Measuring MRI noise
Hoiting, Gerke Jan

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2005

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.
Chapter 4

Materials and methods

To compare the analysis of frequency modulated signals with Fourier transforms and the root-mean-square method, programmed test signals are fed directly to the gradient amplifiers of a Magnetic Resonance Imager.

4.1 Materials

All the experiments described in chapter 6 are performed on a 1.5 tesla Philips S15/ACS, located at the Magnetic Resonance Laboratories of the Eindhoven University of Technology. The gradient coils are driven by Copley Model 232M/S gradient amplifiers. Input signals to the gradient amplifiers are limited between $-10$ V and $+10$ V and the maximum gradient strength is 10 mT/m with a minimum gradient rise time of 1 ms. The same experiment with only one sweep rate is performed on a Philips Intera 3 tesla MRI scanner (maximum gradient strength 30 mT/m, minimum gradient rise time 200 $\mu$s), located at the BCN Neuroimaging Center in Groningen. On this scanner, the responses to pink noise and to pulses were also recorded. These data are all presented in chapter 7. For both scanners, experiments were carried out for all three gradient directions.

A LabVIEW program (National Instruments, LabVIEW 6) is custom built to feed the programmed signals to the gradient amplifier and simultaneously acquire the gradient current monitor signal (a voltage proportional to the electric gradient current) and the microphone signal (see appendix A.1). These tools were used to generate input signals to the scanner within the range from 0.1 V up to 5.0 V, or less if necessary to avoid clipping. The signal to the scanner was transmitted, and the output signal of the current monitor and the microphone signal were recorded to hard disk via a digital acquisition board (National Instruments, NI 6052E).

The microphone is a Brüel & Kjær 4190 condenser microphone, which is attached to a ZC0026 Preamplifier. This is connected to a Modular Precision Sound Analyzer
Chapter 4

Type 2260 via a 10 m long extension cable (AO0442). Microphone and preamplifier are located in the iso-center of the scanner.

As no RF signals are used for these measurements, a phantom was not needed, and the head coil was removed from the scanner. Although during the measurements no phantom or head were present in the scanner which would influence the sound field, recording the sound pressure level at the scanner’s isocenter is believed to give a good indication of the SPLs that patients will be subjected to.

During analysis, sound pressure levels were calculated from the microphone signal. A control experiment has been performed which showed that the calculations were within 0.1 dB of the Sound Analyzer readings.

All analog signals are low-pass filtered (KEMO, 8-pole Bessel, cut-off frequency 14 kHz) before feeding the signals to the scanner, or before acquisition.

4.2 Signals

4.2.1 Signals at 1.5 T

Input signals are programmed in MATLAB (The MathWorks Inc., version 6) and stored as 16-bit integer files. These files contain frequency modulated signals with bandwidths between 80 and 2200 Hz, depending on the sweep rate. All signals are sampled at 51.2 kHz. The lengths of the input signals are kept constant at 25 s. To avoid onset effects, all signals had a 5 s fade-in. The frequency modulated signals have a constant frequency during the fade-in; after the fade-in the amplitude is kept constant while the frequency is increasing. At the end of the signal, the frequency is also kept constant while the amplitude is decreasing in order to avoid offset effects (see figure 4.1). During the period of constant amplitude, the sweep rate is set between 10 and 16384 Hz/s. For the sweep rates of 10, 20, 50, 100, and 140 Hz/s this period is 15 s, for the sweep rates between 256 and 16384 Hz/s this period is 16 s. At low sweep rates several blocks are required to cover the sweep range. For the sweep rates above 256 Hz/s, the time is too long in combination with the sweep rate. In these cases, after reaching the upper frequency limit (in all these cases 2128 Hz) the frequency is decreased again with the same sweep rate, down to the lower frequency limit in these signals (80 Hz). This is repeated until the 16 seconds have passed.

4.2.2 Signals at 3 T

For the experiment performed on the 3 T scanner, only the sweep rate of 20 Hz/s is used. The bandwidth varied from 40 Hz to 3340 Hz. All other conditions are as described in section 4.2.1.

To measure the noise response of the 3 T scanner, a noise signal was fed also directly to the gradient amplifiers. This pink noise with a bandwidth from 40
to 3500 Hz was generated with a noise generator (Dynamic Signal Analyzer HP 35670A). The rms amplitude of this signal was 0.2 V.

The unidirectional pulses were programmed on the scanner’s pulse programming environment. No external control signal was used for this experiment. The pulses had a 0.2 ms rise time to half of the maximal gradient current; after 0.2 ms of constant current, the gradient current dropped to zero in 0.2 ms. This trapezoidal pulse has a total duration of 0.6 ms; the width of the trapezoid at half the maximum height is 0.4 ms, this width will be denoted full-width half-maximum. The repetition time of the pulses was 4 s.

### 4.3 Methods

Transfer functions were derived for all sweep rates and all amplitudes, as well as for the noise response and the pulse response. Comparisons have been made between amplitudes and between sweep rates. Responses to the frequency modulated
stimulus signals were analyzed with Fourier analysis and rms analysis.

4.3.1 Fourier analysis

The analysis of the data with Fourier transforms for the low sweep rates (≤ 140 Hz/s) is performed to give a constant frequency resolution. A Kaiser-Bessel window (β = 10)\(^1\) of two seconds wide was multiplied with both the current monitor signal and the sound pressure signal. The choice for a Kaiser-Bessel window was made for the good trade-off between main lobe width and side lobe level (Harris [1978]). The spectra corresponding to the bandwidth covered by the central 0.5 seconds are saved; this piecewise analysis is repeated after shifting the window 0.5 s, until the end of the file (see figure 4.2, panels E and F). All spectra from the separate files are combined and divided to give the transfer for the specific amplitude and sweep rate.

For the high sweep rates (≥ 256 Hz/s), the window width is inversely proportional to the sweep rate. The window width is twice the time the signal needs to cover the desired bandwidth. As this bandwidth is covered multiple times with these sweep rates, the transfer functions of the different parts are averaged.

4.3.2 Root-mean-square

Alternating electric currents give alternating Lorentz forces that produce the vibrations which lead to acoustic radiation. In these experiments, the amplitude of the electric current is constant. With a flat frequency response of the MRI scanner, the vibration amplitude of the scanner’s shrouds would also be constant over frequency. This, in turn, would lead to a constant air particle displacement. The local sound pressure, however, is proportional to the particle speed (equation 3.2). For sinusoidal plane waves, this particle speed depends linearly on frequency when the particle displacement amplitude is constant. In order to match the averaging window for SPL measurements, the rms of the electric current is taken over 125 ms intervals, and related to the corresponding root-mean-square value of the sound pressure.

The covered bandwidth within one 125 ms interval increases with the sweep rate. With the sweep rate of 16384 Hz/s, the complete bandwidth from 80 to 2128 Hz is covered within the 125 ms. Therefore, transfer functions are only derived with sweep rates up to 140 Hz/s. The frequency resolutions of the transfer functions with sweep rates from 10 to 140 Hz/s range from 1.25 Hz to 17.5 Hz, respectively.

---

\(^1\)The Kaiser-Bessel window \( w(t) \) between \(-T\) and \(T\) is given by \( w(t) = \frac{I_0(\beta \sqrt{1 - \frac{t^2}{T^2}})}{I_0(\beta)} \), with \( I_0 \) the modified Bessel function of the first kind.
Figure 4.2: How frequency modulated time signals (left column) behave under Fourier transformation to the frequency domain (right column). Panel A: example of frequency modulated signal (0-80 Hz within 4 s); panel B: the Fourier transform of the frequency modulated signal in panel A; panel C: windowing of part of the time signal; panel D: the Fourier transform of a windowed part of panel B; panel E: stepwise taking parts of the time signal; panel F: the corresponding Fourier transforms (see section 4.3.1).