Effects of surface roughness and turbulence on propagation of shock waves above a curved surface

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Introduction

Outdoor sound propagation is affected by refraction, turbulence and ground effect. The use of laboratory models for assessing these effects has a considerable history. Previous work has emphasized linear propagation. No previous work has considered the simultaneous effects of turbulence and ground roughness on weak acoustic shocks in the shadow zone. This paper describes laboratory experiments in which acoustic shocks from electric sparks have been used to model the propagation of sonic booms. A cylindrical curved surface was used to simulate atmospheric refraction effects and a heated grid was used to generate turbulence. The curved surface was either smooth or rough. A 1/8" B&K microphone array was used to measure propagation along the surface and along the surface normal at several positions. The influence of turbulence and surface conditions on peak pressure (P_{max}), rise time (defined as the time from 10% of P_{max} to 90% of P_{max}) and the spectrum of the received acoustic shocks have been investigated. The experiments have enabled separate assessment of the effects of turbulence and roughness in the shadow zone caused by the curved surface. In addition some assessment of the combined effects of roughness and turbulence has been possible.

Apparatus and measurement

In the 10m×7m×8m anechoic room in the Ecole Centrale de Lyon, a convex curved plastic surface with a radius of 2m was used to create an acoustic shadow zone for propagation of acoustic impulses from an electric spark source. Thermal turbulence was created by means of a heated 4.4×1.1m grid with a square mesh of 9 cm and a maximum heating power of 64 kW. Two fixed 1/8" microphones were flush with the curved surface (M1 and M2 in Figure 1). Two different depths (small and large) of the acoustic shadow zone were created by locating the electric spark source at radial heights of 160mm and 100mm above the curved surface. The baffled microphones were arranged along a radial line at distances between 104 and 508 mm from the surface. Measurements without turbulence were made for each source height (a) over the smooth curved surface both along the surface and along the radial line and (b) over a rough curved surface made by sticking 0.8mm grain sand paper on to the smooth plastic but only along the radial line. 100 pulses were measured at each receiver position in the absence of turbulence. 1000 pulses were measured in each position with turbulence.

Results and discussion

The results obtained in the absence of turbulence over the smooth surface vary as expected with the depth of the shadow zone showing between 3 and 6 dB reduction in peak pressure at the lower receiver positions for the lowest source position.

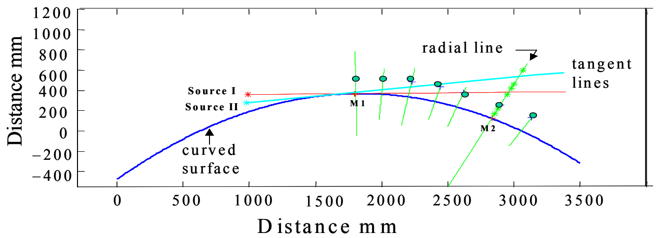


Figure 1 Plan view of experiment. There are six positions along the radial line numbered consecutively with increasing radial distance from the curved surface from 104mm to 508mm.

The upper two graphs in Figure 2 compare data for peak pressure and rise time obtained along the radial line over the smooth curved surface using the lower source position without and with turbulence. The increased mean peak pressure in the shadow zone is the result of scattering from the turbulence and the penetration of the shadow zone by creeping waves. Turbulent scattering may be the cause also of decreased peak pressures in the illuminated zone.

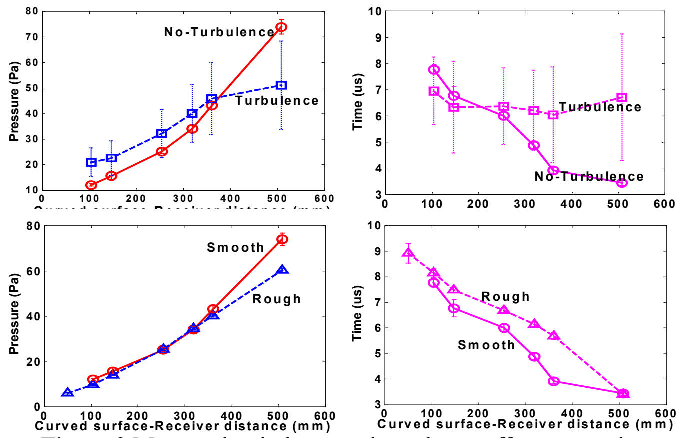


Figure 2 Measured turbulence and roughness effects on peak pressures and rise times with lower source position. Solid lines represent data without turbulence. Broken lines show mean data and standard deviations with turbulence.

The lower two graphs in Figure 2 show data obtained over the rough surface in the absence of turbulence and with the lower source position. The data indicate that the surface roughness decreases the peak sound pressure levels. For all except the highest receiver, roughness increases the rise times. Although the data are not shown, with the higher source position surface roughness *increases* the peak sound pressure level in the illuminated zone by 1dB and *steepens* the shock wave.
Spectral analysis of the data obtained without turbulence and with the lower source position (Figure 3) reveals that, at the position closest to the curved surface on the radial line,

surface roughness increases the received sound levels by 16dB at low frequencies and decreases them by 3.5 dB at high frequencies.

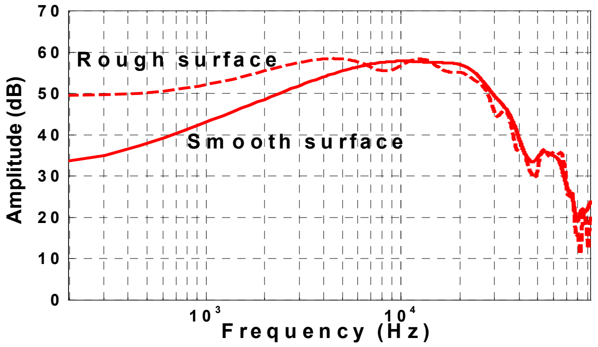
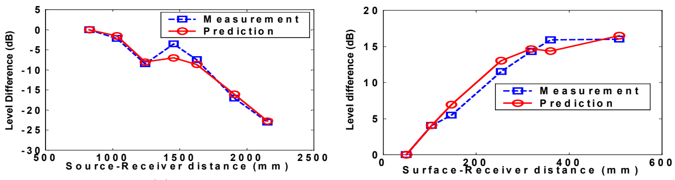


Figure 3 Spectral analysis of the data over rough surface with lower source position, the broken curve is over the rough surface, the solid curve is over the smooth surface

These effects decrease with increasing receiver height. The low frequency effect is caused by the surface wave associated with the multiple scattering along the rough surface[1]. The high frequency effect is associated with the roughness-induced effective surface impedance [2].

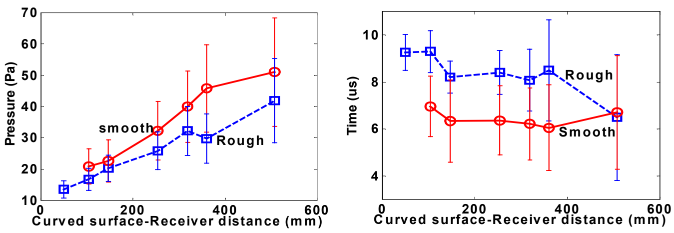
Both smooth and rough surface data at 20 kHz obtained from spectral analysis has been compared with residue series predictions[3]. The discrepancies (Figure 4a) between the measured data at 20 kHz along the smooth curved surface and the theoretical predictions using residue series solution combined with the two-parameter impedance model[4] with parameters appropriate to an acoustically-hard surface σ = 50000 kPa s m^{-2}, α = 50 m^{-1}) are less than 0.5dB except at one point in the penumbra region.



(a) (b)

Figure 4 Comparisons between residue series predictions (broken lines) and measurements (solid lines) (a) along the smooth surface (b) along the radial line from the rough surface.

Over the rough surface (Figure 4b) predictions at 20 kHz (using σ = 20000 kPa s m^{-2}, α = 50 m^{-1}) and data obtained along the radial line are within 1 dB for receiver heights less than 300 mm. The discrepancy of 1.3 dB at the second highest receiver is similar to that in the penumbra region observed with the data along the smooth surface.



(a) (b)

Figure 5 Combined effects of roughness and turbulence along the radial line, with lower source position. Broken lines – rough.

The combined effects of roughness and turbulence along the radial line have been investigated. The results (Figure 5a) indicate that the roughness decreases the mean peak pressures by between 1 and 3.8dB both in the shadow zone and in the illuminated zone compared with turbulence alone. Figure 5b shows that surface roughness increases the rise times significantly in the presence of turbulence. Finally it has been found that roughness has a significant effect on the distribution of peak pressures and rise times during turbulence (Figure 6).

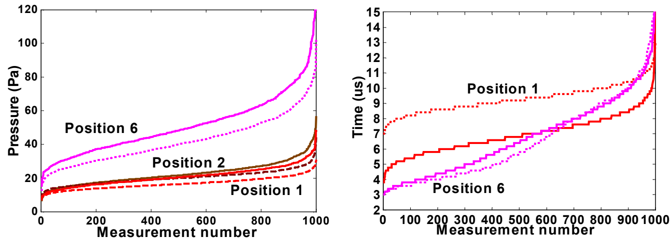


Figure 6 Distributions of 1000 peak pressures (left figure) and rise times (right figure) at various receiver heights, over smooth (solid lines) and rough surface (broken lines), with turbulence and lower source position.

Conclusions

The laboratory results reported here show that there are significant effects due to both ground roughness and atmospheric turbulence on the propagation of broadband shock waves in the atmosphere. In the deep shadow zone it is found that turbulence increases the peak sound pressure levels by 5 dB but that surface roughness decreases the peak sound pressure levels by up to 2.6 dB at the same receiver. In the illuminated zone, turbulence is found to decrease the peak sound pressure level by 2 dB whereas surface roughness increases the peak sound pressure level by 1dB and causes the shock wave to be steeper. During turbulent conditions, surface roughness is found to change both the mean peak pressures and rise times and their distributions considerably compared with smooth surface turbulent conditions. The baffled array has been found to have directivity effects near grazing incidence[5]. This will be subject of further work. However most of the measurements reported here are not near grazing. Moreover compensation for the reported directivity would tend to increase some of the effects observed.

Acknowledgement

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