Detection of Open Water in the Ice by Phase Contrast from the Board of the Underwater Vehicle

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Abstract. The impulse parametric sonar’s structural scheme for the interfaces detection, recognition and classification by amplitude, phase and frequency features of several echo signals at primary pump, sum and difference frequencies, and second harmonic components is considered. Safety navigation supplying for underwater vessel under the ice cover, ice thickness gauging above the vessel, the patches of ice-free water detection in ice-fields, which is suitable for surfacing etc by means of these equipment are suggested.

1. Introduction
For the safe surfacing of an underwater vehicle in the Arctic, it is first necessary to detect a patch of ice-free water, determine its boundaries, evaluate the size and shape, measure the thickness of the young ice in it. In this case, the side-scanning method of sound-scattering surface is effective [1, 2]. The sonar image depends on the amplitude properties of the secondary ultrasonic field scattered from the lower surface of the water-ice interface, specifically, this makes possible to approximately determine the areas of pack ice (uneven area) and young ice (more even area), as well as find a patch of ice-free water. These patches are distinguished by “acoustic contrast”, i.e. have relatively low backscatter coefficient. As an additional classification feature, you can use such parameter of the interface as acoustical impedance, which characterize the dynamic response of the interface to an elastic wave’s action. As a result, in the reflected wave the phase shifts occur either for sound pressure (acoustically “soft” interface) or for the vibrational speed of medium particles (acoustically “hard” interface).

2. An impulse sonar-ice fathometer with the classification mode
In [3-5], similar method and it’s realizations for fish-finding echo sounders are proposed, which make possible to distinguish echo signals from acoustically “soft” swimming-bladders of fish against an acoustically “hard” bottom. The main disadvantage of the method and location devices is the complexity of the radiating path’ making with the required characteristics. One of the promising directions in the design of devices for distinguishing acoustic impedance of interfaces and underwater objects according to the phase characteristics of echo signals is the use of location systems with a parametric radiating antenna [6 – 9]. Figure 1 shows the block diagram of the locator, and Figure 2 shows stress diagram at various points of the channel for processing the phase characteristics of the echo signals of the high-frequency receiving path of locator [10]. The radiating path of the of the locator includes generators 1 and 2, which produce harmonic signals $U_1$, $U_2$ with frequencies $f_1$, $f_2$, ...
chronisator-modulator 3, power amplifier 4, electro-acoustic transducer (EAT) 5, which emits a powerful sounding pulse into the water medium.

Next, a nonlinear interaction of ultrasonic pump waves with frequencies \( f_1 = \omega_1 / 2\pi \) and \( f_2 = \omega_2 / 2\pi \) occurs in the propagation channel. The result of the interaction is the generation in the water medium of signals of difference \( F = f_2 - f_1 \) and sum \( f_+ = f_2 + f_1 \) frequencies, second harmonics \( 2f_1, 2f_2 \) of pump waves. A polyharmonic signal with frequencies \( f_1, f_2, f_+ = f_2 + f_1 \), \( F = f_2 - f_1, 2f_1, 2f_2 \) propagates in the water medium, reaches moving and stationary objects, and is reflected from them. The acoustic impedance of the water medium is \( Z_{med} = \rho_{med} c_{med} \), where \( \rho_{med} \) is the density of the medium, and \( c_{med} \) is the speed of sound in it. The acoustic impedance of objects is \( Z_{obj} = \rho_{obj} c_{obj} \) ≠ \( Z_{med} \), where \( \rho_{obj} \) is the density of the object, and \( c_{obj} \) is the speed of sound in it. If the acoustic impedance of the object \( Z_{obj} \) is greater than the acoustic impedance of the medium \( Z_{med} \), then the reflected waves have the same phase as the incident ones. If \( Z_{obj} < Z_{med} \), then the reflected waves change the phase by \( \pi \) radians. Moving an object with a radial velocity \( v_r \) leads to Doppler frequency shifts of reflected acoustic vibrations of all wave processes \( \pm f_D(\pm f_1) \), \( \pm f_D(\pm f_2) \), \( \pm f_D(f_1) \), \( \pm f_D(f_2) \), \( \pm f_D(f_+) \), \( \pm f_D(F) \), where \( \pm \) correspond to the approach or moving away of the object. The reflected spectral components of the polyharmonic signal reach the receiving EAT 6 and 11 of the locator (U4). All reflected components of the polyharmonic signal contain definite amplitude, phase, and frequency information about the objects and its interfaces. This information allows you to evaluate reflectivity, acoustic impedance, characteristics of the movement of objects and the distance from them to the antenna system 5, 6, 11.
In the LF receiving path, the amplitude characteristics of the echo signals are processed. Processing consists of filtering (band-pass filter 7), amplification (amplifier 8) and demodulation (detector 9) of the electrical signal U5. The signal U5 corresponds to the difference frequency \( F = f_2 - f_1 \) echo from the interfaces and objects. Next, the electrical signal is supplied to the second input of the indicator 10, which is triggered by a sync pulse from the additional output of the chronisator-modulator 3.

![Figure 2](image-url)  
Figure 2. Stress diagram at various points of the channel for processing the phase characteristics of the echo signals of the HF receiving path of locator [9].

In the HF receiving path, the amplitude characteristics of the echo signals are processed. Processing consists of filtering (bandpass filters 12, 13, 14), amplification (amplifiers 15, 16, 17), demodulation (detectors 18, 19, 20) and multiplication (21) of electrical signals U6 \( (2f_1) \), U7 \( (f_c) \), U8 \( (2f_c) \). The resulting voltage \( U9 = U6 \times U7 \times U8 \) corresponds to the echo signals of the HF radiation from the interfaces. The electrical signal U9 is supplied to the third input of the indicator 10. The signal levels U6, U7, U8 correspond to the spatial directivity characteristics (DC) of the EAT 11. Electric signals of large amplitude correspond to the major maximum on the acoustic axis of the EAT 5, 6, 11. Electric signals of small amplitudes correspond to the minor lobes. The multiplication of electrical signals \( U6 \times U7 \times U8 \) ensures the conservation of large-amplitude electrical signals and attenuation of small-amplitude electrical signals. This leads to the suppression of additional maxima in the resulting DC [8, 9].

The operability of the phase receiving path is based on the application of the method for obtaining the phase-frequency characteristic of the interface [10]. It is used two pairs of the coherent harmonic acoustic signals of multiple frequencies \( f_2, 2f_2 \) and \( f_1, 2f_1 \). Information on the presence or absence of a phase shift by \( \pi \) radian upon reflection from the interface of a pair of the coherent harmonic acoustic signals of multiple frequencies \( f_1, 2f_1 \) can be obtained after processing – filtering, amplification, bringing to a single frequency and phase detection. The initial phases \( \phi_{01} = 2\phi_{01} \) and phase incursions of the signals are compensated after processing both due to the double passing of the distance \( z \) to the boundary, and due to the time \( t \) before the arrival of the echo signals. The difference in phase shifts remains, determined by the ratio of the acoustic impedances of the object’s surface and the medium. The difference in phase shifts occurs when signals are reflected from the interface. So, for example, the phase difference reduced to the same frequency of phase-coupled signals of multiple frequencies \( \omega_2 = 2\pi \cdot (2f_1) = 2\omega_1 \) and \( \omega_1 = 2\pi \cdot f_1 \) is
\[ \Delta \phi_R = 2\alpha t_1 - 2\frac{2\alpha z}{c_{med}} + 2\phi_{31} + 2\phi_{R1}(\omega_1) - (2\alpha t_1) + 2\left(\frac{2\alpha z}{c_{med}} - \phi_{32} - \phi_{R2}(\omega_2)\right) = 2\phi_{R1}(\omega_1) - \phi_{R2}(\omega_2) \]

where \( \phi_{R1}(\omega_1) \) and \( \phi_{R2}(\omega_2) \) are the values of phase shifts for the sound pressure of acoustic signals reflected from the surface.

Reflection of acoustic signals of multiple frequencies \( f_1, 2f_1 \) occurs without a phase shift by \( \pi \) radian when irradiating acoustically “hard” objects, (immersed part of the hull of the surface vessel, water-ice interface) whose acoustic impedance \( Z_{obj} \) is greater than the acoustic impedance of the propagation medium \( Z_{med} (\phi_{R1}(\omega_1) = \phi_{R2}(\omega_2) = 0^\circ) \) and \( \Delta \phi = 0^\circ \). Reflection of acoustic signals of multiple frequencies \( f_1, 2f_1 \) occurs with a phase shift of \( \pi \) radians when irradiating acoustically “soft” objects, (water-air interface) whose acoustic impedance \( Z_{obj} \) is smaller than the acoustic impedance of the propagation medium \( Z_{med} (\phi_{R1}(\omega_1) = \phi_{R2}(\omega_2) = 180^\circ) \) and \( \Delta \phi = 360^\circ - 180^\circ = 180^\circ \).

Filtering (bandpass filters 22, 23), amplification (amplifiers 24, 25), extraction of electrical signals U10, U11 with pump frequency \( f_1, f_2 \) and frequency doubling occurs in the channel for processing the phase characteristics of the echo signals of the HF receiving path (Figures 1, 2) U12, U12’ (frequency multipliers 26, 27). Then, using phase detectors (28, 29), the phase shift is determined for the echo signals of frequencies \( f_1 \) and \( 2f_1, f_2 \) and \( 2f_2 \) when reflected from the interfaces. The echo signals U13, U13’ with frequencies \( 2f_1 \) and \( 2f_2 \) are supplied to the second inputs of phase detectors (28, 29) through phase shifters (30, 31) are used as reference signals. Compensation of the difference of diffraction phase shifts for signals \( f_1, 2f_1 \) and \( f_2, 2f_2 \) formed by a parametric radiating antenna is carried out using phase shifters (30, 31). The electrical signals U17 and U18 are supplied to the control inputs of the phase shifters. The amplitudes of these signals in time are proportional to the magnitudes of the differences of the diffraction phase shifts. The shaping unit of control voltage 33 generates electrical signals U17 and U18. This occurs after the sync pulse from the chronisator-modulator 3 is supplied at the control input of the block 33. The voltages U14 and U15 generated at the outputs of the phase detectors 28, 29, when locating an acoustically “soft” interface (“water-air”), have one polarity, and acoustically “hard” interface (“water-ice”) – another. There is a "phase" contrast. The signals U14 and U15 are supplied to the two inputs of the matching circuit 32. At its output, the resulting signal U16 is generated only if the signals U14 and U15 have the same polarity. The resulting signal U16 is supplied to the fourth input of the indicator 10 and is displayed by video pulses of a definite polarity in the corresponding places of the sweep line of the CRT. This makes it possible to detect unfrozen patch of water suitable for surfacing by the “phase” contrast or to obtain additional data on the thickness of ice from the underwater vehicle.

In the channel for processing the frequency characteristics of the echo signals of the HF receiving path, filtering (bandpass filters 14, 23), amplification (amplifiers 17, 25) and the extraction of electrical signals with frequencies \( (f_2 \pm f_{D(f_2)}) \) and \( (2f_2 \pm f_{D(2f_2)}) \) occur. Further, these signals are supplied to the first and second signal inputs of a two-input analog key 36. An electric signal with a Doppler frequency shift from the output of the key 36 is supplied to the first input of the frequency discriminator 37. Electric signals with frequencies \( f_2, 2f_2 \) without a Doppler shift from the output of the second two-input analog key 35 are supplied to the second input of the frequency discriminator 37. Both inputs of the second analog switch 35 are connected to the output of the high-frequency generator 2 with a frequency \( f_2 \). The first input of the analog key 35 is directly connected to the output of the generator 2. The second input of the analog key 35 is connected to the output of the generator 2 through a frequency multiplier 34 with a multiplication factor 2. Selecting a specific pair of signals \( (f_2 \pm f_{D(f_2)}) \), \( f_2 \) or \( (2f_2 \pm f_{D(2f_2)}) \), \( 2f_2 \) is carried out by the operator, which feeds with control unit 39 corresponding signals to the control inputs of analog keys 36 and 35.

The electric signal with a frequency corresponding to the Doppler shift \( (f_{D(f_2)}, f_{D(2f_2)}) \) is extracted at the output of the frequency discriminator 37. This allows to calculate two values of the radial component of the velocity \( u_{P(f_2)}, u_{P(2f_2)} \) of approach (+) or moving away (–) of the object and the locator.
in the block of secondary processing of Doppler information 38. The values of the radial component of the velocity can be found from the relations

\[ u_{p(2)} = \pm \frac{c_{med} \cdot f_{D(f2)}}{2 \cdot f_2} = \pm \frac{f_{D(f2)}}{K_{V/(f2)}}, \quad u_{p(2)} = \pm \frac{c_{med} \cdot f_{D(2f2)}}{2 \cdot 2f_2} = \pm \frac{f_{D(2f2)}}{K_{V/(2f2)}}, \]

where \( K_{V(f2)}, K_{V(2f2)} \) are the velocity sensitivities of the frequency receiving path of the locator for acoustic signals at frequencies \( f_2 \) and \( 2f_2 \). The velocity sensitivity is an increment of the Doppler frequency when the velocity changes by 1 knot; \( c_{med} \) is the velocity of sound in the medium.

A significant difference between the information signals U16 during irradiation of the ruffled sea surface and the uneven lower ice edge is a periodic change in the location of U16 on the sweep line of indicator 10. The U16 signal changes both in amplitude and in sign of the video pulse. This is due to the mobility of the free water surface, in contrast to the static uneven bottom edge of the ice. The measurement of the speed of vertical movements of the moving free surface “water-air” should be used to increase the reliability of the classification according to the “phase” contrast of the interface when detecting unfrozen patch of water suitable for surfacing.

3. Conclusion

Technical solutions [6 – 9] are promising for use as hydroacoustic systems for providing near-underwater surveillance during ice-navigation. For example, if on the lower edge of the ice there are two protrusions of the same size, located at a distance \( D \) and separated by a deep crack (Figure 1). On the echogram, these protrusions are combined in one and therefore increase the thickness of the ice almost twice. To avoid this, in the direction finding by maximum method it is necessary that the angle \( \Delta \theta \) be equal \( \Delta \theta = 0.6 \cdot \sqrt{\mu} \cdot \theta_{0.7} \). The coefficient \( \mu \) is (0.05 – 0.15), when the operator uses a visual indicator. Then, the protrusions can be registered separately with a deviation of \( \Delta \theta \) in the region of the maximum of the DC of the EAT. Let us evaluate the accuracy of the direction finding by maximum method by the LF and HF amplitude paths of the short-range locator [10]. In this device, the angular width of the DC of the EAT at the level of 0.7 is: HF path – with the proposed signal processing \( f_s = 476 \) kHz, \( 2f_1 = 456 \) kHz, \( 2f_2 = 496 \) kHz – \( \theta_{0.7HF} = 1.6^0 \); in the absence of side lobes; LF path – for \( F = 20 \) kHz – \( \theta_{0.7LF} = 6.4^0 \) in the presence of side lobes with levels up to 13%. With vertical sounding from a stationary underwater vehicle located at a depth of 20 meters, the device provides separate detection of two protrusions at distances of \( D_{HF} \approx 0.2 \) m and \( D_{LF} \approx 0.8 \) m. The accuracy of direction finding \( \Delta \theta \) of the protrusions by the operator (\( \mu = 0.1 \)) using the device is: for the HF path with the proposed processing – \( \Delta \theta_{HF} = 0.28^0 \); for the LF path on the difference frequency signal \( F = 20 \) kHz – \( \Delta \theta_{LF} = 1.3^0 \).

The accuracy of measuring the mobility of the interface at the pump wave with frequency \( f_2 \) and at its second harmonic \( 2f_2 \) is different. The angular widths of the main maximum are related by the relation \( \theta_{0.7}(f2) = \sqrt{2} \cdot \theta_{0.7}(2f2) \). At the ruffled water-air interface, which makes vertical movements, two different concentric sites \( S_{2(f2)} \) and \( S_{2(2f2)} \) are irradiated. This leads to the appearance of differences in the Doppler spectra of these frequencies. The width of the Doppler spectra is determined by the approximate ratio [11]

\[ \Delta f_{D(nf2)} \approx 4 \cdot (nf2) \cdot \frac{D_s}{c} \cdot \sin \Theta \cdot \frac{\theta_{0.7(nf2)}}{2}, \]

where \( \Theta \) is the sliding angle of the acoustic beam relative to the interface, \( n=1, 2 \) is the number of the harmonic component. The root-mean-square error \( \delta F_D \) of measuring the Doppler frequency shift due to fluctuations in the average frequency of the spectrum can be estimated from the approximate ratio \( \delta F_D \approx m \cdot D_{fD} \), where \( m \) is a certain constant coefficient, \( D_{fD} \) is the width of the Doppler spectrum of the signal [11].
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