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APPLICATION OF PHASED ARRAYS IN THE STUDY OF SURFACE ROUGHNESS NOISE

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ABSTRACT

The generation of sound by turbulent boundary-layer flow over a rough wall has been investigated theoretically and numerically. The roughness elements were speculated to behave like point dipoles with the dipole strength due to scattering of the near turbulent pressure fluctuations by a roughness element. The roughness-generated noise was shown to be comparable to the trailing-edge noise on an aircraft. Experiments were also performed and the results confirmed that roughness noise is not a negligible sound source.

In this study, phased arrays were applied to localize the possible dipole sound sources due to roughness elements on a flat plate. The radiated sound from two rough and one smooth plates in an open jet was measured by 48-channel phased arrays at three locations. The rough regions were manufactured by a square distribution of rigid, hemispherical bosses on a rigid plate. The beamforming source maps obtained at different locations have displayed some features of dipole sources, and the rough plates have shown higher source strengths than the smooth plate. Simulated source maps were obtained for a distribution of incoherent dipoles with source strengths predicted by theory and distributed over the rigid plate. They exhibited encouraging similarities to the measured source maps.

1 INTRODUCTION

The generation of sound by turbulent boundary-layer flow over a rough wall has been investigated theoretically and numerically [1]–[5]. Howe has developed theoretical models on surface roughness generated noise [1]–[4]. In his theory, the rough surface was modelled by a random distribution of rigid, hemispherical elements over a rigid smooth plane. The near-field hydrodynamic disturbances in the turbulent boundary layer interact with the surface irregularities and produce sound by diffraction. The roughness elements were speculated to behave like point dipoles [4] with the dipole strength due to scattering of the near turbulent pressure fluctuations on an element. Liu *et al.* [5] recently extended Howe's diffraction theory to quantify of the far-field radiated roughness noise. They estimated the roughness noise from a Boeing-757 sized aircraft wing with idealized levels of surface roughness, and concluded that it may exceed the trailing-edge noise in high frequency region.

However, experimental work on surface roughness noise is not easy due to its very low spectral levels. Hersh [6] measured the sound radiated from the exhaust of sand-roughened pipes with various grit sizes in an anechoic chamber. He found that the overall sound pressure level showed a 6th power variation with flow speed, consistent with a dipole source. Liu *et al.* [5] studied the radiation of sound from two rough plates in an open jet, and the measured noise spectra exhibited encouraging agreement with numerical predictions in 1–2.5 kHz frequency range.

In this study, phased microphone arrays were applied to localize the possible dipole sources due to roughness elements on a rigid plate. The radiated sound from two rough plates and one smooth plate in an open jet was measured by high- and low-frequency arrays at three different locations. The source patterns and strengths obtained by beamforming were illustrated and discussed. Based on the numerical prediction scheme of Liu *et al.* [5], simulated source maps for a distribution of incoherent dipoles over a rigid plate were obtained for comparison with the experimental results.

2 EXPERIMENTAL SETUP

The experiments were performed in the open jet of a low-speed wind tunnel, as shown in Fig. 1. The wind tunnel has a speed range of 0–31.0 m/s and the inner cross-section of its outlet is 0.586×0.35 m^2. Plastic foam lined in the inner wall to reduce noise travelling inside the tunnel. A flat plate was placed on the centreline of the open jet with a recess of 0.64×0.64 m^2 machined into the plate surface. Small boards with rigid, hemispherical plastic beads in parallel rows were flush mounted in the recess to form a rough region. Each row spans the

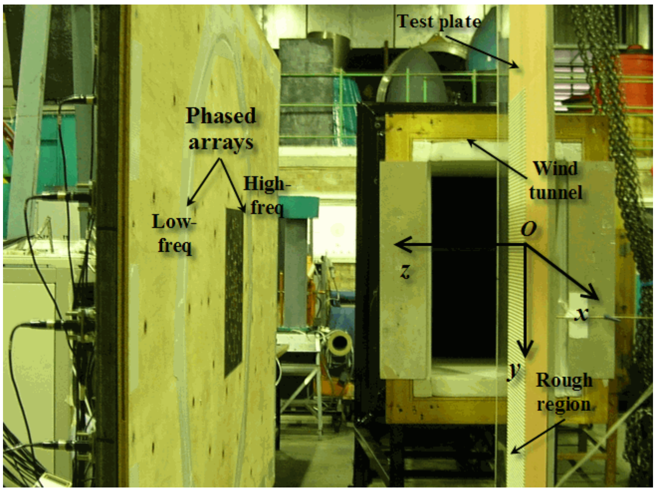

Fig. 1. Schematic of the experimental setup.

entire height of the open jet. The rough region was located at 0.34 m from the leading edge of the plate, where the flow was tripped, to ensure that the roughness elements are contained entirely within the boundary layer [1]. Three different surface conditions were tested, as listed in Table 1(a), where R and σ are the roughness height and roughness density [1][5].

Both high- and low-frequency phased arrays were applied to localize the possible dipole sources on the rough plates. Each array consists of 48 microphones located in optimized concentric circles or ellipses and flush mounted in a rigid board. The radiated sound from the rough and smooth plates was measured at three different locations to explore the features of possible dipole directivities. The locations of the array centre are shown in Table 1(b) with the coordinate origin set at the centre of the rough region (see Fig. 1). During a test the acoustic pressures were synchronously measured by array microphones at a sampling frequency of 120 kHz (high-frequency array) or 30 kHz (low-frequency array) and a duration time of 60 s. Then the acoustic data were post-processed and source maps for 1/3-octave frequency bands were generated through beamforming. The source powers were converted to sound pressure level (SPL) at a reference distance of $1/\sqrt{4\pi}$ m from the source [7].

Table 1. Summary of the experimental parameters: (a) test conditions, (b) array locations.

(a)	R (mm)	σ (%)
Rough1	4.0	50
Rough2	3.0	44
Smooth	0.0	0

(b)	x (m)	y (m)	z (m)
Location 1	0.04	0.025	0.47
Location 2	0.18	0.025	0.64
Location 3	0.36	0.025	0.60

3 RESULTS AND DISCUSSION

3.1 Noise spectra

The narrow-band cross spectra of the rough and smooth plates are compared in Fig. 2 for the flow speed $U = 30$ m/s. The rough plates produce higher noise spectra than the smooth plate in the frequency range 800–2800 Hz. The spectral peak of Rough1 is above that of Rough2, but Rough2 has higher spectral level than Rough1 throughout the 1750–2800 Hz frequency range. This is because the sound radiation from smaller roughness elements will be dominant at higher frequencies.

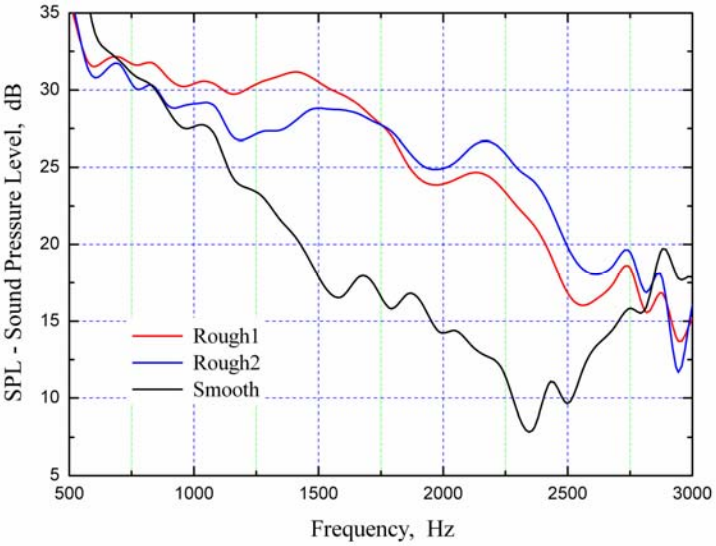

Fig. 2. Comparison of noise spectra for Rough1, Rough2 and Smooth, $\Delta f = 64$ Hz, $U = 30$ m/s.

3.2 Effects of array locations

Based on the noise spectra in Fig. 2, Fig. 3 illustrates the beamforming source maps of the two rough plates obtained by the high-frequency array at three locations. The inner dark square delineates the boundary of the rough region and the black line on the right denotes the trailing edge. The flow direction is from the left to the right, and the colour bar gives the SPL data in dB. The coordinate origin of the source maps is fixed at the array centre.

As can be seen in Fig. 3, Location 1 produces a major lobe upstream and a secondary lobe downstream, though not so distinct, because the array centre is close to the central rough region. However, there is only one major lobe in the source maps at Locations 2 and 3. Higher SPL can be observed as the array shifts downstream to Locations 2 and 3 despite the nearest distance at Location 1. All these features suggest a dipole source in the flow direction.

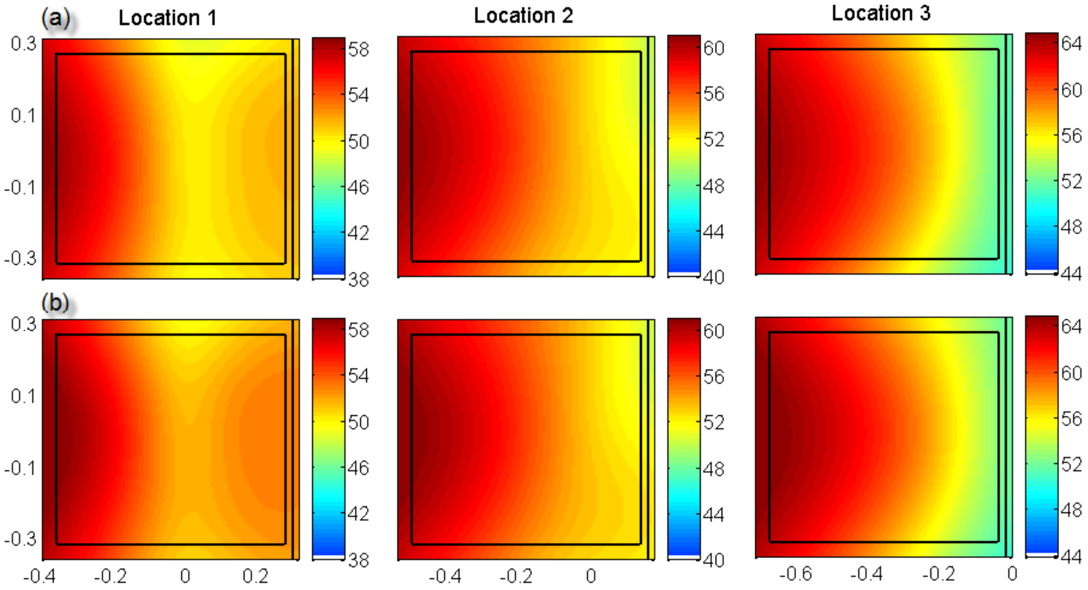

Fig. 3. Comparison of beamforming source maps at three different locations: (a) Rough1, (b) Rough2. High-frequency array, $f = 2000\,Hz$, $U = 30\,m/s$.

3.3 Comparison of rough and smooth plates

The beamforming source maps for rough and smooth plates are compared in Fig. 4. Both high- and low-frequency array data are shown for specific frequencies. The SPL data of rough and smooth plates are shown on identical reference scales for ease of comparison. Note that the rough region in Fig. 4 is only half of that in Fig. 3 to reduce the interference of sound scattering from the trailing edge.

As shown in Fig. 4, the source strengths of the rough plates are 10–15 dB higher than those of the smooth plate. At the chosen frequencies Rough1 produces higher SPL than Rough2, and the source maps obtained with the low-frequency array have better resolution than those with the high-frequency array. In Fig. 4(b) major lobes can be observed in the upstream rough regions because the developing boundary layer thickness along the plate chord makes the downstream rough region less significant as a sound scatterer. The sound sources around the trailing edge are also seen. The weaker sound sources in Fig. 4(b) than those in Fig. 4(a) are probably due to the better resolution of the low-frequency array.

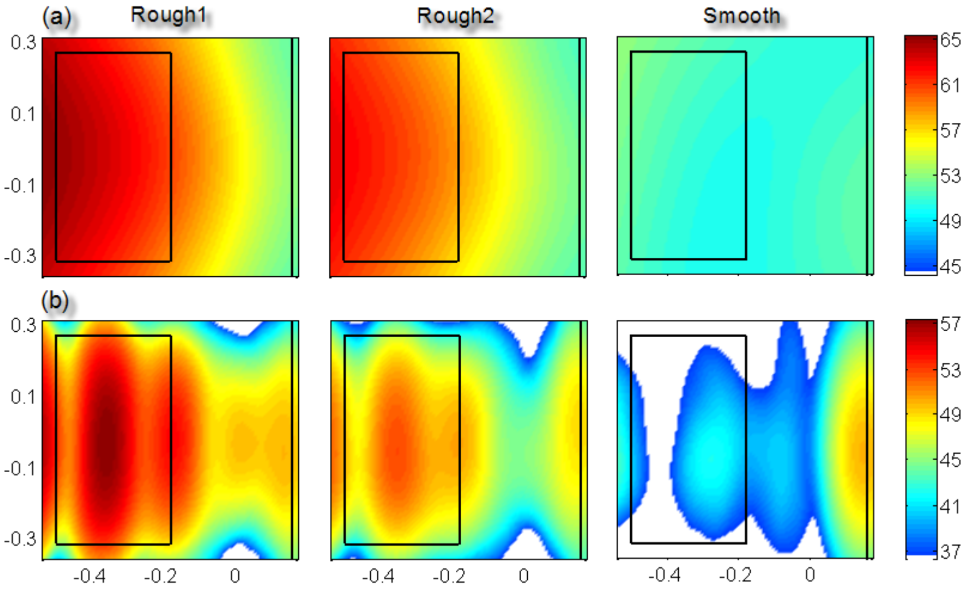

Fig. 4. Comparison of beamforming source maps for rough and smooth plates: (a) High-frequency array, $f = 1600$ *Hz; (b) Low-frequency array,* $f = 1250$ *Hz.* $U = 30$ *m/s.*

3.4 Comparison of measurement and simulation

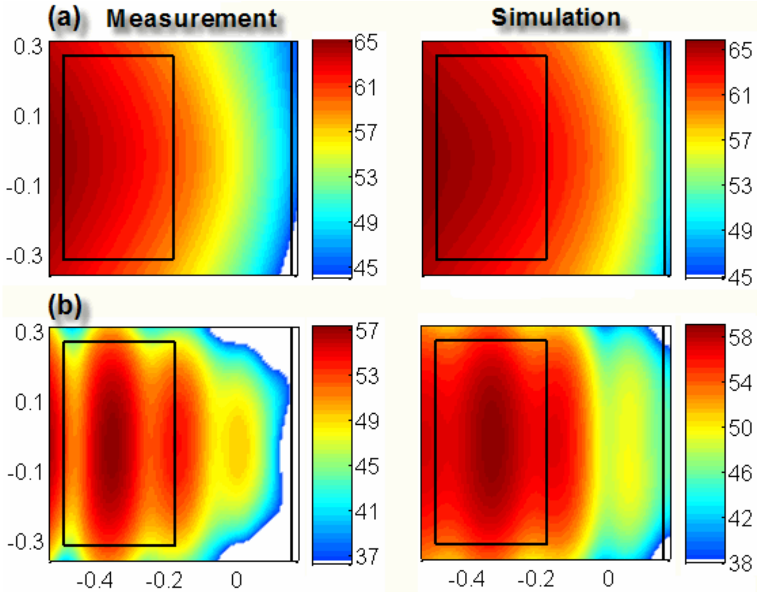

Fig. 5. Comparison of measured and simulated beamforming source maps for Rough1: (a) High-frequency array, $f = 1600$ *Hz; (b) Low-frequency array,* $f = 1250$ *Hz.* $U = 30$ *m/s.*

Fig. 5 shows the comparison of beamforming source maps by measurement and simulation. The measured and simulated results due to the high- and low-frequency arrays are compared for Rough1 at 1600 Hz and 1250 Hz, respectively. Contamination in Fig. 4 from other sound sources, e.g. trailing edge, was eliminated by subtracting the smooth-plate source powers from the rough-plate ones, so that "clean" source maps of measured roughness noise were obtained in Fig. 5 for easy comparison.

A simulation code SIMSRC [7] was utilized to model a distribution of dipole sources due to roughness elements over a rigid plate. In this code a pair of coherent monopoles with opposite phase is created on each hemisphere element. The sound due to each roughness element is incoherent with other pairs of monopoles. The numerical prediction scheme by Liu *et al.* [5] was applied to calculate the monopole magnitudes. The image sources were also included due to the reflecting rigid plate.

The source maps of measurement and simulation exhibit encouraging similarities in both source patterns and source strengths, as shown in Fig. 5, although the simulated SPL is a bit higher. This confirms that the surface roughness noise is a dipole source in character. Nevertheless, somewhat higher source strengths in the downstream portion of the rough region can be observed in the simulated source maps.

4 CONCLUSIONS

The application of phased arrays in this study has confirmed the dipole nature of surface roughness noise. The beamforming source maps obtained at different locations have shown features of a dipole source, and 10–15 dB higher source strengths have been observed on the rough plates than on the smooth plate. The encouraging similarities between measured source maps and theoretical simulation have provided a preliminary validation of the numerical prediction scheme of Liu *et al.* [5] which was based on Howe's theoretical model [1]. Further work needs to be carried on regarding the somewhat lower axial gradients of source strengths predicted by the simulation code.

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