Low-noise Broadband Receive Amplifier for Real-Time Magnetic Particle Imaging

I. Schmale[1], B. Gleich[1], J. Rahmer[1], C. Bontus[1], J. Kanzenbach[1], J. Schmidt[1], O. Woywode[2], J. Weizenecker[3], and J. Borgert[1]
[1]Philips Research Europe, Hamburg, Germany, [2]Philips Medical Systems, Hamburg, Germany, [3]University of Applied Sciences, Karlsruhe, Germany

Introduction

Magnetic particle imaging (MPI) is a new tomographic imaging modality first presented in 2005 [1]. It directly and quantitatively images the concentration of iron-oxide nano-particle. By means of a broadband data acquisition, MPI also is a very fast imaging modality allowing real-time volumetric imaging [2, 3]. After a motivation for broadband reception, this abstract describes the inherent challenges of and a technical solution for a low-noise broadband receive amplifier for MPI. This new amplifier is part of a new pre-clinical MPI system with ~12cm bore size.

Methods

MPI is based on the non-linear response of iron-oxide nano-particles to an applied oscillating magnetic field. Higher harmonic and mixing response frequencies are generated, which need to be detected over a broad frequency range. Spatial encoding is achieved using a *selection field* that confines the signal response to a small region called the *field-free point* (FFP). The FFP is rapidly moved over the object of interest using *drive fields* in three orthogonal spatial directions. With different drive field frequencies in all 3 directions (24.51kHz, 25.25kHz, 26.04kHz), the FFP follows a 3D-Lissajous trajectory, along which the field-of-view is sampled [1, 3].

The speed of any imaging modality, expressed in terms of voxels/second, directly depends on the bandwidth of the acquired signal, provided SNR is sufficient. In an attempt to capture as many harmonic and mixing response frequencies as possible, the MPI receive bandwidth covers 50kHz to 1MHz. A repetition rate of the Lissajous pattern of 46.42/s allows to receive 950kHz / 46.42Hz ~ 20000 response frequencies simultaneously. For the currently used particles, insufficient SNR leave ~10000 frequencies useful for image reconstruction.

In order to be able to capture such a large number of frequencies, an extra effort in broadband reception has to be made, as the receiving element is a high-Q coil. Whilst its impedance $Z = 10\mathrm{m}\Omega + j\omega\ 15\mu\mathrm{H}$ is dominated by the inductance, it is the small resistance, to which the receive amplifier needs to be noise-matched. *Narrow-band* noise matching is straightforward and can give ultra-low noise performance at and very near to the design frequency [4]. However, the matching circuitry itself, with its additional reactive elements, drastically increases the noise figure at all other frequencies. It can be shown that *broadband* matching of a single receiver to a high-Q coil can never be realized [5], no matter how complex a network might be conceived. Nevertheless, very satisfactory noise factors can be achieved by abandoning the small-band matching approach and simply choosing the best transistor type with respect to noise performance. JFETs are preferably applied in view of their very low minimum equivalent noise temperature of less than 1K at 1MHz and their low 1/f noise corner frequency.

Based on these considerations, a modular oil-cooled receiver (20°C) has been developed, in which up to 32 assemblies of 12 NXP BF862 Si-JFETs operate in parallel. The input-referred voltage noise density u_n of a single JFET corresponds to a resistance of $R_n=2/3*1/g_m$. Given a trans-conductance $g_m = 40\mathrm{mS}$, this yields $R_n = 17\Omega$ and $u_n = \sqrt{(4kTR_n)} = 0.52\mathrm{nV}/\sqrt{\mathrm{Hz}}$. With e.g. 200 transistors in parallel, we reduce R_n to $85\mathrm{m}\Omega$ and u_n to $37\mathrm{pV}/\sqrt{\mathrm{Hz}}$ without sacrificing bandwidth.

Results and Discussion

Figure 1 shows the resulting noise factor (referred to a fixed $10\mathrm{m}\Omega$ source resistance) as a function of frequency and of JFET count based on a complete noise model including input-referred voltage and current noise. A trade-off between bandwidth and noise factor becomes visible: the more JFETs, the better the noise factor at lower frequencies, but the smaller the bandwidth. Near to the minimum, at which voltage and noise current contributions are equal, the JFET input capacitance (C_{iss} ~ 10pF) resonates with the coil inductance. Beyond that resonance, the received signal is basically short-circuited by the JFET input capacitance leading to a sharp rise in noise factor, and hence, a restriction in upper bandwidth.

In the pre-clinical MPI demonstrator, the actual number of employed JFET assemblies, therefore, is variable in order to adapt to the optimum w.r.t. image quality. In particular, the signal strength at the response frequencies depends on the properties and concentration of the nano-particles. A higher signal strength permits to use a receiver configured with a smaller number of parallel JFETs and hence a higher maximum noise factor, in order to achieve a larger reception bandwidth.

Future calculations should include frequency dependence of the Litz-wire based coils and temperature dependence of the JFET's noise mechanisms. These will be the key tuning parameters on the path towards a broadband MPI system dominated by patient noise.

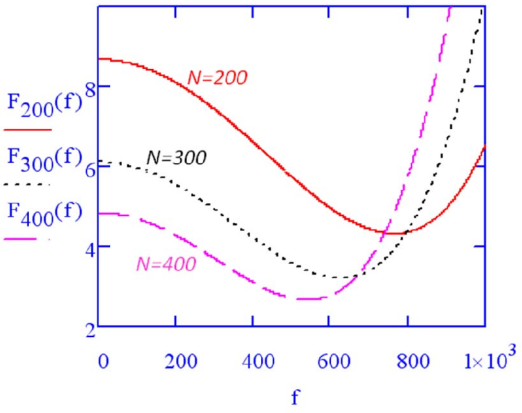

Figure 1: Noise factor as a function of frequency f (in kHz) for several numbers N of parallel JFETs.

Conclusion

Despite theoretical limitations on broadband matching, we demonstrated that low-noise reception is feasible when using the optimal transistor type and count whilst completely waiving a matching network. This allows collecting 10000 frequencies from a wide frequency range, enabling rapid high-resolution spatial encoding as necessary for real-time 3D magnetic particle imaging.

References

[1] Gleich B and Weizenecker J. Tomographic imaging using the nonlinear response of magnetic particles. Nature 435:1214-1217 (2005).
[2] Weizenecker J, Gleich B, Rahmer J, Dahnke H, Borgert J. 3D real-time in vivo MPI. Phys. Med. Biol. 54:L1-L10 (2009).
[3] Schmale I. et al. An Introduction to the Hardware of Magnetic Particle Imaging. WC2009, IFMBE Proc. 25/II:450-453 (2009)
[4] Goodwill PW, Scott GC, Stang PP, Conolly SM. Narrowband Magnetic Particle Imaging. IEEE Trans. Med. Imag. 28:1231-7 (2009).
[5] Fano R. Theoretical limitation on the broadband matching of arbitrary impedances. MIT Research Lab Techn. Rep., no. 41 (1948)
[6] Tietze-Schenk Halbleiter-Schaltungstechnik Springer (1999)