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AN ANALYSIS OF THE INFLUENCE OF SELECTED DESIGN AND MATERIAL PARAMETERS ON HIGH-SPEED EDDY-CURRENT BRAKE PERFORMANCE

ANALIZA WPŁYWU WYBRANYCH PARAMETRÓW KONSTRUKCYJNYCH I MATERIAŁOWYCH NA PRACĘ WYSOKOOBROTOWEJ HAMOWNICY INDUKCYJNEJ

A b s t r a c t

This paper presents an analysis of the influence of utilizing rotor materials of different magnetization and conductivity on steady-state torque-speed characteristics for a high-speed eddy-current brake. The analysis involves rotors of different active lengths, with or without axial slits and a copper layer on the surface. The calculations were carried out using two and three-dimensional numerical models, partially verified on the laboratory test-stand.

Keywords: *electromagnetic brake*, *eddy currents*, *finite element method*

S t r e s z c z e n i e

Artykuł prezentuje wyniki analizy wpływu użycia różnych materiałów wirnika o różnej krzywej magnesowania i konduktywności na charakterystyki mechaniczne wysokoobrotowej hamownicy wiroprądowej. Analiza obejmuje wirniki o różnych długościach czynnych z nacięciami osiowymi lub bez nacięć osiowych oraz warstwy miedzi na powierzchni. Obliczenia są prowadzone z zastosowaniem dwu- i trójwymiarowych modeli numerycznych, częściowo zweryfikowanych na stanowisku pomiarowym.

Słowa kluczowe: *hamownica indukcyjna*, *prądy wirowe*, *metoda elementów skończonych*

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1. Introduction

In the most cases, eddy currents in massive elements of electromechanical converters deteriorate in their performance and efficiency. However, there is a group of converters of which the principle of operation relies upon utilizing the eddy currents induced by magnetic field. This group contains eddy-current brakes of which the main advantage is converting mechanical energy into heat without physical contact [1–3]. This type of device is successfully used as brakes in tracked vehicles and high-speed turns, providing a very high value of braking torque, minimum noise emission as well as reliable operation. Because of the aftermentioned properties, eddy-current brakes are especially useful in the measurement of the torque of devices operating at very high rotational speeds e.g. electric motors designed for driving vacuum cleaners, centrifuges or compressors.

An example of a such an application was presented in previous works by authors [4, 5] where the designed eddy-current brake was used for carrying out torque measurements on the low-power motor operating at rotational speeds of up to 100 000 rpm. In this paper, investigations on this brake will be continued and will involve an analysis of the influence of using different rotor materials on torque-speed characteristics. For that purpose, numerical models of the brake will be used. The main objective of this study, being the continuation of work [5], is searching for methods of improving the brake performance by utilization appropriate rotor material.

2. Design parameters and numerical models

The considered brake consists of two main elements. The stator is made of a steel sheet (M400-50A) and equipped with two pairs of symmetrically spaced coils with different numbers of turns (z_1 = 85 and z_2 = 120) generating a constant magnetic field of two poles. The winding is supplied from a DC power supply with a current of rated value I_N = 10 A. During operation of the brake, a tangential force is acting on the armature. This force is measured using force transducers and gained by the electronic unit, and consequently the braking torque is also measured. Bearing in mind the specific operating conditions of the brake (working at very high rotational speeds) the rotor diameter was calculated so as to maintain a working air-gap width of δ = 2 mm. The wide air-gap facilitates the positioning and alignment of the rotor in relation to the stationary stator sheet package.

For the investigation carried out on this work, two rotors made of steel with various material properties were produced. DC-magnetization characteristics of these steel rotors are illustrated in Fig. 1. The rotor materials with various magnetization characteristics also differ in their electrical conductivity. The conductivity of steel A (high carbon) is of 2.43 MS/m, while of steel B (low carbon) of 5.74 MS/m.

Due to the specific geometry of the analyzed converter (see. Fig. 2), the authors focused mainly on utilizing three-dimensional models for carrying out the investigation. However, because of the very long time duration of the execution of these models, it was justified to use a two-dimensional model in the preliminary calculations. In such models, it was necessary to take into account the so-called rotor-end effect (presence of the current density vector components that are perpendicular to the shaft axis) [6]. Based on the literature study, it can be stated that one of the most commonly used methods for taking into account the end-effects in the two-dimensional models is to apply in computations the effective conductivity of the material being a product of the real conductivity of the rotor material and the so-called rotor-end factor. It is possible to determine its value either by using analytical or numerical methods. Considering the specific structure of the rotor, the authors applied the rotor-end factor in computations obtained analytically, based on the simple formula given by O'Kelly [7]:

$$k_e = \frac{L_z}{L_z + \tau}, \tag{1}$$

where:

k_e – rotor-end factor,
L_z – active length of the rotor,
τ – length of the arc on the rotor surface for whose chord is equal to the stator tooth width.

The rotor-end factor for the 2D model determined by using the abovementioned formula gives value of 0.52. The results obtained from this model will be compared in the next section with the results from a three-dimensional model and measurements.

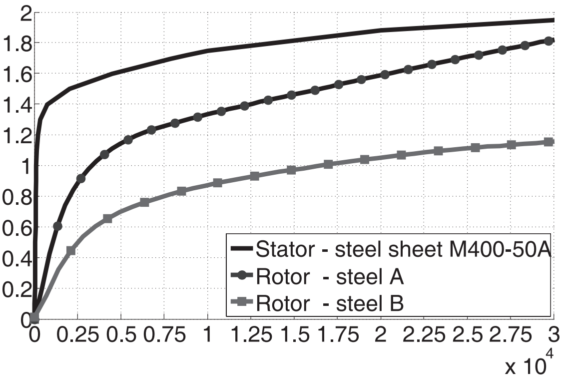

Fig. 1. Magnetization characteristics of the used materials

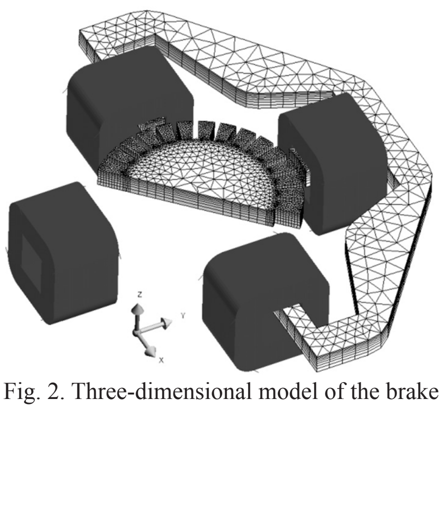

Fig. 2. Three-dimensional model of the brake

3. Calculation results

3.1. Homogenous rotors

The first step of the research was to perform a series of computer simulations for a basic structure of the solid rotor using the two and three-dimensional models and comparing their results with the results of the measurement on the physical model (Fig. 3).

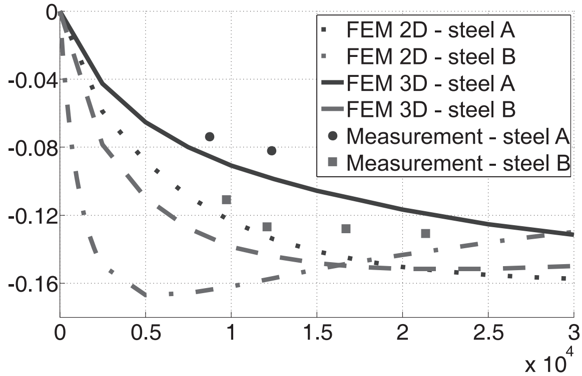

Fig. 3. Steady-state braking torque vs. speed for the brake for the rotor with a basic construction (the uniform solid rotor of the length equal to the stator core length)

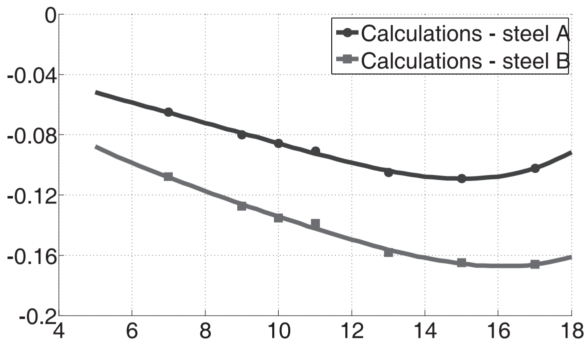

Fig. 4. Braking torque vs. active rotor length for the brake equipped with the uniform rotor at rated speed

As can be seen from the plot above, there are significant differences in the results of the calculations by the two and three-dimensional models. This proved that the physical phenomenon in the analyzed device (the rotor-end effect especially) cannot be modeled properly using the two-dimensional model. Hence, the three-dimensional model must be used for further computations. It is supposed that the main reason for the discrepancies in the calculation results by the 3D models and the measurement results is that the hysteresis losses in the rotor were neglected in computations. From the analysis of the results presented earlier in the plot, it can be observed that, from the point of view of the braking torque value, better electric properties of the rotor material are much more important than its magnetic properties.

The authors also carried out a series of simulations to determine the effect of changing the active length of the rotor on the produced braking torque. The active length of the rotor adopted as a parameter for simulation was varied as $L_Z \in$ <5.18> mm. The results obtained from the calculations are shown in Fig. 4.

The most interesting conclusion from the analysis of the calculation results is the non-monotonic nature of the braking torque variation as a function of rotor length. The length corresponding to the extreme of the above-mentioned function varies depending on the type of steel.

In conclusion, the analysis of the characteristics (Figs. 3 and 4) allows us to make an unambiguous choice of selecting rotor material (steel B), keeping in mind the most important parameter – the maximum braking torque value.

3.2. Rotors with copper coating

Searching for other methods to increase the braking torque, the authors also investigated the impact of modifying the structure of the rotor by applying a copper layer coating to its surface. Preliminary computational results suggesting the effectiveness of such a solution are presented in the paper [5]. The copper ring, in contrast to the steel, has a much higher electrical conductivity while maintaining the diamagnetic properties. While keeping a constant air-gap length, the utilization of the thick layer of copper results in the introduction of an additional reluctance, and significant increase of the rotor equivalent conductivity ratio at the same time. The calculations for the two types of steel and different thickness copper rings are presented in Fig. 5.

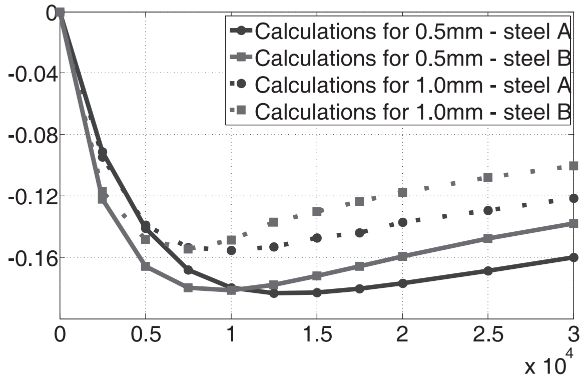

Fig. 5. Steady-state braking torque vs. speed for the brake with the rotors coated by thin copper layer

Utilization of an additional material (copper) resulted in an increase in the value of the braking torque. As can be seen, the position of the extremum of the developed torque was considerable shifted simultaneously. This is caused by significant weakening of the main flux produced by the winding due to the eddy currents induced in the copper layer.

From the authors point of view, an interesting problem, is the determination of the optimal copper layer thickness coating the rotor. The performed series of numerical simulations allowed for the accurate determination of this value. However, in this case, limitations associated with the maximum current density in the copper area should be kept in mind; hence, it is impossible to exceed the certain minimum thickness of copper coating. The calculation results for the selected analyzed materials are shown in Fig. 6.

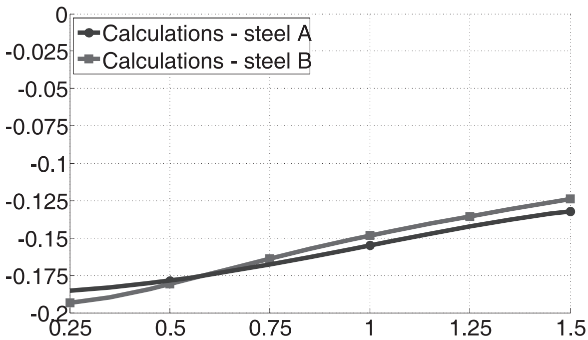

Fig. 6. Braking torque vs. thickness of the copper layer at rated speed

3.3. Rotors with axial slits on the surface

The brake analyzed in the paper belongs to the group of devices with solid rotors. In the case of solid-rotor induction machines, one of the methods for improving the operational performance, widely described in the literature, is to make a series of axial slits on the rotor surface [6, 8]. This results in a significant increase in the depth of the magnetic field penetration into the rotor, and as a consequence, an increase in torque values [8].

Because of significant differences between the construction of a typical solid-rotor induction machine and the considered brake, the authors decided to analyze its performance when it is equipped with the slitted rotor shown in Fig. 7.

The new structure has 30 slits with a depth of 7 mm, distributed symmetrically on the rotor circumference. Other structural parameters of the model remained unchanged.

The obtained results of numerical calculations for the modified structure of the rotor are shown and compared with the basic rotor structures in Fig. 8.

Unfortunately, the characteristics illustrate a decrease rather than an increase of braking torque. The reason for this should be sought in the very small ratio of active length of rotor in relation to its outer diameter. Another cause for the reduction in the value of the torque is the

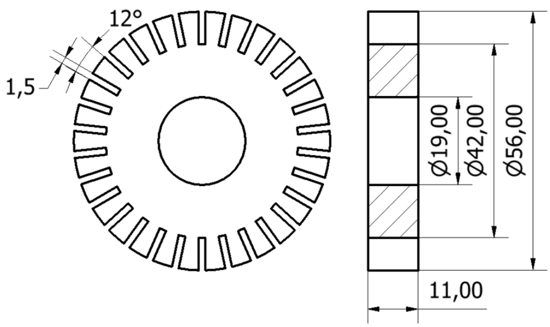

Fig. 7. Slitted rotor

characteristic structure of the brake stator. A small area of the stator pole shoe is associated with a relatively large dispersion of the main flux. Exemplary density distributions of eddy currents induced on the disc are shown in Fig. 9.

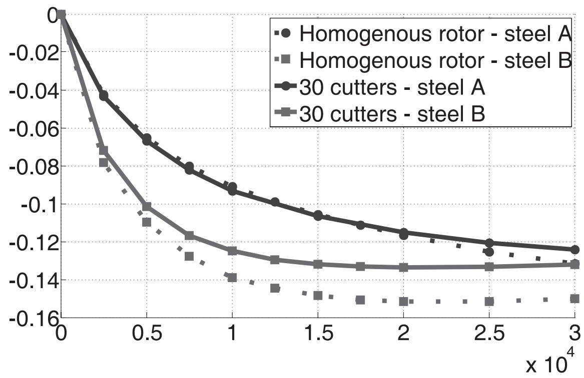

Fig. 8. Comparison of steady-state braking torque vs. speed characteristics for the brake with uniform and slitted rotors

4. Summary

The main issue posed in this study was to analyse the effect of using different rotor materials on high-speed induction brake performance. The calculation results were partly verified by taking measures on the test-stand. The two-dimensional models were already omitted at an early stage of the research and full analysis in three dimensional space was carried out. On the basis of the characteristics, the effect of material parameters on the brake operating conditions was clearly defined. Among the most interesting results, the dependence of the braking torque on the rotor length with the clear extremum can be mentioned. The positive effect of an additional copper layer (0.2–0.5 mm) on the mechanical characteristics of the brake has been confirmed.

It was also shown that it is inappropriate to perform slits on the surface of the rotor. In such a case, the observed decrease in the braking torque is mainly caused by a small ratio of the active length to the rotor diameter and narrow pole shoes. The only positive result for this modification is to improve the coefficient of heat dissipation to the environment associated with the increased heat exchange surface with the air. The obtained results of the simulation allow designing a new rotor with increased active length, coated with a thin copper layer – this would significantly improve the achievable braking torque. However, it should be emphasized that it is advisable to apply the optimization methods to determine the most appropriate structural parameters of the rotor in terms of braking torque. The most important conclusion from the investigation is that a high value of electrical conductivity of the rotor material is much more important than its good magnetic properties. This is because of a relatively high length of air-gap resulting in the linearizing of the brake magnetic circuit.

a)
b)
c)

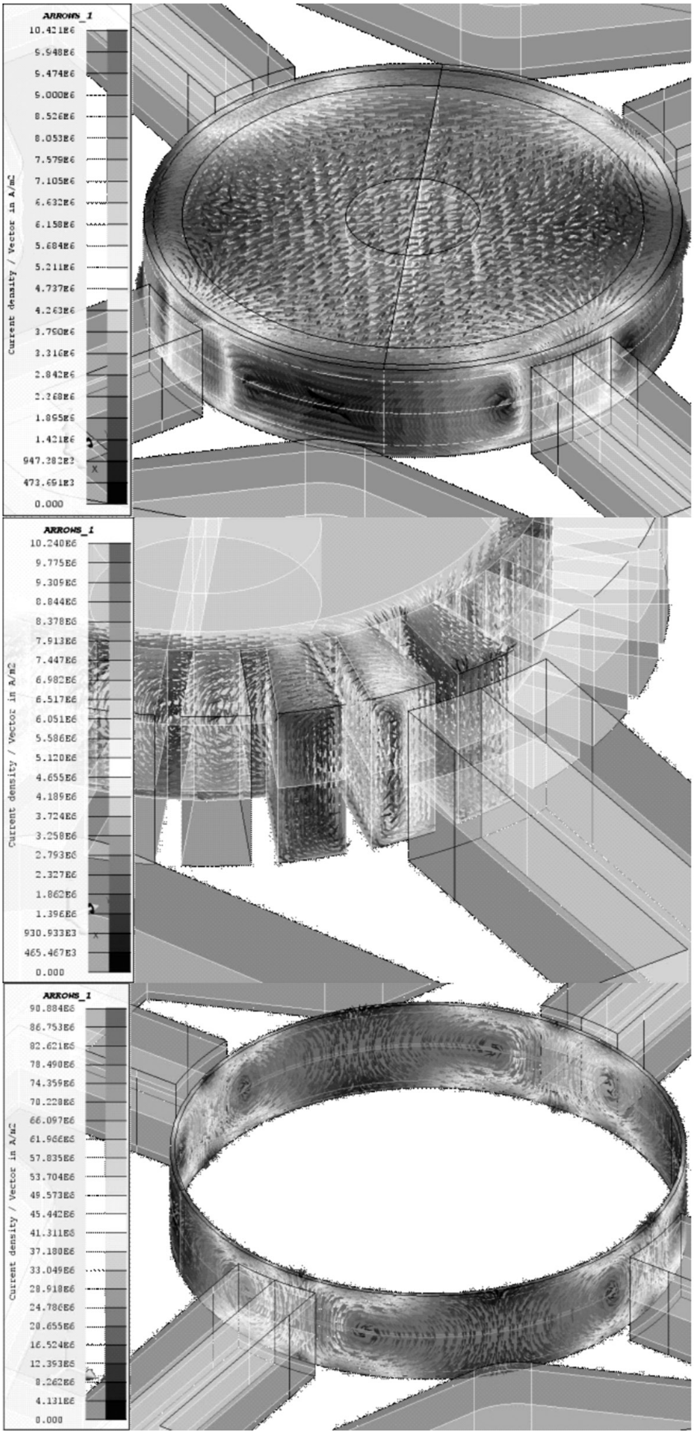

Fig. 9. Current density distribution a) uniform rotor, b) slitted rotor, c) rotor with copper layer

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