Optimization of a High Force Tubular Linear Drive Concept with Discrete Wound Coils to Fulfill Safety Standards in Industrial Applications

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Abstract— **This paper deals with the next step of development of a tubular permanent magnet linear drive concept for industrial applications up to 3000N thrust force where low cogging forces are required to fulfill safety standards. The presented linear drive concept is designed for easy production and assembly of a few hundred units per year. It can be manufactured on standard production machines because all ferromagnetic parts are made of standard not-laminated steel. This results in a very economic product. Further more the drive concept includes an internal low cost position sensor based on the hall-effect. The different steps of development are proven by measurements of thrust and cogging forces of different prototypes.**

Keywords—**linear machine, permanent-magnet machine, linear synchronous machine, electric drive**

I. Motivation

Linear electromagnetic machines become more and more important for industrial applications because in some cases they have numerous advantages compared to rotating counterparts. They are providing high thrust force directly to the load without the need of mechanical gears. This results in a high efficiency, a high dynamic performance and a more simple construction of the system. Cogging forces are an essential disadvantage of a permanent magnet linear drive. There origin is the interaction between the permanent magnets of the armature and the iron of the stator. Not only high thrust forces but also low cogging forces of the linear drive are important for industrial applications. For example squeezing machines or moulding presses are spring-loaded systems to achieve certain industrial safety standards. The needed force prior the plunger processes of the workpiece is equivalent to a progressive load deflection curve. In case of emergency safety standards (e.g DIN EN 692) have to be aware. The plunger has to move out of the safety section in a specific time even in the case of blackouts. This leads to standards of low cogging forces.

The focus of this paper deals with the optimization of cogging forces of this linear drive concept. The speciality of this motor is the stator which is not slotted in the conventional way and build with discrete coils mounted on poles in radial direction. Every ferromagnetic part is made out of steel without any laminations. Low priced steel components are used to manufacture the linear drive on standard production machines (e.g. turning lathe). The simple manufacture and an easy assembly due to an economic production. The research and development of this linear drive concept is done by cooperation of one university and two companies.

II. Design of the Linear Drive Concept

This particular tubular linear drive concept consists of three main parts, a stator which is build with discrete coils mounted on poles in radial direction, a permanent magnet armature and an internal position sensor based on the hall-effect. Figure 1 presents a simplification of the real design. It shows one half of a sectional drawing of one basic segment of the linear actuator. The rotation axis is at the lower edge of the drawing.

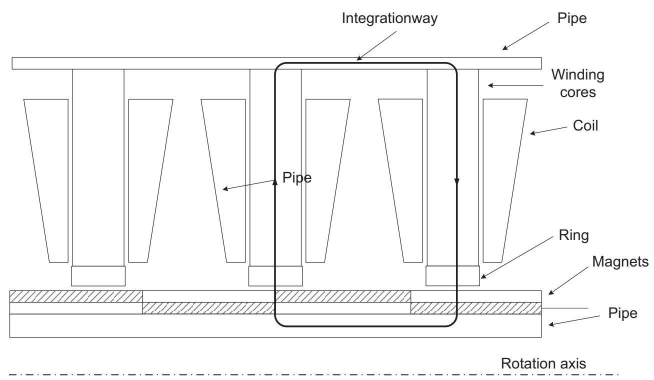

Fig. 1. Sectional drawing of the linear machine.

The stator comprises a pipe and three stars (one for every phase). Each star is composed of eight winding cores and a ring in the center. For a better use of the winding area the star of the second phase is shifted 22.5 degrees concerning the position of the stars of the first and third phase (figure 2). The arrangement of eight discrete coils per phase offers the possibility of four operating voltages which can be implemented by different types of wiring. The following connections are available: all stator windings can be connected in series or parallel or just four times two windings parallel or two times four windings parallel.

The corresponding armature consists of a steel pipe and four magnets mounted on the surface. For this particular design the radial magnetization was chosen to minimize the magnetic flux distance outside of the ferromagnetic material. Only the small airgap and the magnet height must be bridged by the magnet flux as shown in figure 1. This results improve efficiency. In addition the cogging forces can be reduced by eliminating the flux density, which concentrates at the magnet edges caused by the radial flux. The segments may be arranged in axial direction in any desired manner, which results in modularity of the actuation stroke and/or actuating force.

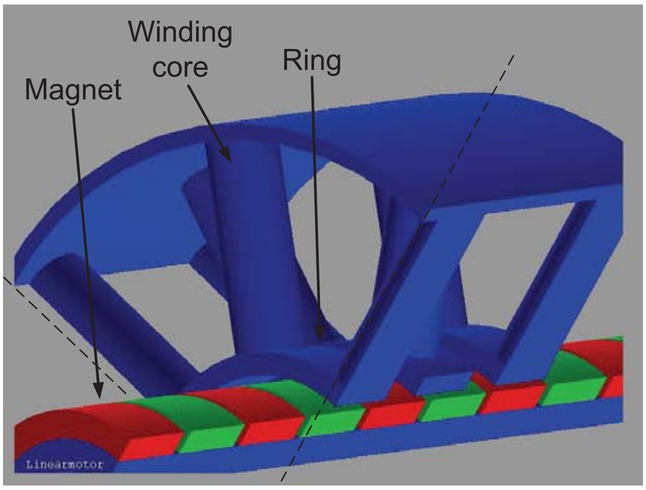

Fig. 2. Configuration of the shifted winding cores.

In one main application field this linear drive is not used for precise positioning. The requirements are to regulate pressure, flow or force of an industrial process, for example in squeezing machines. In theses special applications the force is the highest ranking closed-loop control and the position is only needed for lower control loops. A linear positioning sensor is required because it is difficult to control this type of drive sensorless. The permanent magnets on the armature provide a sinusoidal field in a certain distance outside the winding area which can be used to measure the position, already shown in [3],[4]. Figure 3 shows the place where the small positioning sensor is mounted in the machine. The sinusoidal field can be detected by placing the sensor in an optimal distance of the magnets.

III. Economic manufacture of the Linear Drive

Three more prototypes (like in paper [6] presented) are built based on the research results in high thrust forces. The basic segments can be manufactured on standard production machines because all field carrying parts can be made of steel without any laminations. Inexpensive standard production machines will also be used for the future series production of some hundred machines per year. Every ferromagnetic part of the linear drive like the pipe of the stator or the armature or the winding cores and rings of the stars can be made of standard steel components. This design is ideally suited for implementing a modular system because most of the components can be used identically in all embodiments and this yields to high potential savings.
The prototypes vary in the number of basic segments. Three

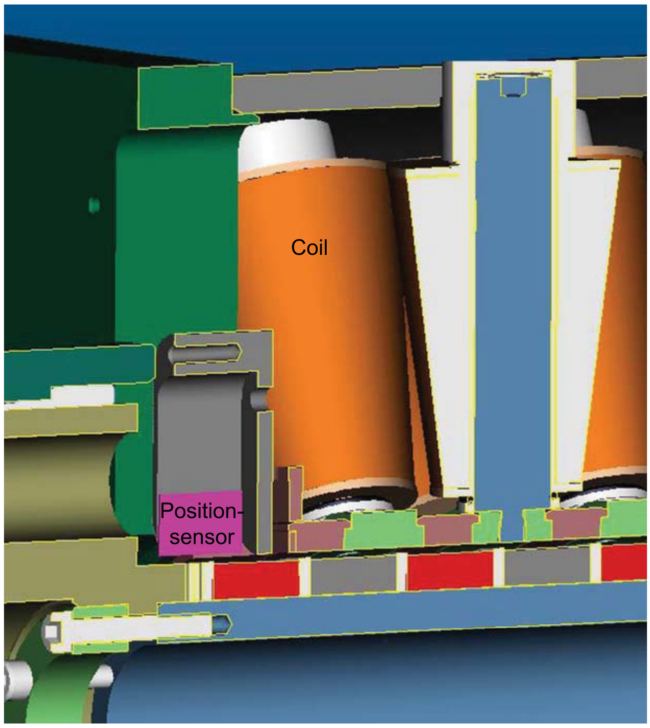

Fig. 3. Placing of the internal positioning sensor.

machines with maximum rated forces of 1600N (2 segments), 2400N (3 segments) and 3200N (4 segments) are built for testing the linear drive concept concerning the production (tolerances), the easy assembly and the operating in different industrial applications. One of them is shown in figure 4.

Fig. 4. Prototype with four basic segments

One basic segment of the stator consists of three stars, each of them equipped with eight discrete coils connected in parallel. Discrete coils are easy to manufacture. The stator is shown in figure 5.
Furthermore the amount of copper of the concentrated windings is smaller than the needed copper in known tubular linear motors, which results in an additional cost reduction. Figure 6 shows the winding area.
The armature of the machine is assembled of one steel pipe which is supported by two bearings outside at both ends of the pipe. These linear bearings in the two pipes at the left and right

Fig. 5. Stator of the build prototype

Fig. 6. Stars with discrete wound conical coils

end of the stator (figure 4) allows axial movements. To achieve a high force density NdFeB, a rare-earth magnet material, is used for the magnets. This material has the advantages of a high coercive field strength and a low recoil permeability.[8] For the design of the linear drive concept ring-shape magnets are used with radial magnetization. The ring-shape magnets can easily mounted on the surface of the pipe and fixed at both ends. On the one hand, in comparison to plate-shape magnets which also can be used, ring-shape magnets have the advantage of simple assembly. They can be attached to the magnetic carrier pipe without the usage of any adhesive. On the other hand plate-shaped magnets have the advantage of being inexpensive. But the advantage of simple assembly outbalances and leads to further cost reduction.

An other low priced part of the linear drive concept is the small positioning sensor. It can be designed by two low-cost hall sensor elements, some surface mounted devices and a small pcb. In comparison of an expensive standard linear sensor the internal one does not need any extra space outside the drive [3],[4]. The sensor has an accuracy of 200μm to 500μm which is lower than the accuracy of conventional linear sensors (accuracies from 50μm up to 10μm) but it is absolute sufficient for the position measurement in the lower control loop.

IV. Measurements

The achieved force of the built prototype shown in figure 4 with four basic segments is presented in figure 7. The red line shows the force produced by the machine at rated current. The force is not constantly distributed throughout the moving range of the armature and varies from 3000 to 3450 N. This band is a result of the proportion between the rings and the magnets of the linear drive. It has to be minimized by optimizing the geometry in future developments. For the testing environment a constant thrust force throughout the actuating stroke is not required. For example in squeezing machines the maximum force has to be reached at one point of the stroke, where the plunger processes the workpiece. The needed load before squeezing is equivalent to a progressive load deflection curve.

The green line shows the results of a simplified 2D-simulation of the built construction. The simulated thrust force is 7 percent (average) higher than the measured force. This follows from the simplified simulation geometry which equates to the half sectional drawing of one basic segment in figure 1. Winding cores and coils can not be modeled as concentrated parts in a 2D-simulation of a tubular drive. The measured lower forces results from additional scattering losses in the concentrated windings.

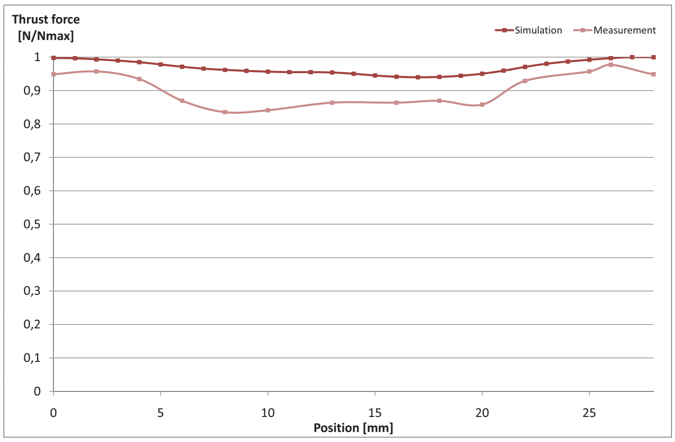

Fig. 7. Active force of the constructed linear drive in comparison to the simulation

Not only the thrust force but also the cogging forces of linear drives are important for industrial applications. It is necessary to be conform with safety norms. In case of a moulding press, safety standards (e.g DIN EN 692) have to be aware which leads to standards of low cogging forces. The cogging forces over the actuating stroke of the prototype (four basic segments) are shown in figure 8. The measured force, plotted in blue, is pulsating with the effective length of the magnets and is changing the polarity within each magnet. The maximum amplitude is approx 350 N which is 10% of a rated value. The red line shows the simulated cogging forces which matches the characteristics of the real measurements.

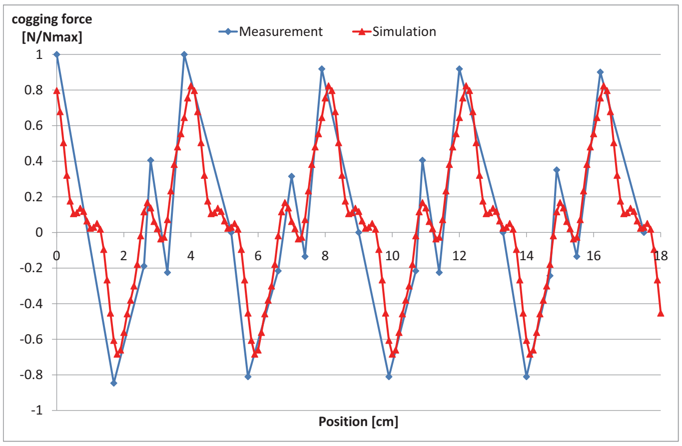

Fig. 8. Cogging forces of the constructed linear drive in comparison to the simulation

The chart in figure 9 presents the measured maximum cogging force of all built versions of the linear drive concept in comparison to the simulation. The maximum cogging force is plotted over the width of the ring. The measured and simulated values of the here presented prototypes are shown at the right edge of the chart.

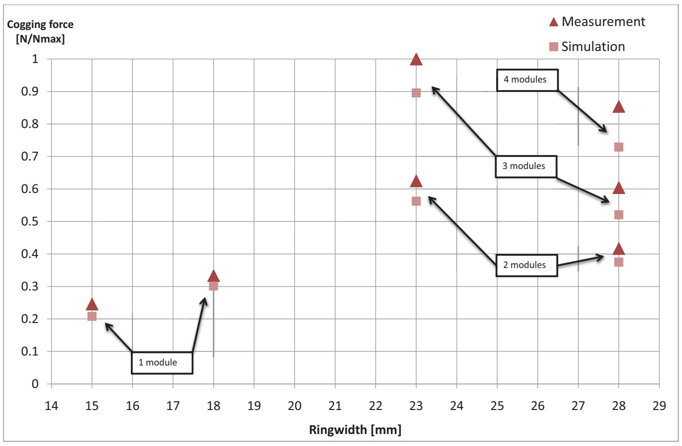

Fig. 9. Maximum cogging forces of all constructed versions of the linear drive in comparison to the simulation

Because of the high cogging forces it is not possible tu use the linear drive in an other field of application, where special safety standards have to be fulfilled. They have to be minimized in the next development step to test the machine in theses applications.

V. Optimization of the Cogging Forces

The origin of the cogging force is the interaction between the permanent magnets of the armature and the rings of the stator. It can be calculated (1) by the change of the magnetic Co-Energie in the airgap.

$$F_c(x) = -\frac{1}{2}\Phi^2\frac{\partial R}{\partial x} \qquad (1)$$

According to this equation all approaches of the reduction of cogging forces can be summarized as follows:

- Variation of the magnetic remanence
- Constant magnetic reluctance in the airgap
- Optimal arrangement between slots and permanent magnets

The calculation of an optimal arrangement between the rings and the permanent magnets is chosen to find a minimum of the cogging forces. In comparison to the other possibilities, this adaption is the low priced option concerning material, manufacturing and assembly of the machine. The cogging forces can be calculated on the analytical way under consideration of the magnetic path, the equivalent network, the induction in the airgap and the Co-Energie. Furthermore a detailed model of the linear drive is built in a 3D-simulation environment for the optimization of the cogging forces. Figure 10 shows the miscoloured picture of a part of the model. These simulations conduce to the illustration of the magnetic flux between the stator and armature to get more detailed information about the generation of force in the airgap. They also attend to ensure the analytical calculations.

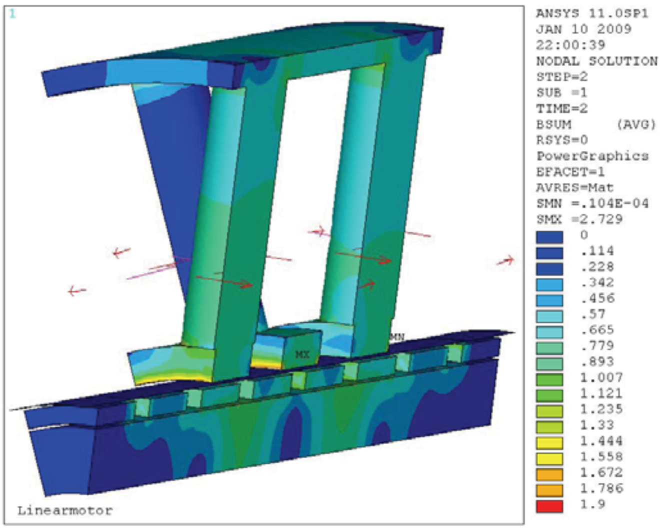

Fig. 10. Miscoloured picture of a part of the 3D-Model

The simulation results shown in figure 11 and 12 reference only on the variation of the geometric parameter thickness and width of the ring. The geometric parameters of the magnets (hight and width) are already defined because of the required thrust force. The charts presents the simulated positiv and negativ maximum cogging forces of two, three and four basic segments of the linear drive concept versus the particular parameter. Figure 11 shows the variation of the ring thickness. The characteristics of the curves indicate that the cogging forces are independent from the thickness in a range of 5 to 15 mm. The actual thickness of the ring is 10 mm. It was also defined by the dimensioning of the thrust force.

The variation of the ring width is displayed in figure 12. The actual width of the rings is 28 mm and labeled in the chart. The measured maximum cogging forces of the three different prototypes are already presented in figure 9. The curve of the simulated values of all three machines show a common local mini-

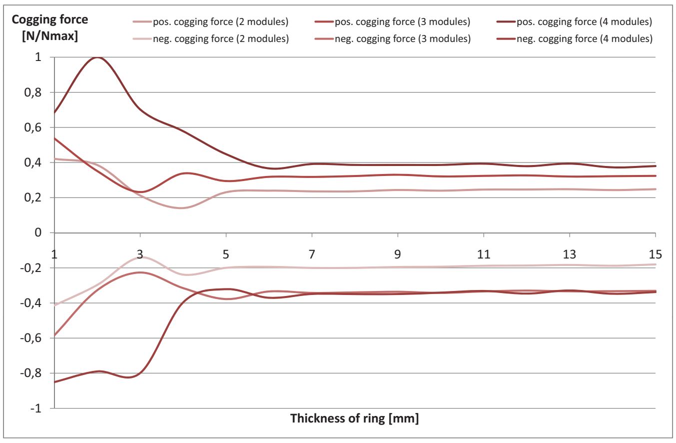

Fig. 11. Simulation results of the cogging forces by variation the ring thickness

mum of the cogging forces at the width of 32 mm. The cogging forces can be reduced approximately down to 50% of the actual measured values. The characteristics of the curves indicate that the amplitude of the cogging forces depends no longer on the construction inside the linear drive. In fact a cogging force occurs whenever a magnet moves in or out of the stator area.

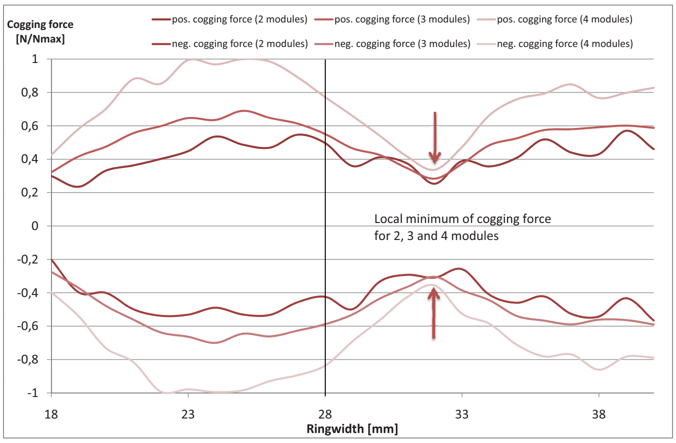

Fig. 12. Simulation results of the cogging forces by variation the ring width

VI. Conclusion

The presented linear drive concept offers an innovative design which results in an cost efficient production of some hundred units per year on standard production machines. The properties with regard to the modularity of the actuating stroke and actuating force are described. Up to now thrust forces up to 800N per segment are possible. Not only the thrust force but also the cogging forces of the linear drive are important. In industrial applications certain safety standards have to be observed which leads to standards of low cogging forces. The measured maximum cogging forces are approximately up to ten percent of the thrust force. It has to be halved in order to fulfill the standards. This optimization is presented in the paper. The previous development is proven by the demonstration of a prototype with measurements of thrust and cogging forces. The actual research work is focused on the optimization of thrust force by increasing the force per segment up to 1600N, proving the encountered minimum of cogging forces and preparing the motor for serial production.

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