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# COMPARISON OF SELECTED METHODS OF STRESS MEASUREMENTS IN FERROMAGNETIC MATERIALS

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**Change in magnetisation of a ferromagnetic subjected to mechanical stress is known as Vilarie's effect. The paper describes contactless measurement of stress based on this effect. The measurement signals generated by magnetoresistive transducer were compared to measurements of deformation conducted with strain gauge transducer at the same time. Qualitative and quantitative similarities have been observed in the recorded signals. The simplicity of the contactless stress and vibration measurement with magnetoresistive transducer has been demonstrated. This method makes possible measurements even if the material is characterised by low magnetostriction coefficient.**

## 1. INTRODUCTION

The changes in magnetisation $J$ or magnetic induction $B$ due to stress $\sigma$ are equivalent to the strain $\lambda = \delta l/l$ (i.e. magnetostriction) for a given magnetic field intensity $H$. These relationships determine "piezomagnetic" sensitivity $d$ of a material. The thermodynamic approach to relationships in question is shown in Eq. (1.1) where magnetostrictive Joule's effect is coupled with Vilarie's magnetoelastic effect [1, 2, 3]:

$$\frac{1}{l}\left(\frac{\partial l}{\partial H}\right)_{\sigma} = \left(\frac{\partial B}{\partial \sigma}\right)_{H} = d. \tag{1.1}$$

Depending on the polarity of magnetostriction, the direction of acting forces may cause increase or decrease in magnetisation. The reversible magnetoelastic changes occur in a limited range in all materials magnetically polarised and showing magnetostrictive properties. The complex thermodynamic calculations [2] described by a basic formula (1.1) can be reduced to an identity:

$$d \cong \lambda \tag{1.2}$$

and this means that magnetic susceptibility coefficient $d$ is equal to magnetostriction coefficient $\lambda$.

Change in ferromagnetic element magnetisation due to mechanical stress is reflected in the change of magnetic field intensity at the surface of this element. In order to test the usefulness of magnetic measurement method a prototype test stand has been set up. The measurements of mechanical stress were conducted with two methods (magnetic and with strain gauges) and results were compared.

## 2. COMPARISON OF MECHANICAL STRESS MEASUREMENT PROCEDURES FOR MAGENTIC AND STRAIN GAUGE MEASUREMENT METHODS

The differences in two measurement methods have been shown in the signal acquisition and processing diagram (Fig. 1). The stress measurement with bridge strain gauge is based on mechanical to electric conversion. The changes in bridge output voltage, which depend on material deformation, are analysed. The measurements done with bridge magnetoresistive transducer are based on the principle of magnetic to electrical conversion. The contact with element being tested is not required [4,5,7,9]. During the signal processing the magnetomechanical phenomena described by Villarie take place.

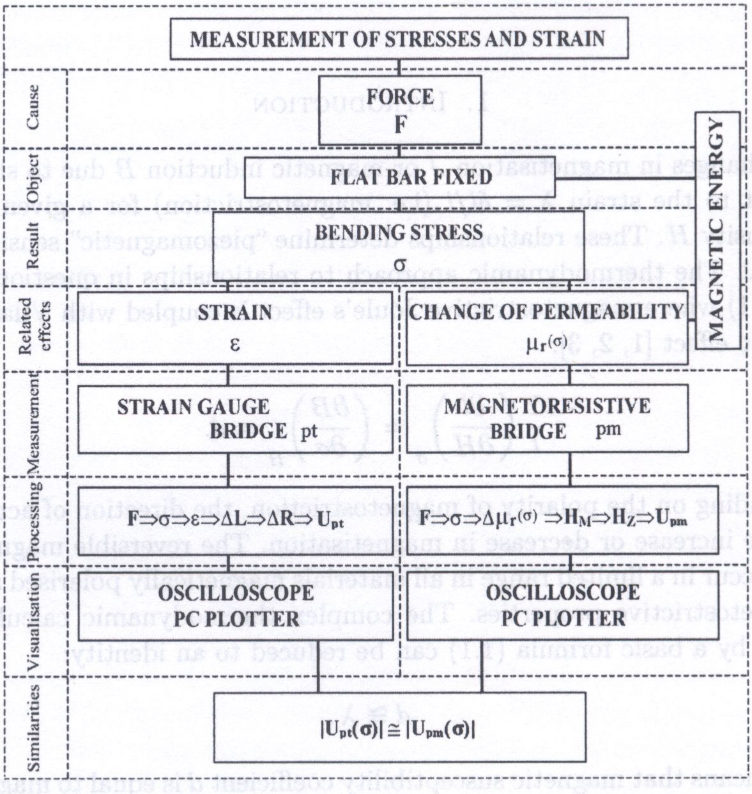

FIG. 1. Data acquisition and processing for measurement methods applied.

## 3. MAGNETOMECHANICAL PARAMETERS OF TESTED MATERIAL

If magnetomechanical parameters of material are known, then it is possible to initially assess feasibility of using magnetic methods in stress measurement. Whether such measurement is possible, depends on magnetostriction coefficient $\lambda \neq 0$. Majority of ferromagnetic materials used in industry and based on iron is characterised by positive magnetostriction coefficient in the range $0.5 \div 5 \cdot 10^{-6}$. However, nickel alloys are characterised by negative magnetostriction coefficient. The magnetic susceptibility of the material can also be described by magnetisation vs. stress curves. The percentage values of the remaining alloy components of tested steel (magnetisation curve has been previously determined) are set out in Table 1.

**Table 1. Chemical composition of investigated material.**

| Material | components [%] | | | | | |
|---|---|---|---|---|---|---|
| | C | Si | Mn | Cr | Ni | Mo |
| Alloy composition | 0.07 | 0.85 | 1.2 | – | – | – |

Changes in the hysteresis loop due to stress show magnetic susceptibility of a tested material. The practical use of magnetic measurement methods in stress testing relates to the lower limit of elastic deformation. For tested steel this limit is equal to 60–80 MPa (there the magnetomechanical changes due to tension and compressing are linear [6, 8]). The magnetic hysteresis loops determined with FERROTESTER for a steel wire (alloy as in Table 1) have been shown in Fig. 2.

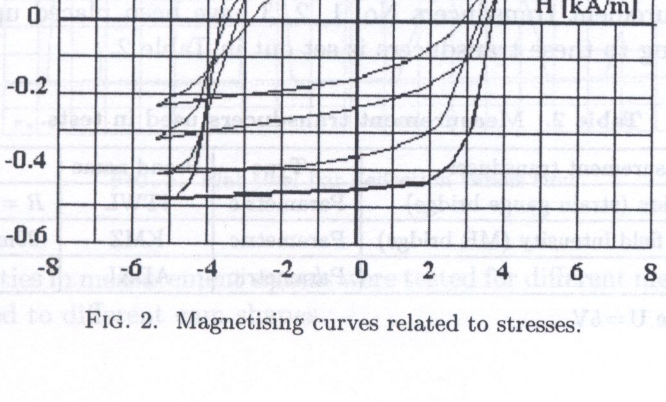

FIG. 2. Magnetising curves related to stresses.

The values of static stresses set were successively equal to $\sigma_0 = 0\,\mathrm{MPa}$, $\sigma_1 = 240$ MPa for elastic deformations and $\sigma_2 = 360$ MPa, $\sigma_3 = 480$ MPa, when elastic deformation limits were exceeded.

## 4. TEST STAND

The test stand has been designed in such a way that it is possible to conduct simultaneously measurements of dynamic cyclic loading.

The tests included the surface deformation measurements $\varepsilon$ done with a strain gauge ($U_{\mathrm{pt}}$), deflection $f$ measurements done with a potentiometric transducer ($U_{\mathrm{pp}}$) and magnetic field intensity $\mathrm{H}_n$ measurements done with a magnetoresistive transducer ($U_{\mathrm{pm}}$). In addition, the vibrations were recorded with an ADXL transducer $U_{\mathrm{ADXL}}$). A flat bar fixed at one end was subjected to a force generated by a mechanical cam system.

The bar was magnetised by a permanent magnet belonging to a vibration transducer fastening appliance. The functional diagram of the test stand equipped with a cam has been shown in Fig. 3.

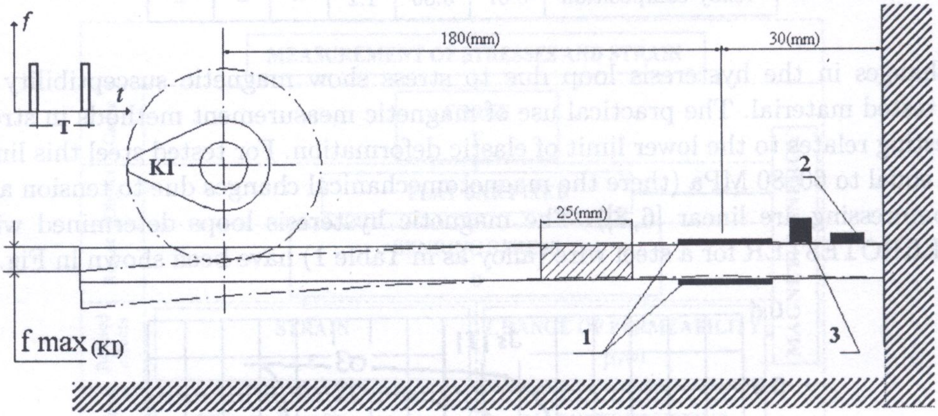

FIG. 3. Test stand functional diagram.

The measurement transducers No. 1, 2, 3 have been placed upon the bar. Data pertaining to these transducers is set out in Table 2.

**Table 2. Measurement transducers used in tests.**

| No. | Measurement transducer | Type | Brand name | Sensitivity |
|---|---|---|---|---|
| 1 | Deformation (strain gauge bridge) | Parametric | ITWL | $R = 120\ \Omega$, $k = 2.2$ |
| 2 | Magnetic field intensity (MR bridge) | Parametric | KMZ | 20mV**/ (KA/m) |
| 3 | Vibration | Parametric | ADXL | 300 mV/g |

**Supply voltage U = 5V.

Apart from the cam shown in Fig. 3, different cams were used. Their cross-sections are shown in Fig. 4. The contact face of KII cam ends in a miniature bearing. The ball bearing asymmetrically placed acted as another cam – numbered KIV. The cam lifts differed in heights.

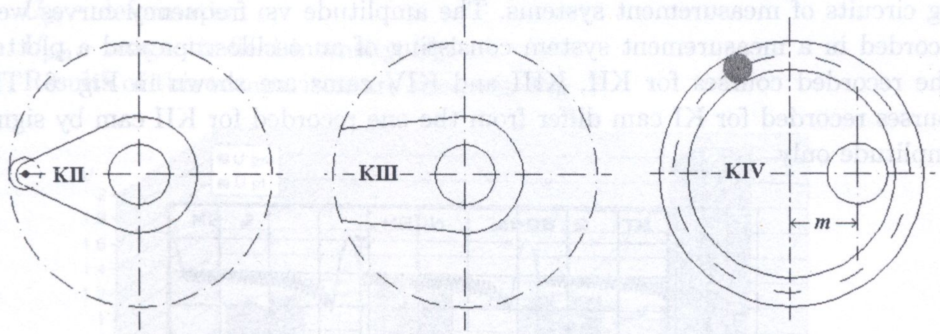

FIG. 4. Different cam shapes (KII to KIV).

The cam shape influenced the course of forces acting upon the bar. Every cam was characterised by different properties influencing bar's deflection and the proportion of deflection time to cycle period. Figure 5 shows the voltage courses of potentiometric transducer measuring bar's deflection.

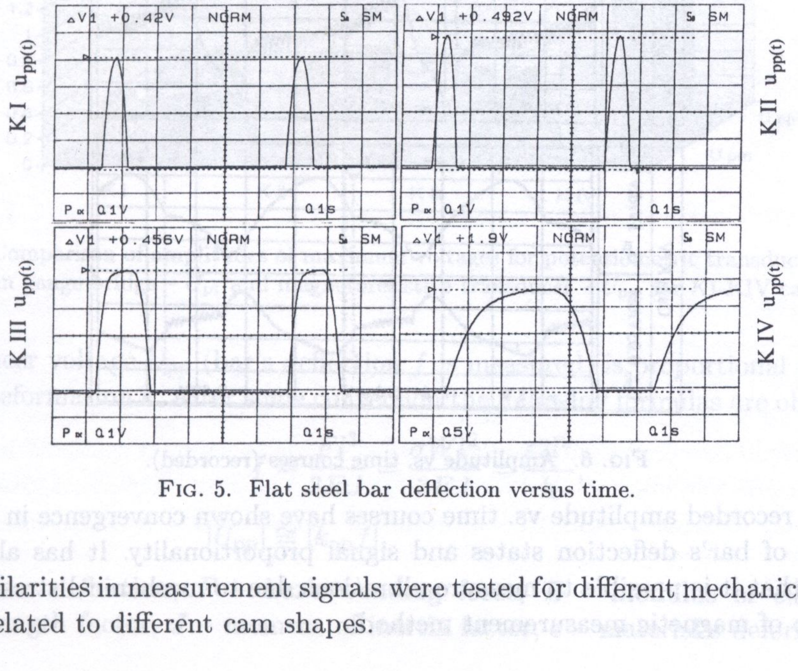

FIG. 5. Flat steel bar deflection versus time.

The similarities in measurement signals were tested for different mechanical input forces related to different cam shapes.

## 5. MEASUREMENTS

Stress measurements were conducted independently for each cam. The deformation, magnetic field intensity and bar deflection were measured. Very precise amplifiers (INA 114 series) manufactured by Bur-Brown were used in amplifying circuits of measurement systems. The amplitude vs. frequency curves were recorded in a measurement system consisting of an oscilloscope and a plotter. The recorded courses for KII, KIII and KIV cams are shown in Fig. 6. The courses recorded for KI cam differ from the one recorded for KII cam by signal amplitude only.

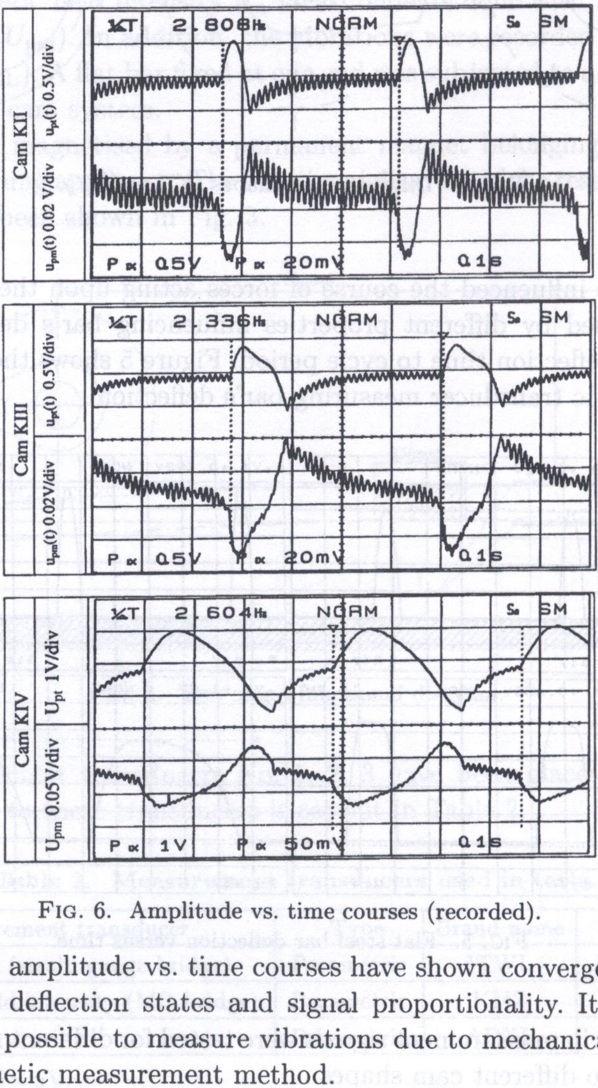

FIG. 6. Amplitude vs. time courses (recorded).

The recorded amplitude vs. time courses have shown convergence in relation to time of bar's deflection states and signal proportionality. It has also been proven that it is possible to measure vibrations due to mechanical stresses with the help of magnetic measurement method.

## 6. COMPARISON OF TEST RESULTS

The measurement transducers output voltages maximum amplitudes were compared for each cam:

$U_{\mathrm{pp}}$ – deflection $f$,
$U_{\mathrm{pt}}$ – deformation $\varepsilon$,
$U_{\mathrm{pm}}$ – magnetic field intensity $H_n$.

Results of this comparison are shown in Fig. 7.

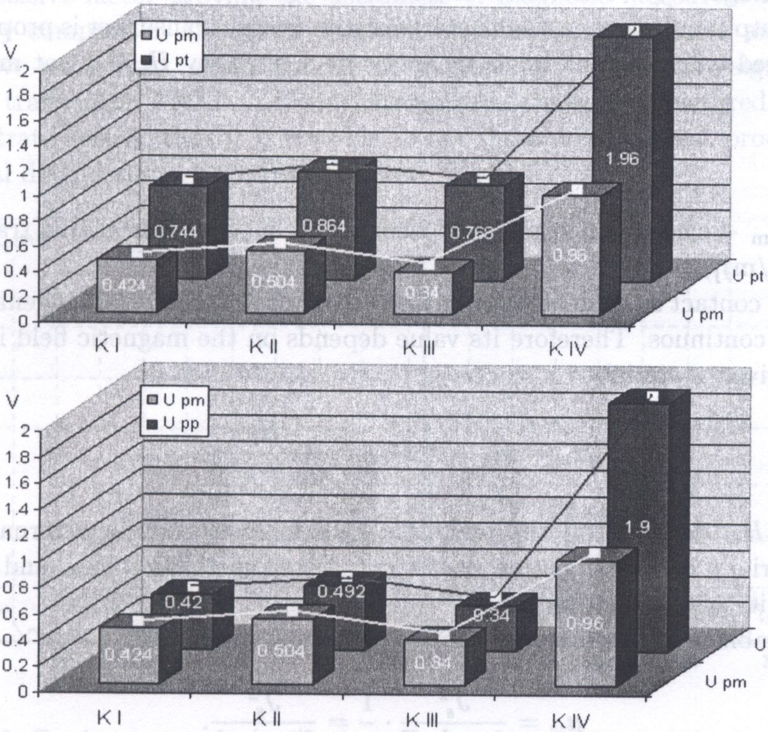

FIG. 7. Comparison of amplitudes of maximum voltages for potentiometric transducer – $U_{\mathrm{pp}}$, strain gauge bridge – $U_{\mathrm{pt}}$ and magnetoresistive transducer – $U_{\mathrm{pm}}$ for KI-KIV cams.

Transducer voltage $U_{\mathrm{pp}}$ (bar's deflection $f$ is measured) is proportional to force $F$ and deformation $\varepsilon$. After some conversion the following formulas are obtained:

$$f = \frac{Fl^3}{3EJ} = \frac{\sigma W l^2}{3EJ} = \frac{\varepsilon 2 l^2}{h}, \tag{6.1}$$

$$|U_{\mathrm{pp}}| \cong |k_{\mathrm{pp}} f|, \tag{6.2}$$

where $f$ – deflection, $F$ – bar's bending force, $E$ – modulus of elasticity, $W$– strength factor, $J$ – moment of inertia factor, $\varepsilon$ – material's deformation,

$h$ – flat bar's thickness, $l$ – $F$ force's arm, $k_{\text{pp}}$ – conversion coefficient of potentiometric transducer.

Output voltage $U_{\text{pt}}$ of potentiometric transducer operating in a full bridge circuit is proportional to deformation $\varepsilon$ and is equal to:

$$U_{\text{pt}} = \varepsilon k U_z, \tag{6.3}$$

where $\varepsilon$ – deformation, $k$ – coefficient of deformation sensitivity, $U_z$ – bridge supply voltage, $U_{\text{pt}}$ – conversion coefficient of strain gauge.

The output voltage $U_{\text{pm}}$ of magnetoresistive bridge transducer is proportional to measured value of tangent to magnetic field intensity $H_{nf(Hw)}$ at material's surface:

$$U_{\text{pp}} = k_{\text{pm}} H_{nf(H_w)}, \tag{6.4}$$

where: $k_{\text{pm}}$ – conversion coefficient (sensitivity of magnetoresistive transducer [mV/(KA/m)]).

At the contact surface between magnetic material and air the tangential component is continuos. Therefore its value depends on the magnetic field intensity $H_w$ in a given material:

$$H_w = H_z - N M_m = \frac{H_z}{(\mu_r - 1)N}. \tag{6.5}$$

Intensity $H_w$ depends on the magnetic field intensity of the external source $H_z$, material's demagnetisation coefficient $N$, magnetisation $M_m$ and relative permeability of the material $\mu_r$.

Permeability of the material changes due to stress (6.1):

$$\mu_w = \frac{J_s^2}{3\,\mu_0\,\lambda_s E} \cdot \frac{1}{\varepsilon} = \frac{J_s^2}{3\,\mu_0\,\lambda_s\,\sigma}. \tag{6.6}$$

where $J_s$ – saturation magnetisation, $\mu_0$ – permittivity of the free space, $E$ – modulus of elasticity $\varepsilon$ – longitudinal deformation, $\lambda_s$ – material's coefficient of magnetostriction.

Figure 7 shows proportionality between amplitude values $U_{\text{pt}}$ $U_{\text{pm}}$ and they are related to $U_{\text{pp}}$ as well. The "mirror reflection" of the $U_{\text{pm}}$ signal, i.e. decrease in its amplitude accompanying increase in stress, is characteristic of materials having a positive magnetostriction coefficient $\lambda_s$. In view of conducted tests, the conformity of signal amplitudes of different measurement transducers is significant

$$|U_{\text{pt}}| \cong |U_{\text{pm}}|. \tag{6.7}$$

It must be noted that an indirect factor in the magnetic field intensity measurements was magnetisation of the material by permanent magnet of vibration transducer, which is shown in data acquisition and processing scheme as a side branch (cf. Fig. 1 – magnetic energy).

## 7. Conclusions

A decisive factor proving the usefulness of magnetic measurements is produced by comparison of courses recorded by vibration transducer and magnetoresistive transducer, shown in Fig. 6. Amplitude vs. frequency signals of vibration transducer ADXL and magnetoresistive transducer pictured in Fig. 8 demonstrate clearly, that it is possible to use these measurement procedures in technical diagnostics.

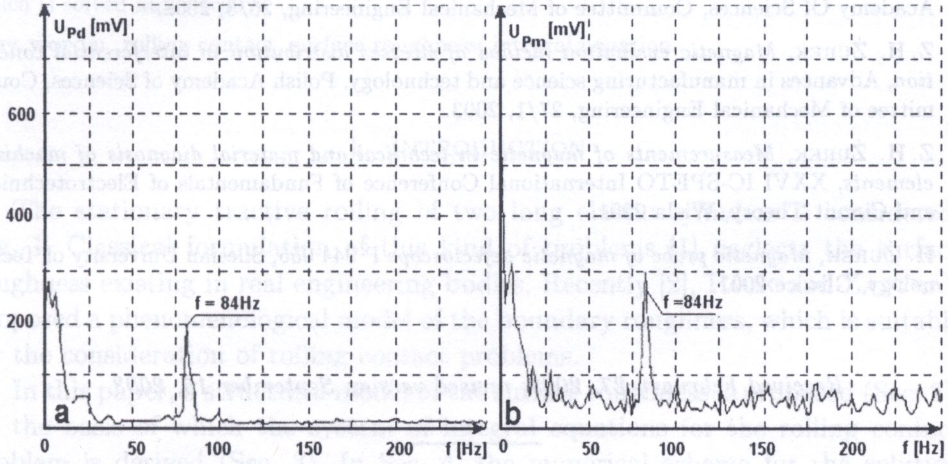

FIG. 8. Fourier spectra of: a – vibration transducer, b – magnetoresistive transducer.

Figure 8b shows that even magnetic noise emitted by the test stand did not interfere with frequency values of natural frequencies of flat bar.

Stress measurements conducted with the help pf magnetoresistive transducers have this advantage over known and used induction transducers such as Ring Toroductor torque transducer [3] that they are much cheaper and can be miniaturised. Measurement systems with parametric transducers such as magnetoresistors make possible design and construction of simple measurement and control circuits for qualitative and quantitative analysis of stress and vibration in machine parts made of ferromagnetic materials. This analysis is indispensable for technical diagnostics [6, 7].

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