Torque and Translational Force Estimation for Ferromagnetic Objects: the Saturation Effect

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Introduction: Translational force and torque that acts on the ferromagnetic object in the magnetic field depends on the shape and volume of object, magnetic field strength and spatial gradient of the static magnetic field[1]. Ferromagnetic objects in the MR-environment experienced linear magnetic region or saturation region. conventional approximation of the force and torque on the ferromagnetic ellipsoid of revolution are based on the linear magnetic region[2]. However, almost ferromagnetic objects placed in the saturation region in the commercial MR-scanners. Therefore, it is necessary to considered saturation region for these objects. Here, the approximated strength for the magnetic field that can be saturated the almost ferromagnetic objects will be presented. a simple simulation with Ansoft Maxwell 3D will be performed to show the Cast-Iron as a ferromagnetic object placed in the highly saturation region. Also, it will show that just by using the linear region, the approximation of force will be 1.5 times overestimated in comparison by considering of real states for these objects.

Methods: Analytical approaches, shows if a ferromagnetic spherical object exposed to a magneto-static field, total intensity of the magnetic field inside it, is 3 times greater than the applied field[2]. This approximation is just valid for the ferromagnetic objects in the linear region. Therefore, the threshold strength for the external magnetic field to saturated the ferromagnetic object is $1/3$ times of the Bs, where Bs is the threshold for the saturation value for the inside of the object's magnetic field and can be obtained from the B-H curve of the object. for example for the soft Iron, Bs=2.13T or for the high permeability iron alloys is B_s= 1.6 - 2.2 T. therefore almost ferromagnetic materials such as iron, nickel, cobalt and their alloys saturated if the applied field is greater than .7 Tesla. Conventional approximation formula for the magnetic energy of the ferromagnetic ellipsoid of revolution are based on the (Eq.1)[1,3] Where n_a , n_r are the demagnetization factors along the axis of symmetry and radial axis, also, V is the volume of the objects, m_s, M and B are the saturation value for the magnetization, magnetization and external applied magnetic field, respectively. Also, θand φ are the angle between the external field with axis of symmetry and dipole moment angle with the mentioned axis, respectively. In the strong saturation state for the objects approximately $\theta \simeq \varphi$.With using the virtual works methods, the closed form formula can be simply obtained for these objects in 2 regions (Eq.2),(Eq.3).

Results: Ansoft-Maxwell-3D software used to simulated a 1.5 Tesla magnetic field. By exposing a ferromagnetic materials with nonlinear B-H curves shown the almost ferromagnetic objects are highly saturated in this field strength. Fig.1 shows this fact for a cast-iron spherical object. By using a fringe-field map of the 3-T machine and by considering 2 magnetic region for the iron sphere with R=.6cm and proper function fitting to obtained points, the translational force in the z direction specified in Fig.2. also the maximum value for the force measured that shown in the Fig.2.

Discussion and conclusion: maximum torque occurred inside of the bore and near to the Isocenter. based on the B-H curves of the almost ferromagnetic objects, if the strength of the machine greater than the **.7** Tesla, These objects are in the saturation state. the torque formula in the linear region would be applied in the low Tesla machine(**<.7T**). As the static magnetic field increase, the torque limited with the saturation value for the magnetization. Therefore, it is wrong to use the torque equation in the linear region for the high-Tesla scanner. for the needle $(n_a \to 1, n_r \to 0)$ or coin $(n_a \to 0, n_r \to .5)$ the estimation based on the linear region cause is so wrong and caused the too weak estimation. If the saturation region is not be considered for the ferromagnetic object, the amount of force rapidly increased with increasing in the static magnetic field and cause the poor estimation for the translational force. Fig.2 shows the $F_{linear}(\max)/F_{measured}(\max)\,(sphere\ geometry) = \frac{17.9}{11.8} \approx 1.5$, for the Cast-Iron in the 3-Tesla machine. Also the close agreement between the maximum measured force and Maximum calculated value can be seen in the Fig.2.

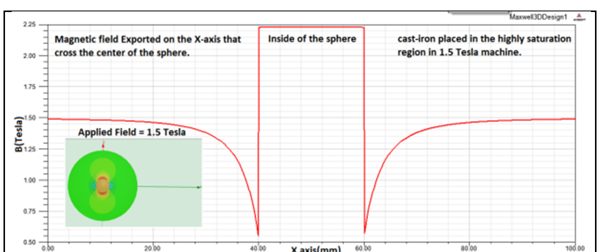

Fig.1 Magnitude of the magnetic field export in the X-axis for Cast-Iron spherical object in the 1.5 Tesla magnetic field.

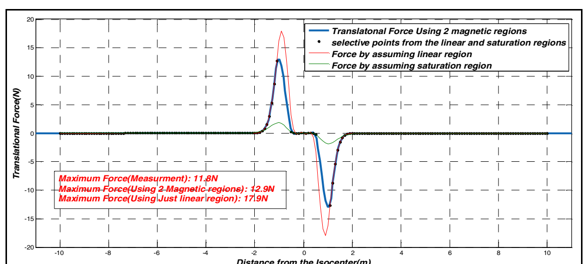

Fig.2 Translational force in the Z-direction on the soft-Iron Spherical object with V=1cm^3 in 3-Tesla MRI.

$$U_{linear} = \frac{VB^2}{2\mu_0}\left[\frac{\cos^2\theta}{n_a} + \frac{\sin^2\theta}{n_r}\right] \qquad Eq.1A$$

$$U_{saturation}\frac{1}{2}\mu_0 V(n_r - n_a)m_s^2\sin^2\varphi - Vm_s|B_0|\cos(\theta - \varphi) \qquad Eq.1B$$

$$F_z(linear) = \frac{V}{\mu_0}B_0\frac{\partial B_0}{\partial z}\left[\frac{\cos^2\theta}{n_a} + \frac{\sin^2\theta}{n_r}\right] \qquad Eq.2A$$

$$F_z(highly\ saturated) = vm_s\frac{\partial B}{\partial z} \qquad Eq.2B$$

$$|T|(linear) = \frac{V|n_r - n_a|}{2n_a n_r \mu_0}|B|^2\sin(2\theta) \qquad Eq.3A$$

$$|T|(highly\ saturated) = \frac{\mu_0 V|n_r - n_a|}{2}m_s^2\sin(2\theta) \qquad Eq.3B$$

Refrences:

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