A Novel Magneto–Elastic Force Sensor Design Based On Terfenol–D

Oppermann Klaus, Zagar Bernhard G.
Institute for Measurement Technology, Johannes Kepler University Linz
Altenbergerstraße 69, A–4040 Linz, Austria
klaus.oppermann@jku.at, bernhard.zagar@jku.at

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. By the reason that Terfenol–D has one of the largest magnetostrictive constant known we anticipated to get a higher sensitivity of the force sensor as compared to other materials e. g. steel.
A simple and robust single coil sensor set–up is introduced. The dependency on the characteristic parameter of this set–up the reluctance R_m is determined vs. both the mechanically applied force and vs. the frequency of the excitation signal. These parameters are needed to determine the optimal trade–off between the sensitivity and the dynamic behaviour of the sensor.
A prototype of the electronic to measure force by measuring the inductance L of the single coil sensor set–up is presented. The capability of the sensor set–up is demonstrated by quasi–static compressive force steps in the range of $0.1 \leq F_c \leq 2$ kN.

1 Introduction

Force measurement is an often demanded task in modern industrial applications. There are many sensory effects known, but only two effects the geometry–effect, used in so called strain gauges and the piezo–electric–effect are of wide spread use.
Most available force sensors are based on the geometry effect [1] that converts mechanical stress via a well defined deformation element into a proportional strain value. This deformation can be determined by strain gauges glued on the surface of the deformation element. One advantage of strain gauges is their ability to measure strain in loaded machine parts by gluing them on to the surface of the interesting part. After suitable calibration the applied force can be determined. To get accurate results usually a well defined deformation element with implemented temperature compensation is necessary. The temperature compensation is done by using at least two strain gauges forming a measurement bridge. Thereby the strain gauges have the same temperature and so the temperature implied resistance change is compensated for. However, this advantage that the strain gauges can be fixed to nearly every surface constitutes also the largest drawback of strain gauges. Because a lot of know how in preparing the surface is necessary to obtain reliably accurate results.
The piezo–electric–effect is normally utilized for dynamic force measurement with the drawback it is limited to dynamic forces only.
In this paper the magneto–elastic–effect is taken under further investigation. A literature search has turned up only one commercially available sensor that is based on this effect. This sensor is called pressductor and is manufactured by the company ABB[1]. The pressductor is used for special applications, where extreme robustness and a large overload factor are necessary (e. g. in a roller mill).
The pressductor uses two perpendicularly oriented magnetic coils, one excitation and one read out coil. The coupling factor of the two coils depends on the mechanically applied load to the sensor. The coupling factors dependency can be explained by the mechanical induced magnetic anisotropy of the sensor material steel. The large overload factor of the sensor can be explained by the magnetic anisotropy saturation of the material well below the mechanical elastic load limit.
Our idea is to increase the sensitivity of such a sensor based on the magneto–elastic–effect [2] by changing the sensor material to the very promising Terfenol–D [3], and also to minimize the complexity of the sensor

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

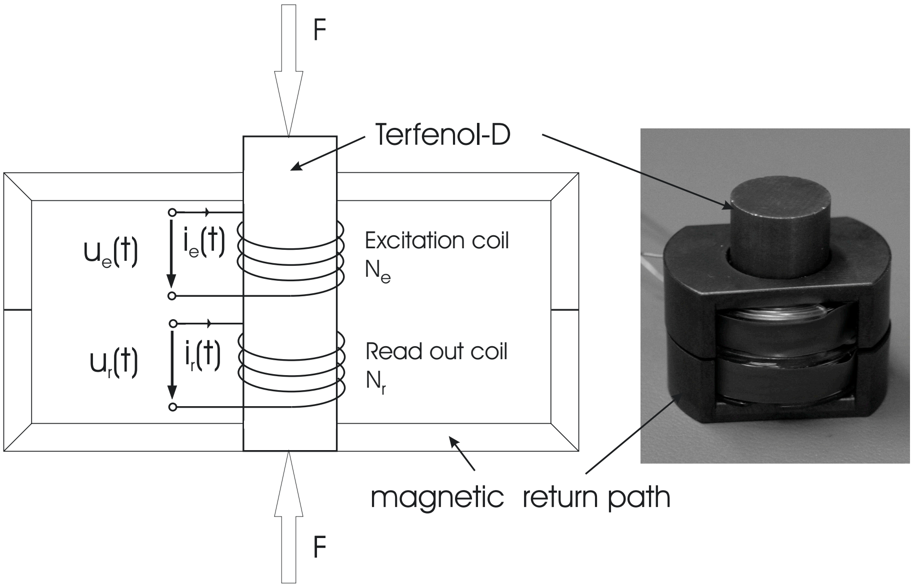

Figure 1: Schematic model of the sensor set-up with the described return path (left) and a photo of the prototype (right).

arrangement by using only one coil to determine the magnetic reluctance of the closed magnetic circuit comprising the sensor. The aim is to design a very robust and cheap sensor.

2 The Material Terfenol–D

Terfenol-D is a rare earth element alloy of terbium, dysprosium and iron. This material provides one of the largest known magnetostrictive constants. Hence the main field of use is in high power ultrasonic transducers (supplier is Etrema products, Inc.).

To design a force sensor the inverse effect is utilized, which is called magneto-elastic or Villari–effect. The useability of the inverse effect in combination with the material Terfenol-D was demonstrated in the literature [4, 5, 6, 7]. Those researchers used a commercially (by Etrema products, Inc.) available force actuator and adapted it to measure force. Due to the arrangement of that particular actuator one is only able to measure dynamic forces. The arrangement of this transducer consists of a single read out coil and a closed magnetic circuit with a permanent magnet induced magnetic flux. The dependency of the permeability of the sensor material Terfenol-D to the applied mechanical load results in a dependency of the magnetic flux in the magnetic circuit. The first time derivative of the magnetic flux induces a voltage in the read out coil. Due to the time derivative one is only able to measure mechanical load changes.

In order to be able to measure static forces, too, our approach is to determine the magnetic reluctance. The magnetic reluctance is also depending on the permeability of the sensor material and can be determined by measuring the inductance of the coil.

The prototype of the force sensor is shown in Fig. 1. It comprises of two coils the read out and the excitation coil to measure some material parameters (e. g. the magnetic hysteresis). The final sensor set–up consists of a single coil only. The main part of the set–up is the Terfenol–D rod with a diameter of $\varnothing = 13$ mm and a length of $l = 28$ mm. A magnetic return path of ferrite material is implemented to close the magnetic circuit. The ferrite material was selected in order to reduce eddy current losses in the return path and therefore to increase the sensors sensitivity. Since the sensor material Terfenol–D is a rather good conductor eddy current losses in the rod are unavoidable. In this set–up the mechanical load is directly applied to the Terfenol–D rod. Since Terfenol–D is a rather brittle material it can easily be destroyed by tensile stress so we apply compressive forces only.

To determine the sensitivity of the sensor the change of the magnetic reluctance R_m vs. mechanical load and vs. the excitation frequency was measured. For these measurements the magnetic circuit of the set–up (shown in Fig. 1) was separated into two parts the sensor material R_{probe} and the return path $R_{ferrite}$, therefore $R_m = R_{ferrite} + R_{probe}$.

The relative magnetic permeability μ_r of the magnetic return path is assumed to be constant over the

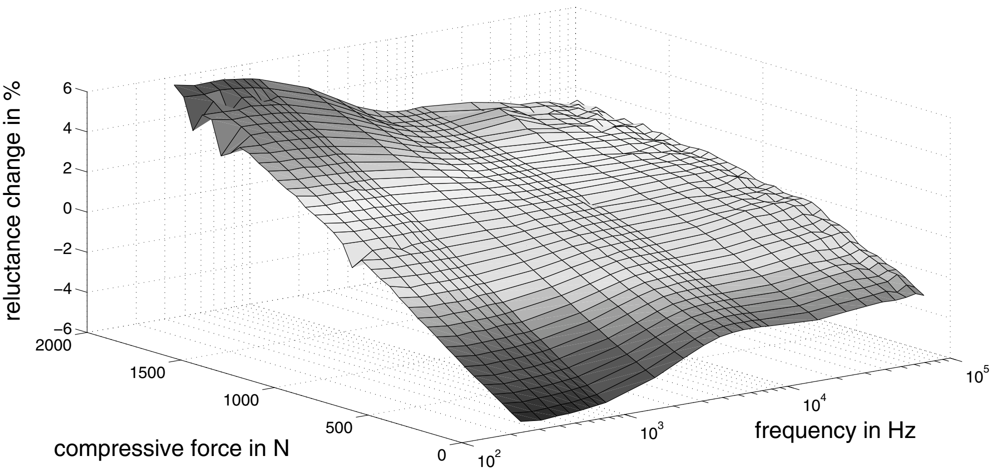

Figure 2: Relative magnetic resistance change of the set–up (see Fig. 1) vs. applied compressive force and vs. excitation frequency.

small excitation used. In this case the total magnetic resistance R_m (see Eq. 1) is only dependent 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. 2 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 was used to characterize the sensor because it is the characteristic parameter of the set–up and it is easy to calculate the force dependent inductance L by Eq. (2). This figure further shows that the sensitivity decreases with higher driving frequencies. This decrease can be attributed to eddy current losses in the Terfenol–D part and 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.

$$R_m = \oint_{l_m} \frac{l}{\mu_0 \mu_r(l) A(l)}\, dl \quad (1)$$

$$L(F) = \frac{N^2}{R_m(F)} \quad (2)$$

3 Electronics

As mentioned above the magnetic resistance R_m can also be determined using a single read out coil by measuring the inductance $L(F)$ only.

In order to measure the force dependent inductance $L(F)$, the coil of the sensor is part of a quarter AC–bridge with an appropriate impedance (L_1, R_1) and two variable resistances (R_2, R_3), to balance the bridge (the bridge circuit diagram is shown in Fig. 3). The bridge is driven by a small excitation signal with a frequency of 20 kHz, thus low frequency drift effects and low frequency interferences are minimized. The chosen excitation frequency allows a maximum measurable force bandwidth of 2 kHz. Due to the eddy current losses the sensitivity of the sensor decreases at higher driving frequencies (see Fig. 2). So the chosen driving frequency turned out to be a good compromise of sensitivity and dynamic behaviour.

The bridge signal is demodulated by the linear variable differential transformer (LVDT) chip AD698 (Analog Devices). This chip provides the supply signal for the bridge and does all the signal conditioning, filtering and interfacing necessary. All functions of the AD698 chip can be customized by external passive electronic components. Following a demodulation and an analog to digital conversion step the force signal is processed further in a digital signal processing unit (Blackfin DSP, Analog Devices). A photo of the printed circuit board including the signal processing unit, the analog to digital converter, the LVDT driver AD698 and some additional features is shown in Fig. 4.

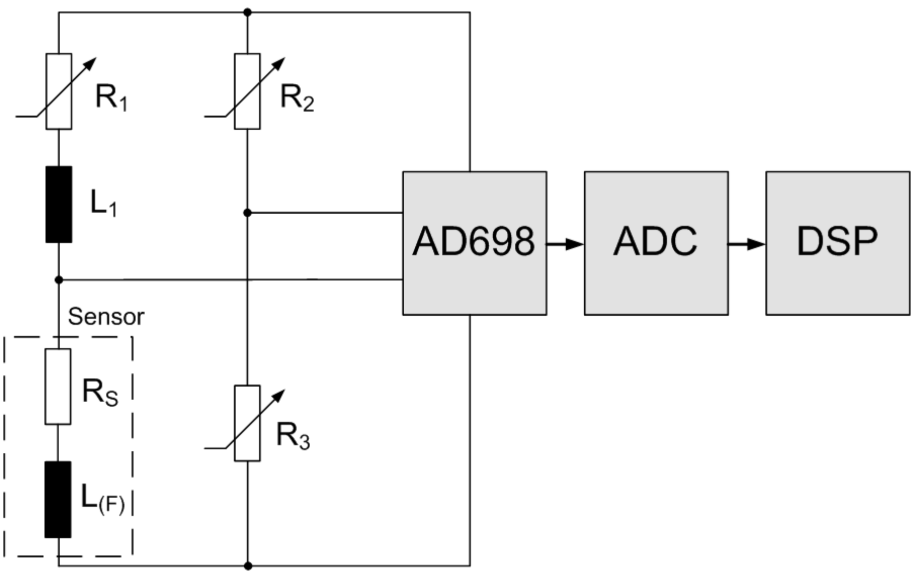

Figure 3: Blockdiagram of the electronic including the AC–bridge circuit, an AC–bridge signal conditioning IC (AD698), an A/D converter and a Blackfin type signal processing unit of Analog Devices.

To show the capability of the sensor system we measured the amplified bridge signal of the quarter bridge after demodulation vs. the applied mechanical compressive force to characterize the system (Fig. 5). In this diagram one can see four loading cycles, which were measured under ambient temperature conditions during the course of a day with at least one hour break in between each. These four measurement cycles demonstrate the reproducibility of the sensor characteristic. The mechanical load was applied by a tensile testing machine (TIRA Test 2703) in quasi–static 100 N compressive force steps in the range of $0.1 \leq F_c \leq 2$ kN.
As one can see in Fig. 5 the voltage vs. the mechanically applied force is nearly linear. Part of the variability seen is attributed to the mechanical effects of the testing machine used.

4 Conclusion and Future Work

We demonstrated the capability of the magneto–elastic–effect in combination with the material Terfenol–D. The advantages of the introduced sensor are a higher sensitivity as compared to a steel sensor, because of the higher magnetostrictive constant of Terfenol–D. The robustness of the sensor is guaranteed by the magnetic saturation of the material well below the mechanical elastic load limit. Because of the excitation frequency of 20 kHz the sensor is robust against external interferences. So far we only measured quasi–static compressive forces, since Terfenol–D is a rather brittle material and can be damaged easily in case of only small tensile stress.
In a future step we want to design a complete sensor that needs to be mechanically prestressed to extend the measurement range into the tensile stress region. The ultimate goal is to design and verify a robust force sensor able to measure both compressive and tensile static and dynamic forces.

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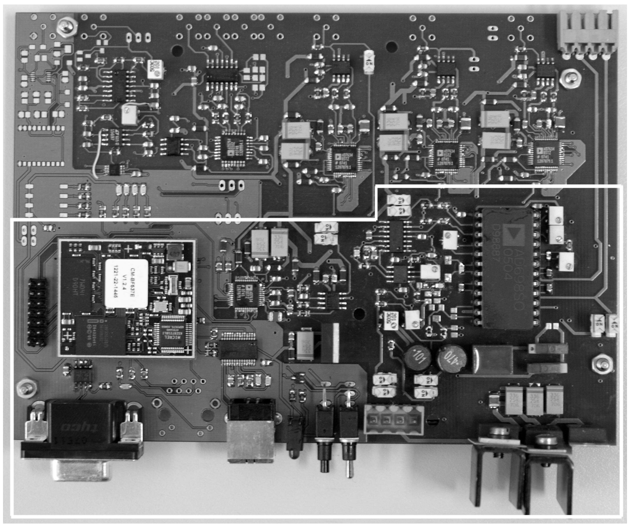

Figure 4: Printed circuit board with AC–bridge, the signal conditioning IC AD698 (Analog Devices), a analog to digital converter and a Blackfin processor. Only the part outlined in white is used for the measurement, the remaining components are glue electronics and interface circuits to a PC.

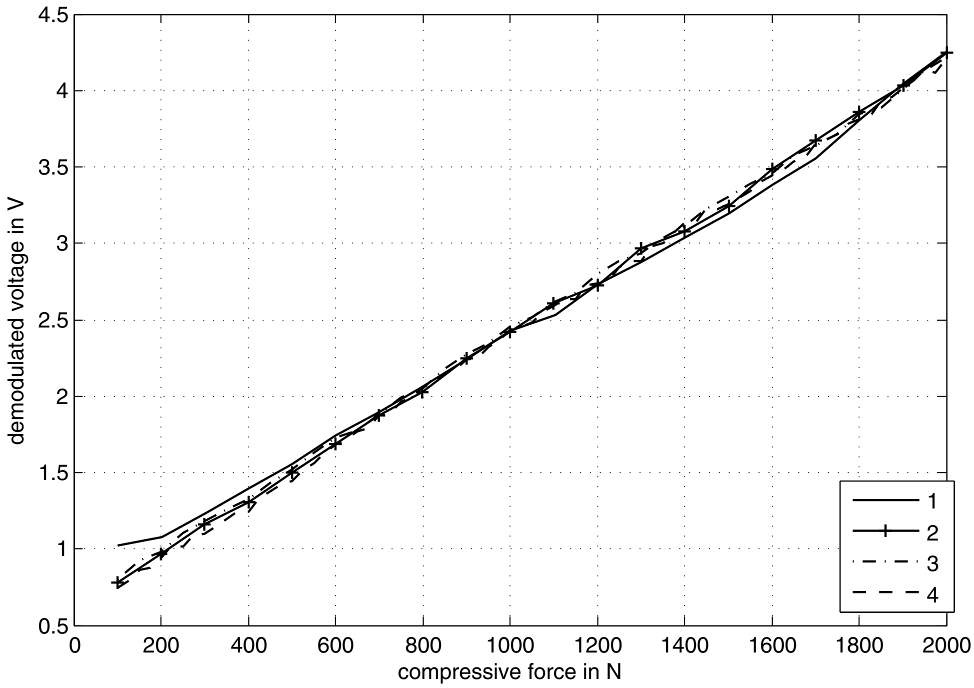

Figure 5: Diagram of the measured demodulated voltage of the quarter bridge vs. quasi–static compressive force steps from 100 N to 2000 N. The curves 1 to 4 are measured over a time span of an hour thus incurring a slightly varying temperature. Part of the variability seen is attributed to the mechanical effects of the loading machine used (TIRA Test).

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