Magnetic field gradient waveform monitor (MFGM)

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INTRODUCTION: Fast, efficient MRI measurements rely on magnetic field gradient system with high fidelities. Great hardware improvements, such as actively shielded gradient coil and delicate gradient waveform pre-emphasis, have been made to meet this goal. Modern MRI techniques, however, see a trend putting an increasing expectation on gradient system perfection [1]: single shot (EPI, RARE) and Non-Cartesian (radial, spiral) data acquisition, phase contrast imaging, diffusion weighted EPI, and the emerging techniques such as Ultrashort Echo Time (UTE) imaging [2]. Numerous methods have been developed to measure MRI gradient waveforms and k-space trajectories for correcting the remaining hardware imperfections. The most widely used method to characterize eddy currents behavior is a slice selection method by Duyn [3]. The most promising new strategy appears to be magnetic field monitoring (MFM) with RF microprobes [4].

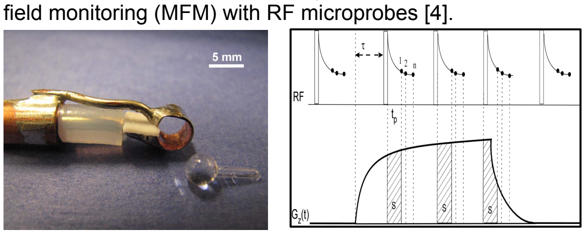

Fig. 1: MFGM probehead and pulse sequence

The new concept, pure phase encode magnetic field gradient monitor (MFGM), was recently proposed by us [5,6] to solve four critical problems related to the above two methods: (i) limited gradient waveform duration (100 ms); (ii) limited k value (1 mm^{-1}) / net gradient area (50 ms · mT/m); (iii) limited gradient strength (40 mT/m); (iv) susceptibility matched RF microprobes required. In the presented work an enhanced MFGM method is proposed to measure $B_0(t)$ field evolution associated with the gradient waveform. For the first time the four advantages outlined above are illustrated in a realistic application.

METHODS: The MFGM employs a NMR microprobe, Fig. 1(a), for measuring arbitrary magnetic field gradient waveforms and concomitant $B_0(t)$ field evolution. The pulse sequence is illustrated in Fig. 1(b). A small doped water phantom (dia 3 mm, T_2^*, T_2, T_1 ~ 100 μs) within a single turn solenoid RF coil was excited by a series of closely spaced broadband RF pulses. Repetitive FID signals are received by this microprobe. Each FID determines the amplitude at one specific time of a gradient waveform by a FID single point acquisition scheme, Fig. 1(b), S. With a FID multiple point acquisition, each FID determines one or several specific gradient amplitudes for a high temporal resolution or an increased data acquisition efficiency. Placing one MFGM probe at three different locations or using an array of three MFGM probes enables us to measure the gradient waveform G_x, G_y, and the associated $B_0(t)$ simultaneously.

With conventional MFM / Duyn slice selection, the measurable gradient waveform duration is limited by the transverse magnetization decay (sample T_2^*). This critical problem was solved by the presented method. Continuously RF pulsing permits arbitrarily long duration waveforms to be measured. MFGM has no limit on gradient area maximum / k maxima. In addition MFGM can readily measure gradient strength up to 3,000 mT/m. The NMR RF coil utilized is extremely easy to fabricate, compared with MFM RF microprobes. Susceptibility matching for improved static field homogeneity is not required.

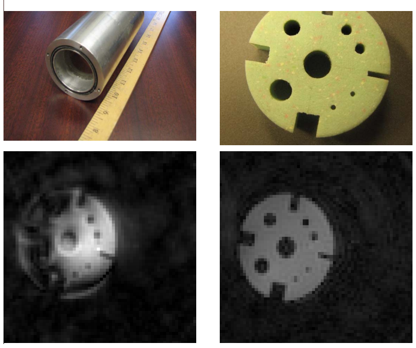

Fig. 2: Imaging within aluminum vessel. Phantom photo (top right), uncorrected image (bottom left), corrected image (bottom right).

RESULTS AND DISCUSSION: The enhanced MFGM was used to measure and correct the large eddy currents for imaging within or around a metal device. Fig. 2(a) shows a highly conductive metal structure. Though such conductive metal structures are critical elements in some MRI applications [7], the presented work portrays it as an extreme example for MFGM applications in MRI. The vessel was carefully centered inside a gradient set along the B_0/G_z axis on a 2.4 T small bore superconducting magnet. The goal was imaging with an RF coil which was within the aluminum vessel. A resolution phantom image using single shot Spiral SPRITE [8] is shown in Fig. 2 (b). MFGM probe was placed at three different locations inside the aluminum vessel to monitor the gradient behavior. The measured gradient waveforms and B_0 field are shown in Fig. 3(a). The accurate knowledge of true gradient waveform allows different image correction strategies. Digital adjusting / pre-emphasizing the gradient waveforms is a possible option. Alternatively a simple interpolation gridding correction was chosen. The actual k-space locations for Spiral SPRITE were calculated from measurements, as shown in Fig. 3(b). The B_0 phase shifts for each k-space were also calculated from $B_0(t)$ field measurements. From Fig. 3(b), the ideal Spiral SPRITE acquires k-space data on rectilinear grid points and the actual k-space sampling is no longer Cartesian due to eddy currents. A straightforward cubic polynomial interpolation was used to grid the non uniformly sampled data. The B_0 phase Shifts were also corrected for each k-space sample. The image with both G(t) and $B_0(t)$ corrected was shown in Fig. 2(c).

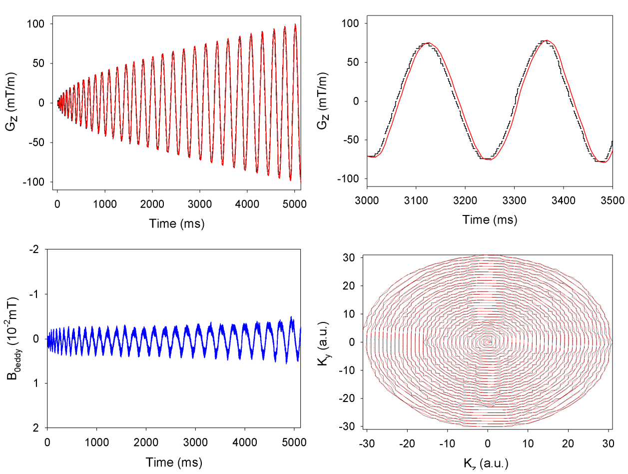

Fig. 3: MFGM measurements. Top: Spiral SPRITE G_z monitored (red) vs ideal (black). Bottom left: monitored B_0 field. Bottom right: k-space trajectories monitored (red) vs ideal (black).

CONCLUSION: A novel pure phase encode magnetic field gradient monitor (MFGM) for measuring gradient waveforms and concomitant $B_0(t)$ field is presented. Due to its merits MFGM has a great petential of use in a wide range of MRI applications.

REFERENCES: **[1] M.A. Bernstein et al. Handbook of MRI pulse sequences, 2004. [2] I.C Atkinson et al. Magn Reson Med. 62 (2009) 532-537. [3] J.H. Duyn et al. J. Magn. Reson. 132 (1998) 150-153. [4] C. Barmet et al. Magn Reson Med. 60 (2008) 187-197. [5] H. Han et al ISMRM workshop, Arizona, U.S Jan 2009. [6] H. Han et al. J. Magn. Reson, in press (2009). [7] Z. Zhang et al J. Magn. Reson. 193 (2008) 259-266. [8] H. Meghan et al J. Magn. Reson. 165 (2003) 219-229.**