Research Article

Andrzej Waindok* and Bronislaw Tomczuk

Field analysis & eddy current losses calculation in five-phase tubular actuator

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Abstract: Field analysis including eddy currents in the magnetic core of five-phase permanent magnet tubular linear actuator (TLA) has been carried out. The eddy currents induced in the magnetic core cause the losses which have been calculated. The results from 2D finite element (FE) analysis have been compared with those from 3D calculations. The losses in the mover of the five-phase actuator are much lower than the losses in its stator. That is why the former ones can be neglected in the computer aided designing. The calculation results have been verified experimentally.

Keywords: five-phase linear actuator, eddy current losses, modelling of tubular linear drive, finite element method

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1 Introduction

There are different linear actuators e.g. pneumatic, hydraulic, piezoelectric, electrostatic, electromagnetic and hybrid ones. The electromagnetic ones are lately most popular. They characterize high stroke, quite high force, good dynamic properties and relatively high resolution [1]. A special case are active magnetic bearing actuators, which are characterized by high precision and very good dynamics [2, 3].

To provide proper power for the electromagnetic actuators, the controlled power system have been proposed. For example, linear reluctance motors (LRM) [4] can be controlled by electronic systems. The simple controlled bridge improves the parameters of the LRM, and enables the tracking of the mover location. Also there are number of pulse-width modulation (PWM) circuits to obtain a variable current at the motor terminals with dc-feed.

To take the advantages of all opportunities mentioned above, all power loss should be taken into account in the designing of a new construction. However, the losses in the actuator mover with permanent magnets (PM’s) separated by ferromagnetic rings, are much lower than those in its stator. That is why the former ones may be negligible as well. However, the comparison should be supported by tests.

The eddy current losses in the linear actuator were calculated in [5]. The permanent magnets actuator was equipped with stator made from Somaloy. However, the results have been given without measurement tests.

In [6], the eddy current losses have been included by a semi-empirical formula involving the total losses after axial cutting in the stator magnetic circuit. In [7], the total losses have been calculated using some analytical expressions in each element of the discretization mesh.

In all papers mentioned above the losses have been calculated for steady-states. However, this state of actuator operation practically exists only in some cases, e.g. actuator with blocked mover. In all investigations the hysteresis and eddy current losses have been included as the total ones. There is no paper about linear actuators, where the hysteresis losses would have been included using the advanced models of hysteresis (Preisach or Jiles-Atherton’s models). Only for the rotary orientated field the core losses have been divided into hysteresis loss and eddy current ones [8–10].

The power losses strongly heat the linear machine. To determine the maximum values of the current intensity and the thrust, they should be calculated as exactly as possible. In the paper an analysis of eddy current losses for a 5-phase permanent magnet tubular linear actuator (TLA) has been studied [11]. The actuator construction has been developed in Department of Electrical Engineering and Mechatronics at Opole University of Technology.
2 Description of the actuator construction

The test stand with our physical model is presented in Figure 1. The actuator is supplied with a pulse width modulation (PWM) device. The nominal current and force values are $I_N = 2.75 \text{ A}$ and $F_N = 290 \text{ N}$, respectively.

Scaled half of the cross-section through the actuator symmetry axis is given in Figure 2. Main parts of the actuator have been depicted in this figure. The Joule’s power losses in the windings are main losses of the actuator under its operation. As the windings of our actuator have been made from relatively thin wires, we neglected the eddy-currents inside them. Thus, the winding losses are easy to calculate.

In other parts of the actuator the losses are difficult to determine. Especially in the magnetic core. The ferromagnetic parts of the device are made from solid steel. Thus, we can suppose that eddy current loss component is significant in the total losses of the core.

The material parameters of the actuator main parts are given in Table 1. The permanent magnets with the coercive force of $950 \text{ kA/m}$ have been used.

3 Mathematical model

Two dimensional model has been created with using the FEMM software. In case of 3-dimensional finite element method (FEM), the Elektra software of the Opera-3d package has been used. The harmonic current supplying has been assumed in both cases. To simplify the calculations, the linearization of the B/H curve has been adopted. The total, complex magnetic vector $\mathbf{A}$ and electric scalar $V$ potentials are used

$$\mathbf{A}(t) = \mathbf{A}_m e^{i\omega t}, \quad V(t) = V_m e^{i\omega t}$$ (1)

where $\omega$ is the angular frequency of the excitation current. In our case, the value was $\omega = 188.4 \text{ rad/s}$. The vector quantity $\mathbf{A}_m$ and scalar quantity $V_m$ are potentials in the complex form. The equations which to be solved are:

$$\nabla \times \left( \frac{1}{\mu} \nabla \times \mathbf{A}_m \right) + i\omega \sigma \mathbf{A}_m + \sigma \nabla V_m = \mathbf{J}_s$$ (2)

$$i\omega \sigma \nabla \cdot \mathbf{A}_m + \nabla \cdot (\sigma \nabla V_m) = 0$$ (3)

where $\mathbf{J}_s$ is the excitation current density vector.

The eddy current density vector $\mathbf{J}$ is calculated from knowledge of potential $V$:

$$\mathbf{J} = -\sigma \nabla V$$ (4)

The eddy current losses in each region have been determined with using the expression:

$$P_{\text{eddy}} = \int_{\Omega} \left( |\mathbf{J}|^2 / \sigma \right) d\Omega$$ (5)

where $\Omega$ – volume of conducting region.

4 Calculation results

The calculations of the eddy current losses have been carried out for different cases. Two different excitation current values have been assumed in the analysis: $I_N = 2.75 \text{ A}$ and $I = 5.66 \text{ A}$. For the nominal excitation current $I_N$, when the magnetic flux density values are relatively low, the saturation of the core can be omitted.

In the case of maximum current value $I = 5.66 \text{ A}$, stator segments can be saturated (Figure 3). In this case the
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![Figure 3: Magnetic flux density distribution in cross-section of the TLA for maximum current value $I = 5.66$ A](image)

Table 2: Results of losses calculation for $I_N = 2.75$ A [W]

<table>
<thead>
<tr>
<th>Actuator region</th>
<th>3D model</th>
<th>2D model</th>
<th>2D model quasi-nonlinear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator</td>
<td>23.45</td>
<td>25.74</td>
<td>23.06</td>
</tr>
<tr>
<td>PM’s</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Ferromagnetic</td>
<td>0.86</td>
<td>0.91</td>
<td>0.85</td>
</tr>
<tr>
<td>rings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brass pipe</td>
<td>1.37</td>
<td>1.40</td>
<td>1.46</td>
</tr>
<tr>
<td>Total losses</td>
<td>25.79</td>
<td>28.15</td>
<td>25.48</td>
</tr>
<tr>
<td>CPU time [m:s]</td>
<td>3:54</td>
<td>0:9</td>
<td>0:33</td>
</tr>
</tbody>
</table>

nonlinearities of the magnetic material have higher impact on the core-losses. Thus, three different models have been compared, in the paper. In case of 2-dimensional calculations a linear time-harmonic model and a quasi-nonlinear one have been used. The nonlinearity has been approximated by a multi-segmental curve, which makes possibility to include different permeability values in each element of the magnetic core. In case of the 3D analysis the algorithms are similar, thus only time-harmonic model has been analyzed. Results of eddy current losses calculation were presented and some of them were verified experimentally.

The eddy current losses have been calculated in the core and other parts of the actuator (Table 2). It is evident, that the main part of the losses is in the stator of the actuator. In the brass pipe region the losses are visible, as well. In Figure 4, the eddy current distribution in the halved cross section of the actuator is shown. The highest values of eddy currents are observed on the inner parts of the stator segments and in the brass pipe, in the middle of the segments. The differences between models are not significant and are mostly visible for eddy current losses in the stator.

In case of higher excitation current values, there are visible more significant differences between numerical models (Table 3). In the stator there are observed differences of 20% between 3D model and 2D quasi-nonlinear model. It is mostly due to saturation effects, which are not included in the 3D linear model. The difference between 3D and 2D model are below 9% and are mostly due to differences between algorithms. The eddy current losses in

![Figure 4: Distribution of eddy current density magnitude in the cross-section of TLA for nominal supplying ($I_N = 2.75$ A): a) 3D model, b) 2D model, c) 2D quasi-nonlinear model](image)
Table 3: Results of losses calculation for $I = 5.66$ A [W]

<table>
<thead>
<tr>
<th>Actuator region</th>
<th>3D model</th>
<th>2D model</th>
<th>2D model quasi-nonlinear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator</td>
<td>99.00</td>
<td>108.85</td>
<td>120.71</td>
</tr>
<tr>
<td>PM’s</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>Ferromagnetic rings</td>
<td>3.62</td>
<td>3.84</td>
<td>4.04</td>
</tr>
<tr>
<td>Brass pipe</td>
<td>5.79</td>
<td>5.92</td>
<td>5.89</td>
</tr>
<tr>
<td>Total losses</td>
<td>108.87</td>
<td>119.07</td>
<td>131.09</td>
</tr>
<tr>
<td>CPU time [m:s]</td>
<td>3:47</td>
<td>0:8</td>
<td>3:43</td>
</tr>
</tbody>
</table>

other regions of the TLA (PM’s, ferromagnetic rings and brass pipe) are similar in all calculation models. As it was in the case of nominal current excitation, the stator eddy-current losses make 90% of total losses.

For maximum current value, the histogram of eddy currents distribution in the TLA (Figure 5) is similar to that obtained for nominal current supplying. However, the values of the current density are approximately twice more higher.

5 Measurement verification

Some measurement verification has been made as well. Calculation results were verified on a specially designed physical model of the actuator – it has a cut in a stator segments along the axis of symmetry. Such a construction is more advantageous due to decreasing eddy current losses about 50%. Additionally, due to this cut, only the 3D model has been verified experimentally (there is no axis symmetry in this case).

For the rated current value $I_N = 2.75$ A, from the measurements, we obtained the power losses $P_{meas} = 17.4$ W, while from calculations we obtained $P_{calc} = 13.22$ W. The difference in the two results is due to the simplicity of the mathematical model. First of all, we did not consider the hysteresis loss. Secondly, the linear material properties were assumed. The difference is also due to the measurement errors in small power values. The errors can be up to 10%.

For higher value of the current supplying e.g. $I = 5.66$ A, the measured value of core losses is 82.5 W. Including the expression for the total losses [1], we can suppose, that the hysteresis losses make 30% of the total core losses. Taking into account the hysteresis losses we calculated the core losses $P_{calc} = 76.4$ W. For the nominal current value $I_N = 2.75$ A the corrected calculated core losses value is $P_{calc} = 18.1$ W, while the measurement one is $P_{meas} = 17.4$ W.

6 Conclusions

The main constructional part of the mover is a tube from brass or stainless steel. The eddy current losses in it should be taken into account, because they amount 7% of the to-
tal eddy current losses. The lowest density of losses is observed in permanent magnets and can be neglected.

The nonlinear B/H curve has been linearized and it could increase the calculation error. Due to very complicated modelling, the hysteresis loop has not been taken into account.

For both 2D and 3D models the histograms of the eddy current distributions are nearly the same. Despite all simplification of the mathematical model, the results are proper and could be used in the designing of presented linear actuator constructions. However, 2D calculations demand much experience of the designer. Due to non-saturated magnetic core in case of nominal supplying, the nonlinearity applying is useless. The calculation time increases significantly from 234 s to more than 5 hours in the nonlinear case.

References