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MATERIAL CHARACTARIZATION FOR A TERFENOL–D BASED FORCE SENSOR

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Abstract – In this paper the magneto–elastic–effect is taken under further investigation, to determine the utility of the novel material Terfenol–D in force sensor applications. A measurement set–up is designed and the characteristic material parameters like magnetization diagram, butterfly diagram and the reluctance dependent on the applied mechanical load is determined. The results demonstrate that it is possible to sense both static and dynamic forces with only a single read out coil. The resultant simple arrangement of the set–up combined with the not fully utilized overload capability given by the elastic range of the sensing–material Terfenol–D guarantees its robustness.

Keywords: force sensor, magneto–elastic effect, Villari effect

1. INTRODUCTION

Force sensors comprise a large fraction of the sensor market. There are several sensory effects known upon which commercial sensors are built. These are to name just a few: the geometry– [1], the piezo–electric–, the opto–elastic– [2], the magneto–elastic–effect [3].

Most of the commercially available sensors are based on the geometry–effect that converts mechanical stress via a well defined deformation element into associated strain values subsequently sensed through various kinds of so called strain gauges [1]. If one is interested in dynamic force measurements typically the piezo–electrical effect is utilized.

Sensors based on both effects might show some drawbacks. Strain gauges are prone to adverse environmental conditions effecting the glue–joints to name just one factor and piezo–electric output signals are very high impedance and therefore need high quality electronics that might degrade performance in the high temperature regime.

In the paper the magneto–elastic–effect [3, 4] is taken under further investigation regarding the ability of the novel material Terfenol–D to combine extreme mechanical robustness with accurate measurement properties.

A literature search has turned up only a single commercial sensor — the pressductor — based on the magneto–elastic–effect that is available through ABB[1].

This particular sensor uses two perpendicularly oriented magnetic coils — one the excitation and the other the read out coil — whose magnetic coupling properties are weakly but almost linearly dependent on the geometric variation of the deformation element.

The excitation coil is fed by an AC current inducting, in case of mechanically induced magnetic anisotropy, a secondary voltage.

The advantages of such a sensor is its robustness, that can be explained by the induced magnetic anisotropy saturation occurring well below its mechanical limiting load.

Our proposed idea is to further minimize the sensors complexity by reducing its arrangement to only a single coil. Furthermore it was decided to improve sensitivity — with respect to ABB's sensor — by reverting from plain steel to the novel very promising material Terfenol–D [5]. Terfenol–D exhibits the greatest currently known magnetostrictive effect and conversely also shows the magneto–elastic–effect utilized here.

2. MATERIAL SPECIFICATION OF TERFENOL–D

Terfenol–D is a rare earth element alloy of terbium, dysprosium and iron, it was developed in the 1960's at the Naval Ordnance Laboratory in the United States of America. As above–mentioned Terfenol–D is a material with one of the largest known magnetostrictive constant. Hence, its main field of use is in high power ultrasonic transducers (supplier is Etrema products, Inc.).

With the aim to build a force sensor the inverse effect is utilized, which is called Villari–effect or magneto–elastic–effect [6]. Some research reported in the literature [6, 7, 8] has demonstrated the useability of this inverse effect. These researchers used a commercially (by Etrema products, Inc.) available pressure actuator and adapted it to sense force, although limited to dynamic forces.

2.1. *Material testing set–up*

In a first attempt in designing a sensor it is necessary to determine the change of the material parameter (in our case the

[1] ABB . . . Asea Brown Boveri AG, www.abb.com

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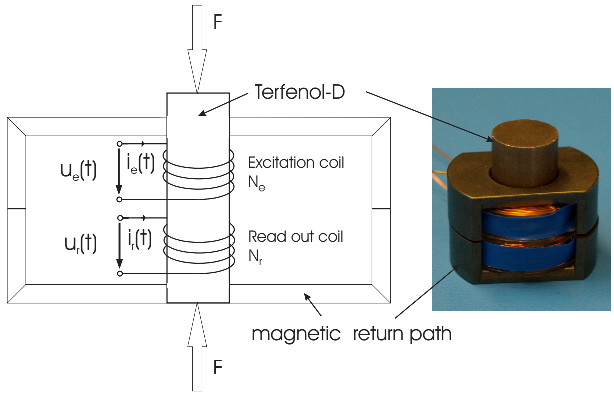

Fig. 1. Schematic model of the sensor with the described return path on the left side and a photo of the prototype on the right side.

relative permeability μ_r) vs. the desired physical measurand. To characterize the material a measurement set–up like shown in Fig. 1 is needed. The set–up consists of the Terfenol–D specimen utilized as transducting element as well as elastic body, one excitation coil, one read out coil and a magnetic return path. The force in the range of $0 \leq F_{compressive} \leq 3$ kN is directly applied to the Terfenol–D probe, that has a diameter of $\varnothing = 13$ mm. It is important to apply only compressive forces to the probe, because Terfenol–D is a brittle material that could be destroyed easily in case of tensile stress. To reduce eddy–current losses the magnetic return path is made of ferrite material, unfortunately the elastic body is Terfenol–D a rather good conductor. So eddy current losses in the probe are unavoidable.

2.2. Magnetic hysteresis and butterfly diagram

To determine the sensitivity of the sensor material the dependency of the relative permeability μ_r (the magnetic hysteresis diagram, B vs. H) and the magnetostrictive coefficient (actually the full so–called magnetostrictive butterfly diagram) under different conditions (mechanical prestress) was measured.

For these measurements the excitation coil is carrying an AC current causing a magnetic flux $\phi(t)$ and a magnetic flux density $B(t)$ within the probe. The butterfly diagramm (Δl vs. magnetic field strength H) can be determined by measuring the excitation current $i_e(t)$ leading (through the magnetic path length l_m) to H and by accurately measuring the magnetically induced, mechanically hampered (through applied prestress) expansion of the specimen. This mechanical expansion $\Delta l(t)$ in the probe (initial length $l = 28$ mm) is measured by an interferometrically measuring (with the laser–vibrometer: Polytec OFV–5000) necessary because the expected magnitude is below the μm–range. The first time derivative of $\Psi(t) = N_r\phi(t)$ induces a voltage in the read out coil (N_r turns) as shown in (1) from which the magnetic hysteresis diagram can be determined.

By measuring the electrical parameters it is possible to determine the magnetization diagram (B vs. H, is shown in the right diagram of Fig. 2). The magnetostrictive butterfly diagram (Δl vs. H, is shown in the left diagram of Fig. 2) of the Terfenol–D probe. Since the expansion of the specimen is rather small in absolute terms (in the nm range) an averaging over several periods of the vibrometer signal is necessary to smooth out noise induced artifacts.

$$u_r(t) = -\frac{\Psi(t)}{dt} = -N_r\frac{d\phi(t)}{dt} \quad (1)$$

2.3. Magnetic resistance of the set–up

For the anticipated sensor design the parameter — the magnetic resistance or reluctance R_m dependent on the relative magnetic permeability μ_r — is of more importance than the relative permeability μ_r. Hence the reluctance is the direct measurable quantity of the sensor set–up. For its measurement the same set–up is used as for the magnetic hysteresis measurement. In this set–up the magnetic circuit consists of two distinct parts the probe R_{probe} and the magnetic return path $R_{ferrite}$, therefore $R_m = R_{probe} + R_{ferrite}$ if the air gap is assumed to be zero.

The relative magnetic permeability μ_r of the magnetic return path is assumed to be constant over the small excitation used. In this case the total magnetic resistance R_m is only depending on the relative permeability of the probe $\mu_{r\ probe}$. As known both the excitation current and the read out voltage are necessary to calculate the parameter $R_m = \theta/\phi$. The calculation assumes the magnetic flux $\phi(t)$ to be sinusoidal, that implies that the excitation current $i_e(t)$ has to be sinusoidal, too and that the excitation on the magnetic hysteresis has to be small to get a linear relation.

In Fig. 3 the relative change of R_m in % is plotted vs. the mechanical load of the probe and vs. the excitation current frequency to clearly demonstrate the sensory capability of the material. R_m is plotted because it is the characteristic parameter of the set–up and it is easy to calculate the force dependent inductance L by (3). This figure shows that the sensitivity decreases with higher driving frequencies. This decrease can be attributed to both the eddy current losses incurred in the Terfenol–D probe and the magnetic leakage flux. With these results we are able to find the best trade–off between excitation frequency determining the dynamic behaviour of the sensor and the sensitivity.

$$R_m = \oint_{l_m} \frac{l}{\mu_0\mu_r(l)A(l)}\,dl \quad (2)$$

$$L(\mu_{r\ probe}) = \frac{N^2}{R_{m\ probe}} \quad (3)$$

The magnetic resistance R_m of the set–up over a large span is nearly proportional to the mechanical load of the probe. For the sensor set–up R_m can be also determined using a single coil set–up by measuring the inductance $L(F)$. $L(F)$ can be determined by connecting the single coil to an AC–bridge. Hence this measurement set–up can also be used as a very simple sensor. The functionality of a sufficiently accurate

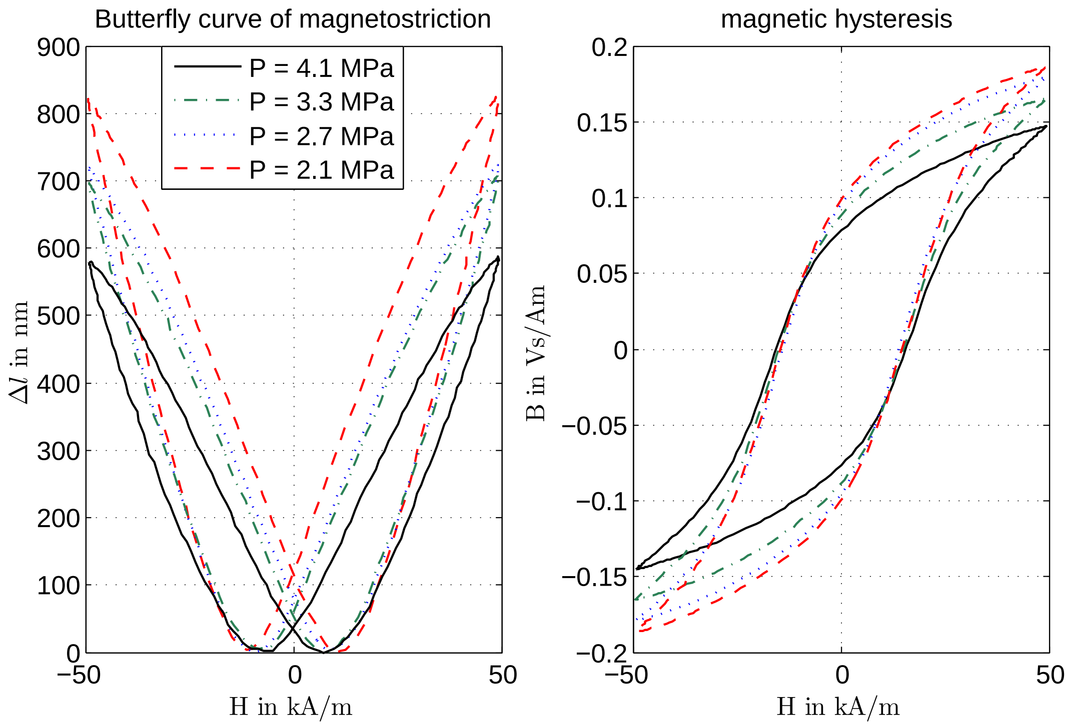

Fig. 2. The left diagram shows the butterfly–curve of the magnetostriction and the right diagram shows the magnetic hysteresis of the sensor material Terfenol–D both with different applied prestresses. The legend of the left diagram describes different prestresses of the curves of both diagrams.

AC–bridge can be realized by a discrete time network with some high quality analog front–end.

The determined material parameters of Terfenol–D are important for the design process to find the best trade–off between excitation frequency determining the dynamic behaviour of the sensor and the reduced sensitivity due to the unavoidable eddy current losses. Now with these results it is possible to design the measurement electronic for the set–up.

3. ANALOG FRONT–END

To determine the applied mechanical load the sensor is connected in a quarter AC–bridge circuit (see Fig. 4). With the variable resistances (R_2, R_3) the bridge is balanced and the impedance (L_1, R_1) is adjusted to the impedance ($L_{(F)}$, R_S) of the read out coil of the sensor set–up shown in Fig. 1. To determine the mechanical load the AC–bridge is connected to a linear variable differential transformer chip (LVDT) produced by Analog Devices Inc. The LVDT chip is able to drive the bridge with an appropriate excitation signal up to a frequency of 20 kHz. The chosen excitation frequency allows a maximum measurable force bandwidth of 2 kHz. Due to eddy current losses the sensitivity of the sensor decreases at higher driving frequencies. So the chosen frequency turned out to be a good compromise of sensitivity and dynamic behaviour. The LVDT chip also demodulates and amplifies the bridge signal and delivers an analog voltage proportional to the mechanical load.

To show the capability of the sensor we measured the analog output signal of the LVDT vs. the applied mechanical load. The mechanical load was applied via a testing machine (TIRA Test 2703) in quasi–static compressive force steps in the range of $0.1 \leq F \leq 2$ kN. The results are shown in Fig. 5. As one can see the voltage vs. the applied mechanical load is nearly linear.

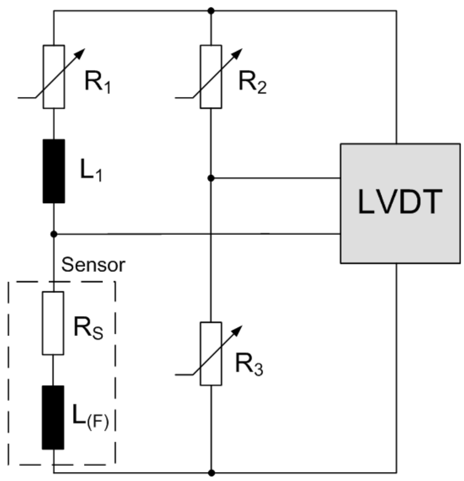

Fig. 4. Assembly of the sensor electronic, which is connected to an AC–bridge. The bridge signal is demodulated and amplified by the LVDT chip of Analog Devices Inc. The LVDT chip delivers an analog output signal, that is proportional to the applied mechanical load.

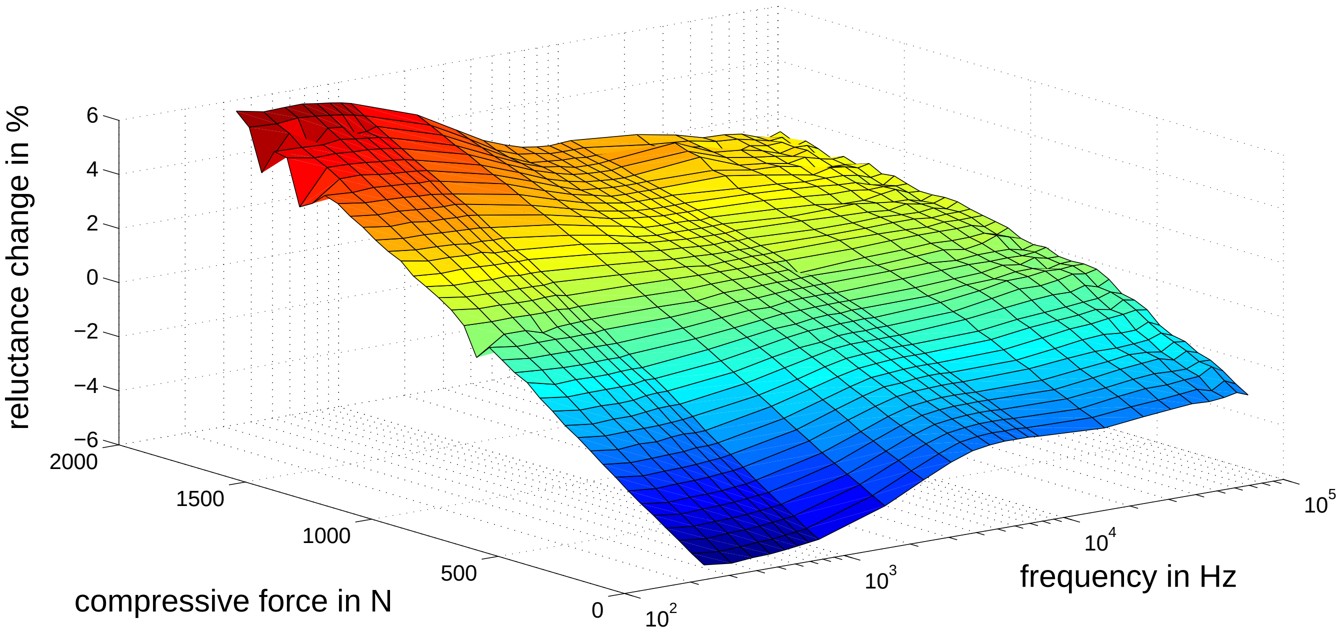

Fig. 3. Relative magnetic resistance change of the set–up (see Fig. 1) vs. applied compressive force and excitation frequency.

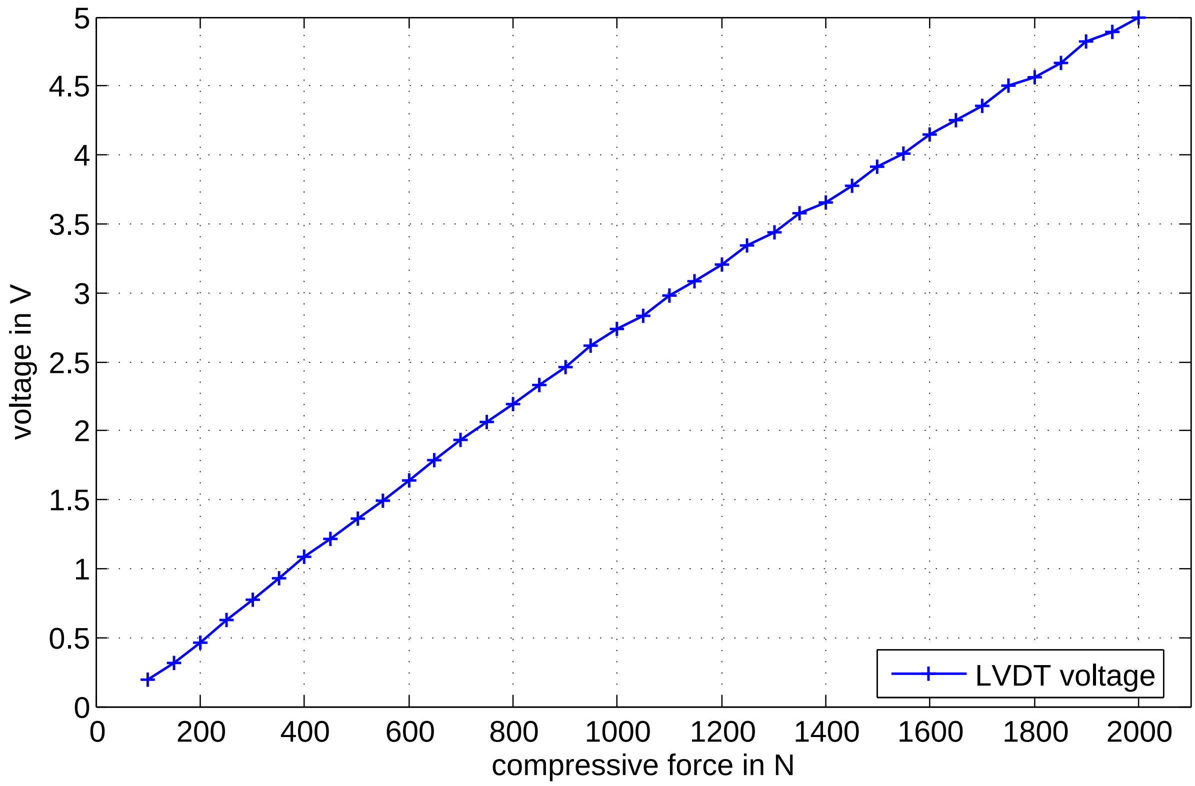

Fig. 5. Output voltage of the LVDT chip vs. the applied mechanical load with quasi–static compressive force steps from 100 N to 2000 N.

4. CONCLUSIONS AND FUTURE WORK

An approach to measure force based on the magneto–elastic effect was shown. The dependency of the magnetic resistance R_m of the set–up (see Fig. 1) was demonstrated. We showed that it is possible to measure force with a very robust single coil transducer. The robustness of the sensor can be explained by the magnetic saturation properties demand to utilize only a small band of the elastic range of the material, so the sensor naturally provides a large overload factor.

Future work is the design of a loading unit able to apply the necessary prestress (on the order of 15 MPa depending on the selected force range) to avoid loading the sensor with tensile stress in the alternating load case that could easily destroy the brittle Terfenol–D elastic element. With this loading unit we are able to perform both static and dynamic measurements.

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