Experimental validation of a distribution theory based analysis of the effect of manufacturing tolerances on permanent magnet synchronous machines

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An experimental study on the effect of permanent magnet tolerances on the performances of a Tubular Linear Ferrite Motor is presented in this paper. The performances that have been investigated are: cogging force, end effect cogging force and generated thrust. It is demonstrated that: 1) the statistical variability of the magnets introduces harmonics in the spectrum of the cogging force; 2) the value of the end effect cogging force is directly linked to the values of then remanence field of the external magnets placed on the slider; 3) the generated thrust and its statistical distribution depend on the remanence field of the magnets placed on the translator. © *2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).* [http://dx.doi.org/10.1063/1.4975994]

I. INTRODUCTION

Workmanship and materials tolerances are often neglected in the design of electric machines but on the contrary, actual performance of electric machines are strongly influenced by the manufacturing process and material properties used in the assembly process. In each of the assembling steps deviations occur which are caused, for instance, by mistakes in positioning tools or by the tolerances in the electrical and magnetic characteristics of the materials. These deviations may generate undesired parasitic effects such as torque ripple, losses or acoustic noise. In order to improve the design of electric machines, these effects have to be considered especially in machines used in industrial drives for high performance applications. An especially key point is the fact that tolerances in magnetic materials have a remarkable effect on cogging torque value.[1–3] Many previous papers studied the effects that these tolerances have on the rotating permanent-magnet synchronous motors performances,[1,3–5] while this work focuses on the evaluation of these effects on the Tubular Linear Ferrite Motors (TLFM) performances for two reasons: 1) the effects of tolerances are considerably strong on linear machines as their asymmetrical geometry doesn't allow a cyclic behavior: 2) linear machines tend to have many magnetic poles and therefore they are a good experimental system for exploring the effect of tolerances on the characteristics of magnets.

The machines parameters that have been considered in this paper are:

- cogging force;
- end effect cogging force;
- generated thrust.

The study consists preliminary in an experimental analysis of the magnitude of the remanence flux-density (B_r) of a sample of 100 commercial magnets and successively on the simulation of the performances of several motors built with various subsets of the examined magnets. In order to make a comparison between the magnets of the considered sample, for each magnet the axial magnetic induction field was measured in 10 different points, placed along the axis of the magnet. The measured values were used to estimate the remanence in each magnet, to make some simulations
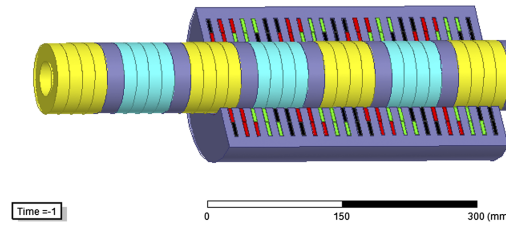
FIG. 1. Structure of the TLFM. The circle in red and blue are the magnets in Hallbach configurations placed on the translator. The areas in gray and yellow describe the stator. End effects are generated in areas a and c and cogging force is generated in area b.

useful in assessing the impact of the deviations on the performance of the TLFM as well as in evaluating how the choice of the magnets influences both its cogging force and the end effect force as well as the generated thrust.

The paper is divided in 5 sections: the first section contains the introduction, in the second section the considered TLFM is presented, in the third section the experimental tests on the magnets are discussed and in Section IV the results of the simulations are given and finally in Section V conclusions are drawn.

II. THE MACHINE OF REFERENCE

The studied motor is a three-phase machine with short stator and 24 slots. The stator winding is made up of 48 concentric cylindrical coils, located inside the 24 slots (2 concentric coils for each slot). The considered stator winding is a pitch reduced of 5/6 one that determines two pair pole.

The translator is made of 36 ring shaped magnets in Hallbach configuration divided by rings of ferromagnetic material mounted on an aluminium support (see Fig. 1).[2]

The geometrical characteristics of the Ferrite magnets are: outer diameter 80 mm; inner diameter 40 mm; height: 15 mm; The direction of magnetization is axial (parallel to the height).

III. TESTS ON THE MAGNETS

The commercial magnets are affected by constructive differences that determine possible deviations in the magnitude of the remanence flux-density B_r and in the angle of the direction of magnetization. These deviations can influence significantly the cogging force value of the electrical machines under design because the actual induction field generated by the magnets is directly linked to the remanence field. In particular, the variation of B_r has the most important effect.[6]

The datasheet of commercial magnets usually provides the values of magnitude of the remanence flux-density B_r within a certain interval. In order to determine the influence that the manufacturing tolerances have on the TLFM performances a sample of 100 commercial magnets has been considered.

FIG. 2. Measurement bench. The Hall effect probe, the plastic rings as well as a ferrite magnet are on the left. The measuring system is shown on the right. The measurement equipment is placed inside a semi anechoic room. The system is able to measure magnetic induction field.
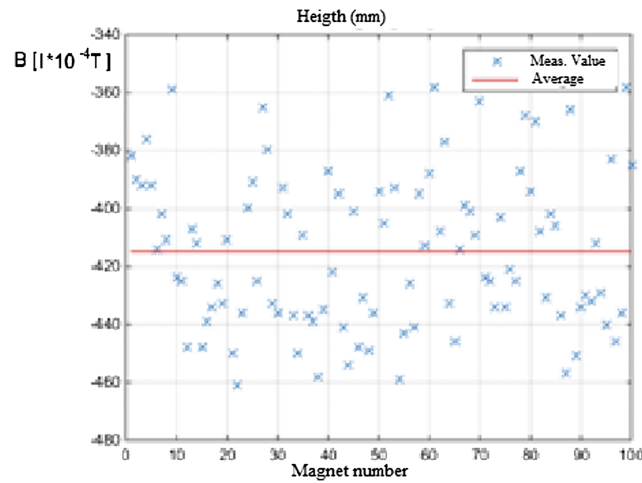
FIG. 3. Flux density in the centre of the magnetic ring.

The magnets have been tested on a test bench purposely designed and set up.

In order to make a comparison between the magnets of the considered sample and under the assumption that the induction field externally measured can be related to the remanence of the magnet, the axial magnetic induction field for each magnet, was mapped in 10 different points, placed along the axis of the magnet. In particular the height, expressed in mm, chosen for the execution of measures were: -15, -10, -5, 0, 5, 10, 15, 20, 25 and 30 (see Fig. 2). To ensure the measurement repeatability a plastic support for positioning both the magnet and the probe of the measuring instrument, in such a way that their mutual position was the same for each of various heights, has been built (see Fig. 2).

The induction field measures were performed by using a magnetic meter (model GM08 - Hirst Magnetics) with an axial Hall probe inside an electromagnetic semi-anechoic chamber.

As an example, the Fig. 3 and Fig. 4 show the values of the axial magnetic induction field measured on the axis of the magnets and the corresponding average value, at two different heights (0 mm and 15 mm).

Finally, Fig. 5 shows the distribution of the values of the flux density at a height of 25 mm. The average value is 0.01T with a relative variance of 20% and the values are distributed in a range between 0.008 and 0.0125 T. Fig. 5 shows that the actual value of the field can vary significantly.
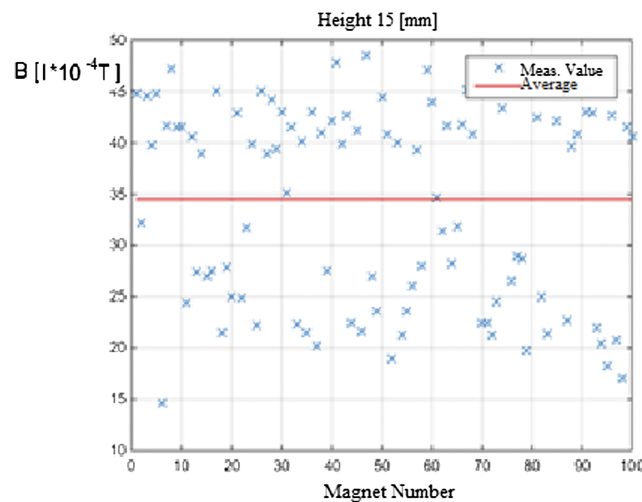

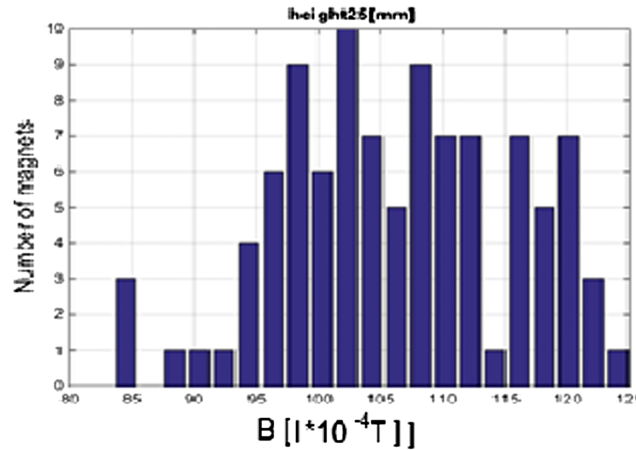FIG. 4. Flux density on the axis of magnetic ring at an height of 15mm.

FIG. 5. The distribution of the values of the flux density at a height of 25 mm.

IV. SIMULATIONS

The measured distribution of the characteristics of the magnets were used to make some simulations aimed to assess the impact of the statistical deviations on the performance of the reference machine.

The study of the characteristics of the machine was made via precise numeric field computations. For this purpose, the ANSYS-Maxwell software was used; Maxwell uses the accurate finite element method to solve static, frequency-domain, and time-varying electromagnetic and electric fields.

Preliminarily, several mathematical models of an isolate ring shaped magnet have been identified by using the distribution shown in fig. 5. Different values of B_r have been considered with the aim of identify the B_r value which, set in the simulation software, simulates with better approximation the behavior of each single magnet. The used B_r values vary from 0.48 T to 0.35 T, with a step of 25 mT.

On the basis of these evaluations, in order to assess the impact of the deviations on the performance of the references machine, three different simulations of the machine have been done:

- in the first one a reference motor made of identical magnets having B_r =0.4 T (this simulation has been used as a template for the evaluation of the tolerances effects). This case is named "identical magnets";
- in the second one the motor was made of 36 magnets having the highest BR value among 100 commercial magnets. This case is named "best magnets";
- in the last simulation the motor was made of 36 magnets randomly chosen. This case is named "random magnets".

The generated force and thrust was calculated by using Maxwell stress tensor technique.

The simulations showed that the magnets manufacturing tolerances have a significant effect on all the performances of the magnets. More particularly we examined the following performances:

- cogging force;
- end effect cogging force;
- generated thrust.

A. Cogging force

In fig. 6 it is shown a comparison of the cogging force in the three reference cases that have been examined. The analysis has been done by computing by a FEM solver the force between the stator and the slider for the movement of the magnets placed on the slider from one stator tooth to the following one.
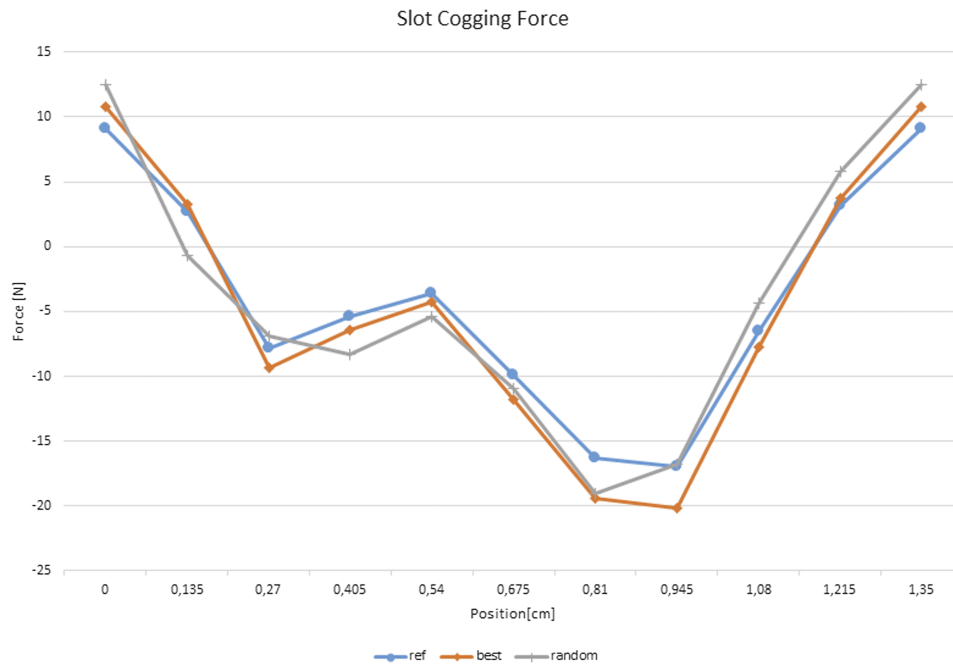
FIG. 6. A comparison of the cogging force in the three reference cases that have been examined. In the examined linear machine the distance between two poles is 1.4 cm, that is equivalent to half pole pitch. In a rotating machine this distance is equivalent to an angular distance equal to π.

It can be seen how the case of identical magnets and best magnets are quite similar. The case "best magnets" presents a slightly higher value of the cogging force. This fact shows how slot cogging force is related to the level of remanence: the higher the remanence, the higher the slot cogging force. On the contrary, the case "random magnets" present a behavior, which is qualitatively different from the previous ones and an harmonic analysis shows that in the case of random magnets new harmonics in the spectrum of the cogging force are generated. This is caused from the higher variability of the cogging force in this case in comparison with the two previous case which presents a higher uniformity.

B. End effect cogging force

In fig. 7 it is shown a comparison of the end effect cogging force in the three reference cases that have been examined. The analysis has been done by computing by a FEM solver the force between the stator and the slider for the movement of the magnets placed on the slider from a position completely external of the stator to a position completely internal.

It can be seen how the three cases can be ranked monotonically. The case "best magnets" presents a higher value of the end effect cogging force. On the contrary, the case "random magnets" presents a behavior, which is less intense than the previous ones. Also in this case the higher the remanence, the higher the end effect cogging force. However, in this case an harmonic analysis shows that no new harmonics in the spectrum of the end effect cogging force are generated. This is caused from the fact that end effect cogging force depends essentially on the average value of the Br of the external magnets that interacts with the stator.

C. Generated thrust

In order to compute the generated thrust the analysis has been done by computing by a FEM solver the average force between the stator and the slider for the movement of the magnets placed under the rated supply condition. The average value of the thrust was 400 N with a variance of 13%. The generated force and thrust were calculated by using Maxwell stress tensor technique.
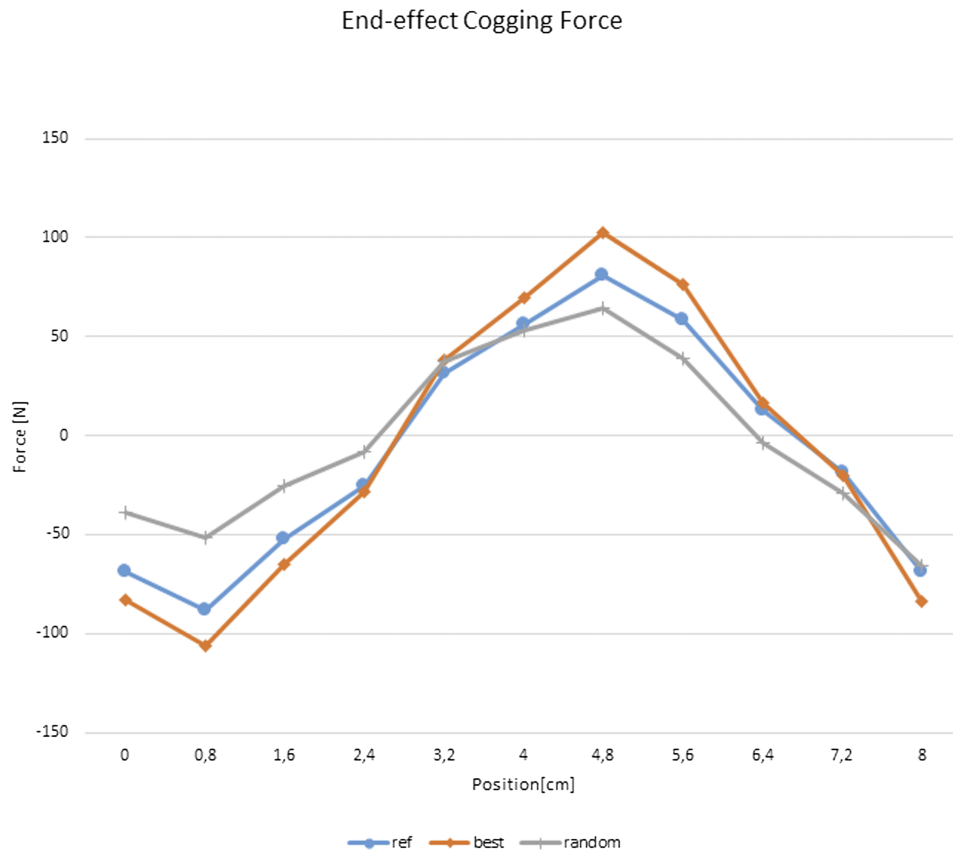
End-effect Cogging Force

FIG. 7. A comparison of the end effect cogging force in the three reference cases that have been examined. The maximum *x* here presented (8cm) is maximum distance that in the simulation the translator can travel out of the stator.

The case "best magnets" presents a higher value of the generated thrust and on the contrary, the case "random magnets" presents a behavior, which is less intense than the previous ones. The statistical distribution of the generated thrust was analogous to the one of the magnets with a variance slightly lower than that of the magnets as one can see in fig. 8. This is caused from the fact that the thrust depends essentially on the average value of the magnetic induction generated by the magnets that interacts with the stator current.
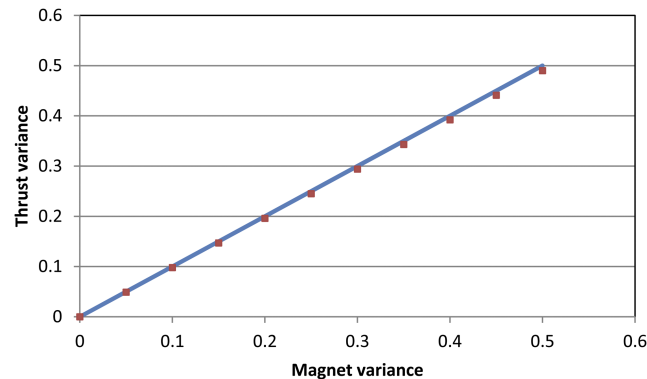

FIG. 8. A comparison between the variance of the distribution of the magnet and the variance of the distribution of the thrust. The continuous line represents a perfect concordance between the two variances, the squares are the calculated thrust variance for a given magnet variance. In the presented case, the thrust variance seems to be slightly lower than the variance of the distribution of the magnets.

V. CONCLUSIONS

This study presents an experimental study on the effect of permanent magnet tolerances on the performances of a TLFM. The performances that have been considered are: cogging force, end effect force and generated thrust. It has been shown that:

1) the statistical variability of the magnets introduces harmonics in the spectrum of the cogging force;
2) the value of the end effect cogging force is linked to the values of then remanence field of the external magnets placed on the slider but the harmonics generated by the end effect cogging force do not depend on the variability of the magnets;
3) the value of the generated thrust and its statistical distribution is directly linked to the values of then remanence field of the magnets placed on the slider.

ACKNOWLEDGMENTS

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