High-intensity aerial ultrasonic source with a stripe-mode vibrating plate for improving convergence capability

Youichi Ito*

College of Science and Technology, Nihon University,
8–14, Kanda-Surugadai 1-chome, Chiyoda-ku, Tokyo, 101–8308 Japan

(Received 13 June 2014, Accepted for publication 13 December 2014)

Abstract: The generation of high-intensity aerial ultrasonic waves is achieved by focusing the acoustic waves radiated from a vibration plate into a point. We developed a new point-converging source of high-intensity aerial ultrasonic waves that comprises a striped-mode rectangular vibrating plate to radiate an aerial ultrasonic wave with high efficiency and paraboloid reflectors. The roughness corresponds to the stripe interval arranged on the surface of the paraboloid reflector. The roughness difference depends on the wavelength of the sound wave. The new convergence method that we propose can converge all ultrasonic waves radiated by the vibrating plate. In addition, the reflectors used to converge the radiated ultrasonic waves are characterized by a much simpler construction than the conventional reflectors. The ultrasonic source fabricated on an experimental basis produced the maximum ultrasonic pressure of about 15,000 Pa (178 dB) at the supplied electric power of 50 W.

Keywords: High-intensity ultrasonic wave, Aerial ultrasonic sound wave, Ultrasonic sound source, Point convergence, Stripe-mode vibration plate

PACS number: 43.35.Zc [doi:10.1250/ast.36.216]

1. INTRODUCTION

The effect of ultrasonic waves becomes more marked with increasing intensity. Many research and development efforts have been made on applications using high-intensity aerial ultrasonic waves in a gas [1–6]. We have been developing a variety of technologies using high-intensity aerial ultrasonic waves. This technology has the significant advantage that it can be used in a noncontact manner [7–10]. High-intensity aerial ultrasonic waves may be applied in the atomization and removal of a liquid. Several technologies that employ these phenomena have been developed. The irradiated high-intensity aerial ultrasonic waves can be used to instantaneously atomize and remove a liquid that has entered a narrow channel or void [11–13]. If this becomes practically possible, a cleaning liquid, for example, that leaks into a narrow gap or channel on a circuit board on which electronic devices are mounted or on a precision machine part can be expected to be removed with ease.

Recently, we have developed a new method of aerial ultrasonic inspection that uses high-intensity aerial ultrasonic waves [14,15]. This method differs from existing methods in that it detects solid material defects by analyzing vibrations on the surface of an object, upon excitation using high-intensity aerial ultrasonic waves. To realize such technologies using the specific effect of aerial high-intensity ultrasonic waves, it is necessary to effectively produce such ultrasonic waves. To this end, we developed a source of aerial ultrasonic waves using circular or rectangular flexural vibration plates.

Also, we developed an ultrasonic source to converge the ultrasonic waves radiated by these vibration plates. An ultrasonic source comprising a combination of a stripe-mode vibrating plate and the emission direction converter has already been developed to converge ultrasonic waves radiated by the vibrating plate at a single point [16]. However, the emission direction converter had a very complicated structure. Therefore, it was very difficult not only to manufacture but also to maintain the converter during practical use. Moreover, it uses only part of the ultrasonic waves radiated by the vibrating plate owing to the principle of converging ultrasonic waves. These problems may constitute a great obstacle to its practical use.

We developed a new point-converging source of high-intensity aerial ultrasonic waves that comprises a striped-mode rectangular vibrating plate to radiate aerial ultrasonic...
waves with high efficiency and parabolic reflectors [17]. In this paper, we discuss the technology for converging ultrasonic waves radiated by rectangular flexural vibration plates, which involves a new method completely different from the conventional concepts. The new technology to converge ultrasonic waves may supersede the conventional methods. The new converging method that we propose can converge all the ultrasonic waves radiated by the vibrating plate. In addition, the reflectors used to converge the radiated ultrasonic waves are characterized by a much simpler construction than the conventional reflectors. Furthermore, the source of ultrasonic waves proposed by us can produce an ultrasonic wave having a much higher intensity than the conventional sources.

2. DETAILS OF ULTRASONIC WAVES RADIATED BY STRIPE-MODE VIBRATING PLATE

Figure 1 shows the device for generating ultrasonic wave vibrations. It is equipped with a rectangular metal plate that, when driven sinusoidally, produces vibrations in a complicated pattern of high order. We vibrated this plate in the striped mode [18]. Figure 2 shows the plate vibrating in the striped mode with \( L \) and \( W \) representing the length and width of the vibrating plate, respectively. In this case, \( \lambda_p \) is the wavelength of flexural waves in the vibrating plate. The wavelength of flexural waves is defined by the following factors: specific constants of the material of the vibrating plate, thickness, and vibrating frequency. \( d \) is the pitch of nodal lines of the vibrating plate and is in the relation of \( 2d = \lambda_p \). \( L \) and \( W \) are given by \( L = (N_{\text{even}} - 0.5) \cdot d \) and \( W = N_{\text{odd}} \cdot d \), respectively. Here, \( N_{\text{even}} \) is an even number and \( N_{\text{odd}} \) is an odd number. The small vibrating faces between the nodal lines of vibrations radiate ultrasonic waves if the adjacent faces vibrate in opposite phases. Therefore, these radiated ultrasonic waves interfere with each other, as a result of which radiation has main lobes in specific symmetrical angular directions with respect to the normal line passing through the center of the vibrating plate. As a consequence, the vibrating plate radiates ultrasonic waves in four directions from its two faces.

Figure 3(a) shows an example of the results obtained when the ultrasonic waves radiated by the stripe-mode vibrating plate were measured in the \( Y-Z \) plane. In addition, Fig. 3(b) shows the measurement results of the phase distribution of the ultrasonic waves in the same plane. These figures indicate that the ultrasonic waves radiated by the vibrating plate propagated in the area between the two sets of parallel lines \( \overline{\circ}1-\overline{\circ}1' \) and \( \overline{\circ}2-\overline{\circ}2' \) in Fig. 3(a) in the symmetrical directions marked by the arrows. Representing the wavelength of ultrasonic waves radiated by the vibrating plate as \( \lambda_s \), the angle of radiated ultrasonic waves \( \theta \) shown in the Figs. 3(a) and 3(b) is given by the equation \( \theta = \sin^{-1}(\lambda_s/\lambda_p) \).

On the other hand, it is shown that the striped pattern in direction \( Z \) appeared in the area between the lines \( \overline{\circ}1' \) and \( \overline{\circ}2 \) in Fig. 3(a). This indicates that the ultrasonic waves propagating in the symmetrical directions interfered with each other and propagated also in direction \( Z \). Moreover, Fig. 4(a) shows an example of the results obtained when the ultrasonic waves radiated by the stripe-mode vibrating plate were measured in the \( X-Z \) plane. Figure 4(b) shows the measurement results of the phase distribution of the ultrasonic waves in the same plane.

However, the lengths of the ultrasonic waves propagating in direction \( Z \) were different from those of the ultrasonic waves radiated by the vibrating plate, as can be seen from above results. The wavelength \( \lambda_z \) of ultrasonic waves propagating in direction \( z \) is given by the equation \( \lambda_z = \lambda_s/\cos \theta \). Regarding the ultrasonic waves that had a
striped ultrasonic pressure distribution, the adjacent waves (S_a and S_b) had opposite phases to each other.

If flat reflecting plates perpendicular to the vibrating plate are placed on the both sides of the vibrating plate, all the ultrasonic waves radiated by the vibrating plate propagate also in the direction of the Z axis. Two reflecting plates are placed at the distance DL symmetrically from the center of the vibrating plate. Representing a positive integer as n, DL is given by the equation

\[ DL = \frac{n\lambda_a}{C} \]

where \( C = 2 \sin \frac{\theta}{2} > \frac{L}{2} \). Figures 5(a) and 5(b) show the measurement result of the sound pressure distribution and the phase distribution in the Y–Z plane in the case of arranging the two reflecting plates.

3. PRINCIPLE BEHIND CONVERGENCE OF ULTRASONIC WAVES

3.1. Outline of Ultrasonic Source

Figure 6 shows a schematic view of an ultrasonic source, manufactured by the conventional method, for converging ultrasonic waves radiated by a stripe-mode vibrating plate into one point. The figure shows that emission direction converters are installed on the front and back faces of the vibrating plate.

The construction of the radiation direction transducer is very complicated, as shown in the figure. Each of the emission direction converters consists of separators placed perpendicular to the surface of the vibrating plate and parabolic reflecting plates located between the separators. The separators are positioned adjacent to each other along the nodal lines of the vibration plate.

Ultrasonic waves are radiated from between the separators of the emission direction converters, and part of each ultrasonic wave arrives at point 0. The parabolic reflecting plates are positioned by properly adjusting their focal lengths and their relative distances from the vibration plate. The phase of the arriving ultrasonic wave is controlled by adjusting the focal distance of each parabolic reflecting plate. In this case, the parabolic reflecting plates focus ultrasonic waves into the x–z plane.

Ultrasonic waves are radiated from between the separators of the emission direction converters, and part of each ultrasonic wave arrives at point 0. The parabolic reflecting plates are positioned by properly adjusting their focal lengths and their relative distances from the vibration plate. The phase of the arriving ultrasonic wave is controlled by adjusting the focal distance of each parabolic reflecting plate. In this case, the parabolic reflecting plates focus ultrasonic waves into the x–z plane.

The converging of sound waves in the y–z plane can be achieved by adjusting the phase relationship of sound waves from the open planes that are formed by the...
By this operation, the ultrasonic waves with the same phase arrive at point 0. As a result, the ultrasonic waves converge at point 0.

3.2. New Technique for Converging Ultrasonic Waves

Here, we propose a new technology for converging the aerial ultrasonic waves radiated by a rectangular stripe-mode vibrating plate. This converging technology is completely different from the concepts of the conventional methods of converging ultrasonic waves. The reflector used for converging ultrasonic waves has a very simple construction compared with those of the conventional ultrasonic sources. Theoretically, this technology makes it possible to converge all ultrasonic waves radiated by the vibrating plate.

The principle of the converging method is explained below. Figure 7 illustrates the principle by which the ultrasonic waves radiated by the vibrating plate converge at one point. Curve H, as shown in the figure, indicates the parabolic line that comprises focus F, vertex A, and a straight line connecting focus F to vertex A. A reflector is placed along the rotary paraboloid that is rotated around axis Z. The reflector has such a size that it covers one rectangular vibrating plate. A rectangular piston on the X–Y plane shown in Fig. 7 is vibrating sinusoidally, and ultrasonic waves are radiated in the direction perpendicular to the vibrating plane. They are reflected by the reflector and all waves are incident at focus F in the same phase. In short, the ultrasonic waves radiated by the rectangular piston converge at one point.
Next, we describe how the ultrasonic waves radiated by a striped-mode vibrating plate converge at focus F. It is believed, as mentioned above, that sound waves having wavelength $\lambda_z$ propagate along direction $Z$ in the vicinity of the vibrating plate. Therefore, if a stripe-mode vibrating plate is placed instead of the rectangular piston shown in Fig. 7, ultrasonic waves radiated by the stripe-mode vibrating plate converge at focus F of the paraboloid for the same reason as described above. Figures 8(a) and 8(b) illustrate the principle behind the convergence of ultrasonic waves radiated from a stripe-mode vibrating plate to a point.

Fig. 8 Schematic drawing explaining the principle behind the convergence of ultrasonic waves radiated from a stripe-mode vibrating plate to a point.

Obtained by rotating parabola $H_a$ around the $z$-axis in the range from point $P_1$ to the point $P_4$. As already described, $S_a$ and $S_b$, which represent the sound waves radiated by the stripe-mode vibrating plate, propagate in direction $Z$ with opposite phases. Ultrasonic waves $S_a$ (solid line) are reflected by reflector $R_a$ placed along paraboloid $H_a$ with the focal distance of $f_a$. On the other hand, ultrasonic waves $S_a$ (dashed line) are reflected by reflector $R_b$ placed along paraboloid $H_b$ with the focal distance of $f_b$. Points $B$ and $F$ are the vertex and focus of parabola $H_b$, respectively. Therefore, $BF$ is the focal distance $f_b$ of parabolic line $H_b$. Thus, $S_b$ waves converge to focus $F$. For ultrasonic waves $S_a$ and $S_b$ in phase at focus $F$, focal distance $f_b$ is given by $f_b = f_a + \lambda_z/4$.

As a consequence, all the sound waves radiated from the front surface of the vibrating plate converge at point F. Considering the ultrasonic waves radiated from the front and back faces of the vibrating plate being in opposite phases, the reflectors are placed in the appropriate positions to ensure that the ultrasonic waves converge at the focus of the paraboloid.

Figure 9 shows the outline of the proposed point-converging aerial ultrasonic wave source. The reflectors have sizes such that they cover the entire faces of the striped-mode vibrating plate. The surfaces of the reflectors have a striped pattern of concaves and convexes. The widths of concaves and convexes are equal to the pitch $d$ between the nodal lines of the vibrations produced by the vibrating plate. The depths of the concaves and convexes...
have the relationship described in the principle of convergence. In addition, flat reflecting plates perpendicular to the vibrating plate are placed at the two sides of the vibrating plate.

4. SIMULATION OF ULTRASONIC WAVE CONVERGENCE

The characteristics of converging ultrasonic waves obtained using the proposed technique were analyzed with COMSOL, a finite-element analysis software. This analysis makes use of the ultrasonic waves radiated by the stripe-mode vibrating plate at a driving frequency of 19.65 kHz, as indicated in Table 1.

The paraboloid reflectors for converging ultrasonic waves are designed using the proposed method so that the ultrasonic waves converged at position $R = 120$ mm, as shown in Fig. 9.

The results of the analysis are shown in Figs. 10(a) and 10(b). Figure 10(a) illustrates the sound pressure distribution in the $x-z$ plane, while Fig. 10(b) shows the distribution of sound pressure in the $y-z$ plane, including the highest sound pressure point shown in Fig. 10(a). The results indicate that the ultrasonic waves radiated by the vibrating plate converged around point $R = 120$ mm.

On the other hand, Figs. 11(a) and 11(b) show the results of the analysis of the convergence of ultrasonic waves obtained using rotary parabolic reflectors having no roughness. The results reveal that the ultrasonic waves could not converge at the expected position. The above-described findings verify that the appropriate roughness of the reflector surfaces effectively contributed to the convergence of ultrasonic waves.

5. CHARACTERISTICS OF NEW ULTRASONIC SOURCE

First, the basic characteristics of a point-converging ultrasonic source fabricated on an experimental basis will be described. A longitudinal vibration system of the ultrasonic source, as shown in Figs. 1 and 9, consists of a bolt-clamped Langevin-type transducer (BLT), an exponential horn, and a vibration transmission rod. These elements are all made of aluminum alloy. Aerial ultrasonic waves are aerially generated by a stripe-mode vibrating plate (aluminum alloy plate, JISA 2017-T4) connected to the tip of the vibration transmission rod. Details of the vibrating plates used in the prototype excitation are shown in Table 1. The reflectors installed on the back and front faces of the vibrating plate are made of chemical wood, and designed and manufactured so as to ensure that the ultrasonic waves radiated by both faces of the vibrating plate converge at point $R$ far from the opening of the ultrasonic source. The frequency to drive the ultrasonic source is 20 kHz. The sound pressure was measured with a 1/8-inch-diameter condenser microphone (made by GRAS 40DP; frequency range, 6.5 Hz–40 kHz; upper limit sound level, 178 dB).

Figure 12 shows the sound pressure distributions around the convergence region of the ultrasonic waves produced by the experimentally manufactured ultrasonic source. Here, the solid line indicates the result of the new focusing method using the sound waves radiated from both sides of the vibrating plate. For comparison, the dashed line in the figure shows the characteristic of the convergent ultrasonic wave radiated by the conventional ultrasonic source with the same vibrating plate. Figure 12(a) shows the sound pressure distribution in the direction of the

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Details of vibrating plate and ultrasonic sound source.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [kHz]</td>
<td>Length ($L$) [mm]</td>
</tr>
<tr>
<td>19.65</td>
<td>327</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\lambda_a$ [mm]</th>
<th>$\theta$ [°]</th>
<th>$\lambda_c$ [mm]</th>
<th>$R$ [mm]</th>
<th>$f_a$ [mm]</th>
<th>$f_b$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.52</td>
<td>21</td>
<td>18.79</td>
<td>140</td>
<td>177.5</td>
<td>182.2</td>
</tr>
</tbody>
</table>
The figure indicates that the sound waves radiated by the experimentally manufactured source converged at a position 140 mm from the edge of the vibrating plate. Figure 12(b) shows the sound pressure distribution in the direction of the $y$-axis; the sound pressure was maximum at point F. Figure 12(c) shows the sound pressure distribution in the direction of the $z$-axis. The sound pressure was maximum at point F. Figure 13 shows the sound pressure distribution in the $y$–$z$ plane at the convergence point of ultrasonic waves radiated by the ultrasonic source. The above result indicates that the ultrasonic waves radiated by the vibrating plate converged at a point close to the designed position.

Figure 14 shows the relationship between the electric power supplied to the ultrasonic source and the sound pressure at the convergence point. For comparison, the figure also shows the sound pressure characteristic of the conventional ultrasonic source with the same vibrating plate. The figure indicates that the ultrasonic pressure produced by the new sound source increased in proportion to half the electric power supplied to the ultrasonic source, and the converging ultrasonic wave had about two times higher intensity than those provided by the conventional sources. The converging ultrasonic wave with a very high intensity of about 15,000 Pa (178 dB) was produced at a supplied electric power of 50 W by the ultrasonic source driven at 20 kHz.
This converging technique is quite different from the concept of sound wave focusing of conventional methods. By adopting the proposed method, the structure of the reflector used in wave convergence has become very simple compared with that of a conventional sound source. Moreover, in the proposed method, it is theoretically possible to converge all sound waves radiated by the vibrating plate. Through the trial of a sound source driven at a frequency of 20 kHz, the realization of sound waves converging as designed has been confirmed. The intensity of the converged sound waves in the experiment became twice that in the case of using a conventional sound source. The converging ultrasonic wave with a very high intensity of about 15,000 Pa (178 dB) was produced at a supplied electric power of 50 W.

**REFERENCES**


