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Contact-free electro-magnetic reactance based mechanical tension sensors

Anatol Schwersenz; Philipp Cörlin; Christian Leiser; Tobias Kitzler; Tobias Senkbeil; ; Sebastian Schwiertz; Lutz May
[1] TRAFAG GmbH Sensors & Controls, Zeilbaumweg 18, 74613 Öhringen, Germany
[2] TRAFAG GmbH Sensors & Controls, Kelterstraße 59, 72669 Unterensingen, Germany
[3] TAM GmbH, Münchner Strasse 33, 82319 Starnberg, Germany

anatol.schwersenz@trafag.de; philipp.coerlin@trafag.de; christian.leiser@trafag.de; tobias.kitzler@trafag.de; tobias.senkbeil@trafag.de; sebastian.schwiertz@trafag.de; lutz.may@tam-sensors.com

Abstract

Motion determines our life. Therefore it is crucial to know the forces we need to get in movement. It is possible to measure the mechanical tension in mechanical components like shafts and pull rods by electro-magnetic stimulation of the bulk material. Using inductive sensors in a specific geometric constellation to the transmitter the sensor signals can be used to measure torsional moments or tensile and compressive stress.

The combination of planar coil systems, magnetic flux conductors and advanced calculation algorithms for transmitter- and sensor signals results in an advanced contactless sensor adaptable for any mechanical stress measurement.

Due to the perfect laterally reversed arrangement of the sensor coils to the transmitter the components of the mechanical stress can be separated. Hereby arises a new contact-free sensor for numerous applications.

Key words: torque sensor, force sensor, torque measurement, embedded sensor, planar coils, pcb coils, ferrite, planar system

Measurement Principle

In shafts and rods without permanent magnetization the magnetic domains are in random orientation *(Fig.1)*. With the rising strain the magnetic domains arrange more and more. Whereas compressive and tensile strain leads to common mode orientation to the force axis torque moments will result in a screw-line arrangement.

The stimulation with an alternating magnetic field leads to a response of the domains. These responses will be measured simultaneously by quadrant-sensors. With the measurement of the four signals and calculation in the implemented electronic the strain is determinate.

Orientation of magnetic domains

In shafts and rods without permanent magnetization the magnetic domains are more or less in random orientation *(Fig1)*. With the rising strain the magnetic domains arrange more and more. Whereas compressive and tensile strain leads to common mode orientation to the force axis *(Fig.2-3)* torque moments will result in a screw-line arrangement in the magnetic domains. *(Fig.4)*

Fig.1

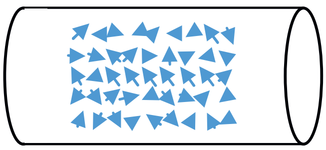


Fig.2

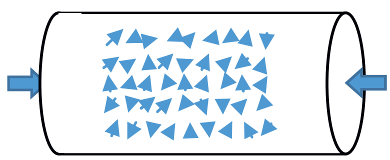


Fig. 3

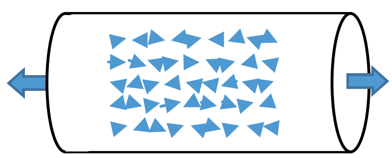
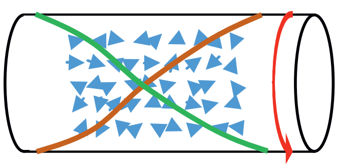


Fig. 4



Active sensor concept

The shaft, the magnetic back, and the gaps lead to a magnetic circuit. With the generator coil in the center this magnetic circuit is permanently stimulated. In the surrounding sensor coils the feedback will be collected in the particular arm of the magnetic circuit. These result in four signals. These signals are summed up crosswise and the two sum signal channels are balanced like in a Wheatstone bridge. Fig.6 shows the geometric concept of a sensor head with the generator in the center and the four sensor channels.

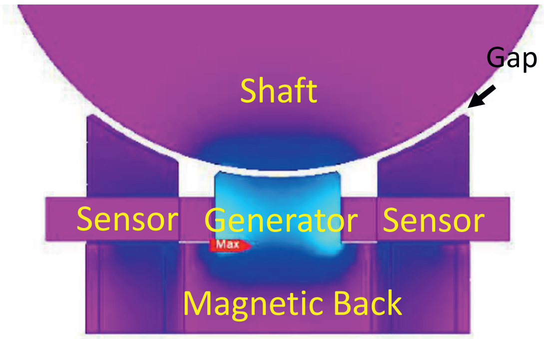


Fig.5

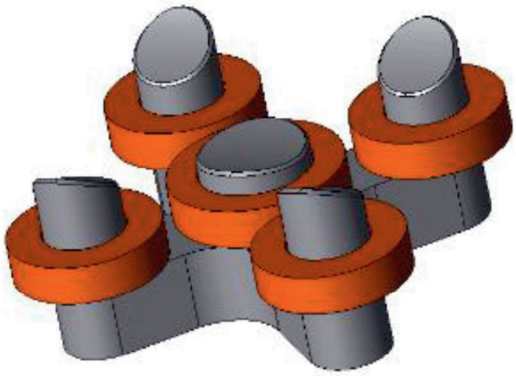


Fig.6

The sensor signal is a function of the stimulation and the magnetic circuit. The magnetic circuit is determined on one hand by the magnetic back and the gap which is kept as constant as possible. On the other hand by the shaft. In the shaft there are the randomly orientated magnetic domains with the superimposed deflection due to the mechanical stress tension.

Magnetic Design Optimization

In order to achieve the best performance of the whole sensor system it is substantial to perform parameters studies. With the complexity of the whole arrangement and the mathematic back round these studies need to be made in a finite magnetic simulation. To close the magnetic behavior to the electronic on the other side and with the transient response of the system the simulations are made in JMAG. Fig.7 shows an example of the penetration depth study.

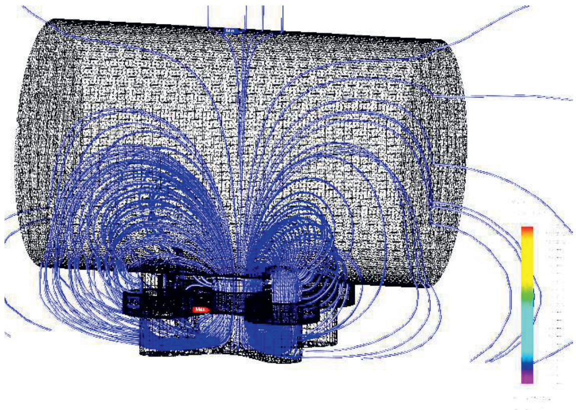


Fig.7

Hardware Integration

As described above all potential effects in the sensor head need to be minimized. To get a stable and repeatable signal in one head is already a challenge. To get a comparable signal from sensor to sensor over lots is a much bigger task. To solve this issue the coils where made as PCB-coils where the repeatability is established in design data.

By this it is inherent to the production process that the coils will be comparable every time.

Production of coil-PCBs offers an almost infinite scalability. Fig.7 shows a production panel with normal panelization with 336 planar coil-systems per PCB-production panel.

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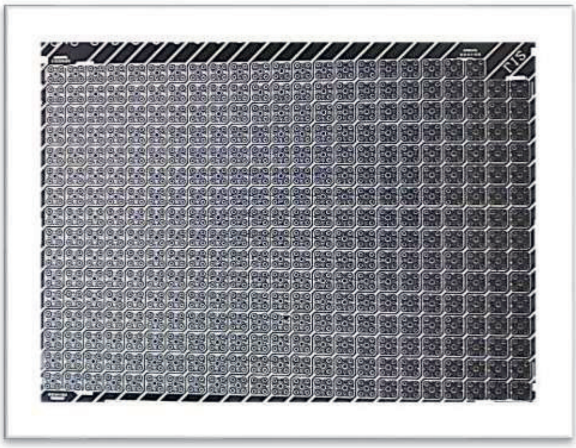

Fig.7

The magnetic back is produced in a standard production for ferrite with a sensor optimized magnetic powder formulation. Even this process is infinitely scalable.

The integration of the magnetic circuit based on the PCB-coils and the magnetic back shows an unbeatable repeatability that enables serial production of the sensor without any trimming or balancing even in high volumes.

The further integration of the measurement electronic and software into a sensor head makes the system vastly compact and robust against external influences. This arrangement leads to much better results than separated systems regarding noise and signal stability. *(Fig8-9).*

The result is an ultra-compact sensor for all mechanical strain situations. It can be used as single phase scale, torque meter, force sensor and various other measurements where mechanical stress is involved.

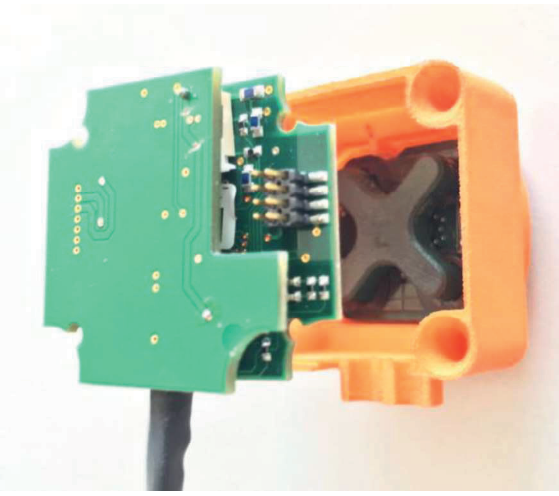

Fig.8

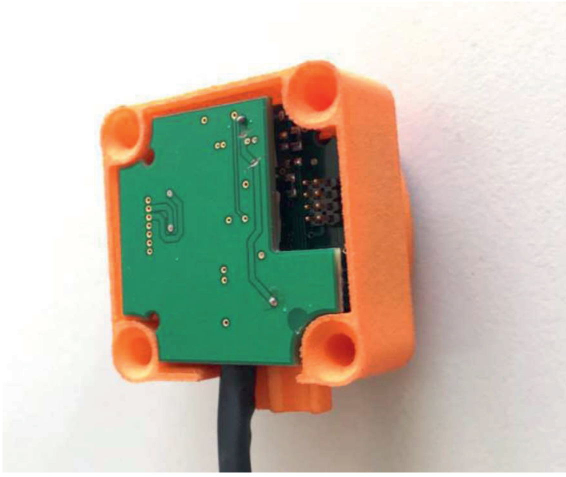

Fig.9

Force and Torque Measurement with Transient and Locally Divergent Materials

As written above the central generator coil stimulates the shaft continuously with an oscillating magnitude. The sensor coils around the generator work as receivers. The magnetic loop is closed by the magnetic back, the shaft and the gap between shaft and magnetic back.

The senor coils receive the generator signal effected by the gap, and the magnetic condition in the shaft. The magnetic behavior of the shaft is determined by the material itself superimposed by the change induced to the magnetic domains due to tensile stress.

With the manufacturing process of the shaft there is a pre-orientation of the magnetic domains imprinted resulting in a variation of the magnetic behavior as function of the shaft angle ψ *(Fig.10)*. In first order the sensitivity of the magnetic domains are not affected by the local divergent manufacturing condition.

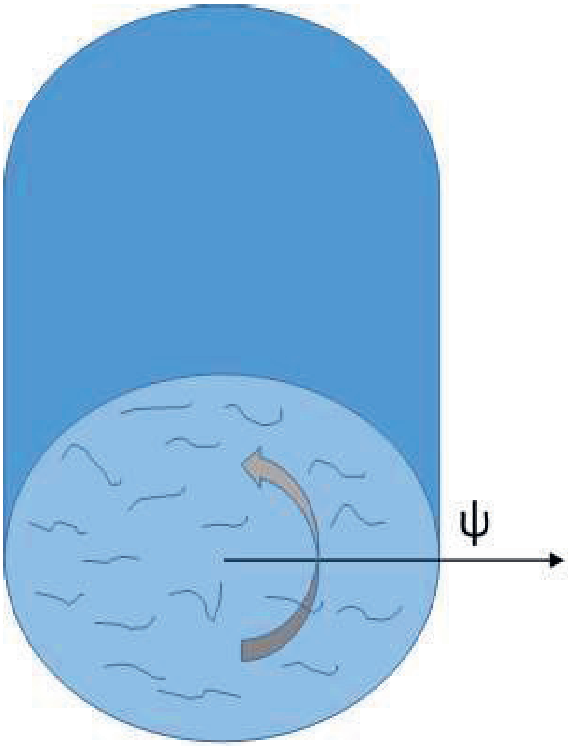

Fig.10

The magnetic circuit and the feedback in the receiver coils is described by the ΔB and ΔH in the B-H curve *(Fig.11)* which shows the system behavior with the stimulation by the generator.

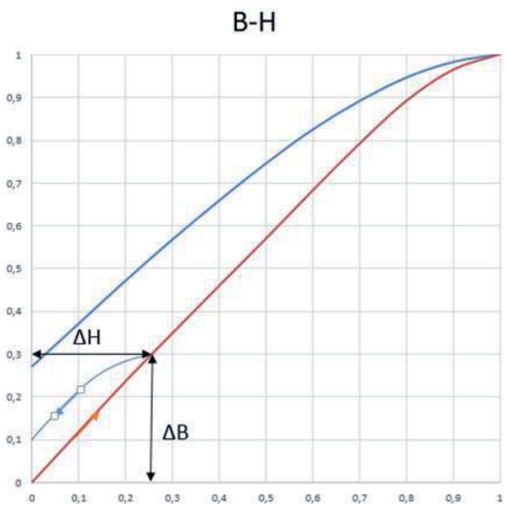

Fig.11

The local (ψ) and the local permeability $\mu_r(\psi)$ is described by the following equation *(Eq.1)*. Whereas ΔB;ΔH need to be measured for all angles.

$$\mu_r(\psi) = \frac{\Delta B}{\mu_0 * \Delta H}$$

Eq.1

The local permeability as function of the angle was measured and is representive shown in *(Fig.12)*.

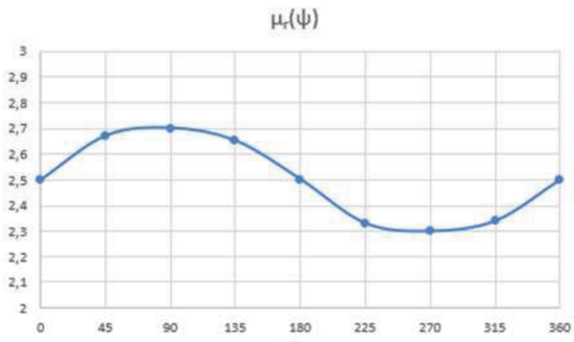

Fig.12

This shows how dramatic the impact can be. This superimposing effect makes the remaining signal for force or torque und a rotating shaft almost useless

In order to solve this angle effect a multipole sensor was created. With an even number of sensor heads located around the shaft the integral sensor concept is able to average the angle issue at the same time the gap sensitivity is remarkable reduced.

Integral Sensor and Application as Weighing Scale

This displayed application of the integral sensor concept shows the system as a scale mounted on a pull bar. The pull bar diameter is 50mm. The sensor heads are in this application a quadrupole sensor *(Fig.13)*.

The four sensors measures the forces along the pull axis. Transverse forces are almost completely suppressed.

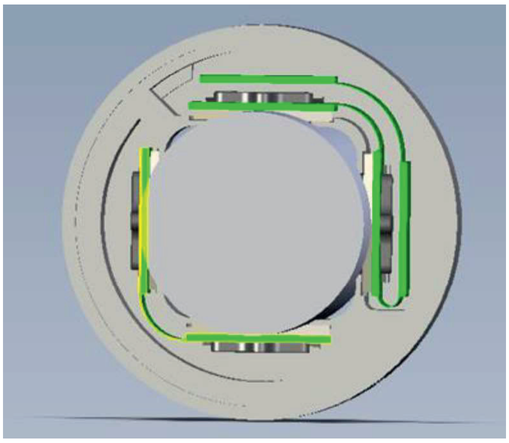

Fig.13

Full scale in this application was 200kN. The sensor shows an excellent linearity.

The sensor signal differs for increasing and decreasing loads which is a system inherent error due to the remaining magnetic hysteresis in the shaft. *(Fig.14)*.

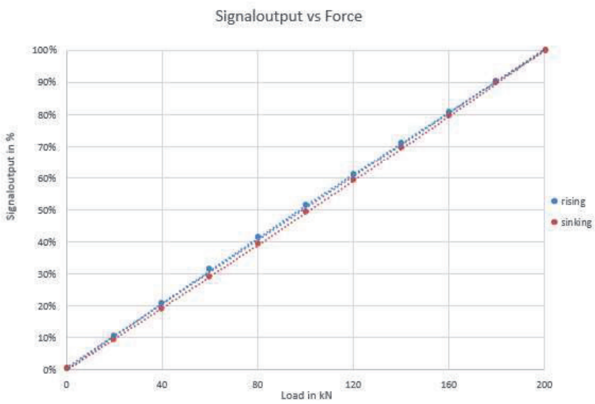

Fig.14

Nevertheless already with this lack the quadrupole sensor system result in an overall total error better than 1.5 % of full scale (*Fig.15*).The hysteresis error is the dominating error source. With the integrated µC based sensor electronics this error can be almost fully recalculated and by this in the data interface compensated.

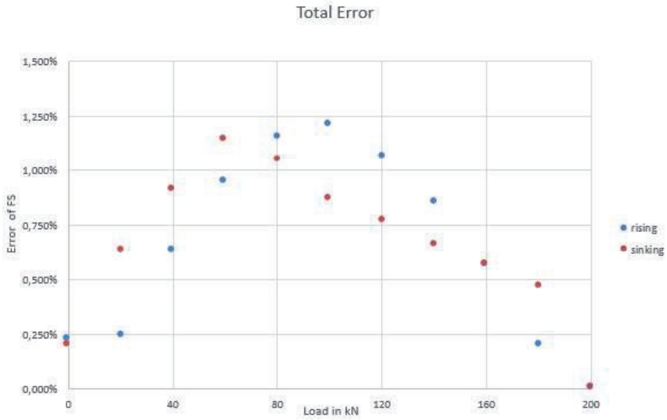

Fig.15

After recalculating the hysteresis effect it remains an overall error better than 0.5 % of full scale *(Fig.16)*.

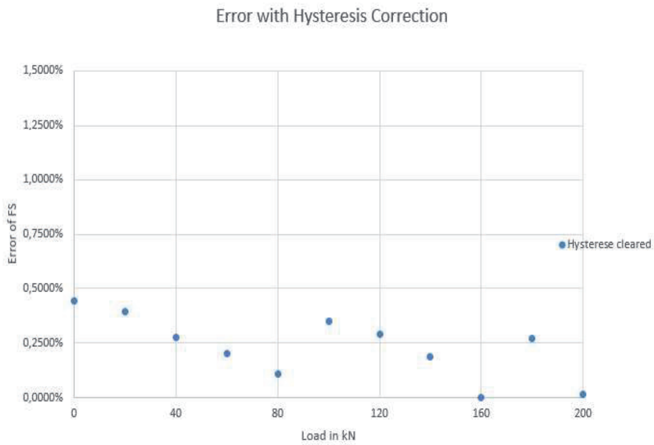

Fig.16

Summary

A new fully integrated Force and Torque sensor platform was developed. From scratch the approach for a serial product was a main target. By using existing mass production an unbeatable reliability is achieved.

For most applications the customization is reduced to the use of standardized sub ensembles which cut down all efforts for adaptions.