Novel Method to Measure and Characterize Shim Induced Eddy Current Fields with Calibration Applications for Dynamic Shim Updating at 7T

Alex A Bhogal[1], Jos Koonen[2], Jeroen Siero[3], Vincent Boer[3], Dennis Klomp[3], Peter Luijten[3], and Hans Hoogduin[3]

[1]*Radiology, University Medical Center Utrecht, Utrecht, Utrecht, Netherlands,* [2]*Philips,* [3]*Radiology, University Medical Center Utrecht*

Introduction: Dynamic Slice Based shimming at high field is gaining interest [1]. Rapidly switching shim fields between slice acquisitions improves overall B0 homogeneity but induces Eddy Current (EC) fields that must be characterized and compensated for. Methods used to achieve this have been based on 1D linear projection spin echo sequences or field probe assemblies [2][3]. Using linear projections, distinct measurements must be repeated to attain sufficient non-degenerate data for EC field characterization. Correct spatial refocusing of spins in the presence of field inhomogeneities can be difficult. Sampling EC fields using field probes is an attractive alternative however building the required setup is expensive and technically challenging. Here, a novel method is presented to measure and characterize EC fields generated due to the rapid switching of shim coils. Results are used to calibrate a Dynamic Shim Updating (DSU) unit for pre-emphasis and eddy current compensation for slice-based applications without the need for field probes or projection based measurements. Complete 3D datasets are acquired providing complete spatio-temporal characterization of eddy field self and cross terms for up to third order.

Materials and Methods: All measurements were done on a Philips 7 Tesla system (Philips, Cleveland, OH, USA). The 7T scanner is equipped with non-superconducting shim coils up to third order. These include both shielded Z2S and unshielded Z2 coils and a shielded Z0S coil. Shim coils are driven by external amplifiers (+/- 10A) linked to a Dynamic Shim Updating unit (Resonance Research Incorporated, Billerica MA). Phase images of a spherical phantom (diameter = 10cm) containing a $CuSO_4$ solution (100g of $CuSO_4$ per 1000ml of H2O) were acquired. This phantom allows the use of very short repetition times (TR) without the need for crusher gradients or RF spoiling techniques. The sequence depicted in fig 1 was used to measure time-varying phase changes due to EC field effects. To generate EC fields, a 7A shim step was switched on for a 3s settling time (Ts). One line in K-space consisting of 32 points was sampled in each 5ms TR. This process was repeated N times (N = 601) for each phase encoding step (Py and Pz). The final N 3D volume datasets contained the time-evolution of phase data over 3005ms. A reference dataset was acquired in a similar way without stepping any shim coils. Shim fields up to third order were spatially fit to each of the phase datasets. Subtraction of the reference dataset from the EC dataset eliminated any background field contributions present in the phantom itself. Field decay curves (as functions of the fitted Spherical Harmonic (SH) function co-efficients) were temporally fit to a triple exponential function. The resulting amplitudes and time constants were used as inputs into the DSU unit for pre-emphasis and compensation.

Results: Fig 2 displays the time evolution of SH co-efficients over 3005ms derived from fitting a reference dataset and a dataset in which the Z2X shim was stepped at 7A (scaled to 10A). Z2X compensation results using a shim step of -5A (scaled to -10A) up to 505ms (N=101) are also shown. The relative strength of the eddy current fields (in terms of fitted co-efficients) and the strengths of all cross terms produced by shim steps (scaled to 10A) are provided in table 1. Diagonal elements represent self-term eddy fields and remaining values represent associated cross-terms. The threshold used to identify whether the co-efficient range was sufficient to indicate a significant cross-term was defined as being 3 times the noise level [4]. These ratios represent the factor by which the magnitude of measured field exceeds the noise level for a given term. The maximum self-term fields strengths (Hz/cm^n) are provided.

Conclusion: The calibration technique described herein characterizes the behaviour of self and cross-term eddy current fields generated by switching shim coils up to third order. Using a larger phantom, this method can be used to fit shim fields up to any order without additional measurements or field probe hardware.

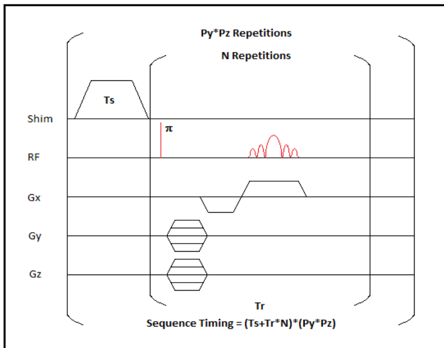

***Figure 1**: Eddy Current Measurement Sequence*

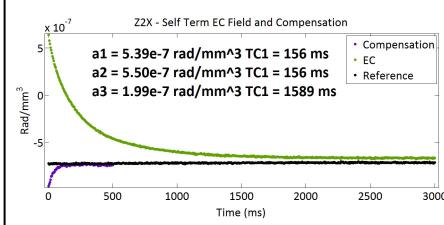

***Figure 2**: Fitted SH co-efficients for Z2X self term field and no-shim reference scan. Amplitudes and time constants for triple exponential temporal fits are provided. Results from compensation also shown over 505ms.*

Switched Term	Fitted Term															
	X	Y	Z	Z2	ZX	ZY	X2-Y2	2XY	Z3	Z2X	Z2Y	Z(X2-Y2)	ZXY	X3	Y3	F0
Self Term (Hz/cm^n)	2.00	2.69	1.53	.008(Z2S)/ 4.23	7.82	7.84	6.15	6.20	.007	.008	.008	0.41	0.42	0.15	0.15	.0046
X	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Y	-	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Z	-	-	6	-	-	-	-	-	-	-	-	-	-	-	-	-
Z2S	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5
Z2	7	-	6	79	7	-	-	-	-	3	-	-	-	3	-	289
ZX	5	-	-	-	203	-	-	-	-	-	-	-	-	-	-	-
ZY	-	7	-	-	-	83	-	-	-	-	-	-	3	-	-	-
X2-Y2	6	3	4	-	-	-	121	4	-	-	-	-	-	3	-	-
2XY	-	8	-	-	-	-	-	390	-	-	-	-	-	-	3	6
Z3	-	-	135	3	6	-	-	-	12	-	-	-	-	-	-	-
Z2X	136	-	-	3	10	-	3	-	-	41	-	-	-	3	-	4
Z2Y	-	187	-	-	-	3	-	5	-	-	21	-	-	-	-	-
Z(X2-Y2)	3	-	5	-	7	-	4	-	-	-	-	59	-	-	-	5
ZXY	-	5	6	-	-	-	-	8	-	-	-	-	103	-	-	3
X3	4	-	-	-	-	-	-	-	-	-	-	-	-	46	-	10
Y3	-	8	3	-	-	-	-	4	-	-	-	-	-	-	73	7
F0S	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 1: Fitted values represent the ratio of the range of the fitted co-efficients between EC and reference datasets. This ratio defines the magnitude by which self and cross terms exceed the noise levels for each shim term over a 3005ms time period. The strength of measured self term fields are provided in Hz/cm^n. A '-' indicates that the range of fitted co-efficients did not significantly exceed noise levels.

Acknowledgements: This study was part of the EU Artemis high profile project.

References: [1] Koch et al JMR(180) 2006 [2] Gruetter R. et al MRM(29) 1993, [3] Barmet C. et al MRM(60) 2008 [4], Juchem C. et al CMRB(37B) 2010