CONTROL OF TRANSFORMER NOISE USING AN INDEPENDENT PLANAR VIRTUAL SOUND BARRIER

JianchengTao[1], Xiaojun Qiu[2] and Jie Pan[3]

[1] Key Laboratory of Modern Acoustics, Institute of Acoustics, Nanjing University
Nanjing, 210093, China
Email: jctao@nju.edu.cn

[2] School of Electrical and Computer Engineering, RMIT University
Melbourne VIC 3001, Australia
Email: xiaojun.qiu@rmit.edu.au

[3] School of Mechanical and Chemical Engineering, the University of Western Australia,
Perth, WA 6009, Australia
Email: jie.pan@uwa.edu.au

Abstract

A virtual sound barrier (VSB) can be applied to reduce transformer noise radiated outward from an opening of an enclosure without scarifying natural ventilation and lighting. Although a traditional independent VSB system consisting of multiple single channel active noise control systems has shown practical potential for solving the noise problem of real transformers, the instability associated with the system decentralization needs to be investigated. In this paper, a stability assessment method is proposed for the independent VSB system consisting planar arrays of control loudspeakers and error microphones first. Then the distance between the control loudspeaker and its collocated error microphone that is required for stability is investigated based on the frequency characteristics of the noise and the Green's function in free field. Finally, the system stability and the noise reduction performance of a 44-channel independent VSB system installed at the room opening of an onsite 110 kV transformer are presented.

1. Introduction

Transformer noise is dominated by low frequency harmonic components, and traditional passive noise control treatments usually encounter thermal and spatial restrictions [1]. Much research has shown that the active noise control technique can be an effective solution for the transformer noise control since 1950s [2−7]. One major challenge in the active noise control applications for large transformers is the cost of controller, control sources and related circuits for multi-channel systems. For instance, it was found that about 80 control sources and 96 error microphones were needed to achieve global noise control for a 160 MVA power transformer in a suburb [8].

Indoor substations are widely used in recent days in cities due to the safety, maintenance and environment benefits [9]. The transformers are often placed in an enclosure with one opening where the noise mainly radiates outward. The active noise control system with planar arrays of control sources and error sensors can be applied at the opening, and this can be regarded as a planar "virtual sound barrier" (VSB) to reduce the noise radiation outwards without sacrificing natural ventilation [10]. It was reported that a fully-coupled planar VSB system with 15 channels could provide 16 dB and 7.7 dB noise reductions at 100 Hz and 200 Hz respectively in the far field when it was installed on a 5 m^2 opening [11].

It was further reported that the noise reduction performance of such a VSB system is nearly the same as a sealed glass window below 300 Hz in a real substation [12]. For these fully coupled VSB systems, the processing requirement of the controller grows at the rate of the square of the channel number, which makes the implementation of the multichannel adaptive algorithm in current available digital signal processing platforms almost impossible when huge numbers of control channels are required. Therefore a decentralized system, such as an independent VSB system which only considers the transfer function between each control source and its collocated error microphone, is used to reduce the computation complexity.

The instability arises with the system decentralization and this issue has been discussed in the implementation of decentralized feedback control systems [13−15]. Elliot et al. investigated the interaction between multiple feedforward active noise control systems in the frequency domain and found that the system stability could be estimated through the eigenvalue analysis [16]. A sufficient but not necessary stability condition was further proposed based on the Gerschgorin circle theorem, and it required a much smaller interval between the control source and its corresponding error microphone for stability than the actual value when the channel number is larger than 2. Cordioli et al. investigated the noise reduction performance of an active noise control system surrounding a transformer in free filed, and found that simple decentralizations may result in a considerable degradation of the noise reduction; however the investigation object is not the planar VSB system and the system stability has not been considered comprehensively [17].

In this paper, an independent planar virtual sound barrier is proposed to reduce the transformer noise through the room opening. First, the stability assessment method based on the eigenvalue analysis is introduced for the independent planar VSB system. Then, the parameter choice especially the space interval between the control loudspeaker and its collocated error microphone is investigated. Finally, the noise reduction performance of a 44-channel independent planar VSB system implemented at the opening of an onsite transformer room is presented.

2. Theory

2.1 Virtual sound barrier

A sketch map of the planar virtual sound barrier (VSB) for transformer noise control is presented in Fig. 1, where a transformer is located inside a room with one opening. The VSB system is composed by a planar control loudspeaker array, a collocated error microphone array near the room opening and a real-time controller. Assuming the transformer noise mainly radiates through the opening, the noise radiated outward should be reduced by minimizing the sound pressure level at the error microphones.

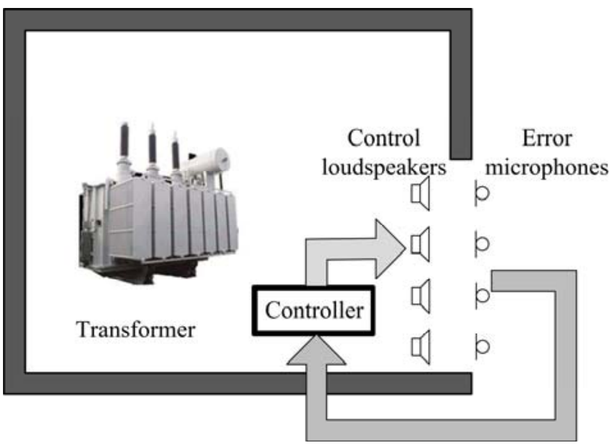


Figure 1. Sketch map of the planar virtual sound barrier

2.2 Stability assessment for the independent VSB

Assuming there are M control loudspeakers and M error microphones in the VSB system, the signal vector from the error microphones can be expressed as

$$\mathbf{e} = \mathbf{p} + \mathbf{Z}\mathbf{Q}_{\mathrm{c}}, \tag{1}$$

where $\mathbf{p}$ is the sound pressure vector from the primary source, $\mathbf{Z}$ is a $M \times M$ matrix of the transfer functions from the control loudspeakers to the error microphones, and $\mathbf{Q}_{\mathrm{c}}$ is the control loudspeaker strength vector.

When the VSB system is fully coupled, the strength of each control loudspeaker is adjusted in response to the error signals at all error microphones, and the transfer function matrix $\mathbf{Z}$ is adopted in the optimization. However when the VSB system is independent, the strength of each control loudspeaker is adjusted with only the error signal at the related error microphone, and a diagonal matrix $\mathbf{Z}^{\mathrm{I}}$ is employed. The off-diagonal elements of $\mathbf{Z}^{\mathrm{I}}$ are zero but the diagonal elements are the same as those of $\mathbf{Z}$, where the superscript $^{\mathrm{I}}$ is used to indicate that the system is independent.

For an independent planar VSB system, the gradient of the cost function of the ith channel can be formulated as [18]

$$\nabla J_i^{\mathrm{I}} = 2Z_i^{\mathrm{I}} e_i + 2\beta_i^{\mathrm{I}} Q_{\mathrm{c}i}^{\mathrm{I}}, \text{ for } i = 1, 2, 3, \ldots, M, \tag{2}$$

where Z_i^{I}, e_i, β_i^{I} and $Q_{\mathrm{c}i}^{\mathrm{I}}$ are the transfer function, error signal, weighting factor and the control loudspeaker strength, respectively, of the ith independent channel. The weighting factor of each channel, β_i^{I}, can be adjusted separately in the independent VSB system instead of a single constant value adopted in the fully coupled system. The weighting factor can be adjusted to constrain the strength of the control loudspeaker and it should be zero to obtain the best noise reduction performance at the error sensors.

Assuming Eq. (2) equals zero, the optimal strength of the control loudspeaker can be directly calculated as

$$\mathbf{Q}_{\mathrm{c}}^{\mathrm{I}}(\infty) = -\left[\left(\mathbf{Z}^{\mathrm{I}}\right)^{\mathrm{H}}\mathbf{Z} + \boldsymbol{\beta}^{\mathrm{I}}\mathbf{I}\right]^{-1}\left(\mathbf{Z}^{\mathrm{I}}\right)^{\mathrm{H}}\mathbf{p}, \tag{3}$$

where $\boldsymbol{\beta}^{\mathrm{I}}$ is a diagonal matrix with the diagonal elements being the weighting factors of all channels. If $\boldsymbol{\beta}^{\mathrm{I}}$ equals zero, the control loudspeakers' strength can be expressed as $\mathbf{Q}_{\mathrm{c}}^{\mathrm{I}}(\infty) = \mathbf{Q}_{\mathrm{c}}(\infty) = -\mathbf{Z}^{-1}\mathbf{p}$. This indicates that the noise reduction performance of the independent VSB system is the same as that of the fully coupled one with a zero weighting factor.

In practical applications, the cost function minimization is typically implemented by adopting an iteration algorithm. The control loudspeakers' strength can be obtained by [16,17]

$$\mathbf{Q}_{\mathrm{c}}^{\mathrm{I}}(n+1) = \mathbf{Q}_{\mathrm{c}}^{\mathrm{I}}(n) - \boldsymbol{\mu}^{\mathrm{I}}\nabla\mathbf{J}^{\mathrm{I}}, \tag{4}$$

where n is the iteration number, $\boldsymbol{\mu}^{\mathrm{I}}$ is a diagonal matrix consisting of the step sizes of μ_i^{I}, and $\nabla\mathbf{J}^{\mathrm{I}}$ is a column vector composed by the gradients of the cost function $\nabla\mathbf{J}_i^{\mathrm{I}}$. Substituting Eq. (3) into Eq. (4), it can be found that [16]

$$\left[\mathbf{Q}_{\mathrm{c}}^{\mathrm{I}}(n+1) - \mathbf{Q}_{\mathrm{c}}^{\mathrm{I}}(\infty)\right] = \left\{ \mathbf{I} - 2\boldsymbol{\mu}^{\mathrm{I}}\left[\left(\mathbf{Z}^{\mathrm{I}}\right)^{\mathrm{H}}\mathbf{Z} + \boldsymbol{\beta}^{\mathrm{I}}\right] \right\} \left[\mathbf{Q}_{\mathrm{c}}^{\mathrm{I}}(n) - \mathbf{Q}_{\mathrm{c}}^{\mathrm{I}}(\infty)\right]. \tag{5}$$

To ensure this iteration equation converge for large n, the moduli of all eigenvalues of the matrix in the square brackets of the first term on the right side should be less than unity, which means that the real parts of all the eigenvalues of $(\mathbf{Z}^{\mathrm{I}})^{\mathrm{H}}\mathbf{Z}+\boldsymbol{\beta}^{\mathrm{I}}$ must be positive [16]. For the independent VSB system, $\mathbf{Z}^{\mathrm{I}}$ is a diagonal matrix, and the sign and symmetry of the matrix $(\mathbf{Z}^{\mathrm{I}})^{\mathrm{H}}\mathbf{Z}+\boldsymbol{\beta}^{\mathrm{I}}$ depends on the specific values of all elements. When the weighting factors in $\boldsymbol{\beta}^{\mathrm{I}}$ are sufficiently large, $(\mathbf{Z}^{\mathrm{I}})^{\mathrm{H}}\mathbf{Z}+\boldsymbol{\beta}^{\mathrm{I}}$ tends to be the diagonal and positive matrix $\boldsymbol{\beta}^{\mathrm{I}}$, so the independent VSB system should be stable with a small step size matrix $\boldsymbol{\mu}^{\mathrm{I}}$. However, it is not recommended to employ large weighting factors to enhance the system stability because the noise reduction performance decreases with the increase of the weighting factors. A more reasonable choice is to adjust the transfer function matrix $\mathbf{Z}$ by the parameter optimization of the VSB system to make the real part minimum of the eigenvalues of $(\mathbf{Z}^{\mathrm{I}})^{\mathrm{H}}\mathbf{Z}$ positive so that the independent VSB can perform the same as the fully coupled one in terms of both the noise reduction and the system stability.

3. Numerical simulations

The dimension of the room opening for a real 110 kV indoor transformer is 8.3 m in width and 2.8 m in height. If the noise components of 100 Hz and 200 Hz are chosen as the control target, the interval between control loudspeakers should be less than 0.85 m, which is one half of the wavelength corresponding to 200 Hz [13]. Considering the system cost and the installation convenience, the interval of the control loudspeakers is chosen as 0.7 m and 0.8 m in the vertical and horizontal direction respectively, so a total of 44 control loudspeakers are placed with 4 rows and 11 columns as shown in Fig. 2. One error microphone is placed in front of each control loudspeaker, and the distance between the control loudspeaker and its collocated error microphone is D_{ce}. The error microphones are numbered according to its collocated control loudspeakers, for example, the error microphone at the left bottom and right top is numbered as E1 and E44 because the corresponding control loudspeakers are numbered as S1 and S44.

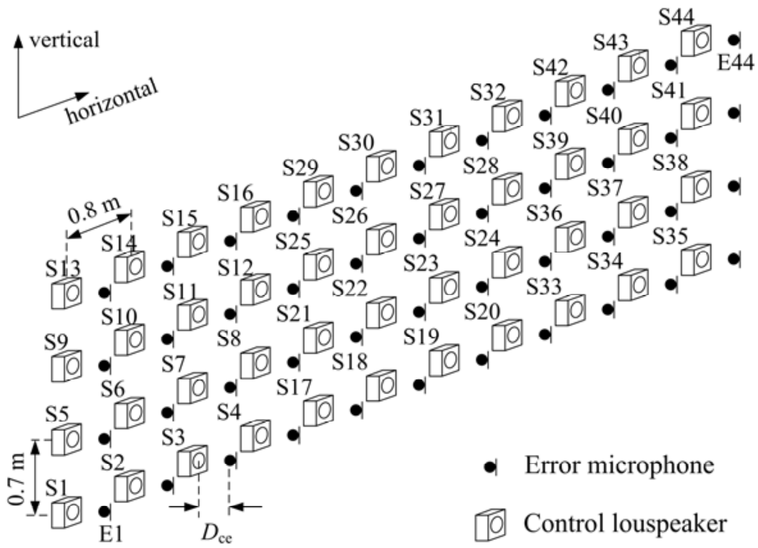


Figure 2. Arrangement of a 44-channel planar VSB system

To achieve the best noise reduction performance, the weighting factor is set as zero for each single channel. The variation of the smallest real part of the eigenvalues of $(\mathbf{Z}^{\mathrm{I}})^{\mathrm{H}}\mathbf{Z}$ with respect to D_{ce} is shown in Fig. 3, where the Green's function in free field is adopted to calculate the transfer functions in the matrix $\mathbf{Z}$. It can be found in Fig. 3 that the real part minimum of eigenvalues decreases with the interval D_{ce} in general, and becomes negative when D_{ce} is sufficiently large. This indicates that the interval between the control loudspeaker and its collocated error microphone should be sufficiently small to ensure the system stability. When the real part minimum of the eigenvalues equals zero, the upper bound of D_{ce} for system stability is determined.

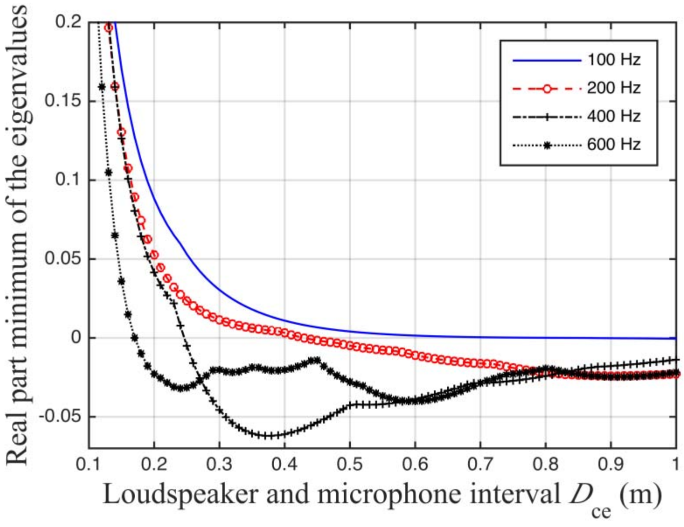


Figure 3. Variation of the real part minimum of the eigenvalues with the distance D_{ce}

The variation of the upper bound of D_{ce} for stability with the frequency is presented in Fig. 4 with a frequency interval of 1 Hz. It can be found that the upper bound decreases first and then increases with the frequency below 600 Hz. Considering that the target frequencies in transformer noise control are 100 Hz and 200 Hz, 0.2 m is chosen as the interval between the control loudspeaker and its collocated error microphone in the experiments.

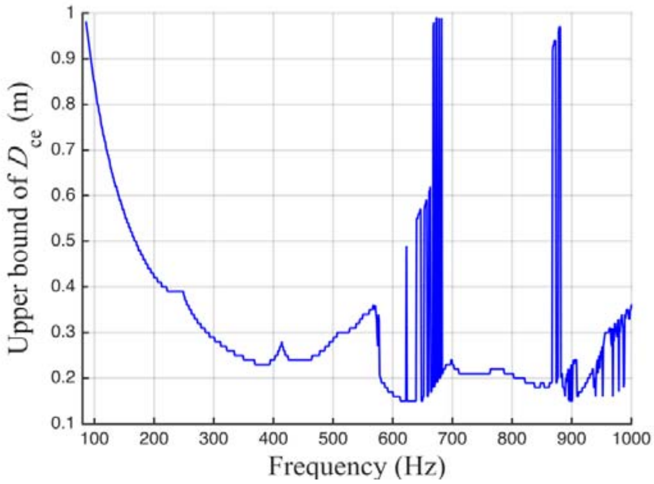
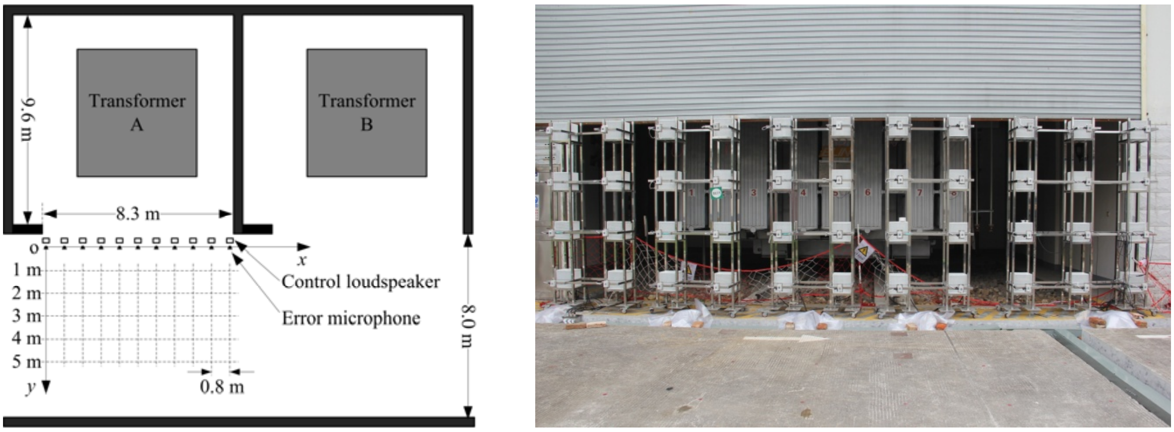


Figure 4. Upper bound of D_{ce} for system stability at different frequencies

4. Experiments

The top view of the substation in the implementation is shown in Fig. 5(a), where two 110 kV transformers are placed in two separate rooms with the front surfaces opened for ventilation and maintenance. The dimension of the room opening is about 8.3 m × 6.2 m, and the upper part of the opening for transformer A is sealed with a sound insulation material whose insertion loss is about 20 dB at 100 Hz. An independent planar VSB system with 44 channels was implemented at the lower part of the opening (2.8 m high) for transformer A. The control loudspeaker array is placed 0.2 m outside the opening for the safety reason, and an enclosing wall with a height of 2.2 m locates 8 m away from the room opening. To evaluate the noise reduction performance, a horizontal plane at the height of 1.2 m is chosen. As shown in Fig. 5 (a), the projection of an error microphone at the far left column is chosen as the coordinate origin, 55 points with a 0.8 m interval in *x* axis and a 1 m interval in *y* axis are chosen as evaluation points, and the sound pressure level at these evaluation points is measured.



(a) (b)

Figure 5. System setup in the experiment (a) top view of the substation (b) front view of the independent virtual sound barrier

The control loudspeakers and error microphones are placed as shown in Fig. 5(b), and all of them are connected to a 44 channel adaptive controller running the independent FxLMS algorithm. The reference signal is obtained using the self-generated 100 Hz and 200 Hz sinusoid signals because the frequency shift of the transformer noise peaks is within 0.5% in low frequency [19].

The transfer functions from S1~S16 to E1~E16, S17~S32 to E17~E32 and S33~S44 to E33~E44 are measured. Based on these measured values, the transfer function matrix $\mathbf{Z}$ can be approximately generated at each single frequency by setting other elements except Z(1:16,1:16), Z(17:32,17:32) and Z(33:44, 33:44) to zero. The real part minimum of the eigenvalues of matrix $(\mathbf{Z}^{\mathrm{I}})^{\mathrm{H}}\mathbf{Z}$ is calculated and presented in Fig. 6. The real part minimum of the eigenvalues is 0.008 and 0.037 at 100 Hz and 200 Hz, which indicates that the implemented VSB system is stable at these two frequencies.

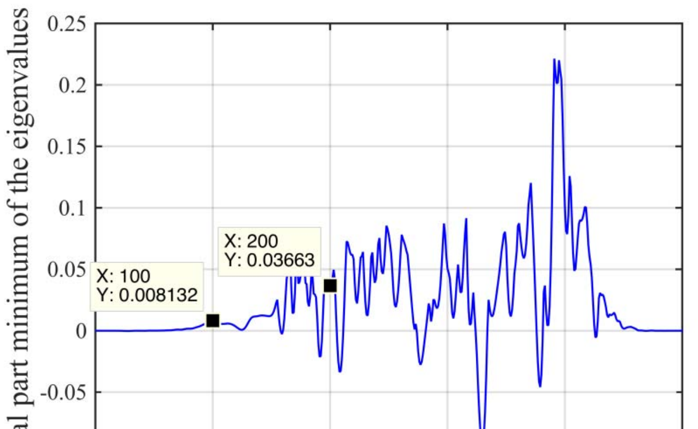


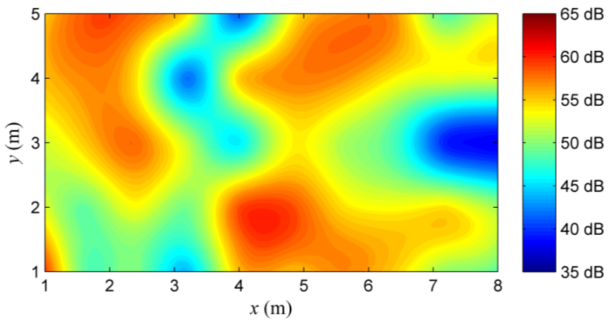
Figure 6. Real part minimum of the eigenvalues at different frequencies

To reduce the interference of the unexpected environmental factors, for example, the noise radiated by a passing vehicle may also contain 100 Hz and 200 Hz components, the weighting factors are adjusted to 1×10^{-5}, 6×10^{-4} and 1×10^{-4} for the channels corresponding to E1~E16, E17~E32 and E33~E44 in the experiment. The noise reduction at each error microphones is presented in Tab. 1, where it can be found that the averaged noise reduction at 100 Hz and 200 Hz is 17.5 dB and 22.9 dB respectively. It can also be found that the noise reduction at microphones from E17 to E32 is lower compared to the values at other microphones, and the reason is that a relative larger weighting factor is adopted at the single channel active noise control systems corresponding to these microphones.

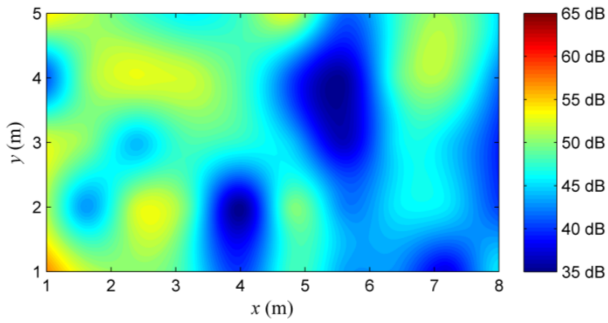
Table 1. Noise reduction at error microphones at 100 Hz and 200 Hz

No.	Noise reduction (dB)		No.	Noise reduction (dB)		No.	Noise reduction (dB)	
	100 Hz	200 Hz		100 Hz	200 Hz		100 Hz	200 Hz
E1	37.0	35.0	E17	0.6	9.3	E33	21.6	29.9
E2	41.8	38.1	E18	5.8	13.8	E34	22.3	34.6
E3	46.0	35.8	E19	5.9	15.4	E35	22.7	24.5
E4	40.3	23.4	E20	6.9	13.6	E36	20.1	30.8
E5	27.7	38.5	E21	8.8	7.2	E37	16.6	20.4
E6	30.6	42.6	E22	4.9	12.4	E38	6.9	20.3
E7	29.5	27.6	E23	3.3	10.8	E39	17.8	13.3
E8	30.4	25.4	E24	9.7	10.0	E40	25.6	28.9
E9	3.9	18.0	E25	6.9	15.6	E41	9.0	25.0
E10	13.4	17.6	E26	7.0	14.3	E42	6.7	31.2
E11	20.9	22.8	E27	12.2	11.2	E43	11.1	27.0
E12	17.8	26.4	E28	14.4	10.9	E44	17.5	32.7
E13	22.7	35.8	E29	14.4	12.6	Average	17.9	22.9
E14	31.3	34.7	E30	12.4	12.0			
E15	32.5	34.2	E31	12.0	7.7			
E16	26.9	38.1	E32	13.2	20.1			

The sound pressure distribution at the evaluation plane without and with the control of the planar VSB system is shown in Fig. 7. The maximum sound pressure level is 63.3 dB and 58.6 dB at 100 Hz when the independent planar VSB system is turned off and on respectively. It is obvious that the sound pressure level is effectively reduced by comparing Fig. 7(a) and Fig. 7(b) and therefore the effectiveness of the independent VSB system is verified. The maximum sound pressure level is 61.6 dB and 59.8 dB at 200 Hz when the planar VSB system is turned off and on respectively. Figs. 7(c) and 7(d) show that the sound pressure level in the region 4 m < *x* < 5 m is well reduced, however the overall noise reduction at the whole evaluation plane is not obvious compared to the result at 100 Hz.



(a)



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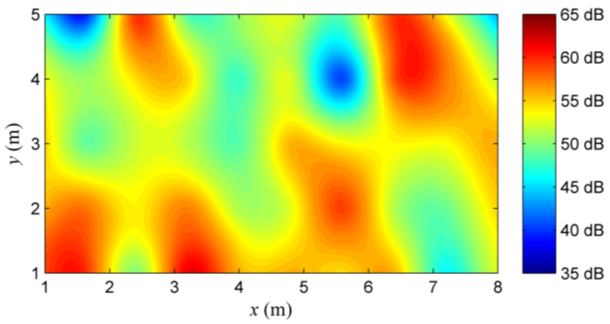
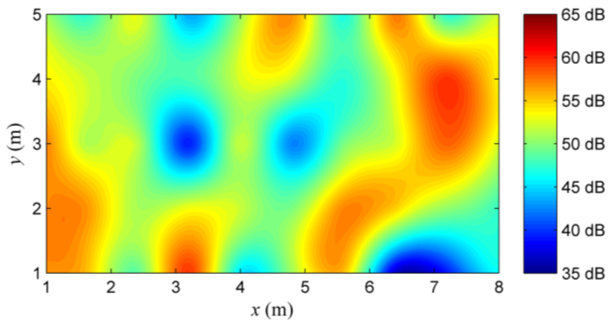


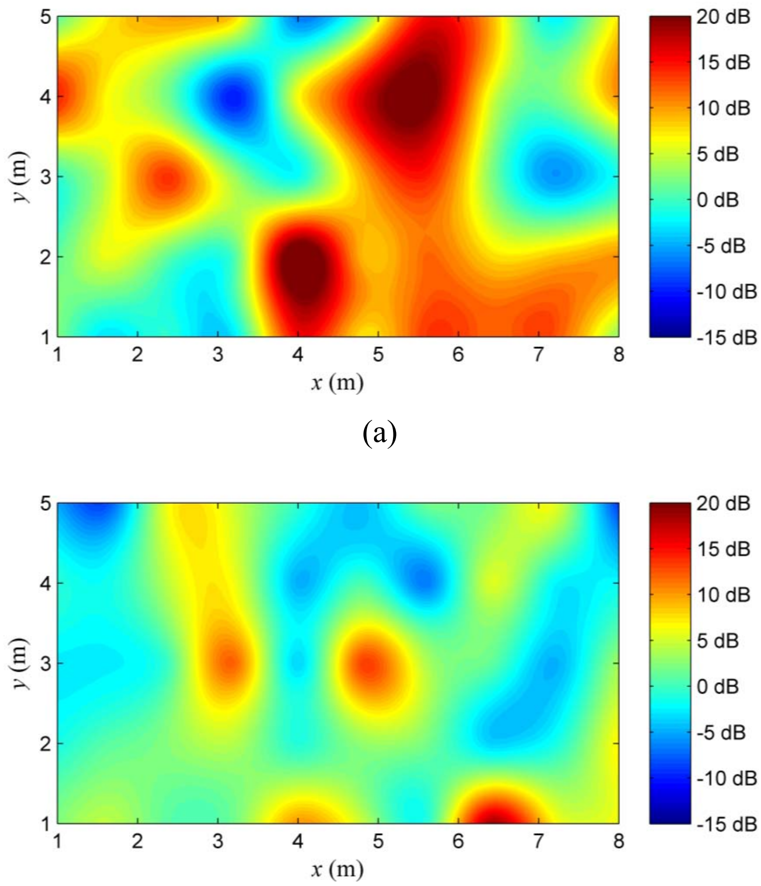
(c)



(d)

Figure 7. Sound pressure distribution on the evaluation plane (a) without control at 100 Hz (b) with control at 100 Hz (c) without control at 200 Hz (b) with control at 200 Hz

The noise reduction at the evaluation points of the planar VSB system is presented in Fig. 8. The maximum and the minimum noise reduction at 100 Hz are 23.8 dB and −10.1 dB respectively. The negative noise reduction may be caused by two reasons. Firstly, transformer B also contributes to the total sound pressure level at the evaluation points because it remains working no matter the VSB system is turned on or off and there is no treatment on its room opening. Secondly, the primary noise level is relative low at the areas where the negative noise reduction occurs as shown in Figs. 7(a) and 8(a), and therefore the measured noise reduction can be easily affected by environmental change.



(a)

(b)

Figure 8. Noise reduction on the evaluation plane (a) at 100 Hz (b) at 200 Hz

It can also be found from Fig. 8(b) that the noise reduction is positive for most evaluation points at 200 Hz, and the maximum and the minimum is 18.8 dB and −8.9 dB respectively. Compared to the results at 100 Hz, the noise reduction in evaluation plane is lower at 200 Hz although the averaged reduction at error microphones is 4.0 dB higher. The reason is that the interval between control loudspeakers is fixed in the implementation and it is harder to control the sound propagation when the frequency increases.

6. Conclusions

This paper presents an application of the independent planar virtual sound barrier to control the transformer noise through a room opening. The system stability of independent virtual sound barrier is evaluated based on the eigenvalue analysis. Based on the Green's function in free filed, the space interval between the planar arrays of the control loudspeakers and the error microphones is investigated, and it is found that a 0.2 m interval is sufficiently small for ensuring the system stability for the control of the 100 Hz and 200 Hz components of transformer noise. A 44-channel independent planar VSB system with the designed parameters has been implemented at the room opening of a 110 kV transformer, and the system stability and the noise reduction performance are verified.

Acknowledgements

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