Applying superposition of 2D results to model 3D field distributions in magnetically linear devices using an example of an axial flux permanent magnet coreless motor

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The paper focuses on methodologies for field simulation in magnetically linear devices using an example of an axial flux permanent magnet coreless motor. Two approaches are investigated, both relying on representing the true 3D field patterns by superimposing axisymmetric 2D solutions, one harnessing the finite element modelling and another based directly on the Biot-Savart law. The results have been compared with full 3D solution using commercial software and verified experimentally.

***Index Terms*—Magnetic fields, finite element analysis, axial flux permanent magnet motor.**

I. Introduction

THE design of electromechanical energy converters is often assisted by numerical field modelling, primarily the finite element method. The designer is faced with a dilemma whether to use the more precise but computationally cumbersome full 3D models or simpler but less accurate 2D simulations; it has also been suggested that combining the 2D and 3D formulations may offer the most efficient solution [1]. Another consideration is the availability of commercial software set against the development of in-house design programs and methods with inevitable implications of costs and other required resources. The challenge is therefore to create procedures offering a good balance between accuracy, speed and convenience. In the case of magnetically linear devices (or where linearity may be assumed) a superposition of simpler 2D results may offer a good alternative to full 3D modelling and such methodology is pursued in this paper. As a convenient example, and to provide better focus, a practical device is considered in the form of an axial flux permanent magnet coreless motor (AFPMCLM).

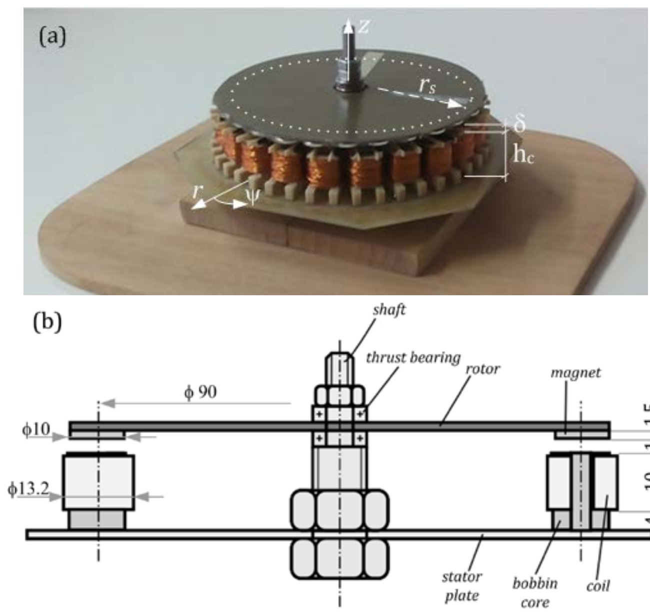

Fig.1. The AFPMCLM: (a) view; (b) cross-section.

II. The Example AFPMCLM Motor

A 28-pole low power motor has been designed and built as shown in Fig. 1. The stator plate is made of an insulating material similar to that used as a laminate in printed boards. The stator consists of 21 solenoidal coils connected in star and fed from a three-phase supply. Each coil has 140 turns wound on a plastic bobbin. The simplicity of this design is striking compared to other axial flux machines [2], [3].

The rotor is made up of 28 uniformly distributed Nd-Fe-B magnets attached to a disk made of a polyamide. The magnets have magnetic permeability close to that of air. The rotor is fixed to a shaft. The gap between the magnets and the upper surface of the coils is 1mm.

III. The Concept of Superposition

In devices like AFPMCLM, where all parts are either non-magnetic or may be assumed to have permeability close to that of air, superposition may be applied, which offers a possibility of developing simpler and faster design procedures while maintaining acceptable accuracy. In our case symmetries have been exploited and two particular simplified approaches applied, both based on the idea of modelling each magnet and each coil individually and superimposing the solutions. Consequently, two algorithms have been developed, one using a 2D axisymmetric finite element (2D FE) formulation and another applying directly the Biot-Savart law. The FE model uses the edge values of vector potential $\boldsymbol{A}$ which, because of axial symmetry, mean $2\pi r A_\psi$; the resulting FE model is very simple and appropriate for creating a bespoke algorithm rather than relying on commercial software. The application of Biot-Savart law leads to an analytical solution, but –because of the type of functions involved [4] –computation takes more time than the 2D FE solution (as shown later). In both approaches it is assumed that the solution for each magnet and each coil is axisymmetric; moreover, each magnet is represented by an infinitely thin cylindrical current sheet with appropriate current density representing the axial value of magnetisation vector. The global solution may then be obtained by superimposing all component results, bearing in mind that it is not necessary to repeat calculations for each magnet or coil; instead two solutions only are needed, for one coil and one magnet, which then need to be scaled (according to the value of the coil current or magnetisation vector) and transposed from local to global coordinate system, resulting in very efficient computation.

The ensuing bespoke algorithms allow the electromagnetic torque and the axial force between the stator and the rotor to be estimated; the relevant component torques and forces are obtained from the Maxwell stress formulation [5].

IV. Results

Figures 2 to 5 present selected results obtained using the two algorithms compared with full 3D solutions using commercial software Maxwell 3D (based on classical FE formulation and no superposition applied). Specifically, Figs 2 to 4 show components B_r, B_ψ and B_z of the flux density as a function of the angle ψ along the circle of radius $r = r_s$ on the plane $z = h_c+0.5\delta$ (refer to Fig.1). The motor is on load with phase currents $i_a = 1$A, $i_b = i_c = -0.5$A, and the axis of the magnet magnetised in the direction of the stator coincides with the axis of the coil in phase A. Figure 5 demonstrates the variation of the electromagnetic torque as a function of the angle α between the stator and rotor field axes, while the instantaneous phase currents are as specified above.

The magnitude of the torque obtained from the Biot-Savart computation is only 2.06% different from the value measured for the prototype, thus increasing confidence in the proposed methodologies. Interestingly though, the results from Maxwell 3D contain a lot of ‘noise’ (as shown in Fig. 5), with some values differing by as much as 8% from the Biot-Savart results, suggesting inaccuracies in the 3D modelling, despite the fact that over one million elements have been used.

The crucial comparison, however, given overall good agreement between the results, is between computing times, as summarised by Table I. Note the efficiency of the 2D FE model and thus its appropriateness for design optimisation purposes, while in this case the Biot-Savart approach is the most accurate.

TABLE I
Comparison Between Computation Times

Method of field computation	Computing time
2D FE (with superposition)	5 seconds
Biot-Savart (with superposition)	26 seconds
Maxwell 3D	30 minutes

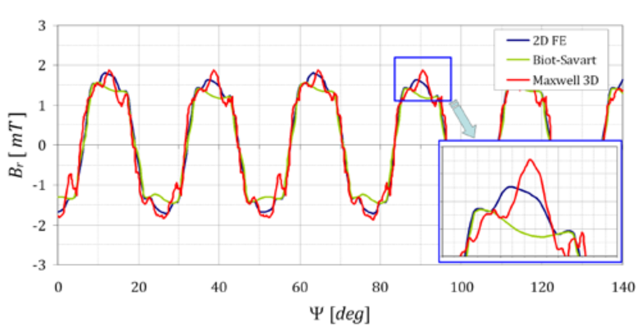

Fig. 2. The distribution of component B_r, $B_r(\psi)$ for $r = r_s$ and $z = h_c+0.5\delta$.

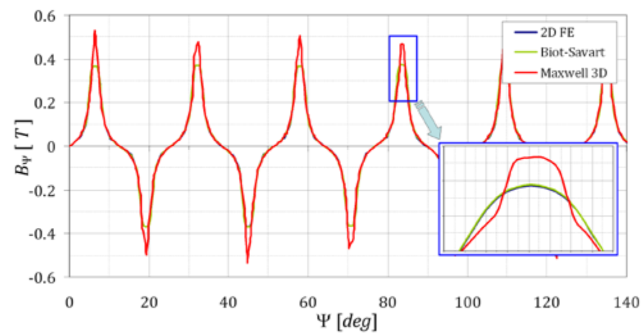

Fig.3. The distribution of component B_ψ, $B_\psi(\psi)$ for $r = r_s$ and $z = h_c+0.5\delta$.

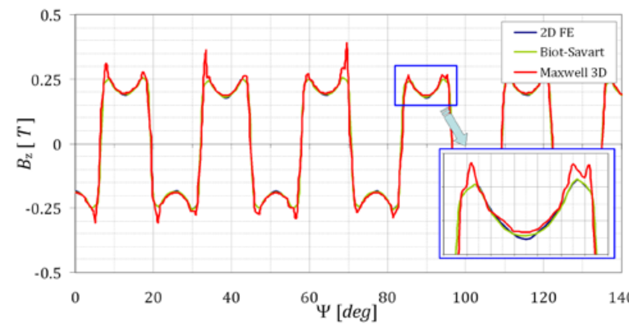

Fig. 4. The distribution of component B_z, $B_z(\psi)$ for $r = r_s$ and $z = h_c+0.5\delta$.

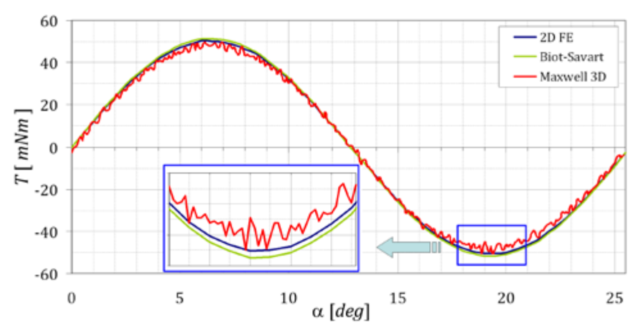

Fig. 5. Electromagnetic torque as a function of the angle α.

V. Conclusion

In this paper we argue that for magnetically linear systems, or when non-linearity may be neglected, a superposition of 2D solutions may offer a very efficient methodology for practical design, far superior in view of significantly reduced computing times and competitive in terms of accuracy to 3D modelling. The efficiency of this approach for design optimisation will be explored further in the full version.

References

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