Operating Characteristics of Actively Damped Motor Spindles

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Abstract

This paper discusses operating dependencies of permanent magnet motor spindles for milling applications with a stator-integrated actuator system. An active electromagnetic actuator system is able to reduce chatter vibrations by applying radial forces, oriented contrary to the deflection of the shaft. The described actuator system is integrated into the stator slots of a standard stator core. Next, the electromagnetic coupling of the actuator winding and the usual motor winding is described. Furthermore, possible rotor-position and operation-depending forces are derived.

1 INTRODUCTION

As is well known, chatter vibrations limit the tool life and especially the milling tool performance. As a result, the motor spindle cannot utilize its full power. This leads to a lower performance than the theoretical limit and therefore to a lower productivity. Chatter vibrations strongly depend on the rigidity of the individual components of the machining center. However, the eigenfrequencies of the machining center components are not known, as they are not delivered to the customer and may vary in the assembled machining center [1, 2]. Furthermore, the affinity to chatter vibrations is influenced by the dimensions of the milling tool and the geometry of the workpiece. A prediction of the occurrence of chatter frequencies during the milling process is therefore a challenging task. The current strategy to avoid chatter vibrations is the manual tuning of process parameters, like the spindle speed or cutting depth. An unstable operating point in the stability lobe diagram is then iteratively modified until a stable operating point is reached.

Additional damping systems mounted near the workpiece [3], on the outside of the spindle [4] or inside the spindle [5,6] aim to reduce chatter vibrations independent from their source. Such systems can have either an active or a passive principle of function. Based on previous research [5,7,8], a novel integrated actuator system (see *Fig. 1*) was analyzed in [6]. It is also the object of research in this paper. This actuator system works similar to an active magnetic bearing, which is integrated into the stator core. Previous researches [5,7,8] started with a dedicated element and an axially split stator and rotor core. After a successful analysis of the first approach, the damping actuator is integrated into the stator slots as an individual second winding system, similar to a double layered winding of a conventional electrical machine. A major advantage over the prior solution is the highly flexible manufacturing in terms of required damping force.

The integrated actuator winding system shows a position dependency of the resulting radial forces due to the main field of the motor winding and its saturation in combined operation. Those position dependencies are the subject of this paper and will be discussed next. The design calculations are made by using a Finite Element model.

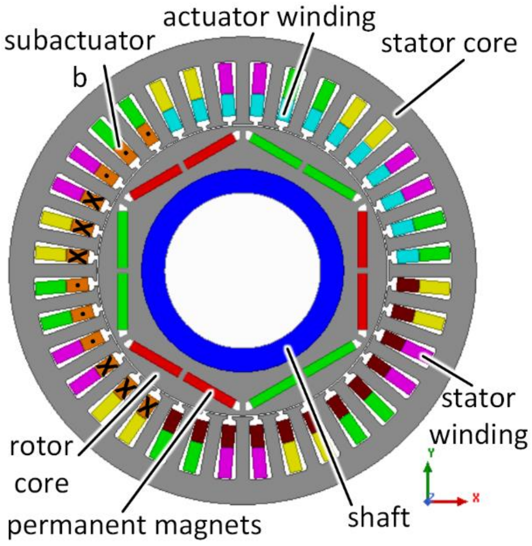

Fig 1: Six-pole permanent magnet synchronous machine with stator-integrated actuator system.

2 POSITION DEPENDENCY IN LINEAR IRON

As described in [6], the motor and the actuator winding have decoupled harmonic spectra. However, both windings influence each other through their shared magnetic path. For the sake of simplicity, only the influence of the motor winding on the actuator winding is analyzed. For the first part of the analysis, a simplified model with linear materials, a relative permeability of $\mu_r = 2000$, and a rotor without permanent magnets is used (see *Fig. 2*).

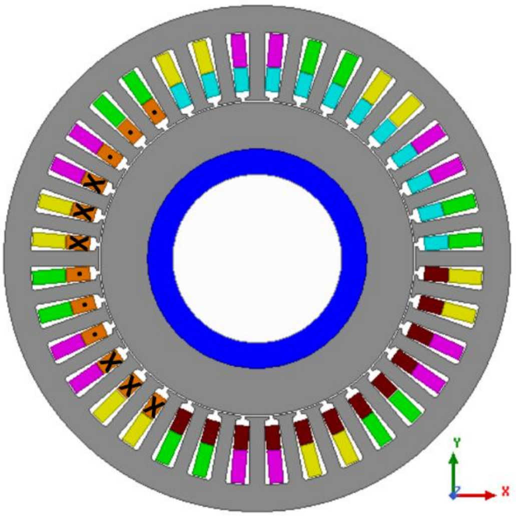

Fig 2: Simplified model of Fig. 1 with linear materials.

Subactuator b is fed with a direct current of $I_{\mathrm{DC}} = 22\ \mathrm{A}$. The current in the motor winding is a symmetrical, sinusoidal three-phase system of initially $I_1 = 1\ \mathrm{A}$ and is increased to about $I_1 = 50\ \mathrm{A}$ in eight steps. The least value corresponds to the rated current of the prototype from [6]. The resulting radial force in x-direction over one third of a rotor revolution is shown in *Fig. 3*. Due to the linear material parameters, the force is purely sinusoidal.

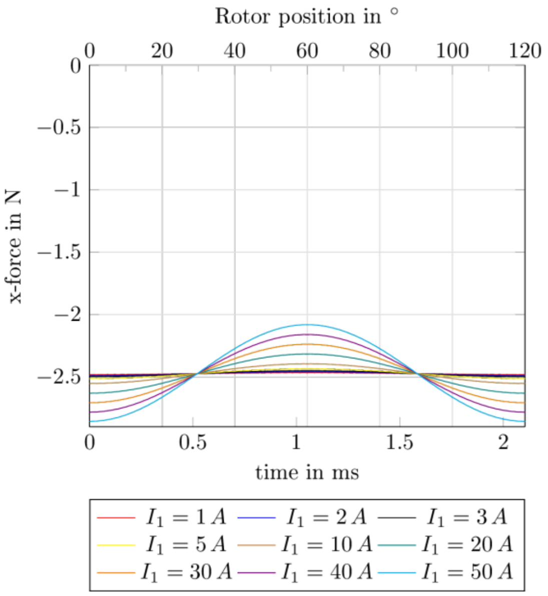

Fig 3: Force in x-direction using linear materials and a direct current of $I_{DC} = 22\ A$ in subactuator b.

The resulting y-force is lagging by 90 electrical degrees in relation to the force in x-direction and is also sinusoidal. *Fig. 4* shows the x- and y-forces in a combined diagram. The colour scale is identical to *Fig. 3*. The orientation of the main field of the simplified model at zero degrees matches the orientation of the magnetic field from the permanent magnets in *Fig. 1*.

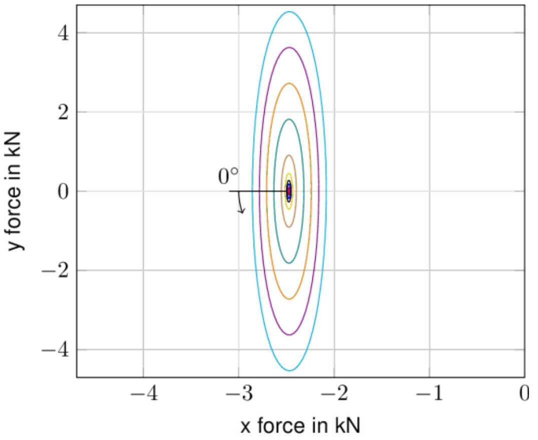

Fig 4: Resulting force direction and magnitude over one third of a rotor revolution, linear materials considered.

The force in x-direction stays negative over the examined third of a revolution. However, it is modulated by the varying poles of the main field beneath subactuator b. The y-force alternates between a positive and a negative maximum. They occur periodically and the first maximum is reached, when the rotor turns 90 electrical degrees in counter clockwise direction from the position in *Fig. 1*. The rotor positions associated with the maximum negative x-force, minimum negative x-force and maximum negative or positive y-force, according to *Fig. 4*, are shown in *Fig. 5 to 7*.

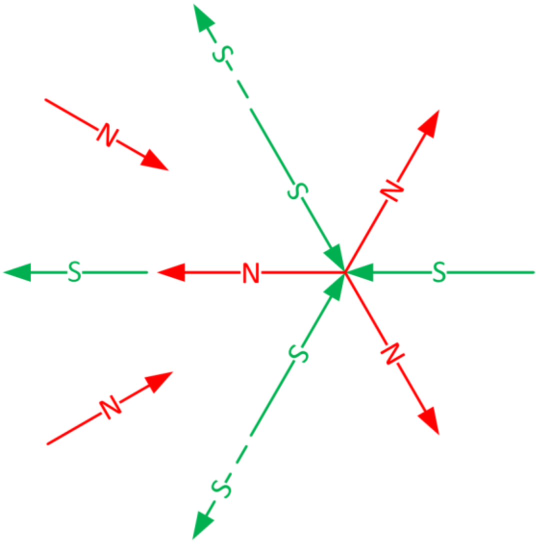

Fig 5:Rotor position with minimum negative x-force, according to Fig. 4.

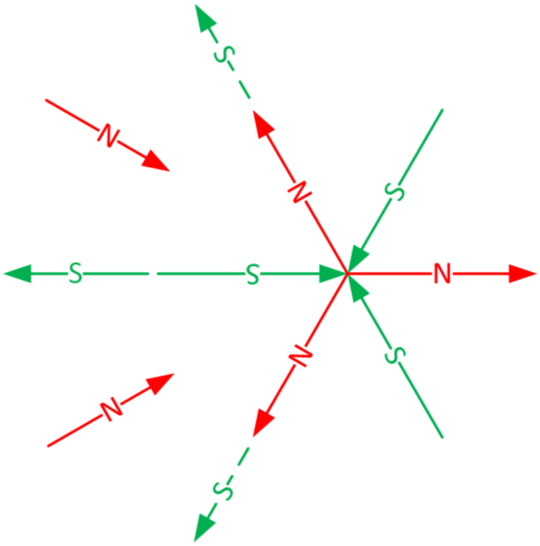

Fig 6: Rotor position with maximum negative x-force, according to Fig. 4.

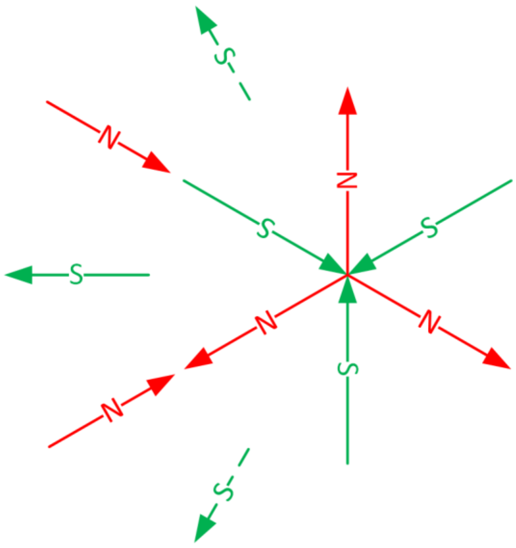

Fig 7: Rotor position with maximum y-force, according to Fig. 4.

3 POSITION DEPENDENCY IN NON-LINEAR IRON

The previously described position dependency of the actuator system, caused by shared magnetic paths of motor flux and actuator flux, is now extended by the consideration of non-linear materials. By reasons of mechanical stability and eddy current losses, M235-35A is chosen as a sample material for the stator as well as for the rotor core. The geometry is identical to *Fig. 2*. *Fig. 8* shows the resulting forces in x-direction, when subactuator b is fed with a direct current of $I_{\mathrm{DC}} = 22\ \mathrm{A}$ and the current in the motor winding is increased to $I_1 = 50\ \mathrm{A}$ in nine steps.

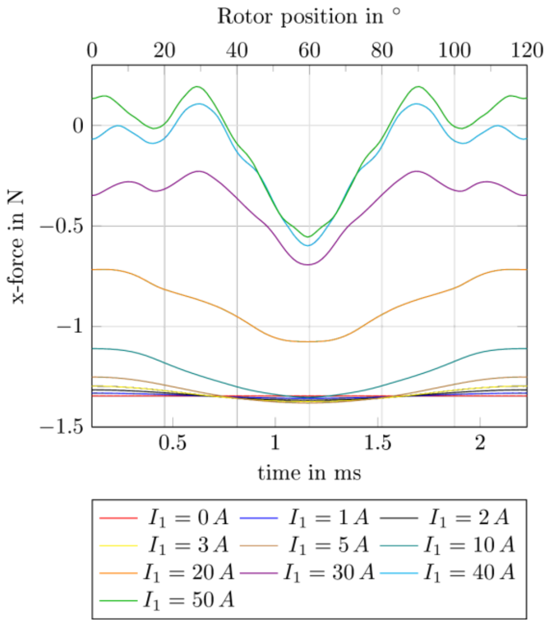

Fig 8: Force in x-direction, non-linear core material considered.

It can be observed that the graphs for $I_1 = 10\ \mathrm{A}$ and above are showing the influence of saturation on the shape and the average resulting force. According to [9], increasing saturation reduces the relative permeability μ_{r} and therefore the resulting force. The force can be calculated with the use of the surface force density

$$\vec{\sigma} = \frac{B_n^2}{2}\left(\frac{1}{\mu_0} - \frac{1}{\mu_0 \cdot \mu_{r,\mathrm{Fe}}}\right). \tag{1}$$

In comparison to *Fig. 3*, the force in x-direction at the initial position is reduced with increasing stator current instead of increased. This leads to more complex assumptions for the control of the actuator system, as it acts completely different than in the linear case and is further influenced by local saturation effects.

In a combined plot of x- and y-forces with non-linear materials as seen in *Fig. 9*, the saturation is noticeable even at an earlier stage. Whereas the graphs in *Fig. 1* are elliptical and concentric, the center of the graphs in *Fig. 9* is displaced for a stator current of $I_1 = 5\ \mathrm{A}$. Furthermore, the shape of the graphs is distorted for $I_1 = 10\ \mathrm{A}$ and higher. Stator currents of $I_1 = 40\ \mathrm{A}$ and above are showing even positive forces in x-direction, i.e. the actuator is able to push the rotor away, due to local saturation.

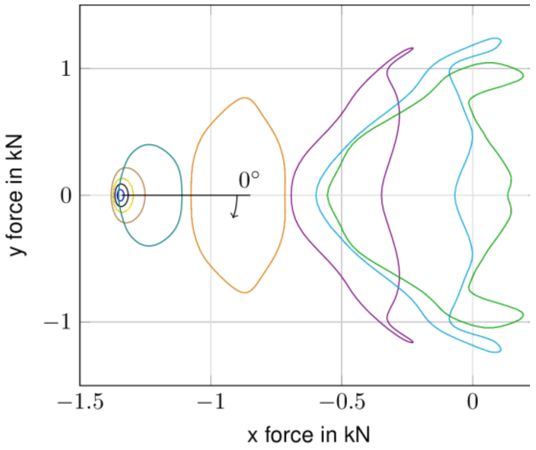

Fig 9: Resulting force direction and magnitude over one third of a rotor revolution, non-linear core material considered.

4 CONCLUSION

Electromagnetic damping of chatter vibrations is favourable to increase tool lifetime and prevent unexpected tool breakdown. The presented approach of a fully integrated damping system has the advantage of being highly flexible in terms of manufacturing, as it mostly uses standard components. However, this method faces challenges in the full load operation with desired active damping. In this scenario, the resulting damping force is reduced and distorted due to the pre-saturated magnetic path. A possible use case is the milling of deep cavities, using long and thin tools, as these processes are low-load scenarios for the electrical machine. The damping system and the stator core can be designed to the required task, in order to lose only a small amount of rated power.

5 ACKNOWLEDGMENT

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