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Technical note

Frequency-domain active noise control for magnetic resonance imaging acoustic noise

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ABSTRACT

The purpose of this paper is to propose a frequency-domain active noise control algorithm for acoustic noise reduction in magnetic resonance imaging and experimentally verify its feasibility. The sound pressure level of noise approaches up to 130 dB in 3 T magnetic resonance imaging. Even it's expected to increase for higher-resolution images in the future magnetic resonance. For this noise, some active methods have been researched, but the reduction performance is not enough to satisfy the safety standard. The noise in 3 T magnetic resonance imaging is measured and analyzed in the time-frequency domain. It has fundamental frequency with its higher harmonics, and the Fourier coefficients of all peaks are slowly varying over time. The variation is small enough, so it can be assumed that the noise is periodic in short time. Based on this assumption, the control signal is determined as the sum of sinusoidal signals designed by using the Fourier coefficients calculated from a fundamental period of noise, then it is applied to the next period. To do this in real-time process, domain transform algorithm, which is time to frequency based on discrete Fourier series, is developed with the same level of computational complexity compared to the conventional active noise control algorithm. Experimental results show approximately 35-dB overall reduction in the frequency range of interest (80–1600 Hz).

1. Introduction

Magnetic resonance imaging (MRI) is an important medical technique and continually used for the diagnosis of diseases and for biomedical researches. When it operates, however, intense noise is generated. The Sound Pressure Level (SPL) approaches up to approximately 130 dB especially in 3 T MRI. Moreover, it is expected that the SPL would increase in the future MRI because the strength of magnetic field will increase for higher-resolution image [1]. It's a safety risk because a patient is exposed to intense noise for over 20 min, and it makes the patient uncomfortable and nervous, and it can cause hearing loss in severe case [2]. Previous studies demonstrated that the noise is generated by vibration of gradient coil. It vibrates because the coils are inside permanent magnet and Lorentz force is applied by the electrical input signal called pulse sequence [3–5].

There are various approaches to reduce the noise. They have 3 categories in noise generation process. First, there are some approaches to control source of the noise. These approaches include modification of pulse sequence and redesign of gradient coil for force balance [6–8]. They were effective, but the performance is limited by trade-off between the resolution of images and noise reduction. Second, some passive methods are introduced. Sound absorbers or liners are applied inside MRI [9,10]. The space is not big enough, so it is mainly effective to reduce high frequency bands of the noise with small-size absorbers. Finally, active noise control (ANC) is applied for an alternative solution [11–14]. Some studies have been reported in the literature. Various algorithms are introduced and the performance is verified by computational simulation [15–18]. But, there are only a few experimental studies. Pre-record ANC showed maximum 40-dB and overall 20-dB reduction performance, but they referred practical limitation that the reference signal must be captured before cancellation [19]. Also, a hybrid algorithm is proposed for FMRI (Functional Magnetic Resonance Imaging) [20]. Simulations and experimental results showed that the hybrid algorithm is stable, has much better convergence speed, and shows faster tracking capability of changes in noise signal than the Filtered-input Normalized Least Mean Squares (FxNLMS) or Filtered-input Recursive Least Squares (FxRLS) algorithms individually. However, the testbed, in which the simulations and experiments are implemented,

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seems to be quite different from real MRI. For practical applications, additional experiments should be implemented. Nest, Self Optimizing Narrowband Interference Cancellation (SONIC) based on Adaptive Comb Filtering (ACF) is proposed [21]. They regards MRI noise is nonstationary. This algorithm is capable of tracking the fundamental frequency and amplitudes of different frequency components of a nonstationary harmonic signal embedded in white measurement noise. In laboratory tests, they show that the algorithm has a potential of operating for MRI noise, but the reduction performance is limited under 20 dB SPL. And multiple reference feedforward ANC algorithm is also proposed [22]. For the reference signals, both gradient excitation and microphone signals are used. In situ testing, they achieved maximum 21-dB overall. Finally, head-mounted ANC system showed maximum 30-dB and 20-dB overall reduction performance [23]. It can be applied for target point inside bore because the head-set consists of piezoelectric speaker and optical microphone which are robust to strong magnetic field. Using a feedback algorithm, the best results showed overall 20-dB reduction. With this results, 130-dB noise could be reduced down to 90-dB noise even with some passive means of maximum 20-dB reduction. It's not enough to satisfy the MRI safety standard.

In this background, we analyze the property of MRI noise by GRE, SPE sequences. And we develop novel ANC algorithm based on the property. Some simulation and experimental results will demonstrate the performance of algorithm.

2. Analysis of MRI noise

A SIEMENS MAGNETOM Verio 3T system (KAIST, Daejeon, Korea) is operated and the overview technical details are shown in Table 1.

MRI is operated with Gradient echo (GRE) and Spin echo (SE) as common pulse sequences in a closed room. The both of operating times are about 50 s for a 2D-image. An ECM microphone is set with distance 1.5 m distance from the bore to reduce the effect by magnetic field, and then we sample the acoustic signal from the microphone. The sampling frequency is 48 kHz which is enough to cover the frequency range of the microphone. The total experimental setup is shown in Fig. 1.

2.1. Time and frequency domain analysis

Figs. 2 and 3 show each sample of time-domain signals by each sequence. We observed that the envelope of each signal has repeating pattern and we could expect it's periodic as previous papers mentioned [24–26]. It's because that the pulse sequences (i.e. electrical input signal), as noise source, repeatedly drive gradient coils with a particular period (GRE: 175 ms. SPE: 100 ms). The pulse sequences is consists of three pulse sequence for three axes. Normally, two pulse sequences for slide selection and frequency encode are not changed by every period for a 2D-image, but the other pulse sequence for phase encode is changed by every period [27]. So we can expect the noise is not ideally periodic.

Table 1
Overview technical details about operated MRI.

Field strength	3 T
Bore size	70 cm Open Bore design
System length	173 cm
System weight (in operation)	8.2 tons
Minimum room size	33 m^2
RF Tim	[102 × 8], [102 × 18], [102 × 32]
Gradient strength	VQ-engine (45 mT/m @ 200 T/m/s)
Helium consumption	Zero Helium boil-off technology

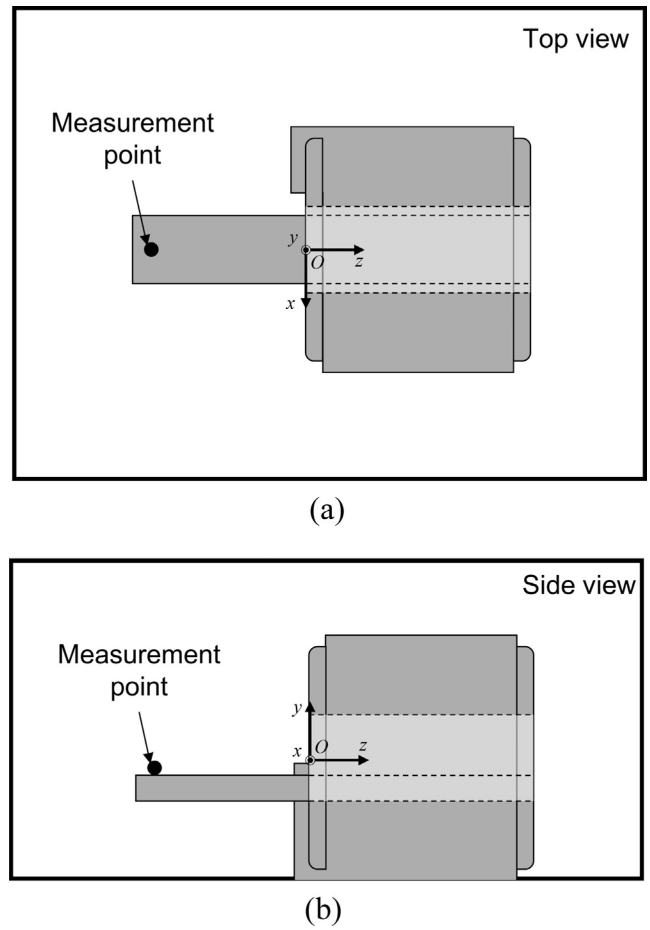

Fig. 1. The schematic diagram of measurement environment. (a) Top view. (b) Side view. The position of measurement point is (0, −0.1, −1.5) m.

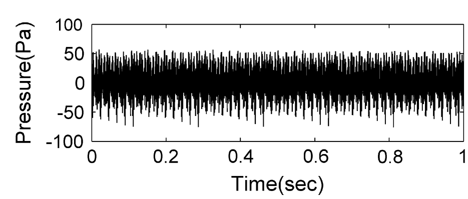

Fig. 2. The noise signal in the time domain by GRE sequence. (fundamental period: 0.175 s).

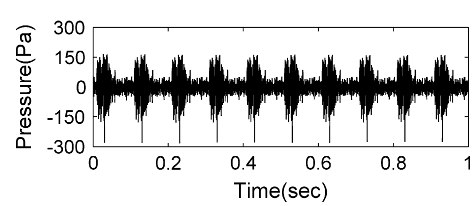

Fig. 3. The noise signal in the time domain by SPE sequence (fundamental period: 0.1 s).

To observe the signals in the frequency domain, power density spectrum (PSD) is calculated with signals for 45 s, and Fast Fourier Transform (FFT) length is the samples for 1 s, and windowing function is Hamming window, and the number of samples by which the sections overlap is a half of FFT length. Figs. 4 and 5 show PSD of each signal. Each has a different frequency components, and the overall envelope has different shape. But, both of them have own