Dynamic Load Inspection on Steel Tendons of Steel Reinforced Concrete Constructions by means of Eddy-Current Sensors

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Abstract. In this contribution a force measurement system will be represented. It applies the method of eddy-current sensor testing. This measurement arrangement is able to detect dynamic tensile loads in prestressings, which are higher then 5 MPa and oscillating up to 20 Hz. Fast measurement rates and low power consumption are the main efforts of the eddy-current sensor system. Developed sensor-arrays can easily be mounted by a special clamp-on technique. Slight steel contact inaccuracies while fixing the sensor-array will be minimised by applying the sensor fusion principle. Operation point stabilisation and calibration has been archived by an adjustable radial magnet field offset over the whole measuring area. A theoretical approach and detailed modelling by finite element methods of the eddy-current sensor in a measurement environment helps to verify the function of the whole system.
Keywords: Eddy-current sensor; tensile stress measurement; steel of reinforced concrete elements; Parameter optimisation; stress, strain, FEM-modelling

Motivation

The increasing demand of reinforced concrete constructions such as bridge constructions requires a reasonable long-term construction monitoring using a competitive multi-sensor technique. Magneto-elastic force measurement on pre-stressed reinforced concrete cables is an investigative method to detect the state of stress and failures of prestressings [1,2,3,4].

1. Introduction

The catastrophies during of the last months regarding building failures by overstressing in Germany, Austria, Poland, and Russia pointed out once more the importance of a constant and continuous surveillance of building constructions. Long-term monitoring with diverse measuring techniques at present only exists for especially critical buildings, like dams, skyscraper, tunnels or bridge constructions. The economical and spread employment of a durable measuring technique is considered as a worthwhile aim which can be installed easily for the lifetime monitoring of tensile loaded reinforced concrete elements. There are already some monitoring techniques on the market, which meet criteria for building load inspections. Optical operating devices are available which use the excitation of light modes by stretching optical fibres. A use of strain gauges is not recommendable because of their ephemeral adhesive sealing in these special working conditions. However, some inductive and transforming operating devices are existing, which evaluate changes of magnetic values in tensile stressed steel due to applied tensile stress. The University of Braunschweig employs a method, where mechanical stressed ferro-magnetic steel is magnetised cyclically over the shape and form of a hysteresis curve (BH-curve). This measuring technique requires high magnetisation energy and a few seconds for a whole measurement cycles. Therefore, the question arose to develop a fast and economical measuring technique for the regulation of tensile stress in steel reinforced concrete elements [2,3,4,5,6,7].

2. Principle of Sensor and Measurement

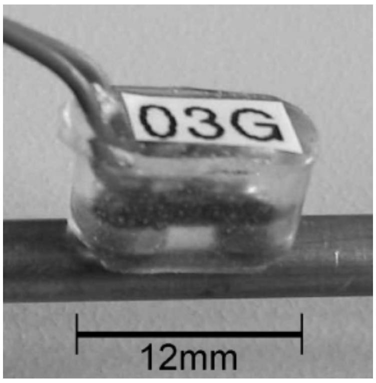

Figure 1 Example of a single Eddy-current coil with ferrite core on 5 mm steel wire.

The coupling between mechanical strain and the change of magnetic characteristics of ferro-magnetic materials is described by the Villary effect [4]. The change of the magnetic permeability in the material is macroscopically measurable evaluating a coupled coil's inductance.
The measurement takes place with an excitation frequency of 1000 Hz, whereby the optimal excitation current with approximately 65 mA depends on the ferrite-steel coupling, the given number of turns of the windings and the desired geometry. For a small sensor geometry ferrite cores of the type EPCOS E8.8 mm with the material identification N30 were used, which carry two serial coils on each yoke with approx. 100 to 125 turns. The principle of the stress measurement technique is shown in *Figure 1*. The industrial applications demand to apply an eddy-current sensor in such a way on the test steel wire that it is durably embeddable in a reinforcing steel environment. Since the steel tendons are to be examined consist of six individual wires, winding themselves within a certain lay length around a core wire, a simple concept for a sensor package from six serially switched ferrite core coils was planned [9,10,11,12].
The challenge was to apply the eddy-current sensors on the steel cable so that they measure long-lasting dynamic charges in the steel. Thereby the ferrites became thereby to the outline of the steel surface adapted around to minimise the air gap. This approach offers several advantages: Mounting-conditioned inductance fluctuations by unevenness at the steel surface can be averaged by the measurement of all six serial connected single sensors. In addition, the concept of sensor fusion can be applied by single evaluation of the six coils by statistical methods estimating errors. A break of an external wire would be indicated to the relating coil by inductance measurements. Besides a symmetrical structure of the sensor favours an optimal rotational symmetry for a cover construction [13,14,15,16].

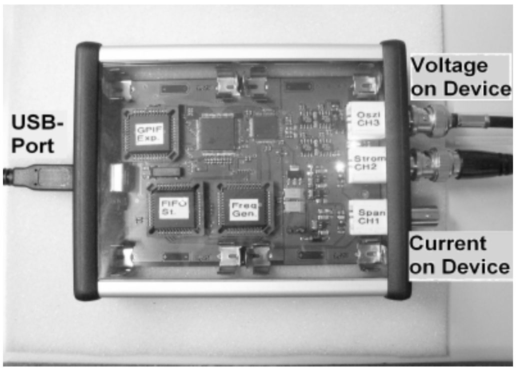

Figure 2 Dimlab128-USB Impedance and Inductance Measurement Device.

The power consumption of a sensor array consisting of six ferrite coils is about 400 mW. This is clearly lower than compared with other inspection techniques. For fast and comfortable inductance measurements, which are also independent of the mains DIMLAB128-USB was developed, which permits measurements with a variable frequency between 1 Hz and 10 MHz and adjustable amperage between 0.1-100 mA. At a sampling rate of 100 Ms/s inductance measurements are possible with oscillating stress amplitudes far above the demanded 20 Hz.

3. FEM-Simulation

In this simulation two different measuring scenarios were examined. At first, the ferrite with coils was placed on the steel surface and excited as described above. Then, the magnetic coupling of two annular magnets with the same eddy-current coil arrangement was introduced to a second model. The objective of this investigation was to verify whether a magnetic stabilisation of the operating point during the inductance measurement would be reached. For this, the given geometry and material sizes, as well as the excitation current and frequency were taken into account.

It is obvious that the penetration depth of the current density in an arrangement without magnets is higher but no exact statement can be made over the effective direction of the steel's magnetisation under the ferrite core (see *Figure 3*). In *Figure 4*, the arrangement including annular magnets, it has to be recognised that the magnetisation vectors under the ferrite core always stays in a perpendicularly position to the main stress direction. Only the applied tensile load alters the magnetic behaviour of the steel. The penetration depth in the steel changes as a function of the distance between the annular magnets and the ferrites. Thus, higher eddy-current densities in a smaller steel volume are reached to excite a higher flux density improving the operation point of the steel permeability. The exciting ferrite coil modulates the operating point of the differential magnetisation in the steel at the array operation point. This process depends nevertheless on of the inserted mechanical stress.

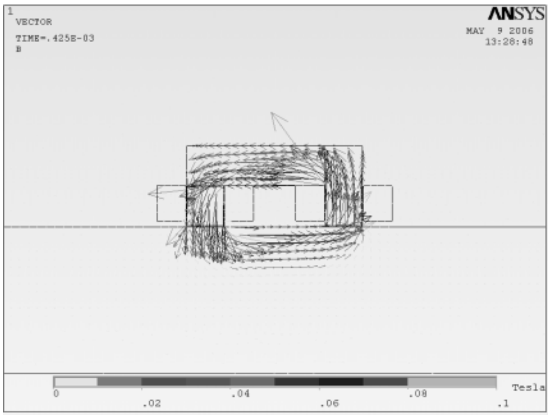

Figure 3 Flux density in Ferrite coil placed on steel without stabilising magnet.

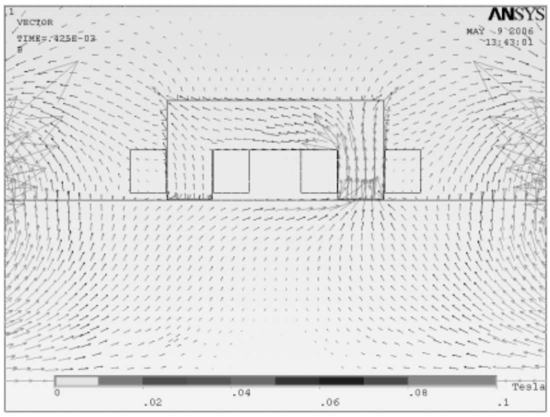

Figure 4 Flux density in Ferrite coil placed on steel with stabilising magnet.

Since FEM programs generally do not allow any connections between mechanical stress and the changes the magnetic values the applied stress cannot be modelled. This simulation has to be understood as static computation for the operating point.

4. Stabilisation of Measurement Operation Point

The optimal and desirable sensor frequency range declines with increasing numbers of turns because of the capacitive coil layers coupling. Another reason for a moderate frequency is due to the skin effect, which reduces the penetration depth of the magnetic field. It occurred that in a lower frequency range than 1 kHz the hysteresis between a loaded and unloaded state is extraordinary high. Best results were measured within ranges far above 1 kHz. So, 1 kHz is a compromise for this case. For the employed ferrite type the number of turns N should not be larger than 120 and smaller than 80. Otherwise the absolute change of the parameters L_s and R_s would be too small due to a change of the mechanical stress [10,11,12,13,14,15,16]. The above-described effect of hysteresis appears while measuring the coil inductance because of the steel's magnetisation changes under applied stress:

$$\left.\frac{\mathrm{d}B}{\mathrm{d}\sigma}\right|_H = \left.\frac{\mathrm{d}\lambda}{\mathrm{d}H}\right|_\sigma \qquad \text{with} \qquad B = \mu_0 \cdot (H + M) \tag{1}$$

The conversion of mechanical into magnetic energy takes place following the above-mentioned relation (1) with low amplitudes and without irreversible memory processes. The magnetostrictive coefficient λ represents the magnetomechanical sensitivity, whereby ($\mathrm{d}\lambda/\mathrm{d}H$) with constant σ expresses the change of the magnetostriction with variation of the magnetic field. ($\mathrm{d}B/\mathrm{d}\sigma$) represents the change of the magnetic flux density with variation of the mechanical stress σ under a constant H-field. This means that materials with large magnetostrictive coefficients achieve a high sensitiveness of magnetomechanical stress measurement. Steel of the sort St1860 tends to magnetic hardness with rising remanence, high coercity and a weak negative magnetostriction [17,18,19].

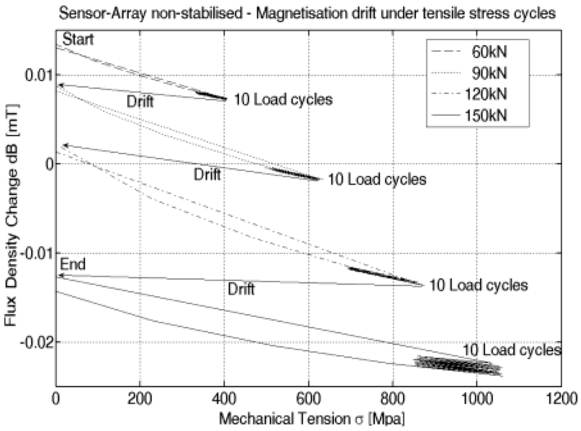

Figure 5 Measured flux drift after load cycle without magnet stabilisation.

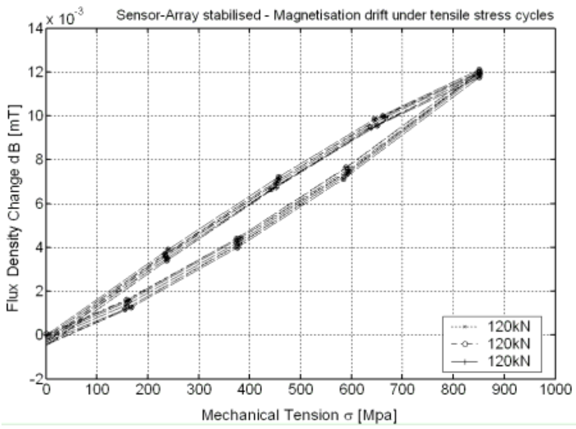

Figure 6 Measured flux drift after load cycle with magnet stabilisation.

Figure 5 shows a strong drift of the remanence in the steel specimen during several load cycles. Thereby, the direction of the drift's sign depends on the magnetic previous history of that steel. The measurement of the flux density in the steel during several load cycles showed an increasing magnetisation and a remanence introduced by the applied tensile stress. Replacing a ferrite between two annular magnets the magnetic condition at the test point would stabilise clearly. *Figure 6* illustrates the repetition accuracy of the flux measurement of three load intervals each with 10 cycles. The remanence drift $\mu_0 \cdot \mathrm{d}M$ shown in *Figure 5* while cyclical steel stressing affects the measurement of inductance L_s in the way:

$$\mathrm{d}L_s = \frac{\mathrm{d}B(t) \cdot A \cdot N}{H \cdot l_m} \qquad \text{with} \qquad \sigma\| \sim -\frac{\mu_0 \cdot (H + M) \cdot H}{2} \tag{2}$$

When a material shows a positive magnetostrictive behaviour (see *Figure 7c*), the change of the measured coil inductivity $\mathrm{d}L_s$ by tensile stress σ will be positive, (also as shown in *Figure 7a)*. Whereas A and l_m represent the effective geometric conditions of magnetic circuit. However, if a material such as St1860 with high-grade tensile residual stress presents a negative magnetostriction (see *Figure 7d*), the change of the coil inductance $\mathrm{d}L_s$ likewise declines see *Figure 7a)*. Within both in measurements a hysteresis between the starting and the end load point occurred a load-conditioned change of remanence in the steel. The zero level inductivity has been changed observably [10,11,16].

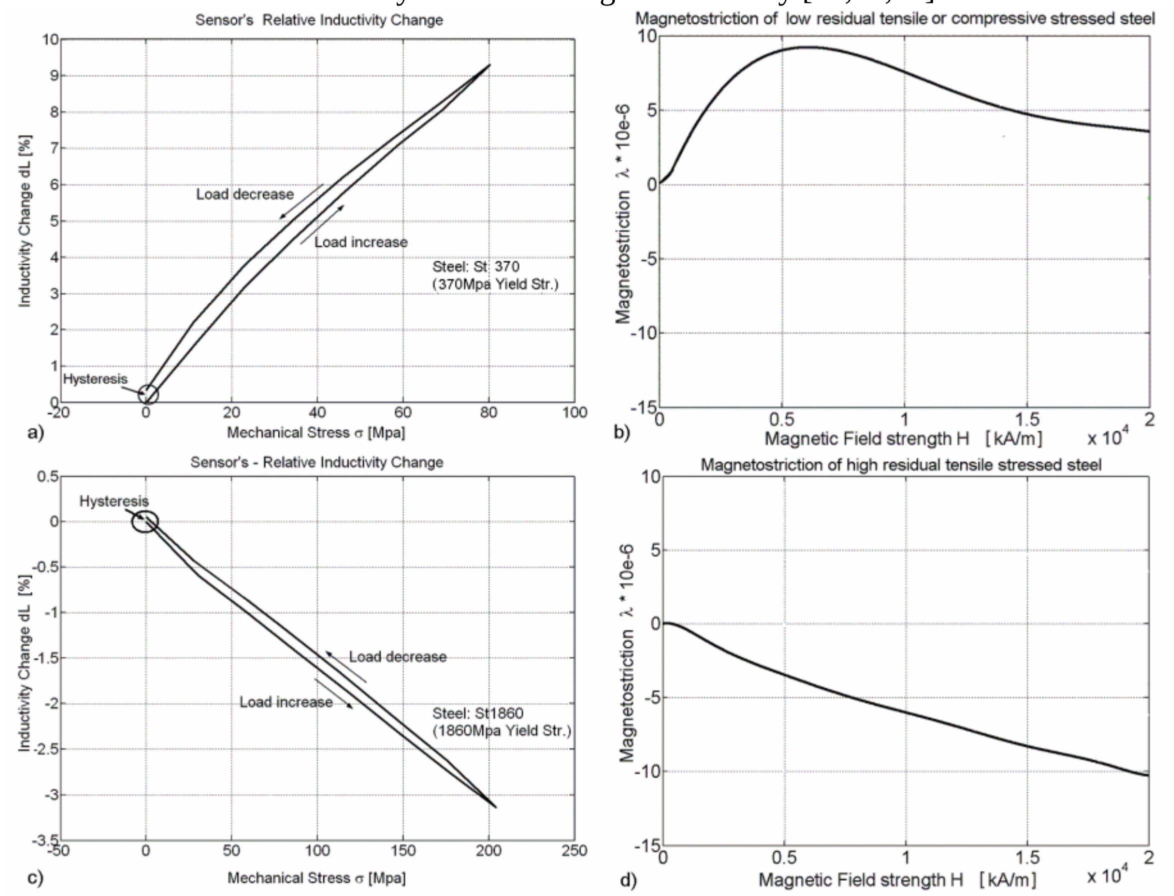

Figure 7 Comparison of inductance measurements of negative and positive-magnetostrictive steel samples.

The simulation and measuring investigations showed that the presence of static magnetic fields makes sensor operating point stabilisation possible. The polarity of the opposite magnet surfaces must be homopolar. *Figure 9* shows the principle of the inductance measurement with annular magnet stabilisation.

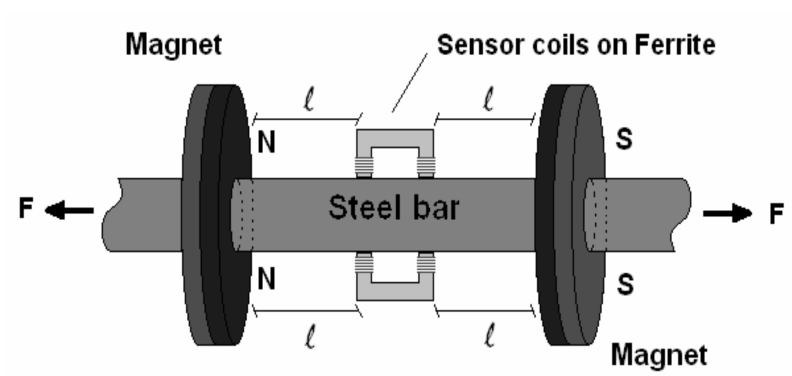

Figure 9 Schematic of ferrite coils enclosed of annular neodymium magnets set on pre-stressed steel cable.

By changing the magnet's symmetric distance to the ferrite core or the magnetising force the sensitivity of the sensors is adjustable. In addition, the coil's initial inductivity value can be specified adjusting that distance. From the applied homopolar axial magnetic field a strong decrease of the magnetisation at the measuring point in stress direction results, even if the steel has already been magnetised by stress influence. Without employment of annular magnets flux densities between 0-10 mT/100 MPa after each load cycle must be counted.

5. Experimentation

A test steel cable of the quality St1860 was clamped into a 250 kN stress machine and loaded as shown in *Figure 10* cyclically. To have a more visible comparison to the measurement results of the eddy-current sensor arrays the dynamics were set within a range of seconds. The other reason was the slow dynamics of the stress machine. All sensor arrays were placed in a distance of approximately 250 mm, whereby only two arrays were stabilised by annular magnets. After several load cycles within 0-1000 MPa the sensitivity of the sensors could be determined. The sensitivity of the sensor application was between:

$$\frac{0.025}{\text{MPa}} \text{ und } \frac{0.03}{\text{MPa}} \text{ after calculation: } \frac{L_{s\sigma 1} - L_{s\sigma 0}}{100\,\text{MPa} \cdot L_{s0}} \cdot 100\% \,. \qquad (3)$$

After the calibration of the sensor arrays one day was paused. The steel was left thereby under a tension of +50MPa. The measurement setup is illustrated in *Figure 10*.

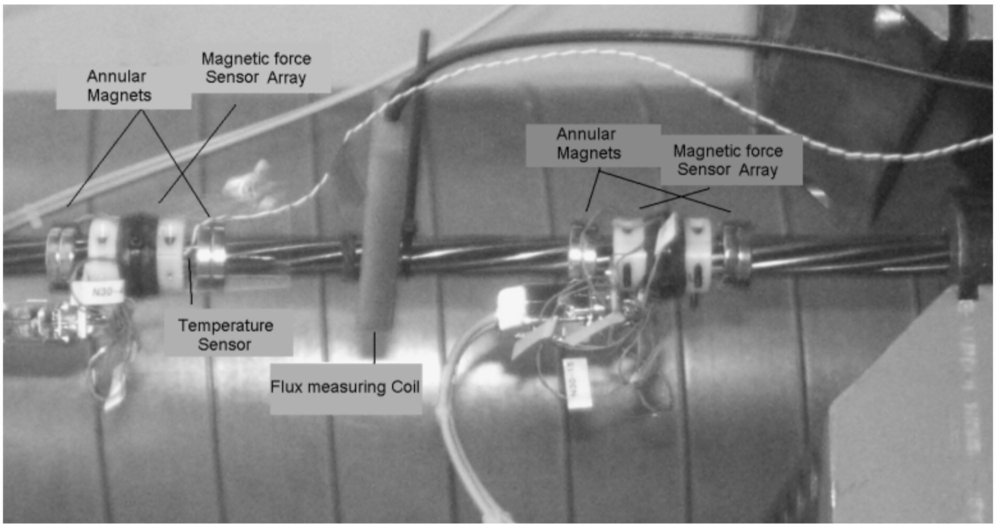

Figure 10 prestressing steel quality St1860 in tension device with the visible sensor arrays 1 and 2, annular magnets flux probe and temperature sensor

The prestressing was loaded within a force interval between 5 and 120 kN. Related to the steel's surface area (A_{st}=140 mm²) the maximum applied stress was approx. 860 MPa. See the force progression in *Figure 11:*

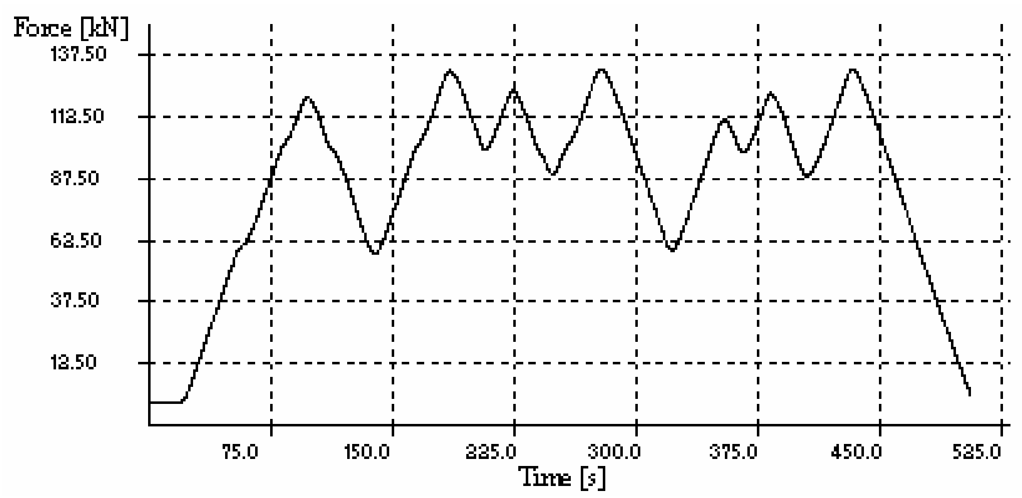

Figure11 mechanical force progression of the stress machine, which was applied on the steel cable specimen

The three employed sensor arrays all reflect the same stress characteristics, produced by the stress machine. Since all arrays had to be exploited by rotation, a multiplexer had to be accomplished. For an optimal switching process gold contacted relays were used. Unfortunately, this choice affected the system speed negatively and has to be considered later. While the sensor arrays 1 and 2 were under magnetic influence the experiments showed no considerable inductance drift around the measurement operating point. But the effect occurred with sensor array 3 visibly whereas the measurement operating point has clearly arisen because of the magnetisation the steel wire. See *Figure 7*. The drift led to deviation of 150 MPa within a range of 850 MPa. This effect changed the initial sensor inductance up to 17%. This was an insufficient result [16].

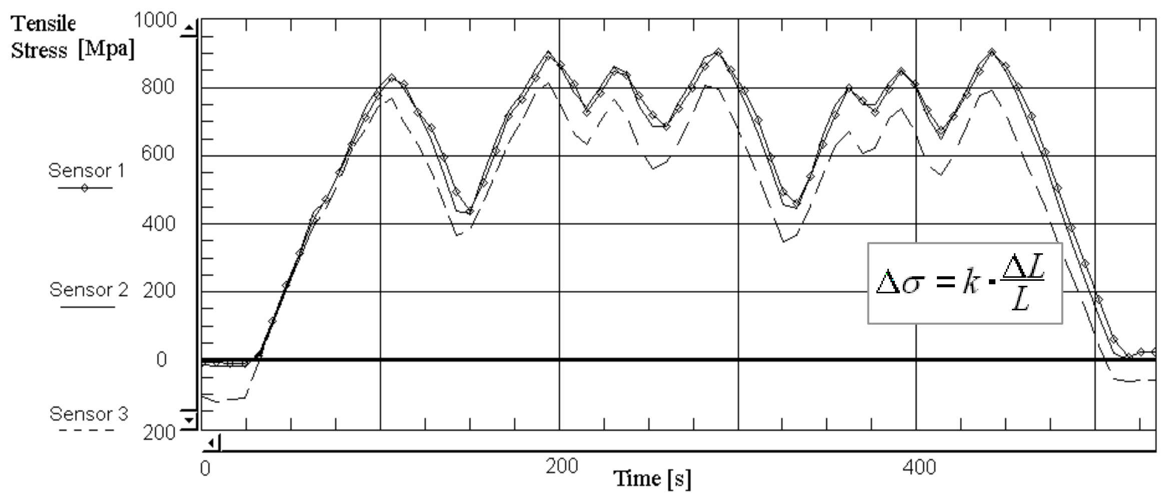

Figure 12 Measurement results of three Sensor Arrays placed in the distance of 250mm on the steel cable

The two stabilised sensor arrays exhibited inductance fluctuations lower than 3%. However this can be attributed at changes of temperature, errors with the stress machine or the curvature of the steel, which has to be verified further. Above all it is necessary to implement a temperature compensation for the entire measuring system in the future.

6. Resume/Outlook

The measuring system DIMLAB128-USB offers an opportunity to quantify mechanical stress in steel wires according to the previous determination of the eddy-current sensor sensitiveness. This is important because of the individual magnetic and magnetostrictive material behaviour. Annular magnets stabilise the operation point of the inductivity measurement. Hence, the inductivity is the parameter, which has to be converted into mechanical stress. The measuring technique is a mobile device due to the low power consumption of DIMLAB128-USB and the developed sensor-arrays. The power input is definitely lower compared to other measuring systems by approximately 400 mW per sensor array. A supply of this technology can also be ensured by means of battery operation or the USB-port of a Notebook. An implementation of individual software is necessary for measurement savings and evaluation and can be adapted and refined universally. It has to be noted that temperature compensation of the entire measuring system is absolute necessary to minimize any measurement errors. The main part of temperature drift generates the ferrite core and annular magnet materials. However, the steel's and copper's changes are moderately. A thoroughly made material selection can help to diminish temperature problems widely.

7. Acknowledgement

This work has been promoted by the Deutsche Forschungsgemeinschaft (DFG). The authors would like to thank for the financial support. They also owe sincere thanks to Dr. W. Zinn, Institute of Material Technology of the University Kassel, and Mr. Dr. R. Kern as well as Dr. G. Dobmann, Fraunhofer-Institute for Non Destructive Testing Methods for their support.

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