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3D magnetic field modeling of a segmented cylindrical Halbach array.

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Nowadays, the need for efficient actuators with high force density in industrial applications is rapidly growing. Permanent magnet (PM) actuators appear to be a very good class of machines to fulfill these requirements. Several papers have been written on the subject of design of PM magnet actuators with various PM configurations. E.g. Halbach structures are exploited to achieve an even higher power density with a little more PM material [1]. Due to the evolution of the hard magnetic materials and production techniques, PMs in various shapes and with different magnetization patterns emerge and the approximation of an ideal Halbach magnetization improves.

In spite of all efforts, the price of these magnets at this moment is still high, and hence, the use of magnets with simple shapes and an easy magnetization is favorable. Using multiple small magnets with a simple shape, more complex magnetization patterns are approximated.

Regarding tubular permanent magnet actuators (TPMAs), several papers are written about the application of quasi-Halbach magnetization, as shown in Figure 1a, with radial and axial magnetized PMs. However, the radial magnetized ring magnet shown in Figure 1b is difficult to magnetize especially for small radii. Therefore, in practice this PM is often approximated by diametrically magnetized segments shown in Figure 1c. This segmented PM results in a 3D effect, hence, for the exact magnetic fields in the actuator, a 3D analysis is required. So far, all papers describing tubular actuators with Halbach magnetization consider the 2D problem with perfect radial magnetized magnets [2]. This results in a field distribution as shown in Figure 1d where the radial component of the flux density is shown as function of axial and angular position. The graph clearly shows no dependency on the angular position and hence a 2D model is sufficient. However, to model the segmentation using diametrically magnetized magnets, a 3D model is required resulting in a field distribution as shown in Figure 2a. Here the radial component of the flux density is dependent on both the axial and the angular position. In this paper two 3D models are derived which provide the magnetic field expression for quasi-Halbach arrays, one with a soft-magnetic core and one with a non-magnetic core. The models can be used for actuators with either outer or inner magnet configuration.

To calculate the magnetic fields, a semi-analytical formulation for the magnetic scalar potential in the 3D cylindrical coordinate system is derived. Although the model is quite complex to derive, it avoids the use of time consuming 3D Finite element analysis (FEA), and once implemented it can easily be used to calculate the 3D field effects. Figure 2b shows the 3D segmentation effect on the rms value of the radial component of the flux density in the middle of the airgap for a small actuator with a translator diameter of 15 mm. As can be seen, by increasing the number of segments the value for Halbach with radial rings can be approximated.

In the paper, the full model is given as well as a list with generalized results. In this list, the effect of the magnetic loading for a certain number of segments for several dimensions can be found. The created model describes a slotless TPMA, however the results are also applicable for slotted actuators. A (non-skewed) slotted TPMA has slots in the radial direction over the whole circumference resulting in a disturbance in the radial component of the flux density as function of translation (z). On the other hand, the segmentation of the radial ring PM affects the radial component of the flux density as well but as a function of the angular position (\theta). Hence, the slotted TPMA can be modeled here as a slotless actuator with a smaller airgap due to the absence of a coil in the airgap.