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AMBIENT NOISE NEAR THE SEA-ROUTE

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ABSTRACT
Ambient noise data measured in an experiment conducted near the sea-route were analyzed. It is observed that, at low frequency, the measured horizontal correlation coefficients at different separations oscillate much larger than that predicted by traditional ambient noise model. The theoretical analyses show that this phenomenon is mainly caused by wind noise together with near shipping noise. An ambient noise model is proposed to combine the effects of both the homogenous statistical distribution of surface noise sources and discrete shipping sources. The proposed model can be used to forecast the ambient noise field near the sea-route.

INTRODUCTION
Detecting or measuring acoustical signals in the ocean is always performed against a noise background. An array of hydrophones is an acoustic antenna which can be used to enhance the received signal-to-noise ratio. The enhancement is often referred to as array gain, which is restricted by the spatial correlation of the noise field. Therefore, the characteristics of the spatial correlation of the noise field are crucial to the array processing techniques. The ambient noise, which is usually the noise background of sonar, has been modelled, such as wavenumber integral based model [1], normal mode based model [1-3], ray based model [4, 5], and so on. However, the ambient noise in shallow water near a sea-route, which is a mixture of discrete shipping noise and wind noise at frequencies from 10 to 300 Hz [6], can not be predicted accurately by the classical noise models mentioned above.

The ambient noise data were measured by a horizontal line array during a three days experiment conducted in the Yellow Sea in June, 2005. It is found that the horizontal correlation of the measured ambient noise at low frequencies has an obvious difference with that predicted by the classical ambient noise model. In fact, the experiment was conducted near a sea-route, where many discrete ships exist nearby. The ambient noise caused by such discrete ships has not been accounted by the classical noise model. In this paper, a new ambient noise model, combining the effects of both surface noise and discrete ship noise, is presented to predict the horizontal correlation of the noise field near a sea-route.

THE CLASSICAL AMBIENT NOISE MODEL [1]
As shown in Fig.1, the random source term on the plane $z=z'$ in the frequency domain is denoted by $S(r')$. The acoustic field from such a source distribution is the solution of the equation (The denotation of the symbols in this paper is the same as that in reference 1)

Figure 1. The geometry for the surface-distributed noise problem.
\[(\nabla^2 + k^2)\phi(r, z) = -S(r')\delta(z-z'), \quad \text{(Eq. 1)}\]

where \(k = \omega/c(z)\). Eq. 1 has the solution

\[\phi(r, z) = \int S(r')g(r, r', z, z')d^2r', \quad \text{(Eq. 2)}\]

where \(g(r, r', z, z')\) is the Green’s function and satisfies the Helmholtz equation

\[(\nabla^2 + k^2)g(r, r', z, z') = -\delta(r-r')\delta(z-z'), \quad \text{(Eq. 3)}\]

and the appropriate boundary conditions. The spatial distribution of the noise field is characterized by the ensemble average of the product of the acoustic field at a point \((r_1, z_1)\) and the complex conjugate of the field at a point \((r_2, z_2)\). This quantity is called the cross-spectral density, which can be written as

\[C_\omega(r_1, r_2, z_1, z_2) = <\phi(r_1, z_1)\phi^*(r_2, z_2) > \]

\[= \int <S(r')S(r^*) > g(r_1, r', z_1, z')g^*(r_2, r^*, z_2, z^*)d^2r'd^2r^*, \quad \text{(Eq. 4)}\]

where \(S\) is the surface noise source function. The correlation function of the surface noise sources

\[q^2N(s) = <S(r')S(r^*) > \quad \text{(Eq. 5)}\]

is taken to be homogeneous and therefore spatially dependent only on the separation, \(s = r' - r^*\), between sources; \(q\) is the surface source strength. For uncorrelated noise sources, the correlation function will be of the form of a \(\delta\) function and is given by

\[N(s) = \frac{\delta(k(z')s)}{k(z)s}, \quad \text{(Eq. 6)}\]

where \(s = |r|\). We also express the noise field points through the difference of displacement vectors, \(R = r_1 - r_2\), and denote the cross-spectral density given by Eq. (4) for angular frequency \(\omega\) as \(C_\omega(R, z_1, z_2)\). The Cartesian coordinate equivalents of the integral representation for the Green’s function are of the form

\[g(r_1, r', z_1, z') = \frac{1}{2\pi} \int g(k, z_1, z') \exp(k \cdot (r_1 - r'))d^2k, \quad \text{(Eq. 7)}\]

Insert these expressions into Eq.(4), and substitute \(R\) for \(r_1 - r_2\) and \(s\) for \(r' - r^*\), the cross-spectral of the ambient noise can be given by

\[C_\omega(R, z_1, z_2) = \frac{8\pi^2q^2}{k^2(z')} \int g(k, z_1, z')g^*(k, z_2, z')J_0(k, R)k, dk, \quad \text{(Eq. 8)}\]

where \(J_0\) is the Bessel function of zeroth order and \(R = |R|\). The normal mode representation of Eq. (8) is given by

\[C_\omega(R, z_1, z_2) = \frac{iq^2}{\rho k^2} \sum m n \Psi_m(z_1)\Psi_n(z_2)f_{mn} \times [H_1(k, R) + H_2(k, R)], \quad \text{(Eq. 9)}\]
where \( f_{mn} = 1/(k_{rm}^2 - (k_{rm}^m)^2) \), \( \Psi_m(z) \) is the normalized amplitude function and \( k_{rm} \) is the propagation wavenumber of the \( m \)th mode.

Generally, the normal mode theory is more appropriate for far field at low frequency in shallow water. In this paper, the normal mode code KRAKEN [7] is used to solve the eigenvalues in Eq. (9) to consider the effects of near field by including the leaky modes.

**ANALYSIS OF THE EXPERIMENT RESULT**

In June 2005, a three days measurement of ambient noise was conducted in the Yellow Sea. The water depth is 31 m. A horizontal line array consisting of 48 hydrophones at 2 m spacing was deployed on the bottom. Ambient noise signals were recorded with a sample frequency of 4.0 kHz for each channel. Figure 2 shows the sound speed profile during the experiment, where there is a negative thermocline from 0 m to 10 m.

The received time series at two hydrophones denoted by \( x_1(t, \Delta T_i) \), \( x_2(t, \Delta T_i) \) were divided into portions of 8192 samples (roughly \( \Delta T_i = 2s \), \( i = 1,2, \cdots, n \) ) and transformed into the frequency domain denoted by \( X_1(f, \Delta T_i) \), \( X_2(f, \Delta T_i) \) with a standard fast Fourier transform (FFT). The horizontal correlation coefficient of the ambient noise between two receivers is averaged over \( n \) time segments according to the following equation:

\[
C_{12} = \frac{1}{n} \sum_{i=1}^{n} \frac{X_1(f, \Delta T_i)X_1^*(f, \Delta T_i)}{\sqrt{X_1(f, \Delta T_i)X_1^*(f, \Delta T_i)} \sqrt{X_2(f, \Delta T_i)X_2^*(f, \Delta T_i)}}. \tag{Eq. 10}
\]

Experimental horizontal correlation as a function of hydrophone spacing at frequency of 100 Hz is shown in Fig. 3 with circles. It is shown that when the hydrophone spacing is 20 m (which is much larger than the half wave length 7.5 m), the experimental horizontal correlation coefficient is up to 0.8, which is much larger than the numerical prediction (solid line) by Eq. (9). The geoacoustic parameters used in the numerical prediction of Fig. 3 are inverted by Li [8] et. al using data measured at the same experiment. Numerical simulations show that the uncertainties of ocean environment parameters are not the cause of differences between the experimental results and the numerical prediction shown in Fig. 3. The beamforming result of the same data as Fig. 3 at frequency of 100 Hz shown in Fig 4 indicates that there is a ship at bearing of 42°. Supposing a ship at the bearing of 42°, the horizontal correlation of sound propagation field (without time delay calibration) at frequency of 100 Hz is shown in Fig. 5. Comparing Fig. 3 with Fig. 5, one can conclude that the measured horizontal correlation is mixture results of the surface noise and that of the discrete ship noise. Nearby discrete ships might cause the difference.
A PROMOTED AMBIENT NOISE MODEL

Supposing a ship located at the point \((r, z)\), the noise background is a mixture of surface noise and shipping noise. On the basis of the classical ambient noise model given by Eq. (4), the noise field at a point \((r_1, z_1)\) can be given by

\[
\varphi(r_1, z_1) = \int S(r') g(r_1, r', z_1, z') d^2 r' + S_1(r) g(r_1, r, z_1, z),
\]

(Eq. 11)

The first item in the above equation is the surface noise field, which is the same as Eq. (2). And the second item is the ship noise field, where \(S_1\) is the ship noise function. \(g\) is the Green’s function, and satisfy the Helmholtz equation Eq. (3) and the appropriate boundary conditions. The nearby ship noise is an important composition of the whole noise field. Generally, the surface noise and ship noise are uncorrelated, i.e.

\[
< S(r') S_1(r) > = 0.
\]

(Eq. 12)

The cross-spectral density between the point \((r_1, z_1)\) and the point \((r_2, z_2)\) is

\[
C_\omega(r_1, r_2, z_1, z_2) = < \varphi(r_1, z_1) \varphi^*(r_2, z_2) > ,
\]

(Eq. 13)

Substituting Eq. (11) and Eq. (12) into Eq. (13) yields the cross-spectral density

\[
C_\omega(r_1, r_2, z_1, z_2) = [ < S(r') S(r^*) > g(r_1, r, z_1, z') g(r_2, r', z_2, z^*) d^2 r d^2 r^* + < S_1(r) S_1(r) > g_1(r_1, r, z_1, z) g_1^*(r_2, r, z_2, z)] ,
\]

(Eq. 14)

where the first item, the same as Eq. (4), is the cross-spectral density of surface noise and the second item is the cross-spectral density of the ship noise. The normal mode representation of the first item is given by Eq. (9) and the normal mode representation of the second item can be given by

\[
< S_1(r) S_1(r) > g_1(r_1, r, z_1, z) g_1^*(r_2, r, z_2, z) \]

\[
= \left| S_1(r) \right|^2 \sum_{m} \sum_{n} \Psi_m^*(z_1) \Psi_m(z_2) \Psi_n^*(z_1) \Psi_n(z_2) e^{-j(k_m R_1 + k_n R_2)} ,
\]

(Eq. 15)

where \(R_1 = |r_1 - r|\) and \(R_2 = |r_2 - r|\).

In order to verify the validity of the promoted model, the experimental horizontal correlation is compared with the numerical result calculated by the classical model given by Eq. (9) and the promoted model given by Eq. (14). Figure 6 shows the comparison of the experimental result, which is the same as that in Fig. 3, with the numerical results at the frequency of 100 Hz, in
which the experimental result is denoted by circle, the numerical result calculated by the classical model is denoted by solid line, and the numerical result by the promoted model with a ship located at the bearing of $42^\circ$ is denoted as dotted line. It is clear that the promoted result is in consistent with the experimental result, while the classical result has a big difference with the experimental result.

Figure 6. The comparison of the experimental horizontal correlation with the numerical results

Experimental results at different time segment with Fig.3 at frequency of 100Hz are shown in Fig. 7 and Fig. 8. Figure 7 shows the horizontal beamforming result of the noise field, from which two ships at the bearing of $94^\circ$ and $30^\circ$ can be observed. Figure 8 shows the comparison of the experimental correlation (circles) and the numerical results calculated by the classical model (solid line) and the promoted model (dotted line) with two ships at the bearing of $94^\circ$ and $30^\circ$. It is also obviously shown that the promoted result is in consistent with the experimental result.

Figure 7. The horizontal beamforming result of the data at different time with Fig.2.

Figure 8. The comparison of the experimental horizontal correlation with the numerical results

CONCLUSIONS
The ambient noise measurements over three days during an experiment conducted in the Yellow Sea in June, 2005 were analyzed. Obvious difference between the experimental horizontal correlation and the numerical result calculated by the classical ambient noise model at low frequencies was observed and explained by the existence of nearby discrete ships. A new promoted model is presented to predict the noise field near a sea-route including both the effect of surface noise and the effect of nearby discrete ships. The experimental data at difference times has been used to verify the validity of the promoted model.
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