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Performance of Spatial Windows in the Spatial Fourier Transform Technique for the Angle-Dependent Reflection Factor Measurement

Wang-Lin Lin^{1,2)}, Chuan-Xing Bi¹⁾, Rob Opdam²⁾,
Yong-Bin Zhang¹⁾, Michael Vorländer²⁾

¹⁾ Institute of Sound and Vibration Research, Hefei University of Technology, 193 Tunxi Road, Hefei 230009, People's Republic of China, ybzhang@hfut.edu.cn,

²⁾ Institute of Technical Acoustics (ITA), RWTH Aachen University, Kopernikusstrasse 5, 52074 Aachen, Germany

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Abstract

The spatial Fourier transform technique is one of the well-known methods for measuring the angle-dependent reflection factor. Due to the effect of the finite measurement lines, using monopole sound sources leads to large deviations, especially at small angles of incidence. Thus, a sound source having proper directivity characteristics, such as a dipole source, is preferable. However, small deviations can still be found at small angles of incidence. In the present paper, a non-rectangular spatial window instead of the commonly used rectangular spatial window is applied to the sound pressures measured on two parallel lines, in order to decrease the effect of finite measurement lines. The performance of non-rectangular spatial window has been investigated by both simulation and experiment. It is shown that using the non-rectangular spatial window can improve the results of the method at small angles of incidence, especially for a monopole source. Therefore, more flexibility in the choice of the sound source is possible.

1. Introduction

The reflection factor is an important parameter describing the acoustic property of an absorbing material. A lot of work has been done on measuring this quantity. The impedance tube method [1] is the most well-known method to measure the reflection factor at normal incidence. Free-field methods, such as the acoustic field methods [2, 3], the pulse-echo methods [4, 5, 6] and microphone array methods [7, 8, 9, 10, 11, 12, 13] have been introduced to measure the reflection factor at oblique incidence. The spatial Fourier transform technique [7, 8] is one of the most famous microphone array methods. It can measure the reflection factors at different angles in one measurement simultaneously, and it is independent of the wave front theoretically [14] and the type of the material [15, 16] (locally reacting or not). Tamura [7, 8] first proposed this method based on the measurements of sound pressure on two parallel lines. Hu [9] then applied it to the prediction of the sound propagation over an absorbing plane. Opdam et al. [10] used a microphone array instead of a scanning system with one microphone to measure the sound pressure and

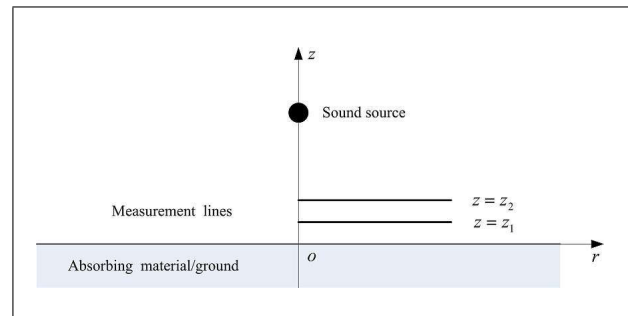


Figure 1. Illustration of the geometry for the spatial Fourier transform technique.

investigated the influence of the edge effect of the material under test using the numerical BEM technique. Recently, Lin et al. [11] investigated the performance of the method when the input data was the sound pressure and particle velocity on one line, or the particle velocities on two lines. However, the spatial Fourier transform technique suffers from the effect of measurement lines with finite length. In particular, if a monopole source is used, the method would lead to large deviations, especially at small angles of incidence which are relative to the normal of the test material. Therefore, a dipole source with its axis along with the normal of the test material is recommended by Tamura [7]. Reasonable results can be obtained after using the dipole source. Nevertheless, deviations can still be found at the small angles of incidence [8]. In the present paper, the non-rectangular spatial windows instead of the rectangular window are applied to the measurement lines in order to decrease the effect of the finite length measurement lines or make the choice of the sound source more flexible. Actually, the spatial windows reduce the contribution of surface elements further away from the center point ($x = y = 0$) in a similar way as given by a vertically directional source.

2. Theory

Figure 1 shows the schematic illustration of the geometry for the spatial Fourier transform technique based on the measurements of sound pressure. A Cartesian coordinate system is used on the surface of an absorbing material, with its origin coinciding with the center of the surface. A sound source is placed on the z -axis. The method involves measurements of pressure, $p(r, z_1)$ and $p(r, z_2)$, on two lines $z = z_1$ and $z = z_2$. When the sound field has axial symmetry with respect to the z -axis, i.e. the sound source has axial symmetry but also the material is isotropic, the sound pressure distribution on two lines can be decomposed into plane-wave components by using the spatial Fourier transform in the radial direction, i.e., the Fourier-Bessel transform, as

$$P(k_r, z_j) = 2\pi \int p(r, z_j) J_0(k_r r) r dr, \quad (1)$$

where k_r is the wavenumber component in the radial direction, the subscript $j = 1$ or 2 , and $P(k_r, z_j)$ is the spatial spectrum of the sound pressure distribution on the line $z = z_j$. The reflection factor $R(k_r)$ at the angle of incidence $\theta = \sin^{-1}(k_r/k_0)$ can be obtained by

$$R(k_r) = \frac{P(k_r, z_1)e^{-ik_z z_2} - P(k_r, z_2)e^{-ik_z z_1}}{P(k_r, z_2)e^{ik_z z_1} - P(k_r, z_1)e^{ik_z z_2}}, \quad (2)$$

where $k_z = \sqrt{k_0^2 - k_r^2}$ with k_0 the wavenumber in air.

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Since the spatial Fourier transform involves an infinite integration as seen in Equation (1), the measurements should theoretically be carried out on infinite lines. However, in practice, the measurements can only be carried out on finite-length lines. This is equivalent to applying a rectangular spatial window to the sound pressure distribution on the measurement lines. When a monopole source is used, it would lead to large deviations especially at small angles of incidence, while the recommended dipole source can lead to the more precise results. However, small deviations still can be found at the small angles of incidence. This rather strong effect of finite measurement lines could be ascribed to the strong spectral leakage (the term used to describe the effect of windowing) caused by the rectangular spatial window. Therefore, the non-rectangular spatial window resulting in less spectral leakage is applied to the sound pressure. The non-rectangular spatial windows investigated in this paper are the frequently-used half Hanning window and the half Tukey window as shown in Figure 2.

3. Numerical simulations

As shown in Figure 1, the sound source is placed at a height of $z = 10$ cm above the surface of an absorbing material with an infinite thickness. The measurements are carried out on two parallel lines, the heights of which are $z_1 = 1$ cm and $z_2 = 3$ cm. The sampling spacing between adjacent measurement points is set to 1 cm, and there are 101 points on each line. This corresponds to a spatial sampling with an upper-frequency limit of about 17 kHz. The sound pressures on the measurement lines are calculated by applying the inverse Fourier-Bessel transform to the corresponding spatial spectrum [7]. The characteristic impedance Z_1 and complex wavenumber k_1 of the absorbing material are calculated by the Delany and Bazley [17] model,

$$Z_1 = Z_0 [1 + 9.08(f/\sigma)^{-0.75} + i11.9(f/\sigma)^{-0.73}], \quad (3)$$

$$k_1 = k_0 [1 + 10.8(f/\sigma)^{-0.70} + i10.3(f/\sigma)^{-0.59}], \quad (4)$$

where Z_0 is the characteristic impedance of air, f is the frequency, and σ is the flow resistivity of the absorbing material in $\text{kPa}\cdot\text{m}^{-2}$ units. The theoretical reflection factor $R_{th}(k_r)$ of the absorbing material at the angle of incidence θ can be calculated by [7]

$$R_{th}(k_r) = \frac{Z_1 \cos \theta - Z_0 [1 - (k_0 \sin \theta / k_1)^2]^{1/2}}{Z_1 \cos \theta + Z_0 [1 - (k_0 \sin \theta / k_1)^2]^{1/2}}. \quad (5)$$

Figure 3 shows the performance of the non-rectangular windows at 1500 Hz for the case of using a monopole sound source. The theoretical value is calculated according to Equation (5). It can be seen that, at small angles of incidence, the results have been both improved significantly by using the half Hanning window and the half Tukey window, compared with those of using the rectangular window. In addition, similar results at large angles of incidence can be obtained by using the half Tukey window as those of using the rectangular window, while a little worse results are found by using the Hanning window. Figure 4 shows the spatial spectrum of the sound pressure on the line $z_1 = 1$ cm after using the rectangular window and two non-rectangular windows. It can be seen that the spatial spectrum becomes smoother at small angles of incidence (small spatial frequency) when using the half Hanning and Tukey windows. This means that the effect of the finite measurement lines is decreased, and therefore better results are obtained. The worse performance of the half Hanning window at the large angles could be attributed to low spectrum

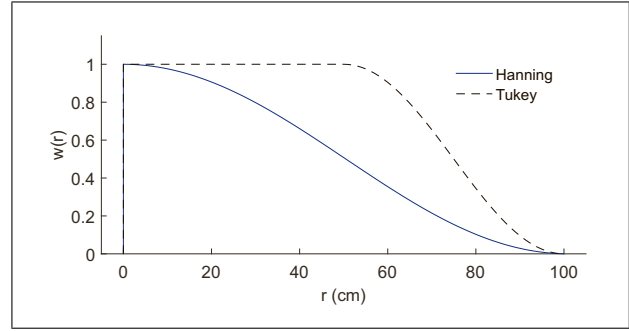


Figure 2. (Colour online) Plot of the non-rectangular windows. The parameter α of the half Tukey window is 0.5, which is the ratio of cosine-tapered section length to the entire window length.

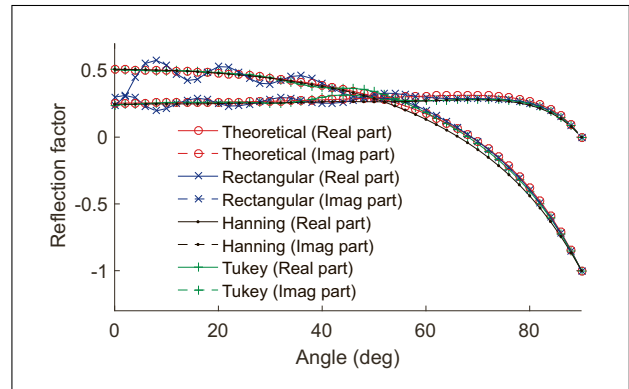


Figure 3. (Colour online) Reflection factors determined by using the rectangular window and two non-rectangular windows; Flow resistivity: $100 \text{ kPa}\cdot\text{m}^{-2}$; Frequency: 1500 Hz; Sound source: Monopole.

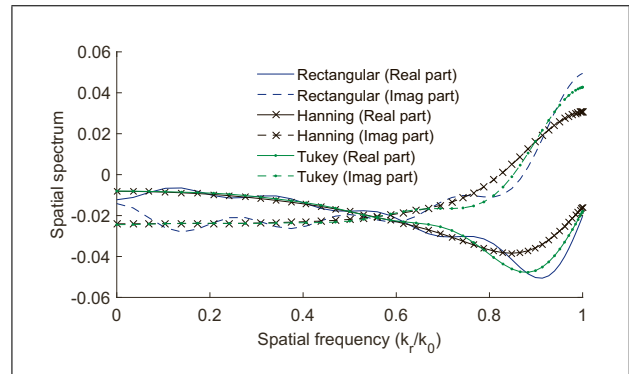


Figure 4. (Colour online) The spatial spectrum of the sound pressure distribution on the line $z_1 = 1$ cm; Flow resistivity: $100 \text{ kPa}\cdot\text{m}^{-2}$; Frequency: 1500 Hz; Sound source: Monopole.

energy as also can be seen in Figure 4. The conclusion can be more clearly found in Figure 5 which shows the relative errors of results. The relative error is defined as

$$Err = |R - R_{th}| / |R_{th}| \times 100\%, \quad (6)$$

where R and R_{th} are the measured and theoretical values of reflection factors, respectively. The similar conclusion can be drawn when $\sigma = 10 \text{ kPa}\cdot\text{m}^{-2}$ as shown in Figure 6. Figure 7 shows the relative error of the result at normal incidence (0 deg) using different kinds of window versus frequency, where $\sigma =$

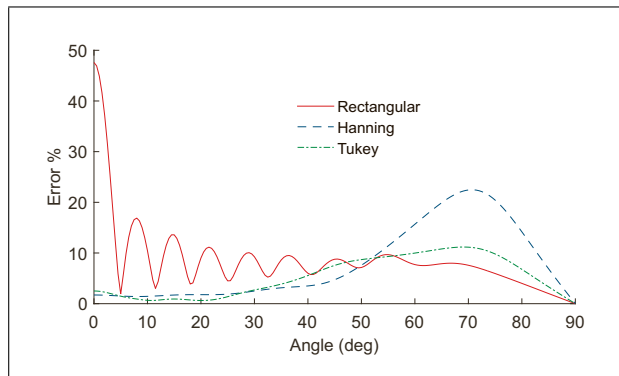


Figure 5. (Colour online) Relative error of using different kinds of window; Flow resistivity: $100 \text{ kPa}\cdot\text{m}^{-2}$; Frequency: 1500 Hz ; Sound source: Monopole.

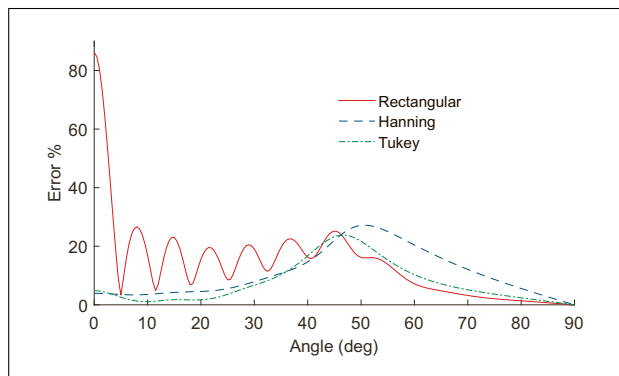


Figure 6. (Colour online) Relative error of using different kinds of window; Flow resistivity: $10 \text{ kPa}\cdot\text{m}^{-2}$; Frequency: 1500 Hz ; Sound source: Monopole.

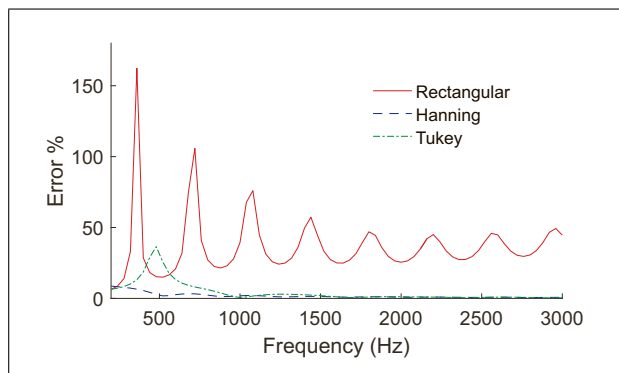


Figure 7. (Colour online) Relative error of the result at normal incidence (0 deg) using different kinds of window versus frequency; Flow resistivity: $100 \text{ kPa}\cdot\text{m}^{-2}$; Sound source: Monopole.

$100 \text{ kPa}\cdot\text{m}^{-2}$. It can be seen that the half Hanning window leads to good results at all frequencies. The results of the half Tukey window are similar as those of the half Hanning window, except that there are large deviations around 480 Hz .

In Figure 8, the same parameters as for Figure 5 were used, but now for a dipole source. It can be seen that the results of using the rectangular window become better compared with the case of the monopole source. The half Hanning window does not perform as well as in the case of the monopole. However, the results at small angles of incidence can be still further improved by using the half

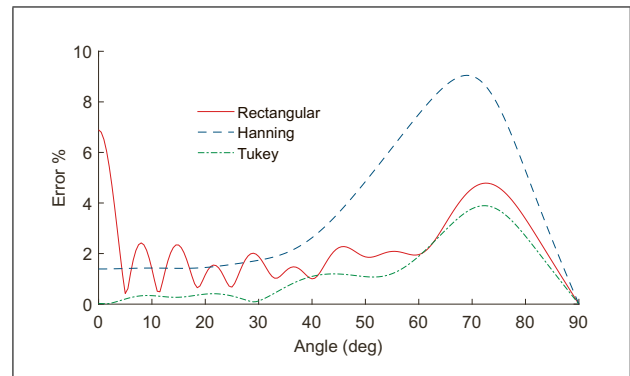


Figure 8. (Colour online) Relative error of using different kinds of window; Flow resistivity: $100 \text{ kPa}\cdot\text{m}^{-2}$; Frequency: 1500 Hz ; Sound source: Dipole.

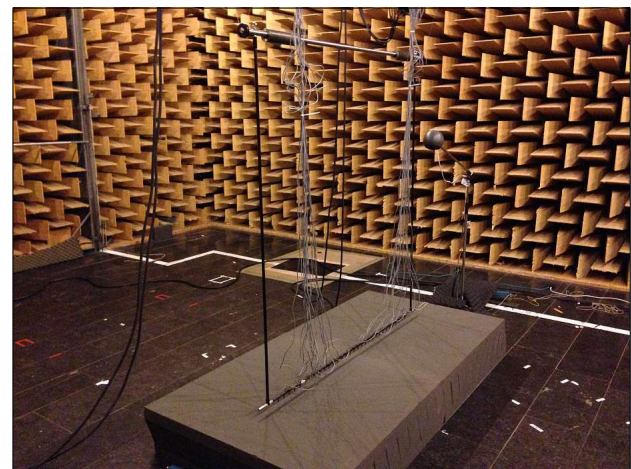


Figure 9. (Colour online) The set-up of the experiment in the hemi-anechoic chamber.

Tukey window. From the analysis above, it can be concluded that the non-rectangular window can be used to decrease the effect of the finite measurement lines and improve the results of the spatial Fourier transform technique at small angles of incidence. For the monopole source, both non-rectangular windows could be used. For the dipole source, the Tukey window with the parameter $\alpha = 0.5$ is preferable.

4. Experiment

In order to further investigate the performance of the non-rectangular window, an experiment was conducted in a hemi-anechoic chamber ($11\text{m} \times 5.97\text{m} \times 4.5\text{m}$). The case of the monopole source was investigated. Figure 9 shows the set-up of the experiment. A loudspeaker mounted on a spherical baffle with a diameter of 12 cm was positioned at a height of 1.06 m above the sample surface and can be considered as a monopole source up to around 2 kHz [10]. The high position of the loudspeaker was chosen according to the aspect that the influence of secondary reflections from the loudspeaker should be reduced. The excitation signal was an exponential sweep at a sampling rate of 48 kHz ranging from 200 Hz to 2 kHz for an FFT degree of 18. This quite high degree covers a measurement time of 5.5 s , which is much more than required but it ensures a very high signal-to-noise ratio, a very high frequency resolution and no need to perform averaging. A linear microphone array made of 32 Sennheiser KE4 microphones was used to measure the

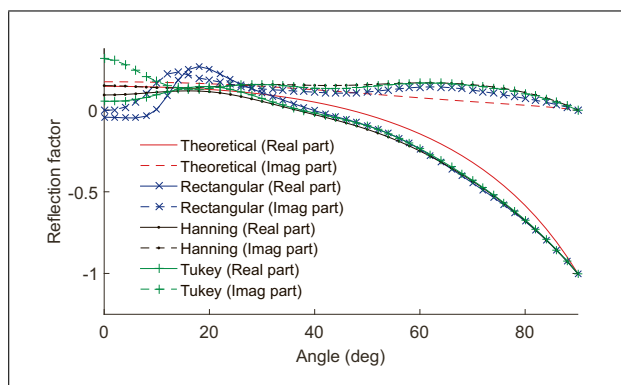


Figure 10. (Colour online) Reflection factor versus angle of incidence at 600 Hz.

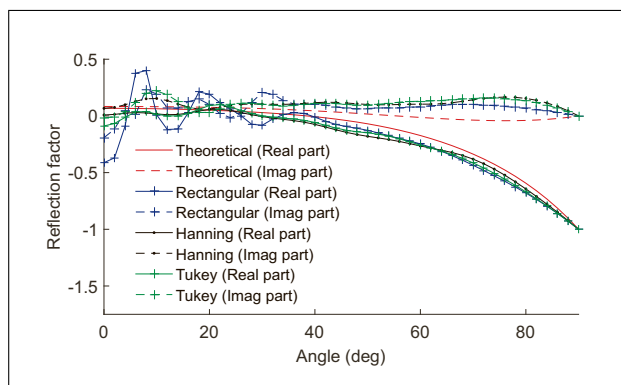


Figure 11. (Colour online) Reflection factor versus angle of incidence at 1456 Hz.

sound pressures at the height of 1 cm and 3 cm above the sample surface. The distance between the microphones was 4 cm and the total length of the array was 1.24 m. The first microphone on the array was placed directly below the loudspeaker. A 253-mm-thick polyurethane foam with a flow resistivity of $5.4 \text{ kPa} \cdot \text{m}^{-2}$ was used as the material under test with a total surface area of 2 m^2 . It was formed by two elements of size 1 m by 1 m. It should be noted that the edge effect of the sample has been proven to be small [10].

Figure 10 shows the experimental results of using the rectangular and non-rectangular windows combined with the theoretical values calculated by the Delany and Bazley [17] model at 600 Hz. Large fluctuation and deviation at small angles of incidence can be found from the results of using the rectangular window. In contrast, the deviations become small when using the half Hanning window. The half Tukey window can lead to similar results as the half Hanning window at the angles of incidence larger than 10 degrees. Meanwhile, the relatively larger deviation at angles of incidence less than 10 degrees can be found from the results of using the half Tukey window, which is in accordance with what has been found from Figure 7 in the simulation. At larger angles of incidence, the results of the half Hanning and Tukey windows both have deviations, and those of the Hanning window are slightly better, which is consistent with what has been found in the simulation. The similar performance of the non-rectangular windows can be also found at 1456 Hz as shown in Figure 11, and the performance of half Tukey window at small angles of incidence becomes better. In conclusion, the similar conclusion as those in the simulation section has also been found by the experiment.

5. Conclusions

This paper focuses on the spatial Fourier transform technique for measuring the angle-dependent reflection factor. Due to the finite length of the measurement lines, using a monopole sound source would lead to systematic uncertainties, especially at small angles of incidence. Therefore, a dipole source which has proper directivity characteristics is suggested [7]. However, small deviations can still be found at small angles of incidence. In order to further decrease the effect of the finite measurement lines, the non-rectangular window was applied to the sound pressure measured on two parallel lines. The performance of the non-rectangular window has been investigated and compared with that of the rectangular window through both simulation and experiment. It shows that the results at the small angles of incidence can be improved by using the non-rectangular, especially for a monopole source. In general, it can be concluded that using the non-rectangular window works for decreasing the effect of finite measurement lines and make the choice of the sound source more flexible. Actually, the non-rectangular spatial window effect is similar to the effect of a vertically directional source. Both give less emphasis on off-axis surface elements. A comprehensive strategy for choosing the type of the non-rectangular window would be developed in future work. It should be noted that the similar performance of the non-rectangular window can be obtained when the input data is the sound pressure and the particle velocity on one line, or the particle velocity on two lines.

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