Effective Impedance of Rough Sea Surfaces

Patrice Boulanger[1], Keith Attenborough[1]

[1] *Department of Engineering, The University of Hull, Hull HU6 7RX, United Kingdom, Email: k.attenborough@hull.ac.uk*

Introduction

To reduce the noise impact of sonic booms from civil supersonic flights, it is likely that, wherever possible, the aircraft will pass through the sound barrier over the sea. This means that prediction of sonic boom characteristics in coastal areas will be important and will involve propagation over the sea as well as the land. The main effect of the finite surface impedance of the ground on sonic boom propagation is on each side of the carpet edge and in the shadow zone [1]. There are less important effects in the primary carpet, where the incidence angle varies quite significantly. It is likely that boom characteristics are modified during near-grazing propagation above a rough sea surface. An effective surface impedance is a convenient way to incorporate the acoustical properties of a rough sea surface into sonic boom propagation models. Given that the specific impedance of seawater is greater than that of air by four orders of magnitude, the sea surface may be considered to be acoustically-hard. Although the sea surface is continuously in motion associated with winds and currents, so that the scattered field is not constant, a sonic boom is sufficiently short compared with the period of the sea surface motion that the roughness may be considered to be static. The objective of this work is to develop models for the effective impedance spectra of rough-hard surfaces corresponding to different sea states.

Theory

The boss theory due to Biot and Tolstoy models rough surfaces of finite impedance but does not account for non-specular scattering (sometimes called incoherent scattering). Inclusion of effects of non-specular scattering has been found necessary when comparing predicted results with measurements [2]. Lucas and Twersky [3] have developed a theory that incorporates a non-specular scattering term in the effective admittance. When used to model 2-D periodic and random hard roughness, this theory has been found to give reasonable agreement with measured ground effect [4]. However, the real part of impedance predicted by Lucas and Twersky's theory for a hard rough surface does not conform to the low frequency limit that is expected from physical considerations. Moreover, it is found to give less satisfactory agreement [5] with hard rough surface data than a Boundary Element Model (BEM). For these reasons, BEM [6] calculations, rather than Twersky's theory, have been used to derive effective impedance spectra for hypothetical rough surfaces corresponding to certain sea states and several incidence angles. There have been several studies of the derivation of effective impedance from excess attenuation (EA) measurements [7]. A novel contribution of this work is to use a winding number integral method [8] to identify the impedance roots of the classical expression for the sound field due to a point source above a smooth impedance plane. Intersecting parabolas are chosen to represent rough sea surfaces. Empirical frequency dependent polynomial fits of BEM-deduced spectra (see Figure 1) are derived for the effective impedance evaluations under the form

$\mathrm{Re}(Z) = \alpha f^{-1}+\delta$ and $\mathrm{Im}(Z) = \alpha' f^{-1/2}+\delta'$. These polynomial forms resemble the 2-parameter model for the surface impedance of rigid porous ground in which the porosity decreases with depth [9],[10]. In this ground impedance

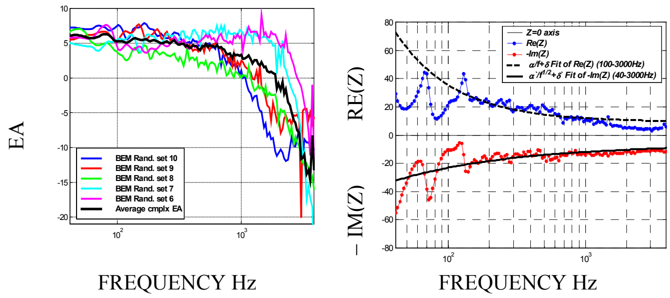

Figure 1: (a) BEM-predicted Excess attenuation Spectra for a point source 0.3 m above the lowest points in five realisations of a 2D surface formed by intersecting parabolas with mean height 0.25m and cusp heights between 0.1m and 0.4m. This corresponds to a grazing angle of 0.012 rad with respect to the horizontal mean height plane. (b) Real and Imaginary parts of the effective impedance spectrum deduced from the mean excess attenuation spectrum and corresponding polynomial fits.

model, the real part is proportional to $1/\sqrt{f}$ and the imaginary part contains terms proportional to $1/\sqrt{f}$ and $1/f$. The form of the fit-polynomials ensure that the real part dominates at low frequency. This is consistent with the BEM results and expected from physical considerations.

Conclusions

The impedance spectra are found to be very sensitive to the roughness profiles in the specular reflection area used in the BEM, and show great effective impedance fluctuations for relatively small (< 1 dB) EA fluctuations. The winding number integral method has been used to conclude that for some roughness profiles there are frequency ranges with only negative real effective impedance roots. It is hypothesized that this effect is due to the enhanced EA in these frequency ranges. As a consequence the complex excess attenuation has been calculated for several random distributions and averaged. Moreover it is found for BEM simulations with parabolically shaped roughness that the effective impedance plane has to be raised between 0.2× and 1× the average roughness height depending on the average roughness height and the incident angle. Values of the

Empirical polynomial fits coefficients α, α', δ and δ' have been computed for six mean roughness heights (sea states) and five angles of incidence. There are inaccuracies in effective impedance fit coefficients estimates due to the particular choices of roughness profiles used for the BEM EA simulations and the particular choice of frequency ranges for the polynomial fits. The angle dependent coefficients at constant roughness height and their error bars are fitted successfully with Gaussian curves and these allow extrapolation to lower angle values (Figures 2-3).

It may be concluded that the general trends for the effective impedance fit coefficients of hard rough surfaces are consistent with the expected decrease in effective impedance with increasing grazing incidence angles (at constant roughness scale) and with increasing roughness scale (at constant incidence angle). The resulting effective impedance polynomials are convenient for implementing in sonic boom propagation codes. Preliminary predictions [11] (Figure 4) indicate that the effect of the sea surface roughness on sonic boom profiles and rise time is comparable to that due to turbulence and molecular relaxation effects. More work is planned to investigate the possibility that the predicted EA enhancements over parabolically-shaped hard rough surfaces

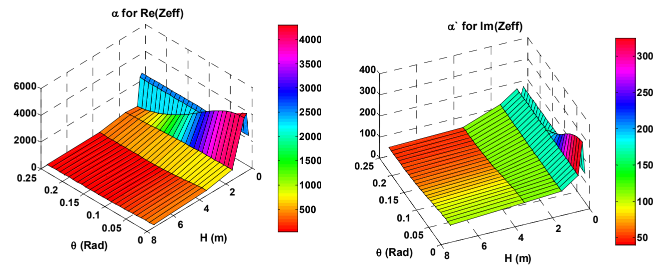

Figure 2: Incidence angle and roughness size dependence of the fit coefficient α for Re(Z_{eff}) (a) and α' for Im(Z_{eff}) (b)

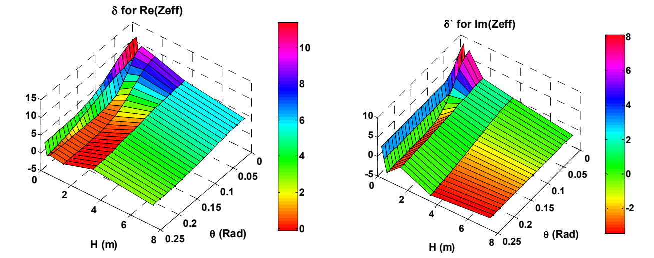

Figure 3: Incidence angle and roughness size dependence of the fit coefficient δ for Re(Z_{eff}) (a) and δ' for Im(Z_{eff}) (b)

may be due to surface wave propagation at grazing angles. The existence of acoustic surface waves have been debated in the early eighties, but experimental measurements of surface waves over small rough surfaces have been published in the past [12], and more recent measurements of outdoor blast noise [13] propagation over rough sea surface show enhanced sound pressure levels indicating surface wave propagation at long range. Therefore, propagation of surface waves might have to be considered when studying grazing sound propagation over a sea surface.

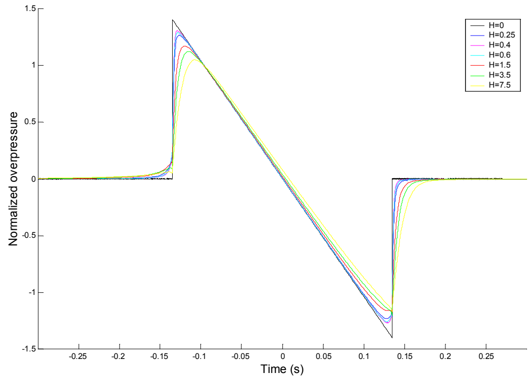

Figure 4: Sonic boom profiles predicted for varying sea-wave heights.

References

[1] F. Coulouvrat, "Sonic boom in the shadow zone: A geometrical theory of diffraction". J. Acoust. Soc. Am., **111**(2) 499-508 (2002).
[2] K. Attenborough and T. Waters-Fuller, "Effective impedance of rough porous ground surfaces", J. Acoust. Soc. Am., **108**(3) 949-956 (2000).
[3] R. J. Lucas and V. Twersky, "Coherent response to a point source irradiating a rough plane" J. Acoust. Soc. Am. **76**, 1847-1863 (1984).
[4] P. Boulanger, K. Attenborough, S. Taherzadeh, T. Waters-Fuller, and Li K. M., "Ground Effect Over Hard Rough Surfaces". J. Acoust. Soc. Am. **104**, 1474-1482 (1998).
[5] P. Boulanger, K. Attenborough," Effective impedance of rough sea surfaces", submitted to JASA 2003
[6] S. N. Chandler-Wilde and D. C. Hothersall, "A uniformly valid far field asymptotic expansion of the green function for two-dimensional propagation above a homogeneous impedance plane" ", J. Sound and Vib., **182**, 665-675 (1995)
[7] S. Taherzadeh, and K. Attenborough, "Deduction of ground impedance from measurements of excess attenuation spectra" ". J. Acoust. Soc. Am. **105**, 2039-2042 (1999).
[8] P. R. Brazier –Smith and J. F. M. Scott, "On the determination of the roots of dispersion equations by use of winding number integrals", J. Sound Vib. **145**, 503-510 (1991).
[9] K. Attenborough, "Ground parameter information for propagation modeling", J. Acoust. Soc. Am. **92** 418□427 (1992): see also R. Raspet and K. Attenborough, 'Erratum:'Ground parameter information for propagation modeling', J.Acoust. Soc. Am. 92 3007 (1992)
[10] R. Raspet and J. M. Sabatier, 'The surface impedance of grounds with exponential porosity profiles', J.Acoust.Soc. Am., **99**(1) 147 - 152 (1996)
[11] F. Coulouvrat, private communication.
[12] H. Medwin and G. L.D'Spain,"Near-grazing, low-frequency propagation over randomly rough, rigid surfaces ", J. Acoust. Soc. Am**.** **79** (6) 657-665 (1986)
[13] D.J. James and G. Kerry, "The Propagation of Blast Noise Across Acoustically Hard Surfaces", Proceeding of Internoise 2000.