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Technical Note

Comparison of mechanical vibration and acoustic noise in the open-air MRI

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ABSTRACT

The paper analyzes and compares spectral properties of an acoustic noise produced by mechanical vibration of the gradient coils during scanning in the open-air magnetic resonance imager (MRI) working in a weak magnetic field. Selection of a usable type of the vibration sensor and the noise pickup microphone for measurement in weak magnetic field conditions is also discussed. The changes in acoustic noise spectral properties caused by loading of the holder of the lower gradient coils by the weight of the examined person lying in the scanning area of the MRI device is analyzed, too. The achieved results will be first of all used to design a correction filter for noise suppression in the speech signal recorded simultaneously with 3D human vocal tract scanning. Finally, the paper describes measurement and determination of the time delay between the resulting noise signal and the vibration impulses originated in the gradient coils. The obtained results will serve for description of the influence of the vibration on the acoustic noise and the way it travels through the plastic holder in the MRI device scanning area.

1. Introduction

The magnetic resonance imaging (MRI) technique is often used in the clinical practice for non-invasive MR scanning and testing of biomedical samples [1,2], as well as different parts of a human body [3,4]. The purpose of MRI scanning of the human vocal tract is to develop 3D models [5] showing propagation of the sound wave in the vocal tract during phonation in real clinical situations, e.g. in observing the influence of various inborn defects in human supraglottal spaces on speech and voice, or simulation of various post-surgical states in patients after oral or throat surgery. The 3D finite element modeling enables also to simulate the influence of the acoustic impedance changes of the vocal tract by phonating into glass tubes or straws used in voice training and therapy [6]. In this case, the MR scan of the human vocal tract structure is carried out simultaneously with recording of a speech signal [7]. On the other hand, this type of MRI devices can also be applied for testing and analyzing of the diamagnetic and paramagnetic materials widely used for body implants or dental casting alloys [8], the soft magnetic materials [9], or the thin layer magnetic materials [10].

The MRI equipment contains a gradient system consisting of three gradient coils that produce three orthogonal linear fields for spatial encoding of a scanned object. Fast switching of the excitation current inside these gradient coils is accompanied by rapid changes of the Lorentz forces. In the static field B_0 environment the significant mechanical pulses cause secondary vibration of the MR scanning area [11].

The whole vibrating structure is surrounded by the air that represents an environment for propagation of a progressive sound wave received by the human auditory system as a noise [12,13]. The frequency spectrum of such a noise has significant components in the audio frequency range [14]. In addition, due to its harmonic nature the acoustic noise produced by this device can generally be treated as a voiced speech signal and it can be analyzed using similar methods as those used for speech signal analysis [15]. Such an approach is very important when the acoustic noise must be suppressed to obtain the speech signal with good quality, e.g. for recording of the human phonation in the noisy MRI environment. We have successfully used the noise reduction method based on limitation of the real cepstrum and clipping of the spurious peaks corresponding to the harmonic frequencies of the mechanical noise [16]. This method works well when the basic pitch period of the human voice differs from the repeating period (given by the TR time) of the running MR scan sequence. In this case, other approaches – usually based on the spectral subtraction – must be used. Application of the two channel noise reduction method [17,18] assumes the use of two recording microphones: one for

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picking up of the noise signal only and the second one for recoding of the superimposed speech and noise signals. Practical realization of this two microphone recording is unrealizable in our conditions, so we use a one-channel modification of the spectral subtraction method. The recoding arrangement uses only one microphone, however, in the first stage only the noise of the running scan sequence is picked up and then the speech signal of phonation with the noise is recorded.

The main motivation of our work was to compare spectral properties of the mechanical vibration and the acoustic noise in the scanning area or/and neighborhood of the MRI equipment working with magnetic field of low magnetic induction B_0 up to 0.2 T. For this measurement, the tested water phantom inserted in the scanning RF coil is used [9,10]. The secondary acoustic noise produced by the vibration in the MRI device is measured and recorded by a microphone. In the first place, the paper deals with selection of a usable type of a vibration sensor and a recording microphone working in a weak magnetic field of the MRI device. Measurement of the directional pattern of the acoustic noise source in the MRI scanning area for optimal design of the arrangement of the noise recording experiment is described next. Simultaneously with noise recording by a microphone, the sound pressure level was measured with the help of a sound level meter for the most frequently used 3D types of scanning sequences implemented in the MRI device. The situation changes when the examined person lies in the scanning area of the open-air MRI and the holder of the lower gradient coils is loaded with his/her weight. Then, the change in spectral properties of the generated acoustic noise is expected, too. To verify this working hypothesis, the noise signal recording and its spectral analysis were performed for different person weights and with the water phantom only (for comparison). And finally, to describe formation of the acoustic noise caused by the vibration and to describe how this vibration travels through the plastic holder of the MRI device scanning area, the time delay between the vibration impulses originated in the gradient coils and the noise signal has to be determined. The obtained results will help to improve the developed cepstral-based and spectral subtraction methods of noise reduction [15,16] in the speech signal recorded during phonation in an MR imager for the human vocal tract modeling.

2. Subject and method

2.1. Sensors for measurement of vibration and noise in the scanning area and the MRI neighborhood

To obtain MR pictures with sufficient quality without any artifacts, interaction with the stationary magnetic field B_0 in the scanning area must be eliminated during the measurement of vibration or noise signals. During the MR scan the signal from the sensor would be heavily disturbed or the electronic circuits could be destroyed due to the high voltage generated by the excitation RF coil of the MRI device. Therefore, we have finally used the vibration sensor based on piezoelectric principle, however, constructed for acoustic musical instruments recording. The majority of the harmonic frequencies of the recorded vibration and acoustic noise signals are concentrated in the low frequency band due to the frequency-limited gradient pulses [11]. For analysis and comparison, we are interested mainly in the frequencies of the range ⟨10 Hz–3.5 kHz⟩ which is similar to the basic frequency range of speech signals. As regards the vibration measurement, we finally decided to use the sensor SB-1 with a piezoelectric transducer mounted on the 1″ brass disc designed primarily for the contrabass pickup [19]. As the sensitivity and the frequency response are not well documented for this type of a musical sensor, its calibration was performed prior to the measurement procedure [20]. The sensor's frequency response in (dB) is calculated as a logarithmic measure of the normalized sensitivity

$$G_{a\log}(f) = 20 \cdot \log_{10}(B_a(f)/B_{a0}), \tag{1}$$

where B_a represents the acceleration sensitivity in (mV/ms^{-2}) and B_{a0} is the acceleration sensitivity at the reference frequency f_{ref}. The measured relative sensitivity B_a of the mentioned sensor is practically linear in the tested excitation voltage range of ⟨5–1050 mV⟩ – see Fig. 1a. Its frequency response as a logarithmic measure of the velocity sensitivity B_v (mV/ms^{-1}) in the tested frequency range ⟨20 Hz–2 kHz⟩ has a relatively flat character (the maximum ripple of 3 dB lies in the area of low frequencies 20–50 Hz) – see Fig. 1b.

In the case of the open-air MRI device with weak magnetic fields (up to 0.2 T) the interaction problem can be solved by the proper choice of the measurement arrangement where the pick-up microphone is located in a sufficient distance from the noise signal source outside the magnetic field area. There are only two requirements for choice of the recording microphone: good sensitivity and a proper directional pickup pattern. As the noise depends on the position of the measuring microphone, the directional pattern of the noise distribution in the MRI equipment neighborhood must be mapped. It means that the parameters of the optimal recording microphone position (the distance from the central point of the MRI scanning area, the direction angle, the working height, and the type of the microphone pickup pattern) must be chosen. The 1″ Behringer dual diaphragm condenser microphone B-2 PRO with the cardioid pickup pattern was finally chosen for noise signal recording in our measurement experiment.

2.2. Determination of spectral properties of vibration and noise signals

The basic as well as the supplementary spectral properties are usually determined from the frames (after segmentation and widowing). To obtain the smoothed spectral envelope, the mean periodogram can be computed by the Welch method [21]. For further detailed analysis the nearest region of interest (ROI) can be determined – see visualization in Fig. 2.

The periodogram represents an estimate of the power spectral density (PSD) of the input signal. When an N_{FFT}-point FFT is used to compute the PSD as $S(e^{j\omega})/f_s$ for the sampling frequency f_s in (Hz), the resulting spectral density in logarithmic scale is expressed in (dB/Hz) – see an example in Fig. 3.

The spectral properties include also the spectral decrease (tilt – S_{tilt}) representing the degree of fall of the power spectrum. It can be calculated by a linear regression using a mean square method. In the case of the supplementary spectral properties [22], the shape of the power spectrum $|S(k)|^2$ of the noise signal is determined using the additional statistical parameters [23]. The spectral centroid (S_{centr}) is defined as a center of gravity of the spectrum, i.e. the average frequency weighted by the values of the normalized energy of each frequency component in the spectrum

$$S_{\text{centr}} = \sum_{k=1}^{N_{\text{FFT}}/2} k|S(k)|^2 \Bigg/ \sum_{k=1}^{N_{\text{FFT}}/2} |S(k)|^2. \tag{2}$$

The spectral spread (S_{spread}) parameter represents the dispersion of the power spectrum around its mean value

$$S_{\text{spread}} = E(x-\mu)^2 = \sigma^2, \tag{3}$$

where μ is the mean value or the first central moment and σ is the standard deviation or the second moment of the spectrum values. The spectral skewness (S_{skew}) is a measure of the asymmetry of the data around the sample mean and can be determined as the third moment