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High Frequency Ship Radiated Noise in Shallow Water

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The stationary acoustic field in a two plane parallel medium, sea surface and sea bottom, when a source near to the sea surface radiates, is characterized by the thickness of the medium and the reflectivity of the boundary surfaces. It is known that the maxima and minima of pressure are produced at some given depths depending on the radiated frequency and distance.
Considering the ship noise as an acoustical source, the frequency spectrum of the acoustic pressure at certain depth, is not only the spectrum of the acoustic ship noise but it is also modified by the wave field originated by consecutive reflections at the boundary surfaces. As a consequence, over the free field spectrum of the ship noise, a series of minima appears. The corresponding frequencies are those for which the receiver is located at the nodes of the stationary wave field.

1.Introduction

The first objective of this study was to find out the effect of the underwater radiated ship noise into the sonar installed at an oceanographic vessel for research. The radiated noise at the far field with the vessel moving at several speeds were evaluated [Carbó] and compared with others European research vessels [Garnier].

The measured radiated ship noise has an usual spectrum [Urick]. The low frequency spectrum is dominated by the harmonic series of line components produced by the propulsion machinery vessel, together with the blade rate lines of the propeller. The high frequency range shows a continuous spectrum and has a slope of –6 dB/octave.

A sound spectrogram of the radiated ship noise moving away from the hydrophone in shallow water shows the parallel lines at low frequencies, while hyperbole lines can be clearly seen at high frequencies. This high frequency spectrogram is produced by the stationary acoustic field set up in a two plane parallel medium, surface and bottom of the sea.

Two hydrophones located at z1 and z2 depth produce two different noise spectrum. The ratio of those spectrum $g(\omega)$ does not depend on the frequency response of the source but it is related with the medium characteristics.

When the ship moves away from the hydrophones, the distance between the frequencies where the spectrum is minimum increases. A spectrogram (frequency-time analysis) of the ratio $g(\omega)$ gives a plot versus time and shows the intensity of the sound in the analysis bandwidth by a color scale record. This representation characterizes the stationary acoustic field in the region where the ship moves.

Experimental spectrograms were realized and the results were very successfully and in a good agreement with the theory prediction in wave propagation in a layer with reflecting boundaries.

2. Theoretical Background

Brekhovskikh develop the theory of sound wave propagation in a homogeneous water layer, bounded in both sides by plane parallel boundaries, on one side by the ocean bottom, and on the other side by the surface of the water.

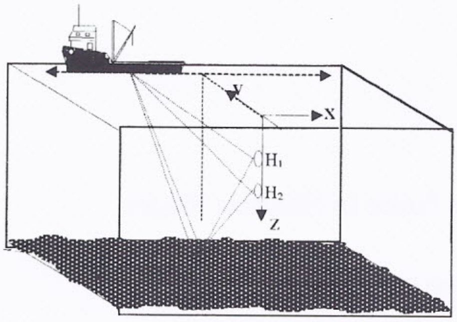

Fig. 1. Experimental set-up.

We consider a layer with the boundaries z=0 and z =h (Fig.1). The source is assumed to be situated near to the sea surface. The wave velocity in the layer will be denoted by c.

The acoustic potential ψ satisfies the wave equation within the layer

$$\nabla^2 \psi + k^2 \psi = 0 \qquad \text{with} \quad k = \omega / c \quad (1)$$

At the surface fulfilling the condition ψ=0 the reflection coefficient is equal to -1, while at the lower boundary the reflection coefficient will be denoted by $+V(\theta)$ and depends of the incidence angle θ. This means that the phase of the wave changes discontinuously by half a period upon reflection from the boundary. Tracing through the number of reflections undergone at the boundaries by the rays corresponding to each of the imagine sources, it is not hard to show that in this case the expression of the field will be

$$\psi = \sum_{n=1}^{\infty} (-1)^n \left[V_1(\theta_n)^{n-1} \frac{\exp(ikR_{n1})}{R_{n1}} + V_2(\theta_n) \frac{\exp(ikR_{n2})}{R_{n2}} \right] \qquad (2)$$

where

$$R_{n1} = \sqrt{r^2 + (2(n-1)h + z)^2} \qquad (3)$$

$$R_{n2} = \sqrt{r^2 + (2nh - z)^2} \qquad (4)$$

$$V_1(\theta_n) = \frac{\dfrac{\rho_2 c_2}{\cos\alpha_{1n}} - \dfrac{\rho c}{\cos\theta_{1n}}}{\dfrac{\rho_2 c_2}{\cos\alpha_{1n}} + \dfrac{\rho c}{\cos\theta_{1n}}} \qquad (5)$$

$$V_2(\theta_n) = \frac{\dfrac{\rho_2 c_2}{\cos\alpha_{2n}} - \dfrac{\rho c}{\cos\theta_{2n}}}{\dfrac{\rho_2 c_2}{\cos\alpha_{2n}} + \dfrac{\rho c}{\cos\theta_{2n}}} \qquad (6)$$

$$\theta_{1n} = atn\left[\frac{r}{2(n-1)h + z}\right] \qquad (7)$$

$$\theta_{2n} = atn\left[\frac{r}{2nh - z}\right] \qquad (8)$$

$$\alpha_{1n} = asin(\frac{c_2}{c} sin\theta_{1n}) \qquad (9)$$

$$\alpha_{1n} = asin(\frac{c_2}{c} sin\theta_{1n}) \qquad (10)$$

$r = (x^2+y^2)^{1/2}$ is the distance in surface from the ship, ρ_2 is the density and c_2 is the sound velocity into the sea bottom and ρ and c into the water.

The field in the layer can also be represented as a set of normal modes, each of which individually satisfies the wave equation and the boundary conditions, and propagates along the layer with it is own velocity.

The ratio of the acoustical potential ψ at two different depth z_1 and z_2

$$g(\omega) = \psi(z_1) / \psi(z_2) \qquad (11)$$

is a function of the water column height h, the noise source distance in surface r, the acoustic impedance of the sea bottom $\rho_2 c_2$ and the wave frequency.

A software has been developed according to this theoretical model to calculate the g(ω) function in several cases. Thickness water layer and bottom acoustical impedance are the checked parameter. Theoretical frequency-time analysis of g(ω,x) function is shown in Fig. 2 concerning a soft bottom (mud) with acoustical impedance closely to the water impedance, and Fig. 3 concerning a sandy bottom. Forth thickness of water layer: 20, 30, 40 and 50 m has been checked. The hyperbola lines begins more and more close one from each other when the layer thickness increases. The color contrast, that is to say the shallow water effect, increase with the sea bottom water impedance mismatch.

3. Experimental results

Experimental cruise has been carried out in the Mediterranean sea near the Ebro river mouth in shallow water (30 m deep) with flat and fine sand sea bottom. The target of the research was a vessel 63 m long and 5 m draught.

An auxiliary boat was used to place two hydrophones Bruel&Kjaer 8104 at 4 and 14 m depth. The distance between the vessel and the boat ranges from 170 m to 600 m being controlled by DGPS. Ship speed remained constant along the trial (4 kt), covering a line approximately parallel to the cost (x axis) first approaching the hydrophones line (z axis) and after going away.

Acoustic data acquisition was recorded in a two channels Digital Audio Tape. Laboratory post process has been realized in a PC with an A/D converter multifunction card AT-MIO-16E-10 National Instruments. Each acquisition has 40000 samples, and the sampling rate is 25 μs. A computed program in MATLAB™ software package has been used to calculate the noise spectrum and the spectrograms.

The spectrum of ship radiated noise in shallow water ($\Gamma_s(\omega)$) may be assumed as the spectrum of ship radiated noise in free field conditions ($\Gamma_o(\omega)$) filtered by the shallow water potential ψ. That is to say:

$$\Gamma_s(\omega,z)=\Gamma_o(\omega)\psi(\omega,z) \tag{12}$$

The ratio of the ship radiated noise spectrum at two different depths z_1 and z_2 does not depend on the ship radiated noise, and it is only consequence of the shallow water behaviour: the column water thickness and the sea bottom reflectivity

$$\frac{\Gamma_s(\omega,z_1)}{\Gamma_s(\omega,z_2)}=\frac{\Gamma_o(\omega)}{\Gamma_o(\omega)}\frac{\psi(\omega,z_1)}{\psi(\omega,z_2)}=g(\omega,z_1,z_2) \tag{13}$$

Fig.4 show the ship noise spectrum in dB ref. 1μP/1m/1Hz got at two different depths, and the Fig.5 shows the corresponding spectrograms of the ship noise from 1 to 600 Hz when the ship moves at 4 knots speed. The higher sound level, due to machinery and propeller noise, is at low frequency (red color). The hyperbolas lines appear up to 100 Hz (blue and green color).

Fig. 6 shows the experimental spectrogram of the function g(ω). This spectrogram is not related with the frequency response of the source and only depends on the medium characteristics. So the red color does not appear at low frequency, and the hyperbolas lines are left as a evidence of the shallow water effect. Experimental spectrograms are in good agreement with the theory prediction in wave propagation in a layer with reflecting boundaries.

4. Conclusion

The radiated ship noise in shallow water produces a stationary acoustic field. Its effect is relevant at high frequencies and clearly observed in the spectrograms. The ratio of spectrograms picked up at two different depths is not related with the ship noise but it is related with the stationary acoustic field. There is a good agreement between the spectrograms ratio and the calculated function "g". With a theoretical model of sound wave propagation in a layer taking into account sea surface and sea bottom roughness, water velocity profile, shear wave propagation into the sediment, bottom velocity profile and noise source depth it will be possible to get better agreement between spectrograms ratio and function "g".

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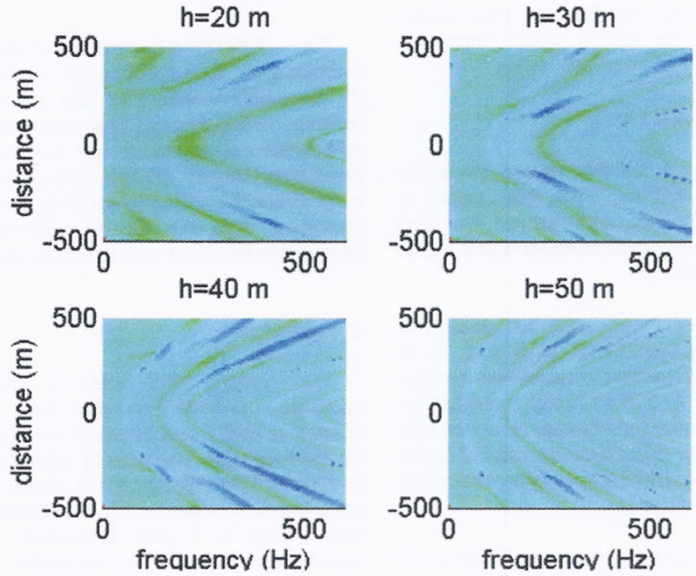

Fig.2. Computed spectrogram "g" function with a soft bottom ρ_2=1500 kg/m^3 c_2=1540 m/s

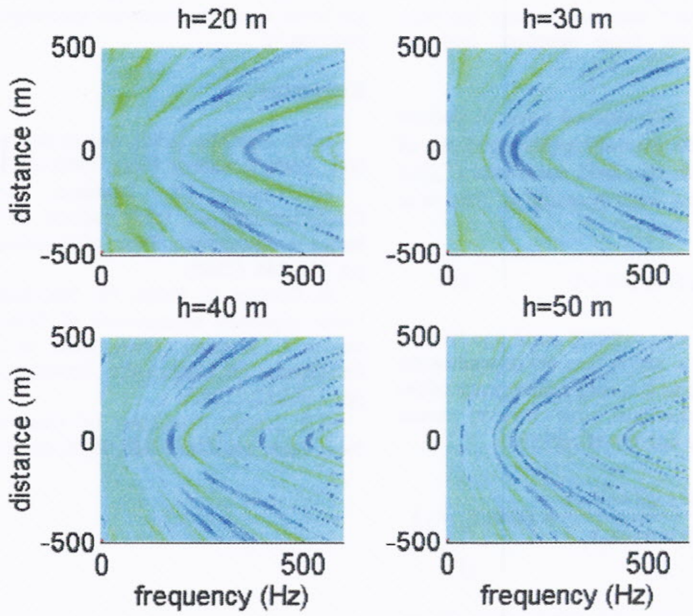

Fig.3. Computed spectrogram "g" function with a sandy bottom ρ_2=2650 kg/m^3 c_2=1600 m/s

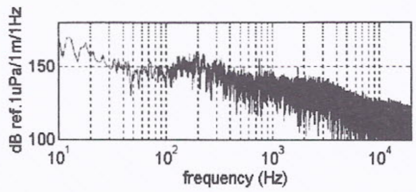

Fig.4.a.Ship noise radiated spectrum (z=14m)

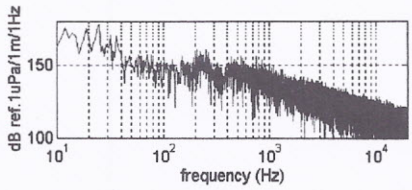

Fig.4.b. Ship noise radiated spectrum (z=4m)

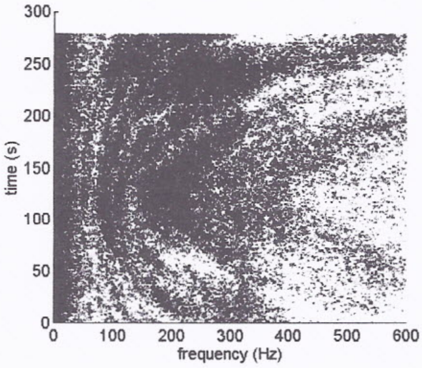

Fig. 5.a. Ship noise radiated spectrogram (z=4m)

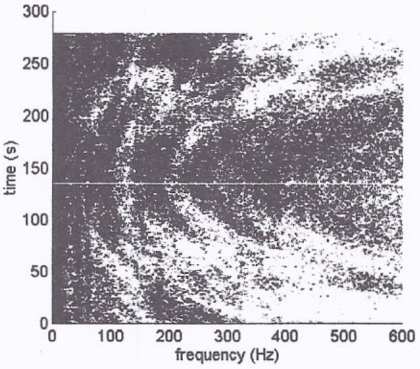

Fig.5.b. Ship noise radiated spectrogram (z=14m)

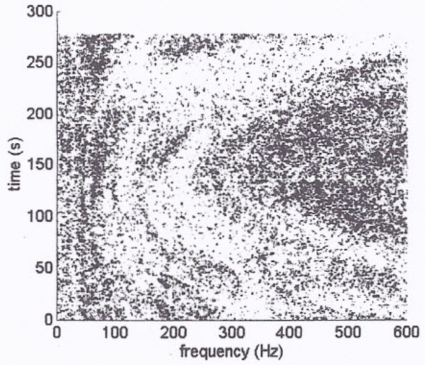

Fig.6. Time-frequency dependence "g" function