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SONIC BOOMS IN SHALLOW WATER: THE INFLUENCE OF THE SEABED

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Sonic booms generated by aircraft contain a broad band of infrasonic frequencies. For example, a measured Mach 2 Concorde sonic boom spectrum shows most energy below 6 Hz, peaking at 2.5 Hz. However, this aircraft speed is subsonic relative to the speed of sound in water, and simple theory indicates that the penetration of the sonic boom from air into water is evanescent in nature. Typically, the transmitted energy is confined to depths less than several tens of metres. If the sea is shallow, then reflection at the seabed may enhance underwater sound levels, a significant effect if the seabed supports seismic interface waves with speeds coincident with the aircraft speed in the relevant frequency range. A model of sonic boom propagation is presented for the case of a shallow ocean with a layered elastic seabed, and results are compared with available experimental data.

1. INTRODUCTION

There is revived interest in aircraft-generated sonic booms and their penetration into water, largely due to concerns over environmental impact on animals. The Acoustical Society of America (ASA) held a Sonic Boom Symposium in October 1998, co-sponsored by the ASA's Physical Acoustics and Animal Bioacoustics Technical Committees. Many of the papers from the Symposium were published in a special collection of the *Journal of the Acoustical Society of America*: Sparrow [1] reviewed the previous work on sonic boom penetration underwater, including the Sawyers-Cook model, and Desharnais & Chapman [2], hereafter referred to as paper DC, presented data from a fortuitous May 1996 recording of a Concorde sonic boom on a vertical line array of hydrophones in shallow water (76 m), along with initial modelling attempts. In 1999, Sohn *et al.* [3] made underwater measurements of sonic booms in the

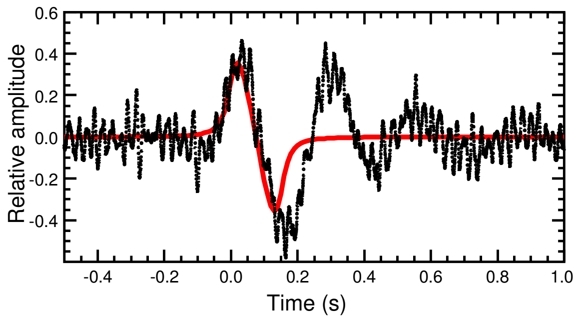

Fig. 1a: Concorde sonic boom time series recorded underwater, compared with the Sawyers-Cook model. (DC Fig. 5a)

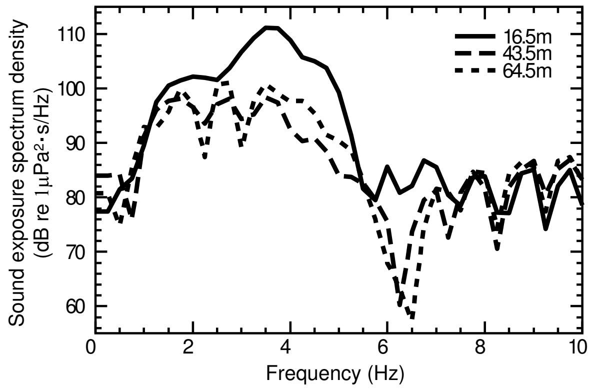

Fig. 1b: Concorde sonic boom spectrum measured at three depths. (DC Fig. 7)

upper 112 m of a deep-water location (1600 m). Recently, Cheng *et al.* [4] developed an analytic seabed-interacting model limited to homogeneous seabeds.

The DC modelling included (1) the Sawyers-Cook analytic model of propagation into an unbounded ocean; and (2) a new numerical model that includes interaction with a multi-layer elastic seabed. In this paper, we provide more insight into the latter model, including improvements made since its inception. The motivation for the work is captured in Figs. 1a and 1b (the same as DC Figs. 5a and 7, respectively) showing the Mach 2 Concorde sonic boom waveform measured at 16.5 m depth and the prediction of the Sawyers-Cook model based on the evanescent decay of an ideal "N-wave" into the ocean, along with frequency spectra at several depths. (Unfortunately, there was no in-air recording made, so the shape and spectrum of the incident pulse is not certain.)

To explain the anomalous ringing in the received waveform, DC considered the hypothesis that the very-low-frequency pulse excites a seismo-acoustic wave in the seabed, which creates a resonance in the water-borne field, illustrated schematically in Fig. 2a. The proposed mechanism is based on the fact that the sonic boom signature occupies the same frequency-speed domain as marine seismic interface waves. It is well known that the speed of the fundamental seismo-acoustic mode decreases monotonically as frequency increases, ranging from several hundreds of metres per second to several tens of metres per second, depending on the seabed type [5, 6]. The broadband sonic boom from an aircraft travelling at speed V could excite a seismic interface wave at the frequency where their speeds coincide, illustrated schematically in Figure 2b. The phenomenon would be difficult to observe if the range of interface wave speeds were narrow, e.g., for a homogeneous seabed [4].

The original DC model could not reproduce the strong secondary peak in the waveform received at shallow depths. To explain the second peak, we now propose adding a time-delayed replica of the original N-wave to the incident waveform. The revised model is a combination of multipath propagation and seismo-acoustic enhancement, as we shall see.

2. THEORY

For simplicity, we assume that the air and water layers are homogeneous and not moving. The sound speed in air is $c_a \approx 330$ m/s and in water is $c_w \approx 1500$ m/s. The density ratio $g = \rho_a / \rho_w \approx 1/800$ is small. The seabed is stratified, that is, properties depend on

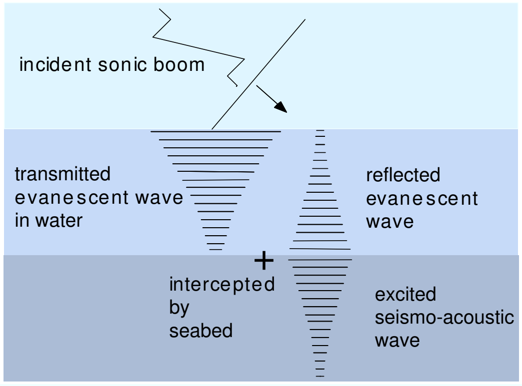

Fig. 2a: Schematic of the proposed enhancement mechanism.

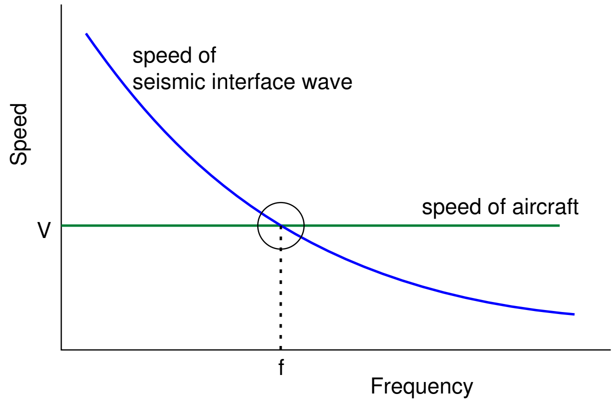

Fig. 2b: The broadband sonic boom from an aircraft travelling at speed V *could excite a seismo-acoustic interface wave at the frequency where their speeds coincide.*

depth but not on range, so that its net effect on the acoustic field in the water is encapsulated in the plane wave reflection coefficient $R(\omega, V)$, for a fixed set of geo-acoustic parameters. There exist standard means of computing $R(\omega, V)$ for an arbitrary plane wave incident from the water layer [2, 7], including the case of inhomogeneous plane waves (waves that have exponential amplitude dependence along the wavefront).

The source is in level flight above the sea surface at constant speed *V*, corresponding to Mach number $M = V / c_a$. The leading edge of the sonic boom from such a source is in fact a cone of half angle $\arcsin(1/M)$. As pointed out in DC, if the receiver is located a horizontal distance lateral to the track, the apparent direction and speed of the sonic boom are modified. The source waveform is the classic N-wave described by Sparrow [1], but the Fourier-synthesis method in DC and below is not limited to this waveform.

2.1. Fourier synthesis of transmitted fields

The incident waveform $s(t)$ is Fourier-analysed into its frequency components, yielding a frequency spectrum $S(\omega)$. The individual plane waves of frequency ω and horizontal speed V strike the sea surface, partially reflect into the air, and partially transmit into the ocean. For $M < 4.5$, the transmitted plane waves are downward-evanescent, that is, they decay as $e^{-\Gamma z}$, in which $\Gamma = \omega(1/V^2 - 1/c_w^2)^{1/2}$. In effect, this evanescent transmission acts as a low-pass filter in the frequency domain, stripping off the high-frequency components of the signal. If the ocean were unbounded, this would be the end of the story, as the frequency-domain filtering analysis has the same net result as the analytic time-domain Sawyers-Cook model [1] for the N-wave incident pulse. This simple "bottomless ocean" model is compared with experimental data in Fig. 1a. Note the rounded shoulders of the modelled N-wave at 16.5 m depth, evidence of the filtering action.

However, if the ocean has finite depth *H* that is not too deep, the bottom intercepts the transmitted field, and acoustic interaction occurs. As the water is homogeneous, there must be a reflected upward-evanescent plane wave with the same decay rate. The acoustic field (magnitude and phase) of the reflected wave at the seabed is equal to that of the downward-evanescent wave multiplied by the reflection coefficient $R(\omega,V)$. This takes care of the boundary condition on the water-borne field at the seabed. In general, the acoustic field in the water is a combination of downward- and upward-evanescent waves. The field returned to the sea surface must be included in the boundary conditions for the fields on either side of the air/water boundary, that is, continuity of pressure and z-component of velocity. Considerable simplification of the equations results from the smallness of the density ratio g, although it is easy to carry forward the equations for finite g, if desired. The calculation is straightforward, and only the results are presented here.

2.2. Model equations

In the limit $g \to 0$, the spectrum of the transmitted acoustic field in the water is

$$S_{\mathrm{trans}}(z,\omega) = S(\omega)\frac{\mathrm{e}^{-\Gamma z} + R\,\mathrm{e}^{\Gamma(z-2H)}}{1+R\,\mathrm{e}^{-2\Gamma H}} \quad , \tag{1}$$

and the time series follows from the Fourier recombination*

$$s_{\mathrm{trans}}(x,z,t) = \int_{-\infty}^{\infty} S_{\mathrm{trans}}(z,\omega)\,\mathrm{e}^{i\omega(x/V-t)}\,\mathrm{d}\omega \ . \tag{2}$$

It would appear that R only becomes important if $2|\Gamma|H$ is small, that is, for water that is sufficiently shallow. For the DC experiment, this value was of the order 8, perhaps not small enough to expect a significant difference; however, one also has to consider the magnitude of R, which can become very large in special circumstances; namely, if there exists a singularity associated with seismo-acoustic coupling between the water and the seabed, which occurs only if the seabed supports shear waves. Ultimately, it is the combined magnitude of $R\,e^{-2\Gamma H}$ that matters. (Incidentally, this does not violate energy conservation, as evanescent waves do not transport energy in the z direction.) Figs. 3a and 3b illustrate the strong dependence of the resonance in R on the shear speed profile c_{s} and the shear attenuation factor α_{s}. Except where noted, we use the DC seabed model with $c_{\mathrm{s}} = 160 z^{0.3}$ and $\alpha_{\mathrm{s}} = 1.5\,\mathrm{dB}/\lambda$.

The expected peak in the transmitted spectrum derives from the possibility that the denominator has a zero, i.e., there exists a frequency for which

$$1 + R\,\mathrm{e}^{-2\Gamma H} = 0 \,. \tag{3}$$

Ignoring the higher-speed acoustic waveguide modes that exist for $M > 4.5$, Eq. (3) has a root only if $|R| > 1$. The root, closely connected with the singularity in R, corresponds to the fundamental seismo-acoustic mode that may couple to the sonic boom.

In addition to the seabed-reflection effect, another significant alteration to the received spectrum derives from adding to the incident waveform a replica of the N-wave, delayed by

* In evaluating Eq. (2) it is important that the phase of R be conjugate-symmetric, i.e. $R(-\omega,V) = R^*(\omega,V)$, otherwise the results are unphysical. This was overlooked in paper DC.

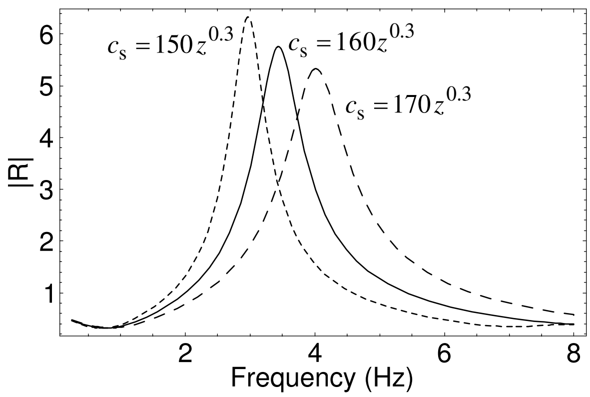

Fig. 3a: Dependence of resonance frequency on shear speed profile for a Mach 2 source.

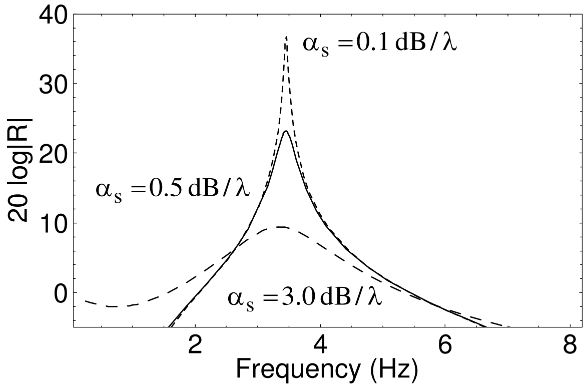

Fig. 3b: Dependence of resonance strength on shear attenuation.

β seconds with relative amplitude α. To account for this in the frequency domain, one simply multiplies the spectrum by the factor $1+\alpha\, e^{i\omega\beta}$. This has the effect of introducing a dip at $f = 1/2\beta$ and a peak at $f = 1/\beta$, the strength depending on the value of α.

3. MODELLING RESULTS

Figs. 4a and 4b show the effects of the elastic seabed on the received spectrum and time series at two different receiver depths. Note that the elastic seabed significantly enhances the spectrum at the receiver at 64.5 m (that is, 11.5 m above the seabed) and creates a ringing in the time series. This is due to the excited seismo-acoustic mode. The ringing follows the arrival of the shock (unlike the DC model, which was non-causal). The effect decreases with height above the seabed (results not shown), and is entirely absent if the seabed is fluid. Fig. 5 shows the effect of adding a replica of the N-wave to the incident pulse, delayed in time by 0.24 s, at 90% of the original strength. (These values were chosen to mimic the appearance of the experimental data.) This introduces a dip at about 2.1 Hz in all received spectra, corresponding to a strong second pulse in the received time series. Possible mechanisms for the additional pulse are multipath propagation in the atmosphere and reflection from a nearby object (such as the research vessel). Neither of these hypotheses have been explored in detail.

4. CONCLUSIONS

Two mechanisms have been proposed to explain the anomalous features in the signature of an aircraft sonic boom underwater: resonant seabed interaction and multiples of the incident N-wave. Neither mechanism by itself explains all the features of the data, yet the combined model remains inconclusive, as there are too many unknown model parameters. The lack of an in-air acoustic record hampers the analysis. The seabed-interaction model shows that the details of the proposed enhancement of the underwater sound field are strongly sensitive to both the shear speed profile and the shear attenuation in the seabed. New experiments are needed to establish if a sonic boom can indeed excite seismo-acoustic waves in shallow water, enhancing underwater sound levels. It is mandatory that such experiments include high-fidelity recording of the in-air signature and a thorough geo-acoustic survey of the site.

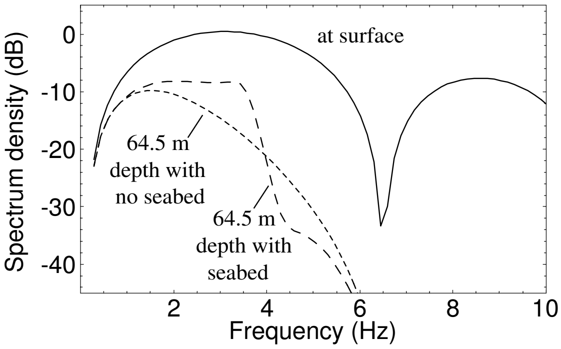

Fig. 4a: Spectrum of N-wave at surface and at 64.5 m depth, with and without a seabed at 76 m depth.

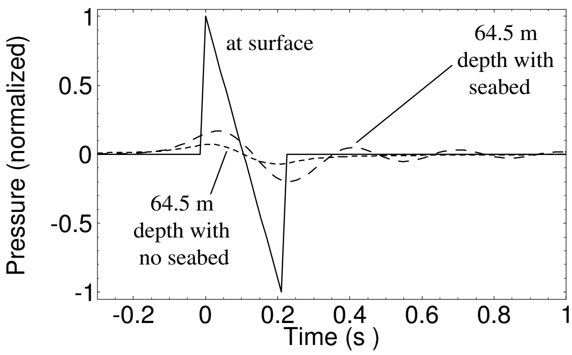

Fig. 4b: Time series of N-wave at surface and at 64.5 m depth, with and without seabed interaction.

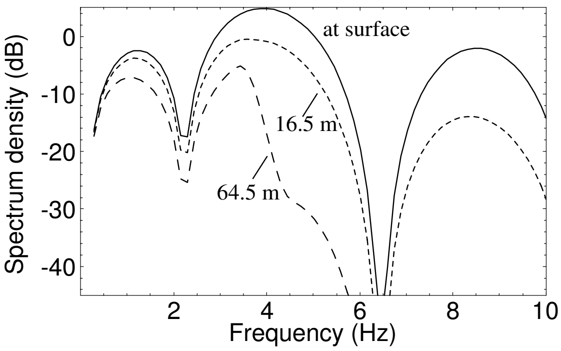

Fig. 5a: Spectrum of complex incident wave at three receiver depths.

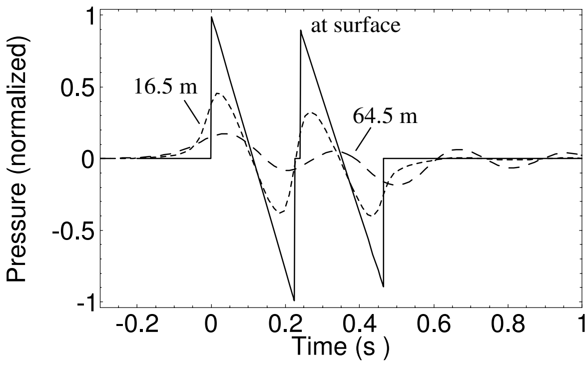

Fig. 5b: Time series of complex incident wave at three receiver depths.

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