Development of a 650 kN tension and compression force transducer

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Abstract

Accurate force proving instruments are key to reliable results in research. This paper describes the development of a 650 kN tension and compression force transducer, based on strain measurement, for a hydraulic research test bench. An optimal design was derived through FE-analyses and the calibration of the force transducer was planned according to the standard ISO 376:2011. The development process was validated by designing and calibrating a prototype. Observations for the development process were gained in the validation process and are discussed together with results from FE-analysis.

Introduction

Force transducers are sensors that measure mechanical loads. The most common force transducers measure forces by virtue of strain gauges fitted to them [1]. The strain gauges are placed on a spring body that deforms elastically under load according to Hook's law [2, 3]. Depending on the direction and magnitude of the load, force transducers have different shaped spring bodies and strain gauges [4, 5]. The principle of radial symmetric shear beams has been shown to be a suitable basis for the design of force transducers used in experimental mechanics [1]. When applied to the spring body of a force transducer, the design consists of a hub and a ring connected by symmetric radial beams. When force is applied to the hub, the individual beam elements behave as shear beams fixed on two sides. Strain gauges are fitted to the beams where shear stress is concentrated under load. This working principle is depicted in figure 1.

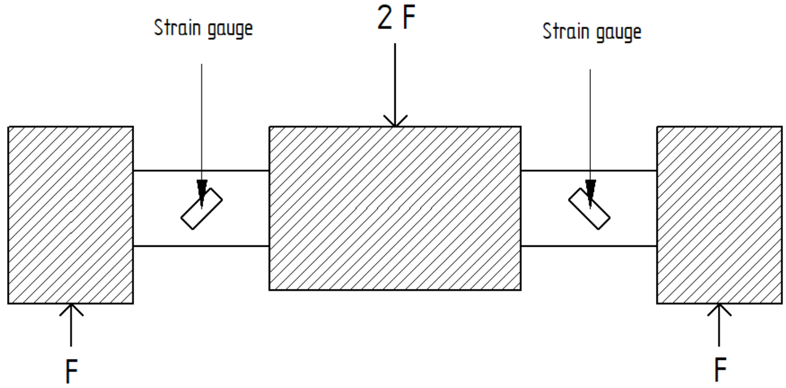

Figure 1. Simplified cross-section of radial symmetrical shear-beam type force transducer showing strain gauge location.

In the context of experimental mechanics, the design is favourable for several reasons: the highest strain concentrations are found where strain gauges are placed [1]. Kleckers demonstrated that the strain field of the spring body of the monolithic radial symmetric shear beam type is evenly distributed in the area of strain gauge installation and contains no peaks, unlike other designs [6]. Consequently, the linearity error produced by this design is low, fatigue life of the strain gauge is high and the transducer's overload capacity is also high [1, 6]. The design's high stiffness resists bending moments and lateral forces and when produced as a monolithic flange sensor, exhibits low hysteresis [7, 1].

The aim of this investigation is to design, manufacture and calibrate a 650 kN force transducer, based on the monolithic radial symmetric shear beam design principle, for a hydraulic test bench measuring compressive and tensile loads produced by two hydraulic cylinders. In addition to measuring the force produced due to the action of the hydraulic cylinders, the force transducer must connect the two hydraulic cylinders together such that a load produced by the hydraulic cylinders does not cause the assembly to significantly deviate from its axis of symmetry and is prevented from rotating, as both cylinders are connected to the frame of the test bench with ball joints. This means that this application also has unique safety critical requirements for the force transducer to resist buckling and bending moments. The maximum tensile load transmitted to the force transducer is 450 kN and the maximum compressive load is 650 kN. Additionally, the force transducer is required to have a measurement accuracy of 1%.

Methods

System Description. The force transducer system consists of a load cell, strain gauges, a Wheatstone bridge circuit, and an amplifier with integrated data acquisition.

Design procedure. The geometry of the spring body and elastic elements of the force transducer was optimised using finite-element analyses (FE-analyses) according to the following parameters:

- Strain in the measurement area of the spring body under maximum force should be (1000μm/m) [8].
- Strain in the measurement area should be as uniform as possible and be minimized in all other parts of the spring body.
- The material of the spring body needs to have a high enough yield strength to achieve a safety factor of two, while producing the mandated measurement strain at maximum force.
- The spring body must be able to withstand 650kN of force at an angle perpendicular to the intended force direction without yielding and be highly resistant against buckling.
- Sufficient space for the fitting of strain gauges to the spring body by hand is required.

DIN EN 1.4462 duplex stainless-steel was chosen as the load cell's material, because of its good resistance to corrosion, suitable modulus of elasticity and high yield strength.

Different curves for the sides of the shear beams, where strain gauges are installed, were tested for optimizing the uniformity of the strain field. A full Wheatstone bridge was used as the basis of the design of electrical circuit, due to its ability to automatically compensate some bending and temperature effects. The full bridge circuit was formed by connecting opposing arms of the bridge to like-strain gauges in series: that is, two opposing arms in compression and two opposing arms in tension. The circuit was designed to be fed by an HBM QuantumX MX410B amplifier providing an alternating excitation voltage, whose amplitude is modulated according to the unbalance of the bridge circuit. In addition to the circuit's excitation voltage input and signal output lines, sensing lines were connected from the amplifier in series with the excitation voltage lines to detect and compensate for voltage loss in the excitation wires. The optimized design of the 650 kN force transducer can be seen in figure 2, along with the electrical circuit superimposed on the optimized design.

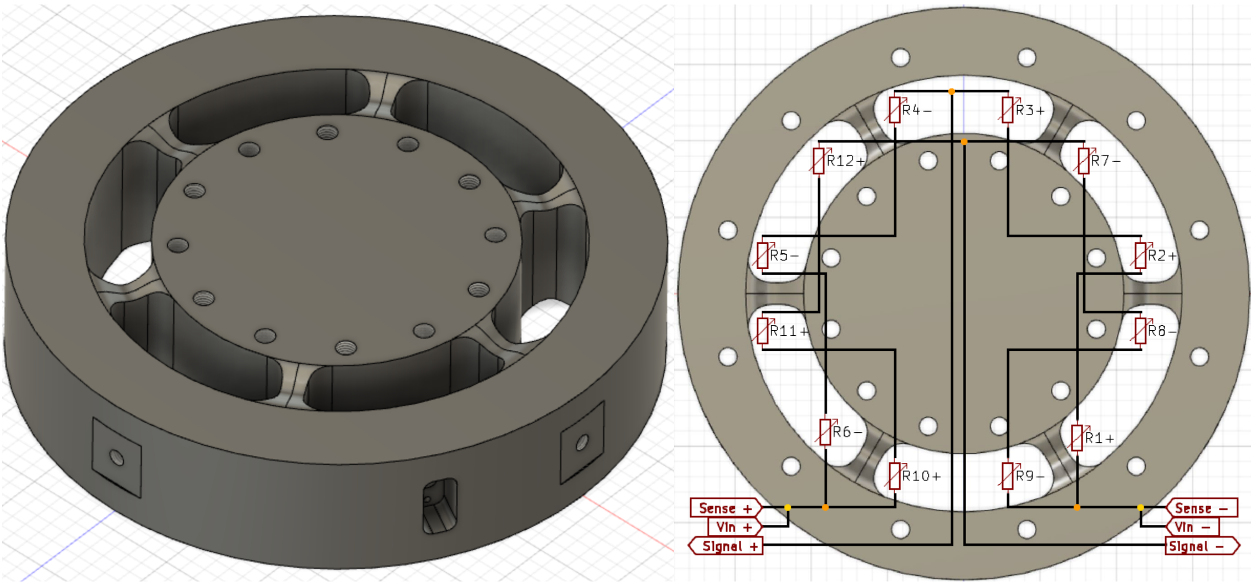

Figure 2. Optimised design of 650 kN force transducer (left), and electrical circuit of 1 MN force transducer superimposed on optimised design (right). Strain gauges in compression marked with (-), strain gauges in tension marked with (+).

12 pc HBM 1-LM11-3/350GE, 350 Ω chrome-nickel strain gauges were specified for the circuit, to be fitted on both sides of each individual shear beam. Chrome-nickel shear strain gauges were chosen instead of equivalent constantan units for two reasons: higher gauge factor meaning higher output signal and greater sensitivity, and an ability to compensate for the temperature dependence of the sensitivity of the transducer, because of the chrome-nickel's inversely proportional relationship between temperature and gauge factor. This is important, as the elastic modulus of steel decreases with increasing temperature, leading to greater measured strain at higher temperatures if no compensation measures are applied [8].

Calibration procedure. ISO 376:2011 "Metallic materials. Calibration of force-proving instruments used for the verification of uniaxial testing machines" is one of the existing standards describing the calibration process for force transducers [9]. ISO 376:2011 thus served as a guideline in developing a calibration procedure for the designed force transducer. A signal was designed for the calibration such that every step starts with preloading the force transducer once or three times. After that, the measurements for the ten different calibration forces are read 30 s after applying or releasing a force. Measurements with zero force applied are also taken. The creep test is only performed during the last step, and the measurements are read 30 s and 300 s after applying and releasing the force.

Process validation. To validate the design process, a prototype force transducer with a load capacity of 1000 N based on the monolithic radial symmetric shear beam design principle was designed, manufactured, and tested. The HBM QuantumX MX410B amplifier and a laptop with Catman Easy V3.5.1 software installed was used for data acquisition and performing measurements. Insights gained from the validation process were used to establish an understanding of the calibration procedure and the performance of the radial symmetric shear beam design principle. The calibration procedure described in ISO376:2011 was investigated by adapting and modifying the preloading procedure to suit the 1000 N force transducer. The transducer was loaded with 100.145 kg resulting in a force approximating the transducer's designed maximum capacity. The load was applied three times, and after each application, the transducer's zero-point signal was recorded. The completed force transducer is depicted in figure 3 along with a static FEM-analysis of its structure.

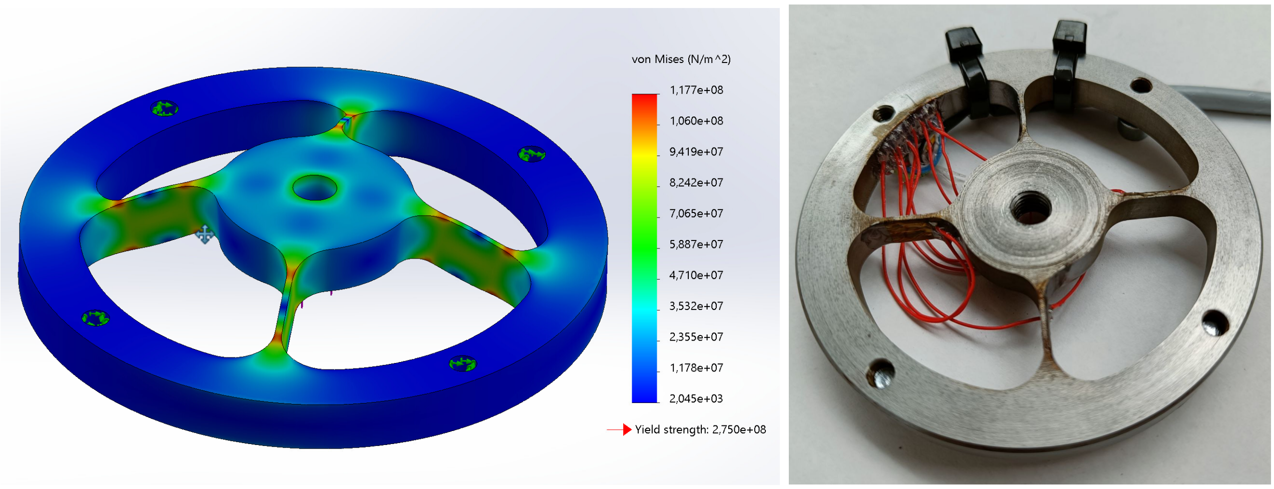

Figure 3. Stress distribution of force transducer at 1000N (left) and manufactured unit (right).

Results

Figure 6 shows on the left, the overall stress distribution of the force transducer when loaded with 650 kN in a static simulation in SolidWorks. For the simulation, force was applied to the hub and the bolt holes in the outer ring were fixed. The stress reaches a maximum of 249 MN/m^2 in the simulation, which is just below half of the yield strength of the specified material, which was tested to be 516 MN/m^2. The stress is very localized in the shear beams. On the right of figure 4, the proposed approximate location and size of the strain gauge has been marked with a white rectangle. The strain gauge is in an area of relatively uniform strain.

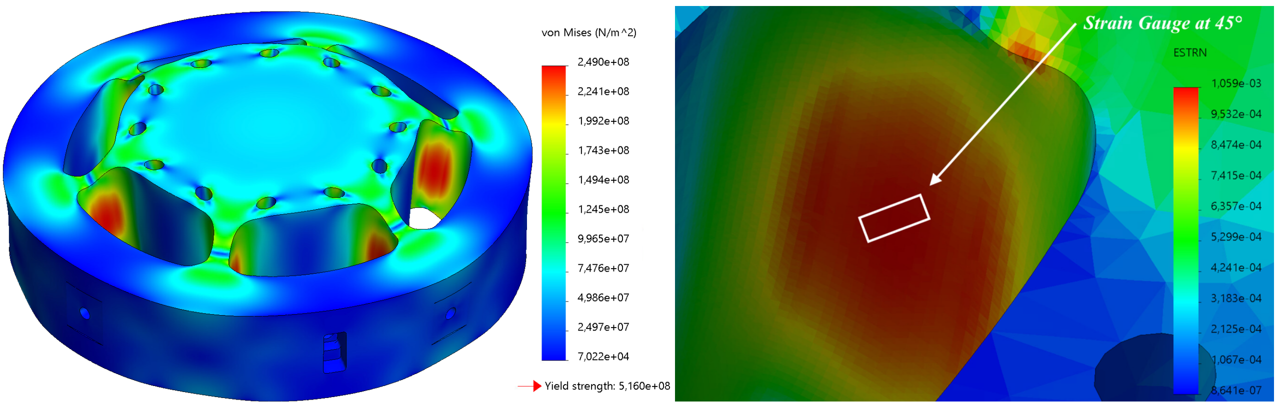

Figure 4. Stress distribution and magnitude in the spring body at 650 kN (left), Strain distribution and magnitude on the shear beam at 650kN with strain gauge (right).

In figure 5 on the right, the inner surface profile of the shear beam relative to the z-axis is concave with a radius of 100 mm, which makes the shear beam 0.25 mm thicker at the point where the corner fillets start. The histogram shows that the stress distribution becomes significantly more uniform when the inner surface is curved.

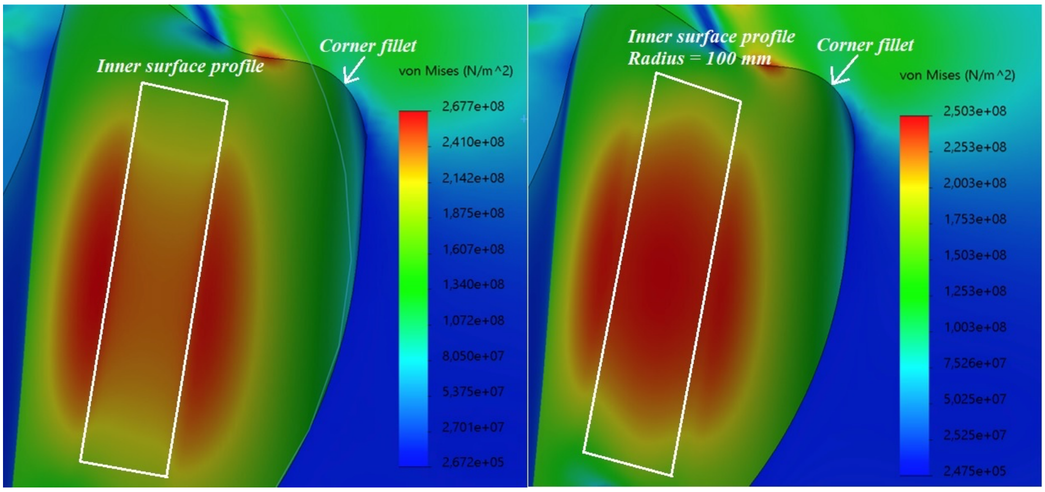

Figure 5. Stress distribution on shear beam surface with flat inner surface (left) and curved inner surface (right).

Process validation results. After preloading the 1000 N force transducer the first time, the zero-point signal increased to the equivalent of 13.0 kg, after which no further change was observed in successive loading. When loading the spring body in the opposite direction with the same weight, the zero-point signal decreased, equivalent to 1.6 kg. After loading it in the original direction again, no significant change was observed.

Discussion

Results from static FEM-simulations conducted on the proposed 650 kN force transducer demonstrated the success with which, after careful geometric optimisation, the design produced uniform stress distribution in the desired measurement area while minimising stress elsewhere in the spring body. The target strain of 1000 µm/m in the measurement area at maximum load was also achieved. Furthermore, the results highlighted the design's excellent stiffness and ability to resist lateral forces. The spring body would not yield due to a force of 650 kN applied from any direction, fulfilling the safety critical requirements relating to the secure attachment of the two hydraulic cylinders.

The differences between the curved and flat shear beam inner surfaces highlight the importance of curvature for producing a uniform stress distribution. In the case of the flat inner surface, minor misplacements of strain gauges could result in large differences in sensitivity.

The process validation results indicate that the material of the spring body settles after being loaded for the first time in any load direction. This suggests that it might be beneficial to overload the 650 kN transducer before calibration to avoid a moving zero-point later in the process.

Based on the outcomes of this study, the radial symmetric shear beam design principle presents as a suitable basis for the proposed application. Future research will consist of calibration of the 650 kN transducer according to ISO376:2011 and an analysis of its behaviour close to the zero point during the calibration procedure under varying environmental conditions.

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