DIRECTIONAL SOUND RADIATION SYSTEM USING A LARGE PLANAR DIAPHRAGM INCORPORATING MULTIPLE VIBRATORS

Yoko Yamakata, Michiaki Katsumoto, Toshiyuki Kimura

National Institute of Information and Communications Technology
Universal Media Research Center
4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan

ABSTRACT

This paper aims to construct a system that produces directional sound radiation. Directional sound is intrinsically radiated from a vibrating resonant body of such instrument as a violin. The directivity is said to give the sound a realistic and spatial effect. To reproduce a sound with such directivity, we propose a method that uses multiple vibrators to artificially induce bending vibrations on a large planar diaphragm. As the first step of this study, we constructed a prototype system and demonstrated that (i) the bending vibration of the diaphragm is controllable by adjusting accelerated vibrations and (ii) the radiated sound obtains directivity as a specified condition by a user using the algorithm we proposed. This directivity of the radiated sound was obvious enough for humans to perceive.

Index Terms— Acoustic transducers, Vibration mode, Directional radiation, Multiple vibrators

1. INTRODUCTION

We have constructed a directional sound radiation production system to ultra-realistically reproduce the sound of a solo instrument that has a resonant body like a violin.

Most researchers require audio speakers to be omnidirectional because such speaker can be assumed to be point sound sources, which is one of the most important physical models in acoustics. However, in reality most instruments, including violins and guitars, never emit such omnidirectional sounds. An instrument soundboard, such as a violin's resonant body, vibrates differently over its surface when it makes a sound[1]. The emitted sound from each place interferes with the emitted sounds from other places, and then the total sound radiated from the soundboard has various spectral patterns that vary in direction and frequency. This directional radiation reflects off walls and other objects and is perceived by the audience to have come from a direction that varies erratically from semitone to semitone. Weinreich named this feature "directional tone color"[2]. He said that directional tone color makes it difficult to reproduce a realistic violin sound using a loudspeaker because the loudspeaker's directional radiation pattern varies with frequency in a regular and continuous manner.

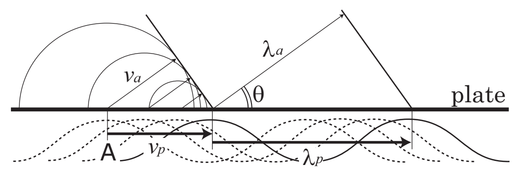
To produce such directional radiation, Mayer used a speaker array[3]. An emitted sound wave from each speaker interferes with the sound waves from the others and forms directional beam radiation. In their method, the variations in beam direction are limited due to the speaker spacing. At higher frequencies, variations in beam direction become significantly less because the wavelength becomes short relative to the speakers spacing.

In response to this problem, we have developed a system that radiates a directional sound by inducing bending vibrations on a large planar diaphragm. These bending vibrations mimic the way the instrument body vibrates when it produces a sound. However, vibrating the diaphragm with the sound source wave is not enough because the resonant frequencies, which determine the vibration mode, of the diaphragm and the instrument do not equate usually.

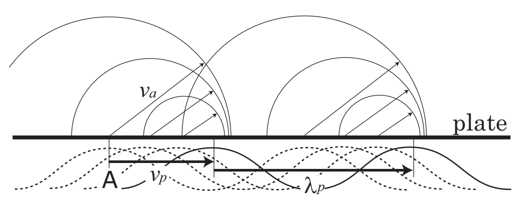
Therefore, in our system, multiple vibrators accelerate the diaphragm cooperatively but independently and control its vibration mode. As a first step of this study, we show the controllability of bending vibration of the diaphragm and directivity of sound radiation produced by the system.

2. DIRECTIVITY OF SOUND RADIATED BY PLATE VIBRATION

In this section, we discuss directional sound radiated due to two types of plate bending vibration: traveling waves and stationary waves.



(a) when $v_p > v_a$ or $\lambda_p > \lambda_a$



(b) when $v_p < v_a$ or $\lambda_p < \lambda_a$

Fig. 1. Sound radiation by a bending wave on a plate.

Suppose a traveling wave is propagating in an infinite plate. In the Cartesian coordinate system (x, y, z), we define the surface coordinate of the plate as $z = 0$ and the traveling wave propagates in the x-direction at an angular speed ω. The propagating wave velocity in the plate is v_p (wavelength $= \lambda_p$) and the acoustic velocity is v_a (wavelength $= \lambda_a$).

While the wave moves from point A at v_p in the plate, a sound wave emitted at the point A moves at v_a. When v_p is larger than v_a, the emitted sounds are reinforced in the same line as shown in Figure 1(a), and together they form a directional radiation whose direction is defined as $\cos(\theta) = \frac{v_a}{v_p}$. Conversely, when v_p is smaller than v_a, the emitted sounds are balanced out and practically very little sound is radiated as shown in Figure 1(b).

A stationary wave is such a wave that seems to remain in a constant position but is regarded as the combination of two traveling waves moving in opposite directions. Therefore, the radiation of it can be taken to be the combination of radiations from the two traveling waves. As we mentioned above, when v_p is larger than v_a, the traveling wave emits a sound radiation with angle θ. When two traveling waves form a stationary wave, their radiations interfere in the air and create beam radiations. Conversely, when v_p is smaller than v_a, there is very little radiation

Waves in such a thin plate like a violin's resonant body are "bending waves" whose velocities are proportional to the square root of their frequencies[4]. There are often complex waves propagating on such a plate; therefore, the plate emits radiations of different powers and directional patterns at the same time.

We exploit these mechanisms to radiate directional sound. The proposed system artificially induces such a bending vibration on a planar diaphragm by vibrating it by multiple vibrators as shown in Figure 2. The vibration mode of the diaphragm can be controlled by adjusting the accelerated vibration waveforms relatively because this bending vibration is determined by not only one but all of the accelerated vibrations. And thereby, the directivity of the radiated sound is also varied as explained above.

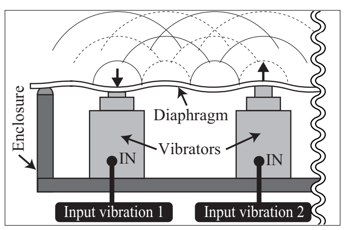
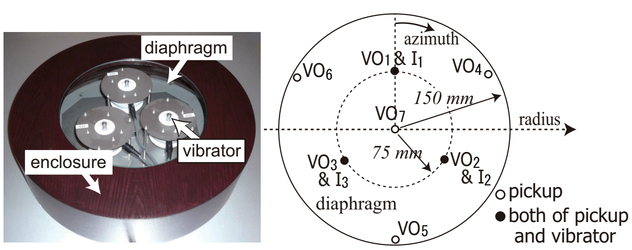


Fig. 2. Inducing bending vibration using multiple vibrators

3. PROTOTYPE SYSTEM OVERVIEW

3.1. System Configuration



(a) Prototype system (b) Position of vibrators (I) and acceleration pickups (VO) on diaphragm

Fig. 3. Constructed Prototype System

To evaluate our method, we constructed a prototype system. Figure 3(a) shows the picture of the prototype system. The system has a large planar diaphragm consisting of a single circular glass plate of radius 150 mm and thickness 3 mm. There are three magnetostrictive vibrators (Fostex GY-1) tightly fastened by a nut to the diaphragm at a radius of 75 mm and equidistant from each other as shown in Figure 3(b). They are driven by an audio device (Roland UA-1000) that is able to stream synchronous independent signals and is controllable by a computer via ASIO. We generated accelerated vibration waves on the computer using MATLAB, which are denoted as I_1, I_2, and I_3 for each vibrator respectively.

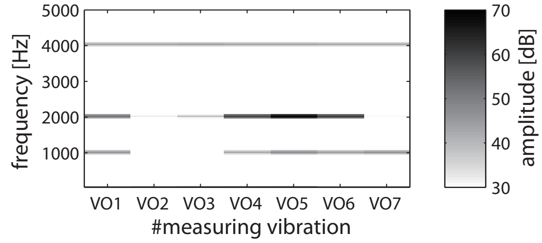


Fig. 4. Spectrums of the measuring vibrations

To prevent interference from out-of-phase sound waves from the rear of the diaphragm, the system has an enclosure 150 mm deep. So that the diaphragm edge is free, there is a gap between the enclosure and the diaphragm edge of 0.5 m (in the future, this gap should be sealed like an usual loudspeaker). The diaphragm is supported only by the vibrators.

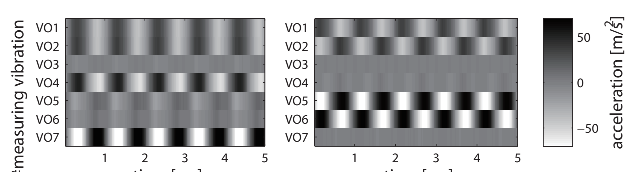
3.2. Property of System Producing Sound

To investigate the property of the sounds the system produces, we accelerated 1 kHz sine wave at only vibrator I_1 and measured the bending vibration using seven acceleration pickups (ONO SOKKI NP-2110) with sampling rate 51.2 kHz. These pickups are tiny and light (0.6 g) and did not seem to disturb the bending vibration. The radius r (mm) and azimuth θ (degree) of the pickups' setting positions were $(r = 75, \theta = 0)$, $(75, 120)$, $(75, 240)$, $(145, 60)$, $(145, 180)$ $(145, 300)$, and $(0, -)$ respectively. The measuring vibrations are denoted as VO_1, VO_2,..., VO_7 for each pickup, as illustrated in Figure 3(b).

Figure 4 shows the frequency spectrums of the measuring bending vibrations. The intensity of the gray indicates amplitude of each frequency in dB. As shown in this figures, not only the vibrator position V_1, but also non-accelerated points $VO_2, \ldots, VO_7$ vibrate significantly. This means that the proposed system radiates sound from all over the diaphragm.

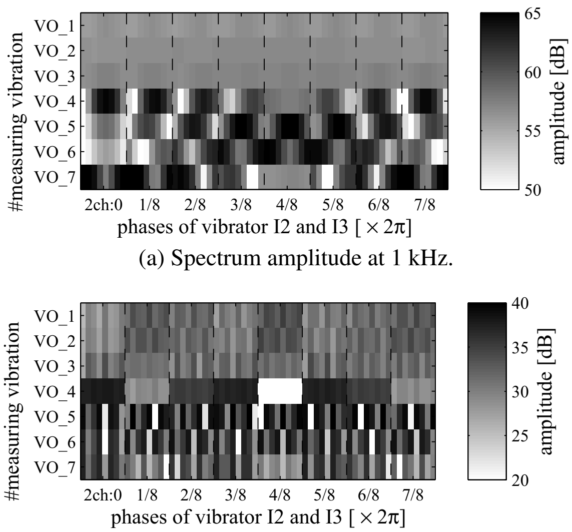
The figure also says that the measuring vibrations consisted of not only 1 kHz signal but also its harmonics despite only 1 kHz sine wave was accelerated. Such harmonics were always observed when a sin sweep from 200 Hz to 2 kHz was accelerated. It means that the proposed system is not adequate to the purpose to reproduce every sound without distortion, while most researches of loudspeaker have been aiming the purpose. We insist that the proposed system should be used for reproducing a sound that has produced by such instrument that has the same sound producing mechanism with the system, thereby innately consists of harmonics as sounds of an violin.

4. CONTROLLABILITY OF BENDING VIBRATION OF DIAPHRAGM



(a) in-phase (b) inverse phase

Fig. 5. The measuring vibrations with accelerating 1 kHz sine wave at I_1 and I_2 in-phase or inverse phase



(a) Spectrum amplitude at 1 kHz.

(b) Spectrum amplitude at 3 kHz.

Fig. 6. Spectrum amplitudes of the bending vibrations at frequency 1 kHz or 3 kHz while the phases of the accelerated vibrations change.

The bending vibration can be controlled by adjusting phases of accelerated vibrations.

Figure 5 shows the waveforms of the measuring bending vibrations under two conditions: (a) when I_1 and I_2 were actuated in-phase and (b) when I_1 and I_2 were actuated rivers-phase. The accelerated vibrations were 1 kHz sine wave. The intensity of the gray indicates the acceleration of vibration. When comparing (a) and (b), one may find that the accelerations of the measuring vibration VO_4,..., VO_7 were significantly changed. It means that the vibration mode of the diaphragm can be changed by phase modulating of accelerated vibrations.

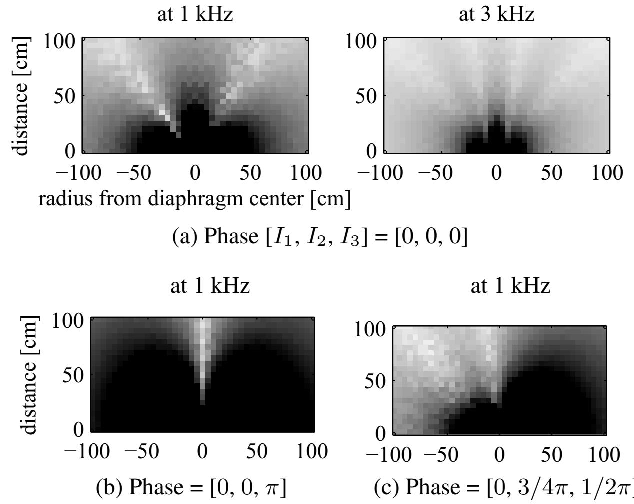
Figure 6(a) shows the spectrum amplitude of the measuring vibrations at 1 kHz while the phases of accelerated vibrations I_2 and I_3 are changing from 0 to 2π by $\pi/4$. The values written on x-axis indicate the phases of I_2, and each area between adjacent dot-lines includes eight data of changing phases of I_3. I_1, I_2, and I_3 were accelerated with 1 kHz sine wave. As shown in this figure, there are some variations among the amplitude patterns of seven measuring vibrations in terms of I_2 and I_3 phases. It means that one can induce preferable vibration mode on the diaphragm by accelerating the vibrations in the corresponding phases.

The vibration mode varies with frequency too. Figure 6(b) shows the spectrum amplitude at 3 kHz in the same data with the 6(a). When comparing (a) and (b), the vibration mode variations seem to be independent from each other. It means that the radiation directions of 1 kHz and 3 kHz sub-sounds differ as mentioned at section 2. And then the spectrum pattern of the radiated sound varies with radiation direction as violin and a guitar sound.

5. DIRECTIVITY OF RADIATED SOUND PRODUCED BY OUR SYSTEM

5.1. Simulation of Radiated Sound

To visualize the sound radiation directivity, we simulated sound pressure in air from the measuring bending vibrations $VO_1, \ldots, VO_7$ from the previous section. In this simulation, the measuring bending vibrations were assumed to be sound sources, and we assumed the acoustic pressure decreased in inverse proportion to distance from the sound source based on the simplified Rayleigh integral[4].



(a) Phase [I_1, I_2, I_3] = [0, 0, 0]

(b) Phase = [0, 0, π]

(c) Phase = [0, $3/4\pi$, $1/2\pi$]

Fig. 7. Simulated sound radiation based on the measuring bending vibrations for each frequency.

Figure 7 shows the acoustic pressure of the sub-sound at 1 kHz or 3 kHz in a plane that is vertical to the diaphragm with 90 degree azimuth angle. I_1, I_2, and I_3 were accelerated with 1 kHz sine wave. In these figures, dark areas are at a higher pressure than white areas.

Fgure 7(a) shows the sound radiation at 1 kHz and 3 kHz when I_1, I_2, and I_3 were accelerated in-phase. In this figure, one may find the radiated direction at 1 kHz and 3 kHz differ. It means that the radiation directions vary with frequency [1].

Figure 7(b) and (c) shows the sound radiations at 1 kHz when the phases of [I_1, I_2, I_3] were [0, 0, π] and [0, $1/4\pi$, $7/4\pi$] respectively. As shown in these figures, one can control the radiation directions by modulating the phases of the accelerated vibrations.

5.2. Algorithm for Phase and Amplitude Adjustments

Based on the previous analysis, we developed an algorithm for modulating amplitudes and phases of the accelerated vibrations as the radiated sound satisfy the following two conditions; (i) a sound captured at one position (hereafter, we call it as a "reference sound" R) equates to a sound source S, and (ii) sounds captured at several points (hereafter, we call them as "control sounds" C_k where k indicates an index of the sounds) differ as specified condition by a user.

Firstly, the short-time Fourier transform (STFT) of S, which is denoted as $\mathcal{F}$, is calculated with M samples hamming window and p% overlapping. The first $\frac{M}{2}$ coefficients are useful because the others are just a mirror image. In the same way, $\mathcal{G}$, the STFT of R, is calculated.

The STFT of accelerated vibration $I_n (n = 1, 2, 3)$, which is denoted by $\mathcal{F}'_n$, is determined as

$$\mathcal{F}'_n(m) = A_n(m) \cdot \mathcal{F}(m) e^{-i\phi_n(m)} \quad m = 1, \ldots, \frac{M}{2},$$

[1]Because we assumed the system's continuous bending waves as a discrete loudspeaker array, it is possible to create ghost beam radiations that do not exist in practice. Such ghost beam radiation commonly appears when the air wavelength is shorter than the distance between each loudspeaker, which corresponds to sounds with frequencies higher than about 5.5kHz in the assumption.

where m is the index of the coefficients and $A_n(m)$ (resp., $\phi_n(m)$) is the multiplier factor of amplitude (resp., the phase shift) for the mth coefficient of $\mathcal{F}$. I_n is calculated by applying an inverse STFT to $\mathcal{F}'_n$ and obtaining its real part.

ϕ_n and A_n are determined according to the following procedure. At the beginning, all coefficients of A_n and ϕ_n are initialized as 0.

At step 1, $\phi_n(m)$ are adjusted one-by-one in the increasing order of m. For each m, set $A_n(m)$ to 1 for all n, and search the most suitable phases $\phi_n(m)$ in terms of the condition of C_k by shifting from 0 to 2π by $\frac{2\pi}{L}$ for $n = 2$ and $n = 3$ individually so that C_k satisfy the specified condition. $\phi_1(m)$ is fixed as 0 as standard.

At step 2, $A_n(m)$ are adjusted for each coefficient by increasing or decreasing the value of $A_n(m)$ as satisfying $||\mathcal{G}(m)|-|\mathcal{F}(m)|| \leq Th$ for all m, where $Th \geq 0$ is a threshold.

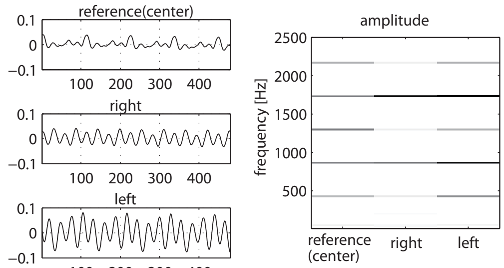
5.3. Experiments and Results

We conducted experiments using the algorithm from the previous section. In this experiment, the reference sound R was captured in front of the diaphragm center. The control sounds were captured in right or left directions with 45 degrees of radiation angle from the diaphragm center, which are denoted as "right" and "left" respectively. All of these sounds are captured at 50 cm away from the diaphragm center. We set the sampling rate for all data at 48 kHz, $p = 50$, $M = 4800$, $L = 8$, and $Th = 5$.

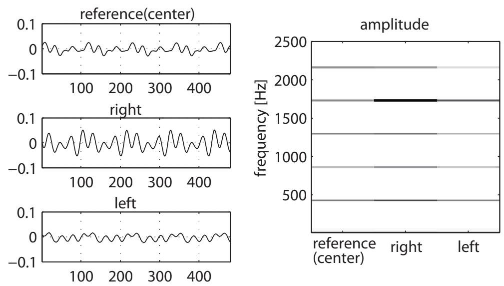
In place of a musical instrument sound, we synthesized the sound source S by combining of 440 Hz sine wave and its harmonics (870 Hz, 1.3 kHz, 1.73 kHz, and 2.16 kHz) with same amplitude for controlling the sound source condition.

At Experiment 1, we specified the condition as the right sound is smaller than the left sound. The result is shown at Figure 8(a). The left side of this figure shows the waveforms of the captured sounds and the right side of this figure shows their spectrum amplitudes. At all harmonic frequencies, the amplitude of the right sound indicates small value than the left sound as specified condition. At Experiment 2, we specified the condition as the right sound is larger than the left sound. The result is shown at Figure 8(b). On the contrary to Experiment 1, this figure shows right sound larger than the left sound as specified condition.

Finally we asked nine subjects to listen to the sound with his/her head center located in the right or left positions and to compare the sounds. In Experiment 1, all subjects said that the sound in the right position was smaller than the left position, and in Experiment 2 they said the opposite. This means the directivity of the radiated sound was obvious enough for humans to perceive.



(a) Adjusted as "right" is smaller than "left"



(b) Adjusted as "right" is larger than "left"

Fig. 8. Waveforms and spectrums of the captured sounds

6. CONCLUSION

This paper aims to construct a directional sound radiation system for reproducing the sound of solo instruments that have resonant body, like violins.

Directional sound is intrinsically radiated from a resonant body of such instruments as a violin. The directivity gives the sound a realistic and spatial effect. To produce such a directive sound, our system artificially induces bending vibrations on a large planar diaphragm using multiple vibrators. The system actuates the vibrators cooperatively but independently and controls the vibration mode of the diaphragm.

The prototype system has a diaphragm consisting of a single circular glass plate of radius 150 mm and thickness 3 mm. There are three magnetostrictive vibrators tightly fastened to the diaphragm.

We showed the bending vibrations of the diaphragm varied drastically according to the accelerated vibration phases by measuring the bending vibrations using seven acceleration pickups. We also showed that the radiation had strong directivity by simulating the radiated sound from the measuring vibrations.

Based on the analysis, we developed an algorithm for modulating the phase and amplitude of the accelerated vibrations as sounds captured at three points satisfy a condition specified by a user.

In the experiments, we set the condition as "the sound of right side is smaller than the left side" in Experiment 1 and the opposite in Experiment 2. The results showed the conditions were satisfied. Human subjects were able to perceive this difference because all the subjects that took part in our test said that the right sound was smaller in Experiment 1 and said the opposite in Experiment 2 correctly.

In the future works, we intend to use our system to evaluate the effect of sound directivity on the way listeners perceive reality and space. We will also extend the type of input sound sources to include captured sounds of real instrument being played, such as a violin.

7. REFERENCES

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