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DESIGN OF MAGNETOELASTIC TRANSDUCERS

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Abstract: Magnetoelastic transducers are classed among the inductive transducers in which the relative permeability of ferromagnetic materials suffers changes under the effect of mechanical load. The change (always of anisotropic character) in the relative permeability results in a change in the impedance of the coil located in the transducer and, in case of several coils, a change in the transfer impedance as well. This paper describes the phases of planning the magnetoelastic transducers in detail, starting from the mechanical load up to the electric output signal. For the planning, the knowledge of the magnetoelastic sensitivity parameters is of fundamental importance, in addition to the estimation of the mechanical stress conditions and the electromagnetic field. The paper describes the method of determining these sensitivity parameters as material constants and their values for certain magnetoelastic materials.

Keywords: complex magnetoelastic sensitivity, complex magnetic permeability, magnetoelastic transducer

1 INTRODUCTION

The magnetoelastic transducers are suitable to be used for measuring force, moment and pressure, respectively, primarily under extremely heavy environmental conditions (high operating temperature, aggressive chemical pollution, intensive electromagnetic interference, vibration etc.). The steps of design are summarized in Figure 1.

In the practice, the design of transducers consists of two main phases. In respect of application possibility, the conditions of acquiring and forwarding the information shall be ensured on the side of mechanical and electrical signal processing as well. For this purpose, a mechanical transmission mechanism that ensures the measurement of a force- or moment vector component of specified direction shall be built in (A_1 in Figure 1) and it shall be ensured that the output signal from the transducer is converted into a conditioned voltage- or current signal (A_2 in Figure 1).

After these preliminary remarks, the design of transducers consists of steps of calculating the changes in impedance or transfer impedance that occur under the effect of a well defined force- or moment vector component (D_1 to D_4 in Figure 1).

2 STEPS OF DESIGN OF MAGNETOELASTIC TRANSDUCERS

In every case, the magnetoelastic transducers are made of ferromagnetic material with magnetic properties largely depending on the mechanical stress conditions. The changes in the magnetic properties can be detected by means of changes in the impedance of a coil mounted within the material or, in case of several coils, the changes in the transfer impedance between the coils.

2.1 Calculation of mechanical stress components

In this phase of design, the

$$\overline{\overline{\mathbf{T}}} = \begin{bmatrix} s_x & t_{xy} & t_{xz} \\ t_{yx} & s_y & t_{yz} \\ t_{zx} & t_{zy} & s_z \end{bmatrix} \qquad \begin{matrix} t_{xy} = t_{yx} \\ t_{xz} = t_{zx} \\ t_{yz} = t_{zy} \end{matrix} \tag{1}$$

stress-tensor shall be determined in each point of the sensing element under the effect of the force vector F_i and M_i moment vector components respectively, and the distributed load p_i. As a general rule, the task cannot be solved analytically, nevertheless, by using one of the finite element methods of calculating the stress condition, the elements of the stress tensor can be calculated ad discrete points. By selecting the density of grid points in a reasonable manner, a trade-off between the contradictory aspects of accuracy and cost effectiveness can be found.

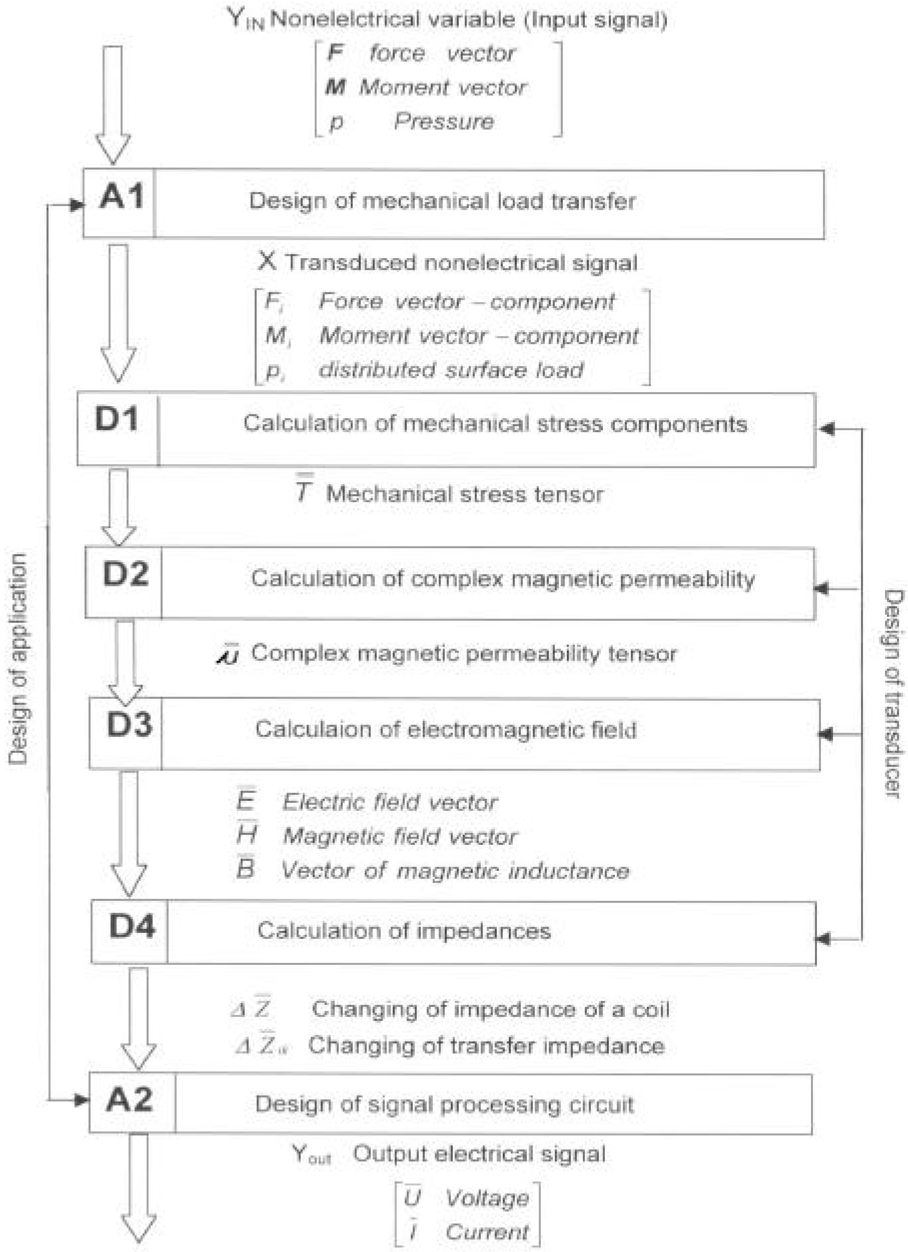


Figure 1. Signals in the magnetoelastic transducer and the steps of the mechanical and electronical design

2.2 Calculation of complex magnetic permeability

The dependence of magnetic properties of ferromagnetic materials on mechanical stress can be described by means of the changes in magnetic permeability. In case of a magnetic field $\overline{\mathbf{H}}$ and magnetic induction $\overline{\mathbf{B}}$ both of sinusoidal time function, the complex magnetic permeability $\overline{m}$ can be defined. [1] The material assumed to be magnetically isotropic in no-load state becomes anisotropic under mechanical load. Thus, the magnetic properties can be described by means of the magnetic permeability tensor $\overline{\overline{\mathbf{ì}}}$, the elements of which are also complex quantities according to the equation (2) as follows:

$$\overline{\overline{\mathbf{ì}}} = \begin{bmatrix} \overline{m}\left[1+\overline{d}_1 s_x + \overline{d}_2\left(s_y + s_z\right)\right] & \overline{d}_3 t_{xy} & \overline{d}_3 t_{xz} \\ \overline{d}_3 t_{yx} & \overline{m}\left[1+\overline{d}_1 s_y + \overline{d}_2\left(s_x + s_z\right)\right] & \overline{d}_3 t_{yz} \\ \overline{d}_3 t_{zx} & \overline{d}_3 t_{zy} & \overline{m}\left[1+\overline{d}_1 s_z + \overline{d}_2\left(s_x + s_y\right)\right] \end{bmatrix} \qquad (2)$$

where $\overline{d}_1$, $\overline{d}_2$, $\overline{d}_3$ denote the complex magnetoelastic sensitivity [2].

As it can be shown, the material constants $\overline{m}_1$, $\overline{d}_1$, $\overline{d}_2$ and $\overline{d}_3$ are of outstanding importance during the design. Their values depend on the material, frequency, operating point and temperature. They can be determined based on the results of measurement, by using the formulas of calculation.

The importance of equation (2) consists in that, under specified circumstances, the magnetizing function $\overline{\mathbf{B}}\left(\overline{\mathbf{H}}\right)$ of ferromagnetic materials and their magnetoelastic properties can be described by specifying 4 complex quantities.

2.3 Calculation of the electromagnetic field.

The sinusoidal electromagnetic field of relatively low frequency inside of ferromagnetic metals can be described by means of Maxwell-equations as follows:

$$\begin{aligned} \mathrm{rot}\,\overline{\mathbf{H}} &= \tilde{a}\,\overline{\mathbf{E}} \\ \mathrm{rot}\,\overline{\mathbf{E}} &= -j\grave{u}\,\overline{\mathbf{B}} \\ \overline{\mathbf{B}} &= \grave{\imath}_0\,\overline{\overline{\mathbf{ì}}}\,\overline{\mathbf{H}} \end{aligned} \qquad (3)$$

where $\tilde{a}$: electric conductivity
w : angular frequency of changes
m_0 : permeability of vacuum

The term $\overline{\overline{\mathbf{ì}}}$ in the equations (3) implicitly includes the mechanical load to be measured, thus, the electromagnetic field obtained as a solution of the system of equations is also a function of the effect to be measured [3]. As a general rule, the system of partial differential equations (3) can only be solved by using numerical methods. It is preferable that the grid system to be used in the solution coincides with the finite-element grid points of mechanical stress condition defined in the equation (1).

2.4 Calculation of impedance

In the knowledge of the electromagnetic field as a function of mechanical load, the impedance components can be calculated.

The elements of a (single-coil) magnetoelastic transducer with impedance output that contain $R\left(\overline{\overline{\mathbf{T}}}\right)$ loss resistance and $L\left(\overline{\overline{\mathbf{T}}}\right)$ inductance can be calculated by means of the Poynting-vector as follows:

$$\begin{aligned} R\left(\overline{\overline{\mathbf{T}}}\right) &= \frac{1}{\hat{\overline{I}}^2}\,\mathrm{Re}\oint_A\left(\overline{\mathbf{E}}\times\overline{\mathbf{H}}^*\right)d\mathbf{A} \\ jwL\left(\overline{\overline{\mathbf{T}}}\right) &= \frac{1}{\hat{\overline{I}}^2}\,\mathrm{Im}\oint_A\left(\overline{\mathbf{E}}\times\overline{\mathbf{H}}^*\right)d\mathbf{A} \end{aligned} \qquad (4)$$

where $\hat{\overline{I}}$: peak value of the excitation current
A : closed area taken into consideration in respect of energy radiation
$d\mathbf{A}$: elementary surface vector

The electric equivalent circuit of transformer-type transducers can be modelled by means of an equivalent "T" network associated with the

$$\begin{vmatrix}\overline{U}_1\\ \overline{U}_2\end{vmatrix} = \begin{vmatrix}\overline{Z}_{11} & \overline{Z}_{12}\\ \overline{Z}_{21} & \overline{Z}_{22}\end{vmatrix} \cdot \begin{vmatrix}\overline{I}_1\\ \overline{I}_2\end{vmatrix} \qquad \overline{Z}_{12} = \overline{Z}_{21} \tag{5}$$

impedance characteristic. In the solution shown in Figure 2. where the no-load output voltage is measured under current generator type power supply condition, the knowledge of transfer impedance z_{12} is sufficient.

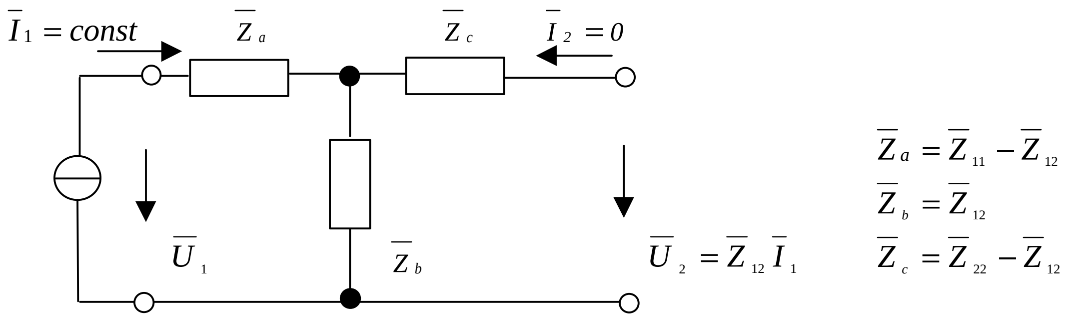


Figure 2. Signal processing of a transformer-type magnetoelastic transducer

The transfer impedance Z_{12} is calculated from the equation as follows:

$$\overline{Z}_{12} = \frac{jw\,N_1}{\overline{I}_2} \int_{A_1} \overline{\overline{\mathbf{i}}}\,\overline{\mathrm{H}}_2 d\mathbf{A}_1 = R_{12} + jw\,L_{12} \tag{6}$$

where:
- N_1: number of turns in primary coil
- $\overline{I}_2$: rms. value of excitation current in the secondary coil
- $\overline{\mathbf{H}}_2$: magnetic field of the secondary coil
- A_1: area of the primary coil
- $d\mathbf{A}_1$: elementary surface vector

3 DETERMINATION OF MATERIAL CONSTANTS

By using the relationships in chapter 2, the magnetoelastic transducer can be calculated and designed, provided that the complex permeability $\overline{m}_1$ as well as the complex magnetoelastic sensitivity parameters $\overline{d}_1$, $\overline{d}_2$ and $\overline{d}_3$ are known.

These values were determined by comparing the measurements performed on the model shown in Figure 3. with the results of calculation. The force ***F*** to be measured acted as an evenly distributed load; the stray inductance of coil can be neglected; thus, the calculations were reduced to a two-dimensional case [4].

3.1 Determination of complex magnetic permeability

The complex magnetic permeability can be determined by means of the experimental model shown in Figure 3. in a load state. As a result of frequency dependence of magnetizing processes, the complex permeability components are also frequency dependent. Figure shows the frequency-dependent complex permeability of certain materials showing magnetoelastic properties, with constant excitation and temperature assumed.

3.2 Determination of magnetoelastic sensitivity parameters

With the static characteristic $\overline{Z}(\mathbf{F})$ of the model shown in Figure 3. known, the magnetoelastic sensitivity parameters can be calculated by means of iteration methods, using the equation (4) and the preceding calculations. In mathematical terms, the values of $\overline{d}_1$, $\overline{d}_2$ and $\overline{d}_3$ with which the difference between the calculated and measured impedance remains below a specified limit. For the calculation the Powell-method proved to be the most suitable [5].

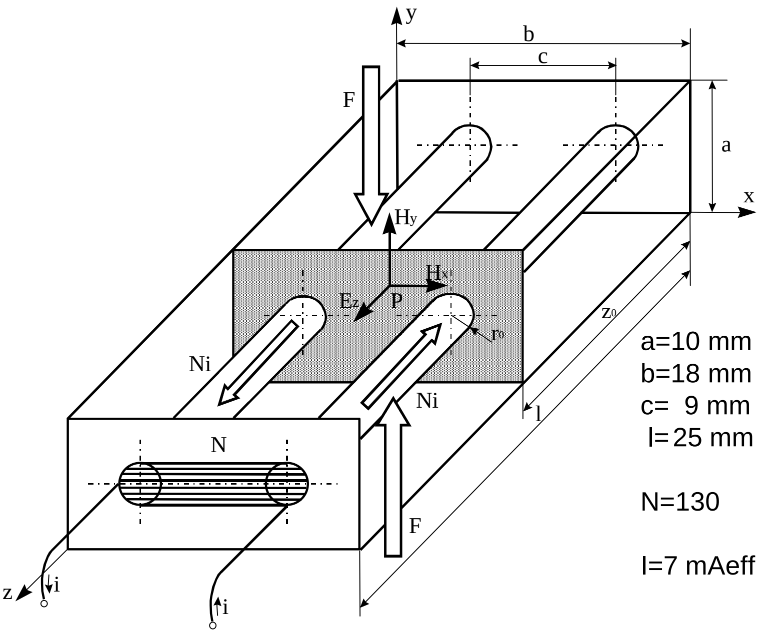
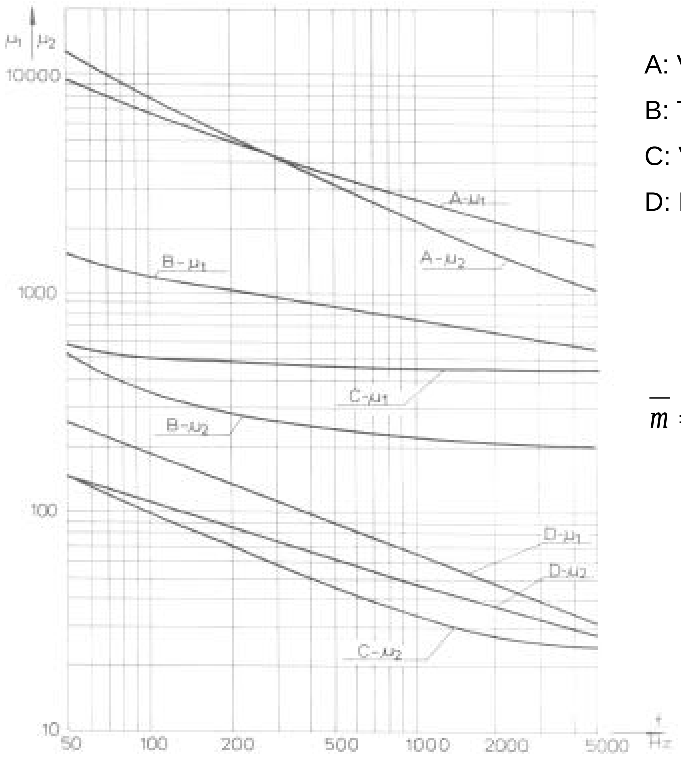


Figure 3. Experimental model for the determination of material constants



A: Vacoperm – 100 (70-80%Ni)

B: Trafoperm – N3 (3%Si)

C: Vacoflux – 50 (49%Co, 2%V)

D: Permendur – 65 (65% Co)

$$\overline{m} = m_1 - jm_2$$

Figure 4. Dependence of complex magnetic permeability on frequency

For the purpose of illustration, Figure 5. shows the values of magnetoelastic sensitivity parameters for 3 different materials measured at *f* = 200 Hz frequency.

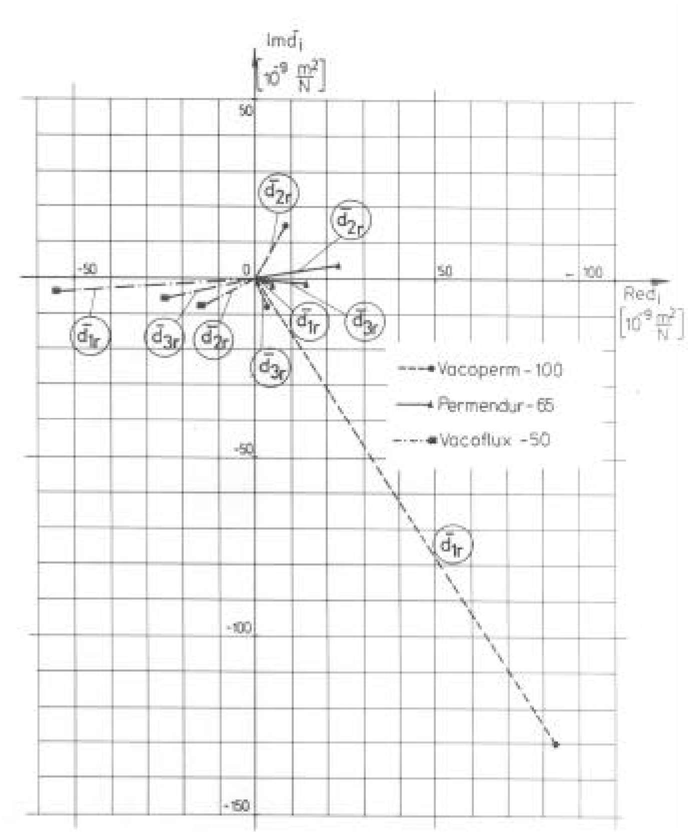


Figure 5. Complex magnetoelastic sensitivities (f=200 Hz)

4 SUMMARY

The design method described here can be used for the design of any type of magnetoelastic transducers. The designer shall be familiar with the finite element calculation method of mechanical stresses and skilled in numerical solution of partial differential equations. The author continuously completes the determination of material constants necessary for the design and makes it available in his publications.

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