

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.

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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

$$\mathbf{G}_{p \times N} \mathbf{A}_{N \times 1} = \mathbf{V}_{p \times 1} \quad (1)$$

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

Because the transfer matrix $\mathbf{G}$ 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:

$$A_{N \times 1} = G_{p \times N}^\dagger V_{p \times 1} = (G^H G)^{-1} G^H V. \quad (2)$$

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

$$J = (V - GA_F)^H (V - GA_F) + \beta A_F^H A_F, \quad (3)$$

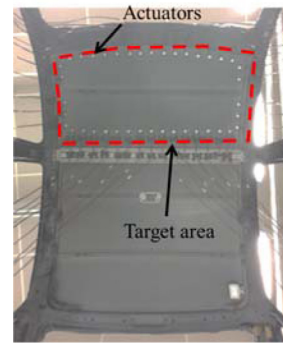
$$A_F = (G^H G + \beta I)^{-1} G^H V, \quad (4)$$

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.

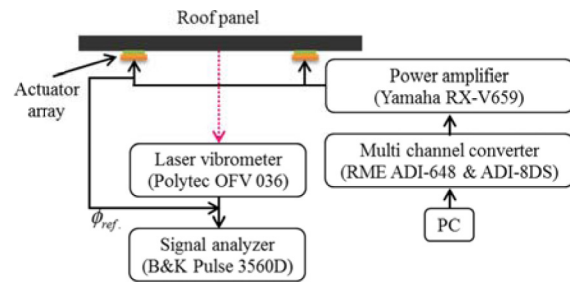
EXPERIMENTAL VERIFICATION

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.



a.



b.

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.

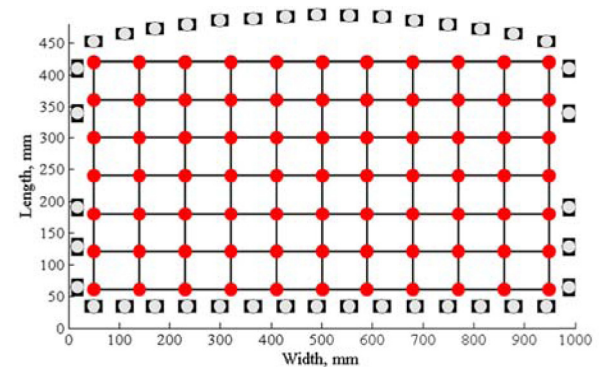


Figure 2. Initial grid for experiments: $\blacksquare$, actuator locations; $\bullet$, observation points distribution.