Influence of Mesoscale Vortex on Underwater Low-Frequency Sound Propagation

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Abstract. To discuss the effect of an ocean mesoscale vortex on underwater low-frequency sound propagation, a theoretical model of a sound field under the action of an ocean mesoscale vortex was established based on acoustic wave theory and ray theory, using the finite element method. The influences of vortex properties and vortex intensity on the characteristics of sound propagation are discussed. The simulation results indicate that, in a cold vortex, the acoustic convergence zone moves toward the sound source, the span of the convergence zone decreases, and the convergence gain increases. Alternatively, for a warm vortex, the convergence zone moves away from the sound source, the span of the convergence zone increases, the sound rays diffuse, and the convergence gain decreases; the greater the vortex intensity, the greater is the effect on the motion and gain of the convergence region.

1. Introduction

Ocean mesoscale vortexes are a common phenomenon in oceans. As one of the primary forms of ocean heat and kinetic energy transfer, mesoscale vortexes are analogous to cyclones and anticyclones in the atmosphere. They are divided into cold and warm vortexes, where the former is a cyclone and the latter an anti-cyclone. The horizontal scale of a mesoscale vortex can reach several hundred kilometres, while the time scale can range from several days to several months. Moreover, they directly affect the temperature–salt structure and velocity distribution of marine environments and also transfer momentum and heat with a greater impact on physical properties of the upper waters of oceans; this, in turn, strongly influences the sound propagation law in deep-sea waveguides [1-2]. Therefore, studying the influence of mesoscale vorticity on sound propagation characteristics is of great significance for sonar detection and underwater engineering technology.

The sound pressure field can reflect the propagation loss characteristics of underwater sound energy, and the sound rays [3-4] can reflect the sound propagation direction and deflection of sound energy. Therefore, a theoretical model of sound field calculations under the action of an ocean mesoscale vortex is established based on acoustic wave theory and ray theory, using the finite element method (FEM). Utilizing this model, the influences of vortex properties and strength on the
characteristics of low-frequency sound propagation are discussed, with a view to providing ocean exploration and research help.

2. Mesoscale Vortex Model
This study mainly uses the Gaussian vortex model to describe a mesoscale vortex in the ocean, discussing the effect of the vortex on sound propagation. The sound velocity of the model is expressed as the following formula (1-3). [5–8]

\[ c(r, z) = c_0(z) + \Delta c(r, z) \]  
\[ c_0(z) = 1500[1 + 0.00737[e^{-\eta} - (1 - \eta)]] \]  
\[ \Delta c(r, z) = DC*exp[-\left(\frac{r-Re}{DR}\right)^2 - \left(\frac{z-Ze}{DZ}\right)^2] \]

In the formulae, \( \eta = 2*(z-1000)/1000 \), and \( DC \) is the vortex intensity, that is, the maximum sound velocity difference between the vortex centre and extension; a negative difference implies a cold vortex, whereas a positive difference implies a warm vortex. \( DR \) is the horizontal radius of the vortex, \( DZ \) is the vertical radius of the vortex, \( Re \) is the horizontal position of the vortex centre, and \( Ze \) is the vertical position of the vortex centre.

3. Simulation of the Effects of Mesoscale Vortex on Underwater Sound Propagation
3.1. Simulation of the Effect of Mesoscale Vortices on the Sound Velocity Gradient in Seawater
Mesoscale vortexes affect the sound velocity distribution in seawater, deflect the propagation of sound rays and sound energy, and alter the distribution of underwater sound fields. For the Gaussian vortex model of appeal, the parameters of the vortex are set as \( DR = 20 \) km, \( DZ = 400 \) m, \( Re = 25 \) km, and \( Ze = 400 \) m. Figures 1 and 2 present the sound velocity contours and sound velocity profiles, respectively, at \( DC = 0, -20, -50, 20, \) and \( 50 \) m/s.

![Figure 1](image_url)

**Figure 1.** Contour diagrams of sound velocities with different vortex properties.
As seen in this comparison, the centre of the warm vortex is the region of the maximum value of sound velocity and the centre of the warm vortex is the region of the minimum value of sound velocity; the greater the vortex intensity, the denser are the contours of velocity and the greater is the gradient of velocity. This indicates that the Gaussian vortex model can describe mesoscale vortexes in the ocean.

### 3.2. Simulation of the Effect of Vortex Properties on Sound Propagation

The parameters of the vortex do not change and are set at a sound source frequency of $f = 100$ Hz; the depth of the sound source is $H = 100$ m. The reference sound velocity of the seawater layer is $c_0 = 1500$ m/s, and the density is $1000$ kg/m$^3$; the sound velocity of the seabed is $c = 1700$ m/s, its density is $2000$ kg/m$^3$, and the absorption coefficient is $0.5$ dB/$\lambda$. Figure 3 presents the two-dimensional sound pressure diagram and sound line diagram at $DC = 0$, $−20$, and $20$ m/s. Figure 4 depicts the comparison of sound propagation loss for a receiving depth of $100$ m in the presence of several types of vortices with different properties and in the absence of a vortex.
Comparing the sound propagation loss and sound ray diagrams in figure 3(A) and (B), it can be seen that the cold vortex moves the sound converging area toward the sound source and away from the sea surface; moreover, the span of the condensing area decreases, sound rays concentrate in the convergent area, and convergent gain increases. Comparing the sound propagation loss and sound line diagrams in figure 3(A) and (C), it is evident that the warm vortex moves the sound convergent area away from the sound source and toward the sea surface; furthermore, the span of the condensing area increases, sound rays spread, and convergence gain decreases. A comparison of the sound propagation loss curves in figure 4 indicates that the convergence area appears first when there is no vortex in the cold vortex ratio, and the width of the convergence area is less than that in the same case. The width of
the convergent convergence zone, while the warm vortex is just the opposite. Considering the second convergent area as an example, when $DC = 0$ m/s, the second convergent area is approximately 26 km horizontally and has a span of 13 km; when the centre of the vortex is at 25 km, the cold vortex moves the convergent area closer to the sound source, and the span of the condensing area is reduced. The second convergent zone has a horizontal distance of approximately 23 km and a span of 11 km. In the warm vortex, the convergent zone moves away from the sound source, the span of the convergent zone increases, and the second convergent zone has a horizontal distance of approximately 28 km, increasing the span to 15 km.

3.3. Simulation of the Effect of Vortex Intensity on Sound Propagation

In order to discuss the effects of $DC = -20, -50, 20, \text{ and } 50$ m/s on the sound propagation characteristics, only the intensity of the vortex is altered; the other parameters remain unchanged. Figure 5 shows the two-dimensional sound pressure diagram and sound line diagram for $DC = -50$ m/s and 50 m/s. Figure 6 depicts the sound at a reception depth of 100 m, when two vortices with different properties and different intensities are considered; a comparison chart of the propagation loss is presented.

![Figure 5. Sound propagation loss and ray diagrams of different vortex intensities.](image-url)
On comparing figures 5(B), 3(C), and 6(B), it is evident that, in the warm vortex, the sound concentrating area moves away from the sound source and toward the sea surface, the span of the concentrating area increases, the sound rays diffuse, and the convergence gain decreases; moreover, as the vortex intensity increases, the sound convergence zone moving away from the sound source becomes more apparent and the sound ray diffusion increases. Comparing figures 5(A), 3(B), and 6(A), it can be seen that, in the cold vortex, the sound concentrating area moves toward the sound source and away from the sea surface, the span of the concentrating area is reduced, the sound rays are more concentrated, and the convergence gain increases; moreover, as the vortex intensity increases, the sound convergence zone moving toward the sound source becomes more evident and the convergence gain increases. This sound propagation characteristic is observed because (1) the centre temperature of the cold vortex is lower than the periphery temperature of the vortex, speed of sound has a negative gradient, sound rays are deflected toward the centre of the vortex, convergence gain of sound rays increases, and location of the sound convergence zone is reflected by the seabed near the sound source; and (2) the centre temperature of the warm vortex is higher than the periphery temperature of the vortex, speed of sound has a positive gradient, sound rays diffuse from the centre of the vortex, and converging area approaches the sea and moves away from the sound source.

4. Conclusion
A theoretical model for sound field calculations under the action of ocean mesoscale vortexes was established based on acoustic wave theory and ray theory, using the FEM. The influences of vortex properties and strength of the acoustic propagation characteristics were discussed; as a result, the following conclusions were obtained:

When the cold vortex centre lies in the convergent zone, the acoustic convergent zone moves away from the sea surface and closer to the sound source, the span of the condensing zone is reduced, and the convergence gain is increased. When the warm vortex centre lies in the convergent zone, the convergent zone moves closer to the sea surface and away from the sound source, the span of the convergence zone increases, sound rays diffuse, and the convergence gain decreases. Moreover, the greater the vortex intensity, the greater is the impact on the movement and gain of the convergence zone.

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