Point-Convergence Type Aerial Ultrasonic Sound Source Using a Flexural Vibrating Circular Plate and High-Intensity Sound Waves Generated by That Sound Source

PACS: 43.25.Vt

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ABSTRACT
The author has developed a high-intensity ultrasonic sound source that converges aerial ultrasonic waves (approx. 20 kHz) radiated from a flexural vibrating circular plate into a point. This sound source is structured by combining a flexural vibrating plate with a circular flat reflecting plate and a paraboloid reflector. The sound source is characterized by its size, which is smaller than any other type of sound source due to its axial symmetry, and by its output of sound wave energy, which is boosted by increasing the radiation resistance of the vibrating plate through a combination with the circular reflecting plate. This paper discusses the principle of sound wave convergence of this sound source and the radiation resistance characteristics as observed when combined with the circular reflecting plate. The sound source was experimentally fabricated. In this case, extremely high-intensity ultrasonic sound waves of approximately 173 dB (electric input: 30 W), which were generated in free space.

1. Introduction
In 1963, a sound source consisting of a flexural vibrating circular plate and an electric ultrasonic transducer was developed as a full-fledged aerial ultrasonic sound source. [1] However, the ultrasonic waves radiated from the flexural vibrating circular plate of this sound source were diffused, when propagated, in a cone-shaped pattern taking the vertical center line of the vibrating plate as its axis. Thus, the sound source could not be effectively utilized and a high-intensity sound field could not be created. Subsequently, various improvement methods were attempted[2],[3], but none of them proved to be practical enough.

The author has developed various types of sound sources [4][5] that generate high-intensity aerial ultrasonic waves and also developed applied technologies[6]-[8] that utilize such sound waves. In addition, the author has developed a sound source using a vibrating circular plate that vibrates in a high-order nodal circle mode. The author has combined various reflectors of different shapes and thereby elucidated a method that allows aerial ultrasonic waves (approx. 20 kHz) radiated from a vibrating circular plate to be radiated as a single beam along the vertical center line of the vibrating plate. [9] A sound source that combines a vibrating circular plate with a circular flat reflecting plate and a paraboloid reflector can converge sound waves radiated from the vibrating plate into a point on the vertical center line of the vibrating plate.[10],[11] It is therefore expected that a high-intensity ultrasonic sound field can be created.

For the purpose of this study, the author reviewed the characteristics of the vibrating circular plate used for the point-converging sound source from various angles and experimentally fabricated a point-converging sound source based on the result of that review. This paper states that very high-intensity aerial sound waves can be generated by this experimental sound source.

2. Principle of Sound wave Convergence
The sound waves that are radiated from a flexural vibrating circular plate to free space become a cone-shaped radiation pattern that has a main lobe in a specific direction taking normal line z that passes through the center of the vibrating plate as an axis as shown in Figure 1, if their vibration mode is of high-order. As shown in Figure 2, place a circular flat reflecting plate in parallel with a vibrating circular plate with its center aligned with the z-axis. The sound waves radiated from the vibrating plate are propagated while being reflected between the vibrating plate and the circular flat reflecting plate. Position the vibrating plate and the circular
flat reflecting plate so that the sound waves radiated from the vibrating plate is in phase with those reflected from the circular flat reflecting plate on the vibrating plate surface. In the positional relationship, the radiation of sound waves in the direction of the main lobe becomes the best and the increased radiation resistance of the vibrating plate allows for increasing the output capacity of the sound source.

As illustrated, place a reflector along the circumference of the vibrating plate. This reflector has a paraboloid of revolution, which is obtained by rotating a part of the parabola that takes point A as its apex, point F as its focal point, and AF as its axis by 360 degrees around the z-axis. The sound waves radiated from between the vibrating plate and the circular flat reflecting plate are reflected by this paraboloid reflector and then enter focal point F. The sound waves radiated from between parallel plates are considered to be almost in phase within the plane vertical to the direction of the main lobe. In addition, the propagation distance of sound waves from each position on this plane to focal point F is equal regardless of the propagation route. Thus, the sound waves are added to each other in the in-phase relationship at focal point F and converged at that point. Figure 3 is a diagram of the point-converging sound source.

![Diagram of point converging ultrasonic sound source](image)

Table I. Two kinds of vibrating circular plates for experiment

<table>
<thead>
<tr>
<th>Vibrating Plate</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [kHz]</td>
<td>20.12</td>
<td>19.63</td>
</tr>
<tr>
<td>Diameter [mm]</td>
<td>184.4</td>
<td>207.8</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Nodal circles</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

3. Characteristics of Flexural Vibrating Circular Plate
3.1 Observation of vibration mode and amplitude distribution of vibrating plate

For flexural vibrating circular plates with different diameters, the exciting frequency was changed and then the vibration mode was observed. The vibrating plate was excited by attaching a vibration transmission rod (duralumin with a diameter of 10 mm) to the tip of an exponential horn (duralumin with a vibration velocity transform ratio of approx. 7) to which a
A bolt-clamped Langevin-type PZT transducer for 20 kHz was connected. The length of the half-wavelength vibrating rod was adjusted to ensure that the vibration system including the vibrating plate was always excited.

As a result, it was found that there were two kinds of vibration modes in which nodal circles appeared clearly. For example, in case of a vibrating plate made of duralumin with a diameter of 207.8 mm and thickness of 1.5 mm, nodal circle clearly appeared within (a) a range between 18.37 and 20.14 kHz and (b) a range between 20.63 and 21.40 kHz. The number of nodal circles was 7 in range (a) and 8 in range (b). In the vibration mode observed in range (a), the diameter of the first nodal circle was similar to the interval between the second and subsequent nodal circles. In the vibration mode demonstrated in range (b), the diameter of the first nodal circle was approximately 3 times as large as the interval between the second and subsequent nodal circles.

Two kinds of vibrating circular plates A and B having the above vibration modes (Table 1) were fabricated and the vibration amplitude in each position in the radial direction of the vibrating plate was measured. Figure 4 shows the measurement results for the vibration amplitudes of vibrating plates A (solid line) and B (broken line).

### 3.2 Angular dependency of radiated sound waves

The author measured the angular dependency of sound waves radiated from vibrating plates A and B. The measurement was carried out in the position approximately 2 m away from the center of the vibrating plate within a plane including the vertical center line z of the vibrating plate. The solid line in Figure 5 shows the angular dependency of sound waves radiated from vibrating plate A. This figure reveals that only a single main lobe of radiated sound waves appears in the direction of approximately 42 degrees from the z-axis. The broken line in Figure 5 shows the result from vibrating plate B. This figure demonstrates that large two lobes appear in the directions of approximately 35 and 44 degrees from the z-axis.

Based on these results, vibrating plate, which would cause one main lobe to appear, was determined as appropriate as the vibrating plate used for this paper.

### 3.3 Radiation resistance of vibrating plate with circular flat reflecting plates

The radiation resistance of the vibrating plate with a circular flat reflecting plate placed in parallel with the circular vibrating plate surface becomes larger or smaller than in the case without using a circular flat reflecting plate. When the radiation resistance becomes larger, the radiation of sound waves in the direction of the angle of the main lobe becomes more favorable and the output capacity of the sound source increases.

The energy $W_a$ of sound waves radiated from the vibrating plate is given by $W_a = r_a \cdot V^2$, where $r_a$ is the total radiation resistance of the vibrating plate and V is the mean vibration velocity. It is elucidated that when a circular flat reflecting plate is placed on the surface of a rectangular vibrating plate that shows flexural vibrations in the striped mode[12], the radiation resistance of the vibrating plate periodically changes as the interval between the two plates varies and increases or decreases as compared with the case without using a reflecting plate. Now the following equation holds assuming that the radiation resistance on the front side of the vibrating plate surface be $r_aF$ and that the radiation resistance on the back side be $r_aB$:
If the relationship of \( r_{\text{RF}} \gg r_{\text{RB}} \) can also be established for the radiation resistance of a circular vibrating plate by this method, the sound wave energy from the front and back sides of the vibrating plate meets \( r_{\text{RF}} V^2 \gg r_{\text{RB}} V^2 \). This means that the sound wave energy supplied to the sound source is given to the front and back sides of the vibrating plate at a ratio equivalent to the relationship of \( r_{\text{RF}} \gg r_{\text{RB}} \) under constant conversion efficiency.

For the purpose of this study, circular flat reflecting plates \( \text{RP}_F \) and \( \text{RP}_B \) were placed in parallel with the front side (side F) and back side (side B) of circular vibrating plate \( A \). When the interval between the vibrating plate and the reflecting plate was changed, changes in the radiation resistance of the vibrating plate were measured.

The solid line in Figure 6 shows the result for the case in which the circular reflecting plate was placed on only the back side of the vibrating plate. It represents radiation resistance \( r_{\text{RB}} \) on side B of the vibrating plate as a ratio to the case in which no reflecting plate is used. According to the figure, radiation resistance \( r_{\text{RB}} \) periodically shows the maximum and the minimum, which are equivalent to approximately one third of the corresponding values in the case where no reflecting plate is used.

The broken line in the figure shows changes in the radiation resistance of the vibrating plate, which occurred when reflecting plate \( \text{RP}_B \) was retained in the position of \( D_B = 5.3 \text{ mm} \) on the back side of vibrating plate \( A \) and then interval \( D_F \) for reflecting plate \( \text{RP}_F \) placed on the front side (side F) of the vibrating plate was changed. According to the figure, the radiation resistance changed in the period equal to the solid line and the change ratio was larger.

![Figure 6.- Radiation resistance characteristic of vibrating plate with reflecting plates](image1)

![Figure 7.- Relationship between driving amplitude and supplied electric power](image2)

### 3.4 Relationship between vibration amplitude of vibrating plate and electric power supplied to sound source

In the case where circular flat reflecting plates \( \text{RP}_F \) and \( \text{RP}_B \) were respectively placed on the front and back sides of a circular vibrating plate, the author carried out measurements for the relationship between the driving amplitude (vibration amplitude at the center of the vibrating plate) and the electric power supplied to the sound source. Figure 7 shows the results of these measurements. P1 shows the case where two reflecting plates were not used; P2 the case where reflecting plate \( \text{RP}_B \) was placed in the position indicated by the arrowhead in Figure 6; and P3 the case where reflecting plates \( \text{RP}_F \) and \( \text{RP}_B \) were respectively placed in the positions indicated by the arrowheads in Figure 6. In P3, the energy values supplied to sides F and B of the vibrating plate were \( P_3+P_1/2-P_2 \) and \( P_2-P_1/2 \), respectively. For example, therefore, when the driving amplitude is approximately 10 \( \mu \text{m} \), 32 W is given to side F and 4 W to side B. The ratio between the two roughly corresponds to that of radiation resistance in Figure 7.

### 4. Experimental Fabrication of Sound Source

#### 4.1 Basics of design

**a. Determination of interval between vibrating plate and circular flat reflecting plate**

When a circular flat reflecting plate is placed on a vibrating plate surface, the radiation resistance becomes the largest at a placement interval of approximately 11.7 mm as demonstrated by the results in Figure 6. However, if a reflecting plate is placed in this position, the interval between the vibrating plate and the reflecting plate becomes too small and the
sound waves radiated from between the two plates placed in parallel might be diffused. In the experimental fabrication, therefore, a reflecting plate was placed in the position of 21.9 mm showing the second maximum as counted from the vibrating plate.

b. Diameter of circular flat reflecting plate

The dimensions of the circular flat reflecting plate is determined based on the interval between the vibrating plate and the reflecting plate, which has been determined considering an increase in the radiation resistance, i.e., the diameter of the circular flat reflecting plate is determined as follows, \( R = R_v - 2D \tan \theta \). Where, \( R \): Diameter of circular flat reflecting plate, \( R_v \): Diameter of circular vibrating plate, \( D \): Interval between vibrating plate and reflecting plate, \( \theta \): Angle formed by the vertical center line of vibrating plate and the main-lobe direction of sound waves

c. Paraboloid reflector

The paraboloid reflector uses a paraboloid of revolution, which is obtained by rotating a parabola that meets the following two conditions by 360 degrees around the z-axis:

* The axis faces the same direction of the main lobe of radiated sound waves.
* The focal point is located on the vertical center line z of the vibrating plate.

Therefore, the paraboloid reflector can be designed by drawing the parabola that meets the above two conditions.

4.2 Experimental fabrication

Based on the above studies, the author fabricated a circular flat reflecting plate to be combined with a flexural vibrating circular plate (vibrating plate A), and a paraboloid reflector to experimentally fabricate a point-converging sound source. The diameter of the circular flat reflecting plate was made slightly larger than \( R \) indicated above and an acrylic plate of 5 mm in thickness was used for this fabrication. The paraboloid reflector was fabricated using resin.

5. Characteristics of Experimentally Fabricated Sound Source

5.1 Distribution of sound pressure in the neighborhood of converging point

The distribution of sound pressure in the neighborhood of the converging point of sound waves from the experimentally fabricated sound source was measured using a 1/8-inch microphone (Model 4138 made by B&K). Figure 8 shows the measurement result for the distribution of sound pressure, which is formed on the z-axis. The vertical axis of the figure assumes sound pressure and the horizontal axis the distance from vibrating plate center. According to the figure, the distance that maximizes sound pressure was 102 mm.

Next, the author measured the distribution of sound pressure in the direction vertical to the z-axis, which passes through the point at which sound pressure becomes the largest. Figure 9 shows the result of the above measurement and its horizontal axis assumes the distance from the z-axis. According to this figure, the distribution of sound pressure was so sharp that sound pressure becomes the largest at the z-axis.

5.2 Relationship between sound pressure at converging point of sound waves and electric power supplied to sound source

Measurements were carried out for the relationship between the sound pressure at the converging point of sound waves and the electric power supplied to the sound source. Figure 10
shows the results of these measurements. According to this figure, the sound pressure at the converging point increased in proportion to the electric power supplied to the sound source to approximately the 0.5th power. When the electric power supplied to the sound source was 27 W, very high-intensity aerial ultrasonic waves of approximately 173 dB were successfully generated.

![Figure 10.-Relationship between sound pressure at converging point and electric input power](image)

6. Conclusions
For a sound source that allowed for converging the aerial ultrasonic waves (approx. 20 kHz) radiated in a cone-shaped pattern from a vibrating circular plate that showed flexural vibrations in a high-order nodal circle mode into a point, the author studied various characteristics of the circular vibrating plate, especially as combined with a circular flat reflecting plate; experimentally fabricated a point-converging sound source that combined this vibrating plate with a circular flat reflecting plate and a paraboloid reflector; and then studied the convergence characteristics.

The results demonstrated that the aerial ultrasonic waves radiated from the circular vibrating plate could be converged into a narrow area including one point on the vertical center line of the vibrating plate. The sound pressure level at the converging point increased in proportion to the electric power supplied to the sound source to approximately the 0.5th power. When the supplied electric power was approximately 30 W, the author ascertained that very high-intensity aerial ultrasonic waves of approximately 173 dB could be obtained.

These aerial high-intensity ultrasonic waves include harmonic components specific to finite amplitude sound waves. It is therefore promising that they can be utilized for various applied technologies in the future.

References:

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