Experimental and Numerical Investigations of the Inverse Magnetostriction-Based Mechanical Stress Sensing

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Abstract — Experimental and numerical investigations on the inverse magnetostriction contactless mechanical stress sensing are carried out. The emphasis is on the eddy currents induced in the sensed part and its effect on the evaluation of the stress-induced magnetization and thus the stress. It is shown, that except for a slight hysteretic behavior, the magnetization is linearly related to the stress and that the eddy current reduces the induced voltage and magnetic flux density and introduces time-delay in the flux density making the evaluation of the stress a challenging task.

I. INTRODUCTION

The inverse magnetostriction, also known as Villari effect, is the phenomenon by which a sample of magnetic material changes its magnetic properties when it is subjected to a mechanical stress. Such change in the magnetic properties of the material can be interpreted in two equivalent ways; namely as change in the permeability of the material or change in its magnetization. The origins of such phenomenon are well explained in the literature, e.g. [1] gives a good quantitative and phenomenological explanation of the magneto-mechanical effects in iron. The inverse magnetostriction has been exploited in many applications such as transducers [2], current sensors [3] and contactless stress sensors [4] among others. The design of such devices requires knowledge of the magneto-mechanical properties of the material, which can be found from different publications for different materials [5], [6]. Most of the published literature on contactless stress sensing concentrates on the relationship between the stress and the magnetization either from hysteric or anhysteretic point of views, and at low frequencies when the magnetodynamic effects can be ignored. In this paper, we consider the contactless mechanical stress sensing and investigate its behavior in applications were the stress is of relatively high amplitude and is fast changing as is the case in stress waves travelling along a steel support or a Hopkinson-like bar. In these cases the fast changes of the stress-induced magnetization in the bar or support will induce eddy-currents and thus hinder the estimation of the magnetizatation through the measured magnetic flux density by a coil around the bar e.g.

Our approach is based on both experimental work and numerical FE simulations to assess qualitatively and quantitatively the effects of eddy currents on the measured signal and how to evaluate the magnetization and stress.

II. EXPERIMENTAL WORK

The experimental work reported here is divided into two parts, one dealing with the material characterization and the other dealing with the stress sensing in a steel bar.

The sensing method considered in this work is of a simple configuration. It consists of a sensing coil of 150 turns, the axis of which coincides with the axis of the sensed Hopkinson-like bar. The coil is introduced around the bar and the voltage induced in the coil when the stress-induced magnetization of the bar is changing in time is used to estimate this magnetization and the mechanical stress.

This method is not as universal as the strain gage e.g. as its output depends strongly on the magneto-mechanical properties of the underlying material. For this reason we carried out measurements of the magneto-mechanical properties of the material under static and dynamic stresses.

The setup for such measurements consisted of a bar-shaped sample the ends of which are worked out to allow for applying both tensile and compressive stresses. The sample is either first subjected to a static stress and then cyclically magnetized or first statically pre-magnetized and then subjected to a cyclic stress. The magnetization of the sample is implemented through additional voltage-fed coils and a magnetic core, whereas the flux density in the sample is measured by a search coil around the sample. The stress is calculated from the force measured by a piezoelectric-based load cell and applied by a hydraulic cylinder. The results of such testing are shown in Fig. 1 and Fig. 2 for the static and dynamic stress cases respectively. The results of Fig. 2 show that the stress-magnetization relationship is slightly hysteretic and linear for a given pre-magnetization.

The other measurements have been carried out on a 3 m length and 10 mm diameter Hopkinson-like bar. The traveling stress pulses in the bar are created by hitting it from one end. The shape of the stress pulses could be adjusted by appropriate choice of the bar-hitting object. A typical result from such test is shown in Fig. 3 where the stress pulse measured by a strain gage, the coil voltage and the corresponding magnetic flux density are plotted.

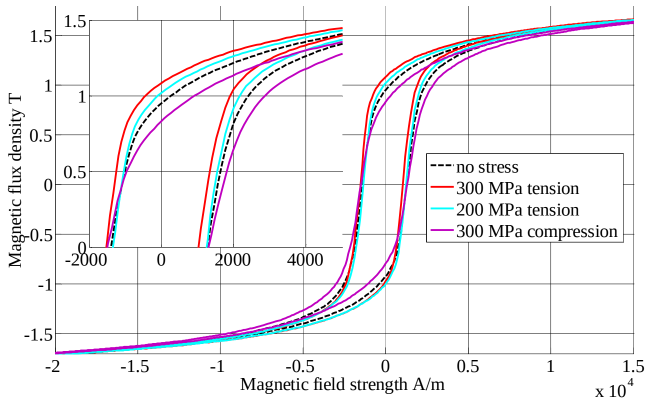

Fig. 1. Measured BH-loops of a heat-treated sample under different static mechanical stresses. The insert is a zoom-in at the region of interest.

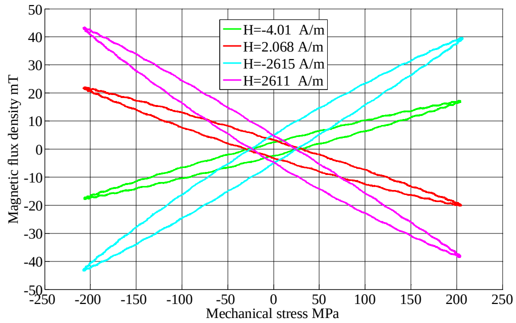

Fig. 2. Measured stress-flux density relationship when the sample was first pre-magnetized and then subjected to slowly (1 Hz) varying mechanical stress. Except for a slight hysteresis, an almost linear stress-magnetization relationship depending on the pre-magnetization is shown.

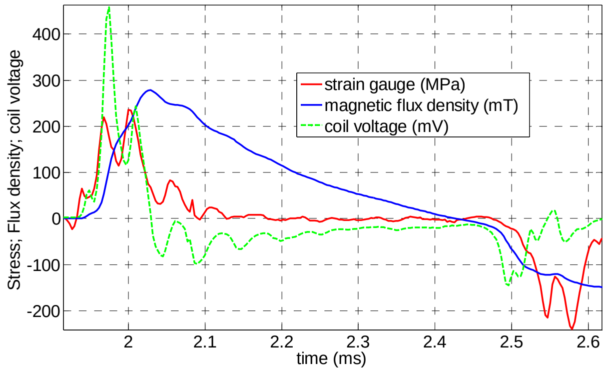

Fig. 3. Measured stress pulse and the corresponding variation of the magnetic flux density as well as the voltage measured by the coil. The time-delay and the slow decay in the flux density are due to the induced eddy currents. The fast variation of the stress is seen in the coil voltage too.

III. NUMERICAL SIMULATIONS

For a better understanding of the nature of the coil signal as well as for the purpose of quantifying the effect of eddy currents in the bar, we carried out 2D axisymmetric time stepping finite element (FE) simulations of the bar. The excitation of the 2D anhysteretic and magnetodynamic FE model was set by an axially traveling Gaussian-shaped magnetization uniform in the radial direction of the bar

$$M_z = \alpha \hat{\sigma} e^{-\frac{\left(\frac{2\pi z}{w} - vt + t_0\right)^2}{w^2}} \tag{1}$$

Where α =160 Am^{-1}MPa^{-1} is calculated from the results shown in Fig. 2 and $\hat{\sigma}$ =300 MPa is the peak value of the stress pulse. z is the axial coordinate, t the time, w =1.8 defines the pulse-width, and v =6000 ms^{-1} is the velocity of the stress wave in steel. t_0 is a parameter used to adjust the position of the pulse and its starting time.

Fig. 4 shows the mesh and the flux lines in the model at the time when the peak of the stress has reached the height z=-1 m, which is further used as the coil's axial location. Fig. 5 shows the imposed magnetization and the probed flux density by two coils situated at this axial location and at two different radial ones. The voltages probed by these coils are also shown. The simulation shows a similar time-delay in the flux density to the one seen in Fig. 3. A strong reduction of the peak value is seen too. In absence of eddy currents, the flux density would be exactly the one shown by the imposed magnetization in Fig. 5.

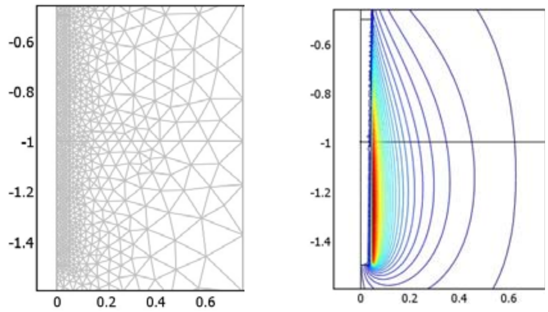

Fig. 4. The model's mesh and the simulated flux lines in the bar and its proximity at the time when the peak of the magnetization is at z=-1 m.

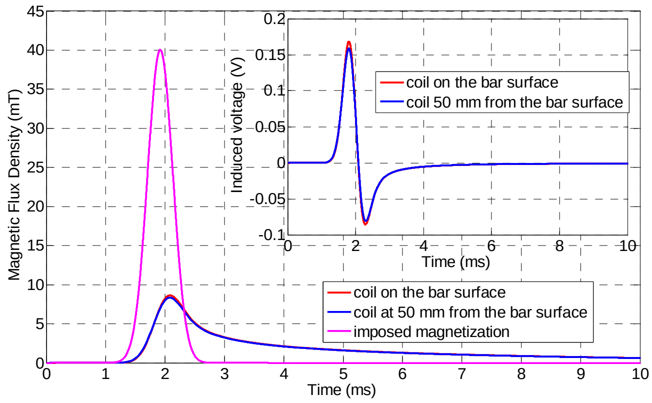

Fig. 5. Simulated flux density probed by a 1-turn coil around the bar, located at z=-1 m and at a radius of either 0.05 m (bar surface) or 0.1 m (50 mm from the bar surface). The insert shows the corresponding voltages probed by these coils. The imposed magnetization is also shown after being transformed into an equivalent flux density (multiplied by μ_0).

IV. ANALYSIS AND DISCUSSION

A discussion of the results presented here and the consequences of the material properties on the induced eddy currents will be given in the full paper. However, it is clear that a way of accounting for these eddy currents is needed. Further it is shown that the location of the coil with respect to the bar does not affect its output very much as the flux densities and the voltages probed by the two coils are almost the same. The pre-magnetization and the material magneto-mechanical properties affect very much these quantities.

V. REFERENCES

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