

# Practical method for evaluating the sound field radiated from a waveguide

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**Abstract:** This letter presents a simple and practical method for evaluating the sound field radiated from a waveguide. By using the proposed method, detailed information about the radiated sound field can be obtained by measuring the sound field in the mouth of the baffled waveguide. To examine this method's effectiveness, the radiated sound pressure distribution in space was first evaluated by using the proposed method, and then it was measured directly for comparison. Experiments using two different waveguides showed good agreement between the evaluated and the measured radiated sound pressure distributions.

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The directivity pattern and axial sound pressure distribution have long been used to evaluate the acoustic performance of a waveguide (Bauman *et al.*, 1993; Geddes, 1989, 1993), but they are insufficient to describe its near-field characteristics. More detailed information is becoming indispensable for the diagnosis and improvement of waveguide structures; such detailed information is also beneficial for judging the product quality. Therefore, the radiated sound field of a waveguide might be a better option to characterize the performance of a waveguide (Duan *et al.*, 2013). However, the direct measurement of the sound pressure at each point in the radiated space may require complicated installations and a large measurement space. Thus a simple and effective method based on the information in the mouth of the baffled waveguide is described in this work. Using an algorithm that is similar to wave field synthesis (Berkhout *et al.*, 1993; Verheijen, 2010), the steady-state information describing the radiated sound field can be obtained.

Consider a waveguide that is mounted on a baffle. The complex sound pressure  $P$  at an arbitrary point  $A$  can be derived from the Rayleigh I integral

$$P_A = \frac{1}{2\pi} \iint_S \left[ \frac{\partial P}{\partial z} \frac{\exp(-jkr)}{r} \right] dS, \quad (1)$$

where the integral is performed over the mouth surface  $S$  [Fig. 1(a)],  $r$  is the distance between the arbitrary point  $A$  and the surface  $S$ ,  $k$  is the wave number, and  $j = \sqrt{-1}$ . Note that the relationship  $\partial/\partial \mathbf{n} = \partial/\partial z$  is used here, where  $\mathbf{n}$  is the normal vector of  $S$ . Meanwhile, the influence of the baffle diffraction is corrected by the method described by Le *et al.* (2011).

In practice, Eq. (1) is usually discretized. Figure 1(b) shows the patch distribution on the surface of the mouth of the waveguide and on another parallel surface that is  $\Delta z$  farther along the  $z$ -direction from the waveguide mouth. Defining  $n_x$  and  $n_y$  as indices for the patches along the  $x$ - and  $y$ -directions, respectively, the discrete form of Eq. (1) is

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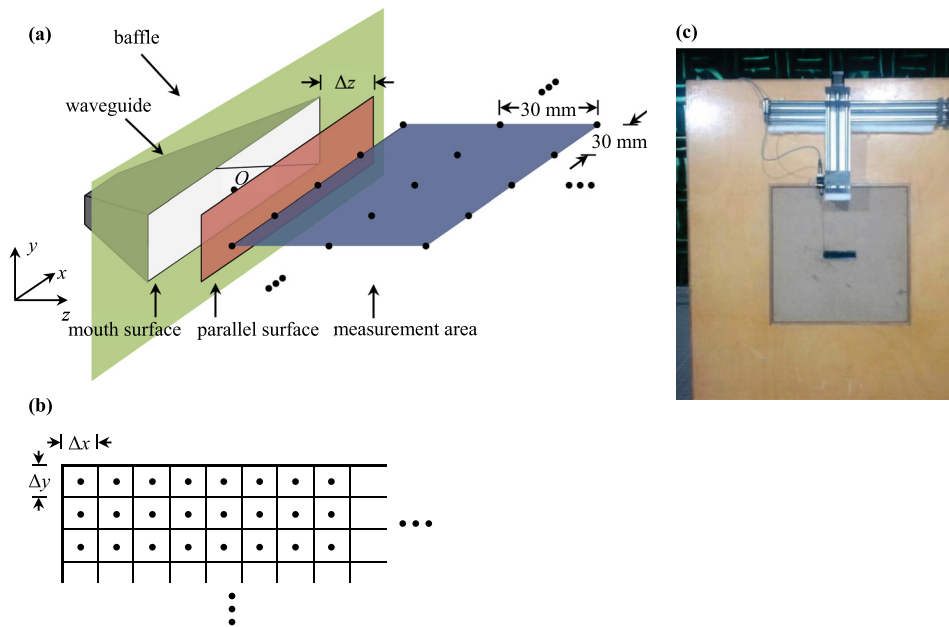


Fig. 1. (Color online) (a) Measurement setup. The sound pressure was measured at points on the mouth surface, on the parallel surface, and in the measurement area. The parallel surface can be obtained by translation of the mouth surface in the  $z$ -direction by the distance  $\Delta z$ . The measurement area is in the  $x$ - $O$ - $z$  plane.  $O$  is the center of the mouth and is also the origin of the coordinate system. The coordinate axes are positioned on the side for clarity. The  $21 \times 21$  measurement points in the measurement area are equally spaced (with a separation of 30 mm) along both the  $x$ - and  $z$ -directions. (b) Distribution of patches for the mouth surface and the parallel surface. The mouth surface and the parallel surface are divided into patches in the same way. The center point in each patch is the measurement point. (c) Photograph of the experimental setup in the mouth. The guides that had not been covered by the sound-absorbing materials are shown for clarity. In the actual experiments, the guides were covered by the sound-absorbing materials completely to reduce the diffraction.

$$P_A = -\frac{1}{2\pi} \sum_{n_x} \sum_{n_y} \left[ \frac{\partial P_{n_x n_y}}{\partial z} \frac{\exp(-jkr_{n_x n_y})}{r_{n_x n_y}} \right] \Delta x \Delta y, \quad (2)$$

where  $\Delta x$  and  $\Delta y$  are the sampling distances,  $P_{n_x n_y}$  is the mean sound pressure at each patch on the mouth surface, and  $r_{n_x n_y}$  is the mean distance between the corresponding patch on the mouth surface and the arbitrary point  $A$ .  $P_{n_x n_y}$  and  $r_{n_x n_y}$  can be approximated by the data obtained at the center of each patch. According to the Nyquist sampling theorem, spatial aliasing arises for the frequencies above,

$$f_{\text{nyq}} = \min \left\{ \frac{c}{2\Delta x}, \frac{c}{2\Delta y} \right\}, \quad (3)$$

where  $c$  is the speed of sound. For the case of  $\Delta x = \Delta y = 5$  mm, which was used in our experiments,  $f_{\text{nyq}}$  is as high as 34.4 kHz when assuming  $c = 344$  m/s.

To compute values for Eq. (2),  $\partial P_{n_x n_y} / \partial z$  data are required. As the conventional sound intensity microphone is too large for the measurement to be performed in the waveguide mouth, a probe microphone was used to measure the sound pressure distributions on the mouth surface and the outer parallel surface [Fig. 1(a)]. Then  $\partial P_{n_x n_y} / \partial z$  can be approximated by

$$\frac{\partial P_{n_x n_y}}{\partial z} \approx \left( \frac{\Delta P_{n_x n_y}}{\Delta z} + jp_{n_x n_y} \frac{\Delta \varphi_{n_x n_y}}{\Delta z} \right) \exp(j\varphi_{n_x n_y}), \quad (4)$$

where  $p_{n_x n_y}$  and  $\phi_{n_x n_y}$  are the magnitude and the phase of  $P_{n_x n_y}$  on the mouth surface, i.e.,  $P_{n_x n_y} = p_{n_x n_y} \exp(j\phi_{n_x n_y})$ . Here,  $\Delta p_{n_x n_y}$  and  $\Delta \phi_{n_x n_y}$  are the differences in sound pressure and in phase between the two patches having the same  $x$  and  $y$  coordinates on the parallel surface and the mouth surface. Note that  $\Delta z$  should be much less than half of a wavelength to avoid errors caused by the periodicity of the phase.

In general, the evaluation method consists of two procedures: (1) measuring the sound pressure distributions on the mouth surface and on the parallel surface [Fig. 1(a)] and (2) evaluating the sound-field information using Eqs. (2) and (4).

To validate the accuracy of the proposed method, the radiated sound fields of two different waveguides were first evaluated by measuring the sound field in the mouths of the waveguides [the two surfaces shown in Fig. 1(a)]; then these evaluated data were compared with those measured directly in the open space beyond the end of the waveguide. The laboratory experiments were conducted in a large anechoic chamber ( $11.4\text{ m} \times 7.8\text{ m} \times 6.7\text{ m}$ ) at Nanjing University. A compression driver (CP385Nd, Beyma) was chosen as the source, and two tweeter waveguides (WG-A and WG-B) were used. The source frequency was varied from 3.15 to 20 kHz. The waveguides were mounted on an IEC standard baffle, and the longer edge of the waveguide mouth was in the  $x$ -direction. The sound pressure was measured using a probe microphone (type 4182, Brüel & Kjær) with a 200-mm-long stiff probe, and the phase reference was the signal generated by the analyzer. A PULSE Analyzer (Type 3160A, Brüel & Kjær) was used to generate signals, analyze data, and store results. To reduce the diffraction as much as possible, all of the microphone guides and fixtures were covered by sound-absorbing materials.

For the measurement in the waveguide mouth, which is used to evaluate the radiated sound field by using the proposed method, the sound pressure was measured both on the mouth surface and on the parallel surface shown in Fig. 1(a). The distance between the two surfaces was chosen to be  $\Delta z = 5\text{ mm}$ . The  $z$ -directional derivative of the sound pressure was then obtained by using Eq. (4). The probe microphone was fixed on a two-dimensional microphone guide, which enabled the movement of the microphone in both the  $x$ - and  $y$ -directions in steps of 5 mm. The microphone guide was driven by a stepper motor, allowing automatic movement.

For the measurement in the open space beyond the end of the waveguide (in the  $x$ - $O$ - $z$  plane), which is used for comparison with the proposed method, the sound

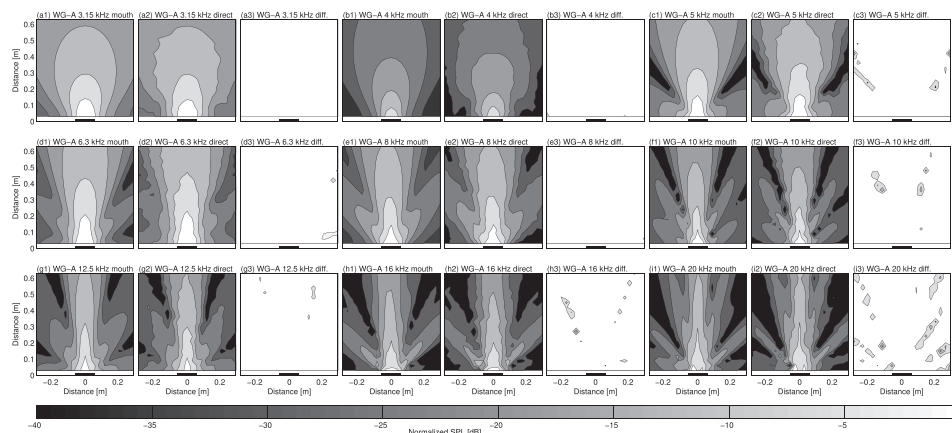


Fig. 2. SPL distributions of waveguide-A (WG-A). Panels (a1)–(i1) show the SPL distributions obtained from the measurements in the waveguide mouth. Panels (a2)–(i2) show the SPL distributions measured directly. The SPLs are normalized to the peak of the data measured directly, i.e., panels (a1) and (a2) are normalized to the peak of panel (a2), panels (b1) and (b2) are normalized to the peak of panel (b2), and so on. Panels (a3)–(i3) show the SPL differences. The absolute data multiplied by  $-1$  are shown for convenience. The thick line in each panel indicates the position of the waveguide mouth.

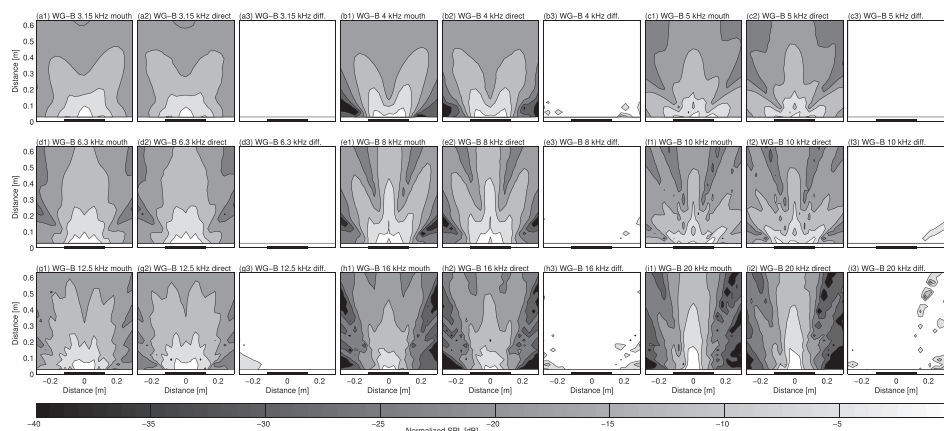


Fig. 3. SPL distributions of waveguide-B (WG-B). Panels (a1)–(i1) show the SPL distributions obtained from the measurement in the waveguide mouth. Panels (a2)–(i2) show the SPL distributions measured directly. The SPLs are normalized to the peak of the data measured directly, i.e., panels (a1) and (a2) are normalized to the peak of panel (a2), panels (b1) and (b2) are normalized to the peak of panel (b2), and so on. Panels (a3)–(i3) show the SPL differences. The absolute data multiplied by  $-1$  are shown for convenience. The thick line in each panel indicates the position of the waveguide mouth.

pressure was measured at the points in the measurement area shown in Fig. 1(a). These  $21 \times 21$  points were equally spaced (with a separation of 30 mm) along both the  $x$ - and  $z$ -directions, such that the total size of the measurement area was  $600 \text{ mm} \times 600 \text{ mm}$ . Another microphone guide was used to guide the movement of the microphone.

The waveguides used in the experiments were designed to morph the spherical wave radiated from the tweeter into a cylindrical, isophasic wave. The waveguides geometrically set all possible sound path lengths from the circular entrance to the rectangular exit to be identical. The geometries of WG-A and WG-B were similar, and only some geometric parameters were different.

Figures 2 and 3 show the sound pressure level (SPL) distributions measured directly and derived from the measurement in the waveguide mouth by using the proposed method, respectively. It can be seen that the SPL difference was generally minor, and it was obvious only when the normalized SPL was quite low (i.e., less than  $-35 \text{ dB}$ ). The ripple-pattern distortion [i.e., in panel (b2) of Fig. 2] might be caused by the diffraction of the microphone guide; it would be much more severe if the microphone guide had no sound-absorbing material covering. It is also worth mentioning that, although the waveguides were designed for the same purpose, the radiated sound fields were quite different. Moreover, these two waveguides were designed to be geometrically symmetric, but the sound fields obtained by the two approaches in this work were asymmetric, which can hardly be predicted from the numerical simulation.

Therefore, this evaluation method shows several advantages: (1) This method is fast and convenient. Since the waveguide mouth is small, this evaluation takes little time and needs only a small set of installations. In addition, the basic theory of this method is quite simple, making the analysis procedure easy and fast. (2) Actual and detailed information about the radiated sound field can be obtained, including the sound pressure, particle velocity, complex sound intensity, wavefront, and directivity pattern.

In summary, this work presents a practical method for evaluating the radiated sound field of a baffled waveguide. The mathematical basis of this method is the replacement of the waveguide with an equivalent monopole source distribution determined by the normal particle velocity in the waveguide mouth. The sound pressure

distribution in the region beyond the end of the waveguide derived from the measurement in the waveguide mouth by using the proposed method was quite similar to the directly measured distribution. Therefore we have demonstrated the validity of this method. Furthermore, this method can also be used in the evaluation of some other acoustic devices, such as the micro-loudspeaker, as long as the measurement of the device requires a baffle and a convenient integral surface can be found.

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### References and links

- Bauman, P. D., Adamson, A. B., and Geddes, E. R. (1993). "Acoustic waveguides—In practice," *J. Audio Eng. Soc.* **41**, 462–470.
- Berkhout, A. J., de Vries, D., and Vogel, P. (1993). "Acoustic control by wave field synthesis," *J. Acoust. Soc. Am.* **93**, 2764–2778.
- Duan, W., Kirby, R., Prisutova, J., and Horoshenkov, K. V. (2013). "Measurement of complex acoustic intensity in an acoustic waveguide," *J. Acoust. Soc. Am.* **134**, 3674–3685.
- Geddes, E. R. (1989). "Acoustic waveguide theory," *J. Audio Eng. Soc.* **37**, 554–569.
- Geddes, E. R. (1993). "Acoustic waveguide theory revisited," *J. Audio Eng. Soc.* **41**, 452–461.
- Le, Y., Shen, Y., and Xia, J. (2011). "A diffractive study on the relation between finite baffle and loudspeaker measurement," *J. Audio Eng. Soc.* **59**, 944–952.
- Verheijen, E. (2010). "Sound reproduction by wave field synthesis," 2nd ed., Ph.D. thesis, Delft University of Technology, Delft, Netherlands.