Hybrid active noise barrier with sound masking

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ABSTRACT

In this paper, a hybrid active noise barrier (ANB) with sound masking capability is considered. To protect the speech privacy, several sound masking techniques have been developed. However, these sound masking techniques based on the superposition of the masker and original sound will lead to increase in the loudness of the sound after masking. Against this problem, this paper proposes a soundproof system which combines an ANB with a sound masking system. The ANB applies a new type of hybrid active noise control (ANC) system, which can reduce the noise diffraction and the noise propagated to the ear positions of the people behind the ANB simultaneously, to attenuate the conversation sound. Consequently, the required volume of the masker sound will decrease because of the smaller loudness of the original conversation sound in the control area. The sound masking system applies a method which can generate masker based on the frequency properties of the original sound. Several simulations are carried out to investigate the sound attenuation and sound masking performance of this system, and the results show that comparing with the traditional sound masking system, the proposed system needs smaller masker sound to achieve the sound masking effect.

Keywords: Active Noise Control, Noise Barrier, Sound Masking
I-INCE Classification of Subjects Number(s): 38.1, 38.2

1. INTRODUCTION

In the open areas such as clinics, pharmacies, banks and offices, leakage of the privacy contained in the conversations has been seen as a very serious problem. To protect the speech privacy, sound masking techniques (1–5) are often used as the solution. Moreover, for the open offices noise problem, it is reported that the employees feel more distracted by the intelligible overhead conversations (6, 7). Therefore, sound masking is also a solution to improve the sound environment in work space and help employees concentrate.

Sound masking covers the intelligible information in conversations by superposing masker sound on the original conversation sound. The masker often uses meaningless random noise (2) such as white noise and pink noise or the sound synthesized according to the frequency property of the original sound (5). However, whatever the masker is, sound masking will lead to increase in the loudness of the sound after masking because of the superposition of the masker.

In this paper, in order to suppress the increase in the sound pressure after masking, a soundproof system combining an active noise barrier (ANB) with a sound masking system is considered. The ANB applies a new type of hybrid active noise control (ANC) system, which can reduce the noise diffraction and the noise propagated to the ear positions of the people behind the ANB simultaneously, to attenuate the conversation sound. Consequently, the required volume of the masker sound will decrease because of the smaller loudness of the original conversation sound in the control area. The sound masking system applies a method which generates masker based on the frequency properties of the original sound (5). Several computer simulations are carried out to investigate the sound attenuation and sound masking performance of this soundproof system.

The rest of the paper is organized as follows. Section 2 introduces the concept of the proposed soundproof system. In section 3, several computer simulations are carried out to investigate the performance of the soundproof system. Finally, the conclusions are given in section 4.

2. HYBRID ACTIVE NOISE BARRIER WITH SOUND MASKING

The proposed soundproof system consists of a hybrid ANB and a sound masking system. In this section, the concept of the hybrid ANB, the method to generate the masker for sound masking and the control system

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combining ANC with sound masking are introduced.

2.1 Hybrid active noise barrier

Figure 1 shows the concept of the hybrid ANB. The ANB is composed of an office partition, 5 feedback (FB) controllers set on the top of the partition and a feedforward (FF) controller set on the back of the partition.

The FB controllers reduce the diffracted noise so that the attenuation against low frequency noise can be achieved in a relatively wide area behind the ANB (8). The FF controller reduce the noise at the control point which is supposed to be located near the ear positions of the people behind the ANB. The two noise attenuation effects superpose in the control area, so that larger attenuation at low frequencies can be expected. The reference signal of the FF controller uses the signal which is internally generated from the error signal of the center one of the FB controllers. Therefore, the usage of a special reference microphone for FF control is unnecessary. Moreover, the FF controller is designed offline in advance so that only the reference signal is used to generate the control signal during the online control process and the usage of an error microphone, which is often implemented in the adaptive ANC system to update the filter coefficients online, become unnecessary. By adopting the above techniques, the electronic devices for control (FF control speaker, FB control speaker, FB error microphone) can be built on the partition.

2.2 Sound masking system

The sound masking system generates masker based on the method proposed in Reference (5) and outputs the masker via the FF control speaker. The masker generation method extracts the spectrum envelope of the original sound, which represents the phoneme information of the sound, and then synthesizes the masker based on the original spectrum envelope to flatten the spectrum envelope of the sound after masking. Moreover, this method also adds the spectrum fine structure information, which stands for the fundamental frequency and harmonics of the personal voice, into the generation of the masker, so that it is more difficult for people to separate the masker and the original sound.

The procedures used in this paper for generating the masker is described as follows.

1. use a microphone to capture the original sound signal and then extract spectrum envelope and fine structure from the signal.
2. reverse the spectrum envelope upside-down along the axis passing through the maximum peak of the spectrum envelope. During this process, the phase information of the original sound signal will be preserved.
3. Add the preserved phase information to the new spectrum which is generated by adding original fine structure to the reversed spectrum envelope and use IFFT to calculate the masker signal.

2.3 Control system combining ANC with sound masking

The block diagram of the control system combining ANC with sound masking is shown in Figure 2. In the block diagram, x is the primary noise source signal. d_B, y_B and e_B are the primary noise, FB control sound and FB error signal at FB control point respectively. d_F, y_{BF}, y_F and e_F are the primary noise, FB control sound, FF control sound and FF error signal at FF control point respectively. $\boldsymbol{W}_{ref}$ and $\boldsymbol{W}$ stand for the primary acoustic path from the noise source to the FB control point and FF control point respectively. $\boldsymbol{G}_B$ and $\boldsymbol{G}_{BF}$ stand for the secondary acoustic path from the FB control speaker to the FB control point and FF control point

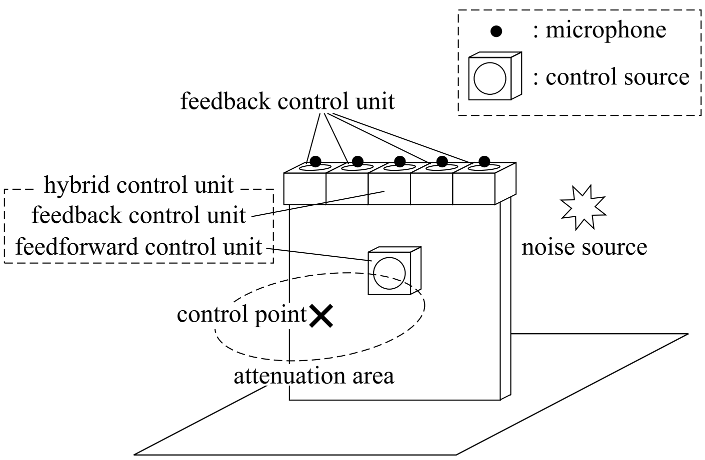


Figure 1 – Concept of the hybrid active noise barrier

respectively. $\boldsymbol{G}_F$ stands for the secondary acoustic path from the FF control speaker to the FF control point. $\boldsymbol{C}_B$ and $\boldsymbol{C}_F$ are the filters in the FB and FF controller. $\boldsymbol{S}$ is the filter to generate masker. The ˆ mark stands for the estimation of signal and acoustic path.

The FB controllers are 5-channel internal model control (IMC) typed FB-ANC system (9). The FF controller is single-channel, and the reference signal of it applies the signal $\hat{d}_B$ which is the estimation of the primary noise at the center FB control point. The control filters $\boldsymbol{C}_B$ and $\boldsymbol{C}_F$ are designed by FxLMS algorithm (9) offline, and used as fixed filters during the control process. For the sound masking part, the masker is generated based on the signal $\hat{d}_B$.

3. COMPUTER SIMULATIONS

In this section, several computer simulations are carried out to investigate the sound attenuation and sound masking performance of the proposed soundproof system. Figure 3 shows the supposed acoustic field and control devices configuration for the simulations. The distribution of the sound attenuation and sound masking effect is calculated in a 600×600mm measurement area behind the ANB, where the measurement points are set at intervals of 100mm. In the simulations, the acoustic paths are represented as 512-tap FIR filters and the control filters in the FB and FF controller are 128-tap FIR filters. The sampling frequency is set as 20kHz by considering the trade-off between control bandwidth and the available computation time for real time control. The primary noise to control is a news audio. The acoustic howling is not considered in the simulations.

3.1 Design for the control filters

The FB and FF control filters are designed offline by the FxLMS based FB-ANC and FF-ANC system (9) of which the block diagrams are shown in Figure 4. In the preceding study (8), it has been confirmed that the FB control can provide extra active noise attenuation in a relatively wide area behind the ANB for the frequency bands up to 500Hz octave band. Therefore, in this paper, the upper bound of the FB control object band is set as 500Hz octave band and lower bound is set as 250Hz octave band by considering the performance of the control speakers. The FF control object band is set from 250Hz to 4kHz octave band.

The sound attenuation at FB and FF control point provided by the designed filters is confirmed by a simulation. The performance of sound attenuation is evaluated by the difference between the sound power

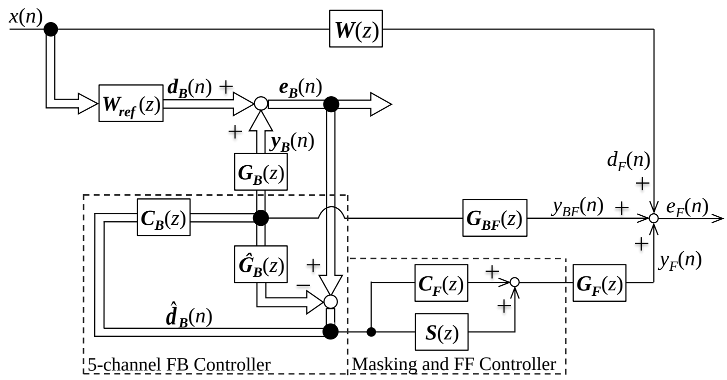


Figure 2 – Block diagram of the hybrid ANC system with sound masking

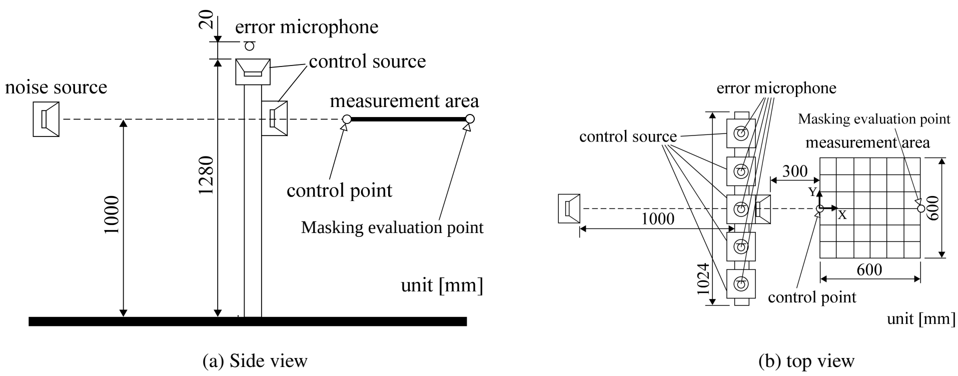


Figure 3 – Configuration for simulations

level before and after control for the octave bands of which the center frequency is up to 4kHz. Data sets of 0.5s cut out from the sounds at the center FB control point and FF control point are analyzed and the results are shown in Figure 5. In the octave bands below the 250Hz, both the FB and FF control can not reduce the sound well because of the performance of the speakers. For the FB control, the sound is amplified in the 1kHz octave band because of the water-bed effect which exists in the time-delayed system feedback control. However, in the 250Hz and 500Hz octave band, about 15dB attenuation is achieved. For the FF control, sound attenuation is achieved in all of the octave bands from 250Hz to 4kHz. The above results indicate that the designed filters can attenuate the object sound effectively.

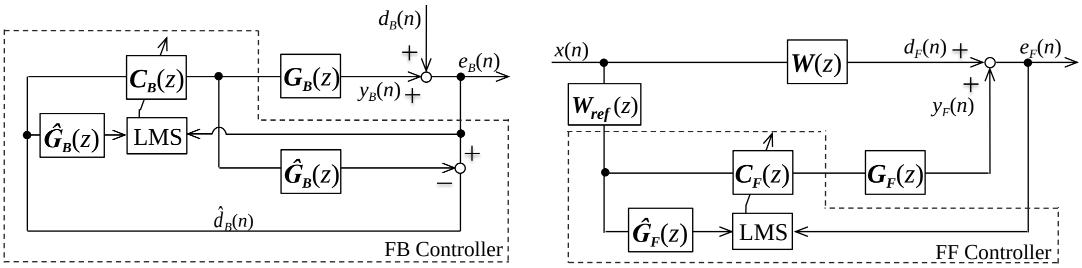
3.2 Sound attenuation performance of the soundproof system

In this section, the distribution of the sound attenuation in the measurement area, which is evaluated by the difference between the sound power level before and after control, is calculated. Three simulations for the FB control only, FF control only, hybrid control occasions are conducted to compare the performance of the proposed hybrid control with the traditional FB and FF control.

Figure 6 to Figure 10 show the results of the sound attenuation contour for the octave bands of which the center frequency is up to 4kHz. In the 250Hz and 500Hz octave bands, the hybrid control can gain about 3dB extra attenuation than the FF control and the sound attenuation area of the hybrid control also be widened due to the superposition of the sound attenuation of the FB control and FF control. In the 1kHz octave band, the sound amplification caused by the water-bed effect of the FB control worsen the performance of the hybrid control comparing to the FF control occasion. The octave bands above the 2kHz are out of the FB control object bands so that the hybrid control performs similarly to the FF control. These results indicate that the hybrid control can improve the sound attenuation at low frequencies.

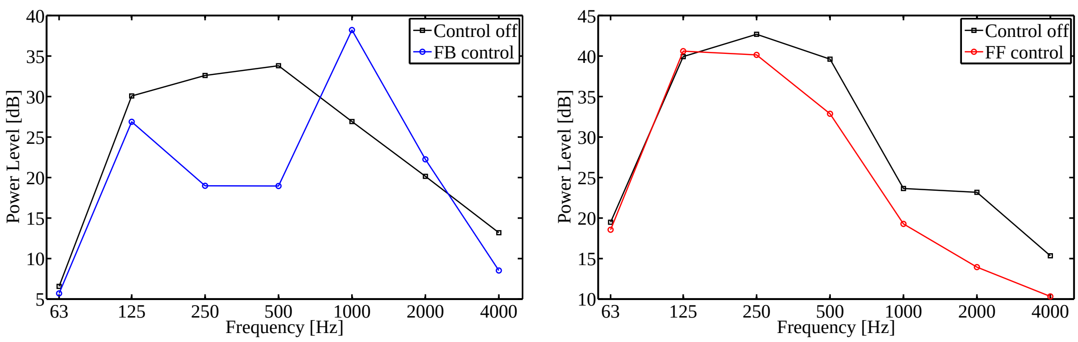
3.3 Sound masking performance of the soundproof system

In this section, the sound masking effect provided by the soundproof system at the FF control point and masking evaluation point shown in Figure 3 is investigated by using the spectrogram of the sound. Three simulations for the hybrid control only, sound masking only, sound masking with hybrid control occasions are conducted. In order to compare the sound pressure after masking for the sound masking only and sound masking with hybrid control occasions, the volume of the masker is tuned automatically in the simulations to ensure that the signal-to-noise ratio (SNR) between the original sound and masker at the FF control point stay



(a) Feedback ANC system (b) Feedforward ANC system

Figure 4 – Block diagram of the FxLMS based ANC system

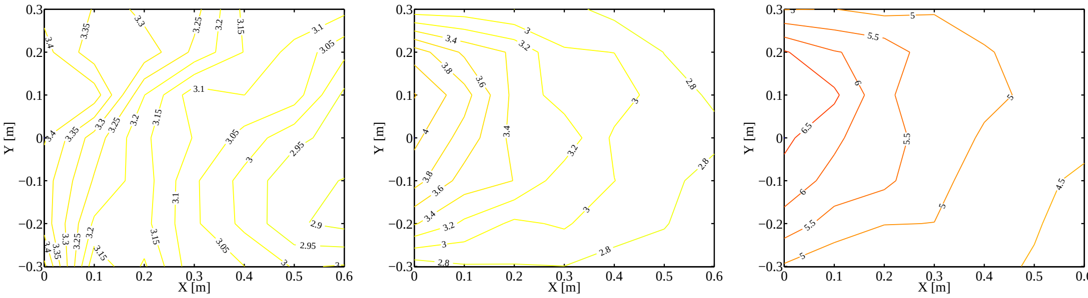


(a) Sound power level at FB control point (b) Sound power level at FF control point

Figure 5 – Sound power attenuation performance of the designed filters

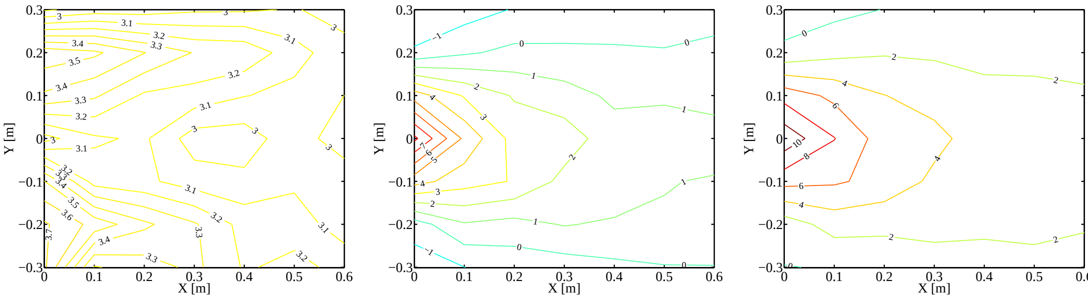
constant during the control process. The SNR is set as -10dB.

Figure 11 shows the spectrogram of the original sound and masker. Against the original sound having



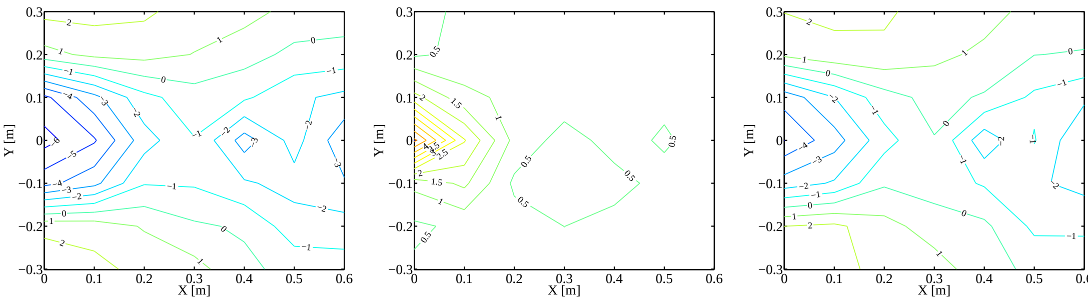
(a) FB-ANC (b) FF-ANC (c) hybrid ANC

Figure 6 – Sound power attenuation at 250Hz octave band



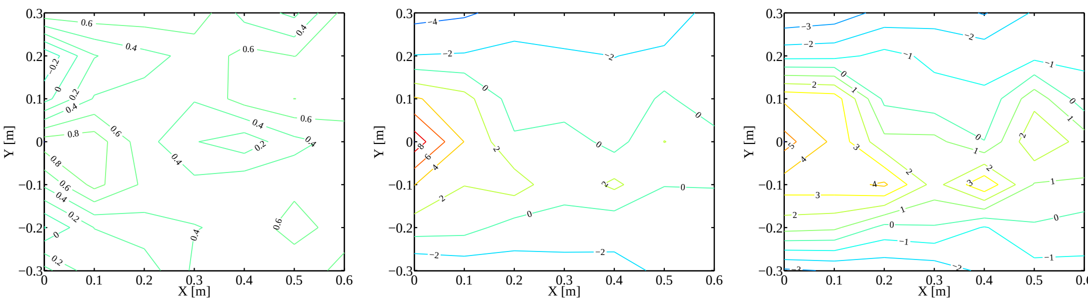
(a) FB-ANC (b) FF-ANC (c) hybrid ANC

Figure 7 – Sound power attenuation at 500Hz octave band



(a) FB-ANC (b) FF-ANC (c) hybrid ANC

Figure 8 – Sound power attenuation at 1kHz octave band



(a) FB-ANC (b) FF-ANC (c) hybrid ANC

Figure 9 – Sound power attenuation at 2kHz octave band

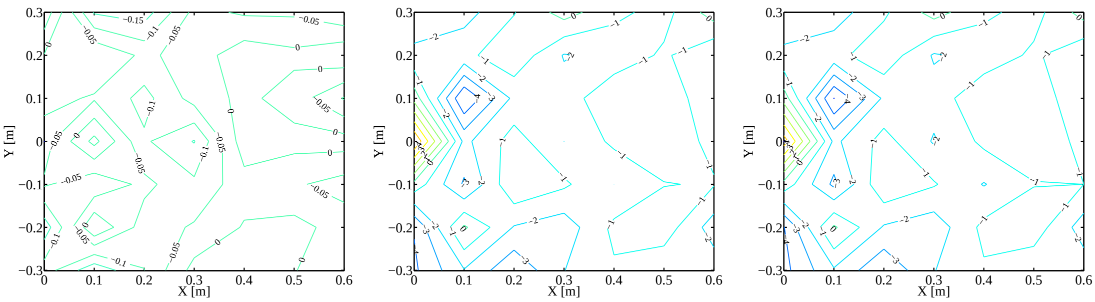
larger power at the low frequencies, the generated masker has smaller power at low frequencies and larger power at high frequencies to flatten the power spectrum of the sound after masking.

The spectrogram of the sound and the result of sound power attenuation with time at the FF control point are shown in Figure 12 and Figure 13. The counterpart results at the masking evaluation point are shown in Figure 14 and Figure 15. At the FF control point, for the hybrid control only occasion, although the power of the original sound is reduced, the shape of the spectrum, which represents the phoneme information of the sound, does not changed much. For both the sound masking and sound masking with hybrid control occasions, the spectrum of the sound after masking is flattened so that the news audio become more difficult to be recognized. However, the sound masking with hybrid control needs smaller masker to achieve the -10dB SNR so that the sound pressure after masking is smaller than the sound masking only occasion. At the masking evaluation point, although the achieved sound attenuation is less than the FF control point, the similar result that the sound pressure after masking is smaller on the occasion of sound masking with hybrid control can be concluded. The above results indicate that the proposed soundproof system can use smaller masker to achieve sound masking effect.

4. CONCLUSIONS

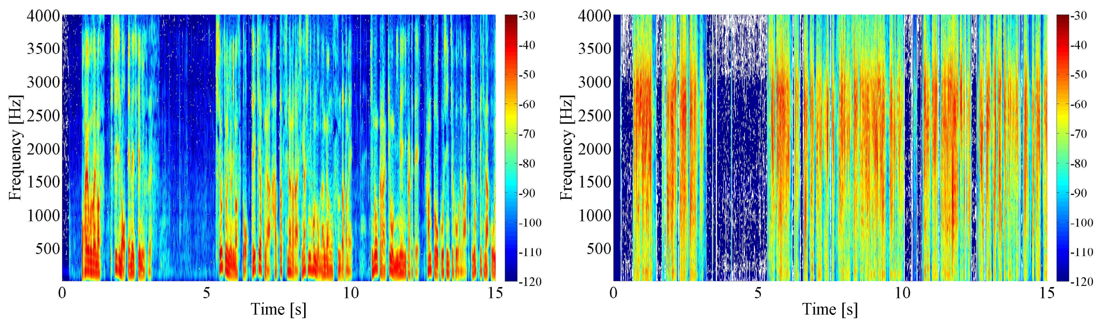
Against the problem that sound masking will lead to increase in the loudness of the sound after masking, this paper proposed a soundproof system that combines a hybrid typed ANB with a sound masking system. The ANB reduces the original sound so that the necessary volume of the masker for the sound masking will decrease because of the smaller original sound.

Several computer simulations have been conducted to validate the proposed soundproof system. The sound attenuation in a 600mm×600mm measurement area has been investigated and the results show that the attenuation for 250Hz and 500Hz octave bands can be achieved in a relatively wide area. For the octave bands above 1kHz, the sound attenuation can be achieved near the control point. Moreover, the proposed hybrid ANB can provide larger sound attenuation and wider attenuation area than the traditional ANB for 250Hz and 500Hz octave bands. Meanwhile, the sound masking performance has also been investigated and the results show that the soundproof system need smaller masker to achieve sound masking effect.



(a) FB-ANC (b) FF-ANC (c) hybrid ANC

Figure 10 – Sound power attenuation at 4kHz octave band



(a) Original sound (b) Masker

Figure 11 – Spectrogram of the original sound and masker

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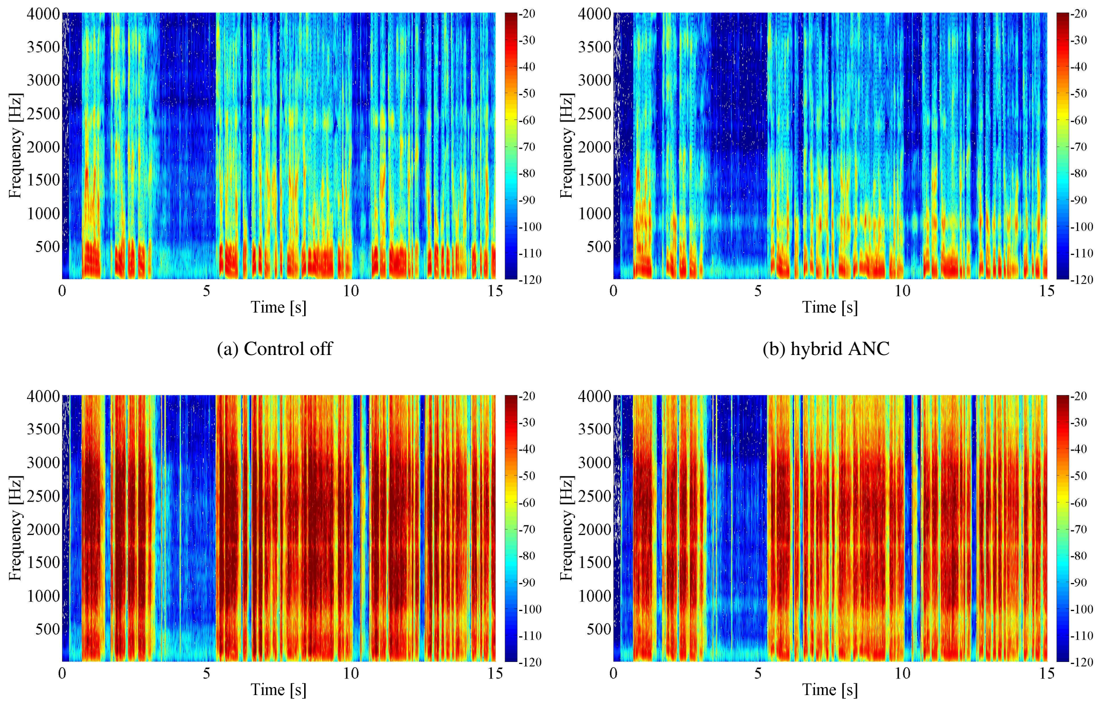


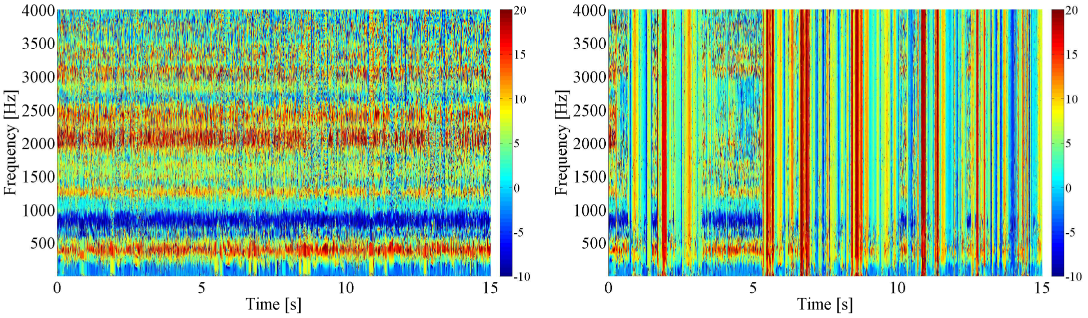
(a) Control off

(b) hybrid ANC

(c) Masking

(d) Masking with ANC

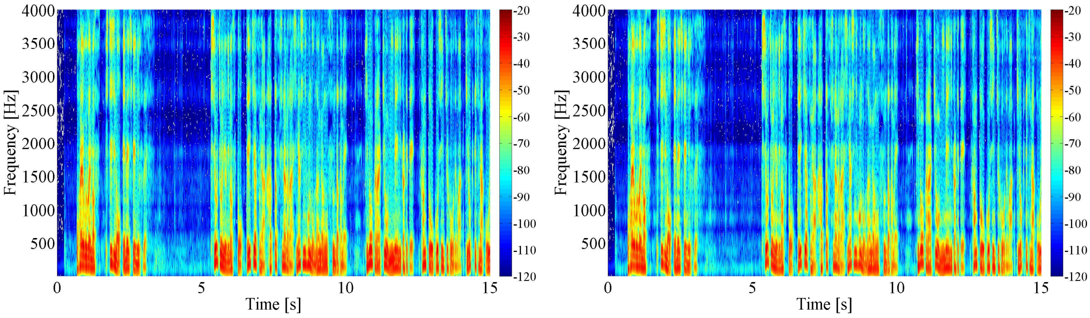
Figure 12 – Spectrogram of the sound singal at FF control point



(a) Difference between Control off and hybrid ANC

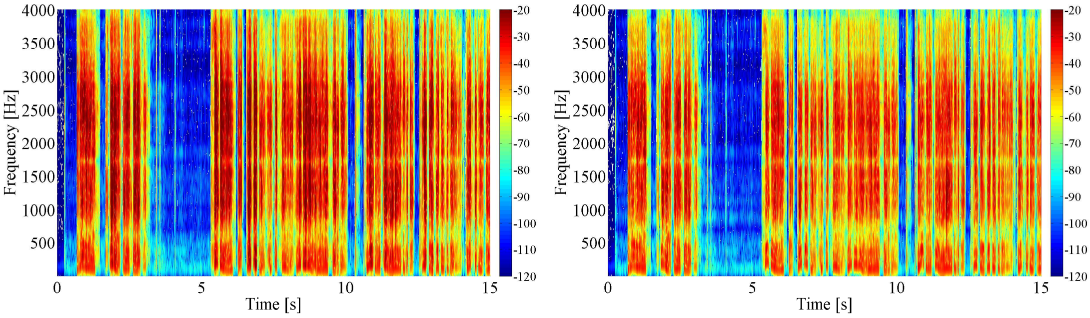
(b) Difference between Masking and Masking with ANC

Figure 13 – Sound power attenuation with time at FF control point



(a) Control off

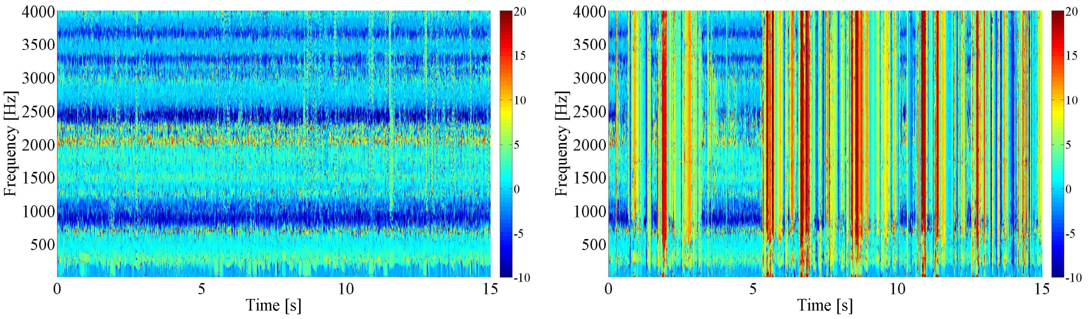
(b) hybrid ANC



(c) Masking

(d) Masking with ANC

Figure 14 – Spectrogram of the sound singal at masking evaluation point



(a) Difference between Control off and hybrid ANC

(b) Difference between Masking and Masking with ANC

Figure 15 – Sound power attenuation with time at masking evaluation point