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COMMUNICATIONS

SUBSTITUTE MODEL AND POWER PARAMETERS OF ELASTOMAGNETIC FORCE SENSOR

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The article describes the diagram of connections for a substitute model of an elastomagnetic force sensor, and its elements calculation. The numerical values of the substitute model elements were rated from the measured parameters of the 200 kN force sensor. Their force dependences are given by graphical representations and analytic functions. The power transforming parameters between the primary and secondary circuits describing the utilisation efficiency of this sensor are presented by relevant substitute analytic functions, too.

Keywords: Electrotechnic, elastomagnetic sensor, force measuring, substitute model, power parameters.

1 INTRODUCTION

Elastomagnetic sensors of force are used for measurement of mainly large pressure forces and torque moments. They are unique and reliable even in very aggressive field conditions. The main task of the reported research was a more complex description of the sensor operational relations, which is not properly mentioned in special technical texts. The description is consisting of substitute model elements specification, and its dependence on the measured force magnitudes. Excepting that, we have defined power parameters and their dependence on the measured force magnitude, too.

The values all these elements and parameters were determined from experimental measurements executed on elastomagnetic sensors for the nominal pressure force, 200 kN.

2 THEORETICAL PART

2.1 Substitute Model

Considering the fact that the sensor design has an electrical connection corresponding to a transformer, we have preferred the substitute circuit of a transformer with a ferromagnetic core. Determination of its elements values was performed from two marginal states, *ie* from an open no-load operation circuit (Fig. 1) and a short circuit (Fig. 2).

The solution of these states gave the following equations for the needed values of elements obtained from the measured data. The equivalent resistance R_1 representing the primary winding resistance was obtained by a direct current (DC) measurement.

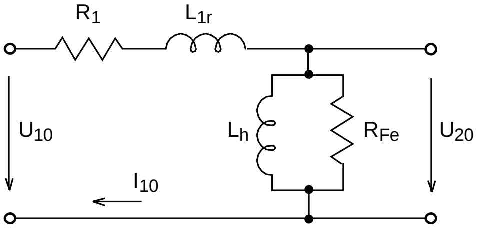

Fig. 1. Open operation circuit

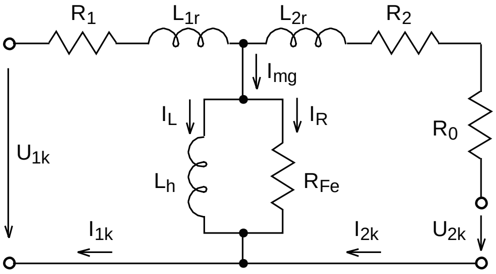

Fig. 2. Short operation circuit

The equivalent resistance R_{Fe} of active losses in the ferromagnetic core of the sensor at its alternating magnetisation can be defined as (1)

$$R_{\mathrm{Fe}} = \frac{U_{20}}{I_{10}\cos\varphi_{U_{20}I_{10}}} \tag{1}$$

and the main self-inductance L_h can be defined as (2)

$$L_h = \frac{X_h}{\omega} = \frac{1}{\omega}\frac{U_{20}}{I_{10}\cos\varphi_{U_{20}I_{10}}}\,. \tag{2}$$

The secondary voltage U_{20} and the primary current I_{10} were measured directly. The phase displacement $\varphi_{U_{20}\text{-}I_{10}}$ between them was determined from the measured active

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input power (P) of the sensor by the schematic diagram in Fig. 5.

$$\cos\varphi_{U_{20}I_{10}} = \frac{P}{U_{20}I_{10}} = \cos\varphi\,. \tag{3}$$

The leakage inductance of the primary winding L_{1r} can be defined from the measured and calculated values (U_{10}, I_{10}, U_{20}, P) at constant frequency by equation (4)

$$L_{1r} = \frac{1}{\omega}\left[\sqrt{\left(\frac{U_{10}}{I_{10}}\right)^2 - \left(R_1 + \frac{U_{20}}{I_{10}}\cos\varphi\right)^2} - \frac{U_{20}}{I_{10}}\sin\varphi\right]. \tag{4}$$

The active resistance R_2 was determined directly by the direct current measurement, too.

The leakage reactance of the secondary winding L_{2r} was determined from the measured values on a short circuit run with the corresponding schematic diagram shown in Fig. 2, (5).

$$I_{2r} = \frac{1}{\omega}\left[\sqrt{\left(\frac{U_{20}}{I_{10}}\right)^2 - \left(\frac{I_{1k}}{I_{2k}}\right)^2 - \left(R_1 + R_0 + \frac{U_{20}}{U_{10}}\cos\varphi\right)^2} - \frac{U_{20}}{U_{10}}\sin\varphi\right]. \tag{5}$$

Since the primary and secondary winding ratio of the tested sensor was $N_1 : N_2 = 1$, the secondary winding translation upon the primary values had no any sense and so we did not involve it in our substitution diagram.

2.2 Power Parameters

The loss number of the sensor ferromagnetic core was determined in dependence on the applied force values to obtain the possibility to sense a temperature rise of the sensor.

$$z = \frac{P}{m} \qquad (\mathrm{W/kg};\ \mathrm{W},\ \mathrm{kg}) \tag{6}$$

where P is the total loss power input of the sensor core and m is its mass.

Because of the complex consideration of the power relations or sensor effectivity estimation, these parameters were selected:

- coefficient γ — expresses the output power P_2 to input power P_1 ratio of the sensor, *ie* what part of the electric input power of the sensor is utilizable on its output in dependence on the electrical rate sensor circuit and measured values.

$$\gamma = \frac{P_2}{P_1} \qquad (1;\ \mathrm{W},\ \mathrm{W}) \tag{7}$$

- coefficient α — expresses the utility output power of the sensor P_{2u} to input power P_1 ratio.

$$\alpha = \frac{P_{2u}}{P_1} = \left(\frac{P_2}{P_1}\right)_{F\neq 0} - \left(\frac{P_2}{P_1}\right)_{F=0} \qquad (1;\ \mathrm{W},\ \mathrm{W}) \tag{8}$$

- coefficient β — expresses the utility output power of the sensor P_{2u} to input power in relation to unit operating force.

$$\beta = \frac{\alpha}{F} \qquad (\mathrm{N}^{-1};\ 1,\ \mathrm{N}) \tag{9}$$

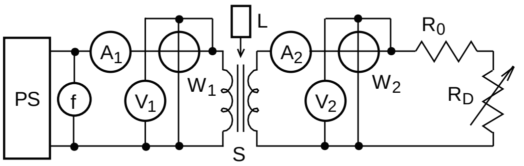

Fig. 3. Measuring equipment connection

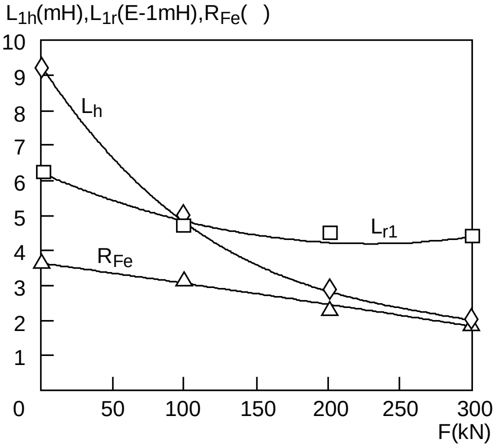

Fig. 4. Calculated values L_h, L_{1r}, R_{Fe} of sensor No. 3

3 EXPERIMENTAL PART

3.1 Variables Measurement for Substitute Model

The measurement of the variables necessary for elements parameters determination of the substitute model and for power parameters determination was realized by the equipment connection in Fig. 3.

Here PS is the power supply maintaining the sensor optimal working conditions (designed and made in our laboratory [2]), measuring equipment: f — frequency meter, A —ammeter, V — voltmeter, W — universal wattmeter. Resistor R_D (resistance decade) served as a sensor loading on its output, R_o was a protective resistor against secondary winding overload, L — hydraulic press for 400 kN force, S — elastomagnetic sensor.

Calculated values are given in Tab. 1

The measured characteristic curves in dependence on the loading force are in Fig. 4.

The analytical expressions of the characteristic curves were processed in MS Excel (10), (11), (12)

$$L_h = -2\times 10^{-7}F^3 + 0.0002F^2 - 0.0619F + 9.2757, \tag{10}$$

$$R_{\mathrm{Fe}} = -10^{-6}F^2 - 0.0056F + 3.6293\,, \tag{11}$$

$$L_{1r} = 8\times 10^{-6}F^2 - 0.0025F + 0.6296\,. \tag{12}$$

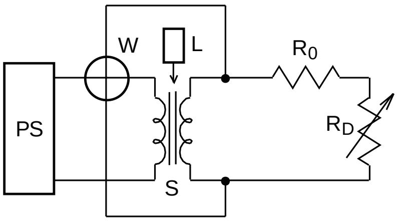

Fig. 5. Measurement of active losses at alternating magnetization in the sensor core

Table 1. Calculated values

F (kN)	R_{Fe} (Ω)	L_h (mH)	$L_{1r} \approx L_{2r}$ (mH)
0	3.600	9.274	0.629
100	3.140	4.795	0.460
200	2.366	2.823	0.446
300	1.855	1.997	0.430

Table 2. Measured and calculated values

F (kN)	z_0 (W/kg)	z_k (W/kg)
0	1.125	0.875
40	0.942	0.798
80	0.710	0.625
120	0.530	0.487
160	0.405	0.375
200	0.323	0.300
300	0.216	0.198

3.2 Variables Measurement for Power Parameters

The measurement of the variables necessary for power parameters determination (α, β, γ) was realized by the equipment shown in Fig. 3. The measurement of active losses originated in the sensor core at alternating magnetization was realized by the equipment in Fig. 5.

Description of the schematic diagram is given in chapter 3.1. The measured and calculated values of the loss number z_o for no-load condition $R_D = 10\,\mathrm{k}\Omega$ and for short — circuit run z_k where $R_D = 0\,\Omega$ are mentioned in Tab. 2 and graphically represented in Fig. 6 (the sensor core mass $m = 0.56$ kg, protective resistor $R_0 = 2.8\,\Omega$). The equivalent analytical expressions in dependence on loading force are: (13), (14)

$$z_0 = 11.068\, e^{-0.0058F}, \tag{13}$$

$$z_k = 9.1328\, e^{-0.0053F}. \tag{14}$$

The calculated values of power parameters α, β, γ are in Tab. 3 and the behaviour of β is represented by Fig. 6. Various R_D values represent, in this case relevant, the input equipment resistance for the sensor output signal processing and are marked as index of parameters α, β, γ.

The analytical expressions of the power parameters characteristic curves in dependence on loading force are:

$$\alpha_{500} = -0.0048F^2 + 2.8369F - 39.2\,, \tag{15}$$

$$\gamma_{500} = 0.0005F^2 - 0.2761F + 48.719\,, \tag{16}$$

$$\beta_{100} = 7\times 10^{-7}F^3 - 0.0004F^2 + 0.0649F + 5.1767\,, \tag{17}$$

$$\beta_{500} = -2 \times 10^{-5}F^2 + 0.0033F + 1.71\,, \tag{18}$$

$$\beta_{2000} = -4 \times 10^{-6}F^2 + 0.0008F + 0.478\,. \tag{19}$$

4 CONCLUSION

Our experimental results, *ie* measured and calculated element values of the elastomagnetic substitute model have a decreasing trend with an increasing load of the sensor.

These shapes of characteristics are in correspondence with the sensor metrological properties [3], [4], and with the evident fundamental principle of this sensor [1].

At a positive magnetostriction coefficient of the core material, the acting pressure force causes a decrease of the material permeability. Due to it, the sensor output voltage signal decreases too, which is in accordance with the main self-inductance decline tendency.

Decreasing magnetization losses of the sensor core material do not mean the equivalent resistance increasing

Table 3. Calculated values of power parameters

F (kN)	50			100			150			200			250			300		
R_D (Ω)	α (10^{-5})	β (10^{-5}/kN)	γ (10^{-5})	α (10^{-5})	β (10^{-5}/kN)	γ (10^{-5})	α (10^{-5})	β (10^{-5}/kN)	γ (10^{-5})	α (10^{-5})	β (10^{-5}/kN)	γ (10^{-5})	α (10^{-5})	β (10^{-5}/kN)	γ (10^{-5})	α (10^{-5})	β (10^{-5}/kN)	γ (10^{-5})
100	370	7.4	152	820	8.2	107	1160	7.7	73.2	1397	6.53	50.3	1509	6.04	38.1	1616	5.38	28.4
500	88	1.76	36.4	200	2.0	25.2	278	1.85	17.4	337	1.68	11.5	361	1.44	9.17	381	1.30	6.34
2000	20	0.40	9.66	57	0.57	6.02	77	0.51	4.0	88	0.44	2.87	102	0.40	1.52	106	0.35	1.49

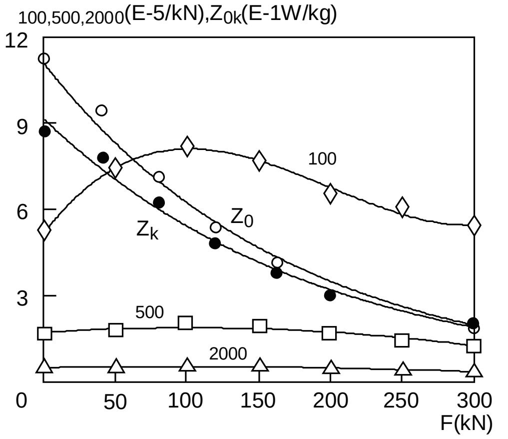

Fig. 6. Specific coefficient of the output power β and specific active losses z_0, z_k

for these losses. Its value decreases because the sensor primary voltage decreases rapidly. The power loss on this resistance decreases by square-law function with this drop of the potential and therefore the equivalent resistance value will be falling, too.

The dropping specific losses expressed by the loss number mean that loading of the sensor by measured force, will be its temperature decreasing, what is of course welcome.

The absolute value of the specific losses in the sensor ferromagnetic core is markedly lower than at common electrical equipment with the magnetic circuits.

Taking into account that the core sensor is in very good contact with a large measured force transferring metal construction, the temperature rise solution of the core sensor is groundless, what is very auspicious conclusion.

The power transforming parameters do not seem to be too favourable at first sight. In spite of it, even so small part of the power input (coefficient α) is sufficient with a great margin to meet the measurement equipment energy consumption. So, for digital indication of the output voltage signal it is not necessary to use any amplifying equipment. The measured values of the power transforming parameters (α, β, γ) can serve indeed at such an equipment design, to be able to ensure automatic measuring of the measured value.

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