AUTOMATIC DEACTIVATION DESIGN FOR PHASED ARRAY SURFACE PROBE IN 1.5T MRI

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Abstract: We have designed and developed an automatic switching mechanism that deactivates and activates a reception coil during the MR experiment according to the phase it is at. The mechanism uses a feedback loop in which a comparator defines whether the current reception signal derives from the RF excitation pulses or the MR signal and then triggers an analog switch at the back-end of the coil accordingly. We applied the mechanism on a custom-made four channel phased array probe and tested its functionality by transmitting RF pulses to the probe of similar length and power to those used in actual MRI systems. The results presented in this paper demonstrate the robustness of the design and its switching accuracy.

1 INTRODUCTION

In the last ten years there has been much progress in the development of fully autonomic probes for MR Imaging and Spectroscopy. In most of the experimental attempts, emphasis is given on the automatic tuning and matching (Hwang and Hoult, 1998; Pérez de Alejo et. al., 2004) of the coils in order to improve the signal-to-noise ratio (SNR) values and accelerate the initialization procedures that keep the patient for an extensive period of time in the MRI bore.

All automatically tuned and matched coils require being compatible with the pulse sequences used in the MR experiment, which implies detuning of the coils during the RF pulse transmission and re-tuning for the MR signal reception. A series of complex automatic deactivation techniques have been developed and tested in the past (Venook et. al., 2005), which function in parallel with the tuning and detuning procedures but suffer robustness and poor results.

The most common deactivation technique that has been applied in both conventional and experimental non-automatic configurations is the use of PIN diodes at the back-end of the probe (Yung et. al., 2003; Barberi et. al. 2000). These configurations, however, are totally dependable on the external signals that the MR scanner supplies in order to turn on or off the PIN diode.

In this study, we present a simple and robust automatic design that undertakes the responsibility of deactivating and activating the probe during the RF pulse transmission and the MR signal reception phase respectively. The design does not require the presence of any external signals and is fully functionable with a large variety of RF pulse lengths and powers.

2 MATERIALS AND METHODS

The automatic deactivation circuitry that was constructed was applied on a prototype human prostate phased array probe, which we designed and developed after simulation modelling and laboratorial measurements.

2.1 Probe Design

The probe is consisted of four rectangular coils of dimensions 8 × 16 cm and the material that was used for their construction was copper tape 1 cm wide and 1 mm thick. The coils are distributed into two pairs of adjacent elements and each pair is positioned inside an orthogonal shaped conductor frame made of acetal (Fig. 1A). When a patient is examined the two frames are locked at a fixed distance so the elements are placed at the center posterior and

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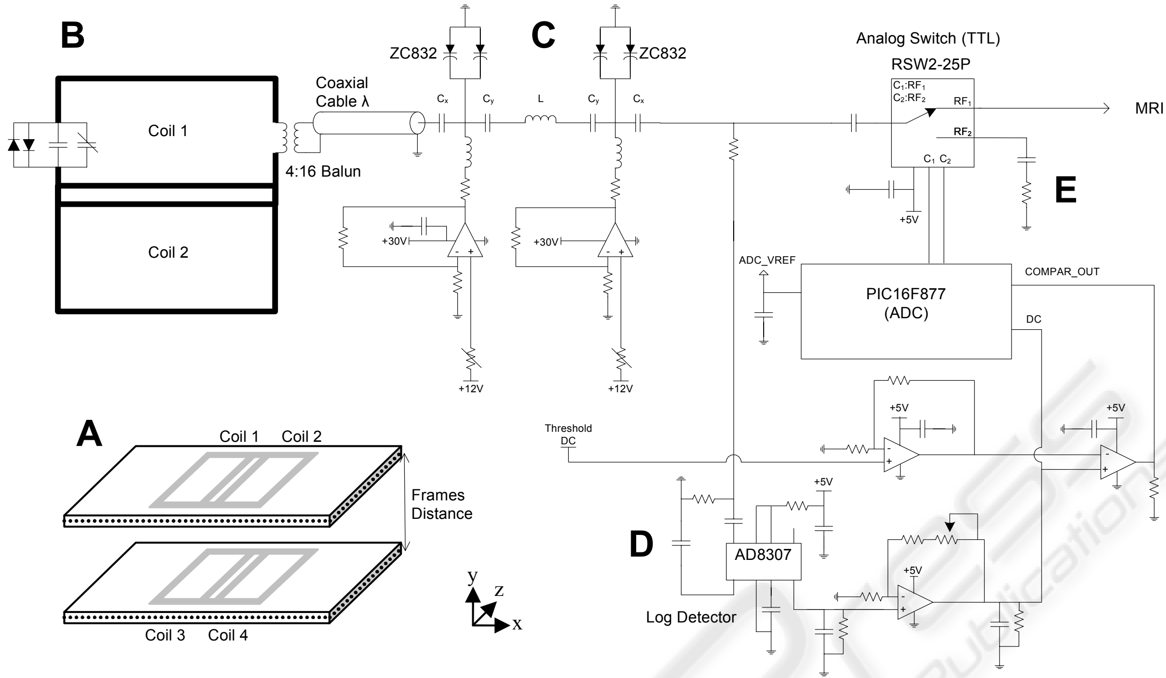

Figure 1: Phased Array probe's design and circuit diagram. Two pairs of coils are positioned inside two acetal frames (A). Each coil carries two antiparallel crossed diodes for passive blocking and a variable capacitor for tuning (B). The fine-tuning/matching circuitries are positioned on four PCBs at λ distance away from the elements. Each PCB includes the automatic deactivation circuitry that interacts with the probe through a feedback loop. The tuning section (C) uses two pairs of ZC832 varactor diodes in a pi-network to match the output impedance. The feedback section (D) rectifies the RF pulses into DC signals, which are then compared to a threshold DC value. The comparator's output is processed in the microcontroller (E), which determines when the probe is in the activation and the deactivation phase and controls an analog switch that connects the probe to the MRI scanner.

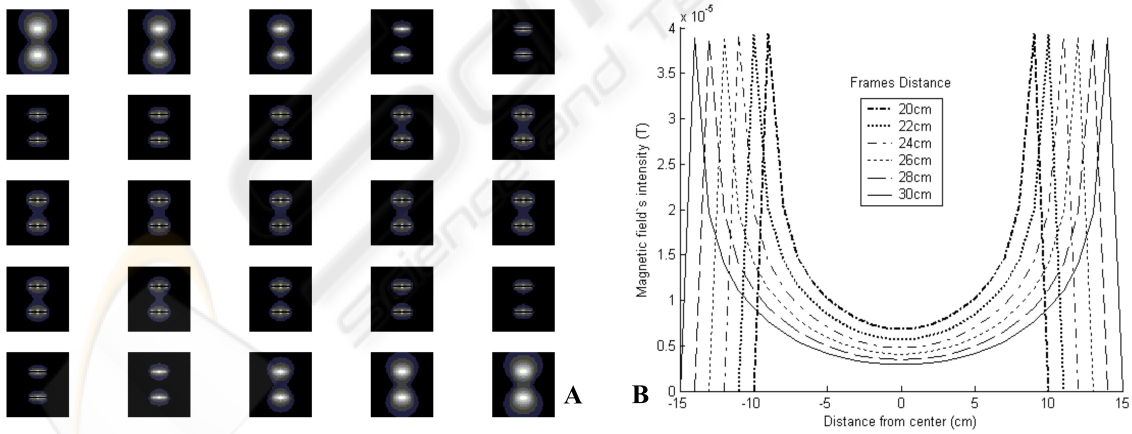

Figure 2: Probe's theoretical simulation results. (A) Computed magnetic field's intensity distribution on various xy planes for frames distance 24 cm. (B) Magnetic field's intensity at the line that connects the centers of the parallel frames for various frames distances.

anterior surface of the pelvic area in order to achieve optimum phased array performance.

Magnetic field and inductance calculations were carried out using the Biot-Savart integral expression (Wright and Wald, 1997). The configuration of the probe was modelled with simulation programming in order to measure the magnetic field's intensity in all three dimensions (Fig. 2A) and calculate the intensity's drop percentage at the center of the pelvic region in comparison to the intensity 1 cm away from the coils at the surface of the test object. The theoretical measurements were done for various distances between the frames of the probe and the results showed that the drop percentage does not fall under 7.66% in the worst case scenario of frames distance 30 cm (Fig. 2B).

The method that was used for the adjacent elements decoupling was overlapping (Roemer et. al., 1990). Theoretical calculations with simulation programming indicated that the distance the adjacent coils should have in order to minimize the mutual inductance is 6.7 cm. That translates in 8-6.7=1.3 cm coils overlap.

The probe is enhanced with a passive blocking network of two anti-parallel high speed diodes (Fig. 1B) that behave as a short circuit when they are forward-biased and serve as a safety precaution for the rest of the system's electronics (Noeske et. al. 2000; Zhang and Webb, 2005). 4:16 balun elements at the back-end of the rectangular loops convert the balanced output signal of the coils to 50 Ohm unbalanced. The tuning and the matching of the probe is manually controlled from a variable non-magnetic capacitor and 2 pairs of varactors in a pi-network (Fig. 1C), which lies one wavelength (λ) away from the coils.

2.2 Automatic Deactivation Design

The function of the MR probe is divided into two phases: the RF pulse transmission phase, during which the probe should be deactivated and disconnected from the MR scanner and the MR signal reception phase, during which the MR probe should be activated. The transition of the probe from the deactivation to the activation phase is controlled by the automatic deactivation circuitry, which connects between the probe and the scanner's preamplifier. The design of the circuitry is based on a feedback loop, which uses the probe's reception signals to define the phase that it is at.

An analog switch (RSW2-25P) is used to block the output of the probe from connecting to the MR scanner, when the RF pulses are transmitted. The switch is triggered by two signals (C1, C2) that a microprocessor sends (Fig. 1E). When the C1 signal is on (activation phase), the RF1 position of the switch is short-circuited and the scanner receives the MR signal. Contrarily, when the C2 signal is on (deactivation phase), the RF2 position is short-circuited and the high-power transmitted RF pulses are grounded, protecting the scanner's preamplifier. The decision between triggering signal C1 or C2 is taken from a comparator (LM393AD), which compares a pre-defined threshold DC voltage with the output DC signal that is rectified from the transmitting RF pulses, using a log detector (AD8307) and two RC low-pass filters (Fig. 1D). Consequently, when the high power RF pulses are transmitted, then the output DC signal's amplitude is higher than the threshold voltage, the analog switch is turned off and the probe enters the deactivation phase (C2 signal triggering). Contrariwise, when the output DC signal's amplitude is lower than the amplitude of the threshold, the analog switch is turned on and the probe is re-activated (C1 signal triggering), receiving low power MR signal from the hydrogen molecules' resonance.

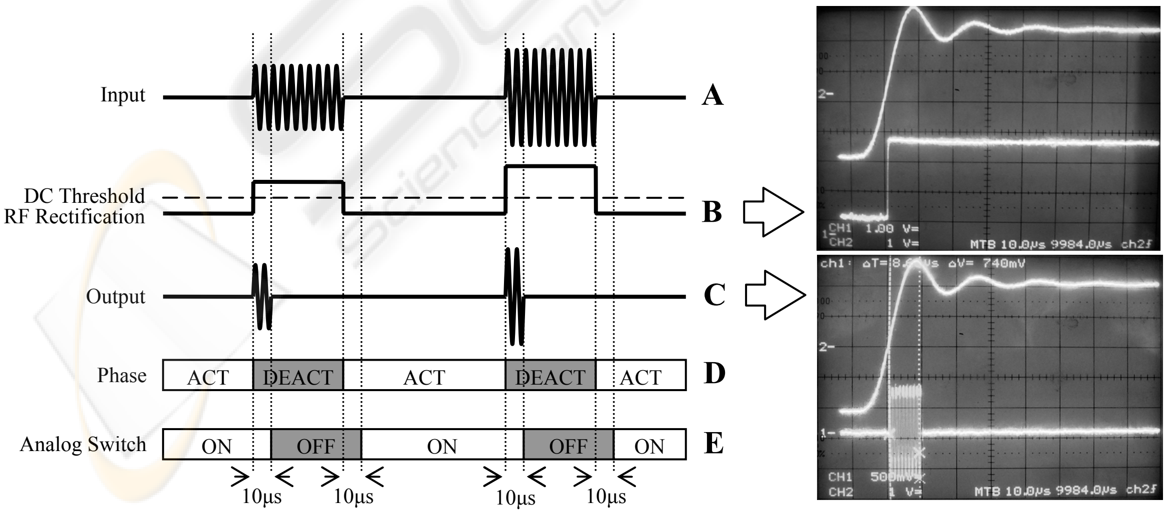

Figure 3: Switching mechanism's experimental results. (A) Transmitted RF pulses that are used as input to define the experiment's phase. (B) DC pulses produced from log detector's RF rectification (lower line in first combiscope figure). (C) Analog Switch's output (lower line in second combiscope figure). 10μs delay was calculated during the switching of the phase. (D) Optimum analog switch's behaviour following the experiment's phases. (E) Actual analog switch's behaviour with the undesired latency. Upper line in both combiscope figures depicts the trigger that generates the RF pulse.

3 RESULTS

Before the testing of the automatic deactivation circuitry we tuned and matched the coils of the probe in the Larmor frequency (63.87 MHz) by applying an average human pelvic region load on the frames and adjusting the values of tuning components. Using the network analyzer (HP8719D) to measure the reflection coefficient we managed to drop the S_{22} parameter at -55 dB, keeping the resonance frequency range below 250 KHz, which led to very accurate tuning. The decoupling between the adjacent elements was also successful, since the transmission coefficient S_{12} drops below -30 dB.

The functionality of the analog switch was tested in the laboratory using a Signal Generator (HP ESG-4000A) and a Combiscope (FLUKE PM3380B). RF pulses of the same power and length with those transmitted from the MRI system were created in the Signal Generator and were sent to the probe as input. The RF pulses varied in length from 2-5 ms and in power from 5-20 dBm.

The first set of measurements examined the log detector's functionality. Specifically, we measured the DC signal produced from the RF pulse rectification (Fig. 3B). The resulting DC pulse is initiated and terminated almost immediately after the beginning and the end of the signal generator's RF trigger respectively. Also, the correspondent DC pulse's amplitude is equal to the RF pulse's amplitude as expected, allowing accurate comparison with the DC threshold.

The second set of measurements showed the output of the probe and verified the turning off and on of the analog switch during the activation and the deactivation phase respectively (Fig. 3C). A potential disadvantage of the method is that there is an undesired latency of 10 μs in the switching process that is capable of producing artifacts in the imaging data (Fig. 3E). The latency is caused mainly from the processing delays of the microcontroller that triggers the analog switch and remains constant without regard to the RF pulse length and power that is triggered.

4 DISCUSSION

Certain improvements could be applied on the automatic switching mechanism of the circuitry in order to overcome the presence of latency in the function of the analog switch. A way to reduce the latency is to control the switch directly from the DC signal that derives from the comparator's output, bypassing the time-consuming processing of the microcontroller.

Also, a practical problem could potentially appear in the clinical application of the automatic deactivation circuitry. The probe detunes itself automatically during the RF pulse transmission and does not require a decoupling signal from the scanner. However, many MRI scanners' protocols run primary tests on the connected probes by sending pulse signals in the opposite direction for software initialization. In that case, the switch would cause compatibility issues and the probe would not be recognized by the MR system.

Our prototype automatic deactivation design is a robust and simplified mechanism that can be applied on self-tunable MR coils. It was tested in various conditions and found to be fully functional and able to switch off or on the probe at all times.

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