

Researches on very low frequency acoustic signal propagation characteristics in different shallow elastic wedge bottoms

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Abstract. Targeted at the issue of extremely low-frequency (<100Hz) acoustic propagation in complex shallow elastic bottom environments. The influence law of different complex elastic bottoms on the acoustic signal propagation at very low frequency by acoustic energy flux has been analyzed with the simulation, which is based on the finite element method. The elastic bottoms which have been studied are the shallow horizontal elastic bottom, and the up-sloping and the down-sloping elastic bottom. The results show that the acoustic signal propagating in the up-sloping and down-sloping elastic bottom environments is more complex than that propagating in the horizontal elastic bottom, and the acoustic energy leaking into those elastic bottoms has very different influence on the acoustic signal propagation, especially in the up-sloping bottom.

1 Introduction

The shallow water environment has attracted more attention in the current study of the underwater acoustics application. In the study of traditional shallow water environment simulation, the Pekeris waveguide has been used to analyse the acoustic propagation. However, in fact, the influence of the acoustic signal propagating in the shallow sloping elastic bottom environment is more complex than that of the acoustic signal propagating in the horizontal shallow water environment. The research on the acoustic signal propagation characteristics in the sloping shallow water environment has therefore been emphasized.

To study the acoustic signal propagation characteristics in the sloping shallow water environment, we have conducted the simulated analysis on the influence laws of different complex elastic bottoms on the low-frequency acoustic signal propagation with the help of acoustic energy flux[1,2] and a commercial finite-element code FEM[3,4] developed by COMSOL AB. Because FEM solves the sound field problem by dividing the environment into discrete units, it can solve the complex sound propagation problem more accurate than the traditional method which is solved by equations and boundary conditions.

2 Calculation of acoustic energy flux in the waveguide

In the past conventional modelling of the vector sound field, the study on the sound field energy change characteristics is almost based on sound pressure. However, the acoustic energy flux is more suitable for analysing the law of acoustic propagation, and the acoustic energy flux has been used to analyse the acoustic propagation in different complex shallow elastic bottom environments.

The sound energy flux in the time domain and in the isotropic elastic media environment can be defined as Eq (1),

$$I(t) = \begin{pmatrix} I_r(t) \\ 0 \\ I_z(t) \end{pmatrix} = \begin{pmatrix} \left[\begin{matrix} T_{rr}(t) & 0 & T_{rz}(t) \\ 0 & 0 & 0 \\ T_{rz}(t) & 0 & T_{zz}(t) \end{matrix} \right] \begin{bmatrix} v_r(t) \\ 0 \\ v_z(t) \end{bmatrix} \end{pmatrix} \quad (1)$$

where $I_r(t)$ is the sound energy intensity in r direction and $I_z(t)$ is the sound energy intensity in z direction. $T_{rr}(t)$ is the stress in r direction and $T_{zz}(t)$ is the stress in z direction. $T_{rz}(t)$ and $T_{rz}(t)$ are the stress in rz direction. $v_r(t)$ is the vibration speed in r direction, and $v_z(t)$ is the vibration speed in z direction. Those are all in the elastic bottom.

According to the Parseval Theorem, the signal energy in the time domain is equal to the one in the frequency domain. The sound energy flux in the frequency domain can be defined as Eq (2),

$$I(\omega) = \begin{pmatrix} I_r(\omega) \\ 0 \\ I_z(\omega) \end{pmatrix} = \begin{pmatrix} \left[\begin{matrix} T_{rr}(\omega) & 0 & T_{rz}(\omega) \\ 0 & 0 & 0 \\ T_{rz}(\omega) & 0 & T_{zz}(\omega) \end{matrix} \right] \begin{bmatrix} v_r(\omega) \\ 0 \\ v_z(\omega) \end{bmatrix} \end{pmatrix}^* \quad (2)$$

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where the “*” is the complex conjugation. Considering the acoustic energy propagation in the elastic bottom, we can define the intensity and propagation direction of sound energy flux as Eq (3).

$$I = \sqrt{\{\text{Re}[I_r(\omega)]\}^2 + \{\text{Re}[I_z(\omega)]\}^2}$$

$$\theta_l = \arctan \left\{ \frac{\text{Re}[I_z(\omega)]}{\text{Re}[I_r(\omega)]} \right\} \quad (3)$$

Because of $\mu=0$, $T_{rz}=T_{zr}=0$ and $T_{rr}=T_{zz}=\lambda^2\varphi=p$ in the fluid layer, the acoustic energy flux can be defined as Eq (4),

$$I(\omega) = \begin{bmatrix} I_r(\omega) \\ 0 \\ I_z(\omega) \end{bmatrix} = \begin{bmatrix} p v_r^* \\ 0 \\ p v_z^* \end{bmatrix} \quad (4)$$

where $I_r(\omega)$ is the sound energy intensity in r direction and $I_z(\omega)$ is the one in z direction. p is the sound pressure in r direction. v_r is the sound speed in r direction, and v_z is the sound speed in z direction. Those are entirely in the water layer.

The transmission loss of the sound energy flux in the water layer and the elastic seafloor can be defined as Eq (5),

$$TL_p = -20 \lg \left| \frac{p(r, z, \omega)}{P_{ref}|_{r=1m}} \right|, P_{ref} = \frac{e^{ik_0 r}}{r}$$

$$TL_v = -20 \lg \left| \frac{v(r, z, \omega)}{V_{ref}|_{r=1m}} \right|, V_{ref} = \frac{1}{\rho c} \frac{e^{ik_0 r}}{r} \quad (5)$$

where the TL_p is the transmission loss of sound energy flux in the water layer and the TL_v is the one in the elastic bottom.

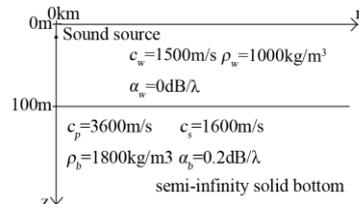
3 Study on acoustic propagation characteristics of elastic bottom environments

We aim to study the acoustic signal propagation on different shallow elastic bottom environments. Environment models such as the horizontal elastic bottom, the up-sloping elastic bottom and the down-sloping elastic bottom have been numerically simulated and are illustrated in Fig.1.

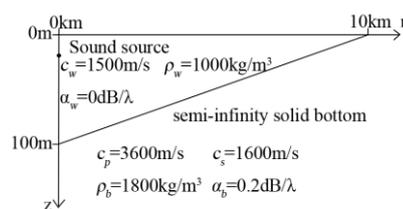
Fig.2 shows the propagation of acoustic energy flux in these three different elastic bottom environments when the source frequency is 50Hz and source depth is 50m.

Fig.2(a) shows the propagation of acoustic energy flux in the horizontal elastic bottom environment. When the acoustic signal propagates in the close range, the acoustic energy goes up and down intensely, and there are many acoustic energy leakages into the elastic bottom. When the acoustic signal propagates in the far range, the acoustic energy goes up and down regularly. There is no acoustic energy leakage into the elastic bottom, and the acoustic energy can propagate in the water-bottom boundary. Fig.2(b) and Fig.2(c) are the propagation of acoustic energy flux in the up-sloping and

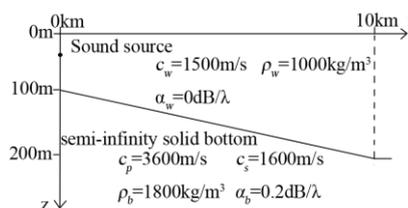
down sloping elastic bottom environments. The acoustic energy propagating in near range resembles the result of Fig.2(a). But when they propagate in the far range, the acoustic energy leaks into the elastic bottom, and the acoustic energy leaking into the up-sloping elastic bottom exceeds the amount leaking into the down-sloping elastic bottom.



(a) The shallow horizontal elastic bottom environment model used in the numerical simulation



(b) The shallow up-sloping elastic bottom environment model used in the numerical simulation



(c) The shallow down-sloping elastic bottom environment model used in the numerical simulation

Fig. 1. The shallow elastic bottom environment model used in the numerical simulation.

The normal-mode theory[5-8] is that when the horizontal distance is farther, the depth in the up-sloping elastic bottom is shallower. The normal mode in the waveguide produces the energy of the coupled normal mode in the non-waveguide, and then it becomes the coupled normal mode in the non-waveguide and leaks more acoustic energy into the up-sloping bottom. Besides, in the down-sloping elastic bottom, it is found that when the elastic bottom is deeper, the normal mode in the waveguide fails to change into the normal mode in the non-waveguide, and couldn't leak much acoustic energy into the down-sloping elastic bottom. But with the change of the bottom topography, the normal mode in the waveguide can still produce the energy of the coupled normal mode in the non-waveguide, and leak into the down-sloping elastic bottom in the far range. In the horizontal elastic bottom environment, the normal mode in the non-waveguide only leaks in the near range.

After the analysis on transmission laws of acoustic propagation in different elastic bottom environments, we will analyse the transmission law of acoustic propagation in up-sloping and down-sloping elastic bottom environments with different tilt angles in 2.1 and 2.2.

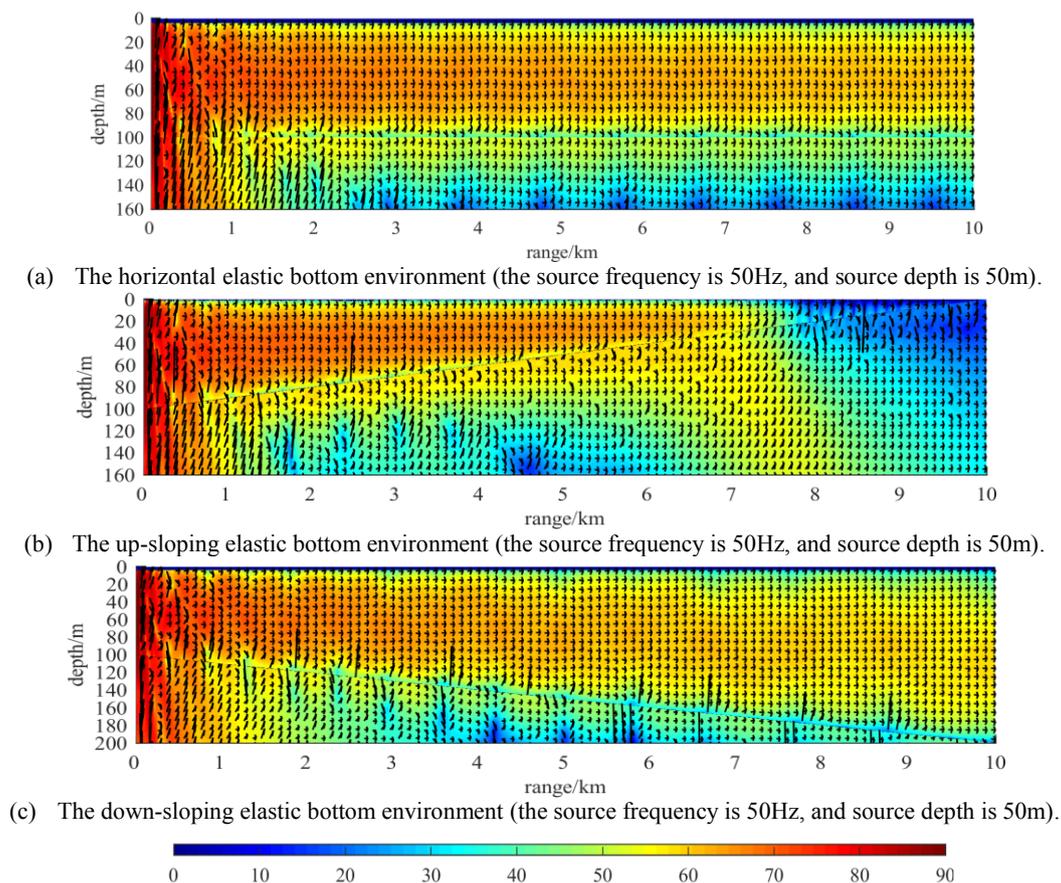


Fig. 2. The propagation of acoustic energy flux in different elastic bottom environments.

2.1 Study on acoustic propagation characteristics of up-sloping elastic bottom environments

In order to research the acoustic propagation characteristics of up-sloping elastic bottom environments with different tilt angles, the tilt angle of the up-sloping elastic bottom has been altered under Fig.1(b). The elastic bottom topographic parameters in up-sloping elastic bottom environments are illustrated in Table 1.

Fig.3 and Fig.4 are the propagation of acoustic energy flux in up-sloping elastic bottom environments with the slop 1 and slop 2 bottom. When the source frequency is 50Hz and 100Hz, the source depth is 50m.

Fig.3 and Fig.4 show the propagation of acoustic energy flux in different up-sloping elastic bottom environments. The results show that the acoustic signal propagates in the close range when the sound frequency is 50Hz and the source depth is 50m. When the angle of the up-sloping elastic bottom is greater, distances of the acoustic energy going up and down intensely are shorter and more acoustic energy leaks into the elastic bottom. If the angle of the up-sloping elastic bottom becomes larger when the acoustic signal propagates in the far range, it owns larger energy and acoustic energy that leaks into the elastic bottom is smaller.

When the sound frequency increases from 50Hz to 100Hz, the acoustic signal goes up and down more intensely in the near range, and the acoustic energy can keep more energy when acoustic propagation happens in the end of the up-sloping elastic bottom. Besides, the acoustic energy that leaks into the up-sloping elastic bottom in more places has been found.

Table 1. The elastic bottom topographic parameters in up-sloping elastic bottom environments.

	Sea Bottom coordinate 1	Sea Bottom coordinate 2
Slop 1	(0km, 100m)	(6000m, 0m)
Slop 2	(0km, 100m)	(8000m, 0m)

2.2 Study on acoustic propagation characteristics of down-sloping elastic bottom environments

We tend to research the acoustic propagation characteristics of down-sloping elastic bottom environments with different tilt angles. The tilt angle of the down-sloping elastic bottom has been changed under Fig 1(c). In addition, the elastic bottom topographic parameters in the bottoms are illustrated in Table 2.

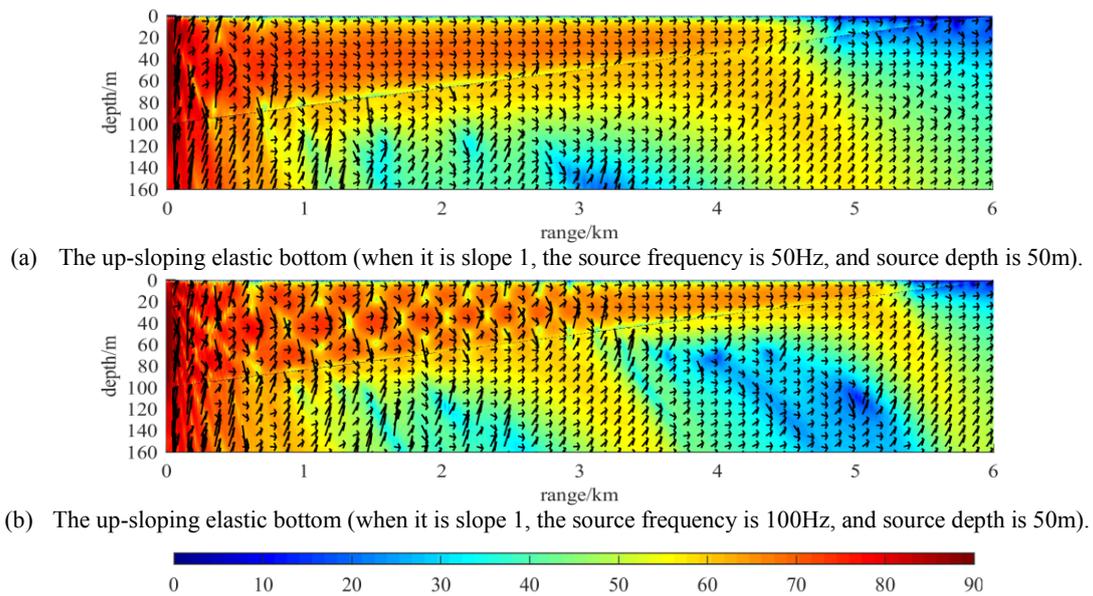


Fig. 3. The propagation of acoustic energy flux in the slope 1 up-sloping elastic bottom environments.

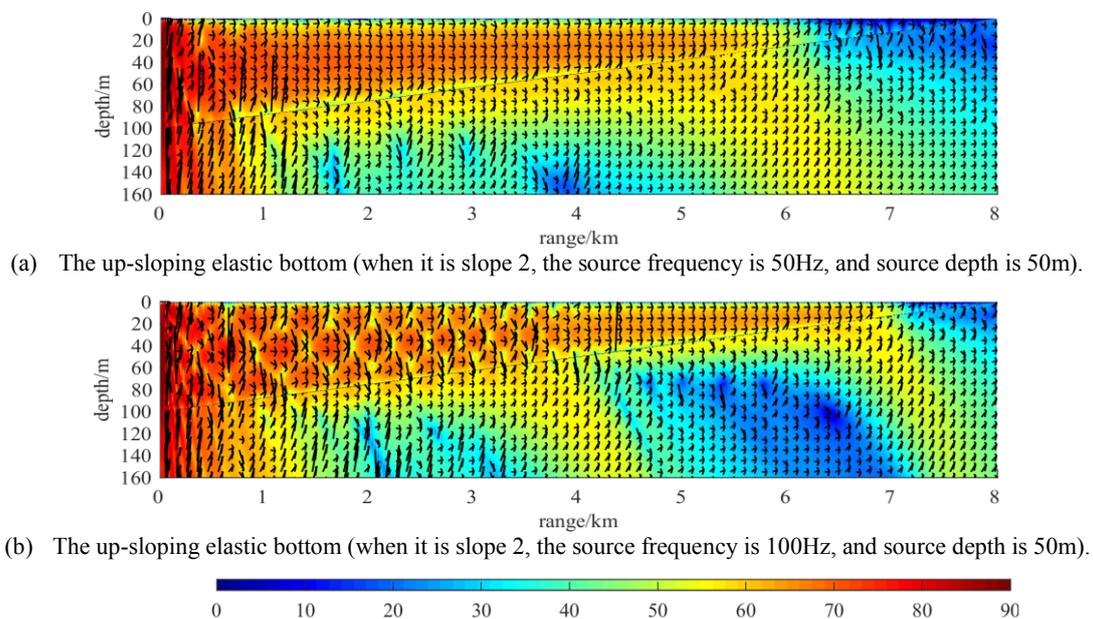


Fig. 4. The propagation of acoustic energy flux in the slope 2 up-sloping elastic bottom environments.

Table 2. The elastic bottom topographic parameters in down-sloping elastic bottom environments.

	Sea Bottom coordinate 1	Spacing
Slop 1	(0km, 100m)	(6000m, 200m)
Slop 2	(0km, 100m)	(8000m, 200m)

Fig.5 and Fig.6 are the propagation of acoustic energy flux in down-sloping elastic bottom environments with the slope 1 and slope 2 bottoms. As the sound frequency is 50Hz and 100Hz, source depth is 50m.

Fig.5 and Fig.6 show the propagation of acoustic energy flux in disparate down-sloping elastic bottom environments. The results illustrate that the acoustic signal propagates in the close range when the sound

frequency is 50Hz and the source depth is 50m. When the angle of the down-sloping elastic bottom is greater, acoustic energy that leaks into the elastic bottom and the range are larger. In addition to that, the acoustic energy goes up and down more intensely when the acoustic signal propagates in the far range. With the increase of the angle of the down-sloping elastic bottom, the acoustic energy ascends and descends more slowly and there is more energy leaking into the elastic bottom.

When the sound frequency increases from 50Hz to 100Hz, the acoustic energy leaks more into the up-sloping elastic bottom in the near range, and the acoustic signal propagates in the far range with more complex laws. The acoustic energy, which leaks into the elastic bottom will propagate more near the water-bottom boundary.

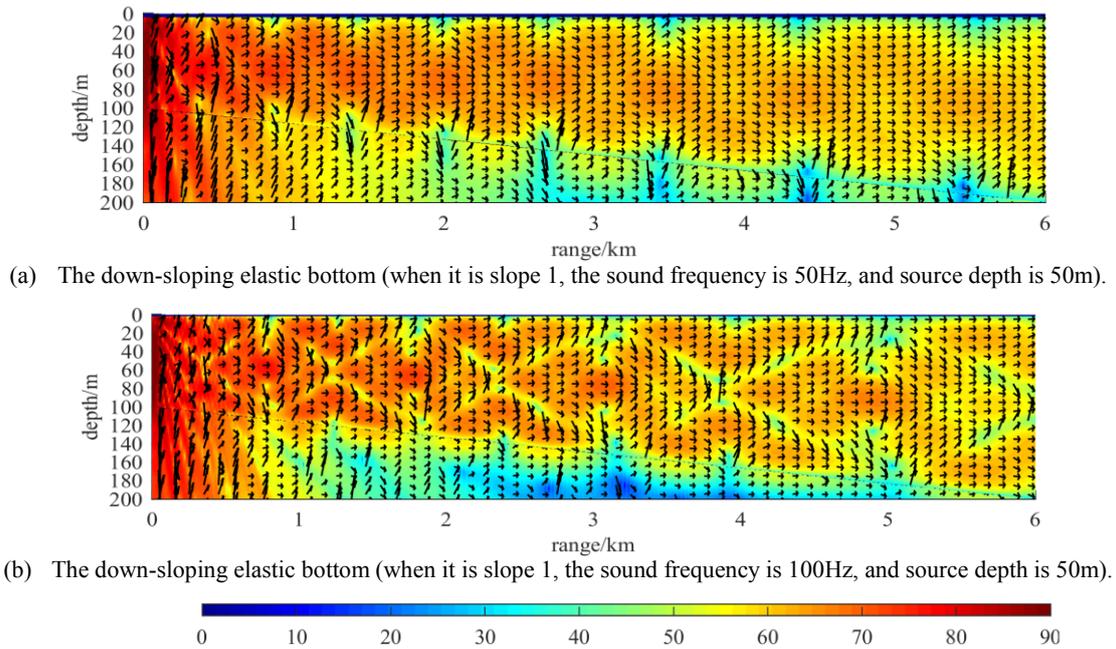


Fig. 5. The propagation of acoustic energy flux in the slop 1 down-sloping elastic bottom environments

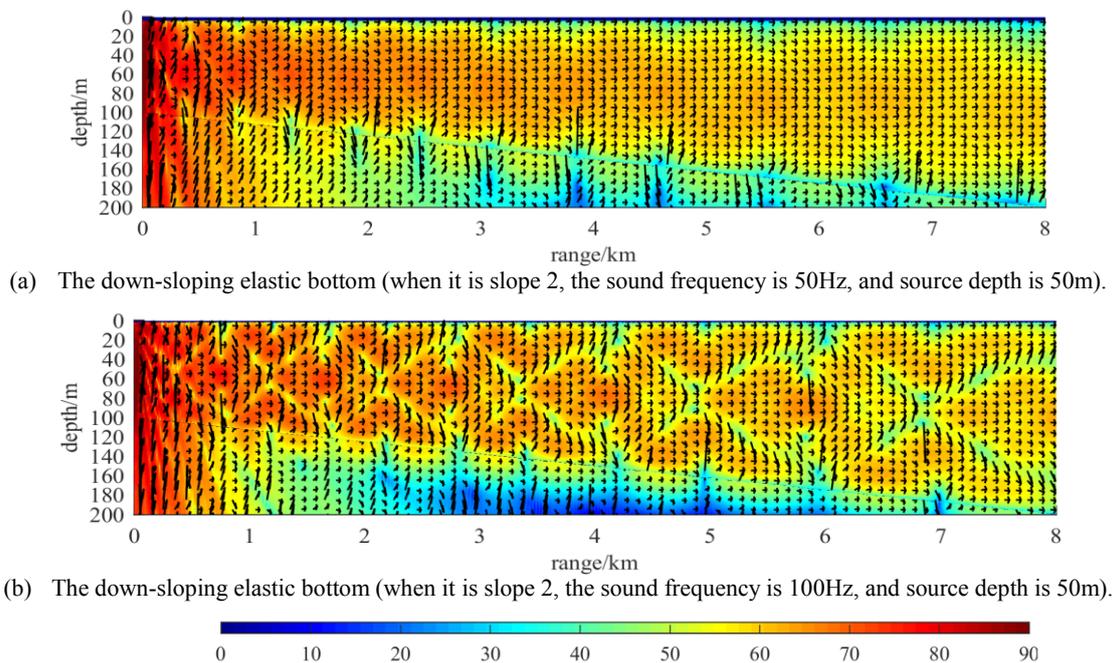


Fig. 6. The propagation of acoustic energy flux in the slop 2 down-sloping elastic bottom environments

3 Conclusions

The acoustic energy flux propagating in different complex elastic boom environments has been simulated on the FE method.

The result shows that the cutoff depth of the waveguide normal wave is related to the sea depth and sound frequency. In different tilt angles of the elastic bottom of the up-sloping elastic bottom environments, the cut-off depth corresponds to different horizontal positions in the same sound frequency. It makes the acoustic energy leak in different positions into the bottom and influences the energy distribution. When we

increase the sound frequency, the position of acoustic energy leaking into the bottom has been enhanced, and the cut-off depth has been shallower. The waveguide normal wave produced is more and farther than before.

In the down-sloping elastic bottom environments the acoustic energy converts to the normal mode in the non-waveguide incompletely. The acoustic energy leaking into the down-sloping elastic bottom is less than that leaking into the up-sloping elastic bottom. In the larger sound frequency, the acoustic energy attenuates faster than before. Thus, the acoustic energy propagates near the water-bottom boundary in the bottom when the sound frequency is 100Hz.

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