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Sound Source System for Investigating the Auditory Perception of Infrasound Accompanied by Audio Sound

Elisa Burke, Johannes Hensel
Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany. elisa.burke@ptb.de

Summary
To gather more basic knowledge about both infrasound-perception mechanisms and the annoyance caused by infrasound, it is important to investigate the influence of the interaction between infrasound and sound at frequencies inside the common audio frequency range (audio sound) on the auditory perception. This paper gives a detailed description of a newly developed sound source system allowing simultaneous monaural stimulation of listeners with infrasound and audio-sound stimuli in psychoacoustic experiments. The sound source system covers a frequency range between 4 Hz and 6000 Hz. It can generate infrasound stimuli and audio-sound stimuli up to at least 123 dB SPL and 80 dB SPL, respectively, with inaudible harmonic distortions. Likewise, during simultaneous generation of high-level infrasound and audio sound, residual unwanted modulation frequencies remain imperceptible, owing to special design features. It can be concluded that the sound source system is suitable for investigating the auditory perception of infrasound accompanied by audio sound.

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1. Introduction

An increasing number of individuals are being exposed to infrasound (IS) with frequencies below 20 Hz. Both older and more recent studies have shown that humans are able to perceive IS [1, 2]. Human exposure to IS causing annoyance and affecting human health [3, 4] have been discussed. At many immission sites, however, human exposure to IS is usually accompanied by sound at frequencies inside the common audio-sound (AS) range (20 Hz $< f <$ 20 kHz). Therefore, it is highly desirable to investigate the role of the combination of IS and AS on the perception of IS. The results of experiments with mammalian cochleae have suggested that IS can modulate AS [5, 6], and this modulation effect may increase the subjective annoyance caused by noise with both AS and IS components.

Within the framework of EMPIR 15HLT03 "Ears II" [7], a European-funded project, a study was designed to investigate the perception of combined IS and AS stimuli in psychoacoustic experiments (e.g. hearing threshold measurements, investigation of the annoyance of combined AS and IS stimuli). This study implied the need for a sound source allowing a simultaneous stimulation with IS and AS, which was expected to meet the following requirements. The IS stimuli should be generated with sufficiently high, i.e. perceptible, sound pressure levels at very low harmonic distortion. More precisely, higher harmonic distortions of the IS stimuli within the AS frequency range were to be well below normal hearing threshold level to enable a stimulation with virtually pure IS. This was difficult to achieve due to the steep slope of the hearing threshold curve below 100 Hz [1, 2]. A difficulty associated with the simultaneous stimulation by IS and AS is that IS may cause a modulation of the AS stimuli by displacing the loudspeaker membrane of the AS source. The corresponding modulation strength needs to be very low, because human listeners are remarkably sensitive to detecting modulation, which is important for speech perception.

Within our project, an insert earphone sound source system, which enables a simultaneous monaural stimulation with IS and AS stimuli for the practical application in psychoacoustic experiments, was developed. The IS and AS stimuli are each generated by separate loudspeakers. Their sound is transferred to an audiometric eartip by means of connecting tubes. An additional sound source (compensation source) is used that delivers IS to the back of the AS loudspeaker membrane to reduce the amplitudes of the unwanted modulation tones of the AS stimuli. This paper gives a detailed description of the technical setup. Furthermore, the sound source system is characterized by acoustic measurements to evaluate whether the requirements stated above are met.

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2. Setup

Figure 1 shows a photograph of the sound source system located in an anechoic chamber and Figure 2 shows a schematic view of the main components of the setup. The sound source system enables a monaural auditory stimulation with IS stimuli and AS stimuli. The AS stimuli are generated by an 8″ (20 cm) electrodynamic loudspeaker (Beyma 8P300Fe/N), known as the audio-sound source (AS source). The IS stimuli are generated by a 15″ (38 cm) electrodynamic loudspeaker (Beyma 15P80/Nd), called the infrasound source (IS source). Each loudspeaker is mounted hermetically in a damped wooden (medium density fibre-board, MDF) box (see box with IS source in Figure 3). The two wooden boxes are coupled by linked tubes (2 polyethylene tubes: 1.5 m and 7.5 m length, 14 mm inner diameter; 1 silicone tube: 0.5 m length and 3 mm inner diameter) which are connected to the same audiometric eartip (3M, E-A-RLink Foam Eartip). The audiometric eartip is used for the monaural presentation of the acoustic stimuli to the ear canal of the listeners. The contralateral ear of the listeners is occluded with an earplug (Honeywell, Bilsom 303 Single-Use Earplug). The enclosed air volume between the loudspeaker membrane and the listener's ear enables acoustic excitation with IS stimuli at a high sound pressure level, since this volume is small compared to the air volume necessary with a free-field or pressure-chamber setup. Higher harmonics of the IS stimuli inside the AS range are attenuated by sound-absorbing material (sheep's wool and acoustic pyramid foam) which is inserted into the 7.5 m long sound tube and below the cover of the wooden box containing the IS source. An inversely mounted horn couples the sound from the volume in the wooden box containing the AS source to the 1.5 m long tube to reduce the loss of sound pressure in the AS frequency range caused by reflections. To minimize noise transmission along the sound tubes (e.g. caused by movements of the listener), all tubes are supported by stands to which they are attached with rubber bands.

A major difficulty associated with the combination of IS and AS is that IS may cause a modulation of AS. This modulation arises when IS, which is transferred by the sound tube to the AS source, interferes with the movement of the AS source loudspeaker's membrane by exerting a force alternating with the frequency of the IS on its front face. Therefore, a modulation of AS occurs with the modulation frequency of the IS. Due to the long IS wavelength and the high IS sound pressure, the membrane of the AS source is displaced uniformly and periodically from its resting position and, thus, its transmission characteristics are changed periodically. Furthermore, the AS is then generated by a moving sound source resulting in a slight frequency modulation of the sound wave caused by the Doppler effect. To compensate for these amplitude and frequency modulations of the acoustic AS signal, an additional 8″ (20 cm) loudspeaker (Beyma 8P300Fe/N), named the compensation source in the following, is mounted below the AS source. The compensation source delivers IS to the back of the AS loudspeaker membrane with the same frequency as the IS source but with a frequency-dependent phase shift adjusted with a time-delay unit (part of a Behringer Ultradrive Pro DCX 2496). The phase is set in a way that the forces exerted on the membrane by the IS at the front are compensated for by the sound field from the back. Thus, the compensation source can reduce the unwanted displacement of the AS source membrane caused by the IS.



Figure 1. Sound source system located in the anechoic chamber.

The optimal value of the time delay for an infrasonic signal applied in a psychoacoustic experiment is already determined manually prior to the experiment by varying the delay for a simultaneous generation of the IS signal (e. g. sinusoid at 5 Hz or at 12 Hz) and a sinusoid in the audio-frequency range (e. g., at 100 Hz or at 1000 Hz). For each time delay, the frequency spectrum of the output of the sound source system is measured (see section 3.1 *Measurement of the acoustic output*). Simultaneously, the level of the IS signals is adjusted so as to maintain an unaltered SPL of the fundamental (e. g. 116 dB SPL at 5 Hz, as applied for Figure 7). Then, the time delay for the applied IS signal is set to the value that best meets the following criteria: the modulation sidebands of the AS stimuli (see section 3.4 for an example of the measured modulation sidebands) are minimized, and the harmonic distortion of the IS stimulus is minimized simultaneously.

The digital waveforms of both the IS and AS stimuli undergo digital-to-analogue (D/A) conversion in separate channels with an external sound card (RME Fireface UC). Three separate amplifiers with low harmonic distortion are

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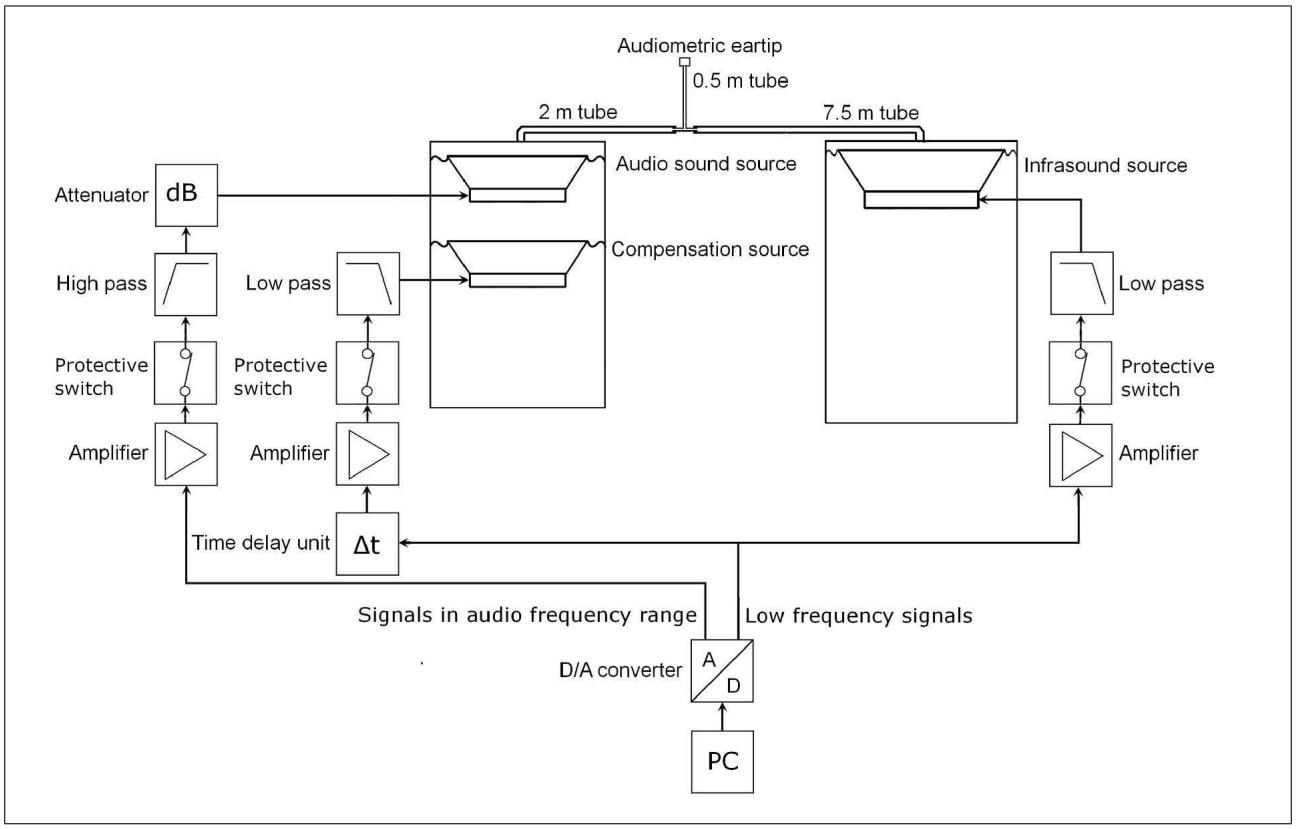


Figure 2. Schematic view of the technical setup of the sound source system.

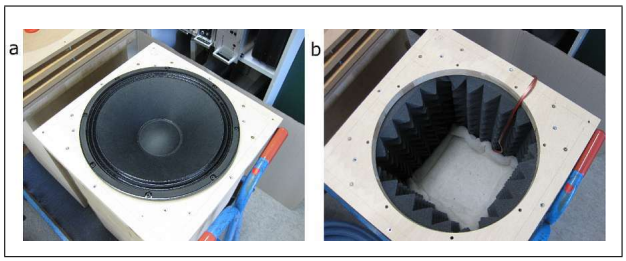


Figure 3. a: IS source loudspeaker mounted in a wooden box. b: Inner volume of the wooden box below the IS source filled with sound-absorbing material (acoustic pyramid foam and sheep's wool).

used (two TIRA BAA 120 amplifiers for the IS compensation source and for the IS source, and one BEAK BAA 120 amplifier for the AS source). A passive analogue second-order high-pass filter (f_c = 460 Hz) and a 30 dB attenuator are inserted between the amplifier and the AS source, and second-order low-pass filters (f_c = 25 Hz, also passive analogue) are inserted into the signal paths of the IS source and of the IS compensation source to suppress the amplifiers' 50 Hz hum and its harmonics sufficiently, so as to be well below the normal hearing threshold level. Furthermore, protective switches are inserted in each of the three signal paths between the amplifier and the high-pass or low-pass filter to avoid excessively loud signals being presented in the case of equipment malfunction. They interrupt the signal transmission when the amplitude of the electrical signal exceeds a critical value to protect the listeners against accidental acoustical stimulation with potentially harmful sound pressure levels.

During listening tests, the wooden boxes containing the sound sources and the sound tubes are located in an anechoic room providing a sufficiently low background noise level even in the IS frequency range. The computer controlling the experiments along with the amplifiers and the associated electric devices (low-pass and high-pass filters, etc.) are located outside the anechoic room.

3. Characterization

3.1. Measurement of the acoustic output

For frequencies f above 100 Hz, the measurement of the acoustic output (sound pressure level) of the sound source system was performed in an IEC 60318-4 occluded ear simulator (Brüel & Kjær UA-1305 (part of Brüel & Kjær Type 4157)) equipped with an ear canal extension (Brüel & Kjær DB 2012) and a preamplifier (Brüel & Kjær Type 2669). For frequencies below 100 Hz, the acoustic output was measured by means of a $\frac{1}{2}''$ low-frequency pressure-field microphone (Brüel & Kjær, Type 4193 + UC0211, on a preamplifier Brüel & Kjær Type 2669). The microphone was placed in a cavity with a volume of 1.3 cm^3 (Figure 4), which is approximately equivalent to the human ear canal volume [8]. During the measurement, the audiometric eartip was connected to the end of the sound tube and was inserted into the cavity (Figure 4) or into

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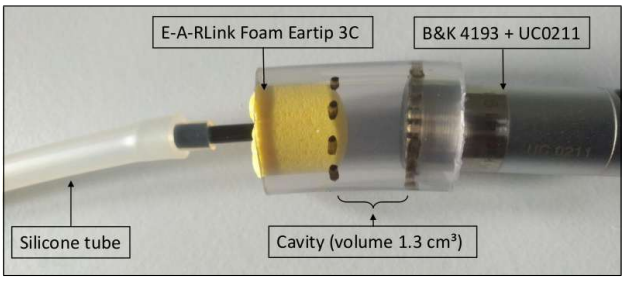


Figure 4. Setup for the measurement of the acoustic output of the sound source system with a low-frequency pressure-field microphone and the audiometric eartip coupled to a cavity.

the ear canal extension of the ear simulator. The measurements for the characterization of the sound source system were performed with a signal analyser (Audio Precision APx555) whose input was the signal of the low-frequency-microphone or of the occluded ear simulator's microphone boosted by a Brüel & Kjær Type 2636 measuring amplifier. The IS and the AS waveforms were digitally generated and were D/A converted in separate channels using the signal analyser's built-in DAC.

3.2. Frequency-dependent sound pressure level

To get an impression of the frequency range covered by the sound source system, the frequency-dependent sound pressure level generated by the IS source combined with the compensation source (see Figure 5a) and by the AS source (see Figure 5b) was each measured at a constant output voltage of the signal generator (100 mV for the AS signals, 315 mV for the IS signals). The results show that the AS source allows a stimulation only between 50 Hz and 6000 Hz. A steep decrease of the sound pressure level is observed for frequencies outside this range. Furthermore, the frequency-dependent sound pressure level exhibits ripples which may be caused by resonance effects of the sound-tube system. Therefore, broadband signals need to be digitally pre-shaped by equalizing them with respect to the frequency response of the sound source to achieve a flat acoustical spectrum of the stimuli. Considering the generation of IS, it is observed that the sound source system provides the highest acoustic output between 10 Hz and 20 Hz. Further measurements show that the sound source system allows an auditory stimulation with IS stimuli above average hearing threshold levels (according to [1]) at least down to 4 Hz.

3.3. Harmonic distortion measurements

It is crucial for an auditory stimulation with pure IS that the harmonic distortions of the stimulus reaching up into the AS frequency range are well below normal hearing threshold level to prevent an effect of the higher harmonics on the perception of IS. Therefore, measurements were performed to analyse the harmonic distortions of IS pure tones at different fundamental frequencies as a function of sound pressure level. Figure 6 shows one example of the harmonic distortion measurement for a sinusoid at 5 Hz

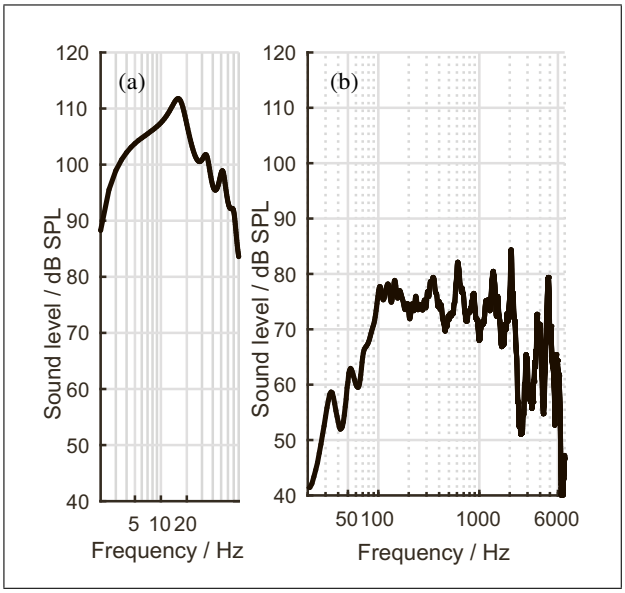


Figure 5. Frequency-dependent sound pressure level generated by the IS source combined with the compensation source (a) and by the AS source (b) measured at constant output voltage of the signal generator (100 mV for the AS signals, 315 mV for the IS signals).

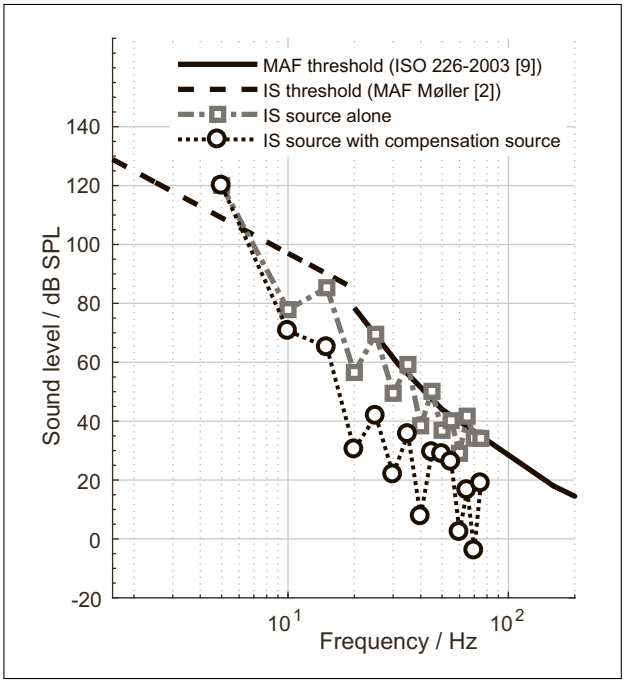


Figure 6. Harmonic distortion measurement for a sinusoid at 5 Hz presented at 120 dB SPL generated by the IS source alone (square markers) and by the IS source in combination with the compensation source (circular markers).

generated by the IS source alone and by the IS source in combination with the compensation source. It becomes apparent that, when both sound sources are driven simultaneously to generate the IS stimulus, the harmonic distortions are reduced by the superposition of the sound waves. Based on the distortion measurements, the maxi-

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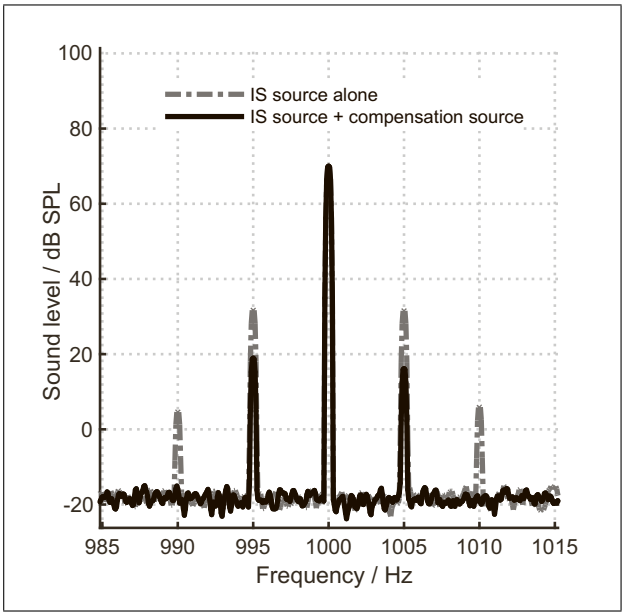


Figure 7. FFT spectrum of the modulation of a sinusoid at 1 kHz presented at 70 dB SPL by a sinusoid at 5 Hz presented at 116 dB SPL. The 5 Hz sinusoid was generated by the IS source alone (grey curve) or by the IS source in combination with the compensation source (black curve).

mum sound pressure level recommended for the IS stimuli generated by the IS source combined with the compensation source was defined as the very sound pressure level at which each of the higher harmonics of the stimulus is at least 10 dB below its average hearing threshold level according to [1, 2]. Satisfying that criterion, the maximum levels at low harmonic distortion measured for a sinusoid at 5 Hz and at 12 Hz were 123 dB SPL and 116 dB SPL, respectively. In general, only pure tone signals are recommended for an IS stimulation with the current sound source system to prevent the generation of additional (i.e., non- harmonic) distortions.

The frequency-dependent maximum level for stimuli inside the AS frequency range was determined as the very sound pressure level below which the harmonic distortions are not perceptible, considering both their threshold level (according to [9]) and potential masking effects (according to [10, 11]) with the AS fundamental frequency as a masker. Based on the measurements of harmonic distortions for sinusoids at 100 Hz, 500 Hz, 1000 Hz, 2000 Hz and at 4000 Hz, it was estimated that the sound source system enables an AS stimulation at low harmonic distortion at least up to 80 dB SPL.

3.4. Modulation of audio sound caused by the presence of infrasound

It is important to ensure that the modulation caused by IS displacing the AS loudspeaker's membrane cannot be perceived. Figure 7 shows the frequency spectrum measured for the simultaneous stimulation with a sinusoid at 1 kHz presented at 70 dB SPL and a sinusoid at 5 Hz presented at 116 dB SPL generated by the IS source alone (grey), or by the IS source in combination with the compensation source (black). It becomes apparent that the levels of the sidebands are reduced by more than 15 dB when the IS stimulus is generated simultaneously by the IS source along with the compensation source. An upper limit of the modulation strength was approximated for the resulting modulation when the IS stimulus is generated by the IS source along with the compensation source. For both a small index of frequency modulation $\beta << 1$ and a small degree of amplitude modulation $m << 1$, the amplitude spectra of the two signals consist only of the fundamental frequency line (carrier) and one pair of modulation sidebands spaced symmetrically (by the modulation frequency) around the carrier, if $\beta = m$ [11]. The difference between AM and FM spectra only lies in the sidebands' phases. For the upper-limit estimation, it was assumed that the modulation was pure AM because, for modulation frequencies inside the IS frequency range, the just-noticeable m for AM is much lower than the just- noticeable β for FM [11, 12]. Therefore, even if both sideband levels in Figure 7 (black curve) were set to the level of the higher one, the resulting degree of amplitude modulation would be $m = 0.006$, or expressed as $20\log(m) = -45$ dB. This value is well below the just- noticeable degree of AM according to [11] and [13], showing that the modulation can be assumed to be imperceptible.

It was considered that non-linearities of microphones can also cause intermodulations, producing signals like the observed sidebands in case of a dual frequency excitation at high sound pressure levels. The contribution of the microphone to the measured distortion is probably very low, since the sound pressure level even of the high-level IS remains well below the 3 % harmonic distortion limit of the microphone which lies above 160 dB SPL. Moreover, it has to be pointed out that the distortions of the actual output of the sound source system would be lower than or nearly equal to the measured distortions, if the microphone non-linearities would contribute to the latter. Thus, the distortions would not be perceptible by a listener in a psychoacoustic experiment as discussed above.

4. Conclusions

This paper illustrates the suitability of the newly developed sound source system for practical applications in psychoacoustic investigations on the auditory perception of IS accompanied by AS. In general, it has to be taken into account that in its current form, the sound source system is limited to monaural stimulation. Within the AS frequency range, the sound source system can generate pure tones or bandlimited broadband stimuli up to 6000 Hz. Furthermore, the sound source system allows the stimulation with IS down to 4 Hz, clearly above average hearing thresholds with levels reaching a maximum of 123 dB SPL at low harmonic distortion. It was observed that the application of the compensation source in addition to the IS source considerably reduces the harmonic distortions of the IS stimuli. Only pure tones are recommended for IS stimulation to

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prevent the generation of additional, possibly detectable, distortions. A modulation was observed when the sound source system generated an AS stimulus and a high-level IS above threshold simultaneously. By means of the compensation source, the modulation can be reduced by more than 15 dB making the modulation imperceptible.

For a future optimization of the system, it would be desirable to reduce even further the harmonic distortion to enable an IS stimulation at a still higher level. This may be realized by a predistortion of the input signals of the infrasound-emitting loudspeakers using the method described by Novak *et al.* [14] taking into account that this predistortion technique would not be suitable for IS signals whose higher harmonics coincide with the amplifiers' 50 Hz hum. Furthermore, it has to be ensured that the digital preprocessing of the IS signal would not generate additional, perceptible distortions in the acoustic output of the sound source system.

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