Eddy-Current Sensors and their Applications to Force and Stress Measurement in Steel Reinforced Concrete.

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Abstract
The monitoring of bridge constructions can be performed by optimised eddy-current sensors to recognise damages earlier and to reduce rehabilitation expenses. The aim is to measure the coil impedance of an eddy-current sensor positioned close to a pre-stressing cable and to conclude the change of stress in steel of reinforced concrete elements. For this purpose, measurements were taken with specified specimen to investigate the influence from the air gap variation and hysteresis curve.

Keywords: Eddy-current sensor; tensile stress measurement; steel of reinforced concrete elements; Parameter optimisation; stress-strain diagram.

1. Introduction

From the raw material iron completely different steel grades can be produced by admixture of different materials such as carbon, manganese, vanadium chrome, phosphorus or silicon etc. While carbon as well as chrome and vanadium determine the hardness of the steel, silicon for example can limit the oxidation process. further, every custom-made steel grade possesses a residual stress into its structure and also a certain magnetisation. As a result of structure variation due to production and admixture, any kind of steel already has a pre-defined complex impedance Z.. Furthermore, this impedance depends on temperature [1].
Due to these facts the precision and the reproducibility of the measurement are clearly restricted. The sensitivity of an eddy-current sensor on force and strain in a ferromagnetic steel bar is normally lower than geometrical and environmental influences. Therefore, the effects of geometrical size, material structure of the specimen, and the environmental temperature resp. self-heating have to be compensated [2],[3]. Additionally, it is necessary to calibrate the sensors before measuring. For the analysis of structure and residual stress conditions in steel, focussing on the magnetic permeability, seen as a material constant, parameter optimisation plays also an important role.

2. Principle of sensor and measurement

With a change of tensile stress on steel, the relative permeability varies. Thus, the inductance Ls of the sensor coil close to a steel bar specimen depends directly on whose permeability. The magneto-elastic effect leads with a constant level of strain on the steel bar to a change of the coil inductance

$$\Delta L_s = \frac{N^2 \cdot \mu_0 \cdot \Delta\mu_r \cdot A}{s} \qquad (1)$$

Under applied tensile stress the inductance of a coil in strain direction can increase while positioned in cross-section the inductance decreases and the converse [4],[5]. The principle of the experimental construction is suggested in fig.1. While a coil is wound up on a ferrite core and put on a steel sample, the steel is loaded with tensile stress. It has to be made certain that the ferrite core rests without air gap close to the steel bar. Since the magnetic circuit is closed now over the iron, variations of the impedance can be measured during mechanical stress.

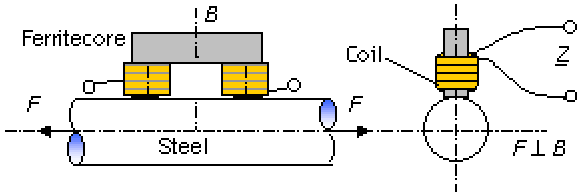

Figure 1: Coil and ferrite core coupled to a steel bar

The load on the material takes place in the elastic area. Comparatively two different materials were investigated. For a principle examination of the experiment, a soft steel (St37) with 6mm square profile and a maximum tensile strength of 370 MPa has been investigated first. The choice of a square profile reduces the air gap between the ferrite core and the steel bar consequently and also undesirable effect on the measuring results.
After this, an original pre-stressing steel bar of the quality St1860 (1860Mpa), which is normally used as pre-stressing for reinforced concrete, was loaded in nearly the same strain range.

3. Experimentation

With the aid of an impedance analyser HP 4284A and a load cell (measuring range 25 kN) several consecutive measurements cycles on each of the two materials were taken which yielded reproducible load cycle.
The specimens are put on a clamping fixture in a manner as seen in fig. 2.

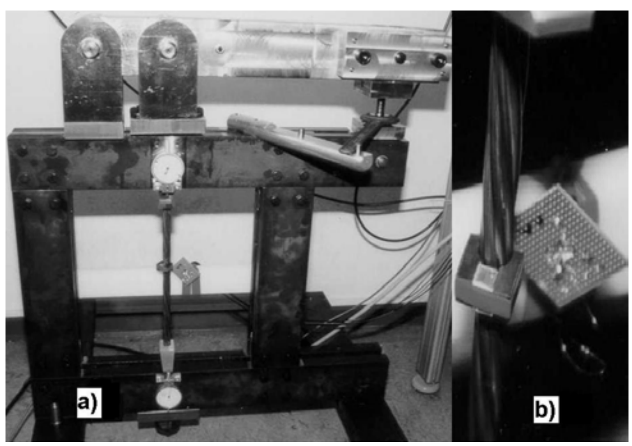

Figure 2: a) Clamping jig with fixed specimen
b) Zoom of specimen and fixed sensor

The curves measured on soft steel clearly show a climbing tendency of inductance and resistance by an increase of tensile stress. Remarkable is a small hysteresis between the same reading points of the load and unload bend. The measurements have been taken under an input terminal voltage of U = 480 mV and f = 1000 Hz, see fig. 3 and 4. The path where the reading points are marked as stars shows the increasing load curve, while the rectangles represents points where the steel has been released from stress.

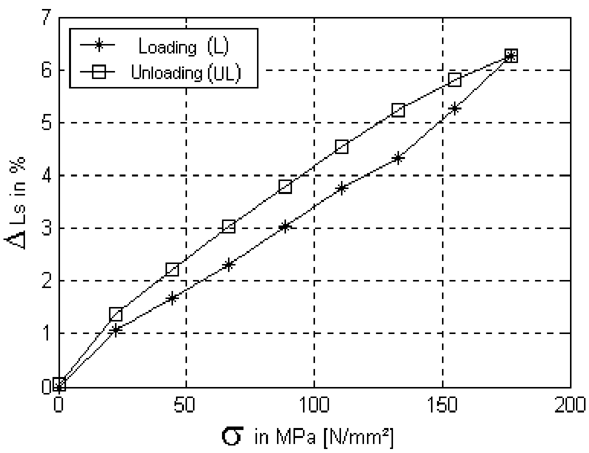

Figure 3: Inductance curve measured on a 6x6mm square bar steel, basic material : St37 (DIN 17100)

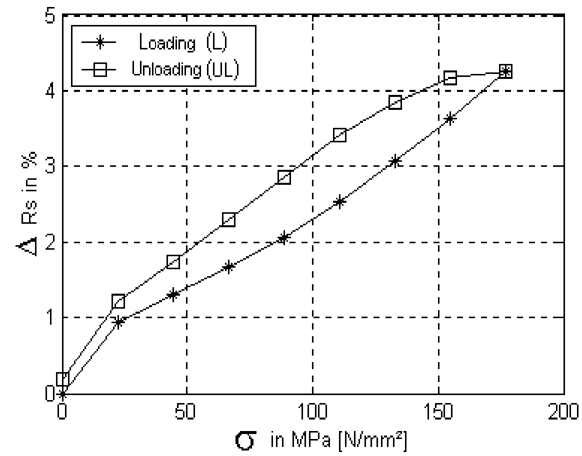

Figure 4: Resistance curve measured on a 6x6mm squarebar steel, basic material: St37 (DIN 17100)

As normalisation does apply: $\Delta Xs = \frac{X_S(\sigma) - X_S(\sigma = 0)}{X_S(\sigma = 0)}$ with $X_s = L_s, R_s$ (2)

On closer inspection of the measuring curves it becomes clear that the relative change of resistance is smaller than those of the inductance.

In contrast to warmly rolled steel cold drawn steel behaves in a different manner. Measurements on tempered material have shown that the inductance and resistance behaves retrograde. This can be attributed to plastic deformation due to the cold-drawing process as well as to the different percentage of solved carbon in the lattice. If metals are deformed plastically, their solidity increases. The rise of solidity is dependent on the speed, with which the deformation happens, and from the tendency of the used material to strain hardening. The strain limit of cold-drawn steel can lie up to 100% higher than natural hard steel.

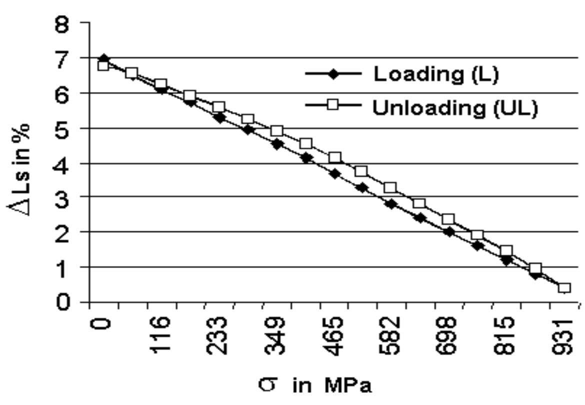

Figure 5: Inductance curve measured on a 5.3mm round steel bar, basic material: St1860 (DIN 10128)

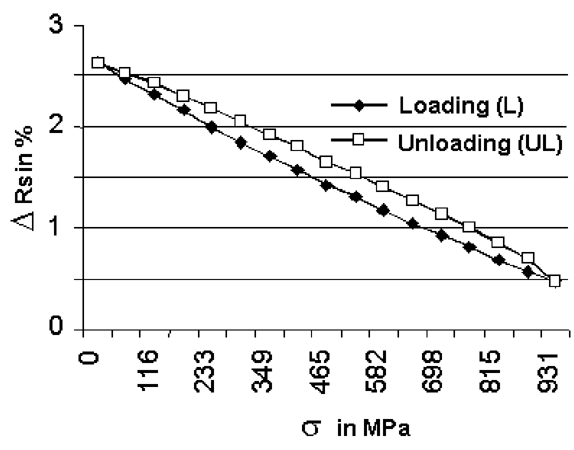

Figure 6: Resistance curve measured on a 5.3mm round steel bar, basic material: St1860 (DIN 10128)

Concerning the cold drawn steel (St1860), the inductance L_s and the resistance R_s decrease with increasing strain almost proportionally. The non-linearity of the inductance characteristic $L_{s,L}$ during the load is smaller than 1 % related to the inductance modification. Hysteresis is likewise small. The hysteresis calculated as the difference of inductance ($L_{s,UL}$ – $L_{s,L}$) with the data of loading and unloading measurement curve is smaller than those of the resistance ($R_{s,UL}$ – $R_{s,L}$), while the inductance modification is clearly larger by strain than those of the resistance, see fig. 5,6.

4. Optimisation of sensor parameter and measurement conditions

The optimisation of sensor parameters and measurement conditions delivers an important contribution for the residual and tensile stress measurement on steel based on the magnetic permeability.

Most important parameters of an eddy-current sensor are, e.g., the geometrical dimension of the ferrite core, the air gap size and the operating frequency as well as the exciting voltage and current.

Those influencing factors should have been optimised before measuring mechanical stress in steel. The aim of this optimisation is also to reach a maximum impedance variation ΔZ of the mounted sensor for a desired frequency range. This range depends on the penetration, the coil and ferrite core geometry and also material properties.

Core dimension

The sensitivity of an eddy-current sensor depends on the geometrical dimensions of the associated ferrite core. Thus, the sensor has been optimised by selecting the adequate core dimension. As an appraisal of results serve the relative change of the sensor coil impedance in the operation frequency area.

The maximum of the relative inductance change rises with removing geometrical dimensions of the ferrite core. Smaller sensors show a more important inductance change. This reveals that the size of soft magnetic core influences the magnetic stray field. A smaller core size leads to a higher magnetic coupling. The maximum size of the ferrite core is also limited by the diameter of the steel-bar. Compared to the ferrite's permeability the change of the steel permeability does not have a very high importance when the used core is too large.

Exciting voltage and current

The parameters of an eddy-current sensor depend also on the magnetic field strength resp. the current I. To analyse the excitation dependency the inductance and resistance are measured in an oscillator level range from 78 mV to 941 mV. In case that the sensor is not mounted on a specimen, the inductance $L_{s,0}$ remains nearly constant, while the resistance $R_{s,0}$ with rising exciting voltage increases. If the sensor is mounted on the specimen, the two parameters R_s and L_s vary with the arising electrical voltage put on. The inductance rises first with increasing voltage, until a maximum. Afterwards the inductance decreases with the voltage continuing to rise. And also the resistance R_s changes within the range of

78mV to 940mV in the same manner as the inductance. Across 940mV the total resistance increases again as a result of the rising temperature. In practice a change of temperature up to 60°C is supposable. Investigations of temperature behaviour must be still accomplished.

The effect of the structure condition of specimen on the inductance is substantially larger than on the resistance. Thus the inductance seems more suitable to measure mechanical stress than the resistance [2]. Figure 7 shows the change of sensor parameters on a measuring frequency of 1kHz.

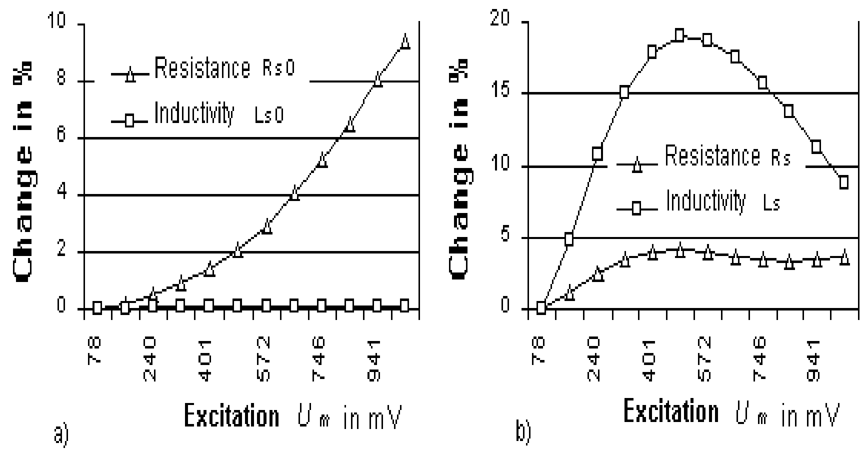

Figure 7: Change of the parameters *R* s and *L*s of the Sensor (E8,8/4/2, *f* =1000 Hz)
a) without steel bar specimen
b) coupled with steel bar specimen.

Air gap

Due to the fact that an air gap has a significant influence on a magnetic circle, also the gap between the ferrite core of the eddy-current sensor and the steel bar has to be kept as slight as possible.

It appears also extreme problematic that a commercial ferrite core like the used one possesses a plane contact area, which has to be enclosed to a round steel bar. Thus, there is no optimal contact between both surfaces and a magnetic coupling decrease is the consequence. See fig 8.

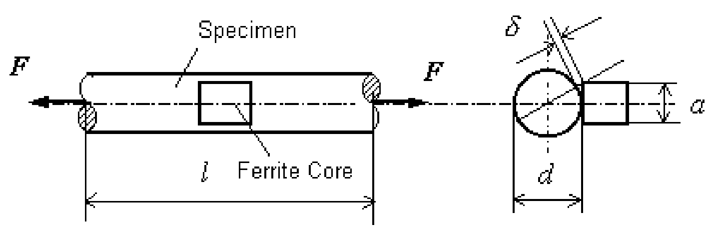

Figure 8: Sensor coil wounded on a ferrite core fixed on a round steel bar specimen

Additionally, under tensile stress the steel specimen in length direction is extended, while its diameter in cross section diminishes. The air gap between the edge of the sensor and the steel is dependent on the bar diameter. Hence, the coil impedance of the eddy-current sensor changes considerably.

Further important optimisations

The optimal and desirable sensor frequency range reduces with increasing number of turns. This is caused by the capacitive coupling of the coil layers. An other reason for a moderate frequency is that due to the skin effect the penetration depth of the magnetic field diminishes too much. For this reasons the number of turns *N* should not be larger than 120. On the other hand *N* may not to be smaller than 60. Otherwise the absolute change of the parameters *L*s and *R* s would be too small due to a change of the mechanical stress. It occurred in this context that in a lower frequency range than 1kHz the hysteresis between a load and unload state is extraordinary high. Best results are measured within ranges far above 1kHz. So, 1kHz is a compromise for this case. Table 1 shows the achieved parameter of the optimised sensor.

Ferrite Core	E8,8/4/2 or E6,3/3/2
Number of Turns	$60 \leq N \leq 120$
Magnetic Field Direction	Parallel to Stress Direction
Excitation Voltage / Current	$500\ \mathrm{mV}$ and $50\ \mathrm{mA}$
Frequency range	$100\ \mathrm{Hz} - 1\ \mathrm{kHz}$
Appropriate Parameter	Inductivity L_s and Resistance R_s

Table 1: Results of sensor parameter optimisation

5. Outlook

In the pre-stressed concrete construction, wires and strand-bundles are often used as tendons. In relation to measurements of single rods or single wires strands and strand bundles additional problems raise according to geometrical form variety. It has to be noted that always all wires of strand bundles do not exhibit the same stress during load changes (change of the total tendon strength). So, it could be necessary to position a sensors on every single rod of a strand to increase the accuracy of the measurement. The developed eddy-current sensors could be used not only for force and stress measurement of tensile steel elements and for the monitoring of pre-stressed bridge cables but also for the measurement of residual stress components.

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