Proceedings of the International Conference DAYS on DIFFRACTION 2020, pp. 95–99

Broadband sound scattering by intense internal waves

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The main goal of the paper is to present application of the interferometric method for data processing in shallow water acoustic waveguides. The source sound field interference patterns are analyzed with 2D Fourier trasformation (hologram), within the framework of interferometric processing. Our purpose is to recover separately the interference patterns of sound field in unperturbed waveguide and its hydrodynamic perturbation by filtering in hologram domain.

1 Introduction

The idea of using interferometry techniques in hydroacoustics was initiated by Chuprov in early 1980's [1]. The scientist first described the interference pattern (interferograms) physics of broadband source within the distance-frequency domain. An interference pattern in acoustic field is created through the waveguide dispersion — the frequency dependence of horizontal wavenumbers of sound field modes. Then the high potential of using the interference pattern to monitor oceanic inhomogeneities [2] and solving some applied problems of hydroacoustics [3] was shown.

Further progress in hydroacoustics interferometry was associated with the using of 2D Fourier transformation of interference pattern (interferometric method of source localization) [4, 5]. In these papers, the criteria of the interferometric method applicability, source detection criteria, estimations of source coordinates (direction, distance, velocity, depth), estimation of noise immunity and stability in relation to variations of waveguide parameters, the criteria of several sources resolving are obtained. The interferometric method has been successfully applied in computational and natural experiments. The possibility of application of spectrograms in hydroacoustic interferometry was previously considered in the paper [6]. However, the extraction of information about source parameters from spectrograms and its application for solving the acoustic inverse problem was proposed for the first time in [4, 5].

The physics basics of source interference pattern recovery are obtained mathematically and are proved by computer modeling and experimental data. As known, hydrodynamic phenomenon — intense internal waves — cause significant variations of waveguide parameters (hydrodynamic perturbation) and lead to interference pattern perturbation. It is necessary to analyze the hydrodynamic perturbation influence on source interference pattern recovery. The possibility to obtain information about hydrodynamic perturbations by using interferometric method has not been considered either. The ocean waveguide dispersion is the reason of interference pattern of broadband noise source. The interference bands are formed in the frequency-time domain [1]. In the case of stationary source, the interference bands are vertical in frequency-time domain. In the case of moving source, the slope of interference bands is different from vertical.

In the papers [1–5] the interferometric processing based on 2D Fourier trasformation is proposed to coherently accumulate the spectral sound intensity along interference bands. The spectral density of the source obtained as result of the 2D Fourier trasformation is called the Fourier-hologram (hologram). The spectral density at hologram domain is concentrated in narrow band as focal spots due to different acoustic mode interference. Source image reconstruction is achieved by filtering the two-dimensional spectral density of the source in the hologram domain. The inverse 2D Fourier transformation of spectral density filtered in hologram domain allows obtaining the pure interference structure of source without noise. Clearing of the source signal from noise does not require knowledge of the signal parametes, noise and transmission function of ocean waveguide. The hydrodynamic perturbation causes the changes of modes wave numbers and leads to horizontal refraction and modes coupling. As a result, the source interferogram can be considered as superposition of two independent components. The first component is source interferogram in unperturbed waveguide (unperturbed interferogram). The second component is interferogram of sound field scattered by hydrodynamic perturbation (interferogram of perturbation). The 2D Fourier transformation of components superposition represents two independent localized spectral spots at hologram domain. First of them is concentrated on the hologram time axis. The second one is localized on the hologram frequency axis. The filtering of different spectral density localization regions allows obtaining unperturbed and scattered fields separately. The inverse 2D Fourier transformation allows reconstruction of unperturbed and scattered sound field interferograms separately. Such interferometric processing of received acoustics signals provides a potential to reconstruct the transmission function of unperturbed waveguide and parameters of the temporal variability of hydrodynamic perturbation.

In this paper, the interferometric processing in ocean waveguide at the presence of intense internal waves (IIW) is considered and validated by using the SWARM'95 experimental data.

2 SWARM'95 Experiment

The SWARM'95 experiment was carried out on New Jersey coast [7, 8]. Two stationary acoustic tracks were at angles $\beta_1 \approx 5^\circ$ and $\beta_2 \approx 39^\circ$ to front of IIW. The angle between acoustic tracks $\alpha \approx 34^\circ$ (see Fig. 1). The first acoustic track was from airgun source to VLA 1 (vertical antenna). The distance between source and VLA 1 was 14.98 km. The second acoustic track was from airgun source to VLA 2. The distance between source and VLA 1 was 17.95 km. The width of IIW front exceeded the acoustic tracks lengths.

During the experiment, numerous sensors were deployed for registrations of hydrodynamics of water layers. They performed high-resolution oceanographic surveys of intensive internal waves by using conductivity-temperature-depth (CTD) casts and tows. The IIW amplitude reached ≈ 10–20 m; the propagation velocity of IIW was ≈ 1.0–1.5 m/s. The interval of time variability of IIW is ≈ 10–15 min. The airgun source was placed at a depth of 12 m and radiated pulses continually. The duration of each pulse was 0.3 s. The time dependence of airgun signal and its spectrum are shown in Fig. 2. The main intensity of the signal was concentrated in 30–650 Hz. The signal from a single hydrophone of a vertical antenna on the depth of 36 m was processed in the paper.

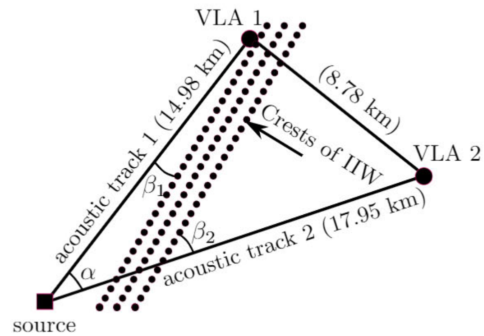

Figure 1: Experiment scheme.

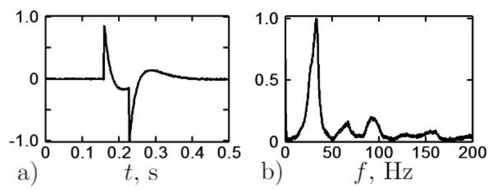

Figure 2: Airgun source signal: time dependence (a), spectrum (b).

3 Interferometric signal processing

On the first acoustic track (source-VLA 1, $\beta_1 \approx 5^\circ$) the IIW caused the significant horizontal refraction. On the second acoustic track (source-VLA 2, $\beta_2 \approx 39^\circ$), IIW caused the significant modes coupling. Horizontal refraction and modes coupling are two different cases of IIW influence on acoustic fields. These cases allow us to analyze the influence of the acoustic track orientation on interferometric processing.

In our approach the interferogram is the square of the sound field absolute value in the frequency-time domain. The interferogram is created by interference of sound field modes. The hologram is 2D

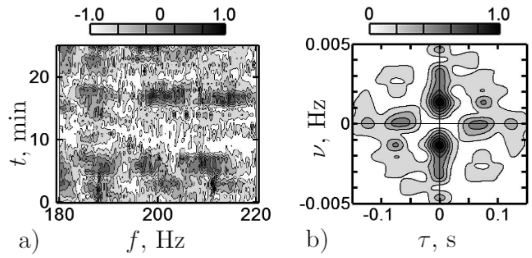

Figure 3: Normalized interferogram (a) and corresponding hologram (b) for range 180–220 Hz. First acoustic track.

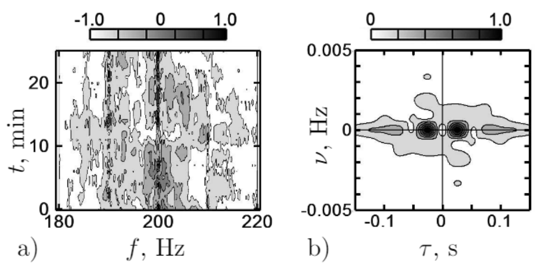

Figure 4: Normalized interferogram (a) and corresponding hologram (b) for range 180–220 Hz. Second acoustic track.

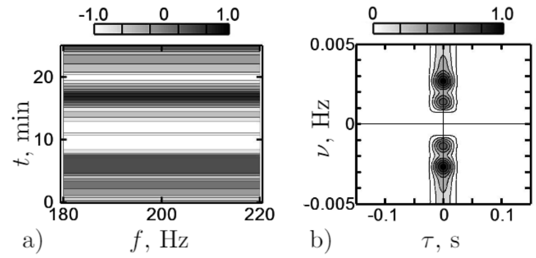

Figure 5: Filtering of hologram of perturbed signals: restored interferogram (a) and filtered hologram (b). First acoustic track.

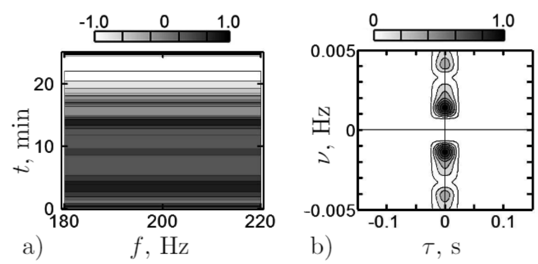

Figure 6: Filtering of hologram of perturbed signals: restored interferogram (a) and filtered hologram (b). Second acoustic track.

Fourier transformation of interferogram. Interferogram and corresponding hologram for frequency band 40 Hz (180–220 Hz) for received signals on both acoustic tracks are shown in Figs. 3, 4. There are two types of features in Fig. 3a and Fig. 4a for both acoustic tracks. The first type of feature is the vertical bands due to modes interference. The second type of feature is the horizontal bands due to IIW. These features of interferograms explain the structure of hologram in Fig. 3b and Fig. 4b with focal spots on time and frequency axes of hologram. The focal spots on time axes correspond to sound field in unperturbed waveguide. The focal spots on frequency axes are due to hydrodynamic perturbation by IIW. Outside of these spots, the spectral density is negligible. The intersection of focal spots of spectral intensity is practically absent. That structure of hologram allows us to separate unperturbed transfer function and perturbation due to IIW in the hologram domain. The described structure of interferograms and holograms is not dependent on the orientation of the acoustic track in relation to the IIW front. So the interferometric processing in the shelf region provides the unique opportunity to obtain unperturbed transfer function at the presence of hydrodynamic perturbation. This opportunity is inaccessible for other processing methods in hydroacoustics. The results of focal spots selection on the frequency axis ν of the holograms and applying an inverse 2D Fourier trasformation are presented in Figs. 5, 6 for both acoustic tracks.

The reconstructed interferogram consists of horizontal bands in the case of filtering of focal spots of the hologram on time axis ν. These horizontal bands are due to the hydrodynamic perturbation by IIW. Their intensity is proportional to the squared amplitude of IIW.

The filtering of focal spots on the time axis τ and the application of inverse 2D Fourier trasformation to cleaned hologram for reconstruction of interferogram of the unperturbed waveguide are shown in Figs. 7 and 8.

The interferogram consists of vertical localized bands. The vertical bands of interferogram are due to the interference of modes of unperturbed waveguide. The count of modes increases with frequency. So, small-scale frequency variability of the transfer function increases with frequency as well.

The sound frequency variation causes redistribution of signal spectral density in focal spots located along the time τ and frequency ν axes in the holo-

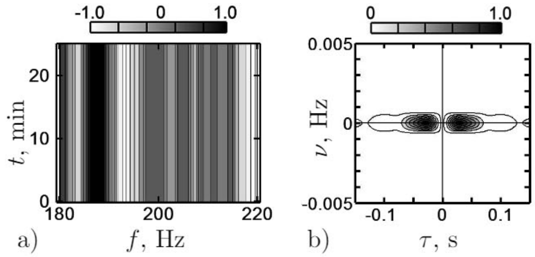

Figure 7: Filtering of hologram of unperturbed signals: restored interferogram (a) and filtered hologram (b). First acoustic track.

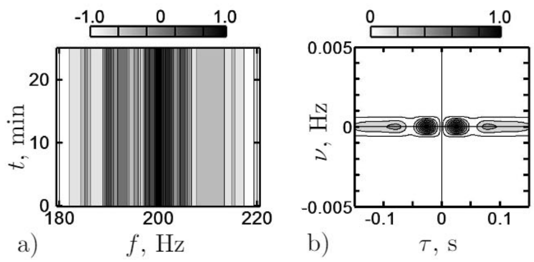

Figure 8: Filtering of hologram of unperturbed signals: restored interferogram (a) and filtered hologram (b). Second acoustic track.

gram domain. The redistribution of signal spectral density in focal spots is described by the ratio:

$$g(f) = \frac{|F_{\max}(\nu, f)|}{|F_{\max}(\tau, f)|},$$

where $|F_{\max}(\nu, f)|$ and $|F_{\max}(\tau, f)|$ are the maxima of focal spots in spectrogram, which correspond to the perturbed and unperturbed signals, respectively. Here f is central frequency of frequency window used for interferometric processing. The frequency dependence of the ratio $g(f)$ with is shown in Fig. 9. The frequency dependence $g(f)$ has resonant form. It has frequency period of variability 34 Hz and 42 Hz. The intensity of focal spots caused by the horizontal refraction on the first track is higher than intensity of focal spots caused by modes coupling on the second track.

4 Conclusion

The interferometric method described above allows us to develop the new approach to acoustic monitoring of hydrodynamic perturbation of ocean environment. This approach is based on analysis of received signals interferogram. The hologram of interferogram consists of two types of focal spots corresponding to unperturbed and perturbed sound field. The reconstructed interferograms can be divided in two types as well. The first type is the interferogram corresponding to unperturbed waveguide. The second type is interferogram of scattered sound field due to hydrodynamic perturbation. So, we can obtain unperturbed interferogram and interferogram of perturbation separately. The unique property of hologram is transmission of unperturbed sound field through inhomogeneous waveguide. The results, presented in this paper, may be used for underwater communication at the presence of hydrodynamic perturbation and for acoustic monitoring of shallow water regions. Summarizing the results of paper, it can be assumed that interferometry is applicable to different types of oceanic hydrodynamics: background internal waves, surface waves, tide, etc. Thus, interferometric processing gives us new opportunities and allows us to understand better the ocean environment by acoustic sounding.

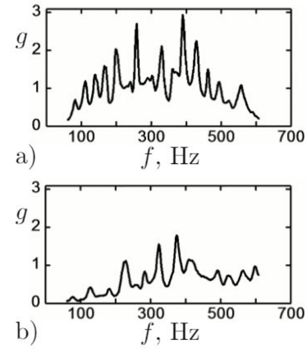

Figure 9: Frequency dependence of the ratio of local-spot spectral maximums: (a) first track, (b) second track.

Acknowledgements

The research was supported by the Russian Foundation for Basic Research, projects 19-08-00941 and 19-29-06075. E. S. Kaznacheeva research was supported by grant of RFBR 19-38-90326.

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