EFFECTS OF PHYSICAL CONFIGURATIONS ON ANC HEADPHONE PERFORMANCE

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The ear-shell which includes a rigid shell and a soft cushion, the reference microphone, the error microphone and the secondary loudspeaker are four main parts of the physical configuration of an active noise control (ANC) headphone. To investigate their influences on ANC performance, the ear-shells of ANC headphones from two different manufacturers are selected and the same method is used to optimize their ANC controllers. It is shown that the ANC performance is different due to the disparities of physical configuration. The coherence between the reference microphone and the error microphone signals is a measure to evaluate physical configuration effects on feedforward structures, and the passive attenuation affected by the rigid shell and the soft cushion is reflected in the magnitude frequency response from the reference microphone to error microphone. The delay of the secondary path is a critical factor to influence the performance of both feedforward and feedback structures.

Keywords: active noise control, headphone, physical configuration

1. Introduction

The first patent about active noise control (ANC) system is proposed in 1930s, ever since, active control of noise in different environments has been explored [1-2]. The ANC headphones are probably the most successful application of active control which are available commercially and are produced by many companies. Passive and active noise control methods are both needed in ANC headphones. The former attenuates the incoming noise by the ear shell which usually includes a rigid shell and a soft cushion, and is most effective at high frequencies. The latter introduces a

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secondary “anti-noise” of equal amplitude but opposite phase inside the ear shell, thereby attenuates the primary noise, and works well at low frequencies [2].

Many methods have been presented to design ANC headphones with good performance [3-6]. For example, in order to design an ANC headphone with a low-cost microcontroller, a modified feedback algorithm and the ways to save computing load and to compensate for the output limit of speakers were provided [3]. The ANC headphones were evaluated in the application of the magnetic resonance imaging where lower sound pressure level for patient exposure is obtained [4]. A systematic analysis was proposed to investigated the causality of a typical feedforward ANC headphone, in particular, the non-causal delay caused by different noise coming directions [5]. It has been shown that lifting the headphone causes changes at low frequencies of the secondary path, and a cost-efficient algorithm in the time-domain has been developed to react to these changes [6].

Nowadays, there are many ANC headphone products in the market; however, their noise attenuation performance, especially the active noise attenuation performance is different with different reasons. This paper aims to investigate the effects of physical configuration on the ANC headphone performance, which includes the ear-shell, the reference microphone, the error microphone and the secondary loudspeaker. An evaluation system was built where two headphones from two manufacturers were used as the prototypes but with their own ANC function being disabled. The ANC controller was designed on the Matlab platform, and the feedforward, feedback and hybrid structures were evaluated respectively.

2. Evaluation system

The evaluation system is similar to the one described in [7]. Two ANC headphones bought from the market were used as the prototype and shown in Fig. 1. They are called "headphone#1" and "headphone#2" respectively in this paper. The wires of the reference microphone and error microphone in the headphone were lengthened and passed through the microphone preamplifier, then connected to the B&K Pulse Analyzer. The secondary source (loudspeaker) in the headphone was also connected to B&K Pulse Analyzer to generate the secondary signal. The B&K Pulse Analyzer was the central device which captures the signals from the reference microphone, error microphone and secondary source and provides the noise signal to the primary noise source (loudspeaker). A laptop was used to monitor the working states of the other devices and save the data. The sampling frequency is 16000 Hz.

(a) (b)

Figure 1: The two headphone prototypes used in the experiments, (a) headphone#1, (b) headphone#2.

As shown in Fig. 2, the experiments were carried out in an anechoic chamber. The two headphones were mounted on a B&K Type 4128C HATS [8], and a loudspeaker system was placed approximately 40 cm away from the HATS to play back the primary noise. The measurements were performed for 4 different incident directions of the primary noise, i.e., "front", "left", "right" and "rear". It is shown in [7] that the performance of feedforward, feedback and hybrid structures on the ANC headphones are obviously different, thus the effects of physical control configuration on the performance of the same three control structures are evaluated respectively in this paper.

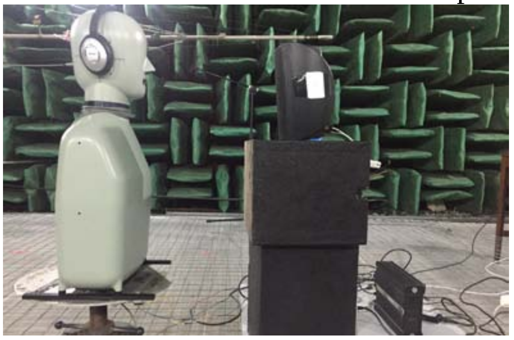

Figure 2: Experimental settings in an anechoic chamber.

3. Results and discussions

Based on the evaluation system described in Section 2, the following data were captured one by one for headphone#1 and headphone#2 respectively. First, the white noise generated by the B&K pulse was sent to the secondary source and simultaneously this signal and the error microphone signal were recorded, then the secondary path (the impulse response from the input of the secondary source to the output of the error microphone) was estimated using the least mean square (LMS) algorithm. Second, the primary noise was played from 4 different incident directions, i.e., "front", "left", "right" and "rear", at the same time the signals from the reference microphone and the error microphone were recorded for the 4 directions respectively, and then the primary paths (the impulse response from reference microphone to error microphone) of the four directions were estimated by the LMS algorithm.

Using the estimated secondary path and the recorded signals of the reference microphone and the error microphone, the optimal ANC controllers of the three structures (feedforward, feedback and hybrid structures) were designed on the Matlab platform respectively, then the ANC performance was evaluated. Detailed performance of the three structures on the same headphone has been tested for the 4 different incident directions respectively [7]. Due to the limited space, the results presented in the remainder of the paper are the average values of the 4 different incident directions. The estimated secondary path and primary paths are 256 taps FIR filters respectively, the ANC controllers are all 512 taps FIR filters.

3.1 Original performance

The original ANC performance of headphone#1 and headphone#2 is shown in Fig. 3. It can be seen from Fig. 3 (a) that the attenuation bandwidth of the feedforward structure is mainly below 2000 Hz. For the 200~800 Hz frequency band, active noise reduction is larger than 20 dB. For the 900~1700 Hz frequency band, active noise reduction is 10~20 dB. On the other hand, for the 200~600 Hz frequency band, the noise reduction of headphone#2 is about 6 dB higher than that of headphone#1, while for the 900~1700 Hz frequency band, the performance of headphone#2 and headphone#1 is very close. For the 1700~2000 Hz frequency band, the active noise reduction of headphone#1 is still above 10 dB, while that of headphone#2 tends to be zero very quickly.

If only feedback structure works, it can be found from Fig. 3 (b) that the performance of headphone#1 is obviously better than that of headphone#2. For the 200~1000 Hz frequency band, active noise reduction of headphone#2 declines from 12 dB to 0 dB, while that of headphone#1 is from 22 dB to 5 dB. For the 1000~2000 Hz frequency band, the noise amplification happens on the headphone#2 due to the waterbed effect, while the headphone#1 also has 0~5 dB noise reduction.

The results of the hybrid structure are shown in Fig. 3 (c). It can be seen that for the 200~700 Hz frequency band, the performance of headphone#1 and headphone#2 is very close and the noise reduction is 30~42 dB. For the 700~1700 Hz frequency band, the noise reduction of headphone#1 is about 7 dB higher than that of headphone#2, while for the 1700~2000 Hz frequency band, the noise reduction of headphone#1 is still in the range of 10~20 dB, but that of headphone#2 tends to be zero very quickly and it even exhibits the noise amplification due to the waterbed effect.

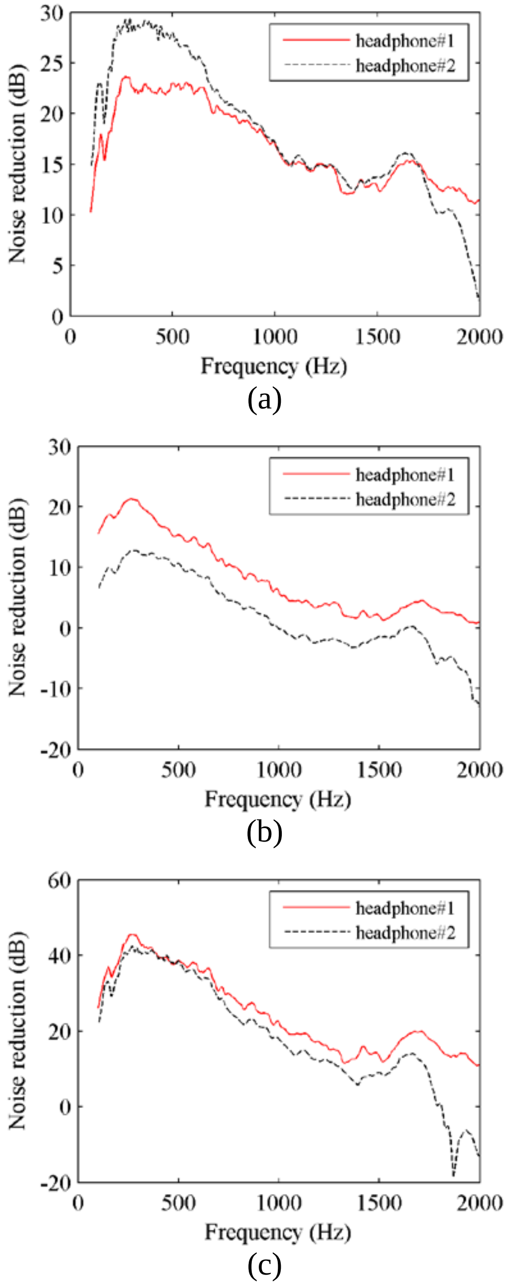

Figure 3: The original ANC performance of headphone#1 and headphone#2, (a) feedforward structure, (b) feedback structure, (c) hybrid structure.

The results in Fig. 3 confirm that although the same method for designing the ANC controller is utilized for both headphone#1 and headphone#2, their ANC performance is significantly different. The reasons are manifold. From the viewpoint of signal and system, the characteristics of the ear-shell, the reference microphone and the error microphone can be mostly described in the signals captured by the reference microphone and the error microphone, as well as the primary path, while the characteristics of the error microphone and the secondary loudspeaker can be described by the secondary path. Therefore the effects of physical configuration are divided into three parts and next three subsections discuss their effects respectively.

3.2 Coherence

The coherence function is a measure of the degree of linear dependence between two signals $x(n)$ and $y(n)$ as a function of frequency. It is determined by the two auto-spectrum ($P_{xx}(\omega)$ and $P_{yy}(\omega)$) of the signals and their cross-spectrum ($P_{xy}(\omega)$) as follows (seen page 57 in [2]):

$$C_{xy}(\omega) = \frac{\left|P_{xy}(\omega)\right|^2}{P_{xx}(\omega)P_{yy}(\omega)} \tag{1}$$

The coherence is a function of frequency ω with values between 0 and 1 that indicates how well $x(n)$ corresponds to $y(n)$ at each frequency. It is derived that the coherence $C_{xy}(\omega)$ can be used to give a simple measure of the reduction that would be achieved by a feedforward ANC system, i.e., the reduction of the error microphone spectrum $N(\omega)$ at frequency ω in decibels is given by (seen page 57 in [2])

$$N(\omega) = -\log_{10}[1-C_{xy}(\omega)] \tag{2}$$

Therefore, using the signals captured by the reference microphone and the error microphone, it is convenient to obtain an estimate of the maximum noise reduction of a real ANC system with Eq. (2). The estimated noise reduction of headphone#1 and headphone#2 using Eq. (2) is shown in Fig. 4.

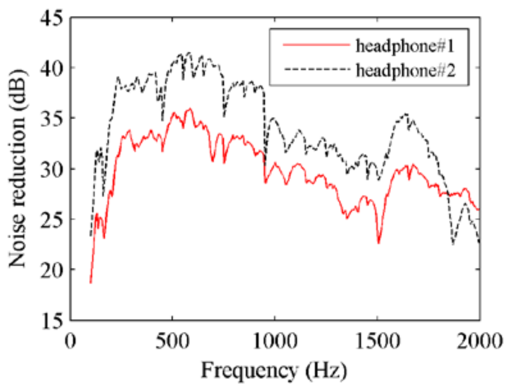

Figure 4: The feedforward structure noise reduction estimation of headphone#1 and headphone#2 using the signal coherence of the reference microphone and the error microphone.

The coherence of the reference microphone and the error microphone signals of headphone#2 is higher than that of headphone#1 when the frequency is below 1700 Hz, so it can be seen from Fig. 4 that the noise reduction bound of headphone#2 with feedforward structure is about 6 dB higher than that of headphone#2 when the frequency is below 1700 Hz. It has been shown in Fig. 3 (a) that for the 200~600 Hz frequency band, the noise reduction of headphone#2 is about 6 dB higher than that of headphone#1. Hence, the results in Fig. 3 (a) is partly explained by Fig. 4, which indicates that when a real ANC headphone product is designed, it is important to verify the coherence of the reference microphone and the error microphone before stepping into the ANC controller optimization. If the coherence is not high enough, some actions must be taken on the physical configuration to increase the coherence of the signals captured by the reference microphone and the error microphone.

3.3 Primary path

The primary path refers to the propagation path of the noise from the outer observation point to the inner observation point of the headphone, which can be characterized by a linear filter (the impulse response from reference microphone to error microphone). The magnitude frequency response of the primary paths of headphone#1 and headphone#2 are plotted in Fig. 5. It is clear that if the frequency is above 2000 Hz, the noise is attenuated 30~50 dB, i.e., due to the passive attenuation of the physical configuration such as the rigid shell and the soft cushion, the high frequency noise can be reduced significantly.

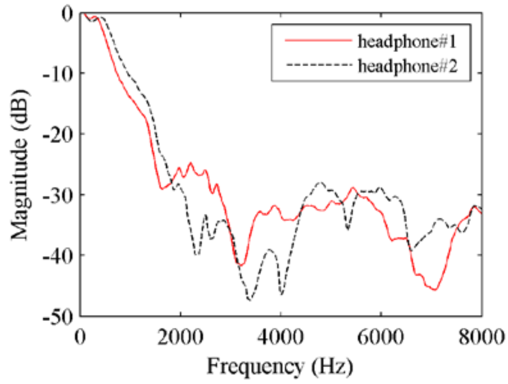

Figure 5: The magnitude response of the primary paths of headphone#1 and headphone#2.

However, for the low frequency noise, especially if the frequency is below 1000 Hz in Fig. 5, only 0~10 dB attenuation can be obtained, thus there is a need to further reduce the low frequency noise by using active control. A good ANC headphone product should effectively combine low frequency active attenuation with high frequency passive attenuation to provide high attenuation of the external noise at a wide frequency range. Therefore, when a real ANC headphone product is designed, it is also important to check the passive attenuation performance of the physical configuration. If the high frequency noise reduction is not high enough, some actions must be taken on the physical configuration, for example, use different materials and structures of the rigid shell and the soft cushion.

3.4 Secondary path

The secondary path refers to the propagation path that the "anti-noise" takes from the output loudspeaker to the error microphone within the quiet zone, which can be modelled by the impulse response from the input of the secondary source to the output of the error microphone. The delay of the secondary path is an important factor to influence the ANC performance. If the delay of the secondary path becomes longer than the delay of primary path, the performance of the feedforward structure will be substantially degraded [2]. On the other hand, the bandwidth over which the feedback structure can be applied is partly determined by the delay of the secondary path and a "rule of thumb" for calculating the bandwidth is also presented in [1].

In Fig. 6, the delay of secondary path of headphone#1 and headphone#2 over the 200~2000 Hz frequency band is plotted, it is found that the delay of the secondary path of headphone#1 is less than 0.06 ms, while that of headphone#2 is 0.09~0.1 ms. The different secondary path delay of headphone#1 and headphone#2 can be used to explain the performance gap in Fig. 3 (b).

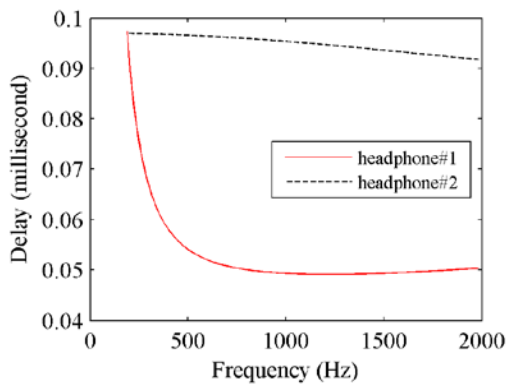

Figure 6: The delay of the secondary path of headphone#1 and headphone#2.

In order to further illustrate the effects of secondary path on the ANC performance, the secondary paths of headphone#1 and headphone#2 are swapped while the other conditions are kept unchanged. The performance comparison is shown in Fig. 7, where "hp#1-orginal" means the original results of headphone#1 shown in Fig. 3 and "hp#1-hp#2SP" means the results of headphone#1 with the secondary path of headphone#2. From Figs. 7(a), 7(c) and 7(e), it can be found that the performance of headphone#1 degrades obviously if its own secondary path is replaced by that of headphone#2, while on the contrary, from Figs. 7(b), 7(d) and 7(f), the performance of headphone#2 improves significantly if its own secondary path is replaced by that of headphone#1.

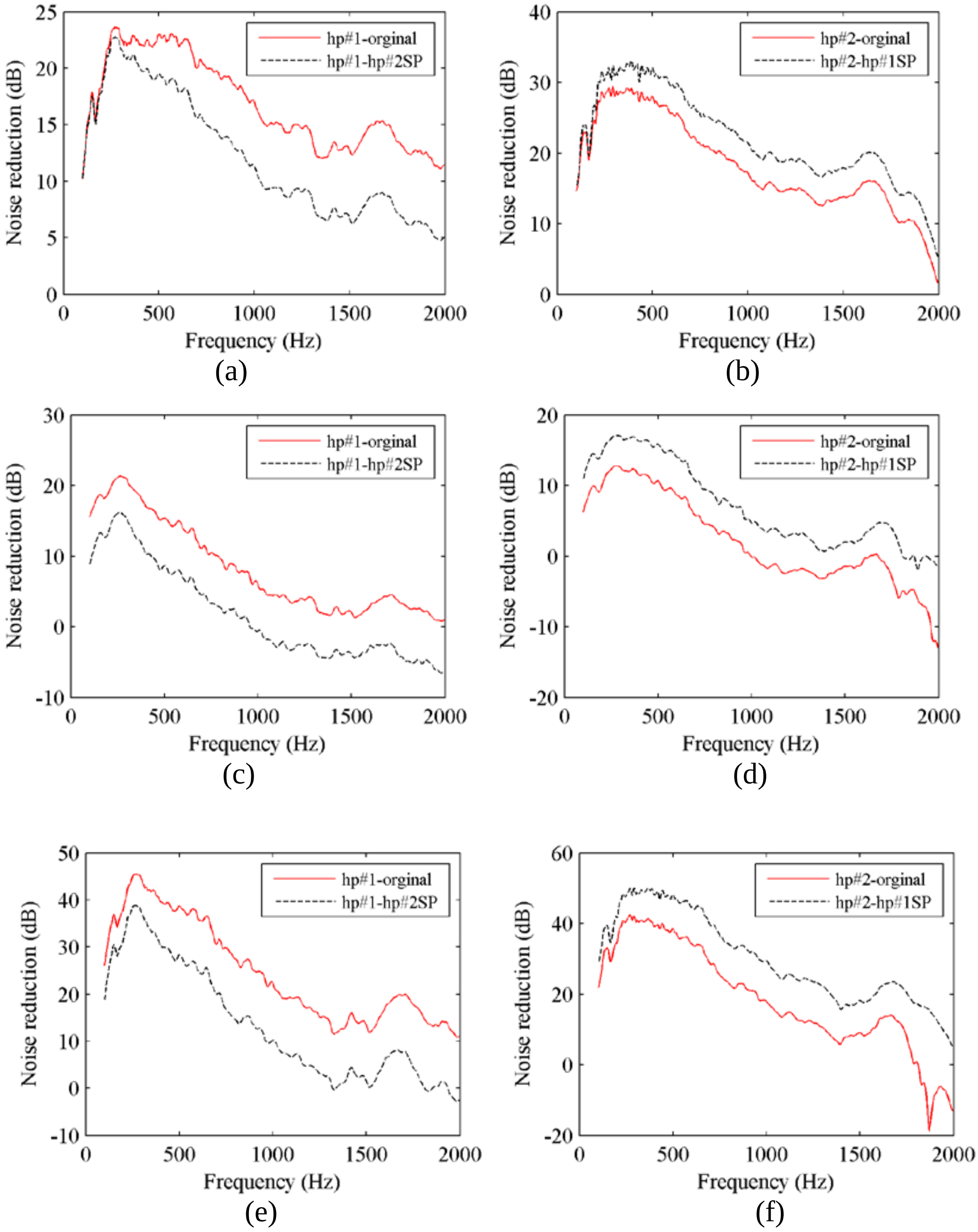

Figure 7: Performance comparison with swapping the secondary path of headphone#1 and headphone#2, (a) feedforward structure of headphone#1, (b) feedforward structure of headphone#2, (c) feedback structure of headphone#1, (d) feedback structure of headphone#2, (e) hybrid structure of headphone#1, (f) hybrid structure of headphone#2.

The longer the delay is, the narrower the bandwidth will be, and the worse the feedback ANC system will have. Therefore, when a real ANC headphone product is designed, it is critical to decrease the delay of secondary path. The benefit with low delay is twofold. For the feedforward structure with lower secondary path delay, there is more allowance left to locate the reference microphone to meet the causality condition and the ANC system is capable of cancelling broadband noise. For the feedback structure with short secondary path delay, the effective bandwidth can be broadened and the noise reduction will be increased. The secondary path in this paper is simple, but for a real ANC headphone product, the digital controller includes the digital-to-analog converter, reconstruction filter, power amplifier, loudspeaker, acoustic path from louder speaker to error microphone, preamplifier, anti-aliasing filter and analog-to-digital converter, so the delay will often be longer than that shown in Fig. 6. More efforts should be spent on the tuning of the physical configuration related to the secondary path.

4. Conclusions

In this paper, an evaluation system was built to investigate the effects of physical configuration on the ANC headphone performance, where two headphones from two manufacturers were used as the prototypes. Due to the inherent difference of physical configuration between the two prototypes, their ANC performance is significantly different even the same design method was utilized to design the ANC controller. From the viewpoint of signal and system, the effects of the physical configuration was analyzed based on the coherence of the signals captured by the reference microphone and the error microphone, the magnitude response of the primary path and the delay of the secondary path. Some helpful suggestions were discussed for the design of real ANC headphone products.

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