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Coil winding process modelling with deformation based wire tension analysis

Florian Sell-Le Blanc, Janna Hofmann *, Rico Simmler, Juergen Fleischer (1)

Karlsruhe Institute of Technology (KIT), wbk Institute of Production Science, Kaiserstraße 12, 76131, Karlsruhe, Germany

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ABSTRACT

For electric motors, the stator designs with tooth coils are predominant. Due to their noncircular shape, the tooth coils display a challenge for highly productive winding processes with a low coil resistance. With the use of a process model a prediction of the central process parameters, like the wire tension, can be achieved. This model consists of a wire deformation based multi-body-dynamic simulation, measurements and analytic model aspects which were validated at a test stand. It can be used to optimize controller and actuator designs for wire tension control systems and enables higher winding speeds and winding quality.

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1. Motivation

Since, the efficiency of power trains in hybrid electric vehicles should be increased and at the same time manufacturing costs reduced, different motor designs and production concepts need to be considered [1]. The stator design with distributed windings is technically suitable because of the nearly sinusoidal magnetic field in the stator (Fig. 1a). But, due to the large winding heads, which occur during their production with the insert technique, the single tooth design utilizing a rectangular bobbin shape (Fig. 1b and c) offers an alternative with benefits regarding productivity. Every stator tooth can be wound directly which results in a high number that can be produced simultaneously [2].

The limiting factor to achieve higher process speeds is the variation of the wire tension during the winding process because of the rectangular bobbin shape. To improve the winding speed further knowledge of the wire tension origin and a winding process model needs to be developed and validated.

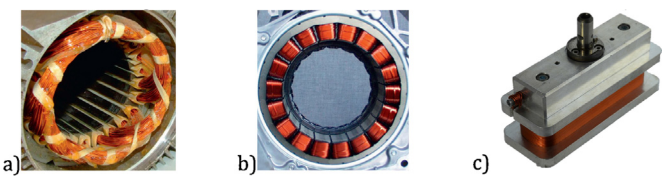

Fig. 1. Different Stator Designs (a, b) [2] and single tooth (c).

* Corresponding author.
E-mail address: Janna.Hofmann@kit.edu (J. Hofmann).

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2. Introduction to linear coil winding process

In order to achieve a high efficiency, the winding copper losses need to be reduced. Therefore, a high fill factor is needed. Compared to other winding schemes the orthocyclic-winding scheme is able to reach a theoretical mechanical fill factor of 90.7% due to the special layer structure in which the windings of the upper layer are in the grooves provided by the lower layers (Fig. 2a).

The only way to produce orthocyclic winding schemes are direct winding processes. As described in [3] the linear winding process is most promising because of its possibility to perform high coil winding speeds linked with small wire stresses which guaranties a higher winding quality. The small stresses are linked to the fundamental principle of the linear winding process.

After the wire is fixed, the coil bobbin starts rotating around the spindle axis of the winding machine. A feeding axis with a wire guide is moving translationally parallel to the winding axis to guarantee the accurate placement of the wire [3] (Fig. 2b).

To achieve a proper wire placement the tensile force, which varies due to the rectangular bobbin design (see green and red line in Fig. 3), needs to be controlled during the process. Therefore, a wire brake is installed to smooth the tension variations and apply a base tension.

Fig. 2. Orthocyclic winding scheme (a) and linear winding process (b) [4].

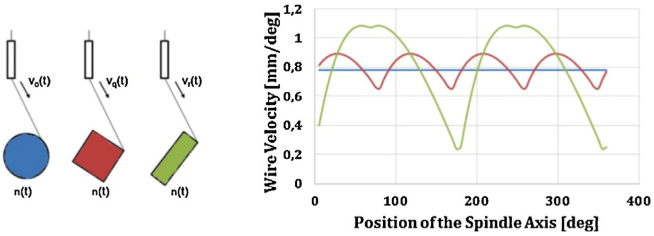


Fig. 3. Wire velocity variation caused by different coil bobbin designs.

3. Dynamic process model of the linear coil winding process

Due to the fact that not all machine-based influences on the process can be measured, a simulation model is needed in order to characterize cross-dependencies between the machine parts and the wire tension. Due to the geometric size of the model, a multi-body-dynamic simulation approach has been chosen as introduced in [4–6].

3.1. Multi-body-dynamic simulation

To fully describe the winding process the whole system (Fig. 4a) from the wire brake (point A) over the dancing lever (point B–C) and the wire guide (point D–E) to the placement on the coil bobbin (point F) needs to be modelled. The implemented simulation model is displayed in Fig. 4b.

As described in [7] the wire modelling and its deformation properties is the most challenging task. As discussed in [8] a rigid body chain connected with G-forces as connecting elements was chosen.

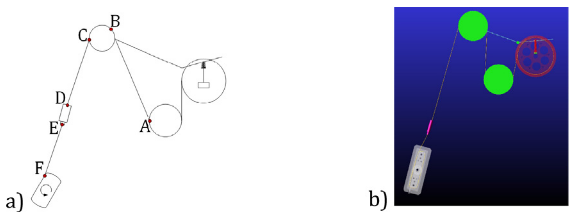


Fig. 4. Schematics (a) and implementation (b) of the multi-body-model.

3.2. Validation of the multi-body-dynamic process model

To validate the multi-body-dynamic model, measurements of the wire tensile force were performed on a table-winding machine TW 2 from the company Aumann GmbH which can be seen in Fig. 5a.

A comparison of the measured and simulated wire tensile force at 5 rev/s is shown in Fig. 6.

From the graph characteristics a statement about the model accuracy can be derived by comparing the relative error of the mean, the maximum and the minimum value. As displayed in Fig. 6 the relative error of the mean wire tensile force of the measurement is consistent with the simulation which is an evidence for the general validity of the deformation model. But, the high differences in the maximum and minimum value show that a more detailed analysis of the wire tension needs to be done. To gain

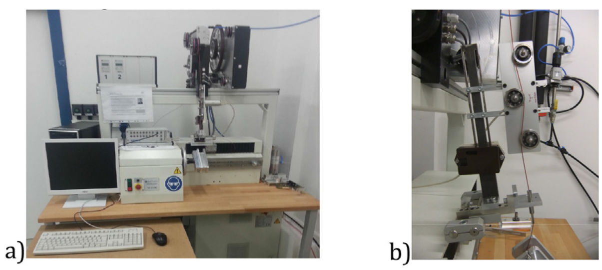


Fig. 5. Table-winding machine (Aumann GmbH) (a) and wire tensile force measurement system (b).

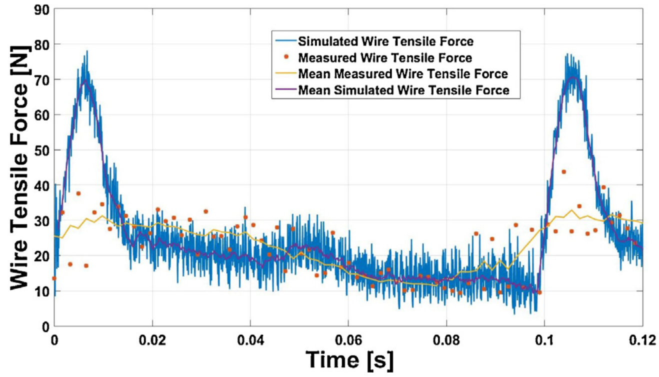


Fig. 6. Comparison of the measured and the simulated wire tensile force at 5 rev/s for the bobbin in Fig. 1c.

a better understanding of it, an analytical process model of the wire tension needs to be developed.

4. Analytical model of the wire tension

The main sources of the wire tension are the wire acceleration which is caused by the free wire length and the system inertia, the wire bending and the bearing friction (Fig. 7). In order to develop an analytical wire tension model these parameters will be characterized in the following sections.

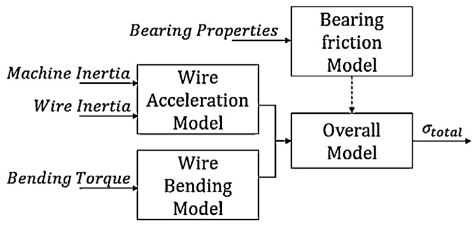
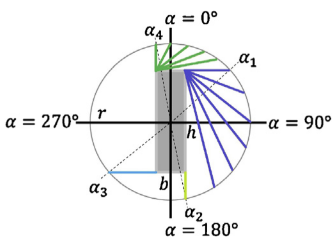


Fig. 7. Elements of the analytical wire tension model.

4.1. Analytical model of the wire acceleration

In order to characterize the correlation between wire acceleration and wire tension the free wire length between the coil bobbin and the wire guide needs to be determined.

The free wire length has already been described qualitatively in [9]. A mathematical description of the angle α which is the basis to describe the free wire length is given in Fig. 8.



$$\alpha_1 = \arccos\left(\frac{h}{2r}\right)$$

$$\alpha_2 = \pi - \arctan\left(\frac{b}{2r}\right)$$

$$\alpha_3 = \pi + \arccos\left(\frac{h}{2r}\right)$$

$$\alpha_4 = 2\pi - \arctan\left(\frac{b}{2r}\right)$$

Fig. 8. Free wire length for non-circular coil bobbins.

In Fig. 8 the variable r describes the distance between the wire guide and the rotation axis of the coil bobbin. Based on the symmetry of rotation the free wire length can be described with two characteristic lengths L_1 (marked green) and L_2 (marked blue). These lengths can be defined with Eq. (1) and (2).

$$L_1(\alpha) = \sqrt{\left(r \cdot \sin\alpha + \frac{b}{2}\right)^2 + \left(r \cdot \sin\alpha - \frac{b}{2}\right)^2} \tag{1}$$

$$L_2(\alpha) = \sqrt{\left(\frac{h}{2} - r \cdot \sin(90° - \alpha)\right)^2 + \left(r \cdot \cos(90° - \alpha) - \frac{b}{2}\right)^2} \tag{2}$$

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