Movement Monitoring for MRI via Measurement of Changes in the Gradient Induced EMF in Coil Arrays

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Introduction: Image quality is degraded in MRI by involuntary movement of the subject during data acquisition, with head movement being a particular problem for fMRI and high resolution anatomical imaging. A variety of approaches have been developed for monitoring head motion during image acquisition and for using the measured motion parameters for prospective or retrospective image correction [1]. Approaches based on optical monitoring [1], navigator MRI measurement [2] and use of small RF coils as active markers [3] have shown particular promise, but each has limitations (e.g. need for line of sight access, spare time in the imaging sequence or additional RF channels). Here we describe an initial evaluation of an alternative approach for monitoring head motion, which involves measuring the pattern of voltage amplitudes induced in an array of small coils by the time-varying magnetic field gradients of the MR scanner. In this pilot work, we have constructed a rig carrying five small coils, which can undergo controlled translations (in x, y and z) and rotations (about the x- and y-axes) inside the scanner, and have measured the changes in the voltages induced in these coils by time-varying x-,y- and z-gradients as the rig position changes, comparing the results with simulations.

Theory

We can describe the voltage induced in a coil by the time-varying magnetic field gradients, G_x, G_y and G_z used in MRI as

$$-V=\frac{\partial}{\partial t}\left(\int_s \vec{B}.d\vec{S}\right)=\oint\frac{\partial\vec{A}}{\partial t}.d\vec{l}=\oint\left(\frac{\partial\vec{A}_x}{\partial t}+\frac{\partial\vec{A}_y}{\partial t}+\frac{\partial\vec{A}_z}{dt}\right).d\vec{l}\quad\text{with}\quad \vec{A}_x=-\frac{1}{2}G_x xy\hat{i}+\frac{1}{4}G_x\left(x^2-y^2\right)\hat{j}+G_x yz\hat{k},\ \vec{A}_y=-\frac{1}{2}G_y\left(x^2-y^2\right)\hat{i}+\frac{1}{2}G_y xy\hat{j}-G_y xz\hat{k}\ \&\ \vec{A}_z=-\frac{1}{2}G_z yz\hat{i}+\frac{1}{2}G_z xz\hat{k},$$

where $\vec{A}_{x,y,z}$ describes the vector potential due to the relevant gradient [4]. These expressions can be used for numerical simulation of the voltage induced in a general coil, and analysis of their form shows that translations and small rotations will produce linear changes in voltage with the motion parameters.

Method: The rig carrying a set of 5 coils is shown in Fig. 1. Each coil has 10 turns and a diameter of 4 cm. In the starting position for recordings, the coil orientations (described in terms of the direction of the normal to the coil are: coil 1(z), coils 2&3 (x), coils 4&5 (y).

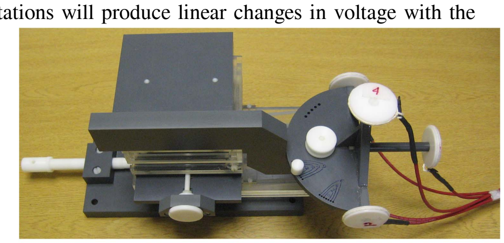

Fig. 1: Experimental set-up: a rig containing five coils.

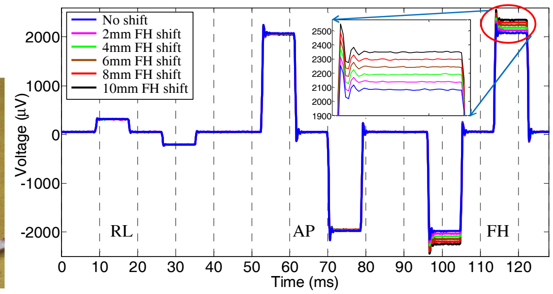

Fig. 2: Voltage recorded on coil 1, during executions of gradients pulses along RL, AP and FH directions due to sequential shift along the z-direction

We used a Brain Amp MRplus (Brain Products) to record the voltages induced in the coil array inside a Philips 3T scanner, using a sequence in which gradient pulses with a slew rate of 2 $Tm^{-1}s^{-1}$ were sequentially applied on the x (Right-Left –RL), y (Anterior-Posterior –AP) and z (Foot-Head – FH) axes. Recordings were made for translations of 2 – 10 mm in 2 mm steps along all three Cartesian axes, and for rotations about the x- and y-axes of 1-5° in 1° steps, and the rate of change in voltage with position was evaluated for different coils/gradients. Simulations were also carried out to evaluate the changes in voltage which would be theoretically expected.

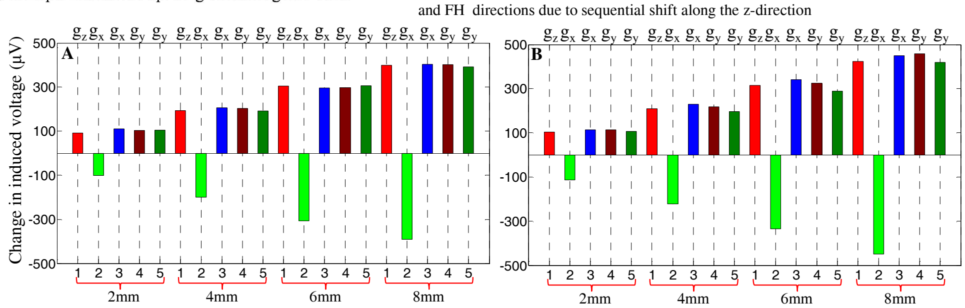

Fig. 3: Change in the induced voltage in the coils due to sequential shift along the z-direction because of the application of x, y, z gradients: (A) numerical simulation, (B) experimental data.

Results and Discussion:

Figure 2 shows the pattern of voltages recorded from coil 1 as the rig was moved in 2 mm steps in the z-direction. Voltages of opposite polarity are produced by the rising and falling edges of each gradient pulse – we calculated half the difference in the average of these to form a measure of the induced voltages – and it is evident that only the voltage due the z (FH) gradient changes appreciably (and linearly) with z-position, as would be expected. The voltages induced in this coil by the RL and AP gradients depend on the constant, x and y co-ordinates of the coil. Figure 3 shows voltages generated in the 5 different coils by the 3 different time-varying gradients as the rig is moved in 2 mm steps in the z-direction, for numerical simulations and experimental measurements. Simulations are in good agreement with measurements and it is clear that the largest changes in voltage with z-position occur in Coil 1 for the z-gradient, Coils 2 &3 for the x-gradient and Coils 4 & 5 for the y-gradient. This pattern of variation and those due to translation in the x-, y- and z-directions and for rotation about the x- and y-axes, are depicted in Figure 4, which maps the coefficients of the matrix A that translates co-ordinate changes into the voltages induced by the 3 gradients in the 5 coils. These coefficients were found by linearly fitting the simulated and measured voltages with respect to the positional change. There is again reasonable agreement between measurement and simulation, particularly for translations; the discrepancies for rotation may reflect the effect of non-linearity in the voltage variation over range of angles studied. The significant differences in the patterns of voltages produced by different types of movement are promising for the prospect of decomposing the voltages generated by a general small movement into a linear superposition of these patterns and thus identifying the motion parameters.

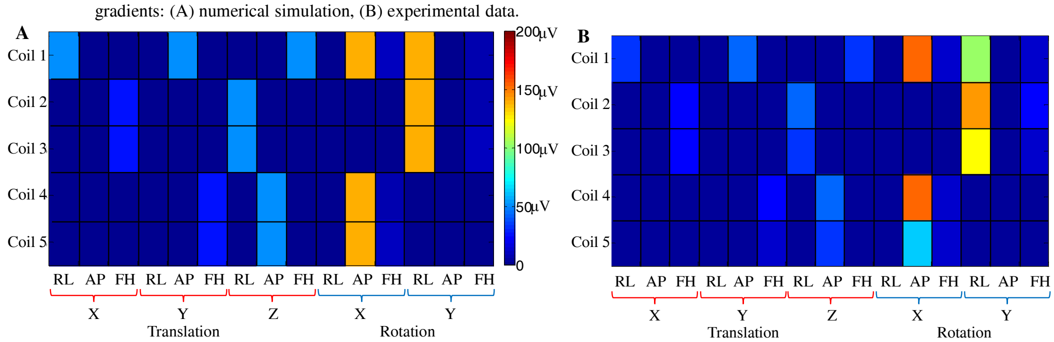

Fig. 4: Coefficients of the matrix A for a system of linear equation AX = V. (A) numerical simulation, (B) experimental data. Colour-bar shows μV/mm for translation and μV/degree for rotation.

References: [1] McLaren *et al,* Magn. Res. Med. 69, 621-636, 2013; [2] Welch *et al,* Magn Reson Med 47, 32–41, 2002; [3] Ooi *et al*, Magn Reson Med 62, 943-954 2009. [4] Bencsik *et al,* Phys. Med. Biol. 47, 557(2002).