Resistance Effect on Eddy Currents in Conducting Cryogenic Warm Bore Cylinders

T. K. Kidane[1], T. P. Eagan[1], Y. C. Cheng[1], V. Taracila[1], T. N. Baig[1], W. A. Edelstein[2], R. W. Brown[1]
[1]Case Western Reserve University, Cleveland, Ohio, United States, [2]MRScience, Schenectady, NY, United States

Abstract

Two ways of calculating eddy currents are considered for a shielded z-gradient design on the conducting cryogenic warm bore, the quasi-static field method and the network method. These two methods give identical results if the resistance is neglected and the time dependence of the eddy current is identical to that of the driving current. On the other hand, when we take the resistance into account the network method gives a reduced and an exponentially decaying residual eddy current. This method can also give an insight into the skin depth effect by further slicing the cylindrical warm bore into concentric layers.

Introduction

An accurate eddy-current calculation on the conductors surrounding the rapid switching gradient magnetic field is often necessary to compensate for magnetic fields caused by these currents in the DSV . Two ways of calculating these currents have been employed by different authors [1, 2, 3]. One standard method of calculation is based on the relationship between the Fourier transforms of the current density of the gradient set and the eddy currents of interest. For discrete z-gradient loops (primary and secondary) at positions z_i and radius r, the eddy-current density on the surface of a cylinder of radius R is given by [1],

$$j_\phi(z) = \frac{1}{2\pi}\int dk f(k) e^{ikz}$$

where

$$f(k) = -\frac{I_0 r I_1(kr)}{R I_1(kR)} \sum_i e^{-ikz_i} \text{ ,}$$

Here I_0 is the current in the primary and secondary gradient coils and the summation runs over the discrete loops. This method assumes a very small skin depth compared to the cylinder thickness and as a consequence the time dependence of the eddy-current is identical to that of the gradients.

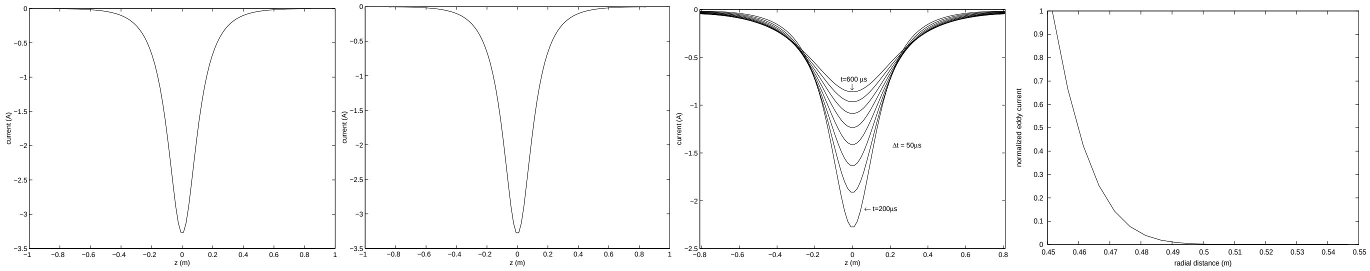
On the other hand the network method [2,3] is based on dividing the cylinders into a number of thin sections for inductance and resistance calculations. The basic assumption in the network method is to assume a constant current throughout the sliced section and consider the DC resistance. The simultaneous coupled circuit equation can be written in a matrix form,

$$[M]\frac{d}{dt}\{i\} + [R]\{i\} = -\{M_0\}\frac{di_0}{dt}$$

where [M], [R] are inductance and resistance matrices, $\{M_0\}$ is the mutual inductance vector between the cylinder sections and the gradient coils, {i} is the eddy current vector in each section and i_0 is the gradient current.

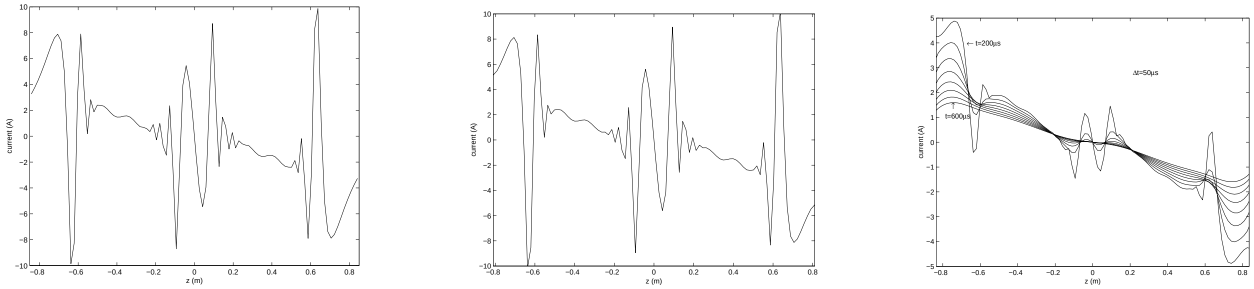
Results and Discussion

We have calculated the eddy current on the conducting cryostat warm bore employing both methods. First, for a simple model, consider a single coil with radius 33 cm at the center of a 170 cm cylinder (figure 1) and for a real z-gradient design (figure 2) with the following dimensions: primary gradient winding radius 33cm and length 99 cm, secondary winding radius 42cm and length 125.8 cm, and cylinder radius 45 cm and length 170cm. We can easily see that if we neglect the resistance of the stainless steel warm bore the time dependence of the eddy-currents will be identical to that of the driving coil and indeed as we can see from the figures 1a, b and 2a,b the magnitude of the currents is also the same for both methods. Figures 1c and 2c show the effect of the resistance which reduces the peak value and changes the time dependence. We also further slice the cylinder into 20 thin shell slices (figure 1d) to study skin depth. Because of this effect the assumption that a constant current flows through each section is not true for thick and relatively good conductors like stainless steel. This can be seen from figure 1d, showing eddy current distributions in the cylinder in the radial direction at the center of the cylinder for a single loop placed at z=0.



a) b) c) d)

Fig. 1. Eddy currents induced on the cryogenic warm bore due to a single coil for 200A maximum and trapezoidal pulse, ramp-up time 200µs: a) quasi-static field method b) network method with R=0, c) network method with the resistance of the cylinder considered and d) current on thin shell slices at z=0, by cutting a 10 mm cylinder into 20 concentric layers obtained using the network method with the resistance considered.



a) b) c)

Fig. 2. Eddy currents due to a shielded z-gradient coil for 200 A maximum and 1ms trapezoidal pulse, ramp-up time 200µs, where a, b and c are calculated for 3.18 mm thick cylinder employing a) the quasi-static field method b) the network method with R=0, c) network method with resistance considered.

Conclusion

Both methods give identical spatial and temporal results if the resistance of the cylinder is neglected. This assumption works for materials with high conductivity. For materials with low conductivity the resistance reduces the residual eddy current significantly. For a stainless steel the peak value is reduced by 50% for the z-gradient (figure 2c) and the time dependence is no longer identical to that of the gradient current. By slicing a 20 mm thick cylinder further into concentric layers we see in figure 1d that the current decays exponentially which suggests that for a known frequency an AC resistance should be used. Fourier decomposition of a trapezoidal gradient current wave form can be used to further incorporate the AC resistance corresponding to each skin depth.

Reference:

1. Turner R, Bowley RM, J Phys E 1986;19:876-979.
2. Edelstein et al., In Proceedings of the ISMRM Fifth Scientific Meeting and Exhibition, Vancouver, B.C., Canada, April 12-18,1997:1472
3. Takao Takahashi, IEEE Transaction on Magnetics, Vol 26, No 2, March 1990:893-896.