TECHNICAL REPORT

Linear microphone array for acoustic impulse response measurements using reciprocal method: Effects of microphone holder

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Abstract: This article describes a linear microphone array used for measuring head-related impulse responses simultaneously at various radial distances using the reciprocal method. The microphone array consists of miniature 5.8 mm diameter electret condenser microphones (ECMs) arranged on a boom, using a 3D printed microphone holder with pillars. The frequency response of the ECM with the 1 mm thick band holder increased monotonically above 5 kHz and was 2 dB higher at 20 kHz compared to the frequency response of the bare ECM. When multiple ECMs were arranged on a boom at 200 mm intervals using microphone holders with a 3 mm diameter pillar, reflections from the pillar and boom were negligible, regardless of whether the height of the ECM from the boom was 30 mm or 60 mm.

Keywords: Acoustic impulse response, Microphone array, Microphone holder, Frequency characteristics, Reflection

1. INTRODUCTION

Microphone arrays, which consist of several aligned microphones, are often used for acoustic measurements. For example, a spherical microphone array, which consists of a large number of microphones arranged in a spherical shape, was used in sound space sensing to record sound information arriving from all around [1]. Various microphone arrays are used for directivity control to receive sound signals from a specific direction [2]. Also, a microphone array is used to allow simultaneous measurement of head-related impulse responses (HRIRs) using the reciprocal method. Zotkin et al. [3] who proposed the reciprocal method in this context, used a microphone array consisting of small microphones spherically arranged on a mesh-like frame composed of ZomeTool.

We have similarly used a microphone array to measure HRIRs at multiple points simultaneously using the reciprocal method, focusing particularly on covering a range of distances from nearfield to farfield [4]. Our microphone array is composed not of expensive condenser microphones typically employed for precision measurements, but of small, inexpensive electret condenser microphones (ECMs) intended for general use. The small ECM we use is EM258 (Primo), with a diameter of 5.8 mm and a thickness of 2.3 mm. According to the catalog, the EM258 has a sensitivity of −32 dB (i.e., 25.1 mV/Pa at 1 kHz), a S/N of 74 dB, a maximum input sound pressure level of 115 dB, and a frequency response range of ±4 dB from 60 Hz to 20 kHz, which are sufficient specifications for HRIR measurements. Zotkin et al. [3] also used ECMs in their microphone array, but the sensitivity of the Knowles FG-3629 ECM they used is −53 dB, which is about 20 dB lower than that of the EM258.

To use this small ECM as a microphone array in a straight line, arc, or plane, a custom microphone holder is used. We had been using cylindrical microphone holders of 8 mm in diameter and 50 mm in length made of machined POM (PolyOxyMethylene) resin rods for circular and planar microphone arrays [4]. For the linear microphone array, the leads of the small ECM were tied to a pole on the boom. However, this method is not sufficient to ensure the accuracy of the positioning of the small ECM and the maintainability of the microphone array, and therefore a new microphone holder was needed. Furthermore, while it is well-known that the mechanical structure of a microphone array inevitably produces some unwanted reflections, rarely are these effects on acoustic measurements quantified or evaluated.

This paper describes how the frequency response of the microphones varies with the shape of the microphone holders and how the amount of reflected waves created by the arrangement of the microphone holders on the boom is
measured. Finally, a linear microphone array using the microphone holders for head-related impulse response measurement by the reciprocal method is described.

2. MICROPHONE HOLDER

Microphone holders for a linear array enable the ECMs to be precisely and reproducibly positioned at desired locations along a boom, which is an aluminum rod of length 1 m and square cross-section $6 \times 6$ mm. This boom is both durable and maintainable, and incurs only low acoustic reflections. The reason for using a square rod for the boom is that it is easy to stand multiple microphone holder pillars perpendicular to the boom. A round rod with circular cross-section would have less acoustic reflections than a square rod, but it would require greater precision and effort in lining up multiple pillars perpendicular to the boom.

The two types of microphone holder we have developed are a modified version of a conventional cylindrical microphone holder [4] and a cylindrical band type to which an ECM is attached. Two types of connection between the boom and the microphone holder were developed: one in which the microphone holder is inserted into a vertical pillar and the other in which a 6 mm square hole is molded into the bottom of the pillar to fit into the boom. In addition, different thicknesses and lengths of the microphone holder pillars were developed.

The microphone holder was designed using 3D CAD software (Autodesk Fusion360) and molded using a 3D printer (Form2, Formlabs). Figure 1 shows photographs of some of the 26 types of microphone holder that were fabricated. The white and transparent holders differ only in color, and are made of the same material.

The dimensions of four types of microphone holder shown in Fig. 2 are described below. Microphone holder A is a conventional cylindrical microphone holder [4] trimmed down to a shorter length, in which a small ECM is placed on a saucer and supported from behind by a cylinder. Microphone holder B fits a small ECM into the front side of a cylinder. In both microphone holders A and B, the hole at the rear of the cylinder is for the lead wire, and the hole is therefore blocked by the 1.6 mm diameter shield wire when an ECM is mounted.

Microphone holder C is a band-shaped ring with the same inner diameter as the outer diameter of the small ECM, so that the ECM is fitted securely into the ring. A 2 mm-diameter rod is formed at the bottom of the band-shaped ring and is inserted into a metal pipe pillar on a boom to fix it in place. In this microphone holder C, the rear of the ECM is open, with only the shielded wires soldered to it. A modified microphone holder C, hereafter referred to as Cp, in which a 3 mm-diameter pillar of 30 or 60 mm length with a boom holder is integrally molded at the bottom of the banded ring, was also fabricated.
length of the pillar was chosen to be either 30 or 60 mm from the upper surface of the boom to the center of the ECM.

3. MEASUREMENT OF IMPULSE RESPONSE

The impulse response measurement system is shown in Fig. 3. The 65,536 points upward Log-TSP signals [5] output from the D/A converter (DAS-miniE2000, COMEX) were amplified by a power amplifier (Evolution 10 A, Creek) to drive a 4-inch fullrange loudspeaker (MG10SD-09-08, Vifa). The reason for using this loudspeaker instead of a miniature dynamic driver unit used in the HRIR measurement using reciprocity was to ensure the signal-to-noise ratio of the measurements. The Log-TSP signal emitted from the loudspeaker was received by the ECM, and its output voltage signal was amplified by a microphone amplifier (MA-BOX205016, COMEX), then fed to the A/D converter (DAS-miniE2000, COMEX). The sampling frequency and the quantization bit rate of the A/D and D/A converters were 48 kHz and 24 bits.

First, impulse responses were measured with a bare ECM held only by its shielded wire; and then with the same ECM mounted in each of the three microphone holders (A, B, and C) on a 4 mm stainless steel rod attached to a microphone stand. Separately, the impulse response of the loudspeaker was measured with a condenser microphone having a flat frequency response (4189, Brüel & Kjær) placed at the same position as the ECM. The frequency response of the ECM was calculated by eliminating the loudspeaker response, i.e., by taking the ratio of the power spectrum of the impulse response measured with the ECM to that measured with the condenser microphone.

Next, impulse responses of the loudspeaker were measured simultaneously with several ECMs attached to the microphone holder Cp, which were placed on a 1.0 m long boom at 200 mm intervals. The number of microphone holders with ECMs attached to the boom was then reduced and the changes in reflected waves were observed in the impulse responses.

4. RESULTS

4.1. Effect of Microphone Holder Shape on the Frequency Response of ECM

The frequency response of the ECM in the bare state (RSP₀) and the frequency response (RSPᵢ, i: A, B, C) of the ECMs mounted in the microphone holders A, B, and C are shown in the upper panel of Fig. 4. The magnitude of the differences between RSP₀ and RSPᵢ, Δ|RSPᵢ| (i: A, B, C).

As shown in the figure, the frequency response of the bare ECM was nearly flat up to 10 kHz, with a gradually decreasing response at higher frequencies, and the 20 kHz response being about 1 dB lower than the 1 kHz response. For all the tested microphone holders, the response of the ECM with the holder attached was higher at high frequencies than the response of the bare ECM. Δ|RSP_A| linearly increased from 3 kHz to 10 kHz then decreased by about 0.8 dB up to 12 kHz before increasing again above 12 kHz. Δ|RSP_B| showed a similar pattern but with a level difference about 0.5 dB greater at higher frequencies. Δ|RSP_C| increased linearly above 5 kHz and reached 2 dB at 20 kHz.

With microphone holder A, a dip of about 2 dB in the frequency response was observed around 12 kHz when the
microphone was not in tight fit with the holder; there was about a 1-mm gap between the backside of the ECM and the holder (Fig. 5). A similar dip was observed with holder B under the same conditions. In contrast, there was no such issue with holder C.

4.2. Reflections from Aligned Microphones on the Boom

Figure 6 shows the impulse response measured with the linear microphone array, at the ECM closest to the loudspeaker. The microphone array consisted of 6 ECMs installed in the modified microphone holder Cp with molded pillar, whose height \( h \) was 60 mm, linearly aligned at 200 mm intervals on the 6 mm square boom. The loudspeaker was placed 0.13 m in front of the closest ECM.

Due to the long transient response of the loudspeaker, reflected waves from the aligned microphones and the boom cannot be observed.

Figure 7 shows the impulse responses for the microphone holder Cp of which the pillar length was 60 mm or 30 mm. The measurement system described in Sect. 3 was used to measure the impulse responses. A miniature dynamic speaker driver unit (HS-930i unit, CREATIVE) [6] was used as the loudspeaker and AT-HA21 as the power amplifier. The measurement signal used was the 65,536 points Maximum Amplitude Optimized (MAO)-TSP signal for the HS-930i unit [7]. Since the miniature dynamic speaker driver unit is designed to generate sound pressure in a closed space, it does not produce enough sound pressure with open space as a load, in particular below its resonance frequency around 3 kHz. Thus, its transient response is shorter than large loudspeakers, and several reflected waves from the aligned microphones and the boom are observed in the magnified amplitude impulse response. Although the reflected amplitudes are small, reflections are observed at around 1.2 ms, 2.3 ms, 2.9 ms,
and 3.5 ms in the impulse response as indicated by arrows in Fig. 7.

Based on the dimensions of the microphone array, the response at 1.2 ms is the reflection from the microphone behind by 200 mm, that at 2.3 ms is the reflection from the microphone behind by 400 mm, that at 2.9 ms is the reflection from the boom joint, and that at 3.5 ms is the reflection from the microphone behind by 600 mm. The amplitudes of these reflections were smaller with the short (30 mm) pillar than with the long (60 mm) pillar, on average by about 1.5 dB in power.

4.3. Linear Microphone Array

Figure 8 shows a photograph of the linear microphone array assembled using the modified microphone holder Cp with a 30 mm pillar. The alignment of the horizontal planes (i.e., the vertical position of the microphones) was checked using a laser marker. The results showed that all the ECMs were aligned in a straight line, but when the shielded wires (1.5D QEV, Fujikura) were connected to the ECMs, both ends of the boom hung down 3 mm due to gravity. A metal ruler was used to check the installation intervals of the ECMs, and there was no change in the installation intervals after several months of use.

This microphone array enables measurement of HRIRs from nearfield to farfield accurately by the reciprocal method.

5. DISCUSSION

With regard to the microphone holder shape, microphone holder C is preferable than microphone holder A or B. This is because microphone holder C has a smaller response increase compared to the bare ECM in the high frequency region than microphone holder A or B. Comparing microphone holder A and B, microphone holder A, which supports the ECM along its lower-half circumference, has a smaller response increase in the high frequency region than microphone holder B, which supports the ECM around its full circumference. In addition, microphone holder C, which supports the ECM in a thinner band than microphone holder B, has a smaller response increase in the high frequency region than microphone holder B. Accordingly, the increased response in the high frequency region of the ECM mounted on the holder compared to the bare ECM is probably due to the holder acting as a baffle. A circular baffle of diameter \( L \) enhances the response at frequency \( f_0 = c/L \), where the wavelength is \( L \), and causes a decline in the response at frequencies below \( f_0 \) by about \(-6\) dB/oct [8]. The \( f_0 \) of a 6 mm diameter ECM is 56.7 kHz. When a 1 mm thick microphone holder B or C is attached to it, the overall diameter increases to 8 mm, \( f_0 \) drops to 42.5 kHz and the response at 20 kHz, which is lower than \( f_0 \), increases by 2 to 3 dB, in agreement with the measured result of 2 dB. When microphone holder A having a 1 mm thick semicircular baffle is attached to the ECM, the increase of the response at 20 kHz is about 1 dB which is less than that caused by microphone holder B or C. The lesser increase in response at 20 kHz for microphone holder A, which has a semicircular saucer, compared to microphone holders B and C is likely due to the reduction in the area of the part acting as a baffle.

With microphone holder A or B, a dip appeared in the frequency response around 12 kHz when the microphone was not in tight fit with the holder. There is no such fitting problem with microphone holder C. The dip that appeared in the loose-fitting condition is likely an anti-resonance caused by the space formed by the gap between the back of the ECM and the holder and the hole in the holder through which the wires pass.

With regard to the microphone holder pillar length, a short pillar that gives the ECM a height of 30 mm above the boom works well. Several reflections from real ECMs are observed, yet their effects are small. The amplitudes of the reflections from the microphone holders were smaller with the short (30 mm) pillar than with the long (60 mm) pillar, because of the smaller reflecting surface area of the pillar. Reflections from the 6 mm square boom are almost none. The shorter the pillar length, the better the mechanical durability. In addition, the shorter the pillar length, the less material is needed for modeling. It took 10 minutes to model the 30 mm-long microphone holder Cp using the Form2 (formlabs).

When calculating the head-related impulse response, the complex spectrum of the impulse response measured at the entrance to the ear canal in the presence of the head is divided by the complex spectrum of the impulse response measured at the center of the head in the absence of the head, thus cancelling out the frequency characteristics of the measurement system, especially the frequency charac-

Fig. 8 Photograph of a 6-channel linear microphone array with a 30 mm pillar.
teristics of the microphone and loudspeaker. Accordingly, if the change in response due to the microphone holder is not significant, there is no need to pay much attention to it. On the other hand, we could take advantage of the increased sensitivity at high frequencies by the microphone holder.

However, when measuring the normal impulse response (such as that of the loudspeaker, the room, etc.), such a cancellation is not possible, so the measured impulse response includes various characteristics of the individual microphones. Therefore, the sensitivity and frequency response of the individual microphones used need to be measured separately if necessary. Fortunately, the sensitivity and frequency response for reliable small ECMs such as the EM258 are generally in accordance with the specifications listed in the catalog.

Gravity-induced drooping at both ends of the boom can be avoided by changing the shield wire to a lighter one or by changing the boom to a harder material. ECMs can also be lined up horizontally by adjusting the pillar length to counter the misalignment caused by the drooping boom. However, since the 3 mm droop is sufficiently smaller than the wavelength of a 20 kHz sound wave, the droop is not considered to be a significant problem for head-related impulse response measurements.

Our linear microphone array was developed to measure head-related impulse responses by the reciprocal method, but it can also be used for ordinary acoustic impulse response measurements using a large loudspeaker.

6. CONCLUSION

A number of microphone holders for small ECMs were fabricated using a 3D printer, and the changes in frequency response of the microphones due to the shape of the microphone holders and the degree of reflected waves caused by the arrangement of several microphone holders on a boom were measured. As a result, the ECM can be placed in a precise position with high reproducibility by using the microphone holder Cp, and a durable and maintainable linear microphone array for head-related impulse response measurement by the reciprocal method has been constructed.

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