TECHNICAL REPORT

Acoustic characteristics of a miniature dynamic speaker driver unit MT006B for measurement of head-related impulse responses by reciprocal method

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Abstract: We measured the input impedance characteristics, input voltage versus output sound pressure characteristics, harmonic distortion characteristics, frequency characteristics, and impulse response of a currently available miniature electrodynamic driver unit (Foster Electric, MT006B) when used as a loudspeaker with an open space load. The nominal input impedance of the driver unit was $16\ \Omega$, and its resonance frequency f_0 was 2.7 kHz. At f_0 , the range of the input voltage level over which the output sound pressure of the driver unit increased linearly was $-10\ \text{dBV}$ (reference 1 V) or less. Below f_0 , the frequency response of the driver unit decreased by 15 dB/oct, while above f_0 it did not drop significantly. When the input signal level to the driver was $-12\ \text{dBV}$, the signal-to-noise ratio between the sound pressure level produced by the driver and the background noise level of the soundproof room was 0 dB at a frequency of 130 Hz for a distance 0.2 m, and at 230 Hz for a distance 1.0 m. These results indicate that the MT006B can be used as an earplug speaker for a fast head-related transfer functions measurement system via reciprocity.

Keywords: Head-related transfer function, Earplug loudspeaker, Miniature electrodynamic driver unit, Frequency characteristics, Harmonic distortion

1. INTRODUCTION

The head-related transfer function (HRTF) is the acoustic transfer function from the sound source to the entrance of the ear canal, and it varies intricately with the sound source position. HRTF is known to play an important role in our perception of spatial sound, and a number of HRTF datasets have been measured so far (e.g., [1–3]). The measurement of an HRTF is nothing less than the measurement of acoustic impulse responses. That is, the HRTF is the ratio of the complex spectra of the acoustic impulse response from the sound source to the ear and that from the sound source to the reference point. The reference point is usually at the center of the head with the head removed [4]. In order to measure the HRTF for many sound source positions, it is necessary to repeatedly measure the impulse response by changing the position of the loudspeaker, which increases the overall measurement time. Since we cannot keep the head posture for a long time [5], the measured HRTFs include measurement errors due to head movement [6].

As one way to measure HRTFs in a short time, Zotkin *et al.* [7] used Helmholtz's reciprocal theorem. In the HRTF measurement method using the reciprocal method, the positions of the loudspeaker and microphone in the conventional HRTF measurement method are interchanged. Namely, a small loudspeaker is placed at the entrance of the ear canal of the head to be measured and a microphone is placed at the observation position. By placing microphones at each observation position, the HRTF of multiple observation positions can be measured simultaneously. As a result, multiple HRTFs with no measurement errors due to head movements can be obtained.

However, the measurement of HRTFs using the reciprocal method requires a small loudspeaker that can be inserted into the ear canal. In other words, the input signal required to measure the impulse response is radiated from a miniature speaker that is embedded in a silicone impression material inserted into the outer ear canal in the form of an earplug.

When this reciprocal HRTF measurement method was first proposed, the miniature earplug speaker was a very small electromagnetic speaker driver unit used in hearing aids and insert-type earphones. These driver units, however, are designed to generate sound pressure in a closed

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space, so if they are used as an earplug speaker with open space as a load, they will not produce enough sound pressure. Zotkin *et al.* [7] used the ED-9689 (Knowles) as an earplug loudspeaker but could only measure the HRTF in the range of 1.5 to 16 kHz. Matsunaga & Hirahara [8] investigated in detail the acoustic properties of three types of ultra-compact electromagnetic driver units including ED-9689 and reconfirmed the low output sound pressure levels at low frequencies. They found that increasing the input voltage of the driver unit generates large second- and third-order harmonics, and that the radiation characteristics of the driver unit are omnidirectional below 10 kHz, but strongly directional above 10 kHz. They thereby demonstrated the problems of using the miniature electromagnetic driver unit for HRTF measurements using the reciprocal method.

In addition to these electromagnetic driver units, small electrodynamic driver units used in intra-concave earphones can be used as earplug speakers. Electrodynamic loudspeakers are generally known to have lower distortion and a wider reproduction frequency range than electromagnetic loudspeakers [9]. Imai *et al.* [10] studied in detail the acoustic characteristics of two miniature electrodynamic speaker-driver units taken from insert-type earphones. They found that the driver units also have lower output sound pressure levels in the low frequency range when used as a loudspeaker with an open space as a load, but their maximum output sound pressure levels are higher and less distorted than those of the miniature electromagnetic driver units, and they are omnidirectional up to 20 kHz. Then, Imai *et al.* [11] measured the HRTFs under various conditions, which are hard to measure without the reciprocal method, by using an earplug speaker with a miniature electrodynamic driver unit. However, due to the short life cycle of commercially available insert-type earphones, those driver units are currently unavailable.

This report describes the input impedance characteristics, input voltage versus output sound pressure characteristics, harmonic distortion characteristics, frequency characteristics, and impulse response of a currently available miniature electrodynamic driver unit when used as a loudspeaker with an open space load. In addition, some practical considerations for using the driver unit as an earplug loudspeaker for a fast HRTF measurement system using the reciprocal method are also noted.

2. MEASUREMENT TARGET: THE MT006B ELECTRODYNAMIC SPEAKER

The miniature electrodynamic speaker driver unit measured in this paper is the MT006B (Foster Electric). The outer dimensions of the MT006B are 6 mm in diameter and 5 mm in length. It can be inserted into an ear canal of diameter at least 7~8 mm [12] (Fig. 1).

Fig. 1 Ultra-small dynamic speaker unit (MT006B).

3. MEASUREMENT METHODS

3.1. Tools and Setup

The acoustic characteristics of the speaker-driver unit were measured in a soundproof room ($3.24 \times 3.58 \times 2.30$ m) with a background noise level of 16 dB. The driver unit and microphone were installed at a height of 1.2 m above the floor, at a distance of r [m]. The driver unit was placed at the end of a 4 mm diameter stainless steel rod inserted into a loudspeaker stand in the bare state.

An audio analyzer (3560C, Brüel & Kjær) was used for the measurement of input impedance characteristics, input voltage versus output sound pressure characteristics (i.e., sensitivity), harmonic distortion characteristics and frequency response. A sinusoidal signal at 1/12 oct. intervals was amplified by a headphone amplifier (AT-HA21, audio-technica) and fed to the MT006B. The sinusoidal sound emitted from the MT006B was received by a microphone (4189, Brüel & Kjær) with a preamplifier (2669, Brüel & Kjær), and its sound pressure level was calculated (Fig. 2(a)).

A Linux based PC and A/D and D/A converters (DASmini-E2000, COMEX) with a sampling frequency of 48 kHz and a quantization accuracy of 16 bits were used to measure the acoustic impulse response. A time stretched pulse (TSP) signal output from the D/A converter was amplified by the headphone amplifier and fed to the MT006B. The TSP sound emitted from the MT006B was received by an electret condenser microphone (EM-258, Primo) of diameter 6 mm. The output signal of the microphone was amplified by the microphone amplifier (MA-BOX 205016, COMEX) and fed to the A/D converter (Fig. 2(b)).

The combined frequency response of the headphone amplifier, the A/D & D/A converters, the microphone amplifier, and the electret condenser microphone was separately confirmed to be almost flat up to 20 kHz.

3.2. Input Impedance

The input impedance characteristic of the speaker driver unit was measured by applying a sinusoidal signal to a circuit with a 3.53-ohm resistor connected in series

Fig. 2 (a) Block diagram of the acoustic measurement system using the B&K audio analyzer. (b) Block diagram of the acoustic impulse response measurement system.

with the driver unit and measuring the voltages across the driver unit and the resistor using the Audio Analyzer. The frequency f of the applied sinusoidal signal was set at 1/24 oct. intervals from 100 Hz to 20 kHz, and the input voltage V_{in} was set to -12 dBV.

3.3. Sensitivity and Harmonic Distortion

The input voltage vs. output sound pressure characteristics of the speaker driver unit were determined by measuring the sound pressure levels of the fundamental and its 2nd to 5th order harmonics. The microphone was placed very close to the loudspeaker driver unit, r was 0.13 m, because the output sound pressure level of the driver unit was low. The input signal to the driver unit was a sine-wave signal with a frequency of 1 kHz and 2.7 kHz, and the input voltage V_{in} was varied from -30 dBV to 6 dBV in 2 dB steps.

3.4. Frequency Characteristics

The frequency response of the speaker driver unit was

Fig. 3 Input impedance characteristics of the MT006B.

determined by measuring the sound pressure level of the acoustic signal at each frequency, received by the microphone at a distance of 0.2 m and 1 m from the driver unit. The input signal to the driver unit was a sine-wave at 1/24 oct. intervals from 100 Hz to 20 kHz, and the input voltage V_{in} was set to -12 dBV.

3.5. Impulse Response

The impulse response was measured using a Log-TSP [13,14] signal with 65,536 samples (Fig. 6(a)). The TSP response was measured by receiving the three-period Log-TSP signal emitted from the driver unit at the microphone a distance 0.2 m from the driver unit. The impulse response was calculated by convolving the inverse TSP signal into the second period of the TSP response waveform.

4. RESULTS

4.1. Input Impedance

The input impedance characteristic of the MT006B is shown in Fig. 3. As indicated by the peak, the resonance frequency f_0 was 2.7 kHz. The nominal impedance of the unit was about 16Ω .

4.2. Sensitivity and Harmonic Distortion

The output sound pressure levels of the fundamental and its 2nd to 5th order harmonic components with respect to the input voltage level V_{in} , when a sine wave signal with a frequency f of 1 kHz or 2.7 kHz was applied, are shown in Fig. 4.

When f was 1 kHz, the measured sound pressure level SPL_{out} of the fundamental component increased linearly with V_{in} from -30 dBV to 6 dBV. In contrast, the SPL_{out} of the second harmonic increased rapidly to a value exceeding that of the fundamental at V_{in} 6 dBV. At V_{in} of -12 dBV, the SPL_{out} of the second and third harmonic components were respectively 31 dB and 47 dB lower than the SPL_{out} of the fundamental component, and the SPL_{out} of the fourth and fifth harmonic components were below the background noise level.

When f was 2.7 kHz, the SPL_{out} of the fundamental component increased linearly up to a V_{in} of -10 dBV. The SPL_{out} of the fundamental component reached a maximum at V_{in} -8 dBV, and decreased when V_{in} was raised beyond

Fig. 4 Relationship between input voltage to the earplug speaker and the level at its fundamental, 2nd, 3rd, 4th and 5th harmonics. The left panel shows the input voltage to output sound pressure level characteristics at 1 kHz, and the right panel at 2.7 kHz.

Fig. 5 Output sound pressure level characteristics of MT006B at $r = 0.2 \text{ m}$ and 1.0 m , and the background noise spectrum of the experimental room.

that value. The output sound pressure level of the second harmonic also increased monotonically below -10 dBV , but it was complicated by the fact that it saturated, decreased, then increased again when V_{in} was above -8 dBV . At V_{in} of -12 dBV , the SPL_{out} of the 2nd to 5th order harmonic components were respectively 26 dB, 41 dB, 54 dB, and 58 dB lower than the SPL_{out} of the fundamental component.

4.3. Frequency Characteristics

The frequency response of the MT006B is shown in Fig. 5. The thick and thin black lines show the output sound pressure level characteristics at $r = 0.2 \text{ m}$ and $r = 1.0 \text{ m}$, respectively. The gray line is the spectrum of the background noise in the measurement room. The output sound pressure level characteristics at $r = 1.0 \text{ m}$ appeared jaggy due to the effect of reflections from the walls and ceiling of the soundproof room, but as expected from the inverse square law, the overall output sound pressure level characteristic was about 15 dB lower than that measured at $r = 0.2 \text{ m}$.

The output sound pressure level of the speaker unit peaked at $f_0 = 2.7 \text{ kHz}$. When the frequency was raised above f_0 , the output sound pressure level changed slowly but did not drop significantly in the frequency range from f_0 to 20 kHz. On the other hand, in the frequency band below f_0 , the output sound pressure level dropped by about 15 dB/oct.

The S/N ratio between the frequency response of the unit and the background noise level of the soundproof room (when measured) was 0 dB at a frequency of about 130 Hz for $r = 0.2 \text{ m}$, and at about 230 Hz for $r = 1.0 \text{ m}$.

4.4. Impulse Response

Figure 6 shows the waveforms of the Log-TSP signal (a) and the TSP response signal received at the microphone (b), the spectrogram of the response (c), and the impulse response waveform (d).

The TSP response signal waveform has an amplitude envelope that reflects the frequency characteristics of the MT006B, with an amplitude maximum at about 0.95 s. The frequency of the TSP signal at this time was 2.7 kHz, and the corresponding sound pressure level was 34 dB, which is lower than the values shown in Fig. 4 because the TSP signal has a short signal duration at each frequency. As shown in the spectrogram of the TSP response waveform, the TSP sound emitted from the unit had a fundamental component that reflected the frequency characteristics of the Log-TSP signal, as well as a harmonic distortion component. The level of the second harmonic found between about 0.9 s to 0.96 s was about 20 dB lower than the fundamental component.

Figure 6(d) shows the impulse response waveform for $\pm 4 \text{ ms}$ centered on the principal response. The impulse response decayed to nearly zero amplitude by about 3 ms after the principal response.

Fig. 6 (a) Log-TSP waveform, (b) TSP response of MT006B, (c) spectrogram of the TSP response, and (d) impulse response waveform around the principal response.

4.5. Inter-unit Variability

The impulse responses of 20 MT006B units were measured with the aim of quantifying the inter-unit variability. The resonant frequency f_0 of these 20 units was found to range from 2.6 kHz to 2.8 kHz; the mean f_0 was 2.7 kHz with a standard deviation of 68 Hz. The difference between the maximum and minimum amplitude levels of the spectra, $\Delta L(f)$, was about 3 dB in the band with a S/N ratio above 0 dB, and $\Delta L(f_0)$ was about 6 dB; the mean $L(f_0)$ was 34 dB, with a standard deviation of 1.4 dB.

4.6. Durability

A simple indication of the durability of the MT006B was obtained by applying a sine-wave signal (at 2.7 kHz) as input continuously for about 1 minute. When the input signal was relatively low in amplitude (−12 dBV), even after 1 minute of continuous use the unit was not discernably hot to touch. In contrast, with a relatively strong signal (2 dBV or more) the driver unit was hot to touch and its output sound pressure was reduced by about 50%.

5. DISCUSSION

The nominal input impedance of the MT006B is about 16Ω , which is about the same as the nominal input impedance of about 15Ω of the miniature electrodynamic driver unit S measured by Imai *et al.* [10].

The resonant frequency of the MT006B is 2.7 kHz, which is slightly higher than the resonant frequency 2.5 kHz of the driver unit S.

The range of V_{in} over which the output sound pressure of MT006B increased linearly was 6 dBV or less at an input signal frequency of 1 kHz, and −10 dBV or less at an input signal frequency of 2.7 kHz. Therefore, the input voltage level V_{in-max} of the MT006B needs to be less than −10 dBV to ensure operation in the linear range. Imai *et al.* [10] measured the V_{in-max} of the driver unit S at +6 dBV, while the V_{in-max} of MT006B was 16 dB lower. Therefore, the maximum output sound pressure level of the MT006B is 60 dB, which is lower than the maximum output sound pressure level 76 dB of the driver unit S.

The frequency response of the MT006B decreased below the resonance frequency f_0 . This is the same as the low-frequency characteristic reported for the driver unit S used by Imai *et al.* [10]. On the other hand, above f_0 , the frequency response of the MT006B changed slowly but, unlike the driver unit S, did not drop significantly. This is presumably because the second resonant frequency of the driver unit S was at 15 kHz, while that of the MT006B was above 20 kHz.

As shown in the spectrogram of the TSP response waveforms (Fig. 6(c)), the MT006B's sound output response to a Log-TSP signal contains harmonic distortion components. Since an ascending Log-TSP signal was used in this measurement, the impulse response of the harmonic distortion component appears earlier than the principal response in the impulse response calculated by convolving the inverse TSP signal into the TSP response waveform [13]. Therefore, the part of the impulse response centered on the principal response and shown in Fig. 6(d), contains almost no effect of the harmonic distortion component.

Although the directivity of the MT006B was not measured, it is most likely to be omnidirectional because the shape and size of the capsule, the shape of the diaphragm, and the type of the electro-acoustic transducer in the driver unit are the same as those of the driver units S used by Imai *et al.* [10]. Since there are no sharp peaks or dips in the frequency response from f_0 to 20 kHz, the effect of the directivity of the earplug loudspeakers, which can be a problem when measuring HRTFs, is considered to be minimal.

Different MT006B units were found to have individual differences to some extent in f_0 and spectral amplitude

levels. However, when calculating the HRTF, the free-field impulse response at the reference point is measured and divided out, so individual driver unit differences are not a problem.

After applying a -12 dBV sine wave signal to the MT006B continuously for about 1 minute, no temperature rise was felt when the unit was touched with a fingertip. Since the detection limit of the temperature change in the fingers is about 0.3 degrees [15], the temperature rise can be considered to be less than 0.3 degrees.

The impulse response of the MT006B converged at about 3 ms, 2 ms longer than the impulse response of the driver unit S measured by Imai *et al.* [10].

In the impulse response measurement using the MT006B, further expansion of the measurable bandwidth in the low frequency range can be achieved by using the additive averaging method or a TSP signal to increase the signal-to-noise ratio by increasing the stall time [16].

There may be other miniature electrodynamic driver units besides the MT006B discussed in this paper. When using such a miniature electrodynamic driver unit as an earplug loudspeaker for a fast HRTF measurement system using the reciprocity method, the following items need to be considered. The input voltage of the driver unit shall be determined by considering the input voltage versus output sound pressure characteristics and harmonic distortion characteristics of the driver unit for a sinusoidal signal at f_0 , after clarifying the resonance frequency f_0 by measuring the impedance characteristics. Since the signal sound emitted by the driver unit contains harmonic distortion components, an ascending Log-TSP signal, which can separate the harmonic distortion components from the principal response, shall be used as the impulse response measurement signal. Since the maximum output sound pressure level of the driver unit is low, the background noise level in the measurement room and in the measurement system should be as low as possible to ensure an adequate signal-to-noise ratio.

6. CONCLUSION

The input impedance characteristics, input voltage versus output sound pressure characteristics, harmonic distortion characteristics, frequency response and impulse response of the miniature electrodynamic driver unit MT006B were measured. As a result, the following were found.

The resonant frequency of the MT006B is 2.7 kHz, and the input signal level of the unit must be less than -10 dBV to reproduce a low-distortion sound. The frequency at which the signal-to-noise ratio between the output sound pressure level of the MT006B and the background noise level is 0 dB was 130 Hz for a distance of 0.2 m and 230 Hz for a distance of 1.0 m in the authors' experimental room.

These results indicate that the MT006B can be used as an earplug speaker for a fast HRTF measurement system via reciprocity.

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