FACTA UNIVERSITATIS (NIŠ)
Series: Electronics and Energetics vol. 9, No. 2 (1996), 263–273

MAGNETOELASTIC FORCE–MEASURING TRANSDUCER

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Abstract. Subject of the paper is a construction of a magnetoelastic force–measuring transducer based on the magnetic permeability alteration in the active sections of a magnetic core, with a channelized magnetic field, under the effect of some mechanical tensions, originating in the sections, which are generated by external forces. Described are several variants of implementing the transducer: depending on the position of the bobbins and their connection to the measuting scheme, it can be differentially inductive or differentially transforming; according to the way the force is applied, it can have one or two active sections. Examined are the principle of operation, the theory and measuring schemes with the different versions of the transducer; enclosed are the results from the experimental tests, indicated are the application possibilities of the transducer in industrial force–measuring devices.

1. Introduction

Magnetoelastic (magnetostrictive) transducers are some of the most perspective among transducers measuring force in an electrical way. They are based on the magnetic permeability variation in a ferromagnetic core under the effect of mechanical stresses which are caused by external forces. All this is due to a number of positive properties of theirs most significant of which are a high sensitivity, big output power, great mechanical strength and stability against overloading, weak influences by atmospheric and chemical factors, long life–time and good dynamic properties. Owing to them the transducers have found a considerable application in numerous industrial force–measuring devices.

These transducers can be divided into two mayor groups: inductive and mutually inductive. With the first group the magnetic permeability variation μ arouses a variation of inductivity L and overall electric resistance z on one or a couple of windings according to the formula

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Manuscript received February 21, 1996.
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$$z = \sqrt{R^2 + (\omega L)^2} \approx \omega L \approx \omega \frac{w^2}{z_\mu} \approx \frac{\omega w^2 s}{l} \mu, \tag{1}$$

where $R \ll \omega L$ is the active resistance of the winding. With the second group the variation of μ arouses a variation of the mutual inductivity M between two or more windings one of which at least is magnetizing, and one is measuring. The variation of M leads to a variation of the induced generated voltage E in the measuring winding in accord with the formula

$$E = \omega M I = \omega \frac{w w_i}{z_\mu} I = \frac{\omega w w_i I s}{l} \mu. \tag{2}$$

In the above formulas ω is the circular frequency of the supply voltage, w is the number of coils on the inductive transducer winding in (1) or the number of coils on the magnetizing winding in (2), w_i is the number of coils on the respective measuring winding, I is the current running through the magnetizing winding, z_μ, l and s are resistance, length and surface of the magnetic circuit in the corresponding sector.

Both the inductive and mutually inductive transducers can be realized as single and differential. With the differential transducers the corresponding measuring windings are arranged on parts of the magnetic core where the mechanical stresses have opposite signs (tensile and compressive). These transducers have substantial advantages of principle over the single ones, i.e. higher sensitivity, better protection against influence of external interference factors (higher accuracy), better linearity of the characteristics and an opportunity of connection in more rational measuring schemes. These advantages determine the need for further development and perfection of the differential transducers, all the more that the existing elaborations of these transducers have a number of disadvantages [1]. An attempt to satisfy this need is the transducer being the object of the present paper.

2. Structure and action principle

The H–shaped magnetic core of the transducer (Fig.1.) is made of ferromagnetic material with expressed magnetoelastic properties. Narrow rectangular openings are worked in its vertical columns 1 and 2 around which are set up two closed magnetic contours independent of each other. The action principle of the transducer depends on the arrangement of the windings and on the way of the force application.

1. Inductive transducer. In this case the windings, respectively W_1 and W_2 are situated on the exterior sectors of the columns. They are connected in two adjacent arms of a bridge for alternating current (Fig.2), in which z_1

and z_2 are the impedances of these windings. If the indicator I connected in the measuring diagonal is a meter for voltage and its input impedance is very big, the indicated voltage is

$$\dot{U}_I = \dot{U}\left(\frac{Z_1}{Z_1+Z_2} - \frac{Z_3}{Z_3+Z_4}\right), \tag{3}$$

where all values are written in a complex form.

In an initial state when no force is applied to the transducer, the bridge is in balance and $\dot{U}_I = 0$, which according (3) is expressed by the condition

$$Z_1 Z_4 = Z_2 Z_3. \tag{4}$$

Since in this state the initial impedance of the windings are equal,

$$Z_1 = Z_2 = Z, \tag{5}$$

it is necessary that

$$Z_3 = Z_4 = Z_0. \tag{6}$$

Usually Z_3 and Z_4 are two controllable resistors of equal resistance but owing to the constructive and magnetic asymmetry of the magnetic columns, and the windings situated of them, the condition (5) is practically unfeasible which necessitates that additional variable elements (bobbins and condensors) should be connected for the complete balance of the bridge.

1a. Force F is applied to one of the columns. It is assumed to be a tensile force applied to column 1. Under these conditions mechanical stresses σ_1 originate in the same column which create an increase of the initial magnetic permeability with $\Delta\mu_1$ (it is applied that the magnetic core is of positive magnetostriction), and consequently an increase of Z_1 with ΔZ_1. It follows from (3) then

$$\dot{U}_I = \dot{U}\left[\frac{Z_1+\Delta Z_1(\sigma_1)}{(Z_1+\Delta Z_1(\sigma_1))+Z_2} - \frac{Z_3}{Z_3+Z_4}\right] \tag{7}$$

and

$$\dot{U}_I = \dot{U}\frac{Z_1Z_4 - Z_2Z_3 + Z_4\Delta Z_1(\sigma_1)}{(Z_3+Z_4)[(Z_1+\Delta Z_1(\sigma_1))+Z_2]} \tag{8}$$

As $\Delta Z_1(\sigma_1) \ll Z_1$, the increase $\Delta Z_1(\sigma_1)$ can be ignored in the denominator of (8), and when (5) and (6) are taken into account, (8) acquires the expression

$$\dot{U}_I = \dot{U}\frac{\Delta Z_1(\sigma_1)}{4Z}. \tag{9}$$

In this case winding W_2, situated around the nonloaded column, functions as a compensating one. Compared to a single, one–winding transducer, the transducer of this type is characterized by a considerably less error, mainly an additive one, resulting from the influence of external interference factors.

1b. Force F is applied in such a way that it functions as a tensile force on the first column and as a compressive force on the second one. If it is assumed that these are respectively column 1 and 2, mechanical stresses σ_1 (tensile) and σ_2 (compressive) are created in them. This produces change of the initial magnetic permeability μ with $+\Delta\mu_1$ in column 1, and with $-\Delta\mu_2$ in column 2, and hence a change of Z_1 with $+\Delta Z_1(\sigma_1)$, and of Z_2 with $-\Delta Z_2(\sigma_2)$, i.e. the conditions of the differential transducer are fulfilled. It follows from (3) then

$$\dot{U}_I = \dot{U}\left[\frac{Z_1 + \Delta Z_1(\sigma_1)}{(Z_1 + \Delta Z_1(\sigma_1)) + (Z_2 - \Delta Z_2(\sigma_2))} - \frac{Z_3}{Z_3 + Z_4}\right] \tag{10}$$

and

$$\dot{U}_I = \dot{U}\frac{Z_1 Z_4 - Z_2 Z_3 + Z_4 \Delta Z_1(\sigma_1) + Z_3 \Delta Z_2(\sigma_2)}{(Z_3 + Z_4)[(Z_1 + \Delta Z_1(\sigma_1)) + (Z_2 + \Delta Z_2(\sigma_2))]}. \tag{11}$$

Since $\Delta Z_1(\sigma_1) \ll Z_1$ and $\Delta Z_2(\sigma_2) \ll Z_2$, the increases $\Delta Z_1(\sigma_1)$ and $\Delta Z_2(\sigma_2)$ can be ignored in the denominator of (11), and taking into consideration both (5) and (6), (11) can be expressed

$$\dot{U}_I = \dot{U}\frac{\Delta Z_1(\sigma_1) + \Delta Z_2(\sigma_2)}{4Z}. \tag{12}$$

The comparison of (9) and (12) shows a higher sensitivity of the differential transducer juxtaposed to 1a case (when $\Delta Z_1(\sigma_1) = \Delta Z_2(\sigma_2)$ it is double) with all advantages that have been pointed out preserved.

2. Mutually inductive transducer. In this case a magnetizing winding W (Fig.1) is situated between the two openings and is connected to a source of alternating voltage, while windings W_1 and W_2 which become measuring are connected in two adjacent arms of a transformer bridge (Fig.3) in which Z_3 and Z_4 have the same purpose as in the Fig.2 bridge. By means of mutual inductivities M_1 and M_2 originating between the magnetizing and measuring windings voltages E_1 and E_2 are induced in the latter generating currents I_1 and I_2. With some approximation it can be written

$$\dot{I}_1 = \frac{\dot{E}_1}{Z_3}, \qquad \dot{I}_2 = \frac{\dot{E}_2}{Z_4}, \tag{13}$$

where all values are in a complex form.

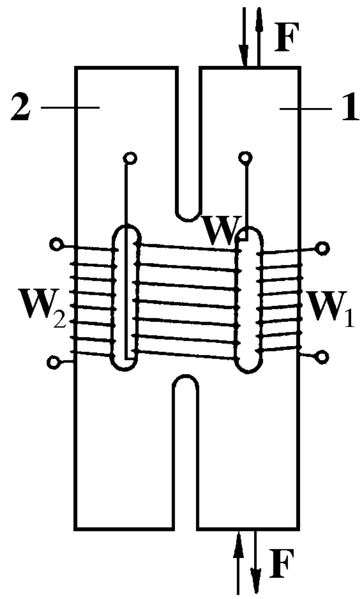

Figure 1. An exemplary structure of the transducer.

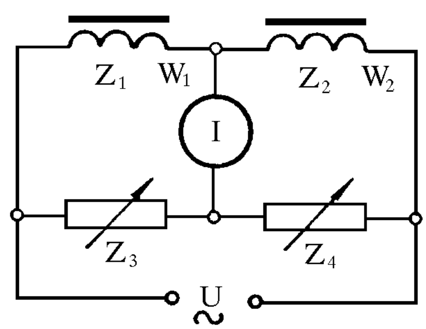

Figure 2. A measuring scheme of the inductive transducer.

The reading of the indicator I in the measuring diagonal at the marked generators taps is proportional to the difference

$$\dot{I}_I = \dot{I}_1 - \dot{I}_2. \tag{14}$$

In the initial state when no force is applied onto the transducer

$$\dot{E}_1 = \dot{E}_2 = \dot{E} \tag{15}$$

and with fulfilling condition (6) the bridge is in balance as $\dot{I} = 0$.

2a. Force F is applied to one of the columns under the conditions of 1a case. The increase of μ with $\Delta\mu_1$ creates an increase of $\dot{E}_1$ with $\Delta\dot{E}_1$ and hence, from (14),(15) and (6) it follows

$$\dot{I}_I = \frac{\dot{E}_1 + \Delta\dot{E}_1(\sigma_1)}{Z_3} - \frac{\dot{E}_2}{Z_4} = \frac{\Delta\dot{E}_1}{Z_0}. \tag{16}$$

In this case, too, winding W_2 functions as compensating, and what has been said about the transducer of 1a case is valid for it.

2b. Force F is applied in such a way that it functions as a tensile force on the first column and as a compressive force on the second one according to the conditions of 1b case. The variation of μ with $+\Delta\mu_1$ in column 1 and with $-\Delta\mu_2$ in column 2 creates a variation of $\dot{E}_1$ with $+\Delta\dot{E}_1(\sigma_1)$ and of $\dot{E}_2$ with $-\Delta\dot{E}_2(\sigma_2)$ with which the conditions of the differential transducer are fulfilled. It follows from (14),(15) and (16)

$$\begin{aligned} \dot{I}_I = & \frac{\dot{E}_1 + \Delta\dot{E}_1(\sigma_1)}{Z_3} - \frac{\dot{E}_2 - \Delta\dot{E}_2(\sigma_2)}{Z_4} \\ & + \frac{\Delta\dot{E}_1(\sigma_1) + \Delta\dot{E}_2(\sigma_2)}{Z_0}. \end{aligned} \tag{17}$$

The comparison of (16) and (17) confirms the higher sensitivity of the mutually inductive differential transducer, too, about which is everything said in 1b case.

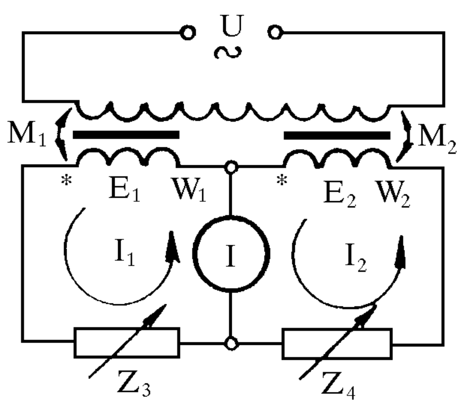

Figure 3. A measuring scheme of the mutually inductive transducer.

3. Basic mechanical dependences

It follows from the action principle of the transducer that it can be tensile (compression) loaded only, or combinedly, tensile and compression loaded. Substantially higher sensitivity and much better metrological characteristics are achieved with a tensile–compression load, an exemplary realization of which is shown in Fig.4. The measured force F is applied to the arm A situated between cylindrical bars B which run through openings, and by means of which the columns are loaded. To the accepted direction of the measured force F correspond the lines and directions of the internal forces P_1 and P_2 loading the columns. It follows from the laws of statics applied in this case

$$P_1(l_2 - l_1) - Fl_2 = 0 \tag{18}$$

$$P_1 - P_2 - F = 0. \tag{19}$$

The test for the properties of the ferromagnetic materials indicate that equal mechanical compressive and tensile stresses create different in value and sign variation of the magnetic permeability. Therefore a most rational use of the transducer's magnetic core could be obtained if in both its columns are created such tensile σ_t and compressive σ_c stresses that the variations of the magnetic permeability resulting from them should be equal. This conditions can be taken into consideration by introducing the coefficient

$$\eta = \frac{P_1}{P_2}, \tag{20}$$

which is such a value that forces P_1 and P_2 create mechanical stresses σ_t and σ_c for which

$$\Delta\mu_1(\sigma_t) = \Delta\mu_2(\sigma_c). \tag{21}$$

For a definite area of the magnetic field intensity, selected as working, this coefficient has an approximately constant value. It has to be taken into account with determining the relation between the geometrical sizes of the magnetic core a, l and the distance x (Fig. 4.). This is accomplished by solving the system of equation (18), (19) and (20). With definite geometrical sizes a and l of the magnetic core for which

$$l_1 = \frac{a}{2} + x \quad \text{and} \quad l_2 = l - \frac{a}{2} + x,$$

this solution allows that the distance be determined as

$$x = \frac{2l - (\eta+1)a}{2(\eta-1)}, \tag{22}$$

to which the measured force F should be applied.

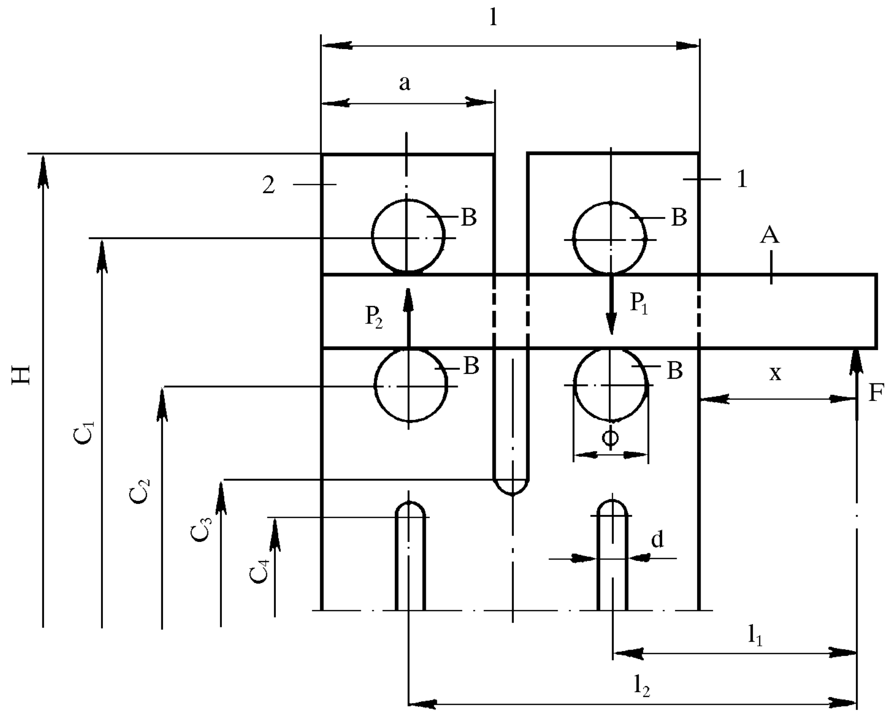

Figure 4. An exemplary tensile–compression loading of the transducer.

To ensure enough high sensitivity and small nonlinearity and mechanical hysteresis errors for the whole range of the measured force, the mechanical stresses in the columns should not exceed the maximum admissible value σ_m which is determining for the maximum force F_m, too, and up to which the transducer should be loaded. Since $P_1 > P_2$, respectively $\sigma_t > \sigma_c$, the force F_m should be expressed by external force P_1 and the mechanical stresses originating in column 1. It follows from the joint solving of (19) and (20)

$$F = \frac{\eta - 1}{\eta} P_1, \tag{23}$$

and after the introduction of σ_m, the force F_m acquires the expression

$$F_m = \frac{\eta - 1}{\eta} ab\sigma_m,$$

where b is the thickness of the magnetic core.

4. Experimental tests

Tested is the differential mutually inductive transducer, tensile and compression loaded (2b case) according to Fig. 4. Its magnetic core is built up by sticking plates of cold–rolled steel TERNI–ARMCO M6T, 0.35mm thick. The line of rolling is perpendicular to the height H, i.e. to the line of the forces (the mechanical stresses). The thickness of the magnetic core is 28mm, and the rest of its sizes are $a = 24mm$, $l = 52mm$, $H = 126mm$, $c_1 = 126mm$, $c_2 = 62mm$, $c_3 = 36mm$, $c_4 = 26mm$, $\Phi = 10mm$, $d = 4mm$. All windings have 100 coils each.

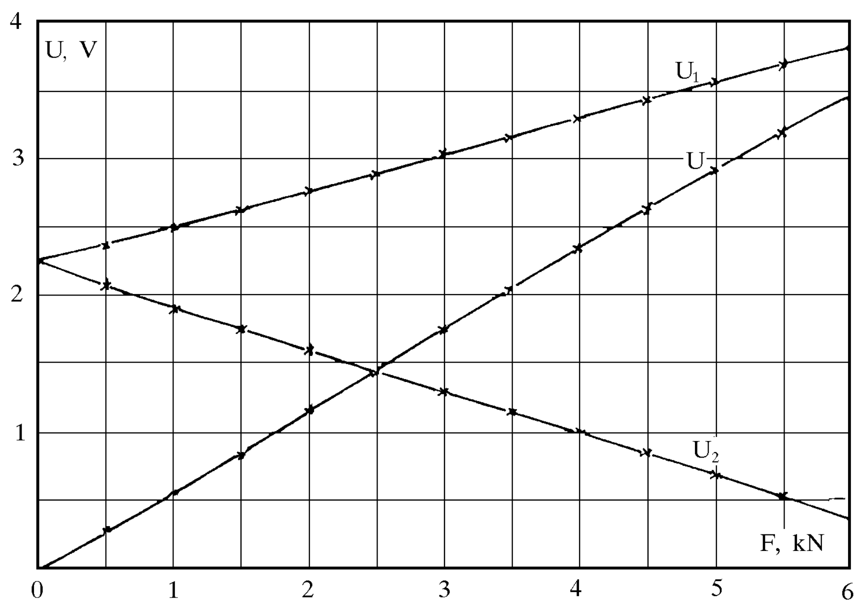

Figure 5. Experimentally obtained dependences of the voltages U_1, U_2 and U on the force F for a differential mutually inductive transducer.

The tests for the steel of the specified trade–mark and line of rolling [1] indicate that for quite a broad area of the magnetic field intensity ($H_m =$

$300A/m \div 600A/m$) the mechanical compressive stresses create a variation of the magnetic permeability about 1.6 times bigger. Hence, in order to fulfil condition (21), a coefficient η= 1.6 is selected, and after its substitution in (22), $x \approx 35mm$ is achieved. In accordance with the results reached in [1], $\sigma_m = 26Mpa$ is accepted as a maximum admissible stress and after its substitution in (24) the maximum force becomes $F_m \approx 6.5kN$. Fig. 5 shows the experimentally obtained dependences of the voltages U_1, U_2 and U on the force F with magnetizing current $I = 0.4A$ ($H_m \approx 500A/m$). These are the corresponding variations of the voltages in the measuring diagonal of the bridge in Fig. 3 in case of winding W_1 connected, winding W_2 connected and windings W_1 and W_2 jointly connected. The experimental results confirm the action principle of the transducer, herewith theoretically considered, in which both measuring windings practically take an equal part in the formation of the total output voltage U. The magnetizing current (magnetic field intensity) increase affects positively the sensitivity and linearity of the dependance $U(F)$, but their increase above definite values ($I = 0.5A$ and $H_m = 650A/m$) is not justiable.

The maximum reduced nonlinearity error assessed in relation to the straight line connecting starting ($F = 0$) and terminal ($F = 6kN$) points of the measuring range is $\pm 1.2\%$. If this range is narrowed at the expense of the initial, most nonlinear area, e.g. from $0.5kN$ to $6kN$, this error decreases to $\pm 0.6\%$. In actual fact this is realized even without special measures with a number of force– and weight–measuring devices in which the transducer is loaded in advance by some force or the tare of the weight measuring device.

The maximum reduced magnetoelastic hysteresis error assessed in relation to the middle line between the ascending and descending branch of the dependance $U(F)$ is $\pm$ 1.0%. It should be noted that the operation of numerous devices, and in particular, those related to industrial weight measurements (proportioners, load stops in hoisting and hauling machines and devices, production counters based on a weight principle, etc.) is realized only along the ascending branch of characteristic $U(F)$ with which the magnetoelastic hysteresis error does not affect accuracy.

5. Conclusions

The transducer has a high sensitivity ensuring direct (without amplification) measuring of forces in a broad range. To measure bigger forces it can be compression–loaded only or tensile–loaded only where F_m is determined by the formula $F_m = ab\sigma_m$. To measure smaller forces a combined tensile–compression loading should be used. The increase of the distance x allows expansion of its measuring area to smaller forces (up to some hundred N) but this leads to not satisfying condition (21).

The most significant errors of the transducer have relatively low values due to its rational construction in which the differential principle is clearly expressed. Its high sensitivity and big output power allow the application of further measures for improving its metrological characteristics.

There are possibilities for more effective use of the ferromagnetic material and for improvement of the metrological characteristics of the transducer by optimizing some of its geometrical sizes.

The transducer has the indispensable metrological and constructive qualities to find a number of application: control of technological processes; operation of devices in automatics; protection against overloading or weight measuring in hoisting and hauling machines and devices, proportioners, etc.

REFERENCES

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