JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
4, **38**, 2000

USE OF MICROCOMPUTER TECHNIQUES FOR DETERMINATION OF PROPERTIES OF ELECTROMAGNETIC FRICTION BRAKES

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A simulation analysis for the evaluation of applicability electromagnetic friction brakes in diagnostic stations as modules for loading drive systems has been carried out in the paper. Transfer functions for plate and powder brakes have been determined using experimental data. The functions have been then verified in computer simulation studies.

Key words: electromagnetic friction brakes, simulation experiments, diagnostic station

1. Introduction

The research carried out by the author (Igielski, 1991, 1999) has indicated that it is possible to apply electromagnetic friction brakes as units exerting a load in diagnostic stations for mechatronic low power drive systems. It has been observed that the range of their application is dependent on the type of the applied brake and properties of the studied system.

Because of the lack of an adequate form of the mathematical transfer function for electromagnetic friction brakes, see Pełczewski (1965), and the impossibility of determining it directly on the basis of an experiment, it has been often hard to state unequivocally whether a given brake might be used also in conditions different from those in which the experiment has been carried out.

Therefore, it has been necessary to search for such a reliable form of the transfer function of electromagnetic friction brakes which would be useful in simulation studies. An approach towards the solution to the problem is proposed in this paper. Results of experimental studies described by Igielski (1994) have been, among others, used in the presented analyses.

2. Determination of behaviour of a load generating system by computer identification methods

The knowledge of the transfer function is required, in particular during development of the model and realisation of simulation studies. The analysis carried out by the author [18] have indicated that for this purpose it is possible to apply, for example, the software package MATLAB described by Ljung (1994) with the use of transmittances of the analysed systems (Janiszowski, 1989, 1991a).

2.1. Transmittances of the studied system

The studies carried out by the author (1996b) have indicated that the easiest way to determine a transfer function, described by a transmittance, in particular in a spectral form, consists in the use of the response to a unit step function. In case of systems being analysed, the form of the transmittance is usually complex, since there is a huge number of factors having influence on their operation. Therefore, it has been decided to accept, for further studies, a parametrical description in the form of a discrete transmittance proposed by Janiszowski (1989, 1991a), which can be determined, for example, by comparison of the response of the studied system and the responses of typical linear systems. However, it should be remembered that formulation of such a model must coincide with the following assumptions:

- step function must be found without disturbances,
- the system can be linearised and then introduced only by means of a simple approximation, which is sufficient for further analysis (which cannot be accurate enough in some cases).

The analysis of the results of experiments by Igielski (1994), which have been carried out for an electromagnetic friction plate and powder brakes, considering, for example, responses to stepwise variations of the supplying current, revealed that such systems have inertial as well as aperiodic properties according to the control theory (Janiszowski, 1991a).

The first task in the experiments was to choose the approximation method and then to determine the parameters. These parameters should be understood in this case as the transmittance coefficients, see Ljung and Soderström (1984), having a general form of continuous functions as follows

$$G(s) = \frac{b_0 + b_1 s + ... + b_m s^m}{1 + a_1 s + ... + a_n s^n} e^{-sT} \tag{2.1}$$

The discussion presented by Janiszowski (1991a), Ljung and Soderström (1984), Ljung (1987) has resulted in the conclusion that it is hard to apply the above relation directly if a numeric technique is applied, and that such a technique constitutes a basis of the majority of the tool software. In the case, it is better to apply the so-called difference equations.

The discrete difference between the parametrical model of the output y of the studied system with one input signal u and one signal of non-measurable disturbance e may be presented, according to Janiszowski (1991a), Ljung and Soderström (1984), in the form of the discrete operator transmittance

$$A(z^{-1})y(k) = \frac{B(z^{-1})}{F(z^{-1})}u(k) + \frac{C(z^{-1})}{D(z^{-1})}e(k) \tag{2.2}$$

while the polynomials A, B, C, D, F of the shift operator z^{-1} have the following form

$$\begin{aligned} A(z^{-1}) &= 1 + a_1 z^{-1} + ... + a_{n_a} z^{-n_a} \\ B(z^{-1}) &= b_1 z^{-1} + ... + b_{n_b} z^{-n_b} \\ C(z^{-1}) &= 1 + c_1 z^{-1} + ... + c_{n_c} z^{-n_c} \\ D(z^{-1}) &= 1 + d_1 z^{-1} + ... + d_{n_d} z^{-n_d} \\ F(z^{-1}) &= 1 + f_1 z^{-1} + ... + f_{n_f} z^{-n_f} \end{aligned} \tag{2.3}$$

In the case when the analysed system is described with a satisfactory accuracy by a simple autoregressive model, called Autoregressive Moving Average (ARMA) having the following form (Ljung, 1987, 1994)

$$A(z^{-1})y(k) = B(z^{-1})u(k) + e(k) \tag{2.4}$$

it should be assumed that

$$C(z^{-1}) = 1 \qquad D(z^{-1}) = 1 \qquad F(z^{-1}) = 1 \tag{2.5}$$

However, it is more convenient to consider the correlated disturbances describes by Ljung (1987) for dynamic systems. In this case the form that is applied most often is the ARMAX model by Janiszowski (1991a), Ljung (1987) being described as follows

$$A(z^{-1})y(k) = B(z^{-1})u(k) + C(z^{-1})e(k) \tag{2.6}$$

where

$$D(z^{-1}) = 1 \qquad F(z^{-1}) = 1 \tag{2.7}$$

2.2. Identification of the systems

One of the most important problems in the identification process will always be a choice of an adequate data series with sufficiently variable input and output signals. Therefore, in case of the considerations presented below, the analysis of the characteristics $M = f(t)$ recorded for the electromagnetic friction brakes introduced by Igielski (1994) has been limited to the time of 2 s for identification purposes. These characteristics were the responses to the unit step function of the supplying current.

The results of measurements achieved during the experiment included a lot of disturbances. Therefore, it has turned out that it is necessary to make a preliminary filtration in order to improve adequacy of the model in relation to the realistic dynamic properties of the identified system. A discrete software filter described by Pełczewski (1980) having the following form has been used for this purpose

$$y_f(k) = \frac{y(k-h) + y(k-h+1) + ... + y(k) + ... + y(k+h+1) + y(k+h)}{2h+1} \tag{2.8}$$

The next step has been the normalisation of the output signal in order to provide a zero average value of the output signal of the system before a step variation of the input signal value.

The ARMAX procedure (see Wierciak, 1994) used in further analyses has been based on the assumption that parameters of the model are described with a sufficient accuracy by the following dependence

$$\begin{aligned} y(k) + a_1 y(k-1) + ... + a_{na} y(k-na) = b_0 u(k-nk) + b_1 u(k-1-nk) + \\ + ... + b_{nb} u(k-nb-nk) + c_0 e(k) + c_1 e(k-1) + ... + c_{nc} e(k-nc) \end{aligned} \tag{2.9}$$

which structure has been assumed by the acceptation of the values of the coefficients na, nb, nc and nk, where the first one is connected with the output signal, the second one with the command (input) signal, the third one with the disturbances and the last one with the time lags.

The minimal value of the sum of squares error of the created model output in relation to the measured (possibly filtered) output signal of the system has been assumed as the identification criterion.

On the basis of the model expressed by (2.9), a description of the identified system has been created in the form of a discrete transmittance

$$G(z) = \frac{Y(z)}{U(z)} = \frac{b_0 z^{mb} + b_1 z^{mb-1} + ... + b_{nb} z^{mb-nb}}{z^{ma} + a_1 z^{ma-1} + ... + a_{na} z^{ma-na}} \tag{2.10}$$

where

$$
\begin{aligned}
ma &= \max(na, nb + nk) - na \\
mb &= \max(na, nb + nk) - nb - nk
\end{aligned}
\tag{2.11}
$$

By transformating formula (2.10) from the space Z to the space S the description of the object as a continuous transmittance is obtained (Janiszowski, 1991a; Ljung, 1987).

Various structures of the model (i.e. combinations of the coefficients na, nb, nk) have been discussed while determining the transmittance of the studied system in the first stage. The most convenient solution, as regards the basic criterion, has been searched for. The criterion has usually been the minimal value of the error function.

In the case of experimental results described by Igielski (1994) for both types of electromagnetic friction brakes, different values of errors determining the transmittance have been achieved for various combinations of values of the coefficients mentioned above. Some results by Igielski (1996b) recognised as the most convenient from the point of view of minimal value of the error function are shown in Table 1 for the plate brake and in Table 2 for the powder brake.

Table 1. Comparison of chosen values of the error equation for various structures of the plate brake model

Values of the coefficients				Values of the error function
Designation of the structure	na	nb	nk	Step in supplied current from 0 to 1.3 A
{1.1}	1	1	0	159
{1.2}	1	2	0	138
{1.3}	1	3	0	96
{1.4}	2	1	0	158
{1.5}	2	2	0	102
{1.6}	2	3	0	100
{1.7}	3	1	0	151
{1.8}	3	2	0	98
{1.9}	3	1	0	89

Table 2. Comparison of chosen values of the error function for various structures of the powder brake model

Values of the coefficients				Values of the error function	
Designation of the structure	na	nb	nk	Step in supplied current from 0 to 0.4 A	Step in supplied current from 0 to 0.5 A
{2.1}	1	1	0	39	117
{2.2}	1	1	1	53	29
{2.3}	1	2	0	38	31
{2.4}	1	2	1	52	19
{2.5}	2	1	0	39	54
{2.6}	2	1	1	52	20
{2.7}	2	2	0	40	32
{2.8}	2	3	1	52	19

The analysis of the structures has made possible to state that:

- model having the structure {1.5} characterised by a value of the error function 20% higher than the best model having the structure {1.9}, but at the same time it is simpler and seems to present physical dynamic properties of the system sufficiently better,
- models having the structure {2.6} and {2.8} will cause problems while trying to transform them into the S space,
- model having the structure {2.4} seems to demonstrate good physical dynamic properties.

Taking into account the above coefficients in equation (2.10) determined by means of the ARMAX procedure in the System Identification Toolbox form the MATLAB package it was possible to state that the most probable models of the studied systems had transmittances of the following form:

— for the plate brake

- discrete

$$G(z) = \frac{0.43z^2 - 0.41z}{z^2 - 1.33z - 0.36} \tag{2.12}$$

- continuous

$$G(s) = \frac{0.43s^2 + 42.84s + 101.77}{s^2 + 63.65s + 164.21} \tag{2.13}$$

— for the powder brake

- discrete

$$G(z) = \frac{0.23z - 0.05}{z^2 - 0.83z} \tag{2.14}$$

– continuous

$$G(s) = \frac{0.23s + 12}{s + 11.02} e^{-0.016s} \tag{2.15}$$

These models have been used during the creation of simulation structures introduced in further part of this paper.

Graphical comparison of the responses of the above models with the experimental data is presented in Fig.1.

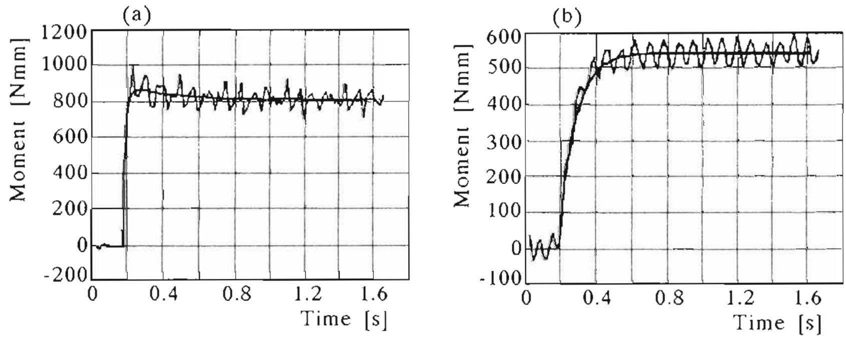

Fig. 1. (a) Comparison of the model {1.1} response with the experimental data for the plate brake during a stepwise increase of the supplying current; (b) comparison of the model {2.1} response with the experimental data for the powder brake during a stepwise increase of the supplying current

The analysis of the characteristics presented in the above figures showed that:

- transfer function of the studied plate brake contains probably a differential component, which makes possible for the developed friction moment to rapidly grow after a rush of the supplying current in the exciting winding,
- the powder brake was characterised with a significant inertia and an observable delay (note the form of the continuous transmittance).

3. Simulation experiments

3.1. Simulation model

In order to compare the results of the experimental studies with the simulation results, the properties of the used test rig should be taken into account in the simulation process (Igielski, 1994).

It has been assumed that in such test rig the drive unit (for instance a low power electric motor) produce constantly the torque M_n having an absolute value equal to the sum of all the other torques occurring in the system that had an opposite values in relation to the torque

$$M_n = M_{op} + M_\rho \tag{3.1}$$

where

M_n – drive torque
M_{op} – resistance torque
M_ρ – friction torque developed by the friction brake to generate a load in the drive unit.

The resistance torque consists of the torque occurring in the system that has opposite direction to the sense of the rotation vector of the drive motor. It is caused, among others, by:

- friction in the bearings of the rotor, the intermediate shaft and the brake,
- resistance occurring in the coupling units,
- viscous resistance of the air (its influence becomes significant when the rotational speed is very high),
- remanence in the magnetic circuits.

It was possible to eliminate a majority of these losses by measuring the reaction torque at the place of mounting the casing of the studied brake (Igielski, 1992b). Therefore, it could be assumed that the value being recorded by the torque-meter would correspond to the torque occurring between the shaft of the brake and its stator. Because the diameter of the shaft was small in case of the studied brakes, the influence of the viscous resistance to motion was disregarded in the first approximation as being insignificant. Results of the studies carried out earlier by the author (Jaszczuk, 1991) have been the basis for the acceptation of such simplifications.

Therefore, it has been assumed, taking into consideration the accepted simplifications, that the value recorded by the torque meter can be described by the following formula

$$M_m = M_\rho + M_r + M_t + M_o \tag{3.2}$$

where

M_m – measured torque
M_ρ – friction torque occurring between the elements of the brake

M_t – friction torque in the bearings of the brake shaft
M_r – torque caused by remanence in the magnetic circuit
M_o – friction torque between the elements of the brake without presence of the magnetic field.

The evaluation of the torque caused by the remanence and friction in the brake units during its idle running is possible, practically, only experimentally.

Since the load being applied in the test rig was known, the formalisation of its mathematical model was possible.

A general equation of motion the drive-braking system in the used test rig has the following form (Pełczewski, 1965)

$$-M_{op_{st}}(t) - M_{\rho h}(t) + M_n = J\frac{d^2\varphi}{dt^2} + 2\nu\frac{d\varphi}{dt} + k\varphi \tag{3.3}$$

where
$M_{op_{st}}(t)$ – instantaneous value of the resistance torque occurring in the system
$M_{\rho h}(t)$ – instantaneous value of the friction torque developed by the brake
M_n – torque developed by the drive motor
J – moment of inertia of the brake
φ – rotation angle of the shaft
ν – coefficient of vibration damping
k – torsional stiffness of the system.

Because of the fact that there are some problems in description of all the phenomena occurring in the electromagnetic brakes, it is usually assumed that the friction torque is described by the simplified dependence

$$M_{\rho h}(t) = K_h i_h^2(t) \tag{3.4}$$

where
$i_h(t)$ – instantaneous value of the current in the exciting winding of the friction brake
K_h – value, being approximately constant for a given brake, depending, among others, on: average friction radius, friction coefficient, structure and properties of the magnetic circuit, number of exciting windings.

The resultant torque occurring in the system will be a source of damped vibrations. In case of the used test rig (Igielski, 1992b) the torsional stiffness k has been understood as a sum of the stiffness of the piezoelectric force transducer k_{pie} and of the torque meter providing the preliminary load k_{mom}

$$k = k_{pie} + k_{mom} \tag{3.5}$$

It was required to take into account the influence of the drive unit, in this case a DC motor, for the complete description of the operation of the test rig.

These modules have been described in a way that is exact enough. Therefore, while assuming a simplification that the influence of thermal effects will be insignificant in any case, it can be assumed, according to Jaszczuk (1991), Wierciak (1994, 1995), that the driving motor will be described by the following equations (Wierciak, 1995)

$$\begin{aligned} u &= Ri_s + L\frac{di_s}{dt} + K_u\frac{d\varphi}{dt} \\ K_m i_s &= (J_s + J_h)\frac{d^2\varphi}{dt^2} + K_d\frac{d\varphi}{dt} + M_{op} \end{aligned} \tag{3.6}$$

and at the same time

$$\begin{aligned} K_m i_s &= M_n \qquad\qquad J_h = J_{st} + J_{zew} \\ M_{op} &= M_{sil} + M_{st} + M_{obc} \end{aligned} \tag{3.7}$$

where

u – supply voltage of the motor
i_s – exciting current
R – resistance of armature circuit
L – inductance of armature winding
K_u – voltage constant
$d\varphi/dt$ – angular velocity of the rotor
K_m – torque constant
J_s – moment of inertia of the motor
J_{st} – moment of inertia of rotating units of the test rig
J_{zew} – external moment of inertia of loading units of the test rig
K_d – viscous damping constant
M_{sil} – torque resulting from static friction in the motor
M_{st} – torque resulting from static friction in the test rig
M_{obc} – torque resulting from external load of the system.

The above mathematical equations have allowed elaborating a simulation procedure. For this purpose the SIMULINK software has been used [19]. A schematic model of the simulation structure based on equations (3.1) ÷ (3.7) is shown in Fig.2.

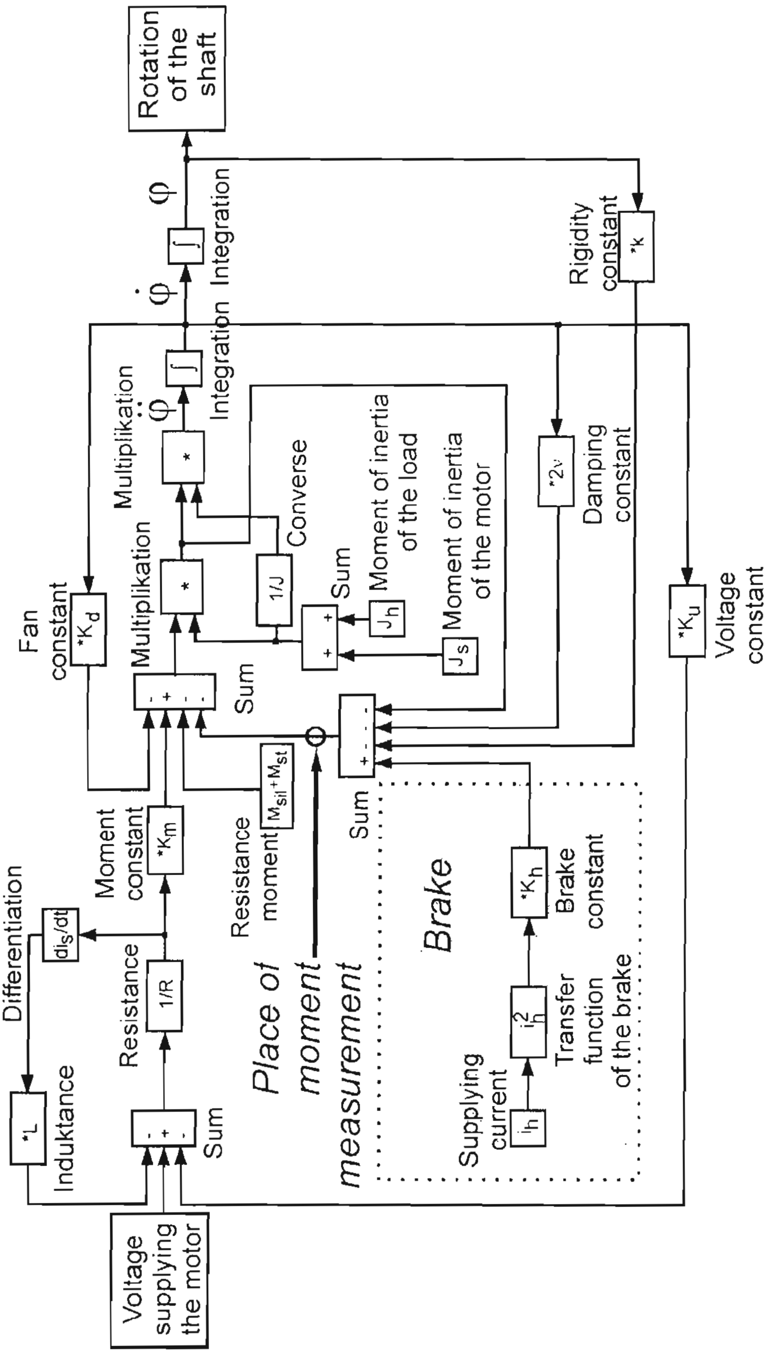

Fig. 2. Simulation structure of the test rig applied for studies of electromagnetic friction brakes for SIMULINK software

The transfer function of the brake according to that model describes mathematically properties of the analysed system. However, preliminary experiments have already indicated that it is practically impossible to use the form of the function described by Janiszowski (1991a). Satisfying results have been obtained by using the transmittance of analysed systems according to the considerations presented by Igielski (1996b), Janiszowski (1989, 1991a,b). The way of determinating the transmittance on the basis of experimental results has already been presented.

The proposed simulation tool enables, first of all, generation of relatively simple and rapid changes of the values of particular parameters of the system. It is possible to use arbitrary forms of input signal functions, for instance: supply voltage of the motor, exciting current of the brake i_h, function of the load (resistance torwue M_{op} or moment of inertia J_h), or transfer functions of particular elements of the test rig.

3.2. Simulation experiments

The simulation studies, which have been carried out, have shown a high compatibility of the results by Igielski (1996a,b) with the results obtained in the experimental studies. They are presented in the form of a comparison of some characteristics found in the experimental and simulation investigations for the plate brake in Fig.3 and for the powder brake in Fig.4.

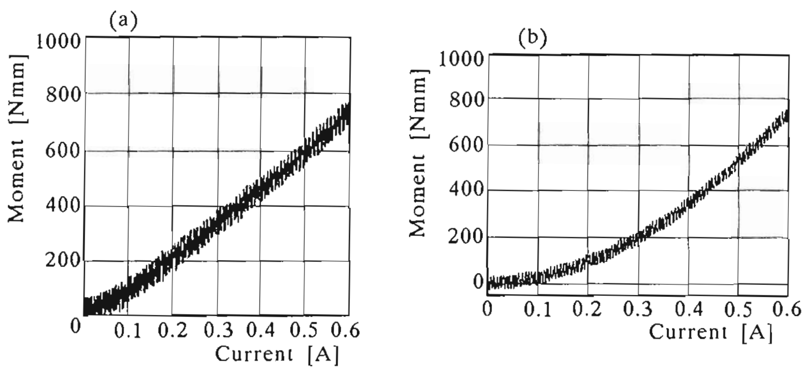

Fig. 3. Comparison of the torque characteristics during linear growth of the exciting current in the plate brake; (a) experimental results, (b) simulation results

The simulation studies have revealed a quite significant influence of the exciting current growth velocity upon the development of the friction torque and have been therefore the subject of further analysis (Igielski, 1994). In this case, the influence of the integral component has been declared as the most

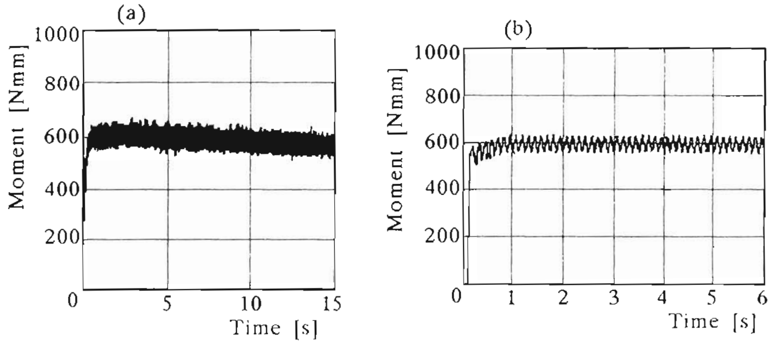

Fig. 4. Comparison of the torque characteristics during stepwise growth of the exciting current in the powder brake; (a) experimental results, (b) simulation results

significant while changing the values of the coefficients in the accepted transmittance of the studied system – it is illustrated in Fig.5. In such a situation, phenomena that are responsible for this, should be recognised. Therefore, most attention has been paid to the hysteresis curve.

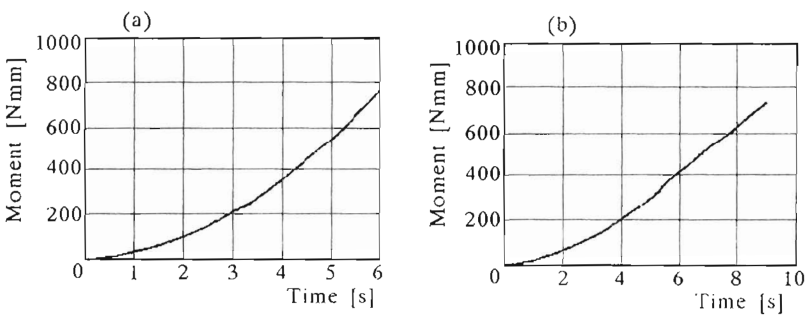

Fig. 5. Simulation of the torque variations developed by the powder brake during linear growth of the exciting current with test rig vibration ignored ((b) the integral component of the transmittance is two times smaller than in Fig.5a)

The results of the experiments have shown that the fact that the hysteresis curve has not created a closed loop in the vicinity of zero can be caused, first of all, by frictional resistance in the bearing. However, the simulation studies did not seem to confirm this. After elimination of the resistance torque from the accepted simulation model, an open loop has still been observed – see Fig.6. The reason for it may be, for instance, a coercive force of the powder. The simulation experiments carried out by the author have shown that it may lead to a significant value of the integral component of the transmittance while at the same time the influence of the differential and inertial components can be practically insignificant in the given case.

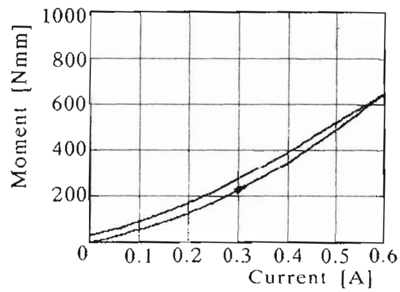

Fig. 6. Hysteresis of the torque developed by the powder brake during a linear increase and decrease of the exciting current

4. Conclusions

The analysis carried out in the paper have confirmed, to a large extent, the possibility of application of a microprocessor technique the determination of properties of electromagnetic friction brakes used in diagnostic stations for drive units at least in two fields:

- Determination of the transfer function of such systems in the form of a transmittance. In that case the use of experimental data is necessary.

  The investigations carried out by the author have indicated that for this purpose it is useful to find, for instance, a system response to the standard input function (stepwise, linear, etc.) which is applied to control processes.

  The carried out analysis has indicated that good results can be obtained while accepting as the identification criterion the minimal sum of error squares of the output in relation to the measured (possibly filtered) output signal of the system, which is commonly applied.

- Carrying out a simulation of the behaviour of such brakes using the transfer function for a particular kind and type of an electromagnetic friction brake, which has been determined before.

  This fact is worth emphasising since the experiments carried out not only by the author have indicated clearly that it is practically impossible to create universal equations of such systems. The reasons are, first of all, magnetic and tribological phenomena occurring in regions of friction (Igielski, 1991, 1994, 1996b).

The simulation studies should be preceded by creation of a diagnostic station model so that experimental verification of the obtained results could be possible.

The results presented in this paper have shown that the simulation experiments can often be a good complement to experimental studies, especially when it is hard to explain the observed phenomena on the basis of the results, or their interpretation is difficult.

On the basis of the results presented in this paper as well as in the author's previous paper, see Igielski (1994), it can be stated that the types of brakes being a subject of the analysis may behave differently in some situations, even though it was assumed by Pełczewski (1965) that the form of equations describing them was similar. It is worth noting that they meet the majority of the requirements for such devices to be satisfied in diagnostic stations: for instance high velocity of friction growth in plate brakes (a significant requirement in case of dynamic studies) and linearity of characteristics in case of powder brakes.

The presented results have enabled to believe that it will be possible for such devices to fulfill these requirements, at least to some extent, in diagnostic stations for low power drive units (Igielski, 1991). Simulation of the behaviour of such brakes in various conditions should allow one to determine, from this point of view, the most convenient ranges of their features.

Because of significant influence of individual features not only of particular types or kinds of the brakes but also of their particular elements, each time before choosing them for diagnostic studies, the mathematical models introduced in the paper should be verified and values of the empirical constants should be determined. Surely, this will make simpler to carry out the experimental studies.

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Wykorzystanie technik mikrokomputerowych do wyznaczania właściwości hamulców elektromagnetycznych ciernych

Streszczenie

W artykule dokonano analizy możliwości wykorzystania metod symulacyjnych do oceny zasadności stosowania elektromagnetycznych hamulców ciernych w stanowiskach diagnostycznych w charakterze zespołów obciążających badane układy napędowe. Wykorzystując dane eksperymentalne wyznaczono funkcje przenoszenia hamulca proszkowego i płytkowego, które następnie zweryfikowano w badaniach symulacyjnych.

Manuscript received August 12, 1998; accepted for print January 7, 2000