Mechanical sensors

Linear Variable Differential Transformer in Harsh Environments—Analysis of Temperature Drifts for Different Plunger Materials

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Abstract—Linear variable differential transformers (LVDTs) are precise linear position sensors capable of measuring position over a wide range. The selection of the plunger material, whether magnetic or nonmagnetic, becomes relevant in environments characterized by high temperatures and temperature variations. Especially for sensors with larger measurement ranges, the sensitivity with respect to temperature increases. In this letter, we present an LVDT design for large displacements which offers a significantly reduced sensitivity with respect to the temperature. Our design uses a plunger made from solid copper. The proposed sensor design has improved linearity and lower temperature drift with respect to existing designs, e.g., sensors with ferrite based plungers. From simulations and experiments we demonstrate a temperature stability of -28.5 to $25.5\,\mu\mathrm{m/K}$, which is comparable to other LVDT designs, which use further temperature compensation techniques. We further study the benefit of our design even for nonuniform heat distributions.

Index Terms—Mechanical sensors, core materials, high temperature, large displacements, linear variable differential transformer, position sensor.

I. INTRODUCTION

Several industries are increasingly dependent on process machinery, where position measurement is a key element [1], [2]. In particular, the iron and steel industry requires position sensors to operate over large displacements and a wide temperature range. Inductive sensing principles, for example, a linear variable differential transformer (LVDT), are characterized by their insensitivity to environmental factors such as dirt, dust, and moisture [3], [4]. As a result, inductive sensing principles are particularly attractive for measurement applications in harsh environments. In addition, LVDTs have a high sensitivity and resolution and a good linearity [1], [5], [6]. Fig. 1 illustrates a variant of the LVDT design.

LVDTs consist of a primary coil and two secondary coils, typically wound on a cylindrical support, and a moving core [7], [8]. The plunger (magnetic or nonmagnetic) moves along the axis, changing the flux linkage between the primary and secondary windings [4]. The properties of an LVDT depend on the geometry, plunger material, windings, excitation, frequency, and environment [6]. A state of the art method for determining the position of the plunger involves a ratiometric evaluation (1) of the sensing voltages [5], [6]. This evaluation technique compensates temperature drift of the LVDT in a narrow range around the center position. These sensors are referred to as self-compensated smart LVDT [6]. In our work, we also utilize this evaluation technique.

Table 1 lists a comparison of research studies including our work on the temperature dependence of LVDTs, highlighting a concise overview of the key facts from each paper.

A good temperature stability (TS) of the LVDT is achieved under either small displacements/ranges and high temperature variations or large displacemens/ranges and low temperature variations [5], [9]. Furthermore, the studies differ in the plunger manufacturing technique,

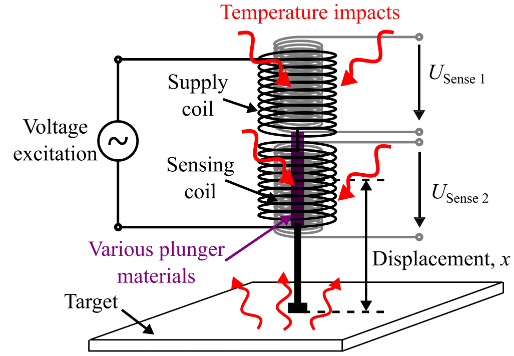

Fig. 1. Sketch of an LVDT structure including temperature impacts on the sensing and supply coils and the moving plunger.

TABLE 1. Comparison of Different Research Studies on LVDT's

Ref.	Range x	$\Delta\vartheta$	Temp. stability	Comment
[6]	60 mm	53 K	-0.075 to 0.018 % FS/K -45 to 11 μm/K	Solid ferrite, no compensation
[5]	14 mm	275 K	-0.009 to 0.006 % FS/K -1.3 to 0.8 μm/K	Solid ferrite, no compensation
[9]	60 mm	15 K	~ 0.0044 % FS/K ~ 2.7 μm/K	Copper wound coil, add. compensation
[10]	60 mm	16 K	~ 0.085 % FS/K ~ 51 μm/K	Solid brass, add. compensation
This work	150 mm	120 K	-0.019 to 0.017 % FS/K -28.5 to 25.5 μm/K	Solid copper, no compensation

e.g., either solid plungers or copper wound moving coils are used. The copper-wound moving coil approach in [9] has a good TS, but requires more effort with respect to the manufacturing. In contrast, the use of a solid plunger ensures a low-cost manufacturing process and minimal tolerance deviations. Grima et al. [9], [10] have a better TS because they have implemented additional temperature compensation. Gruber et al. [4] found that the position drift due to temperature

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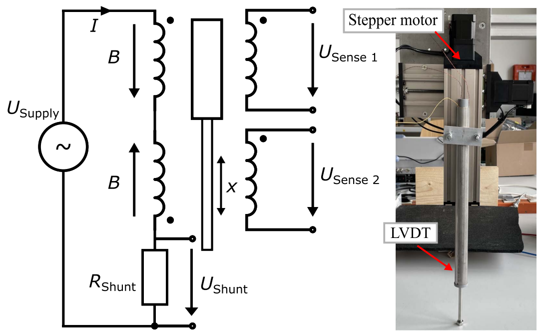

Fig. 2. Sketch of the LVDT electric schematic (left) and photo of the lab setup (right).

variations depends on the position of the plunger. For the specified TS of the individual papers in Table 1, there is little information about the position of the plunger. For our sensor presented in this letter, we provide a worst case TS.

In this letter, we analyze the properties of an LVDT for applications with large displacements ($x > 100$ mm) and high temperature variations ($\Delta T > 100$ K). Our solid plunger made from copper is designed that the plunger itself and the extension bar connected to the plunger has minimal influence on the linearity of the sensor. We demonstrate the benefit of this design for uniform and nonuniform temperature variations on the LVDT. For comparison, we also demonstrate the properties of a ferrite-based plunger. The analysis is based on a direct evaluation of experimental measurements and simulations without any further compensation. The position of the plunger is determined by the standard approach from (1). We show that the TS can be improved by a proper material selection also for temperature gradients across the sensor. At the center position ($x = 0$ mm), the TS is improved by a factor of 20 compared to the worst case and becomes comparable to [5], [9].

II. LINEAR VARIABLE DIFFERENTIAL TRANSFORMER

A. Working Principle

The electrical schematic of the LVDT is shown in Fig. 2 on the left. For the supply coil, the winding direction has been reversed in the middle of the sensor length. This produces two magnetic fields in opposite directions. At the center position of the plunger, the mutual inductance between the supply and sense coils is equal due to the design of the supply coil. When the plunger is off-center, this equilibrium is broken and the two mutual inductances are different.

The position is than evaluated by the ratiometric expression r

$$r = \frac{U_{\mathrm{Sense},1} - U_{\mathrm{Sense},2}}{U_{\mathrm{Sense},1} + U_{\mathrm{Sense},2}} \qquad (1)$$

using the sensitivity of the sensor. $U_{\mathrm{Sense},1}$ and $U_{\mathrm{Sense},2}$ are the sensing voltages [4].

B. Sensor Built-Up for Harsh Environments

Fig. 3 shows the sensor built-up for harsh environments. We have used austenitic stainless steel (1.4301) for the bobbin, housing, and end caps. The two sensing coils are wound on the bobbin first. The supply coil is wound on top of the two sensing coils to reduce the leakage inductance of the transformer. This design allows testing at temperatures above 100 °C up to the melting point of the insulating layer of the enameled copper wire. Our LVDT is 320 mm long has

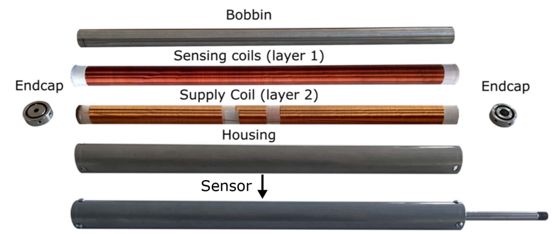

Fig. 3. Photo of the LVDT before and after assembly.

Fig. 4. Comparison of the ferrite and copper plunger.

an inner diameter of 12.5 mm and an outer diameter of 25 mm. The supply coil are 160 mm long and have 364 turns with a wire diameter of 0.43 mm. The sensing coils are 160 mm long each and have 1120 turns with a wire diameter of 0.28 mm.

For the plunger, we chose a ferritic stainless steel (1.4021), which has a relative permeability of $\mu_r = 900$, and copper, because of its high electrical conductivity. The plunger has a diameter of 12 mm and a length of 160 mm. A photo of the corresponding plungers is shown in Fig. 4.

Our solid plunger design is robust, the manufacturing process low cost compared to the moving coil approach in [11]. The linearity of the sensor is improved compared to the solid plunger in [10].

III. EXPERIMENTAL VERIFICATION

In this section, we analyze the properties of the LVDT and perform a displacement measurements, followed by uniform and nonuniform temperature variation of the LVDT for both plunger materials. The measurements are compared with a simulation model.

A. Lab Setup for Measurement Experiments

The lab setup for displacement experiments is shown in Fig. 2 on the right. The LVDT is mounted on a sliding table with a stepper motor positioning system, which serves as a position reference. The sliding table has an accuracy of about 10 μm and allows investigations within a ± 75 mm range. As the displacement increases, the plunger moves from top to bottom. Based on our previous work [4], we use a voltage excitation at a frequency of 3 kHz. The voltage measurements are performed with an oscilloscope-based measurement system.

B. Displacement Measurements and Simulation

A 2-D axisymmetric magnetic field simulation was set up in COMSOL to study the displacement and temperature dependence of the LVDT. We simulated a homogenized multiturn coil model with uniform current distribution, resulting in reduced computational complexity compared to a single-turn coil model. However, it neglects capacitive coupling and skin effect, but the chosen frequency ensures that the skin effect is negligible for the wire diameter. Temperature dependencies are incorporated by means of corresponding material models.

The upper subplot in Fig. 5 shows a comparison between the measured and simulated sensing voltages of both plunger materials.

Copper plunger: The sensing coil facing the plunger has a lower voltage because eddy currents are induced in the plunger, reducing the magnetic coupling between the supply and sensing coils. As the

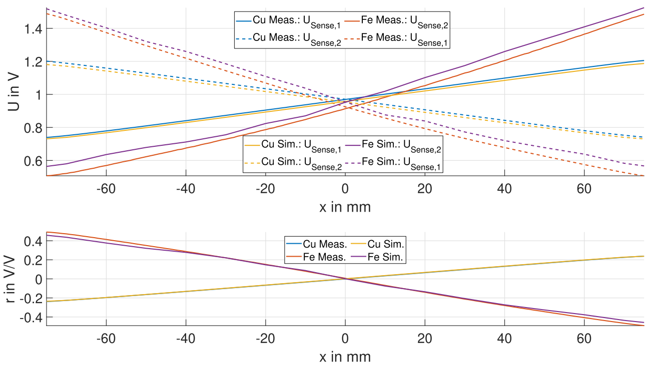

Fig. 5. Measured and simulated sensing voltages of the LVDT for both materials (upper subplot) and ratiometric evaluation (lower subplot).

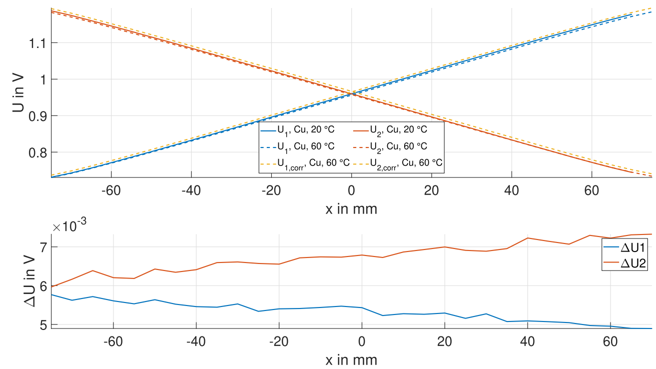

Fig. 6. Sensing voltages (upper subplot) and voltage difference (lower subplot) for uniform heating of the LVDT with copper plunger.

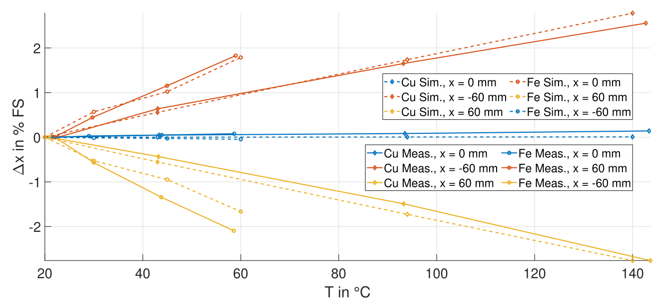

Fig. 7. Measured and simulated position deviation due to uniform temperature variation for both plunger materials.

plunger moves, the magnetic coupling and sensing voltage increases (solid blue curve in Fig. 5).

Ferrite plunger: The sensing coil facing the plunger has a higher voltage because the magnetic coupling between the supply and sensing coils is increased. As the plunger moves away, the magnetic coupling and the sensing voltage decreases (dashed red curve in Fig. 5).

For the ferrite plunger simulation in the frequency domain, the magnetic properties of the plunger are included via the effective B-H curve. As can be seen, the measured and simulated sensing voltages are not linear over the entire displacement and deviate from each other. This is due to variations in magnetic properties between the manufacturer's specifications and the actual material supplied. With the copper plunger, the sensor has an improved linear characteristic over almost the entire displacement compared to the ferrite. Due to the known material properties of copper, the simulated and measured sensing voltages are in very close agreement, almost identical.

The lower subplot in Fig. 5 shows the expression r for the simulation and measurement. The slightly increased deviation between simulation and measurement for the ferrite plunger near the limits of the sensing range again illustrates the drawbacks of inaccurate material property information. Despite these simplifications in the simulation model and the challenges of the material properties, the simulation agrees well with the measurement for both plunger materials and can be used for scaling purposes.

C. Characterization of Uniform Temperature Variations

With the first experiment, we address the temperature dependence of the sensing voltage ($U_{\mathrm{Sense,i}} = k_{\mathrm{I}}(U_{\mathrm{i}} + \Delta U(\vartheta))$) for the copper plunger, where $k_{\mathrm{I}} = \frac{I_0}{I}$ describes the primary current variations, U_{i} is the sensing voltage at room temperature. $\Delta U(\vartheta)$ describes the temperature dependent variations in material properties and geometric expansion. The entire LVDT was placed in a thermal oven and heated to a steady-state temperature of 60 °C. Afterward, we moved the plunger over the displacement range.

The upper subplot in Fig. 6 indicates that the measured sensing voltages at room temperature (solid blue and red curves) is higher than at a uniform temperature of 60 °C (dashed blue and red curves). This is due to temperature dependent changes in the impedance of the supply coil (regardless of the plunger position), which changes the primary current when a voltage excitation is used. The corrected sensing voltages (dashed orange curves), e.g., $U_{\mathrm{i,corr}} = k_{\mathrm{I}} U_{\mathrm{i}}$ are higher than at room temperature. The higher sensing voltage is due to the lower electrical conductivity of copper and the thermal expansion of the LVDT at 60 °C. The lower subplot of Fig. 6 shows the temperature dependence of the sensing voltage $\Delta U(\vartheta) = U_{\mathrm{i,corr}} - U_{\mathrm{Sense,i,Ref.}}$, which is the difference between the sensing voltages at room temperature and the corrected sensing voltages at 60 °C. $\Delta U(\vartheta)$ is in the range of a few mV. In the evaluation of r the voltage $\Delta U(\vartheta)$ cancels out in the numerator, but $2\Delta U(\vartheta)$ remains in the denominator causing a temperature drift. Yet $\Delta U(\vartheta)$ is small with respect to the sensing voltage U_1 justifying the use of r for the determination of the position.

To determine the positional deviation, we performed a second temperature variation experiments and heated the LVDT to 45, 95, and 145 °C while holding the positions constant at $x = [-60\,\mathrm{mm}, 0\,\mathrm{mm}, 60\,\mathrm{mm}]$. Fig. 7 shows the corresponding position deviation between the ferrite and copper plunger.

For comparison, we discuss the properties of the measurement data (solid curve) and the simulation data (dashed curve) at a temperature of 60 °C. Near the limits of the sensing range, e.g., the worst case, the position deviation for the ferrite plunger increases to about 2% FS. For the ferrite core, we achieve a TS from -0.031 to 0.036% FS/K (-53.5 to 46.5 μm/K). The TS for copper is improved by almost 50% compared to the ferrite and is listed in Table 1. At the center position, the position deviation for both materials is less than 0.1% FS due to the symmetric sensor design. Comparing the simulation with the measurement, we observe a close match for the copper plunger, while the position deviation for the ferrite plunger shows larger discrepancies. This discrepancy is mainly due to different temperature properties of the ferrite plunger between literature and real plunger material compared to the well-defined properties of the copper plunger.

D. Characterization of Nonuniform Temperature Variations

With this measurement experiment, we highlight the advantages of using a copper plunger over the ferrite plunger even for nonuniform temperature variations or temperature gradients across the sensor. We

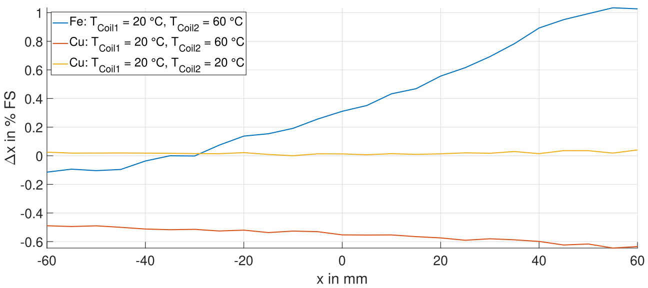

Fig. 8. Position deviation due to nonuniform temperature variation.

built a lab setup that allows one half of the LVDT to be heated to 60 °C, while the other half and the plunger remain near room temperature. This was achieved by the use of a heat gun and compressed air (for cooling). Further compressed air was blown through the sensor to keep the temperature of the plunger constant. A careful adjustment of the setup allowed us to keep all temperatures within 5 K from the desired value. However, the setup allowed us to perform the analysis only for displacements up to ± 60 mm. Yet, since this is close to the sensing range, we consider the results to be representative.

Fig. 8 shows a comparison between the position deviation for the ferrite (blue curve) and copper plunger (red curve) at 60 °C and at room temperature (orange curve).

The deviation at room temperature remains below 0.04% FS and is partly caused by the uncertainty of the stepper motor. At 60 mm, the position deviation of the ferrite plunger is 1% FS, which is mainly due to the change of the material property of the plunger as it enters this section. In the opposite half, the position deviation is less pronounced but still present, indicating that the plunger is already heated. For the copper plunger, the position deviation is below −0.65% FS and almost constant over the range. This is mainly due to a position change of the copper plunger resulting from the thermal expansion of the LVDT. Despite all temperature effects, the use of copper can significantly reduce the influence of nonuniform temperature variations.

IV. CONCLUSION

In this letter, we present a low-cost solid plunger design, which improves the linearity of the LVDT. We show that the temperature dependence of the LVDT for uniform and nonuniform temperature variations can be reduced when using a copper plunger instead of a ferrite. We specify the TS of the LVDT regarding the position of the plunger. For uniform temperature variations, the TS of the ferrite core near the limits of the sensing range is -53.5 to $46.5\ \mu$m/K. With copper, the TS can be significantly reduced to -28.5 to $25.5\ \mu$m/K. The TS remains comparable to the moving coil approach, but without the need for further compensation. In future work, we will investigate the potential for further improving the TS by implementing a model-based compensation. In addition, the LVDT should be isolated to reduce the influence of temperature gradients across the LVDT.

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