On the Complete Analysis of Lenz's Effect on the Artificial Heart Valves during Magnetic Resonance Imaging

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Introduction Cardiovascular magnetic resonance (CMR) is an emerging imaging modality for evaluating patients with various heart conditions. There is increasing need for CMR scans of patients with cardiovascular implants, with the associated safety concerns. Prosthetic heart valves and annuloplasty rings are commonly composed of different metallic materials which, when tested, mostly have exhibited measurable but only minor magnetic field interactions during CMR due to translational and torsion forces. Concerns have been raised in the past, however, after preliminary theoretical assessments of moving valves with tilting disks or leaflets in magnetic fields due to forces generated by the *Lenz effect* [1]. This concern seems prudent considering the development of ultra-high field human MR systems at 7T and above. In the present work, we analyze in detail motion-induced eddy currents and their corresponding adverse magnetic forces due to rotational motion of conducting rings/disks for a range of both uniform and non-uniform magnetic fields of typical MRI systems. The results are potentially of interest to heart valve manufacturers and to safety regulators.

Methods Figure 1 shows the general geometry of a metallic ring rotating in the magnetic field B_0 with the angular frequency of ω ($\theta = \omega t$). Analytical formulations are available based on a simplified approach considering only first-order induced currents. However, the complete analysis of 3D eddy-currents considering both skin effect and proximity effect is only possible by the
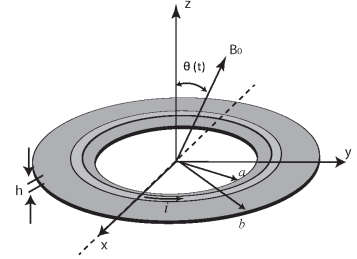

Figure 1: Geometry of a rotating ring in the magnetic field B_0.

application of numerical techniques. We achieved this by directly solving Maxwell's equations in their quasi-static form. The finite element method (FEM) was applied to solve the so-called T-Ω formulation of Maxwell's equations, a very well-developed technique adopted for modeling three-dimensional eddy-current problems [2]. The ANSYS Maxwell 3D package [3] was chosen as the simulation platform as it allows for both rotational and translational motions and automatically calculates motion induced eddy currents. The spatial field distribution of a typical actively shielded MR scanner was mimicked by introducing rectangular blocks of circular current loops as proposed by Sinha [4]. Four pairs of coils were used (Fig. 2) with the geometry and location of each pair of rectangular coil blocks optimized using the Quasi Newton optimizer to mimic the field distribution of a typical MRI system. Motion-induced eddy current i due to rotational motion of the valve were studied in three cases a) a full solid disk with radius of $b=20\ mm$, b) a ring with outer radius of $b=20\ mm$ and inner radius of $a=10\ mm$; and c) a "wire-like" ring with outer radius of $b=20mm$ and inner radius of $a=18\ mm$. The outer radius was chosen based on a reported prosthetic heart valve maximum diameter of 39mm [5]. in all cases the thickness of the disk is $h=2mm$. The FE mesh size was chosen such that doubling the number of elements caused less than 1% change in the final results. The total time of the motion was set to 10 ms with time steps of dt=0.025 ms. The valve was modeled to open with an angular frequency of 9°/s (maximum opening of 90° in 10ms [6]). The magnitude of currents in magnet coils (Fig.2) was increased to produce higher field intensities for motion simulations of Fig.3.
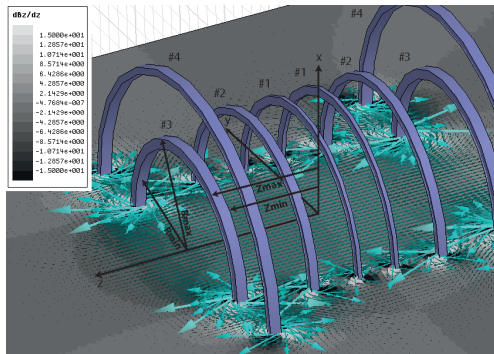

Figure 2-Magnetic field distribution of a typical 3T actively shielded scanner. Vector B_0 (blue) is overlaid on the distribution of field gradient dB_z/dz (gray tone)
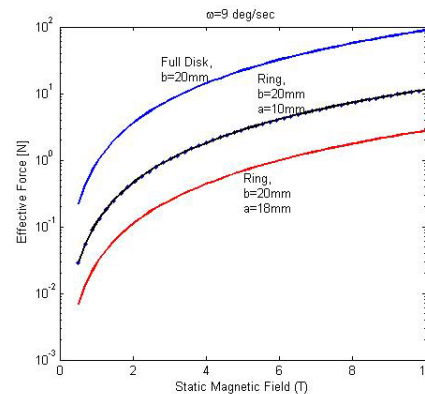

Figure 3: Effective force applied over the valve as a function of magnetic field.

Discussion The predictions of the analytical solution were compared with the results of the FEM analysis for both solid disk and the doubly connected conducting ring. For rings which consist of multiply connected conductive regions, skin effect and proximity effect have a significant opposing effect leading to much less applied forces. Figure 3 shows that for the solid disk, the magnitude of Lenz force reaches values of 10 N at 3T and 100 N at 10 T. However, the value for the wire-like ring (as in mechanical heart valves with strengthening rings), remains <2 N over the entire range. In cases where the valve was located in the highly inhomogeneous fringe field of the magnet (for example, when patients undergo lower limb MRI) the percentage of change of magnetic field over the valve surface was negligible compared to the rate of change of magnetic flux due to the rotational motion of the valve. The worst case estimation of Lenz effect was the operation of heart valves in the homogeneous high intensity field at magnet iso-center. In summary, based on this FEM analysis, mechanical heart valves with strengthening rings can be considered safe even under ultra-high field imaging conditions of 10T. Even at this field, the magnitude of Lenz forces remain less than the typical force of a beating heart, which is 7.2N [7]. Conversely, heart valves with a solid metallic disk are subject to very high adverse forces during MRI even at typical clinical field intensities. For example, the resistive force applied over the surface of a valve with titanium metallic disk at 4T is approximately 14N. Considering the typical surface of the valve, which is usually less than 12.6 cm^2, this force is applying a pressure of 83 mmHg over the valve's disk. If the valve is located in the mitral position, it should open and close under a pressure difference of less than 4 mmHg between the relaxing left ventricle and the left atrium. The high resistive pressure computed here could severely hinder the normal operation of the heart valve and thus this study suggests that heart valves with full conducting disks should be contraindicated in ultra-high field MRI.

References

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