Optimisation of the Slot Dimensions of a Large Air-gap Linear Synchronous Motor

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Abstract: A COMSOL Multiphysics model is used to optimise the slot geometry of a large air-gap linear synchronous motor. Fixed dimensions are used for the pole pitch, stator depth, stator width and air-gap, since the amount of available space is usually limited. A parametric sweep of the slot-width-to-tooth-width ratio is used to find the optimum geometry where the maximum thrust force is produced whilst keeping the amount of heat produced by the windings constant. The maximum thrust force is found to occur when the slot-width-to-tooth-width ratio is between 1.4 and 2. To further refine which ratio is best, one needs to consider other factors such as the magnitude of the cogging force as the reaction plate moves along the stator.

Keywords: COMSOL Multiphysics, AD/DC Module, Geometry Optimisation, Linear Synchronous Motor

1. Introduction

The goal of this study is to use COMSOL as an optimisation tool to find the best slot geometry for a 10-pole/9-slot linear synchronous machine with a large air-gap given a fixed size constraint. The FEA model is created with a fixed stator length, pole pitch and slot depth and a mover consisting of surface-mounted magnets and a back-iron. Given these constraints, the aim is to find an optimum slot-width-to-tooth-width ratio to maximise the thrust force for the same amount of heat produced by the windings. Plots of the parametric sweeps show the optimum region and the trade-offs between the different design options. A constant relative permeability is specified for the stator core and the reaction plate back-iron to reduce the simulation time of the parametric sweeps. To check that there is no significant magnetic saturation occurring, the optimum case is simulated with the full, non-linear BH curve for the materials.

2. Governing Equations

Similar to a typical rotating electric motor, the two components of a linear machine are the primary windings and the secondary mover (reaction plate). As shown in Figure 1, in a permanent-magnet linear synchronous motor the reaction plate consists of an array of strong rare-earth magnets whereas the stator comprises coils of copper wire arranged within slots in a ferromagnetic core. Several stator sections are mounted end-to-end to form a long track.

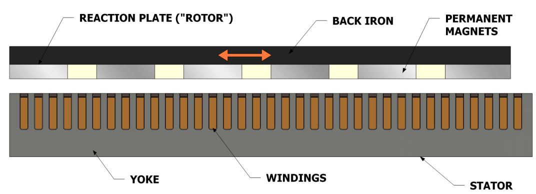

Figure 1. Linear synchronous motor components

The thrust force (F) produced by a permanent-magnet motor can be considered to be a function of three key quantities—the surface area of the air-gap formed between the mover and stator (A), the magnetic loading due to the permanent magnets (B) and the specific electrical loading due to the current flowing in the stator windings (Q). This relationship is expressed in Equation 1.

$$F = B\,Q\,A \qquad (1)$$

The design of a suitable motor for a particular application therefore broadly necessitates a trade-off between these three quantities. The magnetic loading is calculated as the root-mean-square (rms) of the magnetic flux density distribution produced by the magnets along the top of the stator coils (on the air-gap boundary). This assumes though that all of this magnet flux links with the windings. However, due to flux leakage within the coils (across the slots), the effective magnetic loading is slightly lower. Contrastingly, the specific electrical loading is a function of the current density in the coils, the volume of the windings per length of motor and the winding factor for the chosen winding configuration.

Normally, the air-gap surface area is constrained by mechanical considerations, so in order to produce more thrust force, the magnetic loading and specific electrical loading need to be maximised. It is for this reason that the slot proportions are important for motor design. The larger the slots are, the more cross-sectional area of conductor can be accommodated and so the specific electrical loading is higher for the same conductor current density. On the other hand, as the slot width decreases, the effective air-gap reduces (Carter Factor is lower) and thus the magnetic loading increases. Also, as the teeth get wider, they can sustain a higher magnetic loading without saturating should larger magnets be used on the mover or the air-gap is made smaller.

3. Methodology

3.1 Geometry

Assuming that the motor's width is large enough compared to the pole pitch so that the winding overhangs do not have a significant effect on its performance, a 2-dimensional model is used. The geometry is created in COMSOL, driven by a list of parameters so that it dynamically changes for each particular scenario. For elements that repeat over the geometry (for instance, the stator slots), a single geometry is created and then an array transformation is used. The COMSOL feature that allows for a selection to be automatically created when the geometry is 'built' is used and these are named appropriately so that they can be easily assigned materials and physics domains. Creating a geometry in this fashion is not only useful for the versatility that it provides but it also allows for parameter sweeps to be used to find the optimum value for any of the design parameters.

A 10-pole/9-slot motor is chosen for this study, with a pole pitch of 30 mm, a slot depth of 35 mm, a nominal air-gap of 5 mm and a magnet height of 8 mm. A back-iron of 10 mm and stator depth of 50 mm are chosen, given the size restrictions.

The resulting geometry can be seen in Figure 2. The top region is the 10-pole magnet array, with magnets of alternating polarity attached to a back-iron. These components form the moving reaction plate. The bottom region, separated from the reaction plate by an air-gap, is the stator. The stack of laminations forming the stator core has slots into which the coils (red, blue and green rectangles) are wound.

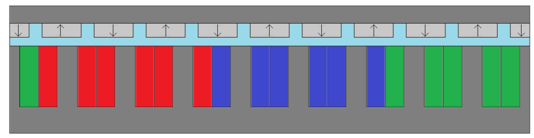

Figure 2. FEA geometry

Since the Maxwell Stress Tensor method is used by COMSOL to calculate the force components, higher accuracy is achieved by refining the mesh along the relevant region boundaries. An appropriate mesh size was found by conducting a mesh analysis.

A user-defined free-triangular mesh is used and its size is specified to be 1 mm along the magnet and back-iron boundaries that border the air-gap, the slot borders and the top of the teeth. An 'extra fine' mesh is used for the rest of the geometry. A portion of the resulting mesh can be seen in Figure 3.

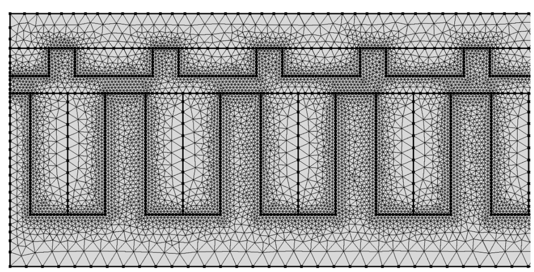

Figure 3. Sample region of FEA mesh

3.2 Materials

A combination of user-defined and 'built in' materials are used. The selections created by the geometry generation are used to allocate the appropriate material to each domain. 'Air' is selected to be the default material.

The reaction plate consists of NdFeB-45H magnets and a mild steel back-iron. A user-defined material is created for the magnets with a relative permeability of 1.049. An interpolation function is used under the material properties of the steel to input the BH curve that dictates the non-linear permeability of the back-iron.

The stator consists of ‘electrical steel’ laminations and copper windings. A user-defined material is used for the laminations and the relevant BH curve dictates the non-linearity of the material. ‘Copper’ from the built-in library is used for the windings.

For the parameter sweep, though, a high constant relative permeability was specified and used for the back-iron and stator laminations, under the assumption that the air-gap region dominates the machine’s performance.

3.3 Physics

The ‘Magnetic Fields’ Physics from the AC/DC COMSOL module is added to the model. A periodic boundary condition is inserted for the left and right edges and is set to be ‘continuous’. This leaves the top and bottom boundaries set to be magnetically insulated. Two Ampère’s Law domains are applied to the alternate sets of magnets to create a magnetisation of 979 kA/m in the positive ‘y’ direction and 979 kA/m in the negative ‘y’ direction, respectively. Two additional Ampère’s Law domains are inserted and applied to the back-iron and laminations.

Six multi-turn coil domains are used to simulate the stator windings. A different name is given to each coil group and a conductor cross-sectional area is specified. The phase currents are calculated so that a 90° load angle is maintained between the magnetic fields of the magnets and the windings to produce the maximum thrust. For simplicity, each coil is set to have a single turn by specifying the number of turns for each domain to be the number of coils in that phase (in this case, 3 coils). The conductor area is calculated assuming a 45% fill factor.

A 3-phase, double-layer, concentrated winding is used. Each coil is wound around a stator tooth, going into the page in one slot and returning out of the page through the adjacent slot. The sides of the windings that go into the page are labelled as ‘A’, ‘B’ and ‘C’ and the corresponding return sides are labelled as ‘$\overline{A}$’, ‘$\overline{B}$’ and ‘$\overline{C}$’. In a double layer-winding configuration, the slot is divided in two for two coil sides, as shown in Figure 4.

An ‘explicit selection’ of each of the 6 winding domains is created under ‘definitions’ in the model’s design tree to match the desired winding arrangement.

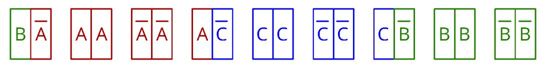

Figure 4. Winding arrangement

A ‘force calculation’ is assigned to the reaction plate domains to calculate the normal and thrust force components.

3.4 Parametric Sweep

A set of ‘stationary’ solutions is found with a parametric sweep of the slot-width-to-tooth-width ratio over a range of 0.5 to 4, in steps of 0.1. Assuming that the teeth are never small enough to saturate, the sweep is run with the lamination and back-iron materials having a high constant permeability.

The amount of heat that a machine can dissipate is normally a design constraint, so that the machine does not overheat. Also, if less heat is produced for a particular thrust force, the machine is more efficient. So, the conductor current density is calculated for each step of the sweep such that the Joule heating due to the “copper losses” is kept constant. This is because in a slow-moving, large air-gap machine, most of the heat produced is due to the copper losses in the windings. The “iron losses” in the core are typically insignificant, since they are dependent on the electrical supply frequency. A plot of how the conductor current density is varied over the range is shown in Figure 5.

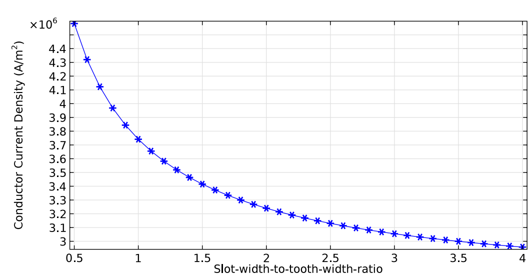

Figure 5. Conductor current density versus slot-width-to-tooth-width ratio

4. Experimental Results

The resulting thrust force, keeping the copper losses constant, is plotted in Figure 6.

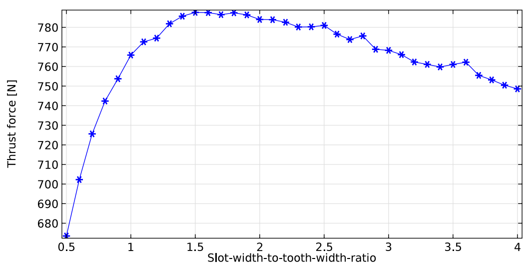

Figure 6. Thrust force versus slot-width-to-tooth-width ratio

Figures 7 and 8 are plots of the magnetic loading and specific electrical loading versus the slot-width-to-tooth-width ratio, respectively.

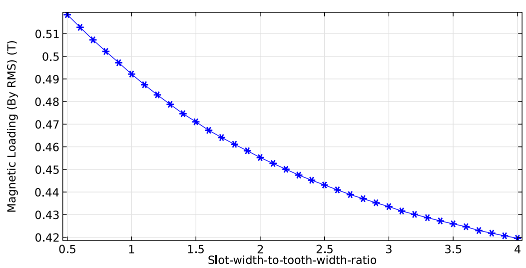

Figure 7. Magnetic loading versus slot-width-to-tooth-width ratio

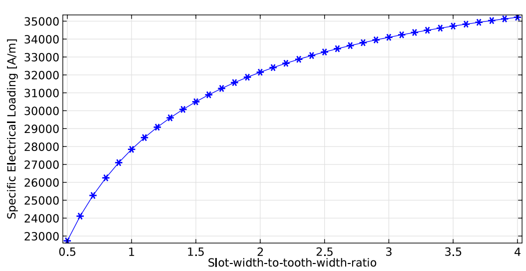

Figure 8. Specific electrical loading versus slot-width-to-tooth-width ratio

Figure 9 shows the peak flux density in the stator teeth as the slot-width-to-tooth-width ratio is varied.

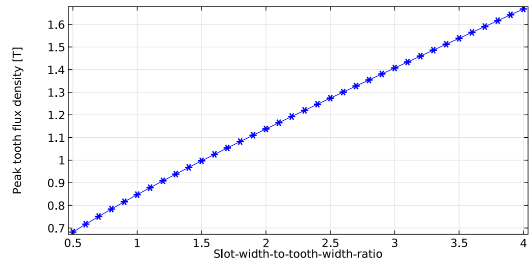

Figure 9. Peak tooth flux density versus slot-width-to-tooth-width ratio

Lastly, Figure 10 shows magnetic flux distribution and density for a slot-width-to-tooth-width ratio of 1.6 (where the peak thrust occurs).

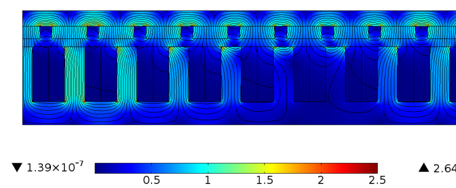

Figure 10. Magnetic flux distribution

5. Discussion

In Figure 6, it can be seen that the peak force is produced when the slot-width-to-tooth-width ratio is between 1.4 and 2. The actual optimum slot-width-to-tooth-width ratio would be found within this broad range by considering other factors such as the magnitude of the cogging force as the reaction plate moves along the stator sections.

The magnetic loading reduces as the slot-width-to-tooth-width ratio increases because the slot width gets larger (see Figure 7). This reduction in magnetic loading is because the reluctance of the magnet flux path increases (the effective air gap is larger due to more flux fringing around the top of the teeth).

Figure 8 shows how the electrical loading increases as the slots get bigger allowing more space for copper. As discussed, the peak force occurs when the best compromise of magnetic loading and electrical loading is found

When the slot-width-to-tooth-width ratio is between 1.4 and 2 (where the peak force occurs), the peak flux density on the teeth is around 1 T, as shown in Figure 9. Since significant magnetic saturation of the materials does not occur until approximately 1.5 T, larger magnets on the reaction plate or a different reaction plate design could be used to raise the magnetic loading. This means that it is probably best to keep the slot-width-to-tooth-width ratio closer to 1.4 rather than 2.

Given that it was assumed that the teeth do not saturate when running the parametric sweep with linear materials, a final study was run using the non-linear material properties for a single slot-width-to-tooth-width ratio of 1.6. As expected, it was found that the magnetic flux density was low enough in the back-iron and stator core for there not to be any saturation effects and that the calculated force is identical to when using constant permeabilities for the materials.

6. Conclusion

The AC/DC COMSOL module was used to find the optimum slot geometry for a 10-pole/ 9-slot, large air-gap, linear synchronous motor. The optimisation was performed for a machine where the application dictates a fixed pole pitch, stator depth and air-gap. The point at which the peak thrust force occurs is found whilst keeping the heat produced constant (by varying the conductor current density in the coils as the slot-width-to-tooth-width ratio is changed).

Since the force produced is proportional to the magnetic loading, electrical loading and the surface area of the air-gap, the peak force occurs where the magnetic and electrical loading are maximised for a particular air-gap surface area. Larger slots allow more copper to be accommodated and thus the electrical loading is higher for the amount of heat produced, whereas the effective air-gap for the magnets increases and so the magnetic loading reduces.

A parametric sweep of the slot-width-to-tooth-width ratio shows that a maximum force is produced when the best compromise between magnetic and electrical loading occurs. This occurs when the slot-width-to-tooth-width ratio is between 1.4 and 2. Since this is quite a large range, other factors and constraints should be considered in order to find the best slot dimensions for a particular motor design.