Multicriteria approach to design of strain gauge force transducers

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Abstract. Force transducers based on strain gauges are ubiquitous in force measuring equipment. Manufacturers of force transducers have to strive for stronger, cheaper and more accurate force transducers in order to compete successfully on the global market. Transducers have to be designed as fast as possible and require as little experimental work as possible. To that end, a reliable design tool is required. In this paper, we propose a new approach to design of force transducers based on strain gauges. The approach is based on the Parameter Space Investigation method and methods of multicriteria optimization. The transducer’s parameters used as design criteria (output signal at rated load, nonlinearity, etc.) are evaluated using Finite Element Analysis (FEA). The FEA results are used to find the optimal locations of strain gauges. This method was implemented in the software system for multicriteria design of force transducers based on strain gauges. The system was used to design a novel force transducer and can be used for developing new strain gauge-based force transducers and optimizing the existing ones.

1. Introduction
Strain gauge force transducers are widely used in force-measuring equipment. The advantages of using strain gauge force transducers include high measurement accuracy, small dimensions. These transducers have good resistance to electromagnetic disturbances and work well with voltage-measuring equipment which is crucial when using transducers in modern measuring systems. Despite the existing wide range of designs [1] the task of further improving force transducers’ design to make them more competitive on the market is still relevant. To that end, the designers will need a new tool of force transducer design that shortens the development cycle and minimizes the amount of experimental work. The rest of the paper is organized as follows. Firstly, we introduce the working principle and design requirements for strain gauge force transducers. Then we will introduce the multicriteria approach to design of strain gauge force transducers; the approach is implemented in a special software system. After that, we demonstrate the work of the proposed approach with an example.
2. Working principle and design requirements for strain gauge force transducers

A strain gauge force transducer is a transducer that converts applied force into electrical signal. It is comprised of an elastic element which is being loaded via a thrust piece. The applied load deforms the elastic element. Mechanical strain in certain areas of the elastic element is measured using foil strain gauges. The measured strain depends on the place where the strain gauges are bonded to the elastic element. Strain gauges are connected to form a circuit known as the Wheatstone bridge circuit. Strain gauges change their resistance because of strain; resistance change creates voltage at the output terminals of the Wheatstone bridge. The voltage is proportional to the applied load [1].

Designing strain gauge force transducers is a multicriteria problem. The input parameters include characteristic geometric dimensions of the force sensor’s elastic element, mechanical properties of the elastic element’s material, configuration of the Wheatstone bridge circuit (type of strain gauges, location of strain gauges, etc.). These parameters are called design parameters. The output parameters, also called objectives or design criteria, are the parameters determining the measurement error (nonlinearity, hysteresis, creep) and other parameters such as the overloading capacity of a transducer, the magnitude of the output signal, etc. These criteria often contradict each other. For instance, the increase of the output signal proportional to the magnitude of the measured strain leads to the increase of nonlinearity and decrease of the overloading capacity.

The design process comes down to choosing the topology of the transducer’s elastic element, defining the dimensions of the elastic element, and determining the locations where the strain gauges will be installed so that the output signal is of desired magnitude, the measurement errors and weight are minimized, the overloading capacity of the transducer is greater than required by the designer.

3. Design method

We propose using the approach based on the Parameter Space Investigation Method [2, 3] and methods of multicriteria optimization [4]. The design process workflow (see figure 1) can be subdivided in two stages.

![Figure 1. Design method workflow.](image)

At the first stage, the designer chooses the parametric topology of the transducer’s elastic element, for example, membrane or ring torsion elastic element. Then the designer chooses the transducer’s parameters that are going to vary in the design process. The designer also specifies the limits within which the parameter may vary. These limits define the design parameter space – an N-dimensional hypercube for the case of N design parameters. The parameter space is investigated using $LP_r$ sequence [5]. Each element of the sequence corresponds to a particular geometry of the transducer’s elastic element within the chosen topology. Each design is simulated using FEA in order to obtain information about the elastic element’s stress-strain state. The analysis is taking into account
Joint IMEKO TC1-TC7-TC13-TC18 Symposium 2019
Journal of Physics: Conference Series 1379 (2019) 012010
IOP Publishing
doi:10.1088/1742-6596/1379/1/012010

geometric nonlinearity [6, 7] and nonlinearity arising from the contact interaction between force transducer and its loading pads [8].

After that, the optimal configuration of the Wheatstone circuit is determined for each elastic element design. This problem comes down to determining such locations and orientations of the strain gauges so that the measured linear strain is maximised while the resultant nonlinearity of the sensor, including nonlinearity of the Wheatstone bridge, is minimized. The problem is solved using the following algorithm. Firstly, a set of possible locations where the strain gauges can be installed is generated. Then the measured strain is calculated for each strain gauge location in the given strain field. To that end, a special mathematical model of strain gauge is used. The model takes into account the dimensions of the strain gauge and its orientation in the strain field. The model is similar to the one used in [9]. It is based on nodal strain data from FEA. After that, possible locations are split into two sets: gauges experiencing tension and gauges experiencing compression. The algorithm iterates through different combinations of tension and compression gauge locations forming full Wheatstone circuits and evaluates the output signal at the rated load and the nonlinearity of the output signal. Finally, the algorithm chooses the optimal configuration having the least absolute nonlinearity and the output signal greater than specified by designer. After that, the values of the remaining criteria (overloading capacity, mass, etc) are calculated using FEA results.

At the second stage, the designer imposes constraints on the design criteria values. The constraints look like “the output signal should greater than 1 mV/V” or “the maximum nonlinearity should not exceed 0.05 % of full scale”. A set of feasible designs that satisfy all the constraints is constructed. After that, a set of Pareto-optimal designs is constructed based on the set of feasible designs. If the set of feasible designs is empty, the criteria constraints can be weakened; in this case the sets of feasible and Pareto-optimal designs are recalculated and re-evaluated. The parameter space can be investigated anew after changing its boundaries. A local search can be conducted in the neighborhood of a certain Pareto-optimal design.

The proposed design method was implemented in a software system for designing strain gauge force transducers. Some of the user interface forms of the developed software system are shown in figure 2.

![Figure 2. User interface of the developed software program.](image-url)
The principle of interacting between the Finite Element software and the software is similar to the system presented in [10]. The information about feasible and Pareto-feasible designs is presented to the designer in the form of scatter plots, histograms, radar charts, etc. If the criteria constraints change, the sets of feasible and Pareto-optimal designs will be reconstructed automatically, as well as all plots visualizing this information. The design results are stored in the database.

4. Case study
The proposed approach will be demonstrated by designing a novel strain gauge force transducer. The measuring range of the transducer is 0…1000 kN. The topology of the transducer’s elastic element is shown in figure 3 (a). The information about design criteria is shown in table 1. Let us elaborate on the criteria. The output signal of most force transducers is 2 mV/V at rated load. However, different compensation elements of the Wheatstone bridge can reduce the output signal by as much as 10%. Therefore, the minimum acceptable value of the output signal at rated load is 2.2 mV/V; this corresponds to the value of strain approximately ±1100 ppm measured using constantan strain gauges with the gauge factor of 2. The material of the elastic element is quenched stainless steel having hardness 40 HRC, the yield strength $\sigma_y$ of 1000 MPa and the ultimate tensile strength $\sigma_u$ of 1200 MPa. We utilized constantan strain gauges actively used in transducer manufacturing. The dimensions of the strain gauge are shown in figure 3 (b).

Figure 3. Topology of the elastic element (a) and the dimensions of the strain gauge (b). The dimensions of the strain gauge and the overall dimensions of the elastic element are in mm.

The explicit calculation of the transducer’s hysteresis is not straightforward. It is not known whether accurate calculation of hysteresis is possible using FEA. The hysteresis simulation presented in [11] is limited to column compression force transducers. However, empirical data shows that transducers exhibiting large hysteresis error tend to have large values of slip at the contact interface between a force transducer and its loading pad. If a transducer slips on the loading pad, the forces of friction convert some of the strain energy into heat. This results in different strain values at the same load during loading and unloading. Therefore, if we minimize the slip value, the dry friction hysteresis is going to be small. The initial constraint imposed on the elastic element mass is arbitrary and can be altered in the design process.

| Criterion name                        | Initial criterion constraint |
|---------------------------------------|------------------------------|
| Output signal at the rated load       | $\geq 2.2 \text{ mV/V}$     |
| Max. nonlinearity                     | $\leq 0.02 \%$ of full scale|
| Slip at the contact interface         | $\leq 1 \mu m$              |
| Mass                                  | $\leq 8 \text{ kg}$         |
The initial investigation included roughly 400 designs in the $LP_\tau$ sequence. The design process revealed that the constraint imposed on the maximum contact slip was too stringent; therefore, it was weakened to 2 $\mu$m. The designer was presented with the Pareto optimal set of solutions. The designer chose the design having the least mass and nonlinearity no more than 0.02% and conducted a local search to order to further minimize the mass. The criteria values for the initial and the final design are presented in table 2.

| Criterion name                          | Initial design | Final design |
|----------------------------------------|----------------|--------------|
| Output signal at the rated load, mV/V  | 2.3            | 2.2          |
| Max. nonlinearity, % of full scale     | 0.02           | 0.01         |
| Slip at the contact interface, $\mu$m  | 12.0           | 2.0          |
| Mass, kg                               | 8.0            | 7.6          |

The picture of the manufactured prototype is shown in figure 4.

The value of creep was not deal with in the scope of the current study. We applied the strain gauges used in “Tenso-M” for manufacturing conventional force transducers. The force transducers manufactured at “Tenso-M” have the accuracy class C3 per OIML R60 and have adequately low values of creep. We used the same material for the elastic element and the same type of gauges, so it would make sense that the creep error would be similar to the creep error of the force transducers manufactured at “Tenso-M”. We measured the creep error according to the procedure specified in OIML R60 using a 1000 kN hydraulic force machine. The creep error time history is shown in figure 5. The creep error does not exceed 0.01% after one hour.

As the hysteresis was evaluated indirectly, we tested the prototype using the 1000 kN hydraulic force machine. The measured values of hysteresis are shown in figure 6. As can be seen, the calculated value of the slip at the contact interface equal to 2 $\mu$m corresponds to the maximum hysteresis of $\pm$0.02% of the full scale. However, it should be noted that hysteresis is not only affected by the friction losses at the contacts, but by the creep of the transducer as well and the internal friction hysteresis of the elastic element material [12]. For instance, strong negative creep coupled with nearly zero dry friction hysteresis can lead to the large overall negative hysteresis that can detrimentally affect the measurement accuracy of a force transducer.
Figure 5. Creep error of the manufactured prototype.

Figure 6. Hysteresis error of the manufactured prototype.

Thus, in order to make a low-hysteresis transducer it is necessary not only to minimize the slip at contact interface, but also select the proper material of the elastic element and the proper strain gauges.

The characteristics of the final design (nonlinearity and hysteresis errors ≤0.02%, creep error ≤0.01% and output signal at rated load 2.2 mV/V) are comparable to the characteristics with the conventional 1000 kN force transducers for industrial applications (the NHS model produced by Keli Sensing Technology and the RTN model produced by HBM), although hysteresis value can be further minimized by placing more stringent constraints on the maximum value of the contact slip. More superior designs can be obtained by subsequent, more thorough investigations of the parameter space and placing more challenging design criteria constraints.

5. Conclusions

In this paper, we proposed a novel multicriteria approach to designing strain gauge force transducers. The approach is based on the Parameter Space Investigation Method, methods of multicriteria optimization and special mathematical model of a strain gauge force transducer. The proposed approach was implemented in a software system that can be used to optimize new strain gauge force transducers and optimize the existing ones. A novel force transducer was designed using the system in order to demonstrate the efficacy of the system.

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