Optimization of a contactless displacement sensor using finite-element analysis

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***Abstract*—This paper deals with the optimization of a novel contactless displacement sensor using finite-element analysis. In previous work the operating principle of this novel approach has been investigated. In order to improve the sensitivity and linearity of the device an optimization is proposed. Therefore an optimization tool is coupled with a finite-element simulationmodel of the sensory device. Both software tools for optimization and finite-element analysis are commercial tools and were being used in this work. During the optimization the length and width of the ferromagnetic material embedded in the planer structure of the detection unit are used as degrees of freedom under the constraints of sensitivity and linearity. The results shows that increasing width and length always improves the sensitivity, while increasing width leads to a higher linearity error and a shorter measurement range. This behavior is a result of the change in magnetic energy and therefore the magnetic flux density distribution in the ferromagnetic material. In a next step the probed solution space could be expanded to add more degrees of freedom to the optimization process.**

***Index Terms*—Displacement measurement, Optimization, Finite element methods, Magnetic sensors.**

I. Introduction

The consequent increase in technical security, functionality and comfort systems requires monitoring of different process parameters. Therefore efficient sensory devices are necessary, for instance in the automotive sector, machinery and plant engineering or consumerelectronics [1], [3].
In these application fields almost 80% of the used sensors are displacement sensors with different characteristics, depending on the used technology [2], [7].

A novel approach for a displacement sensor based on the effect of local magnetic saturation was discussed in previous work [4], [6]. This sensor device consists of a detection unit and a target. The detection unit is a planar structure in which ferromagnetic material and coils are embedded. The target provides a constant magnetic field, which can be observed by the detecting unit. This approach is used for displacement measurement. In [5] the operating principle of this device was investigated by developing a finite-element (FE) simulationmodel. Through measurements the simulationmodel could be verified [6].

A. Initial situation and approach

In further work a sensitivity analysis was done by varying different parameters to study the influence on the output signal of the sensory device. First attempts showed that varying parameters, for instance geometric parameters, like length and width have a significant influence on the output signal, but also increase computation time. In order to minimize computation time an optimization process is proposed, to identify the optimal shape of the device.

B. Objectives

In this work the optimal shape of the previous mentioned sensory device considering the sensitivity and the linearity of the output signal should be developed. The geometric parameters are the length l and the width w of the device, which will be varied during an optimization process under the constraints of sensitivity and linearity. Therefore a complete finite-element simulationmodel associated with a coupled optimization algorithm should be developed. This is done by using the FE software Flux3D in combination with a generalized optimization tool (GOT-It), which are both provided by the french company CEDRAT.

II. Experimental setup, methodology and results

A. Sensor assembly

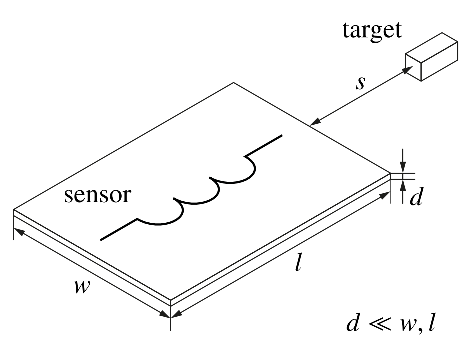

Figure 1: Principle structure of the sensing assembly and associated geometrical. dimsensions

In figure 1 the principle structure of the studied sensor assembly is presented. As the target displacement s relative to the sensor changes, the impedance Z of the sensors coil changes. That impedance is directly proportional to s. The parameters that will be varied in the optimization are the geometric entities width w and length l. The thickness d of the sensor is several magnitudes smaller than its length or width and will not be varied.

B. Numerical software

Due to the special properties of the problem the usage of a 3D model without symmetries is necessary. Moreover the simulation has to be carried out with a transient formulation [6]. As the solution space of the problem is huge and the computation time for one parameter set is in the order of approximately 48 hours, a simple parameter study of the complete solution space is not convenient. To resolve this problem the optimization tool GOT-It is coupled with the FE software Flux3D. After each FE computation the results are pre-processed with a custom python script and handed over to the optimization algorithm which in turn hands back a new parameter set to the FE software.

C. Computation

The mentioned python script that pre-processes the FE-results for the optimization step computes the linearity error Δ_{lin} of the sensors output signal Z and its sensitivity ε. Those two quantities are defined as follows:

$$\Delta_{lin} = \max\left\{\frac{Z_{ideal}(s) - Z_{real}(s)}{Z_{ideal}(s)}\right\} \tag{1}$$

$$\varepsilon = \frac{Z(s_{max}) - Z(s_{min})}{s_{max} - s_{min}} \tag{2}$$

The index *ideal* references an ideal linear characteristic between the maximum displacement s_{max} and the minimum displacement s_{min}. Whereas the index *real* references the computed output signal.
The chosen optimization algorithm is the sequential surrogate optimizer. To reduce the computation time the rounding accuracy is set to 0.1 mm. Its target is to minimize the objective function:

$$\min\{-\varepsilon\} \tag{3}$$

The length l for the optimization is chosen from the fixed set:

$$\frac{l'}{l} = \{1, 1.13, 1.22, 1.3, 1.39\} \tag{4}$$

Three constraints for the linearity error were tested (see Fig. 2). In Fig. 2 the results of the computation are shown.

III. Discussion and conclusion

A. Discussion

Every point in Fig. 2 represents the result of a constraint optimization problem at a given relative length. Any given pair of $\frac{l'}{l}$ and $\frac{w'}{w}$ that is inside the marked region for a specific linearity error will fulfill the chosen linearity error constraint. It becomes apparent that in order to have a linear output signal one has to select a relatively constant ratio of length to width of the sensor.

Another result of the optimization process is that the sensitivity ε rapidly increases with a higher width of the sensor whereas the length has only a small impact on ε. As the sensitivity is the change of Z with respect to s it is dependent on the inductance L of the sensor as indicated in figure 1. A thorough inspection of the FE-results shows that the sensitivity increase is due to a boost in magnetic energy in the sensor. That increase is greater when the width of the sensor is varied than its length due to the given design of the sensor assembly.

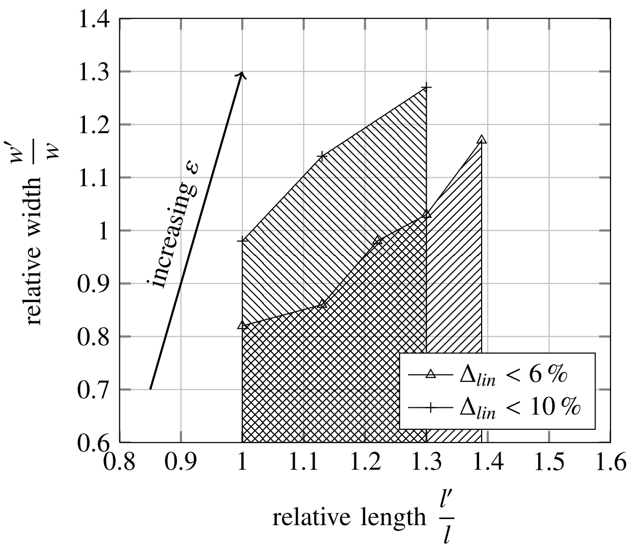

Figure 2: Optimal width/length pairs within a desired linearity error. Computation time for one width/length pair is about 48 hours.

B. Conclusion and outlook

The presented optimization results are a first step towards design guidelines for building a displacement sensor as discussed in this work. It could be shown that the two constraints linearity and sensitivity imply a distinct ratio of the sensors length and width and that an increase in the sensors width has a great impact on its sensitivity. The next step is to expand the probed solution space and to add more degrees of freedom to the optimization process. Further work should also take the environment of the sensor assembly into account.

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