Chapter #

INVERSION OF THE PROPELLER HARMONICS FROM A LIGHT AIRCRAFT FOR THE GEOACOUSTIC PROPERTIES OF MARINE SEDIMENTS

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Abstract: In a recent series of experiments, the sound from a light aircraft flying over a shallow ocean channel was detected on acoustic sensors in the atmosphere, throughout the water column and buried in the sediment. The predominant feature of the sound signature is a series of propeller harmonics extending over the frequency range from about 100 to 800 Hz. As the aircraft flies over the sensor station, a significant Doppler-downshift in the frequency of a given harmonic occurs. The difference in the Doppler-shifted frequency on approach and departure provides the basis of a technique for estimating the speed of sound in the sea bed. Once the sound speed is known, the remaining geoacoustic parameters of the sediment may be determined from the correlations that are known to exist between them.

Key words: propeller harmonics, aircraft noise, geoacoustic inversion, sediment, shallow water

1. INTRODUCTION

It has been known for many years, from the observations of Urick[1], Medwin *et al.*[2] and Richardson *et al.*[3], that the sound from large, fixedwing, multi-engine propeller aircraft (e.g., Lockheed Orion P-3C, de Havilland Twin Otter) is detectable beneath the ocean surface. Recently at SIO, experiments have been performed with a single-engine, propeller-driven light aircraft to establish whether the sound from such an airborne source could form the basis of shallow-water inversion techniques for recovering the geoacoustic properties of the seabed. The first trial flights, using a Socata Tobago TB 10 (2-blade propeller, 180-shp) flying at a speed of 106 knots (53 m/s) and altitude of 66 m, were made during mid-2002 over the Pacific Ocean, about 1 km off the shoreline between Del Mar and La Jolla, southern California. These were followed by a second set of experiments at the same location in September and October 2003 using two aircraft, a Diamond Star DA40 (3-blade propeller, 180-shp) flying at 120 knots (60 m/s), altitude 66 m, and a Cessna 172 (2-blade propeller, 180-shp) at 106 knots, altitude 100m.

In all cases, the sound from the propeller was detected by a microphone mounted just above the sea surface, hydrophones distributed vertically throughout the 15 m deep water column, and hydrophones buried about 1 m deep in the sediment. The bandwidth of the received signals extends upwards from about 100 Hz, depending on the aircraft, to about 800 Hz. The signals themselves take the form of a series of narrow harmonics, each showing a pronounced Doppler down-shift in frequency as the aircraft overflies the sensor station. The harmonics received on the sensors in the water column and buried in the seabed can be inverted to obtain the sound speed and attenuation in the sediment. There is also potential for obtaining the near-normal incidence reflection coefficient of the seabed from the water column sensors, which, if successful, would return the density and hence the porosity of the sediment.

2. PROPELLER SOUND

The sound from a light aircraft, generated mainly by the propeller, is periodic but not sinusoidal. It follows from elementary Fourier analysis that the acoustic signal consists of a fundamental tone with a sequence of harmonics at multiples of the fundamental. The frequency of the fundamental, or first harmonic, is equal to the speed of the engine, usually expressed in revolutions per minute (rpm), times the number of propeller blades, N. Thus, when expressed in cycles per second, the frequency of the fundamental is

$$f_1 = \frac{(rpm) \times N}{60} \quad \text{Hz}, \tag{1}$$

where it is assumed that the propeller is driven directly off the engine, as is usually the case with light aircraft. For an engine turning over at 2000 rpm and driving a three-blade propeller, the fundamental frequency is 100 Hz, with harmonics at 200, 300, ..., Hz.

An example of the power spectrum of the sound from a light aircraft, a Diamond Star DA40 with a three-blade propeller, is shown in Fig. #-1. In this case, the aircraft was stationary on the ground, with the engine running at 2000 rpm. The microphone was a few centimeters above the ground on the port side, in the plane of the propeller, at a horizontal distance of 10 m from the spinner. The propeller harmonics are clearly visible up to a frequency of 2 kHz. Below 1 kHz, additional spectral lines are present, associated with the firing rate of the engine.

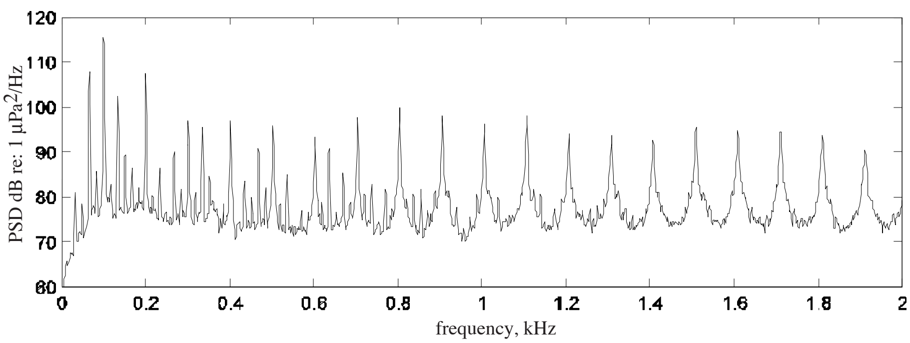

Figure #-1. Spectrum of static DA40.

Under similar experimental conditions, the horizontal directionality of the sound from the aircraft was measured through a quadrant extending from the plane of the propeller on the port side of the aircraft to the axis of the spinner. In Fig. #-2, showing the aspect dependence of the first propeller harmonic and the first engine harmonic, it can be seen that the intensity of both harmonic lines varies only weakly throughout the angular range.

3. DOPPLER SHIFTS

In the experiments conducted a couple of kilometers north of Scripps pier, the sensor station was about 1 km offshore, where the water depth is nominally 15 m. A microphone was located approximately 1 m above the sea surface, a vertical array of 11 non-uniformly spaced hydrophones spanned the water column, and three hydrophones were buried in the sediment at various depths down to 1 m. The aircraft passed directly over the sensor station in straight, level flight at a nominal altitude of 66 m, and was detected on the sensors in all three layers, that is, the atmosphere, the water column and the sediment.

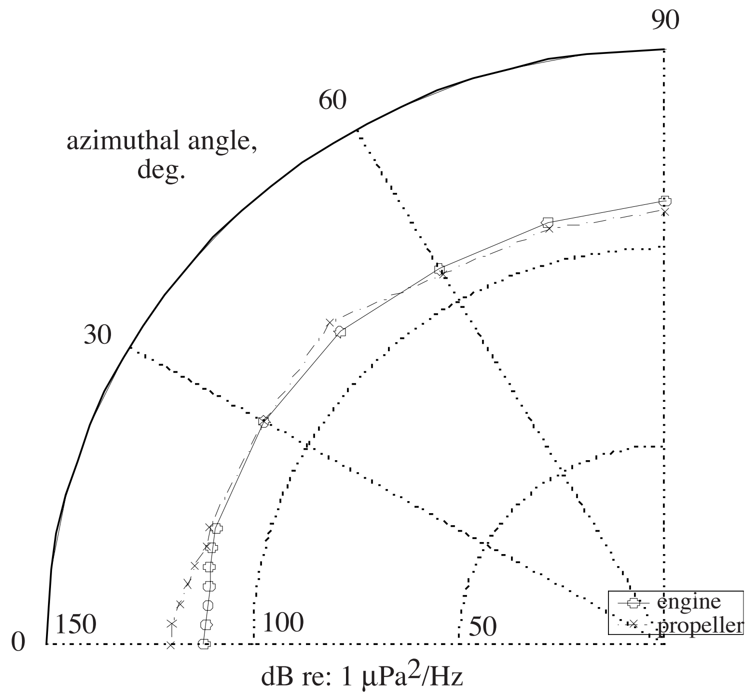

Figure #-2. Aspect dependence of first propeller and engine harmonics.

On the approach to the sensor station, the frequency of any given harmonic is Doppler-upshifted and on departure it is downshifted. This behavior is illustrated in the spectrograms of Fig. #-3, which show the acoustic signature of a Diamond Star DA40 aircraft, as recorded on the microphone in the air, a hydrophone near the bottom of the water column, and a hydrophone buried to a depth of approximately 0.5 m in the sediment. In this case, the aircraft was flying at 120 knots (60 m/s) and the engine was turning over at 2400 rpm. The propeller harmonics are detectable in the water column and the sediment for about ten seconds on either side of the zenith, which translates into a detection range of about 600 m.

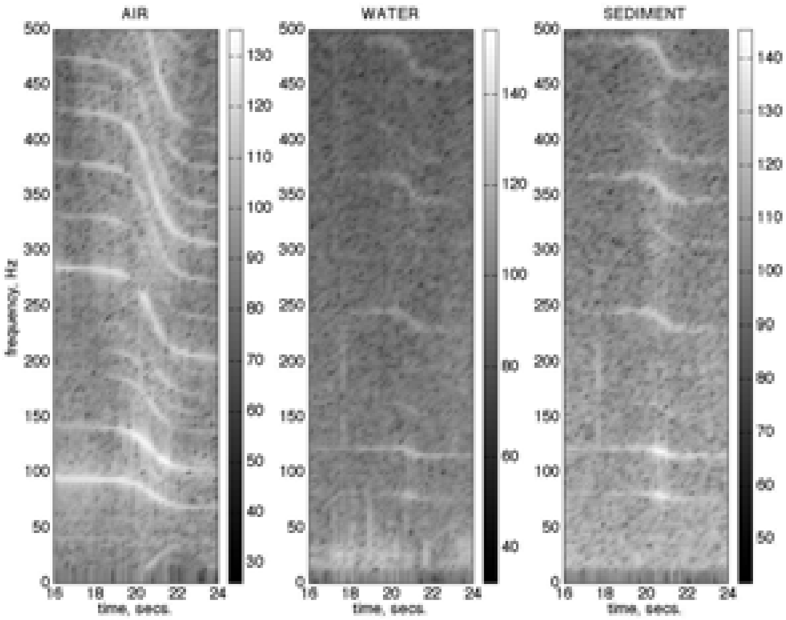

Figure #-3. Propeller harmonics from the DA40 in air, water and sediment.

Around the closest point of approach (CPA), the harmonics from the Diamond Star exhibit a Doppler down-sweep, much like the harmonics from a turboprop aircraft flying at 250 knots (125 m/s) that were recorded by Ferguson[4] in the atmosphere and in deep water at a depth of 20 m beneath the surface. The Doppler-shifted harmonics may be characterized in terms of a difference frequency, that is, the difference between the maximum upshifted frequency on approach and the minimum down-shifted frequency on departure. From inspection of the Doppler-shifted harmonics in Fig. #-3, it is evident that the difference frequency, Δf, is significantly greater in air than in seawater or sediment. In fact, from geometrical acoustics and Snell's law, the difference frequency may be shown to scale inversely with the local speed of sound and thus in going from air to seawater Δf is reduced by a factor of 0.23, which is the ratio of the sound speed in the two media.

The difference frequency is the basis of a technique for measuring the speed of sound in all three layers, the atmosphere, the water column and the sediment. However, rather than use an inversion based on the simple Snell's law result, it is preferable to take account of the modal structure in the water column. This is achieved with a full wave-theoretic model of acoustic propagation in the three-layered medium.

4. FORE-AFT ASYMMETRIES IN THE FIELD

Fore and aft of the source, the sound field in all three layers shows pronounced asymmetries, due largely to the Doppler upshifts and downshifts, respectively, in the frequencies of the harmonics. In the water column, for example, a given harmonic may excite more modes ahead of the source than behind. To investigate such effects, a wavenumber-integral solution of the wave equation has been developed, which yields the sound field in the atmosphere, the water column and the sediment, taking account, of the horizontal motion of the airborne source. In essence, the model consists of three wavenumber integrals, one for each of the layers, which are evaluated numerically to yield the respective acoustic pressure fields. In the current implementation of the model, it is assumed that the sound speed in each layer is uniform but this condition may easily be relaxed, allowing future versions of the model to handle sound speed profiles in the layers.

Fig.#-4 is an example of a transmission loss plot for a moving, airborne source, computed from the wavenumber-integral model. It shows the envelope of the pressure field excited by a single harmonic in the three-layer medium ahead of and behind the source. The aircraft, at an altitude of 50 m and traveling at a speed of 75 m/s, is overflying a 20 m deep channel; and the sound speeds in the layers are 350 (air), 1500 (seawater) and 1800 m/s (sediment). The unshifted frequency of the harmonic is 100 Hz, corresponding to the fundamental of a three-blade propeller turning at 2000 rpm.

All three layers exhibit significant sound-field asymmetries, the most pronounced being in the water column, where it can be seen that there are two modes ahead of the source, giving rise to inter-modal interference, but only one mode behind. In this particular case, the Doppler up- and down-shifts in frequency are such that the second mode is supported when the aircraft is on approach but is cut-off on departure. Also visible in Fig. #-4 are the evanescent tails of the modes in the sediment immediately beneath the seafloor, as well as asymmetrical Lloyd's mirror fringes in the atmosphere, arising from constructive and destructive interference between the direct and sea-surface reflected rays.

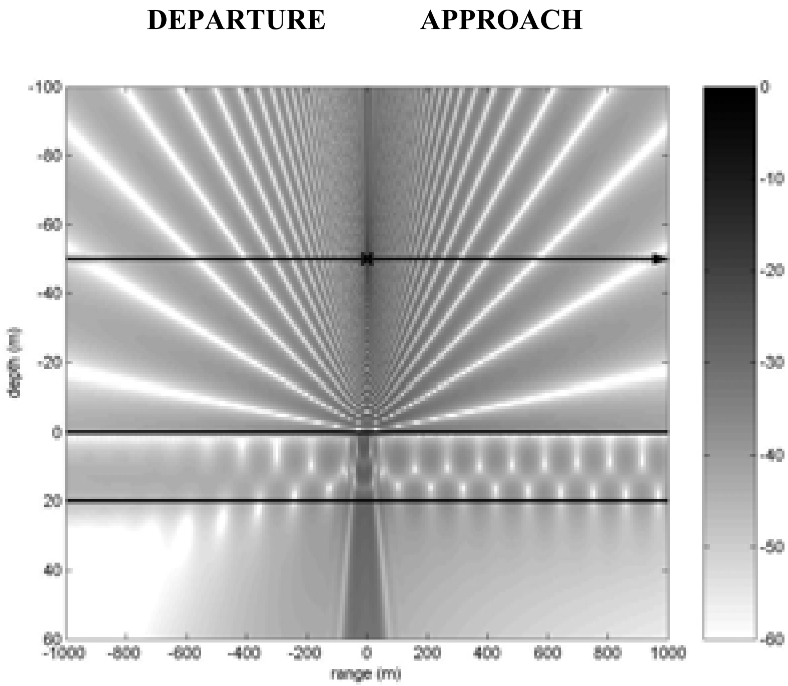

Figure #-4. Transmission loss from a moving source in a three-layer medium. (The grey scale is in arbitrary dB.)

5. INVERSIONS FOR SEDIMENT PARAMETERS

The wavenumber-integral propagation model may be used to perform a full-wave inversion for the geoacoustic properties of the sediment beneath a shallow-water channel. Acoustic data from either the sensors buried in the sediment or in the water column may be used in the inversion procedure. Several approaches to determining the sediment parameters are possible, as outlined below.

In the most computationally intensive inversion procedure, a cost function is formed, consisting of the squared difference between the data and the theoretical model, and the set of geoacoustic parameters that yields a global minimum is considered to represent the actual properties of the sediment. The fact that several of the geoacoustic parameters are strongly correlated[5-7] is not generally exploited in the global minimization technique.

An alternative approach is to determine one property of the sediment, say the compressional wave speed, from which the remaining properties are computed using the correlations that exist between them. A set of algebraic expressions, derived by Buckingham[8], for the inter-relationships between the wave and mechanical properties of marine sediments provides the link between the measured wave property and the remaining parameters.

The speed of the compressional wave in the sediment could be inferred from the *maximum* value of the difference frequency associated with a particular propeller harmonic, as observed on a buried sensor. The maximum Δf corresponds to the refracted (geometric) arrival at the buried sensor, and hence is inversely proportional to the speed of sound in the sediment. A potential problem with this direct measurement of the speed of sound in the sediment is that the evanescent tails of the normal modes may mask the geometric arrival if the sensor is too shallow, that is, too close to the bottom interface.

To avoid this difficulty, it may be possible to measure the speed of sound in the sediment from the harmonics observed on one or more receivers in the water column. From a practical point of view, this approach has the advantage that it is easier to deploy sensors in the water column than it is to bury them in the sediment. A reasonable strategy would be detection of the lateral (head) wave using a vertical array of hydrophones in the channel, since this would yield directly the critical angle of the seawater-sediment interface, from which the speed of sound in the sediment could be inferred (given that the speed of sound in the bottom-water were known).

6. CONCLUDING REMARKS

Some half dozen experiments have now been performed with a single-engine light aircraft overflying a sensor station in the ocean. A sequence of harmonics produced by the aircraft's propeller has been detected by a microphone mounted immediately above the sea surface, by a vertical array of eleven hydrophones distributed non-uniformly throughout the water column, and by hydrophones buried to a depth of about 1 m in the sediment. The frequency range of the observed harmonics extends from approximately 100 to 800 Hz.

Most of the flying experiments were conducted north of Scripps pier, off La Jolla, California, where the water depth is approximately 15 m; but the most recent trial, in October 2004, was at the site of the ONR-sponsored Sediment Acoustics Experiment (SAX99 and SAX04) about 2 km south of Fort Walton Beach in the northern Gulf of Mexico[9]. The nominal depth at the SAX site is 17 m. During all the flying experiments, a SeaBird temperature profiler returned the sound speed profile in the water column.

Based on a geometric model of acoustic propagation in the multi-layered air-water-sediment waveguide, preliminary estimates of the compressional wave speed in the sediment north of Scripps pier indicate a value of 1620 m/s. The sediment in this region is a fine sand with a mean grain diameter of 250 μm. Previous measurements by Hamilton[10,11] in similar materials but at higher frequencies yield sound speed values spanning the range 1630 to 1700 m/s. Since the sediment sound speed returned by the aircraft technique falls slightly below the lower end of Hamilton's range, it is consistent with the idea that frequency dispersion in sediments is weak, of the order of 1% per decade of frequency. This behavior is in accord with the level of logarithmic dispersion predicted by Buckingham's theory[8] of wave propagation in marine sediments.

Acknowledgments

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