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UNDERWATER MEASUREMENTS OF A SONIC BOOM

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# UNDERWATER MEASUREMENTS OF A SONIC BOOM

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*Abstract* - **During a sea trial on the Scotian Shelf, acoustic signals from an unexpected sonic boom were recorded on several hydrophones of a vertical array. The array spanned the lower 50 m of the water column above a sand bank at 76 m water depth. Based on the event time and location, the source of the sonic boom was deduced to be a Concorde supersonic airliner in transit between Paris and New York, travelling at about Mach 2 (roughly 600 m/s). The air-borne sonic boom was heard on the deck of the research vessel during a routine collection of ocean ambient noise samples; the water-borne sonic boom was recovered later during playback of the recording tape for that sample. The horizontal speed of a sonic boom waveform — which matches the aircraft speed — is lower than the speed of sound in the water if the aircraft speed is below about Mach 4.4; the associated water-borne waveform is expected to decay as an evanescent wave below the sea surface. This decay of the amplitude of the waveform is observed along the array. The very calm weather resulted in low ambient noise and low self-noise at the hydrophones, resulting in good signal-to-noise ratio on the upper hydrophones; however, the decreased signal amplitude is more difficult to detect towards the lower part of the water column. The period of the observed waveform is of the order 0.16 s, corresponding to a peak frequency of about 6 Hz. The shape of the measured waveform differs slightly from the theoretical N-shape waveform predicted with Sawyers theory [J. Acoust. Soc. Am. 44, 523-524 (1968)]; this is possibly due to propagation effects caused by seismo-acoustic interaction of the infrasonic waves with the sediments underlying the water mass.**

## I. INTRODUCTION

It was the perfect underwater ambient noise experiment. A vertical array of hydrophones was deployed in a shallow water area, and covered a large part of the water column. The weather was collaborating, with low winds and calm seas. For maximum quietness in the water, all non-essential machinery on the ship was turned off. And the recording equipment was working fine... An Air France Concorde flew north of the experimental site on its way to New York from Paris. A perfect ambient noise sample was suddenly enriched with a perfect sonic boom.

To eliminate the sonic boom impact on people, supersonic commercial aircraft center their high-speed activities over water. As a consequence, a renewed interest on underwater sonic boom propagation is seen in the literature [1-4]. Although it is recognized that the audible noise from a sonic boom is not appreciable at depths deeper than 30-40 m [3,5], this shallow layer is inhabited by a large number of marine species, including whales. Therefore, it is important to understand the impact of supersonic flight over coastal areas.

Very few underwater measurements are available in the literature. The scaled measurements of Waters with dynamite caps as a source [5] are a standard reference. Malcolm and Intrieri [6,7] have also made scaled-measurements using gun-launched small cone-cylinder models with similar results. Young [8] measured sonic booms from a diving F-8 aircraft during a full-scale experiment, but the observed waveforms were strangely complicated. It is believed that the data set presented in this paper will complement what is already found in the literature.

The following section reviews the sonic boom basics, and discusses the underwater propagation of the sonic boom. The measurements are presented next, along with a full description of the experiment. Some modelling of the measured waveforms is also presented.

## II. SONIC BOOM PROPAGATION

The propagation in air of a sonic boom is a well-known and well-documented phenomenon. As the aircraft reaches and overtakes the speed of sound in air, the overpressure disturbance called the sonic boom propagates along a cone-shaped trajectory originating at the aircraft and travelling at the same speed as the aircraft (Fig. 1). The intersection of the Mach cone with land, or in our case with the sea surface, is a one-sided hyperbola (dashed line in Fig. 1) also travelling at the supersonic speed of the aircraft.

The pressure signal as a function of time along the hyperbola approximates an N-shaped waveform at the earth's surface (Fig. 1). The duration $T$ of the sonic boom is related to the aircraft speed $V$. This duration can be approximated with linear theory as $T=L/V$, where $L$ is the length of the aircraft. To accurately determine the duration, however, non-linear effects have to be taken into account. Pierce [9] and Maglieri and Plotkin [10] have shown that the following relationship can be used accurately:

$$T = k\frac{M}{(M^2-1)^{3/8}} \tag{1}$$

where $M$ is the Mach speed of the aircraft (or speed of the aircraft/speed of sound in air) and $k$ is a constant related to the aircraft shape, altitude and other physical parameters. The duration is typically of the order of 100 ms for a commercial supersonic aircraft.

At the sea surface, the airborne wave faces a large impedance contrast, as the speed of sound in water is closer to 1500 m/s. If the speed of the aircraft is less than the speed of sound in water (or approximately Mach 4.4 if the sound speed in air is taken as 343 m/s), the sonic boom is totally reflected by the sea surface for incident angles (normal to the sea surface) less than 13.1° [arcsin(1/4.4)]. The Air France Concorde travels between Paris and New York at a cruise speed of Mach 2 (at an altitude of approximately 18,000 m). The associated sonic boom has an incident angle of 30°, implying that a total reflection of the sonic boom occurs at the sea surface.

In the water, the acoustic field is an evanescent or inhomogeneous plane wave that propagates horizontally but decays exponentially with depth. (This field is necessary to satisfy the condition that the acoustic pressure is continuous across the interface.) The decay is frequency dependent: the lower frequencies penetrate deeper than the higher frequencies.

The first theory to explain the sonic boom penetration in the water was published by Sawyers [11]. The theory was later refined by Cook [12], but the modifications were estimated to be probably too small to be experimentally measured. Sawyers's theory will therefore be used in this paper to model the experimental data. It expresses the pressure $p$ of the sonic boom waveform as a function of depth with the following equation:

$$\pi\frac{p}{p_{surface}} = (2\tau+2\xi-1)\left[\tan^{-1}\left(\frac{\tau-\xi-1}{\zeta}\right)-\tan^{-1}\left(\frac{\tau-\xi}{\zeta}\right)\right] + \zeta\log\left[\frac{\zeta^2+(\tau-\xi)^2}{\zeta^2+(\tau-\xi-1)^2}\right] \quad (2)$$

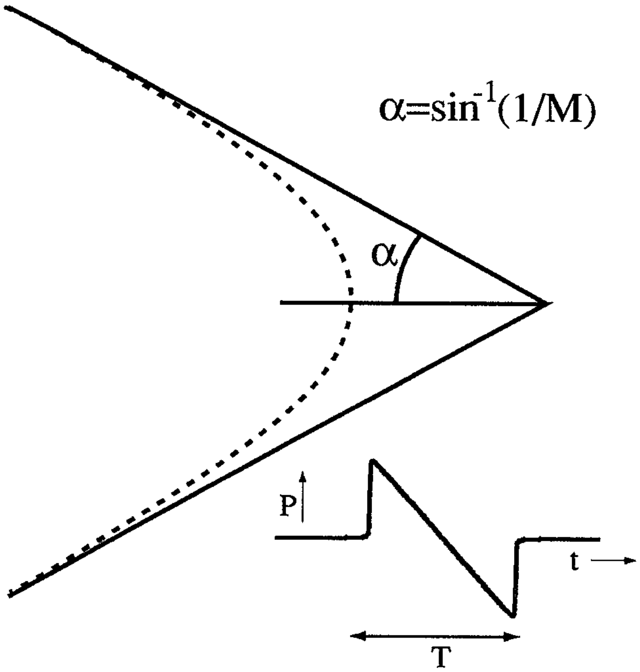

*Fig. 1. Top view of a Mach cone. The dashed line represents the intersection with the sea surface. The lower design represents an N-shaped sonic boom waveform.*

where $p_{surface}$ is the reference pressure at the sea surface. The nondimensionalized parameters of (2) are defined as:

$$\tau = \frac{t}{T} \quad (3)$$

$$\zeta = \frac{z}{m \cdot T} \quad (4)$$

$$\xi = \frac{x}{T \cdot V} \quad (5)$$

$$m = \frac{V}{(1-V^2/c^2)^{1/2}} \quad (6)$$

where $t$ is the time (s), $z$ the depth (m), $x$ the horizontal distance (m) in the direction the sonic boom is travelling [i.e. the boom arrives at $(x,z)=(0,0)$ at $t=0$], $V$ is the aircraft speed and $c$ is the sound speed in water (m/s). Sawyers' theory assumes the ocean's surface to be flat, and does not account for bottom reflections (deep water).

Although (2) was derived with the simplifying assumption that the source of the sonic boom passes directly overhead at Mach number $M$, it is easily generalized to the case of an observation point away from the source track. If the source is at height $h$ and the observation point is a horizontal distance $y$ from the projection of the source track on the sea surface, then the track elevation angle $\theta$ is given by

$$\tan\theta = \frac{h}{y}. \quad (7)$$

The Mach cone may still be viewed as locally plane at the observation point, but the local angle of incidence $\alpha'$ is given by

$$\sin\alpha' = \frac{1}{M}\sqrt{1+(M^2-1)\cos^2\theta}\,. \quad (8)$$

Off-track, the sonic boom is not travelling parallel to the source track, but in a direction forming the angle $\phi$ with the source track, where

$$\tan\phi = \sqrt{M^2-1}\cdot\cos\theta. \quad (9)$$

Also, the local horizontal speed of the sonic boom is not $M$, but $M'$, where

$$M' = M\cos\phi = \frac{M}{\sqrt{1+(M^2-1)\cos^2\theta}}. \quad (10)$$

In summary, Sawyers' 2-D theory still applies, but we must interpret $\alpha$ and $M$ as local effective quantities.

## III. MEASUREMENTS

The underwater acoustic measurements were taken in a shallow water area on the Scotian Shelf (Fig. 2). The sonic boom was heard from the deck of the ship at 9:17 AST on 28 May 1996. This time corresponds to the approximate time of passage of the Air France Concorde flying from Paris to New York (JFK airport). The dark grey line in Fig. 2 represents an estimate of the Concorde path; the actual path is unknown. The typical cruise speed of the Concorde is Mach 2.02 at an altitude of 18288 m. It

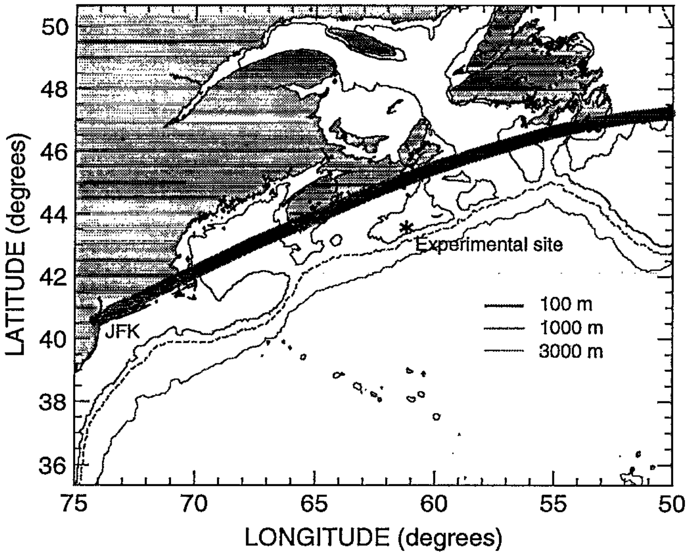

*Fig. 2. Experimental area south of Nova Scotia. The dark grey zone represents the estimated trajectory of the Concorde.*

should be mentioned that the Concorde may have already started its descent when it overflew the area north of the experimental site. The altitude and speed of the Concorde at the measurement time are therefore not known with precision.

The exact location of the experimental site is 43°27.6' N 61°17.2' W. The water depth at this location is 76 m, over a sand bottom. The bottom properties are well-known for this general area and can be found in [13]. The sound speed profile at the site is shown in Fig. 3; the measurement was made with an expendable bathy-thermograph probe deployed at 8:08 AST on the same date. The weather was calm with a sea state of 1, 0.25 m swell (from 280°) and winds at 10 kn.

The data were collected with a vertical line array of 11 functioning hydrophones from 16.5 m to 65 m depth. The spacing between the elements of the array varied between 0.9 and 9.5 m. The array was deployed independently from the ship, which was approximately 2.6 km away when the sonic boom was heard.

Examples of the recorded data are shown in Fig. 4 for the three hydrophone depths of 16.5, 33 and 57 m (dotted lines). The relative time is in seconds [time 0 corresponds to 9:17:36 AST (28 May 1996)] and the same relative shift was applied for the three hydrophones. The amplitude is also relative: 0.6 relative units corresponds to 1.909 Pa in calibrated units. The original sampling frequency of the data is 2048 Hz. The data in Fig. 4 were smoothed with a 0.0122 s (25 points) moving average window to accentuate some of the features in the data, especially for the deeper hydrophones with a much lower signal-to-noise ratio. The solid lines in Fig. 4 represent modelling results which are discussed in the following section - they represent the modelled N-shaped waveform of the sonic boom for an underwater sensor.

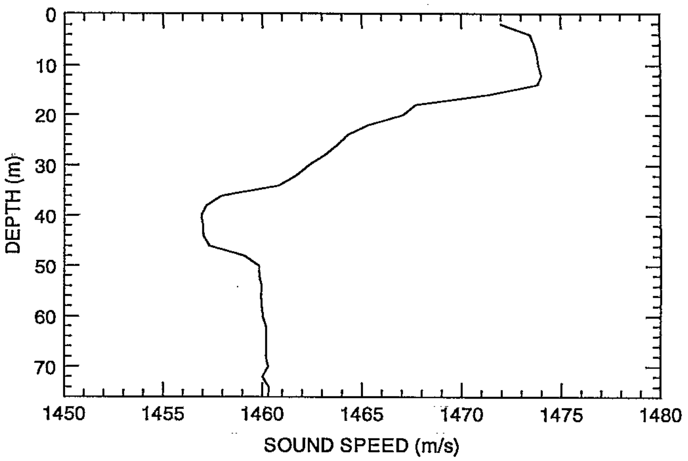

*Fig. 3. Sound speed profile as a function of depth, at the experimental site.*

The most striking feature in the data is the oscillation that follows the first N-shaped waveform. This oscillation is present at all depths (a longer moving average window would bring this out more clearly for the deeper hydrophones). The frequency of this oscillation is difficult to estimate since the moving average has the effect of smearing the waveform. At shallower depth, where the signal-to-noise ratio of the data is higher, the period can be estimated at 0.27 s. The duration of the sonic boom is qualitatively the same at all depths.

The amplitude decreases with depth, as experimentally observed with the scaled experiments of [5-7]. The actual rate of decline as a function of depth is difficult to quantify since the experimental peak fluctuates largely with the background noise. Instead of using the peak, we decided to estimate the total energy content (broadband) of the sonic boom by integrating the square amplitude of the signal for a period of 7 s more or less centered on the sonic boom. This broadband rate of decay as a function of depth is shown in Fig. 5 (circles). A noise level was estimated over a 1-s period preceding the sonic boom, and subtracted from the signal level. In Fig. 5, the units have been multiplied by a relative factor to be comparable with the modelling results (solid line) which are discussed in the following section.

## IV. MODELLING

The time series for each hydrophone was modelled using Sawyers' theory introduced in Section 11. The main variables of (2) are:

- the depth in the water;
- the sound speed in the water (taken here as 1470 m/s);
- the speed of the aircraft;
- the duration of the sonic boom, and
- the horizontal distance between the aircraft and the measurement site.

The first two variables of this list are known. The next two variables were estimated with a curve fitting algorithm, assuming

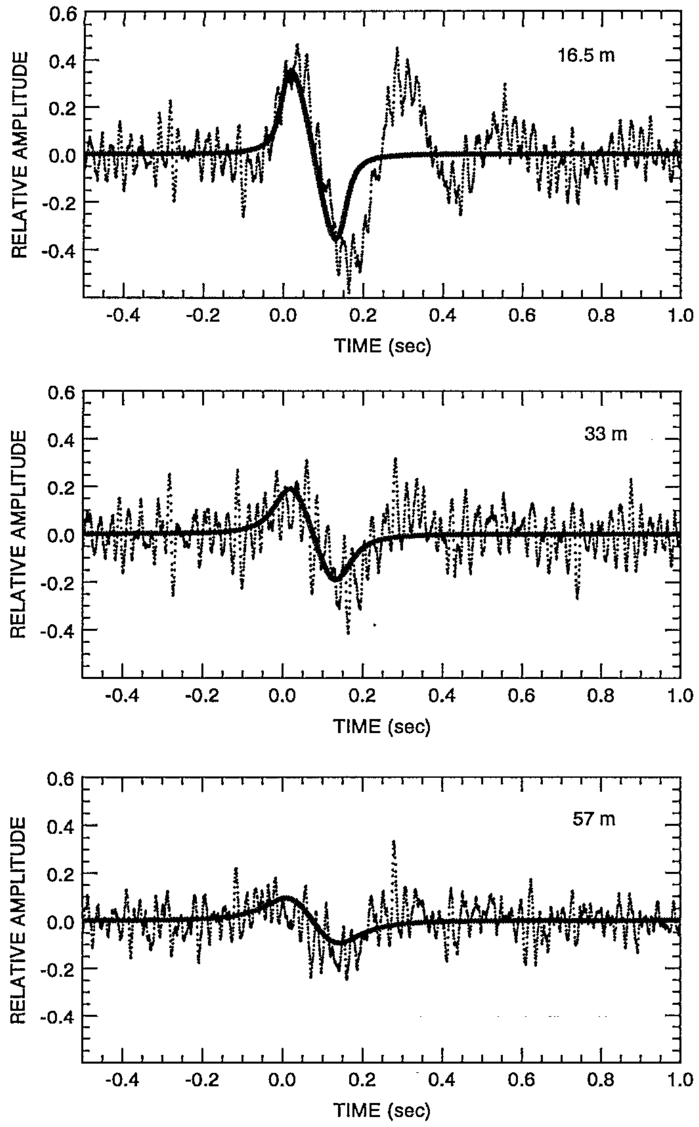

*Fig. 4. Sonic boom data (dotted lines) and model (solid lines) for receivers at 16.5, 33 and 57 m depth. The vertical scale is relative: 0.6 relative units correspond to 1.909 Pa for the data; the model amplitude is relative to the pressure at the sea surface.*

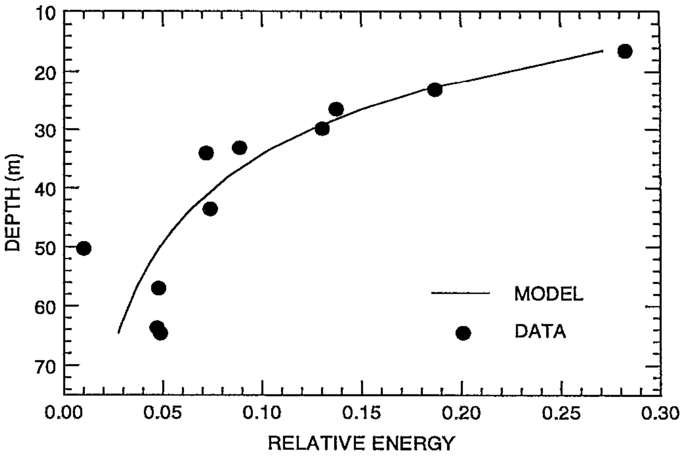

*Fig. 5. Relative energy (normalized to the sea surface) as a function of depth; solid line: model; circles: data.*

a horizontal distance of 0 m. This last assumption has the effect of decreasing the estimated speed of the aircraft, since the speed of the sonic boom is slightly lower off-center of the contact hyperbola at the sea surface.

Using the upper hydrophones' data with a higher signal-to-noise ratio, we estimated an aircraft speed of 600 m/s (Mach 1.75) and a boom duration of nearly 0.18 s. Using the full set of hydrophones, the estimated aircraft speed is 670 m/s (Mach 2) and the duration 0.16. Both speed estimates are believable for what we know of the typical Concorde cruising speed, although the lower bound is more probable due to the horizontal separation between the aircraft and the site. Using the linear theory to estimate the duration of the sonic boom, we obtain a duration of the order of 0.1 s for an aircraft length of 62 m. The non-linear theory cannot be used since we do not know the experimental factor $k$ for the Concorde. Using (1) for the calculated range of durations $T$, we estimate $k$ to be 0.12-0.13. For a comparison, a $k$ of 0.1483 was used for an SR-71 aircraft travelling at Mach 2.6 at 20 km altitude in [1].

For a comparison with the data, the model results obtained with a speed of Mach 2 and a sonic boom duration of 0.16 s are shown in Fig. 4 for three different hydrophone depths. The data were multiplied by an arbitrary factor to optimize the fit with the model. This procedure had to be used since we do not know the signal pressure at the sea surface ($p_0$) due to the lack of a sensor at shallow depth.

The model fits the data better for the lower hydrophones than for the upper hydrophones. The misfit for the upper hydrophones is due to the boom duration which seems too short in the model. However, it is difficult to judge how the original N-shaped waveform is modified by the oscillation following it. The amplitude of the signal, however, fits equally well at all depths, suggesting that the correction factor used on the data was reasonable.

The rate of decay with depth was estimated for the model the same way as for the data. Since the amplitude is normalized to the surface [as we don't know $p_0$ in (2)], the total energy is normalized the same way (energy=1 at the surface). The results are shown in Fig. 5. The model fits this feature of the data very well.

## V. DISCUSSION

A major feature of the data from all hydrophones is a marked oscillation following the expected N waveform. Such a feature was not observed in the scaled experiments of [5] and [6], nor in the full-scale data of Young [8].

This last feature cannot be explained by reflections from the ship at the sea surface, which might have been a problem if the ship had been closer to the array. Similarly, reflections from the seafloor could not be great enough in amplitude to have the large effect seen on the upper hydrophones, considering the exponential decay of the sonic boom amplitude. Also, the wavelength of the sea surface waves was too small to interact with the sonic boom of a much greater length [3].

It is possible that the ringing observed in the sonic boom is due to the excitation of a low-frequency seismic mode at the ocean/seabed boundary. Preliminary modelling has shown that the sonic boom has the appropriate frequency content and phase speed to match such a mode, and the water depth is shallow enough for the evanescent wave to penetrate the layer. Also, the observed ringing is reminiscent of similar effects seen in land-based seismometers responding to sonic booms [14]. To explore this hypothesis, further modelling is required, including time-domain synthesis of wave trains.

## VI. CONCLUSIONS

A sonic boom that originated from a supersonic Concorde aircraft was observed on all hydrophones of a linear array located in shallow water. The evanescent N-shaped waveform was recognizable in the water, with the typical exponential decay of the amplitude with depth. The first part of the observed waveform was modelled successfully using Sawyers' theory.

The waveform was following by some oscillations, of a type not previously reported in the literature. The nature of these oscillations is not confirmed, but they could be due to the excitation of a low-frequency seismic mode at the ocean/seabed boundary. This phenomenon would restrict the observations of these ringing events to shallow water areas over shear supporting seabeds.

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