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Virtual Formation of a Woofer at the Roof Panel of a Vehicle by Using Array Actuators

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Abstract

To hear the powerful and spectrally rich sound in a car is costly, because the usual car audio system adopts small loudspeakers. Also, the available positions of the loudspeakers are limited, that may cause the reactive effect from the backing cavity and the sound distortion. In this work, a part of the roof panel of a passenger car is controlled by array actuators to convert the specified large area to be a woofer. An analogous concept of the acoustic holography is employed to be projected as the basic concept of an inverse rendering for achieving a desired vibration field. The vibration of the radiating zone is controlled to be in a uniform phase, and the other parts outside it are to be made a no-change zone in vibration. The latter becomes a baffle for the woofer, and the backing cavity is virtually infinite if the sound radiation into the passenger cabin is only of concern. Small array actuators are located in the periphery of the target roof panel avoiding the stiffener members. The rendered zonal activities in vibration are fulfilled by solving an inverse vibro-acoustic problem employing the bending wave control. The inverse technique determines the proper weighting for each actuator in the array. Experiment is conducted on a cutout roof panel of a midsize car. The preliminary test result shows that the localized in-phase vibration control yields a maximum deviation of 3˚ in phase differences at the speaker zone.

Introduction

Most vehicle sound systems, particularly for the midsize cars, fail to produce spectrally rich and powerful sound quality because they feature small speakers, which are inappropriate for radiating low frequencies. Furthermore, the speakers installed on some panels, due to the limitation in the available space, suffer from the reactive effect caused by the backing cavity. Also, the sound distortion can happen when a speaker installed on a panel is driven in very low frequency signals, and even causes rattling. Extra payment is required to install a non-standard woofer and amplifier to get the satisfactory sound, which usually costs a lot. A practical alternative to the costly installation of an additional sound system in a passenger car is to control part of the roof panel by array actuators that convert a specified area into a virtual woofer. Previously, people tried to implement the panel structures or accessories of the body panel for the low-frequency sound radiation, but they are not adopted in the practical design due to poor acoustic response. In this work, only a designated circular portion of a body panel is excited to have a uniform phase, and the outer part excluding the vibration zone is controlled as tranquil to be used as a baffle. To this end, an inverse vibro-acoustic problem is formulated, and it is solved to determine the proper weightings, in both amplitude and phase, for each actuator in the array [1]. The roof panel of a midsize is used for testing the validity of the suggested technique.

Theoretical Background

In the previous works, the vibration control of a plate is usually implemented to suppress an entire area or mode or to produce an area that vibrates strongly using actuators placed in dominant positions in the modes of interest [2]. When the vibratory excitation is given at a certain location, an elastic wave passes through the structure in all directions from the driving point as a bending wave. If we have many actuators for the dynamic excitation, the relationship between the input voltage signals of excitations at the actuators and the velocity responses at the observation points on the panel can be expressed in a matrix form as

$$\mathrm{G}_{p\times N}\mathrm{A}_{N\times 1} = \mathrm{V}_{p\times 1}. \qquad (1)$$

Here, p denotes the number of measurement, i.e., observation, points, N the number of actuators, i.e., excitation points, A the matrix of input electric signals, V the vector of the target vibration field, and G the transfer function matrix between the input signals of the excitation actuators and the vibration responses.

Because the transfer matrix G is changeable depending on the boundary condition of the system, and the boundary condition of vibration structure is not easy to define precisely, one should resort to employing the measured frequency response functions (FRF). Complex actuator weightings, A, containing the information on magnitude and phase, can be obtained inversely by using matrix G and rendered vibration field V as follows:

$$\mathrm{A}_{N\times 1} = \mathrm{G}^{\dagger}_{p\times N}\mathrm{V}_{p\times 1} = \left(\mathrm{G}^{H}\mathrm{G}\right)^{-1}\mathrm{G}^{H}\mathrm{V}. \qquad (2)$$

Here, G^H denotes the conjugate transpose of matrix G [3, 4]. In inverse estimation of the actuator weightings, the system usually becomes ill-posed, and the solution obtained would be unstable. Therefore, the regularization is needed to remove such instability caused by the inverse process. In this work, the Tikhonov regularization technique [5] is adopted as

$$J = \left(\mathrm{V}-\mathrm{GA}_F\right)^H\left(\mathrm{V}-\mathrm{GA}_F\right) + \beta\mathrm{A}_F^H\mathrm{A}_F, \qquad (3)$$

$$A_F = \left(G^H G + \beta I\right)^{-1} G^H V, \qquad (4)$$

where J is the cost function for solving the minimization problem, A_F the regularized input voltage signal, and β the weighting constant for the input power. J comprises the error between target field V, rendered vibration pattern GA_F, and the weighted input power.

Experimental Verification

Target Field and Measurement Setup

A preliminary experiment is conducted on the front part of the cutout roof panel of a midsize car, as shown in Figure 1, to verify the proposed control method. The aim is to control all area of the roof panel by array actuators in a target pattern to form a speaker zone and a baffle zone. The vibration of the speaker zone radiating sound is controlled to maintain a uniform phase, and the area outside the speaker zone is to be a tranquil zone or to experience no change in vibration. The latter zone becomes a baffle for the woofer, thus enhancing the acoustic efficiency, and the backing cavity is virtually infinite if the sound radiation into the passenger cabin is the only concern. In the experiment, a central part of the roof panel is used as the first target for virtual formation of a woofer. Small moving coil-type actuators, which are placed on the plate in a free-mounting condition, are located in the peripheral zone of the front side of the roof panel. The spacing between adjacent actuators is 65 mm. Observation points are uniformly selected, with 60 mm in length and 90 mm in width spacing, to avoid the roof rail stiffener. To obtain the mobility and velocity responses from the observation points, a laser scanning vibrometer is used, for which the phase is provided with reference to the excitation signal. Figure 1(b) exhibits a schematic of the measurement set-up. The total number of actuators is 40, and the total number of observation points is 77 as illustrated in Figure 2.

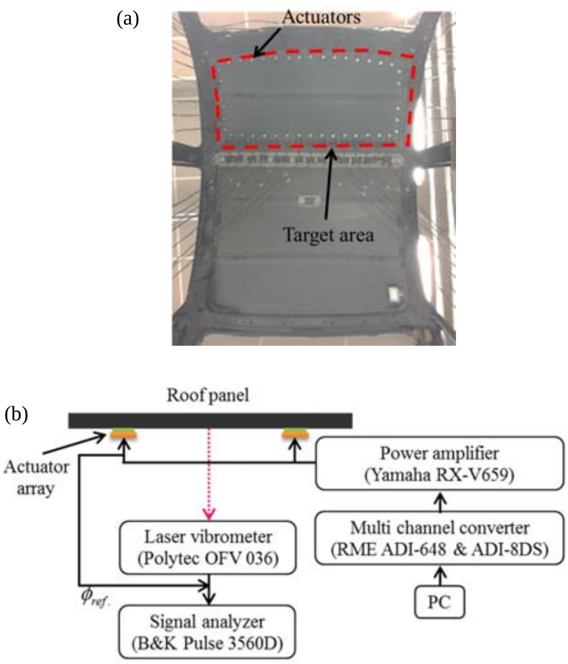

Figure 1. (a) Bottom-view of the panel, (b) schematic of the experimental set-up.

The size of the speaker zone on the panel is determined by the frequency range of interest. To operate a virtual speaker as a woofer, a range of 100 Hz to 200 Hz is generally required. In-phase vibration in the speaker zone can be regarded as a piston movement for a speaker. This piston becomes a baffled simple source when *ka* is less than 1, which means that the directional factor is near unity for all angles [6]. Here, *k* and *a* denote the wavenumber and radius of the speaker zone, respectively. Using this relationship, the proper radius of a virtual speaker is determined to be less than 300 mm. For this reason, a 180-mm circle in the central part of a front side panel that is 480 mm in length and 1000 mm in width is selected for the speaker zone size, and the other part is for the baffle as depicted in Figure 3.

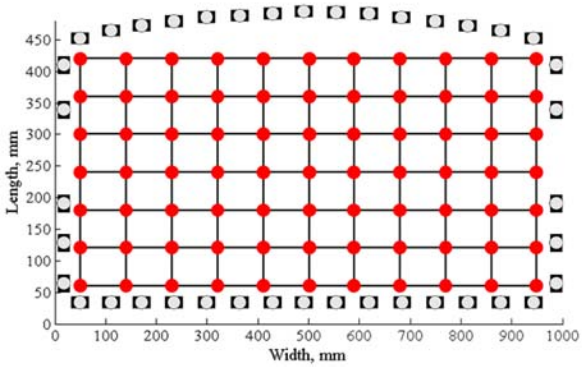

Figure 2. Initial grid for experiments: ◘, actuator locations; ●, observation points distribution.

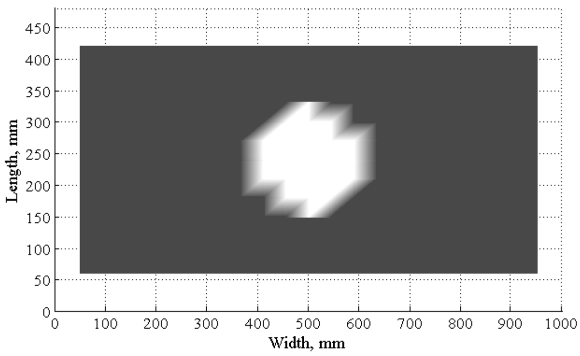

Figure 3. Target field shape. The bright circle denotes the speaker zone, and the remainder is the baffle zone.

Simulation Result for Excitation Frequency Range

The FRF between an actuator and observation points can be measured experimentally. One example of FRF which is measured at the observation point at (230,180) excited from an actuator at (550, 30) is shown in Figure 4. Using these experimentally measured FRFs as the transfer functions, the actuator weightings needed to form a virtual woofer are calculated by using Eq. (4), and the simulation results can be obtained by multiplying the two matrices of transfer functions and actuator weightings. The goal of this work is to achieve a localized in-phase vibration on a panel, and the standard deviation of the vibration phase in the speaker zone is thus of primary concern. Also, the frequency response of the actuator should avoid the 1st vibration mode to induce a linear excitation. In this regard, the operable frequency is decided to be higher than 120 Hz. The simulation is conducted for the 120-200 Hz frequency band as shown in Figure 5. One can find that the frequency range of 158-173 Hz can be picked as the potential frequency range to form a localized speaker zone, yielding a standard deviation of 3˚ in phase. Figure 6 illustrates the magnitude and phase of the simulation result at 160 Hz excitation as an example.

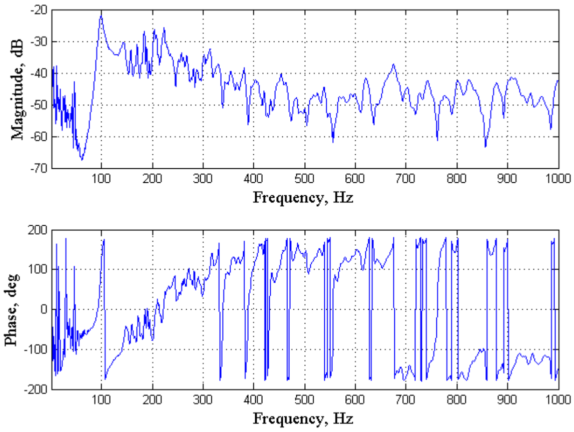

Figure 4. Magnitude and phase of the FRF measured at the observation point at (230,180) excited from an actuator at (550, 30).

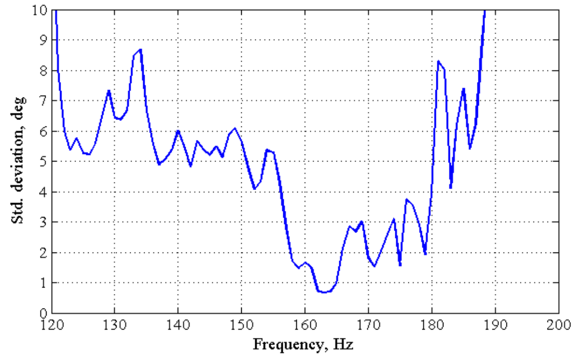

Figure 5. Standard deviation of phase distribution at the speaker zone. The plot can be used for determining the excitation frequency range.

Design Considerations for a Virtual Woofer

To test the in-phase vibration control and discover how the sound radiation forming vibration affect a driver or passenger, representative songs with a low range including our target frequency are selected, namely, ‘Boom Boom Pow’ sung by The Black Eyed Peas and ‘He’s a Pirate’ played by a double bass. To compensate for the speaker characteristics, the tests are conducted in the position shown in Figure 7.

The input signals of the song need to be compared with the speaker response to determine the compensating frequency. The comparison between the input and output response from the microphone shown in Figure 8 show that the speaker has unfavorable characteristics at a frequency range below 200 Hz. To compensate with the use of a virtual woofer from the localized in-phase vibration, the equal-loudness-level contour [7] is considered. Because the sound radiation from the speaker is 40 phon, the equal-loudness-level at the target frequency range is 60 dB, and the virtual woofer should radiate as 60 dB of sound with the speaker. In this way, the subjective response of human auditory system can be partially considered in the output design.

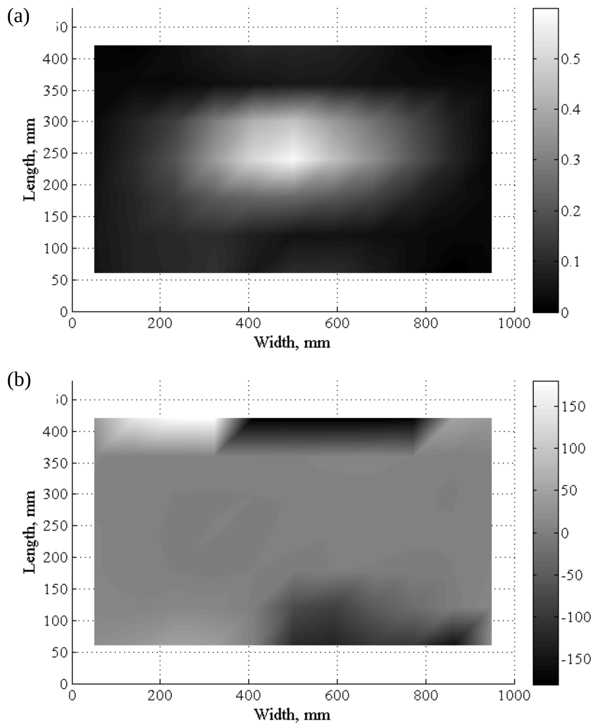

Figure 6. Simulation result with 160 Hz excitation for virtual woofer formation: (a) Amplitude (in mm/s), (b) phase (in deg.).

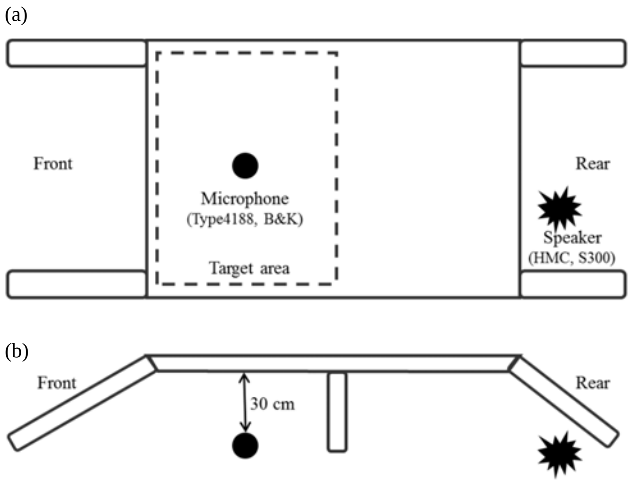

Figure 7. Experimental set-up for comparison of the input signal voltage and output response from the originally installed speaker for a car: (a) Top-view, (b) side-view.

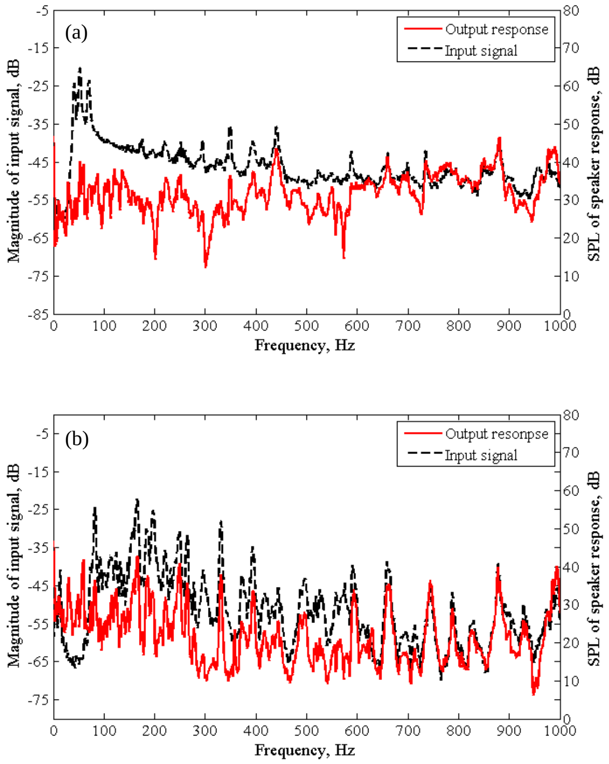

Figure 8. Comparison of input signal voltage and output response from speaker: ——, input signal; -----, output response. (a) 'Boom Boom Pow', (b) 'He's a Pirate'.

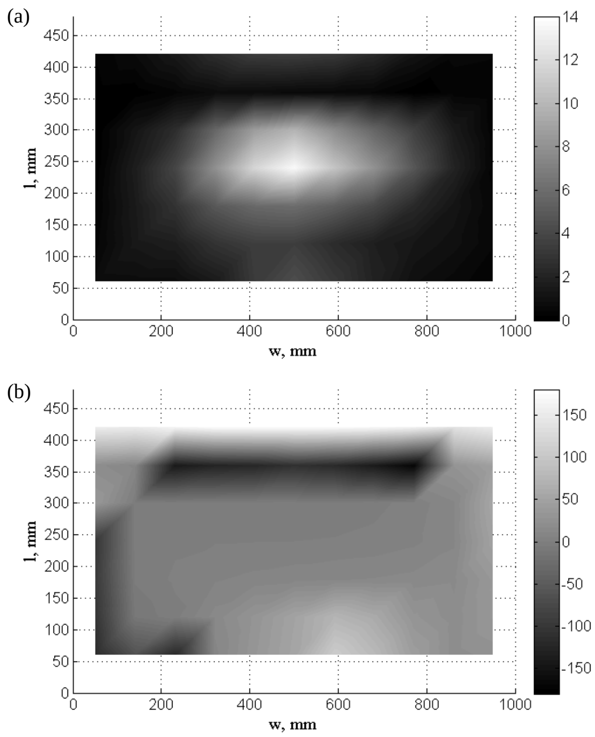

Figure 9. Measured distribution of amplitude and phase when vibration has a peak amplitude. (a) Amplitude (in mm/s), (b) phase (in deg.).

Experimental Results

Figure 9 presents the magnitude and phase of the experimental result when it has a peak by using a filtered signal. The standard deviation of the phase at the speaker zone is 2.5°, which satisfies our initial goal to be within 3°This fact can be thought that the in-phase control of the radiated sound is possible. The sound pressure level (SPL) spectra for two source signals are shown in Figure 10 imposed with the equal-loudness-level contour. One can find that the SPL of the target frequency range, i.e., 158 - 173 Hz, is 60 dB, which is the same as was set using the equal-loudness-level at 40 phon. This ensures the passenger to hear the compensatory sound radiated from the virtual woofer with a good sound quality.

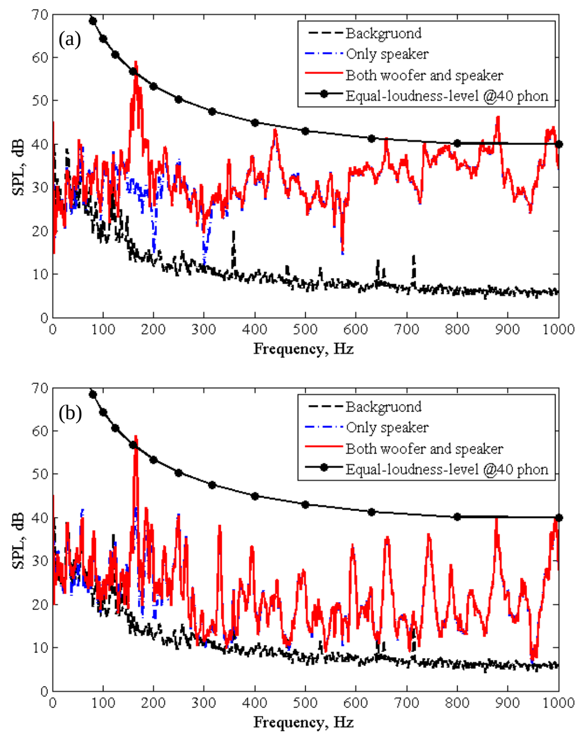

Figure 10. Measured sound level spectra: -----, background noise; -·-·-·-, original speaker only; ——, both virtual woofer and original speaker; —•—, equal-loudness-level contour of 40 phon. Source sound: (a) 'Boom Boom Pow', (b) 'He's a Pirate'.

However, the change of vibration at the rear part of the roof panel outside the target area is not considered in control yet. This means that the vibration which is not controlled or not selected can cause distorted or unwanted sound as a passive secondary radiator. Figure 11 compares the acceleration level spectra measured at the central part of the roof panel in the rear side in two conditions: with or without control. One can find that acceleration in the outside of the target frequency range is not controlled yet, and has a high amplitude. The lesson is that, one should control the system with additional reference to the observation points located outside the main target zone. A further study is needed on avoiding such unwanted vibration, either by including additional observation points or additional control of escaping energy.

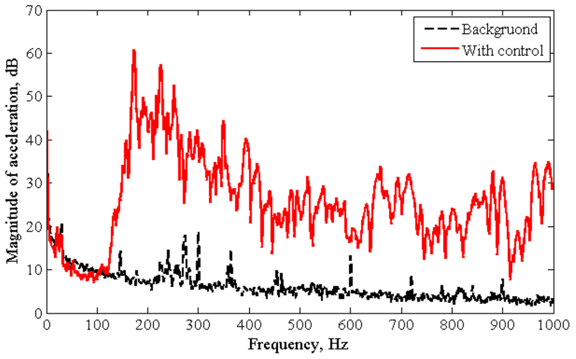

Figure 11. A comparison of the measured acceleration level spectra at the position of central part of the roof panel in the rear side.

Conclusions

In this work, a localized in-phase vibration control is adopted to form a virtual woofer using an array of actuators located at the boundary of a roof panel of a midsize car. An inverse weighting technique based on the bending wave control is used, which is analogous to the acoustic holography concept being projected as an inverse rendering for achieving a desired vibration field. In the actual control, the subjective response is also considered by taking the equal-loudness-level into account, which compensates a poor sound quality in using the originally equipped speaker only. It is noted that the in-phase vibration can be obtained in the speaker zone with a few degrees of error. Because the proposed method is very simple in concept, it can be implemented as a practical method of generating a complicated, virtual sound source in a structure, on condition that the energy transmission to the other panel parts is prevented.

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