Sound from a Light Aircraft for Underwater Acoustics Experiments?

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Summary
A series of ocean-acoustics experiments using a single-engine, light aircraft as the source of sound has been performed about 1.5 km off the coast of La Jolla, California. A microphone monitored the sound of the aircraft above the surface and a vertical array of hydrophones received the acoustic signals in the ocean. Some preliminary findings from these experiments are reported and the prospects for light-aircraft as sound sources in ocean-acoustic inversion techniques are discussed.

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1. Introduction

Although sound from fixed- and rotary-wing aircraft is known to penetrate through the atmosphere–ocean interface [1, 2, 3], few of the previously reported underwater measurements of aircraft acoustic signatures relate to fixed-wing light aircraft with a single piston-engine. Such aircraft are the backbone of general aviation and are commonly used by flying clubs around the world. The sound from a light aircraft is mainly due to the propeller, with a lesser contribution from the engine, associated with the piston firing rate.

As discussed by Goldstein [4], a theoretical description of the far-field pressure from an aircraft propeller was developed by Gutin [5]; and subsequently the theory was extended to include near-field effects [6]. For the purpose of the present discussion, however, it is sufficient to recognize that the propeller produces a fundamental tone at a frequency given by the expression

$$f_{\rm blade} = \frac{BR}{60} \quad \text{Hz}, \tag{1}$$

where B is the number of blades, R is the rpm of the engine, and it is assumed that there is a direct drive from the crankshaft to the propeller, as is the case in most light aircraft. In addition to the fundamental, harmonics appear in the acoustic signature of the propeller at multiples of the fundamental frequency.

According to equation (1), the fundamental frequency of the propeller noise from an aircraft with a two-bladed propeller ($B = 2$) operating at $R = 2500$ rpm is 83.3 Hz, with harmonics at 166.7 Hz, 250 Hz, and so on. The harmonic structure may be observed up to 1 kHz or so, depending on propagation conditions in the atmosphere and flight factors such as aircraft altitude.

The low-frequency region of the acoustic spectrum that is spanned by aircraft propeller noise, say from 50 Hz to 1 kHz, is of interest in connection with measurements of the geo-acoustic properties of marine sediments [7]. Conventionally, an acoustic inversion for the sea-bed parameters is performed using a receiving array of hydrophones and a submerged source.

An alternative approach is to use a light aircraft as the source of low-frequency, broadband sound in underwater acoustics applications. Some of the acoustic energy produced by the aircraft will penetrate into the ocean, to arrive at the receiver via various underwater propagation paths. Since several of these arrivals will have experienced bottom reflections, the potential exists for obtaining the geo-acoustic and bathymetric properties of the sea bed from appropriate inversion procedures.

2. Aircraft Experiments at SIO

A series of experiments is currently being conducted off La Jolla in California, north-west of Scripps pier (32° 53.8′ N, 117° 16.1′ W) in which the sound from a Tobago TB10 single-engine, fixed-wing aircraft with a two-bladed, variable pitch propeller is being monitored with a microphone about 1 m above the sea surface and a vertical array of hydrophones suspended below. This aircraft has a Lycoming four-cylinder, 180 hp engine. Timing and flight data (latitude, longitude and altitude) are continuously recorded with a GPS containing a pressure sensor

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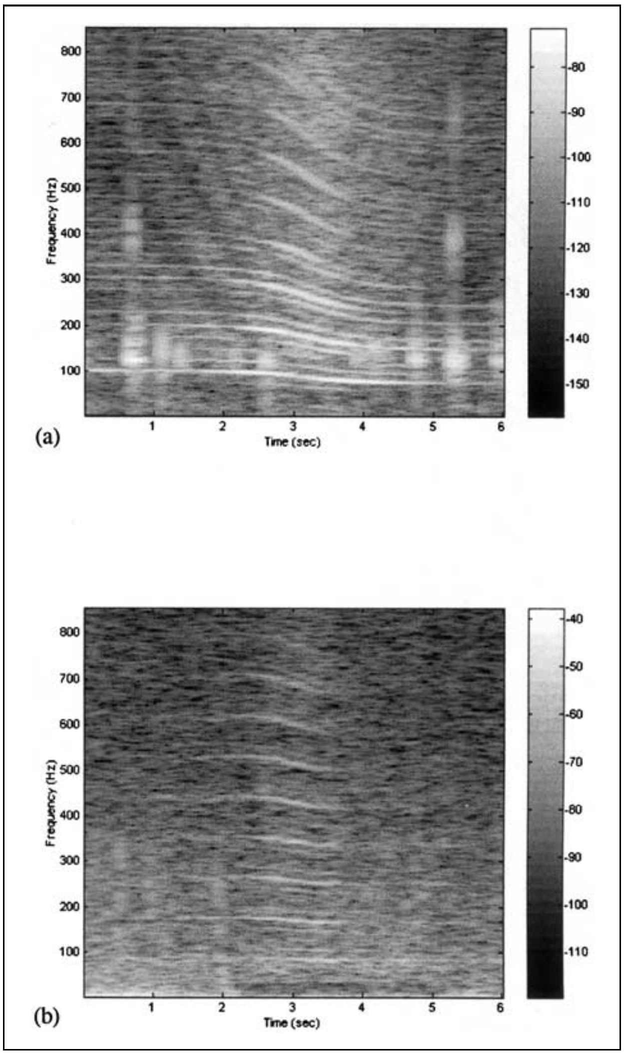

Figure 1. Spectrograms (2.4 Hz resolution) from an overflight of the tobago travelling at a speed of 53 m/s, an altitude of 66 m and with the engine operating at 2500 rpm. (a) Airborne signal from microphone 1 m above the sea surface. (b) Underwater signal from hydrophone 13 m beneath surface. Grey scales are uncalibrated dB.

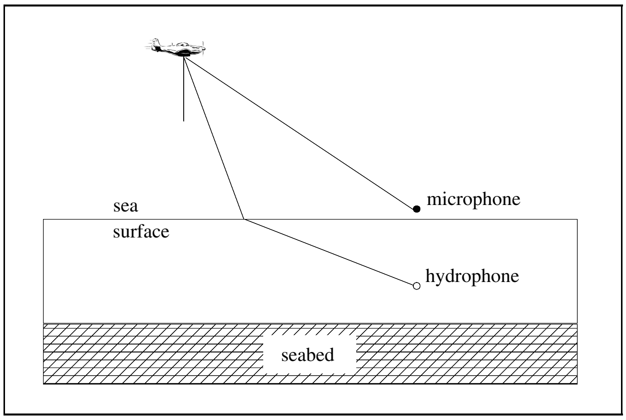

Figure 2. Direct ray paths to the microphone and hydrophone.

(for accurate altimetry data), which is calibrated before each flight.

Examples of the airborne and water-borne arrivals from an overflight of the Tobago, as recorded on 22 May 2002, are shown in Figure 1. The aircraft was flying at a speed of 53 m/s, an altitude of 66 m, with the engine operating at 2500 rpm, which produced a fundamental blade-rate of 83.3 Hz and harmonics at multiples of this frequency.

In Figure 1, the harmonic structure is clearly discernable underwater as well as in air. In both cases, the harmonics appear as a series of uniformly spaced lines extending up to about 1 kHz. A sub-harmonic structure, in the form of three equi-spaced lines between the main harmonics, is also visible in the microphone and hydrophone signatures, which may be due to slight differences in the acoustic amplitudes from the cylinder firings.

Above and below the sea surface, a significant Doppler shift is evident in the spectrograms of Figure 1: a downshift in frequency occurs as the aircraft overflies the receiving station. For a given harmonic, however, the frequency difference between approach and departure is less underwater than it is in air. This simple observation relates to the physics of acoustic transmission through the air-sea interface.

According to Snell's law, the critical angle for air-to-water sound transmission, assuming a smooth interface, is $\theta_c \approx 13°$. At greater angles of incidence, total reflection from the surface occurs, in which case no sound will penetrate into the ocean. Referring to Figure 2, it can be seen that a direct-path ray arriving at the hydrophone is launched from the aircraft at a steeper angle than a direct, airborne arrival at the microphone. The different launch angles of these two rays accounts for the lower Doppler shift of the underwater signals.

If θ is the angle of incidence of a ray launched from the aircraft, the Doppler-shifted frequency is [8]

$$f_D = \frac{f}{1 - \frac{v}{c_a} \sin\theta} \quad \text{Hz}, \tag{2}$$

where f is the unshifted frequency, v is the speed of the aircraft and c_a is the speed of sound in air. For the airborne arrivals, $0 \leq |\theta| \leq 2\pi$; but for the underwater arrivals, $0 \leq |\theta| \leq \theta_c$. Thus, from equation (2), bearing in mind that $v/c_a \ll 1$, the maximum Doppler shift between approach and departure on the underwater arrivals is

$$\Delta f_{Dw} = \Delta f_{Da} \sin\theta_c, \tag{3}$$

where $\Delta f_{Da} = 2vf/c_a$ is the maximum Doppler difference between airborne arrivals. Taking the critical angle of the air-sea interface as 13°, the underwater arrivals should be Doppler shifted by a factor of 0.22 less than those in air. This is consistent with the different Doppler shifts in the spectrograms of Figure 1. The cone angle of the penetration regime could exceed the critical angle, θ_c, if surface roughness were significant, as discussed by Lubard and Hurdle [9].

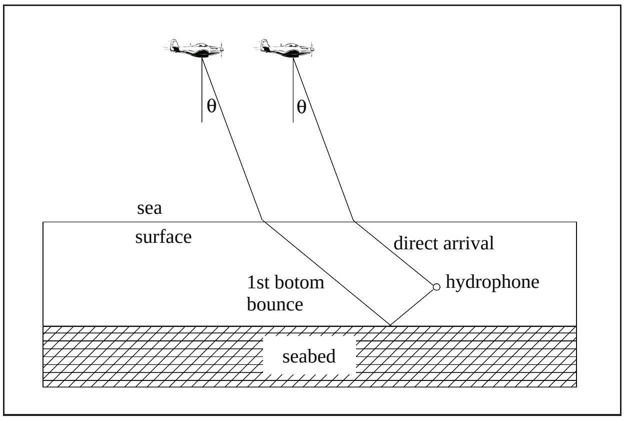

Figure 3. Direct and first bottom-bounce arrivals at the hydrophone.

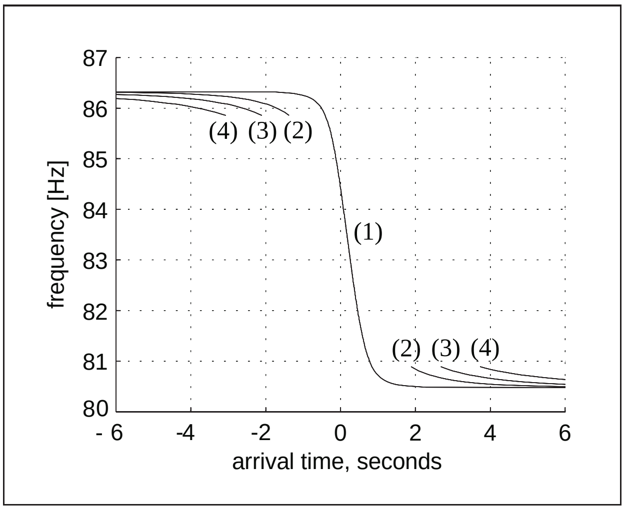

Figure 4. Ray arrivals for the blade-rate fundamental as a function of time: (1) direct; (2) one bottom-bounce; (3) bottom-surface bounce; (4) bottom-surface-bottom bounce.

3. Ray Structure at the Hydrophone

In shallow water, each of the harmonics detected by the hydrophone is a superposition of multipath arrivals, as illustrated in Figure 3, which shows just the direct and single bottom-bounce paths. In this example, two rays have been selected which have the same Doppler shift (i.e., launch angle). From the geometry in Figure 3, it is clear that the bottom-bounce signal is launched before the direct path, and that these two rays will arrive at the receiver at different times.

Moreover, as the aircraft closes on the receiver station, both rays will become steeper. Assuming a fast bottom, the seawater-sediment interface shows a critical angle, which is typically in the region of 30°. When the angle of incidence of the bottom-bounce ray falls below this critical angle, total reflection no longer occurs and the ray will penetrate into the sediment. Therefore, as the aircraft approaches the sensor, the various bottom bounce arrivals will drop out of the hydrophone record, to re-appear symmetrically during departure.

Figure 4 shows an expanded frequency-time plot of several ray arrivals at the blade-rate frequency. These curves were computed using the following parameters: aircraft altitude, 66 m, and speed, 53 m/s; hydrophone depth, 13 m; channel depth, 30 m; sound speed in air, 340 m/s, in seawater, 1500 m/s, and in sediment, 1780 m/s; unshifted frequency, 83.3 Hz. The gaps in the three curves involving bottom reflections span the times when the associated rays are so steep that they penetrate the bottom and thus fail to reach the hydrophone.

The various array paths in Figure 4 may be used to determine the geo-acoustic and bathymetric properties of the sea bed. This could be achieved in several ways. For instance, with two or more vertically aligned hydrophones, the downward-traveling direct and surface-reflected rays could be nulled out, leaving the first bottom-bounce ray as the principal component of each harmonic. The times at which this ray disappears and then re-appears in the acoustic record provide a measure of the critical angle of the bottom. Once the critical angle has been determined, the sound speed of the sediment can be deduced from Snell's law, assuming that the sound speed in the water is known. Such a technique could be augmented by exploiting the correlations that exist between sediment parameters, e.g., the sound speed and porosity [10, 11, 12].

4. Concluding remarks

The preliminary experiments conducted recently at SIO indicate that a light aircraft shows promise as a source of sound for ocean acoustics applications. Good quality acoustic data have been collected above and below the sea surface. These data sets indicate that it may be possible to perform inversions of the aircraft sound to obtain the geo-acoustic and bathymetric properties of the ocean channel.

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