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13. ABSTRACT (MAX 200 WORDS): THE ACOUSTIC EMISSIONS FROM A PROPELLER-DRIVEN AIRCRAFT ARE RECEIVED BY A MICROPHONE MOUNTED JUST ABOVE GROUND LEVEL AND THEN BY A HYDROPHONE LOCATED BELOW THE SURFACE. THE DOMINENT FEATURE IN THE OUTPUT SPECTRUM OF EACH ACOUSTIC SENSOR IS THE SPECTRAL LINE CORRESPONDING TO THE PROPELLER BLADE RATE. THE FREQUENCY ESTIMATION TECHNIQUE IS APPLIED TO THE ACOUSTIC DATA FROM EACH SENSOR SO THAT THE DOPPLER SHIFT IN THE BLADE RATE CAN BE OBSERVED AT SHORT TIME INTERVALS DURING THE AIRCRAFT'S TRANSIT OVERHEAD. FOR EACH ACOUSTIC SENSOR, THE OBSERVED VARIATION WITH TIME OF THE DOPPLER-SHIFTED BLADE RATE IS COMPARED WITH THE VARIATION PREDICTED BY A SIMPLE RAY-THEORY MODEL THAT ASSUMES THE ATMOSPHERE AND THE SEA ARE DISTINCT ISOSPEED SOUND PROPAGATION MEDIA SEPARATED BY A PLANE BOUNDARY. THE RESULTS OF THE COMPARISON ARE SHOWN FOR AN AIRCRAFT FLYING WITH A SPEED OF ABOUT 250 KN AT ALTITUDES OF 500, 700 AND 1000 FT.

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Doppler effect for sound emitted by a moving airborne source and received by acoustic sensors located above and below the sea surface

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The acoustic emissions from a propeller-driven aircraft are received by a microphone mounted just above ground level and then by a hydrophone located below the sea surface. The dominant feature in the output spectrum of each acoustic sensor is the spectral line corresponding to the propeller blade rate. A frequency estimation technique is applied to the acoustic data from each sensor so that the Doppler shift in the blade rate can be observed at short time intervals during the aircraft's transit overhead. For each acoustic sensor, the observed variation with time of the Doppler-shifted blade rate is compared with the variation predicted by a simple ray-theory model that assumes the atmosphere and the sea are distinct isospeed sound propagation media separated by a plane boundary. The results of the comparison are shown for an aircraft flying with a speed of about 250 kn at altitudes of 500, 700, and 1000 ft.

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INTRODUCTION

The acoustic spectrum of a transitting aircraft, when received by a stationary observer, changes with time due to the acoustical Doppler effect. Observations of the acoustical Doppler effect for transitting aircraft have been reported previously, using microphones on land[1] and hydrophones in water.[2]

Urick[2] showed that sound from an airborne source can reach a subsurface acoustic sensor in four different ways: via a direct refracted path, via one or more bottom reflections, via scattering from a rough sea surface, and via the lateral wave (also called the inhomogeneous or evanescent wave). Only sound propagation via the direct refraction path is of interest here.

Whereas Urick studied the intensity of the aircraft's noise signature as a function of time, the present approach considers the variation with time of the Doppler frequency associated with a particular spectral line in the aircraft's acoustic spectrum because, unlike the intensity measurements, the frequency estimates display little variability over short intervals of time. The spectral line corresponding to the propeller blade rate is selected for analysis because it is the most prominent feature in the acoustic spectrum of a propeller-driven aircraft. The blade rate is equal to the product of the shaft rotation rate and the number of blades on the propeller.

This paper considers the acoustical Doppler effect for an acoustic tone emitted by a moving airborne sound source and then received by a microphone and a hydrophone. In the experiment, a turbo-prop aircraft having a constant propeller blade rate flies over a microphone placed just above ground level and then over a hydrophone located in the deep ocean. The acoustic emissions from the aircraft propagate through the air to the microphone via the direct ray path between source and receiver, whereas sound that is transmitted across the air–sea interface arrives at the hydrophone via a refracted ray path—see Fig. 1. The acoustic data from each sensor are processed to obtain estimates of the Doppler shift in the propeller blade rate at short time intervals during the aircraft's transit overhead. The observations are then compared with the results predicted by using a simple ray-theory model.

I. MODEL

A. Microphone

Consider an aircraft that emits an acoustic tone of frequency f_s as it flies at a constant speed (v_s) and altitude (h) in a constant direction so that its flight path passes directly over a microphone located on the ground—see Fig. 2. The sound that is emitted by the aircraft at a horizontal range r arrives at the microphone at a later time t_a, which is given by

$$t_a = \frac{\mp r}{v_s} + \frac{l_a - h}{c_a} = \frac{\pm h}{v_s \tan\theta_a} + \frac{h}{c_a}\left(\frac{1}{\sin\theta_a} - 1\right), \tag{1}$$

where l_a is the separation distance between the source and the receiver, c_a is the speed of sound propagation in the atmosphere, and θ_a is the angle of depression of the microphone relative to the horizontal flight path of the aircraft; the angle of depression is the complement of the angle of incidence. The propagation delay for the sound to travel from the aircraft to the microphone is equal to l_a/c_a.

The Doppler frequency of the acoustic signal received by the microphone at the time t_a is given by

$$f_a = f_s[1 \mp (v_s/c_a)\cos\theta_a]^{-1}. \tag{2}$$

In Eqs. (1) and (2), the upper sign ($-$) applies when the aircraft is inward bound towards the microphone ($t<0$ and $f_a > f_s$), while the lower sign ($+$) applies when the

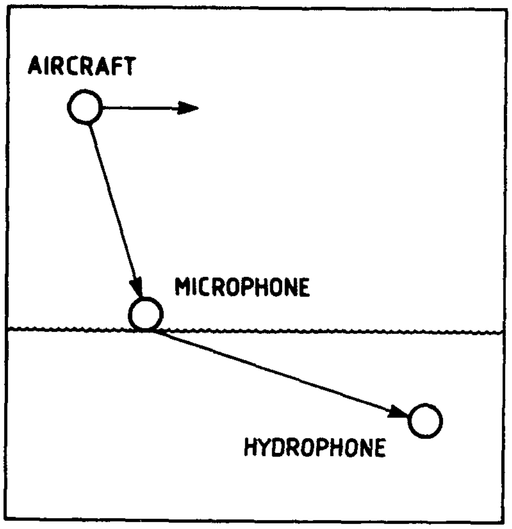

FIG. 1. Sound emitted by the aircraft propagates to the microphone via a direct path, but the sound is refracted after transmission across the air–sea interface where it is subsequently received by a hydrophone.

aircraft is outward bound away from the microphone ($t>0$ and $f_a<f_s$). At the closest point of approach, the aircraft is directly overhead and so $r=0$, $t_a=0$, and $f_a=f_s$.

The atmosphere is assumed to be an isospeed medium for the propagation of sound with the value of c_a being equal to 660 kn.

B. Hydrophone

Similarly, the sound emitted by the aircraft at a horizontal range R (see Fig. 3) arrives at the hydrophone at a later time t_w, which is given by

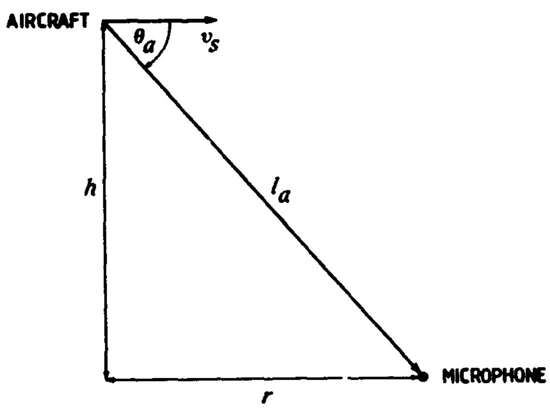

FIG. 2. Geometry for the propagation of sound from the aircraft to the microphone.

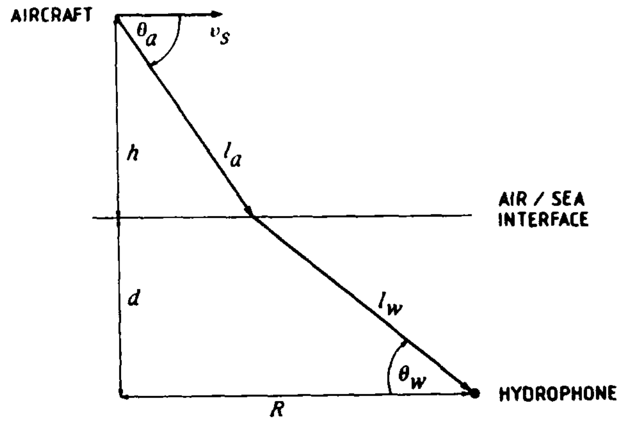

FIG. 3. Geometry for the propagation of sound from the aircraft to the hydrophone.

$$t_w=\frac{\mp R}{v_s}+\frac{l_a-h}{c_a}+\frac{l_w-d}{c_w}$$
$$=\frac{\mp h}{v_s\tan\theta_a}\mp\frac{d}{v_s\tan\theta_w}+\frac{h}{c_a}\left(\frac{1}{\sin\theta_a}-1\right)$$
$$+\frac{d}{c_w}\left(\frac{1}{\sin\theta_w}-1\right), \tag{3}$$

where $l_a/c_a+l_w/c_w$ is the propagation delay for the sound to travel from the aircraft to the hydrophone, c_w is the speed of sound propagation in water, and θ_w is the complement of the angle of refraction. The speed of sound wave propagation in the underwater medium is assumed to be constant, with the value of c_w being equal to 2960 kn.

The Doppler frequency of the acoustic signal received by the hydrophone at the time t_w is given by

$$f_w=f_s[1\mp(v_s/c_w)\cos\theta_w]^{-1}. \tag{4}$$

In Eqs. (3) and (4), the upper sign ($-$) applies when the aircraft is inward bound and the lower sign ($+$) applies when the aircraft is outward bound.

The relationship between θ_a and θ_w is given by Snell's law,

$$\frac{\cos\theta_a}{c_a}=\frac{\cos\theta_w}{c_w}. \tag{5}$$

The critical angle of incidence θ_c is equal to $\sin^{-1}(c_a/c_w)$, that is, $\theta_c\approx 13°$. When the angle of incidence is greater than θ_c, all of the sound energy from the aircraft is reflected from the sea surface, so that none of the acoustic energy from the aircraft is transmitted across the air–sea interface into the underwater medium. Thus, the transmission of sound across the air–sea interface occurs only over an area of the sea surface that corresponds to the base of a cone having an apex angle of $2\theta_c$; the position of the sound source coincides with the apex. The diameter of the "footprint" for sound transmission is proportional to the altitude of the aircraft, with the proportionality constant being equal to $2\tan\theta_c$.

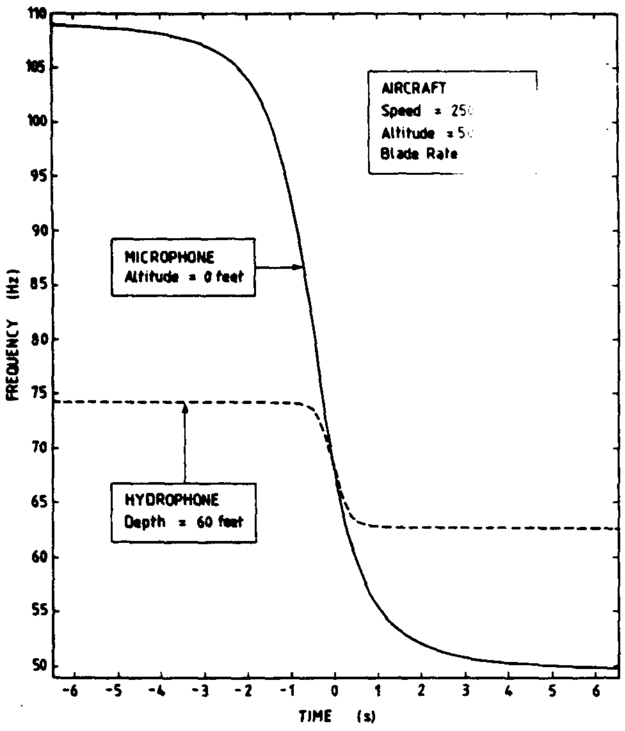

FIG. 4. Predicted variation with time of the Doppler frequency of an acoustic tone emitted by the aircraft and then received by a microphone (solid line), and a hydrophone (broken line). The speed and altitude of the source are 250 kn and 500 ft, respectively. The source (or rest) frequency of the acoustic tone is 68 Hz.

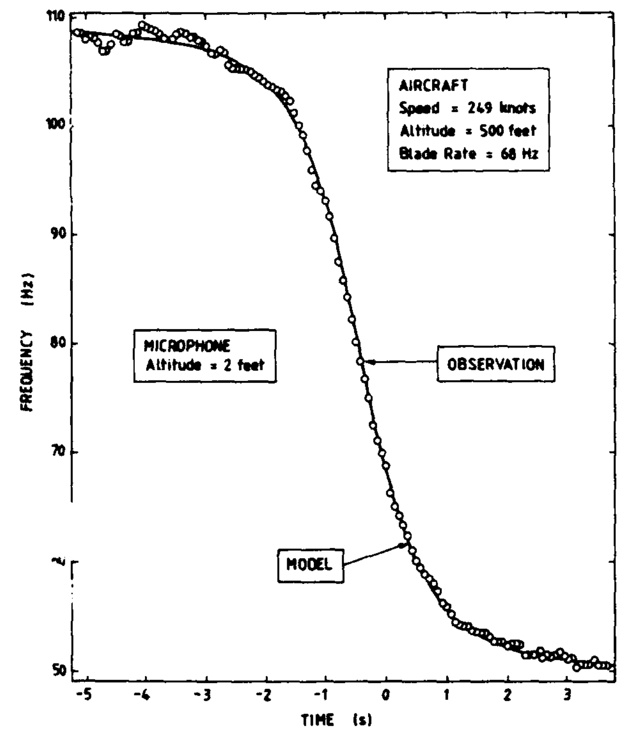

FIG. 5. Observed and predicted variation with time of the Doppler frequency for the acoustic signal received by the microphone which is mounted 2 ft above the ground. The speed and altitude of the aircraft are 249 kn and 500 ft, respectively. The source frequency is 68 Hz.

Now consider the particular case of an aircraft emitting an acoustic tone with a constant source frequency of 68 Hz and flying with a constant speed of 250 kn at a constant altitude of 500 ft. Figure 4 shows the predicted Doppler frequency as a function of time for the signal received by the microphone (solid line), and by the hydrophone (broken line). The microphone is assumed to be at sea level, with the hydrophone at a depth of 60 ft. The Doppler shift of the signal received by the hydrophone is predicted to be much smaller than the Doppler shift of the signal received by the microphone. Also, the transition time from the maximum (up Doppler) frequency to the minimum (down Doppler) frequency is much shorter for the signal received by the hydrophone.

II. EXPERIMENT AND ACOUSTIC DATA PROCESSING

A turbo-prop aircraft with a constant propeller blade rate of 68 Hz flies over a microphone on land and then over a hydrophone in the sea. The microphone is mounted 2 ft above the ground and the hydrophone is at a depth of 60 ft below the sea surface. The analog output from each sensor is converted to a digital data stream. The phase interpolation method[3,4] is applied to the digital time series data so that the Doppler-shifted blade rate can be estimated at each short time interval during the aircraft's transit over each of the sensors. The time resolution of the frequency estimates is 0.024 s for the hydrophone data and 0.072 s for the microphone data.

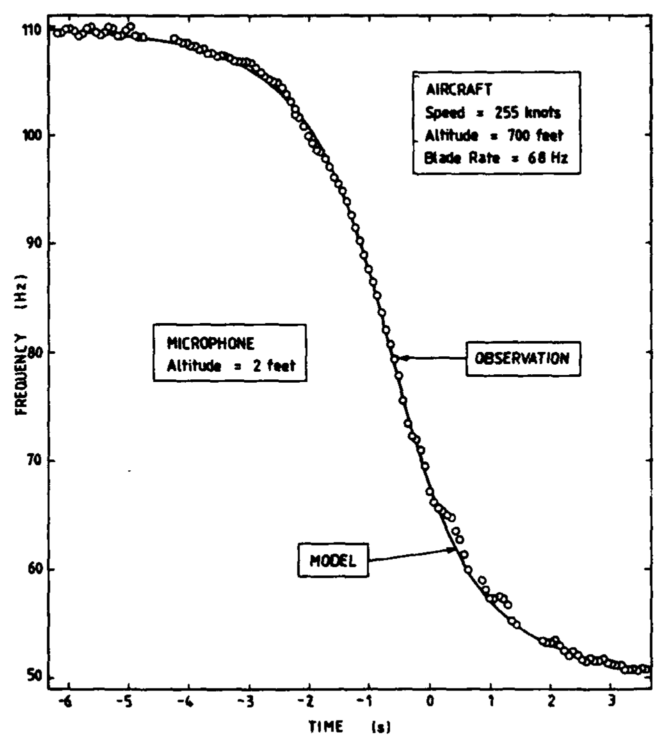

FIG. 6. Similar to Fig. 5 but the speed and altitude of the aircraft are 255 kn and 700 ft, respectively.

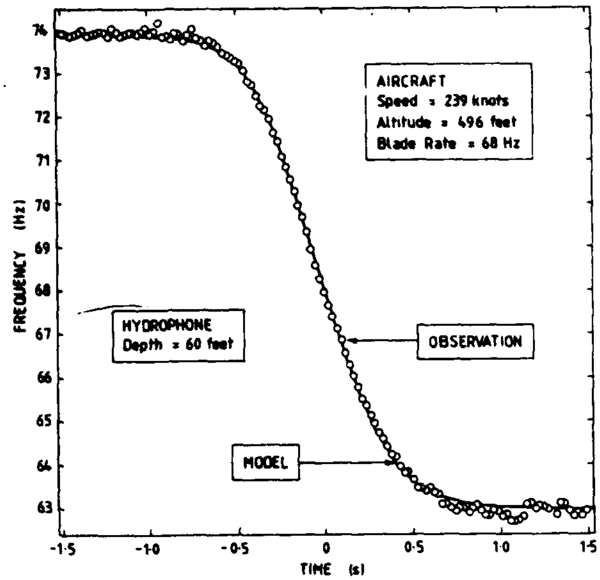

FIG. 7. Observed and predicted variation with time of the Doppler frequency for the acoustic signal received by the hydrophone located 60 ft below the sea surface. The speed and and altitude of the aircraft are 239 kn and 496 ft, respectively. The source frequency is 68 Hz.

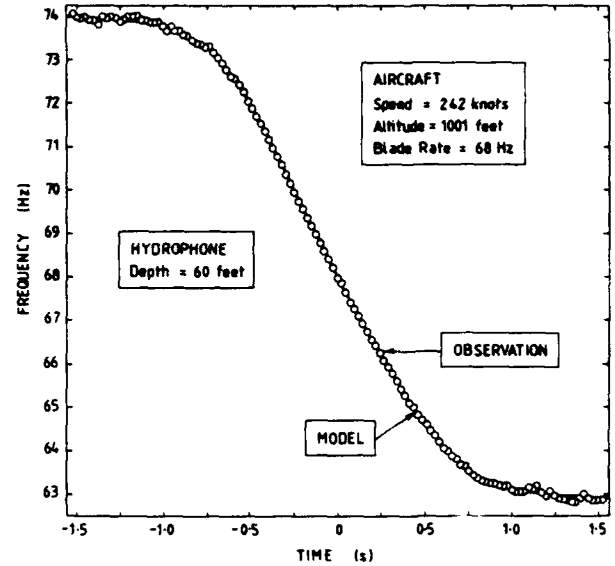

FIG. 8. Similar to Fig. 7 but the speed and altitude of the aircraft is 242 kn and 1001 ft, respectively.

III. RESULTS

The results of the acoustic data processing are shown in Figs. 5 and 6 for the microphone and Figs. 7 and 8 for the hydrophone. Each frequency estimate (or "OBSERVATION") is indicated by a circle. Also shown are the values for the aircraft's speed and altitude that were recorded by instruments onboard the aircraft during each transit; for example, in Fig. 5, the speed is 249 kn and the altitude is 500 ft. These values for the speed and altitude of the aircraft, together with the source (or rest) frequency of the propeller blade rate (68 Hz), are used in Eqs. (1) and (2) to predict the variation with time of the Doppler frequency for the signal received by the microphone. The predicted Doppler frequency-time curve is shown as the solid line labelled "MODEL" in Figs. 5 and 6.

Similarly, Figs. 7 and 8 show both the observed and predicted variation with time of the Doppler frequency for the acoustic signal received by the hydrophone, together with the values of the aircraft's flight parameters.

The excellent agreement between the observations and the model indicates that simple ray theory accurately describes the acoustical Doppler effect for sound that is emitted by a moving airborne source and received by a microphone and a hydrophone. The Doppler effect is much larger for the acoustic signal received by the microphone. The difference between the maximum (up-Doppler) and minimum (down-Doppler) frequencies is 58 Hz for the microphone, but only 11 Hz for the hydrophone. Also, the transition time from the maximum to the minimum Doppler frequency is much longer for the signal received by the microphone; compare Figs. 5 and 7 for which the speed and altitude of the aircraft are similar.

IV. CONCLUSION

Simply ray theory provides an accurate description of the observed variation with time of the Doppler frequency of an acoustic tone, which is emitted by an aircraft and subsequently received by a microphone on land and a hydrophone beneath the sea.

For the signal received by the microphone, the magnitude of the Doppler shift is much larger and the transition time from the maximum up-Doppler frequency to the minimum down-Doppler frequency is much longer than for the signal received by the hydrophone.

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