A Transverse Gradient Detection Coil for Dynamic Pre-emphasis

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Introduction

Spherical harmonic inductive detection coils[1] have been proposed as sensors in a negative feedback system providing dynamic pre-emphasis used to cancel magnetic field harmonics caused by the eddy currents that follow gradient or shim coil switching. The *z*-directed magnetic field $B_z(t)$ can be described as a sum of spherical harmonics of the form $H_{n,m}(t)\ r^n P_n^m(\cos\theta)e^{im\Phi}$ where (r,θ,Φ) are the spherical polar coordinates, P_n^m are the associated Legendre polynomials, and $H_{n,m}(t)$ are time varying coefficients. Instead of using pre-defined transient currents through the gradient or shim coils to cancel the effects of eddy currents on the $H_{n,m}(t)$ coefficients, a feedback system may be used to control automatically the coil currents and thus rapidly establish the desired field. In situations where eddy currents produce appreciable high order harmonics, such as dynamic shimming, this technique may have an advantage over standard pre-emphasis in that it requires neither detailed knowledge of the harmonics nor their interactions; the complex effects of eddy currents being dynamically sensed and corrected by the feedback system. Dynamic pre-emphasis is in its infancy and, until now, has only been implemented for a *z*-gradient in a bench top experiment[2]. We report here on the more difficult feedback control of an *x*-gradient in a similar bench top experiment using, as a feedback sensor, an *x*-detection coil, designed such that its induced voltage is proportional to changes in the *x*-gradient $H_{1,1}(t)$ and no other $H_{n,m}(t)$ coefficients.

Theory

Detection coil design is accomplished by expressing the voltage induced by a changing magnetic field, in an elementary wire density on the surface of a cylinder, in terms of the harmonics of that field. This expression is then used to produce an optimized wire pattern such that the induced voltage is zero for changes in every harmonic except one. Note that such a generalized calculation is far more difficult than the zonal ($m = 0$) case since the complete field (B_x, B_y, and B_z) must be considered rather than merely B_z; successful operation of a transverse detection coil is evidence that such a calculation is not only feasible but correct. The output of the detection coil, once electronically integrated, is proportional to the strength of the detected harmonic. However, due to electronic integrator drift, this method of sensing a magnetic field harmonic has a low frequency cut-off.

Materials and Methods

The bench-top test apparatus includes a gradient coil former of radius 11 cm, a detection coil former of radius 8 cm, and a field plotting apparatus which can move a sniffer coil over the surface of a sphere of radius 4.1 cm. These are enclosed in an aluminium tube of length 122 cm, radius 13.6 cm and thickness 1 cm in which eddy currents are induced. An unshielded *x*-gradient coil was designed using a spherical harmonic matrix method[3] to be free of unwanted harmonics up to and including 5th order. The *x*-detection coil was designed to reject harmonics up to and including 7th order, was hand wrapped using 83 meters of AWG 25 magnet wire, and is 61 cm long. Its response to an *x*-gradient is 0.17 volt meter second/tesla and, from simulation, the response to the next largest harmonic ($n=3$, $m=1$) is 70dB lower. Feedback was achieved using a crossover network where the detection coil was used above 1Hz and a resistor was used to sense the current through the gradient coil below 1Hz.

Square current pulses were fed through the gradient coil and 144 field points were measured on the surface of the sphere as a function of time using a sniffer coil followed by an electronic integrator. After correcting for a small integrator drift, these data were used to compute the spherical harmonics $H_{n,m}(t)$ up to and including order $n=5$ as functions of time. The experiment was then repeated with square voltage pulses fed into the feedback system controlling the gradient coil current.

Results & Discussion

As can be seen in the figure, the eddy currents limit the rise time of the *x*-gradient to about 60 ms without feedback. When the feedback system is used (N.B. no pre-emphasis), the eddy current fields are sensed and immediately corrected, allowing the gradient to be rapidly established. The small initial overshoot in figure b) is typical of a critically damped feedback system. Surprisingly, the field plot revealed that other harmonics (which could, in principle, be controlled with their own detection/feedback systems) were less than 1% of $H_{1,1}(t)$. This was presumably due to the excellent symmetry of the apparatus and thus we plan experiments where we break the symmetry.

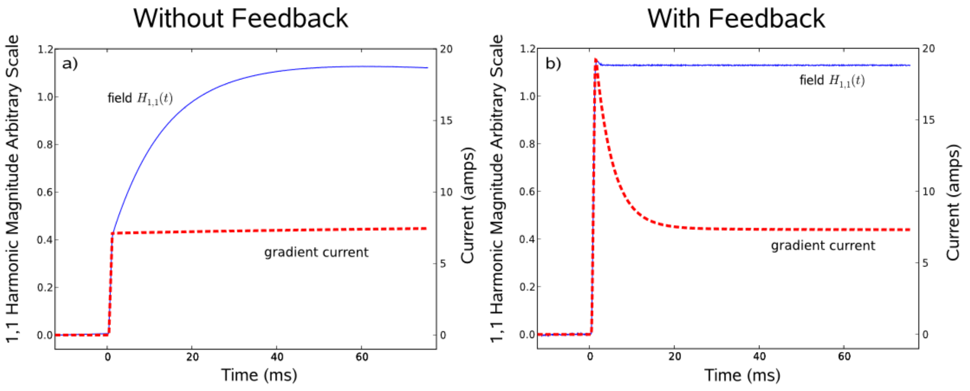

Figure: Plot a) shows the *x*-gradient field and gradient current with neither feedback nor pre-emphasis. The results in b) demonstrate annulment of the effects of eddy currents using a detection coil and feedback; no *a priori* knowledge of the eddy current's effects and no pre-emphasis have been used.

The bench top apparatus is designed to allow the simultaneous feedback control of *x*, *y*, and *z*-gradients as well as B_o transients in order to demonstrate the feasibility of dynamic pre-emphasis in nullifying multiple unwanted harmonics; construction of the remaining channels is under way. The feedback control of an *x*-gradient is an important step towards this goal in that it is the first time dynamic pre-emphasis has been used for a harmonic other than $H_{1,0}(t)$. Moreover, our *x*-detection coil is the first coil built to sense a harmonic with $m \neq 0$, where the full vector character of the magnetic field enters the design calculation. We envision this method applied to full dynamic shimming with numerous shim coils.

References

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