b}}$ is used for calculating the tipping of the whole S-Spring in the following.

Based on these considerations the error of the deflection u_{y} caused by the tipping of the whole S-Spring under load is 8.6 nm/g which leads to an error of deflection of 2.6 µm for a load of 300 g. This effect is with 13 % of the measurement result not negligible and must be compensated.

4. Identification of Mechanical After Effects

By analysing the 3-D topology data of the surface in a suitable way the deformation measurements become independent from drift effects of the experimental setup. Elongations of the experimental setup can be eliminated as well as the tipping of the S-Spring within the experimental setup. The elimination of these influencing factors is very important, especially for time-dependent measurements as the measurement of mechanical after effects. The analytical compensation of the deflection error caused by tipping of the S-Spring allows the evaluation of the mechanical after effect with the required accuracy.

To investigate the mechanical after effects creep measurements are performed. After three preloads with the nominal load of 400 g and a pause of 5 minutes the nominal load is applied for 30 minutes (loading) and then all masses and the load plate are removed for 30 minutes (unloading).

During the creep measurement in the first five minutes after load change every 20 seconds and then every minute one interferometer measurement is taken out.

To visualise the creep behaviour the tipping corrected deflection data of the creep measurement are plotted in figure 9 as function of the time. For the loading the deflection u_y is normalised to the value $u_{y,lc}$ 30 minutes after load change and subtracted by 1. For the unloading the deflection is normalised to $u_{y,lc}$.

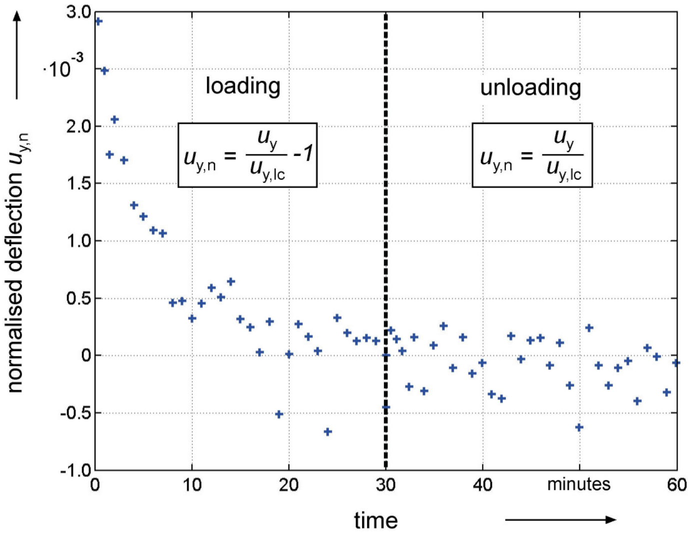


Figure 9 Normalised deflection $u_{y,n}$ as function of the time for the loading and unloading

During loading the deflection decreases with increasing time and during unloading the measured deflection shows no detectable time dependence. This unexpected behaviour could not be explained by mechanical after effects of the S-Spring. In the first place mechanical after effects lead to symmetric time dependencies of the measurement signal for loading and unloading. Secondly changes of deflection caused by mechanical after effects would lead to an increasing deflection during loading.

To verify this inconsistent behaviour series of measurements were taken out with a conventional LC to investigate the influence of the force introduction over a pulley. In a second step the conventional LC was loaded directly in normal mounting position. In both cases not the deflection but the LC signal was measured.

As a result the difference in relative creep of the LC signal loaded by pulley and loaded directly is in the same order of magnitude than the deflection creep measurement of the S-Spring loaded by the pulley. From this result follows that the loading creep is mainly caused by the hysteresis of the pulley and by creep effects of the experimental setup.

For the unloading creep no differences in the creep behaviour between a force introduction via pulley and the directly loaded LC are detectable.

This leads to the conclusion that the loading creep measurements are not suitable to investigate mechanical after effects due to the influence of the experimental setup.

Subsequently the unloading creep measurements are used to calculate mechanical after effects of the S-Spring.

The relative mechanical after effect χ_a is defined by subtracting the deflections X_{lc} direct after load change and deflection X_{30} 30 minutes after load change and relating the result to the deflection X_l under load:

$$\chi_a = \frac{X_{30} - X_{lc}}{X_l}$$

Due to the not detectable change in deflection for the unloading the confidence belt of the deflection data measured is taken as the maximum possible change in deflection to calculate the upper limit of the relative mechanical after effects. From the analysed statistical expanded confidence belt of ±3.1 nm and the loaded deflection of 38.4 µm the mechanical after effect of the S-Spring is calculated to be lower than $\chi_a = 8 \cdot 10^{-5}$.

To attain creep data for the unloading resulting from a higher deflection which leads to a higher resolution of the measurement of mechanical after effects a second creep measurement with a load of 3 kg is taken out. But during unloading the deflection of the S-Spring is recorded as described above.

This second creep measurement leads to similar deflection data without detectable changes of deflection while unloading. The load deflection is calculated to 150.7 µm. Based on this data the mechanical after effect of the S-Spring is substantiated to be lower than $\chi_a = 2 \cdot 10^{-5}$.

5. Conclusions and Outlook

This paper presents first results of experimental investigations performed with a S-Spring with a nominal load of 6 kg and geometry parameters optimized by numerical simulations. Load depending deformation measurements of the S-Spring verify the expected low mechanical after effects.

For the first time the investigations are carried out with a Fizeau interferometer, which delivers 3-D topology data of surfaces. This interferometer enables both investigations of misalignments and tipping effects of the whole S-Spring within the experimental setup as well as calculations of deformations of the S-Spring under load.

The investigations point out with an error of deflection of 8.6 nm/g which affects the measurement result up to 13 % tilting effects of the S-Spring within the experimental set-up are not negligible and has to be compensated analytically.

As a result the S-Spring investigated shows mechanical after effects of $\chi_a = 2 \cdot 10^{-5}$. This value is about a factor of 100 lower in comparison to conventional LCs made of metallic material and therewith confirms material properties given in literature for mechanical after effects of silicon [1].

As demonstrated with the experimental investigations carried out, S-Springs show nearly no mechanical after effects. Therewith S-Spring-LC with sputtered on thin film strain gauges fulfil all basis requirements to compensate electronically non-linearities and enviroment factors within mechatronic systems.

Currently S-Springs with sputtered on strain gauges are investigated concerning their time-depending and temperature-depending behaviour and their linearity. First results seems to confirm the expected high reproducibility.

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