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Measurement of quantities characterizing the properties of an inductive dynamic drive

Streszczenie: *Artykuł stanowi syntetyczny opis metod stosowanych przez autorów do wyznaczenia najważniejszych wielkości pozwalających na scharakteryzowanie właściwości napędu indukcyjno-dynamicznego. Wykorzystywane metody zostały podzielone na bezpośrednie (wyznaczenie prądu cewki i przemieszczenia) oraz pośrednie (wyznaczenie prędkości, przyspieszenia i stanu naprężeń).(**Pomiar wielkości charakteryzujących właściwości napędu indukcyjno-dynamicznego**).*

Abstract: *The article is the synthetic description of the methods applied by authors to assign the quantities characterizing the proprieties of an inductive dynamic drive. The used measuring methods were divided as direct and indirect method, respectively. The experimental registration of the coil current and the disc displacement was classified as a direct method. The simulating determination of speed, the acceleration and the state of stress in the disc with the use of the coil current were classified as an indirect method.*

Keywords: inductive dynamic drive, measurement, displacement, disc stresses.
Słowa kluczowe: napęd indukcyjno-dynamiczny, pomiar, przemieszczenie, naprężenia dysku napędu.

Introduction

Inductive-dynamic drive (IDD) is a type of electrodynamic drive (Fig. 1). It consists of the coil which is supplied from capacitor battery and the movable secondary element which is a well conducting, most often an aluminum disc. The RLC parameters of the coil circuit should have the small values. Hence, the current of coil and magnetic field have impulse character. Such impulse field induces eddy currents of large values in the aluminum disc. This type of drives belongs to the quickest ones not only because of the possibility of large accelerations achieving (a(t)> 100000g), but also because of short reaction time. The reaction time is measured from the moment the impulse appears in the thyristor gate (Fig. 5) until it reaches an expected moment of the displacement. This fact and the repeatability of this process make these drives superior to other kinds of drives such as spring, electromagnetic or explosive. The above mentioned features caused that they are the essential element of the ultra-rapid hybrid circuit breakers (HCB) [1].

HCB are the combination of semi-conductive elements and a contact segment where the disc of the IDD is a movable point of a contact (Fig.1). Because of such hybrid approach, HCB reach a very short time of switching off at the lack of arc.

The process of HCB working might be divided into three stages:
1) the detection of a short-circuit current (the SCD), the start of IDD and the commutation of current from CS to EE,
2) the commutation of the current from EE to PE, (after reaching a suitable gap between contacts),
3) disconnection of the current by PE.

The above mentioned stages show that the IDD is a very important part of the HCB and it has to be characterized by high dynamics, the repeatability of the process and the long-lasting reliability. The IDD fulfils these features on condition that all its parameters are selected correctly.

The phenomena occurring in the IDD can be of a magneto-thermo-elastic character. The IDD model which analyses all these phenomena and takes their coupling into account does not exist yet. Therefore the research of IDD still requires experiments.

To design the IDD one should select such parameters to fulfill the following conditions by IDD:
a) the suitable dynamics - determined on the basis of the courses of displacement, speed and acceleration of the disc,
b) the guarantee of admissible level of tensions.

Unfortunately, these conditions are opposing ones. It is because the reducing the mass of the disc enlarges its dynamics, but simultaneously tensions of the disc increase. The increase of the disc dynamics at the decrease of its mass is realized by decreasing its thickness. However the thickness of the disc should be less than three skin depth because the subsequent layers do not take part in creating electrodynamic force.

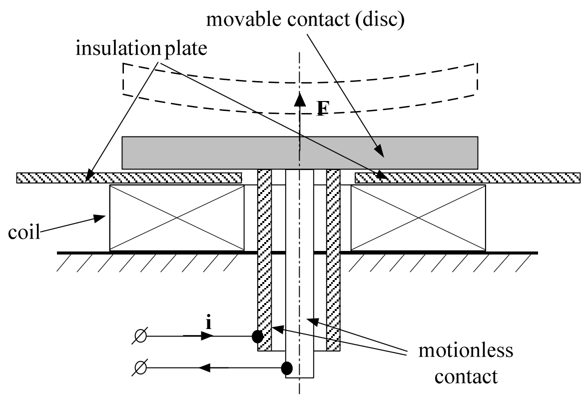

Fig.1. Construction of contact-IDD system and deformation of disc

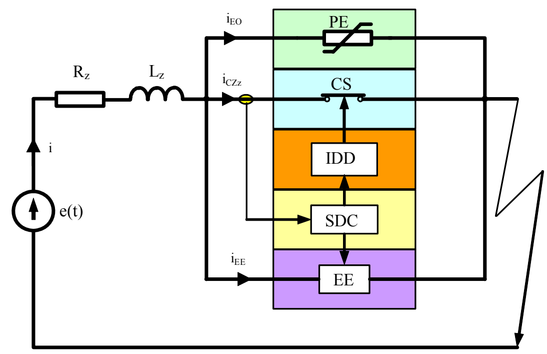

Fig.2. Block diagram of HCB in short circuit
CS– contact segment, IDD - inductive dynamic drive, EE – power electronics element, PE– protective element, SDC - system of current detection

On the one hand the experimental measurement of quantities mentioned in a) and b) is very difficult in realization, on the other hand it is economically groundless. Therefore, the disc displacement and coil current is determined by experimental method. However the time-spacing distribution of magnetic pressure acting on the disc and the state of stresses were obtained by applying complex method (on the basis of mathematical models by using a registered coil current).

These quantities describing the features of an IDD are understood by authors as the "measurement" in the meaning introduced in [2] and interpreted in [3]. In this concept, the term "measurand" results from the generalization of the notion of quantity on time and/or space distributions of vectorial quantities, and on the relationships between them [3].

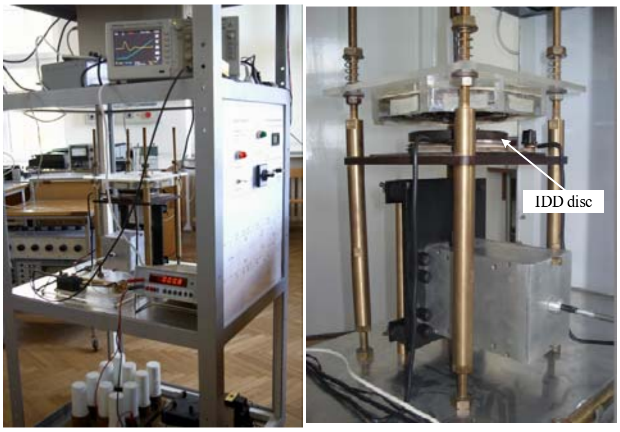

Fig.3. The measuring system and optimeter connected with IDD

Measurement system for experimental test allowing to obtain further used IDD quantities was built in our unit, and is shown in Fig.3.

The method of determining the following values discussed in this article can be presented in the form of the following diagram (Fig.4).

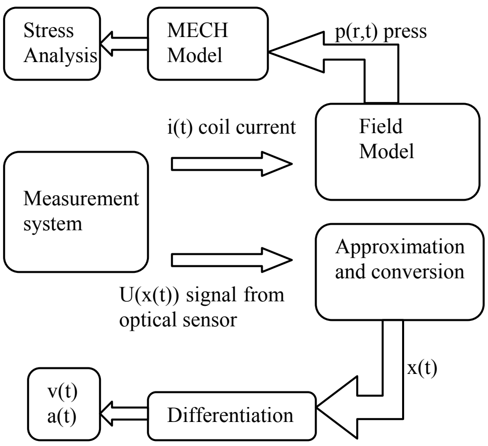

Fig.4. Determining procedure of basic quantities of IDD

The paper is organized as it follows. Firstly, the main ideas concerning an inductive dynamic drive (IDD) and the ultra rapid circuit breakers (HCB) are presented. The characteristic aspects and features of their operation in order to design such devices are discussed. Taking into account, that final result will be an optimization of the disc designing process, some metrological aspects of the inductive dynamic drive research are described. This description is divided into two parts. In section 2 the measurement system for IDD quantities registered directly, it means the disc displacement and the coil current and the presentation of the related procedures and mathematical tools is shown. In section 3, dedicated to IDD pressure and stress analysis based on the indirect measuring method, the main ideas of the use of the disc mechanical model (MECH), based on the solution of vibrating thin plate equation and obtained results, describing the disc properties and parameters are discussed. Finally, the conclusions and indications for future activity are collected in section 4.

Measurement system for IDD quantities registered directly

The diagram of measuring system which makes it possible to register the coil current and the disc displacement is presented in Fig.5. The current waveform is registered by using the low-inductive shunt Rk. The waveform of disc displacement, however, is registered with using of the optical sensor. The screen of oscilloscope with the example of the coil current oscillogram and the voltage signal from optical sensor is shown in Fig.6. The main element of the optical sensor is a photosensitive element. The photoelement is covered by the diaphragm which is connected to the disc. During the movement of the disc the displacing diaphragm exposes the photoelement. Therefore, the increasing output signal appears on terminals of the sensor.

The authors while testing the optical sensor [4,5] decided to apply a photodiode system that is a photoelement which was supplied from an external source E in reverse direction (Fig. 5). This approach provided us with obtaining the larger sensitivity of optical sensor output characteristic. However, one should underline, that the consequence of such a choice was photodiode shot noise generating (Fig.7). To obtain the displacement course in time function x(t) one had to carry out conversion on the basis of the output characteristic U_p which is determined point by point (Fig.7) Hence, to achieve satisfactory filtration of the course U_p the mean square approximation was conducted applying the orthogonal Gram polynomials.

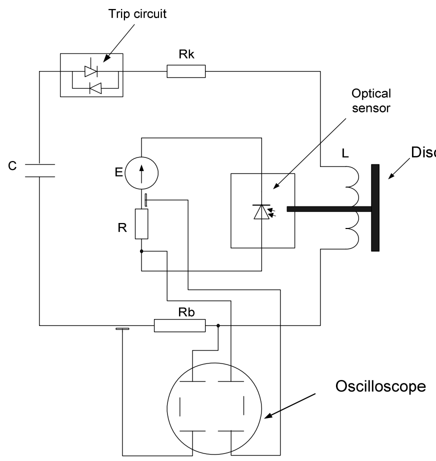

Fig.5. The measurement system to examine the coil current and the disc displacement

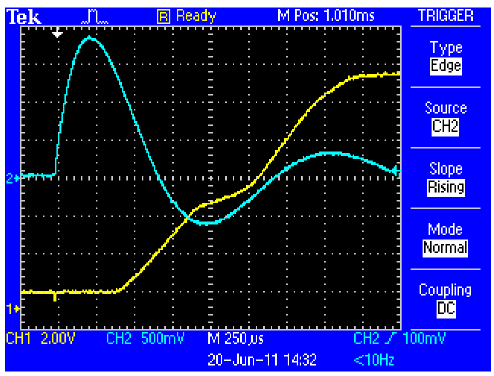

Fig.6. The oscillogram of the disc displacement and the coil current

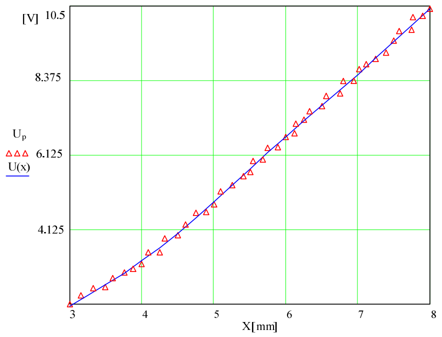

Fig.7. The output approximated characteristic -U(x)

Obtaining each point of optical sensor characteristic requires the shift of diaphragm with the use of the electronic micrometric screw point by point. Therefore it was necessary to determine how many measurement points one had to obtain for a satisfactory approximation because the value of mean square deviation is not the sufficient indicator of measurement points number. Hence, the authors carried out simulations with theoretical function for which disturbance was added [6]. It should be noted that the theoretical function was chosen in such a way so that its shape is similar to the shape of the resulting measurement function.

The theoretical set of measurement points obtained in such way was approximated and mean square deviation was computed. The simulations were carried out for a various number of measurement points. Due to the fact that we came up with the analytical function, we additionally managed to determine the absolute and relative error. To carry out these simulations the authors built their own approximation procedure of data set which is based on orthogonal Gram functions. The application of these functions assumes the same distance between measurement points which was met in considered cases. To create this approximation procedure the Mathcad environment was used in which the Gram polynomials are very easy to formulate (1). This formula automatically generates the next orthogonal Gram polynomials depending on k argument. Additional advantage of the use of orthogonal functions is simplicity of patterns determining polynomial coefficients without the need for solving the system of equations. Hence the simulations can be carried out automatically for every degree of the polynomial. As a result of these simulations the 6th degree of approximating polynomial was accepted as a proper one to further research.

$$\mathrm{Pol\_Grama}(x,k,n) := \sum_{s=0}^{k}\left[(-1)^s\cdot\frac{k!}{s!\cdot(k-s)!}\cdot\frac{(k+s)!}{s!\cdot k!}\cdot \mathrm{if}\left(s>0,\frac{\prod_{i=0}^{s-1}(x-i)}{\prod_{i=0}^{s-1}(n-i)},1\right)\right]$$

(1)

While observing the waveforms of mean square deviation (which was determined with the use of formula (2)) and relative error (Fig.8), the authors made a decision about the sufficient number of measurement points of the output characteristic which were determined point by point. It was assumed that this number should not be smaller than 50 points.

(2) $$\Delta st_n = \sqrt{\frac{1}{n+1}\cdot\sum_{i=0}^{n}(y_i - gL(x_i))^2}$$

where: y_i-set of measurement points, $gL(x_i)$- approximating function

The approximation using Gram polynomials which was applied not only to obtain the output characteristics of the optical sensor, but also in relation to the oscilloscope waveforms generated by the optical displacement sensor during motion. Hence, the smoothed U_{approx} function obtained by approximation (Fig.9) was subjected to conversion using the previously approximated sensor characteristics U(x) (Fig.7).

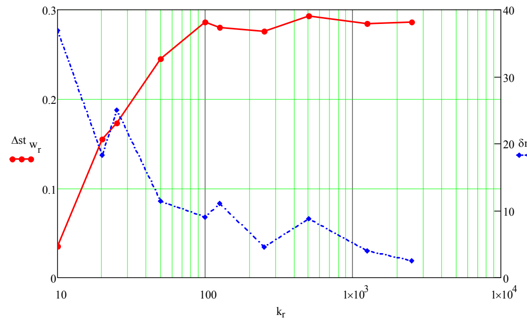

Fig.8. Mean square deviation and relative error in number of measurement function

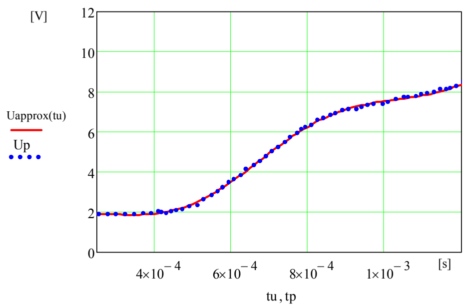

Fig.9. The voltage trajectory on the sensor terminals and its approximation

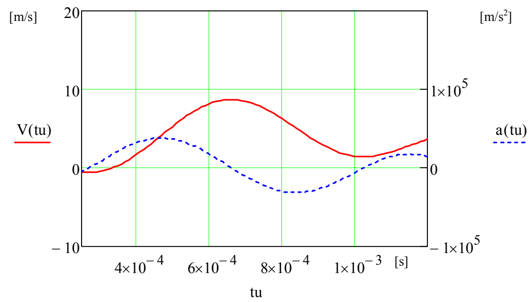

Fig.10. Trajectories v(t) and a(t) after differentiation x(t)

Obtaining the precise displacement function x(t) is essential to be able to use this function to determine speed function and acceleration function which were obtained as a result of differentiation (Fig.10). It should be noted that in the experimental test movement of disc midpoint is recorded. The resulting course of the velocity and acceleration of this midpoint shows oscillatory character of its movement.

IDD pressure and stress analysis based the indirect measuring method

In order to carry out a stress analysis it is necessary to determine magnetic pressure acting onto disc. The pressure can be determined on the basis eddy currents of the disc interacting coil current. There is the circuit model of IDD taking movable disc with coil coupling into account which enables us to determine such pressure [7]. The time of calculations with the use of a PC is too long especially when we have to use a dense mesh. The satisfactory approach was to build a simplified model in programme FLUX applying FEM [8]. The coil current experimentally obtained was the input quantity for the above field model.

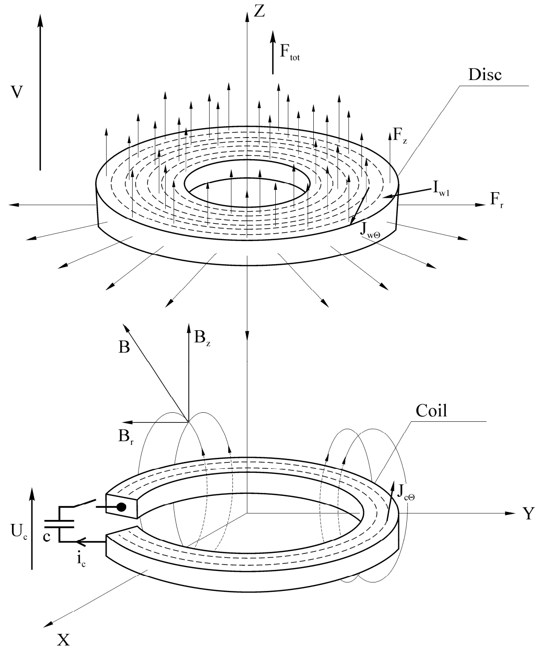

Fig.11. Forces acting on the disc

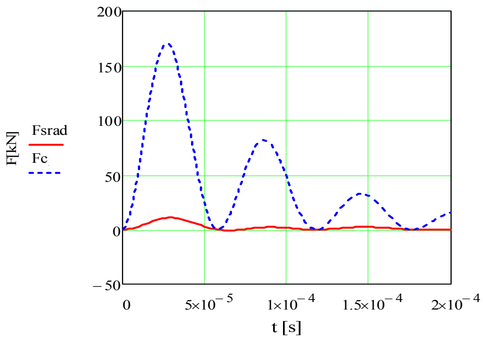

Fig.12 Comparison of total radial and axial forces acting on the disc

Since the tested IDD has a cylindrical symmetry the forces acting on the disc have axial and a radial component (fig.11.). On the other hand, radial forces do not affect the progressive movement of the drive, but their significant value could result in a stiffening of the disc, which should be taken into account in the stress analysis. However, simulation studies for all test cases have shown that the radial forces are small compared to the axial forces (Fig.12).

One should underline once again, that the coil field penetrating the disc is strongly attenuated as a result of skin effect. Hence, the pressure determined on the basis of the interaction of this field with eddy currents is treated as pressure acting onto the surface of the disc.

Thanks to the above approach we can determine the stresses of the disc with the use of mechanical model (MECH). The MECH model is based on the solution of vibrating thin plate equation [9]:

$$\frac{D}{\bar{\rho}}\nabla^4 w+\frac{\partial^2 w}{\partial t^2}=\frac{p(r,\varphi,t)}{\bar{\rho}} \tag{3}$$

where: $\bar{\rho}=h\rho$ - plate mass per unit area, $w=w(r,\varphi,t)$ - displacement, $D=\dfrac{Eh^3}{12(1-\upsilon^2)}$ - flexural rigidity, E, h – respectively: Young modulus, plate thickness, υ – Poisson ratio, $p(r,\varphi,t)$ – pressure distribution.

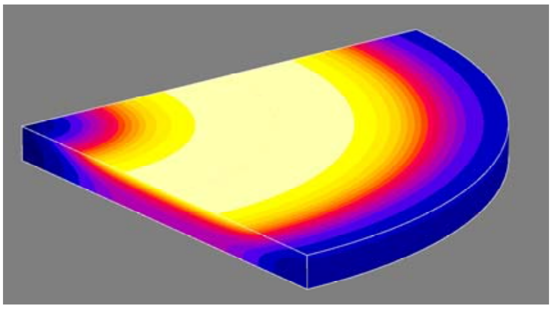

Fig.13 Current distribution of disc in Flux program

The input function for MECH model is magnetic pressure $p(r,t)$ (Fig.14) which is obtained for each filament of the disc and does not depend on φ in considered case because of cylindrical symmetry. In MECH model the disc is divided into 25 filaments. The analytical and numerical approach was applied to solve equation (3) using separated variables method because the forces acting on each disc filament were approximated by cosinusoidal functions. In the first stage of the analysis eigenvalues and eigenfunctions were determined numerically and their orthogonality was checked (Fig.15).

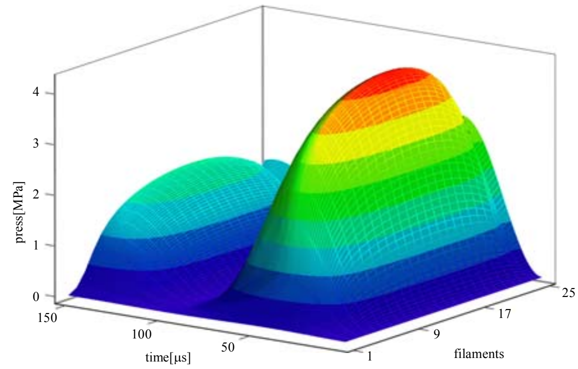

Fig.14. Time-spacing distribution of the pressure p(r,t)

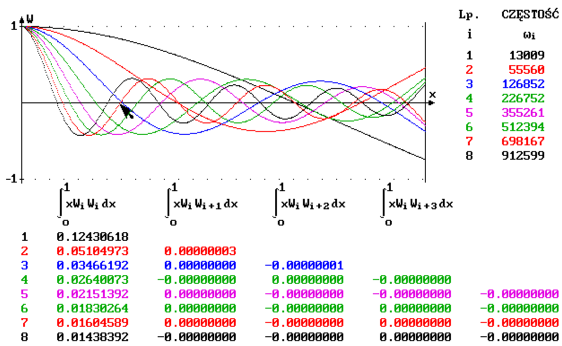

Fig.15. First screen of programm MECH, with finding eigen functions

In the second stage the solution of homogeneous equation (3) with the specified boundary conditions and zero initial conditions was obtained. This solution describes the position of the middle surface of the disk at any point and at any time.

The obtained solution of equation (3) makes it possible to determine reduced stresses in place and time function $\sigma_{zr}(r,t)$. The detailed analysis of MECH model was introduced in [7]. The main screen of the programme realizing MECH model is presented in Fig.16. The screen shows the trajectories of movement (the displacement of the midpoint and the centre of the mass of the disc) and the waveform of maximum values of reduced stress in the bottom part of the screen. The programme also shows the animations of the moving surface of the disc. Optionally one can open the subscreen with stress distribution along the radius. The course of this distribution confirms that the largest tension is in the centre of the disc.

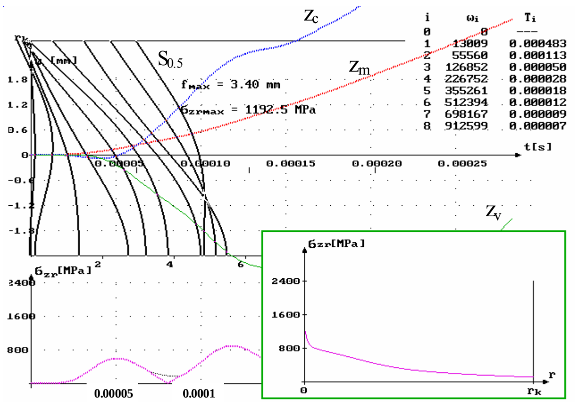

Fig.16. Main screen of MECH programme

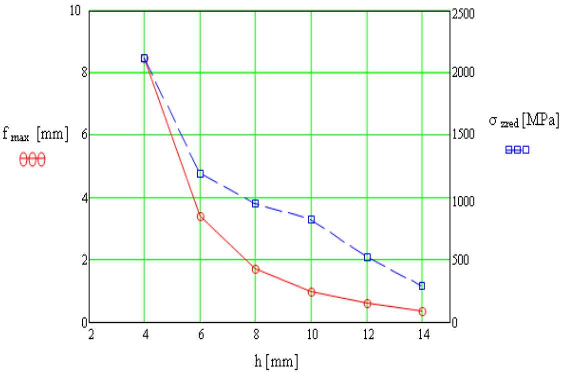

Fig.17. Results of maximal σ_{zr} and deflection for various thickness of the disc

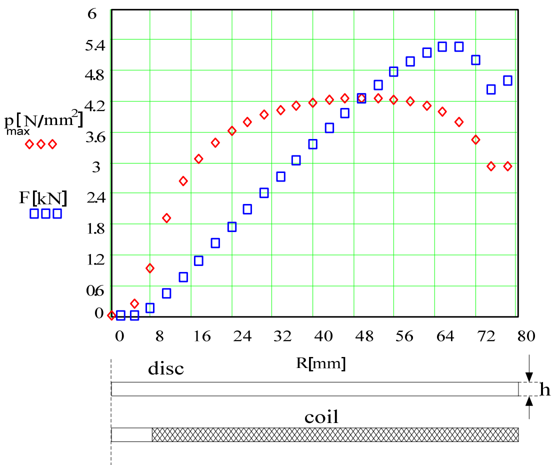

Fig.18. Distribution of pressure and force

On the basis of simulation in MECH model one can determine the essential course of reduced stresses in the disc thickness function (Fig.17). The result of such investigation makes it possible to determine the minimum thickness of disc for which the maximum stresses will not exceed the admissible value. In addition, the study confirmed that the pressure distribution acting on the disc along the radius has a very significant impact on the stress distribution in the disc (Fig.18). Therefore, analyzing the pressure distribution along the radius and the state of stresses one can determine suitable radial dimensions of the coil and the disk for the construction case.

Final remarks

Such quantities as displacement, speed, acceleration and stress analysis decide about proprieties of IDD. The experimental - simulating methods presented in this paper enable us to design IDD which is dedicated to the specific HCB which switches off the short circuit in a defined system. One should underline that the registration of disc displacement concerns only his centre. Hence, it could not be the basis to determine the distribution of stresses.

The solution of the vibrating disc movement and its computer realization was obtained on the assumption that the disc is ideally elastic, homogeneous and isotropic.

Additionally, an assumption is made that disc vibrations are not large. Hence, to describe them one can use a line different equation with the application of Hook's law. This approach is justified because the used material and the dimensions of the disc meet the mentioned requirements. During the disc designing we must remember that not only cannot this disc deform itself but its too big elastic strain is not advisable. On the other hand an exceeding of permissible values of the disc stresses causes a permanent disc deformation, what is applied in technology of thin metal sheets electromagnetic forming [10].

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