Change of pulses propagating in SOFAR Channel by moving front

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ABSTRUCT

A propagation path of sound wave in a deep sea may contain some inhomogeneities, such as sea currents, ocean front and mesoscale eddies. Effects of such inhomogeneities on the sound wave propagation are studied by using the wave theory. We assume three SOFAR propagation areas as a sound propagation environment. The first and the third areas have different SOFAR axes and are a range-independent area. The second area between them is a transfer area in which sound speed profile changes gradually. The transfer area consists of six sub-areas whose SOFAR axes deepen gradually at a certain rate. Assuming the movement of inhomogeneity such as ocean front, the boundary between the first area and the transfer area is moved in the direction of range, and the resulting changes in time of propagated pulses are obtained. As a result we show that propagation time of eigenray changes periodically with movement of transfer area and that the period corresponds to the cycle range of the eigenray.

1. Introduction

The ocean acoustic tomography [1] is a technique to measure a distribution of temperatures over large regions of the ocean by accurately measuring propagation time of sound waves that propagate through the ocean. A number of transducers consisting of a sound source and a receiver are installed around the sea area to be measured. Propagation times of sound waves that propagate between these transducers are measured accurately. Measured changes in propagation time are converted to changes in temperature distribution through inverse problem analysis. In these analyses, the propagation path of an eigenray is usually assumed to be unchanged, and the difference in propagation time for a pulse is converted to the difference in temperature. However, the ocean contains many inhomogeneous media such as sea current, oceanic front, eddy, and microstructure. Those inhomogeneities have strong effects on the paths of sound wave propagation, making it difficult to process signals for the ocean acoustic tomography, and particularly to identify eigenrays.

The propagation of sound waves in a SOFAR channel has been studied for many years, but not many studies have been done on propagation in the sea area where its sound speed profile changes rapidly in horizontal direction (for example, mesoscale eddy and ocean front). Robinson et al. [2] calculated the propagation loss for a propagation path across a sea current. Baer [3] calculated the propagation loss of a propagation path through mesoscale eddy and showed that it varies significantly with depth. But they did not calculate the propagation time. In the ocean acoustic tomography, the change in propagation time is more important than the change in propagation loss.

We previously [4] calculated the propagation times for the eigenrays as a function of position of boundary with changing sound speed profile, in a SOFAR channel consisting of three sound speed profiles. As a result we made it clear that the propagation pulses are changed periodically along with the change in boundary. We also showed that the trace of propagation time with respect to incidence angle of eigenray to the boundary draws a circle.

In this paper, we studies the propagation time of pulses by changing sound speed profile of boundary area gradually to better approximate a real sea area. Usually the ray theory is used when the received pulses are to be identified in the ocean acoustic tomography. But for an area where the sound speed profile changes in a complicated way, it may be difficult to apply ray theory. We use the parabolic equation method to analyze sound wave propagation.

2. STRUCTURE OF SIMULATED AREA

2.1 Sound Speed Profile

In this paper, sound wave propagations in a mid-latitude deep-sea area are simulated. All the sound speed profiles in the assumed sea area are of Munk type, which is a typical type in SOFAR propagation sea area.

Sound speed $c(z)$ of the Munk-type sound speed profile is expressed as a function of depth z as follows [1]:

$$c(z) = c_a[1 + \boldsymbol{e}(\boldsymbol{h} + e^{-h} - 1] \qquad (1)$$

$$\boldsymbol{h} = (z - z_a) / (B / 2),$$

where c_a is the sound speed at the depth of SOFAR axis z_a, and B is a constant.

To approximate a sound speed profile in a mid-latitude, we set c_a=1482m/s, and B=1300. Usually . is set to be a constant value, but to make it closer to the actual sound speed profile, we set the value of . above the SOFAR axis at 0.018 and the value below the axis 0.008. The depth of sea floor is all 5000m. Figure 1 shows the Munk profile with the SOFAR axis depth z_a being 650m.

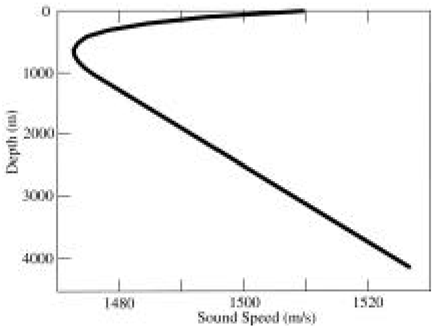

Fig. 1. Sound speed profile used simulation, so-called Munk type profile.

2.2 Three Area Structure

We assume a sound wave propagation environment in which the depth of SOFAR axis increases from shallow areas to deep areas. The environment consists of three areas: area1, area2 and area3, as shown in Fig.2. The sound speed profile in area1 and area3 do not depend on range. Area2 is a transfer area, in which the sound speed profiles are changed stepwise with respect to range. That is, this area consists of six step zones, and the sound speed profile in each step zone is constant. Each step zone has equal horizontal range r_s. The range r_s is set to 2, 5, 10 and 20km to change the extent of the transfer area. The depth of SOFAR axis of the sound speed profile in each zone deepens gradually, from 650m in area1 to 1000m in area3. The depth of axis in the step zones in the transfer area increases by 50m for each step.

The total propagation range from the source in area1 to the receiver in area3 is 300km. To move the boundary between area1 and area2, we change the horizontal range of area1 from 50 to 150km. Since the range of area2 is held at a fixed value (6xr_s), the range of area3 is changed with the change in range of area1.

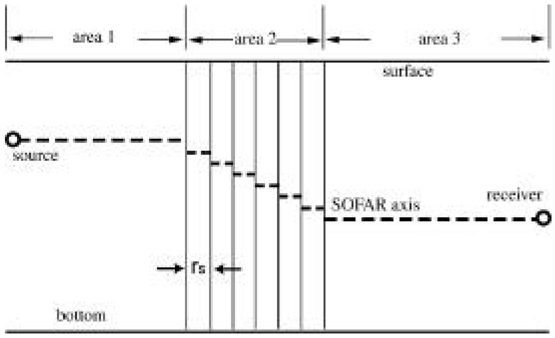

Fig. . Sound speed structure of SOFAR area consists of three area having different axis of SOFAR. Area1 and area3 are range-independent area, arear2 is transfer area.

3. SIMULATED RESULTS

3.1 Selection of Received Pulses

The ocean acoustic tomography that Japan Marine Science and Technology Center is doing in actual sea areas uses pulses around 200Hz. Therefore, using the sound speed profile shown in Fig.1 and using the wave theory, we generate a pulse sequence that are received by the receiver on the axis 300km away from the sound source placed on the SOFAR axis. First, we obtain the sound pressures of sound waves that propagated from the sound source to the receiving point for each frequency from 187.5Hz to 212.5Hz by 0.1Hz in frequency area. Next, the obtained sound pressure spectrum at receiving point is converted to the pulse sequence in time area by inverse Fourier transformation. Figure 3 shows the pulse sequence obtained in such a way. This pulse sequence contains a series of groups consisting of 4 pulses, followed by pulses with large amplitudes at last. The last pulses are those that propagated around the SOFAR axis. They are close to each other, so it is difficult to separate them. When the ray theory is applied to the pulses within a group, the pulse that arrives first corresponds to the ray that is transmitted from the sound source with a negative angle and, after n-1 turns, arrives at the receiver with a positive angle. The two pulses that arrive next correspond to the two rays that are transmitted from the sound source with positive and negative angles of the same magnitude and, after n turns, arrive at the receiver with the same angle (in opposite signatures). The pulse that arrives fourth corresponds to the ray that is transmitted from the sound source with a positive angle and, after n+1 turns, arrives at the receiver with a negative angle. Such pulse group is the distinctive feature of SOFAR propagation and the pulses in the group are easy to separate. Therefore we select two pulse groups P_1-P_4 and P_5-P_8 for our study.

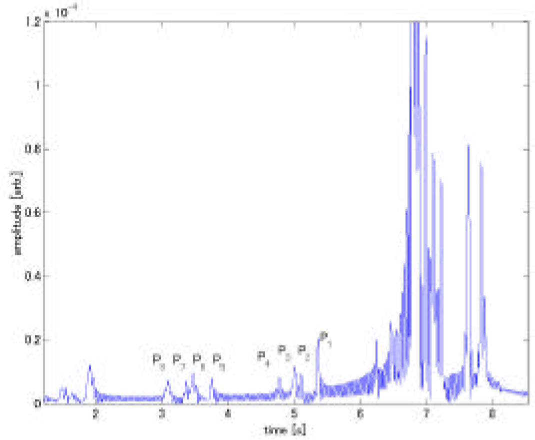

Fig. 3. Pulse sequence received on SOFAR axis at range of 300 km from source.

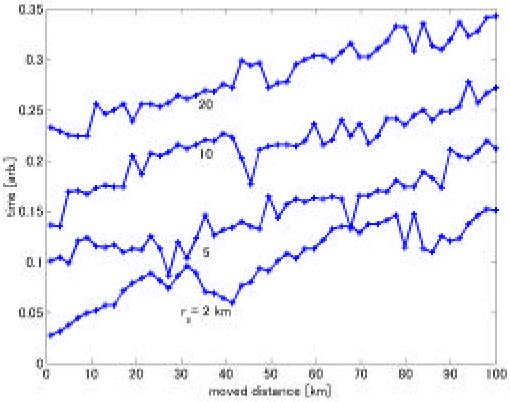

Fig. 4. Changes of propagation time for pulse P_1 shown in Fig. 3. Horizontal axis is the moved distance of the boundary between area1 and area2.

3.2 Changes in Propagation Time

In this section, the change of the propagation time of the pulse is obtained when the range of area1 is incremented from 50km to 150km by

2km. The extent of the change of the transfer area is changed by selecting the width of step zone r_s in area2, (2, 5, 10, 20km). Figure 4 shows the change in propagation time of the pulse P_1 for each r_s .In order to make it legible, each curves are shifted a fixed value. It is seen that the propagation time for r_s =2km changes periodically while increasing with distance and the one cycle range of the curve is about 50km. It is considered that the curves of propagation times for larger r_s include more complicated periodicity. Figure 5 shows the time variations of the pulses P_1, P_4, P_5 and P_8 against moved range of the boundary in the case of r_s =2km. It is seen that the curves for the pulse P_1 and P_4 show the same change and it is the same to the pulse P_5 and P_8. However, the peak distances of the curve for the pulse P_1 and P_5 differ greatly, and one cycle range of the curve for the pulse P_5 is about 40km. It is considered that the incidence angle of the equivalent eigenray to the boundary differs in each other. The curves for the pulse P_2 and P_3 have larger changes than those for the pulse P_1 because of the interference of the pulse P_2 and P_3.

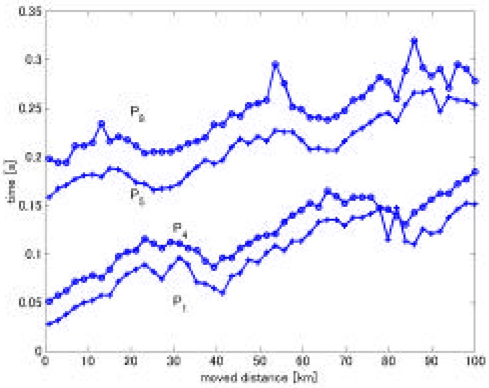

Fig. 5. For the case of r_s=2km, the changes of propagation time for pulses P_1, P_4, P_5 and P_8 shown in Fig. 3. Horizontal axis is the moved distance of the boundary between area1 and area2.

3.3 Changes of Pulse Amplitude

When the range of area1 is incremented from 50 km to 150 km by 2 km, the change of the pressure amplitude of the pulse P_1 as a parameter of r_s are shown in Fig. 6. In order to make it legible, each curves are shifted a fixed value. Although the curve for r_s=2 km is almost fixed over all the moved distance, it has two peaks. The moved distances of the peaks in Fig. 6 are mostly in agreement with those of the valleys in Fig. 4. The curve of r_s=5 is accompanied by small vertical change. When the range of the step zone r_s is furthermore increased, the peaks of the curves are increased. It is considered that the reflected waves at the boundary in the

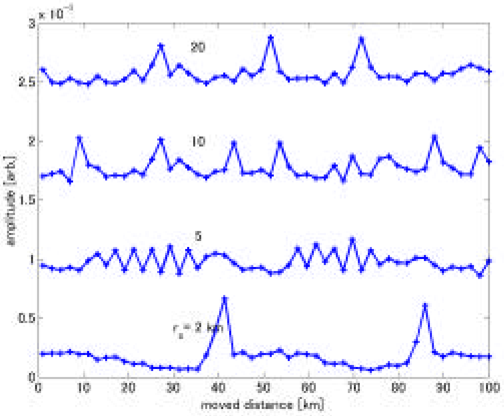

Fig. 6. The changes of pressure amplitude for pulses P_1 as a parameter r_s. Horizontal axis is the moved distance of the boundary between area1 and area2.

transfer area make the peaks. The behaviors of the figures for all other pulses are similar to that of Fig. 6 although they have different peak positions.

As is mentioned above, when the range of area1 is changed, the propagation times of the received pulses are changed, and its amplitude are also changed. It seems that it will be difficult to identify the pulses when the amplitude of pulses are largely changed.

4. SUMMARY

The ocean acoustic tomography measures propagation time of sound wave pulses and, from its data, evaluates the sound speed field and temperature field. Therefore this measurement requires exact knowledge on the sound wave propagation and identification of pulses. We verified the changes of sound waves passing through the transfer area, in which the sound wave profile changes significantly in the middle of propagation path, by using the wave theory. Results showed that the change in time of received pulse associated with the movement of a transfer area is periodical. Therefore the change in propagation time of the eigenray against transmission angle can be expressed as a circle trace with the distance of area 1 as a parameter. Analysis by the wave theory reveals effects of reflections on boundaries in the transfer area.

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