TIME-FREQUENCY STRUCTURE OF NORMAL MODES IN RANGE-DEPENDENT WAVEGUIDES: NUMERICAL MODELING AND FIELD EXPERIMENT

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Abstract: *Numerical simulation is applied to study a broadband acoustic field formed by a point source at a frequency of 200 to 2000 Hz in range-dependent waveguides with a seasonal thermocline. Two shallow-water waveguide models with varying bathymetry are considered: 1) with a smooth bottom depth variation, 2) with a strong bathymetric feature (barrier). Normal mode theory and parabolic equation simulations are used to study the effect of mode coupling in these scenarios. In the range-dependent waveguide with the strong inhomogeneity, the coupling effect appears in oscillations of modal amplitudes ratio in the frequency domain, and additional modal arrivals in the time domain. These results were confirmed in a field experiment at two 2-km acoustic tracks in the coastal zone of the Japan Sea, where time-frequency structures of normal modes were extracted using correlation processing at a vertical receiving array.*

Keywords: *shallow-water acoustics; broadband signal; inhomogeneous waveguide; parabolic equation; normal modes; mode coupling.*

INTRODUCTION. PROBLEM STATEMENT

Remote sensing of inhomogeneities in the underwater environment is commonly implemented using acoustic signals. This includes the reconstruction of sea bottom properties [1], local relief features, and water layer characteristics. In this study, the focus is made on local inhomogeneities which extent are much smaller than the length of the acoustic track. Previous works have shown that such inhomogeneities can induce a mode coupling effect, leading to oscillations of modal amplitudes in the frequency domain [2]. This effect can be leveraged for acoustic remote sensing in field experiments.

In present study we simulate a broadband acoustic field (200 to 2000 Hz) produced by a point source in shallow-water range-dependent waveguides. Two acoustic tracks with different bathymetries are examined: one with a smooth bottom (Fig. 1a) and another featuring an “underwater barrier” that almost touches the thermocline (Fig. 1b). The objective of this study is to analyse the time-frequency structure of normal modes and detect manifestations of the mode coupling effect in numerical simulations and in a field experiment.

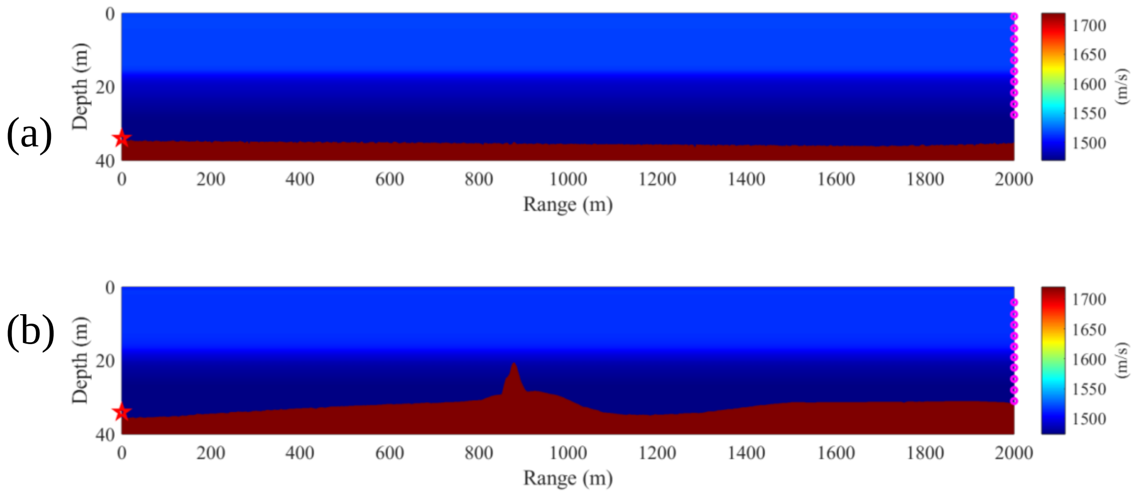

Fig. 1: Waveguide models: (a) with a strong bathymetric feature and (b) with smooth bottom. Red stars mark a point source at depth $z_s = 34$ m. Violet circles at the end of tracks are the receivers of VLA. Sound speed is shown by color. Environmental data were collected in a coastal region of the Japan Sea.

NUMERICAL SIMULATION IN RANGE-DEPENDENT WAVEGUIDES

Pressure field at a given point (x, y, z) with a source frequency f $(\omega = 2\pi f)$ can be represented as a sum of M normal modes [3]:

$$P(\omega, r, z) = \sum_{l=1}^{M(\omega)} A_l(\omega, r)\Psi_l(\omega, r, z)\,, \qquad (1)$$

where $A_l(\omega, r)$ is an l-th mode amplitude, $\Psi_l(\omega, r, z)$ is local mode functions. Using parabolic equation method (RAM) [4] the pressure field $P(\omega, r, z)$ is calculated. Extraction of the local mode amplitudes $\widetilde{A_l}(\omega, r)$ at a receiving array is carried out with local eigenfunctions $\Psi_l(\omega, r, z)$ calculated by KRAKENC [5] according to

$$\widetilde{A_l}(\omega, r) = \int_0^H P(\omega, r, z)\Psi_l(\omega, r, z)\, dz. \qquad (2)$$

This procedure, Eq. (2), was applied both to simulated and experimental data.

If the sound source spectrum $S_0(\omega)$ is known, the time realization of the signal at the receiver can be obtained using the inverse Fourier transform:

$$p(t,r,z) = 2Re\left(\int_{\omega_1}^{\omega_2} S_0(\omega)P(\omega,r,z)e^{i\omega t}d\omega\right). \quad (3)$$

In our modeling, sound source with the uniform spectrum $S_0(\omega) = 1$ is considered.

FIELD EXPERIMENT

The field experiment was conducted in September 2024, in the coastal region of the Japan Sea. Two acoustic tracks had a length R of 2 km (Fig. 1). Bathymetry was measured with an echosounder. A wideband point source, operating over a frequency range of 200 to 2000 Hz [6], was positioned near the bottom at a depth of $z_s = 34$ m. The linear frequency modulated (LFM) signal lasted for 20 seconds was emitted once per minute. Acoustic signals were recorded at a vertical line array (VLA) of hydrophones [7] that spanned the entire water column, with a spacing of 3 meters between recorders (Fig. 1). In total, 30 cycles were transmitted for each of the two tracks, with the time-frequency structures of the normal modes extracted through correlation processing, mode filtering (2) and taking spectrograms (short-time Fourier transform).

Sound speed profiles in the water column were obtained with CTD. During the experiment the seasonal thermocline was observed, and its depth was ≈ 20 m. The characteristics of bottom in the region are taken from [1] and assumed to be constant: density is $\rho_b = 1800$ kg/m^3, sound speed is $c_b = 1740$ m/s, sound attenuation coefficient is $\beta_\lambda = 0.46$ dB/λ.

RESULTS AND DISCUSSION

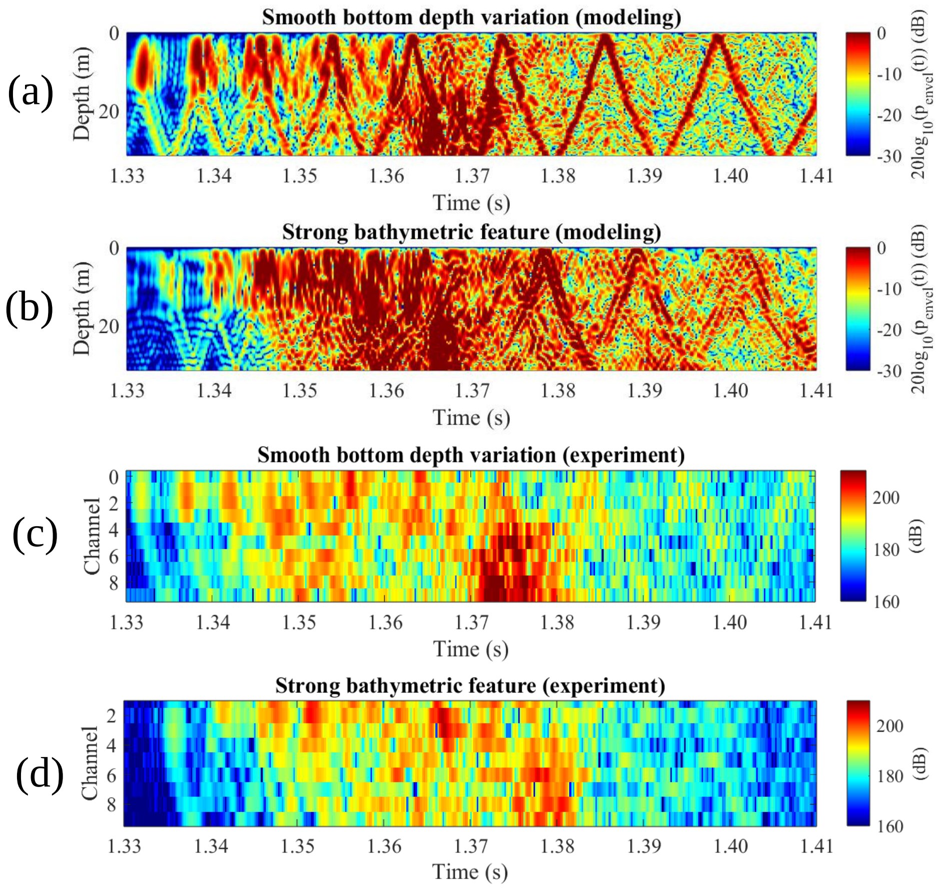

Fig. 2: Spatio-temporal structure of acoustic field $p(t,R,z)$ at the array for 2 tracks shown in Fig. 1; (a) and (b) are the results of numerical simulation. (c) and (d) are the results of the field experiment. The scale is logarithmic.

Figure 2 shows the complicated arrival structure at both tracks. However, first arrivals look similar for two types of waveguides. These arriving rays do not meet the bottom feature and interact with the bottom only near the source. The main part of the received signal is poorly resolved. It is a combination of rays and modes. Analyzing this part of the structure could give information about the presence of the barrier on the track.

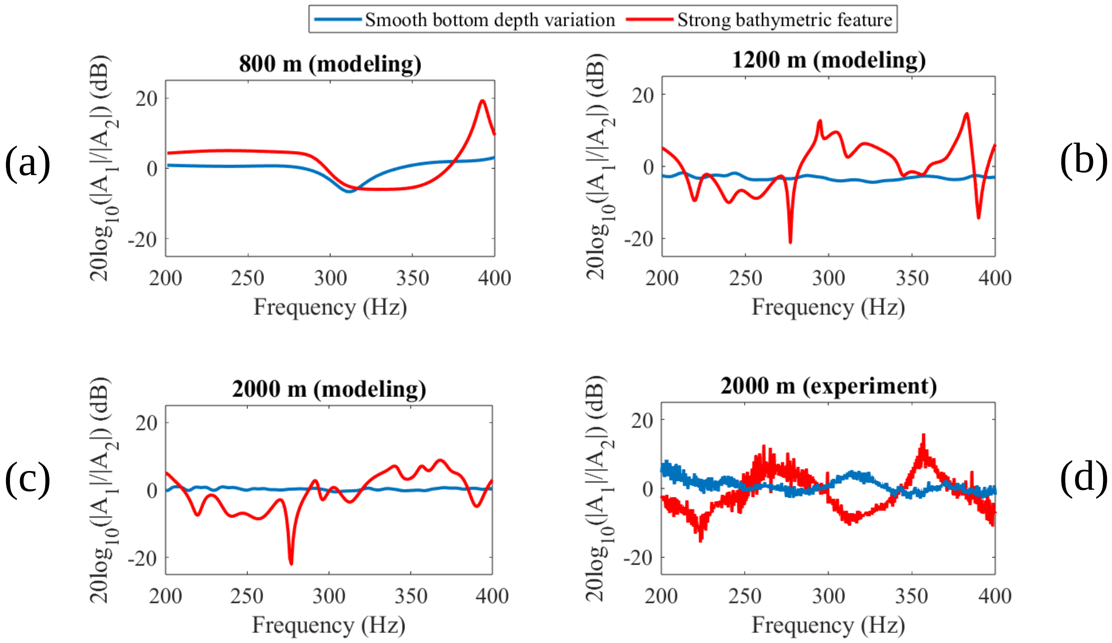

Fig. 3: Ratio of 1-st and 2-nd mode amplitudes on logarithmic scale vs. frequency; (a), (b) and (c) are the numerical simulation results for different ranges from the sound source. (d) is the experimental result for the same range as in (c).

Figure 3 illustrates the amplitude ratio of the first and second modes, $|\widetilde{A_1}/\widetilde{A_2}|$, at different points along the tracks. Note the oscillations of the ratio for the track with a barrier in Figures 3b and 3c, where the barrier is positioned between the source and the VLA (red curve). Conversely, for smooth bottom scenarios (blue curves in all Fig. 3 and red curve in Fig. 3a), the mode coupling effect is negligible. Results from the field experiment (Fig. 3d) show a pattern similar to that from the numerical simulation.

To investigate this effect further, Figures 4 and 5 present the time-frequency mode structures (spectrograms). Figure 4 depicts extracted modes for the waveguide characterized by a strong bathymetric feature, where mode amplitude oscillations in the frequency domain are linked to energy transfer between modes. Some of the "original" (unconverted) modes generate the "derivative" (converted) modes of another numbers after interaction with an inhomogeneity on the track and its manifestation can be seen in mode spectrograms. Following interaction with the barrier, a portion of energy from, e.g. the second mode shifts to the first mode (see Fig. 4a and 4c). Additionally, the seasonal thermocline alters the modal structure, complicating the dispersion curves. At low frequency mode travel time decreases with increasing mode number, resulting in additional earlier arrivals initiated by mode coupling (Fig. 5a and 5c). The observed time difference $\Delta\tau_{1h}$ between earliest (the "derivative" first mode) and main arrival (the "original" first mode) of the first mode is 16 ms in numerical simulation and 20 ms in the experimental data. We can assume that the "original" first mode propagates with a group speed of $V_{gr,1} = 1465$ m/s (sound speed in the water column under the thermocline) while a higher order modes propagates at a speed of $V_{gr,h} = 1515$ m/s (sound speed in the water near the surface), which coupling leads to an earlier arrival of the first mode. The distance between the source and barrier can be estimated as $r_s = \Delta\tau_{1h} V_{gr,1} V_{gr,h} / (V_{gr,h} - V_{gr,1})$, with $r_{s,ex} = 888$ m (experiment result) and $r_{s,mod} = 710$ m (simulation result).

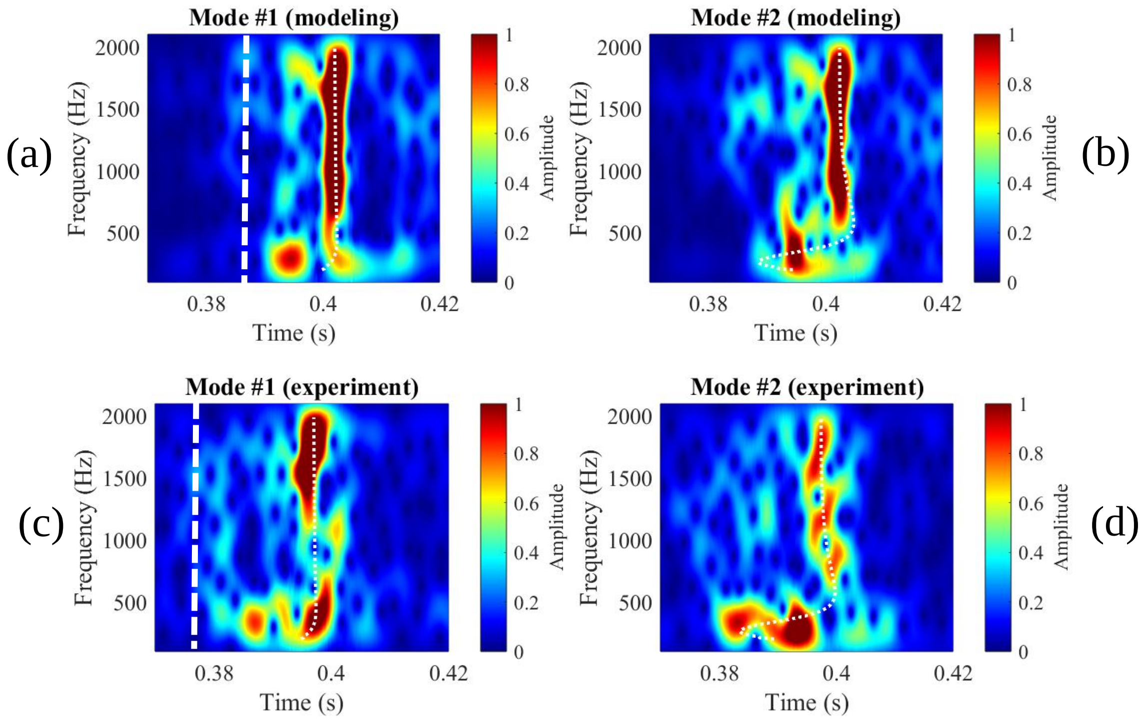

Fig. 4: Time-frequency mode structures for the track with a barrier (Fig. 1b). Top: numerical simulation results for 1-st and 2-nd modes. Bottom: field experiment results for the same modes. Dotted curve is a mode dispersion; dashed line is a mark of the first arrival.

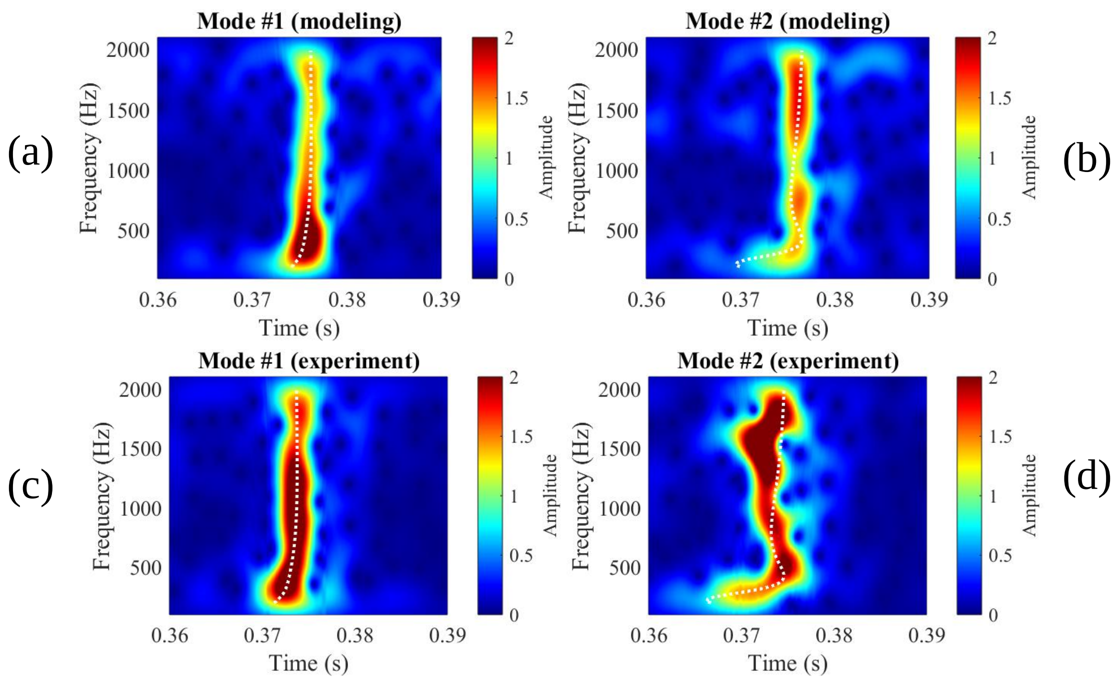

Fig. 5: Time-frequency mode structures for the track with a smooth bathymetry (Fig. 1b). Top: numerical simulation results for 1-st and 2-nd modes. Bottom: field experiment results for the same modes. Dotted curve is a mode dispersion.

CONCLUSION

The simulation of the broadband acoustic field in a range-dependent waveguide with a pronounced bathymetric feature and smoothly varying bottom depths reveals significant effects on acoustic propagation. The presence of a barrier at the acoustic track induces a mode coupling effect. This effect is characterized by oscillations in the modal amplitudes within the frequency domain. Additionally, in the time domain, an increased number of early modal arrivals is observed, which can be used to evaluate the distance between the source and the barrier. These modal features, significant in both frequency and time domains, indicate the complexity introduced by environmental factors like a thermocline and bathymetric variations.

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