Konrad Jakub WALECKI[1], Kazimierz Andrzej ZAKRZEWSKI[1]

Łódź, Politechnika Łódzka, Instytut Mechatroniki i Systemów Informatycznych (1)

The total iron loss determination in the ferromagnetic elements of the electromagnetic speed and torque converter including the magnetization type

Abstract. *In the presented paper the idea and calculation results concerning the total losses in the ferromagnetic parts of electromagnetic torque converter are introduced. Taking advantage of the field calculations it was decided to determine the type of magnetization in the particular regions of converter and evaluate the losses using elliptical hysteresis loop of the materials. The losses calculations were made for the common armature and magnetic wedges in the slots.*

Streszczenie. *Przedstawiono koncepcję i wyniki obliczeń strat w ferromagnetycznych elementach szczególnego przetwornika momentu elektromagnetycznego z uwzględnieniem przemagnesowania płaszczyznowego i osiowego z wykorzystaniem zastępczej histerezy eliptycznej materiałów. W szczególności dokonano obliczenia strat w tworniku i klinach zamykających żłobki twornika. (**Straty w ferromagnetycznych elementach przetwornika momentu elektromagnetycznego z uwzględnieniem przemagnesowania płaszczyznowego i osiowego**)*

Keywords: electromagnetic speed and torque converter, eddy current and hysteresis loss, elliptical hysteresis loop
Słowa kluczowe: przetwornik momentu elektromagnetycznego i prędkości obrotowej, straty wiroprądowe i histerezowe

Introduction

The article presents the concept of calculating total iron loss due to permanent magnets magnetization in the common armature and magnetic wedges of the electromagnetic torque converter prototype. The method of calculating losses in the ferromagnetic materials using a field models taking into account the type of magnetization and elliptical hysteresis loop was implemented. [1].

Using the results obtained from field models, an analysis of magnetization occurring in the particular areas and the armature and wedges were conducted. Hence the next step was the estimation of the losses values.

The common armature and magnetic wedges will be subjected to functioning in wide frequency spectrum, also significantly more than 50 Hz, depending on the desired speed of the generator part, load on the motor part and power loss in the converter. For this purpose, the model of the elliptical hysteresis loop [3] with modifications which results from the kind of magnetization in ferromagnetic elements of converter was implemented.

The object of studies

The electromagnetic torque converter consists of the generator and motor parts, as well as the common armature (Fig.1). The construction is rare and unconventional. Either on the circumference of generator and motor yokes the permanent magnets are arranged. They are magnetized in radial direction. The change of torque and rotational speed is performed by the horizontal displacement of the common armature under the generator and motor yokes.

Considerations will be carried out separately for the generator and motor parts due to the lack of magnetic field symmetry and various magnetization frequencies.

The finite element packages to calculate hysteresis loss usually implement loss curves of magnetic material. Yet the obtained values of the loss are generally smaller than the real ones. The estimation of hysteresis loss depends mainly on the experience (Edwards et at., 1995). Another method is to use the complex permittivity (Magnet pack and the Opera-3d - ELEKTRA / SS and SOPRANO / SS). The calculations (such as time-harmonic) of electromagnetic field distribution values are performed in the presence of hysteresis loss expressed by a linear isotropic or anisotropic complex permittivity. It allows the estimation of hysteresis loss with greater accuracy (plotted hysteresis loops are elliptical). However, the material data necessary for the above calculations is difficult to access [7]. Estimation of the total iron loss using field methods in complex cases, such as electrical machinery remains a major challenge [8] because of the rotating field presence.

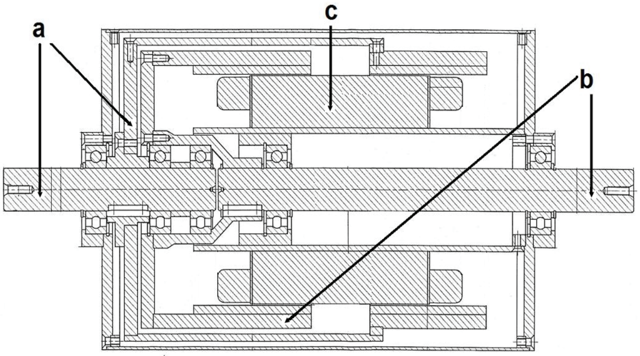

Fig. 1. The prototype of electromagnetic torque converter, a) generator, b) motor, c) common armature

The magnetization type determination algorithm

The proposed algorithm consists of utilization of the finite element method to acquire the data concerning the magnetic flux density distribution in the analysed regions and determination a kind of the magnetization. The next step is use of the gathered data in order to evaluate the iron loss. The field calculations were conducted in FEMM package [9] for 2D model.

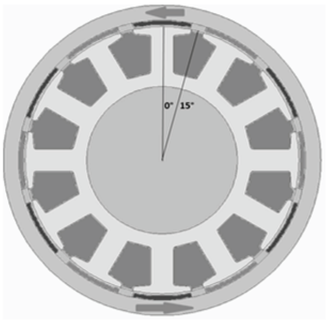

Fig. 2. The electromagnetic torque converter 2d model, the rotation direction of the yoke is shown. The diameter of armature sheet is 160 mm.

We assume the magnetic field distribution is equal along the whole length of the common armature. The magnetostatic calculations are performed for consecutive positions of the permanent magnets relative to the armature.

For all the elements of the finite element mesh the coordinates and the area are stored in the form of matrices. Thanks to the LUA extension language [9] all data are saved in the workspace of the Matlab package. The matrices are as follows.

- Matrix $R=a_{i,1}$, where, i – the number of elements which corresponds to rows number and simultaneously the fixed number of the given element, as well as the position – a=x+iy.
- Matrix $P=a_{i,1}$, where, i – the number of elements which corresponds to rows number and simultaneously the fixed number of the given element, as well as the area – a.

Then for each element in the next consecutive step the values of the flux density vectors Bx and B_y are also stored in the form of matrix.

- Matrix $Bx=a_{i,j}$, where, i –the number of steps which corresponds to the row number, j – the number of elements which corresponds to the number of columns and simultaneously the fixed number of the given element, a – magnetic flux density B_x vector value.
- Matrix $By=a_{i,j}$, where, i –the number of steps which corresponds to the row number, j – the number of elements which corresponds to the number of columns and simultaneously the fixed number of the given element, a – magnetic flux density B_y vector value.

Assuming that the calculations will be performed for 60 steps (id est. for rotation of the yoke with permanent magnets for 60 degrees), the elements number will be $25\cdot10^3$, so the dimensions for the matrix R will be $i=25\cdot10^3$, for the matrices B_x and B_y $i=60$ and $j=25\cdot10^3$ respectively. The gathered information allows plotting a value and direction of vector B for the whole cycle of magnetization for the points 1-8 (Fig. 3). The hodographs are presented in the consecutive figures 4 and 5.

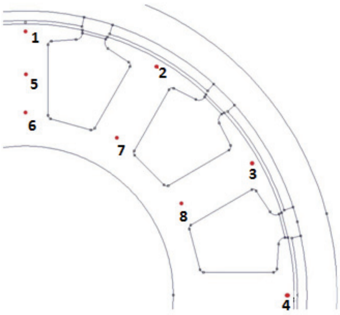

Fig. 3. The points where the magnetization type was determined

The most crucial element of the vector B curve analysis is determining the regions where the plane magnetization occurs and also these ones where one can meet longitudinal magnetization. During the analysis of the magnetization plot along one of the teeth it was found in which region the magnetization type changes. If the ratio B_x/B_y is below 10 % we assume that the magnetization type is longitudinal one, for the remaining region (where B_x/B_y ratio is above 10%) the magnetization type should be plane. In the fig. 6 the change of the magnetization on the section of 1.5 cm along one of the teeth is depicted. There is a border of two magnetization regions in this place. The magnetization changes here its type from plane to longitudinal one. As may be observed in the fig. 7 regions of magnetization type in the common armature are shown.

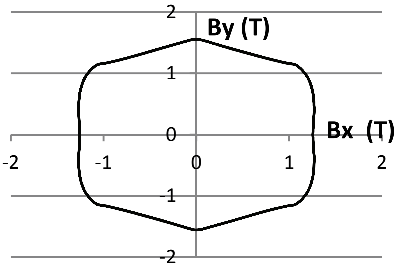

Fig.4. The value and direction of vector B in the point 1, plane magnetization

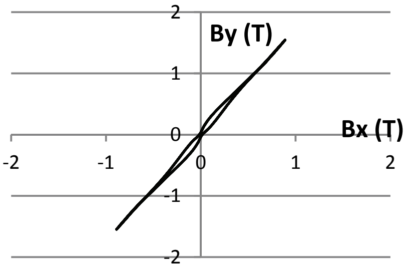

Fig.5. The value and direction of vector B in point 7, longitudinal magnetization

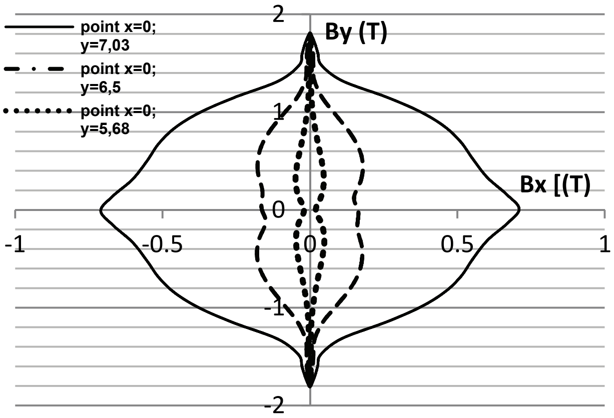

Fig.6. The magnetization type changes from plane to longitudinal one. The ratio B_x/B_y drops below 10 %. Point 6 +/- 1,25 cm along y axis.

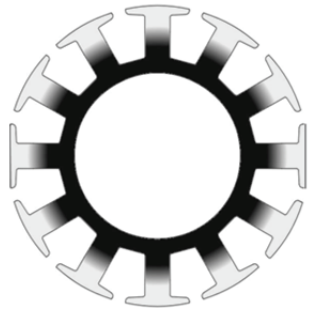

Fig.7. Regions of magnetization in the common armature. Plane magnetization type (bright one) and longitudinal one (dark one)

Because in each tooth occurs the same magnetization effect in order to shorten the computation time one can perform analysis only for one twelfth of the whole area. It is the optimal solution for obtaining the shortest computation time. The regions (one twelfth of the whole area) with the more dense mesh were chosen to analysis. From this regions during consecutive magnetostatic computations one obtains and stores positions and area of each element, together with magnetic flux density Bx and By vector values.

The elliptical hysteresis loop model with modifications

The assumptions of the Zakrzewski's model introduce Fig.11. It presents a finite ferromagnetic element with the thickness d. The magnetic field has the direction of y. The eddy currents flows from the other side in the xz plane and are infinite. The dimensions in the yz plane are limited. We assume that the electromagnetic flux penetrates ferromagnetic material from both sides. Electric field amplitude $\hat{E}_m$ on the both surfaces is equal. It also assumes that the magnetic field is sinusoidal in time, the ferromagnetic material is homogeneous. Both the amplitude of magnetic permeability and elliptical hysteresis angle have a constant value.

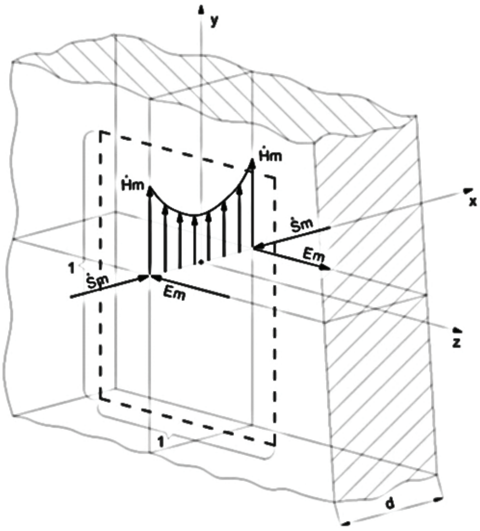

Fig. 6. The magnetic field distribution inside the ferromagnetic material.

Zakrzewski used the elliptical shape of hysteresis loop which reproduces the static hysteresis loop of the metal sheet by introducing the complex permittivity to Maxwell's equations. Lossiness [W/kg] is expressed as formula (1):

$$P = \frac{k^3}{2\gamma\mu_m^2\rho d}\varphi_m^2\xi_\phi \quad (1)$$

$$\varphi_m = B_{mavg}\, d \quad (2)$$

$$k = \sqrt{\pi f \mu_m \gamma} \quad (3)$$

$$\xi_\Phi = \frac{a\sinh(akd) - b\sin(bkd)}{\cosh(akd) - \cos(bkd)} \quad (4)$$

$$a = \cos\frac{\delta}{2} + \sin\frac{\delta}{2} \quad (5)$$

$$b = \cos\frac{\delta}{2} - \sin\frac{\delta}{2} \quad (6)$$

$$\hat{\mu}_m = \frac{\hat{B}_m}{\hat{H}_m} \quad (7)$$

In the analyzed case for the part of armature beneath the yoke of the motor in order to determine the loss values Zakrzewski's formulas were used. The necessary data was taken from magnetic field distribution obtained in field calculations and appropriate catalogue material data [5].

Authors suggest that in order to speed up the calculations formulas (1-7) should be entered into a spreadsheet.

For the magnetic induction B_m=1 T and frequency f_2=10 Hz (n_2=100 rpm), the loss value equals 1,2 W/kg. The value of angle δ at B_m=1 T was taken from previous calculations for metal sheet type EP23 [6].

The losses calculation algorithm in the common armature

When plane magnetization occurs we assume that the iron losses consist of the values separately determined for the values of – B_x and B_y. The specific loss value is determined using the loss characteristics of the given sheet separately for values B_x and B_y. For the computation the loss characteristics of generator steel strip M470 for 50 Hz was used [5]. The loss characteristic was converted for the sheet thickness d=0.5 mm and was presented in Watts per square metre. Than the curve approximation using exponential function was made. It enables the computations of loss for magnetic flux density values of individual triangular mesh elements.

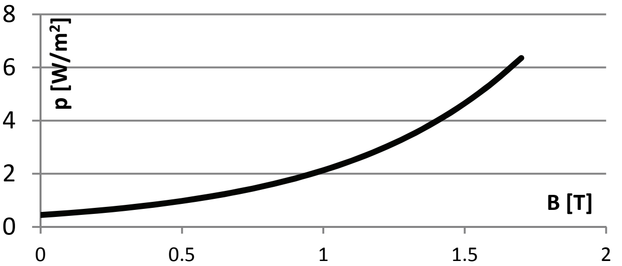

Fig. 7. The approximated core loss characteristic for M470 sheet

The loss computation is performed using the following algorithm. For the maximum calculated via finite element method absolute values of B_x and B_y for each element centroid of analysed region one can determine two loss values (for B_x and B_y respectively) using the loss characteristic presented in fig. 9 (for the region when longitudinal magnetization occurs the loss value is determined only for one maximum value of |B| vector). The read value of elementary loss is than multiplied by area of given mesh element (area of each element is known and stored in matrix P). The total iron loss is the loss in each sheet multiplied by number of sheets in packet. Taking into account condensed pressing of the sheets in the armature we can obtain number of sheets *n* directly from (8)

$$n = l \cdot d, \quad (8)$$

where: l - the armature length which is subjected to the magnetization, d - thickness of single sheet in the packet.

The loss emit only in the iron part of armature packet, so the calculated value *n* should be multiplied by factor 0.92 in order to take into account the lamination thickness and imperfect pressing.

Additionally, the experimentally determined technological coefficient of losses growth rate [4] should be taken into account. It is associated with the cut edges of the sheets, which for cold rolled generator sheets equals k_u = 1.55. The total value of loss is, therefore, the product of the estimated loss and coefficients k=0,92 and k_u=1,55.

Table 1. The summation of losses for specific values of magnetic induction

Regions of magnetization type		The iron losses [W]
plane	for Bx values	Px
	for By values	Py
longitudinal	for |B| value	P
The sum of losses for all regions		P_t=P+Px+Py

The results

The proposed algorithm can be applied for those magnetization frequencies values where the material loss characteristics are available. In general, these characteristics are given usually for 50 or 60 Hz frequencies.

In the analyzed example the iron loss value in the common armature of the generator part was estimated using the described algorithm. At the rotational speed of the generator part n_1 = 500 rpm the magnetization frequency is:

(9) $$f_1 = \frac{pn_1}{60} = 50\,Hz$$

The active length of the common armature under the generator part equals is l_1=75 mm. The resulting loss values for each area of magnetization type represent tab.2. The mass of this armature part is 4.58 kg, which according to the catalogue data for the obtained values of the magnetic induction distribution should give the value of the loss at the level of 24 W. As a result of the proposed algorithm, the estimated value is higher due to the occurring plane magnetization.

Table 2 The iron losses values obtained using proposed algorithm for the given regions for generator part at l1 length

Regions of magnetization type		The iron losses [W]
plane	for Bx values	8,5
	for By values	9,9
longitudinal	for |B| value	16,7
The sum of losses for all regions		35,1

The attempts have been also made to convert the obtained iron loss values for frequencies other than 50 Hz. For the motor part (frequency 10 Hz) the Zakrzewski's formula (1) were used as described in previous paragraph.

The overall loss due to magnetization which comes from permanent magnets and taking into consideration the technological coefficient of losses growth rate k_u=1,55 for the whole common armature (generator and motor parts) equals 36,3 W. This value is a sum of losses calculated using the algorithm (35,1 W) and Zakrzewski's formulas (1,2 W).

The magnetization type recognition in the wedges the common armature slots

In order to determine the losses in the magnetic wedges Zakrzewski's formulas (1-7) were adopted. The corresponding frequency values resulting from the rotational speed were used together with corresponding material data (cast) and the magnetic induction values B_m obtained from the field calculations. Due to the different characteristics of permanent magnets placed on the generator and motor yokes the field calculations were performed separately. To obtain an appropriate a distribution of induction |B| the magnetization characteristic of cast was implemented. Then this material was assigned to the area of magnetic wedges in the field model of converter.

The essential step was the analysis of magnetization direction (x or y) in the wedges, which according to figure 8 determines the dimension d used in Zakrzewski's formula (2).

If the direction of wedges magnetization (Fig.10) would be recognized in the y-axis one should in accordance with the Zakrzewski's assumptions and figure 8 choose dimension d_2. In the case of magnetization which occurs in the x direction the appropriate dimension would be d_1.

The analysis shown wedges magnetization direction occurs in both directions – x and y (fig.10, 11). However, the plotted hodographs (Fig. 12, 13) showed a significant advantage of magnetization in the x direction (the ratio By/Bx = 16%). It allows to assume that magnetization occurs mainly in this direction. Therefore in the Zakrzewski's formulas the dimension d_1 was chosen.

. The further analysis was the substitution to the formula (3) appropriate value of magnetic induction B_m, which varies in the range from -0.9 T to 0.9 T (Fig. 12). The value of B_m=0,9 T was substituted for the wedges under the generator part of the converter. For the wedges under motor part, a value of Bm = 1.49 T (Fig. 13) was used.

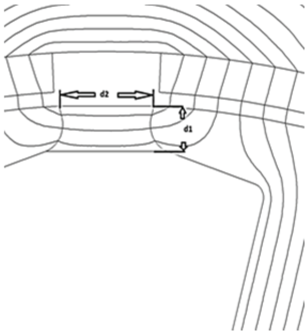

Fig. 10. The magnetic wedges magnetization in the x direction, lengths d_1 and d_2 are marked

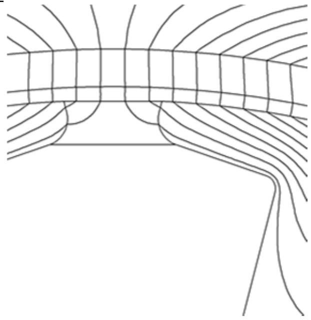

Fig. 11. The magnetic wedges magnetization in the y direction

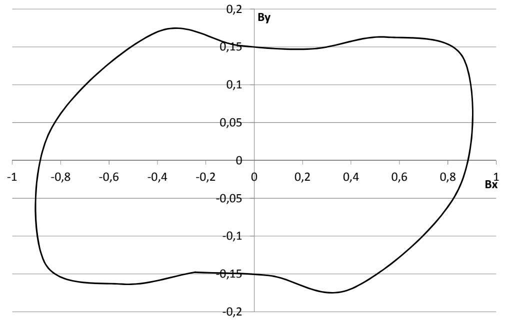

Fig. 12. The magnetization Bx, By [T] hodograph of the common armature wedge (generator part).

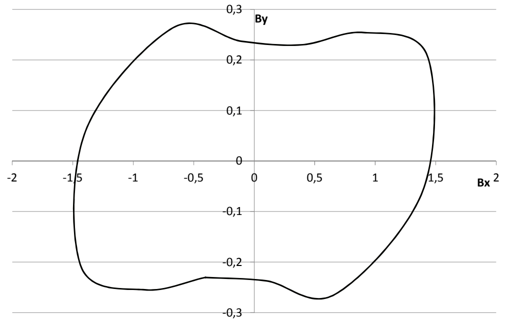

Fig. 8. The magnetization Bx, By [T] hodograph of the common armature wedge (motor part).

In order to calculate the loss using Zakrzewski's formulas the corresponding material data resulting from the wedges material (cast) magnetization characteristic were used, the corresponding dimension d = d_1 = 5 mm, and the corresponding value of H_m. The value of magnetic induction Bm = 0.87 T was taken from the magnetic induction distribution obtained from FEMM package (Fig. 14, 15) and the plotted hodograph (Fig. 12, 13.)

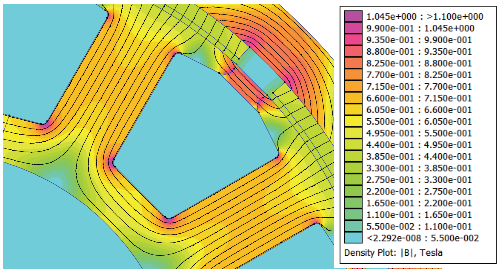

Fig.14. Magnetic flux density for converter with magnetic wedges in FEMM

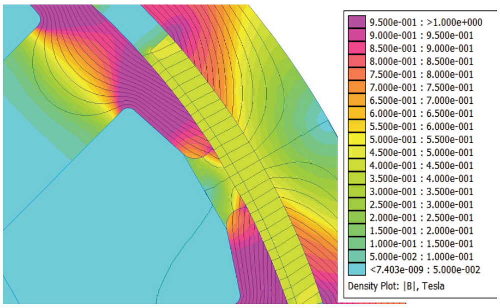

Fig.15. Magnetic flux density for converter with magnetic wedges in FEMM

With the use of equations (1-7) which were built into the spreadsheet and the appropriate variables the losses in the wedges was estimated. The corresponding frequencies value for both generator and motor part were substituted.

The angle δ value was determined on the basis of the hysteresis loop surface area for the cast [2].

In the presented case the estimated value of the losses depends mainly on eddy current losses and to a lesser extent is determined by the angle δ, which is responsible for the hysteresis loss (case of massive iron) (Fig. 16).

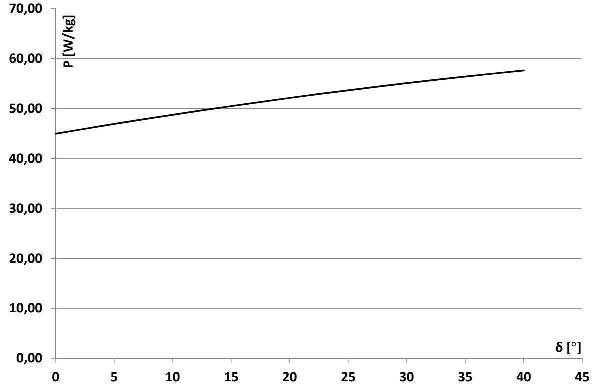

Fig.16. The lossiness of the wedges P [W/kg] from the permanent magnets magnetization in the function of δ angle.

Having known the appropriate values of B_m, frequency and material data one can put the data in to the spreadsheet and use the formula (1). As a result the lossiness value in W/kg is obtained. The mass of wedges is known.

In the given measurement case for n_1 = 500 rpm and n_2= 100 rpm the following loss values in wedges (were obtained:

The wedges placed under generating part (75 mm overlap): 8,9 W

The wedges placed under motor part (15 mm overlap): 0,7 W

Conclusions

The calculations showed the possibility of using in practice the developed method for estimating losses in ferromagnetic materials using field models taking into account the kind of the magnetization with use of an elliptical hysteresis loop [1]. According to the authors the presented an algorithm, although developed for the untypical torque converter, may be useful to calculate the losses in the ferromagnetic elements of machines with different construction and geometry.

Nomenclature

plane magnetization - magnetization which shape is similar to the elliptical one

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***Authors**: dr inż. Konrad Walecki, Politechnika Łódzka Instytut Mechatroniki i Systemów Informatycznych, ul. Stefanowskiego 18/22, 90-924 Łódź, E-mail: konrad.walecki@p.lodz.pl*
prof. dr hab. inż. Kazimierz Zakrzewski, Politechnika Łódzka Instytut Mechatroniki i Systemów Informatycznych, ul. Stefanowskiego 18/22, 90-924 Łódź, E-mail: kazimierz.zakrzewski@p.lodz.pl