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Acoustic Speckle – Interferometry Methods on Coordinate Estimation of Moving Sound Source in Inhomogeneous Medium

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The new approach on estimation of the coordinates of moving acoustic source in inhomogeneous medium with a strong scattering is discussed. The foundation of new approach is the speckle-interferometry methods (SIM), based on correlation features of multi-wave or scattered angle spectrums. It is shown that SIM can provide the same angle (linear) resolution in inhomogeneous medium as for free space. Some results of computer simulation and experiments are presented.

In the first group of experiments the High-Speed 2D-Imaging Ultrasound Camera was used on frequency 1 MHz in water layer with a strong scattering screen in front of acoustical lens. In the second case the trajectory of drilling profile has been reconstructed by SIM processing of low-frequency signals (15-90) Hz, generated by rotator bit, and received by two crossed linear arrays. The results of SIM procedures are compared with the profile estimated before by inclinometers.

The optimal detection and coordinate estimation of moving sound source in inhomogeneous medium is based on matched filtering signal processing. This type of signal processing is the most powerful approach today, because of maximum output signal/noise ratio and maximum potential accuracy of coordinate assessments. Unfortunately the wide practical use of matched filtering procedures is severely limited, because it is necessary to know (calculate or measure) the channel impulse responses (Green's functions) for all possible space positions of the source. For some simple ocean wave-guides with stable vertical stratification matched filtering is available, [1], but in the majority practical cases we can not predict or measure the parameters of propagating medium with the phase accuracy.

The theory and background of alternative new approach on estimation of coordinates of moving source in inhomogeneous mediums, acoustic speckle-interferometry methods, (SIM), were described in [2-6]. The foundation of this theory is the fact that samples of scattered or multi-mode sound fields can be partly correlated when the sound source is moving from one point to another if these shifts are less than interval of space correlation of inhomogeneties. If this is the case one can estimate the correlation function of angle spectrums of scattered fields and determine the coordinates of correlation maximum which are directly related to the source space shifts. The correlation procedure is not the single way to estimate the coordinate changing, and there are some another possible algorithms of signal processing, [2].

Some experimental and computer simulation results on the reconstruction and estimation of the trajectory of moving sound source in inhomogeneous medium with strong scattering are presented below. The experiments have been performed for high frequency signals (2D-Ultrasound Underwater Imaging on 1MHz) and for low frequency signals (Estimation of Drilling Profile for Oil Well on 15-90 Hz) to underline the wide possibilities of the developed approach.

Let place a point sound source O of frequency f and line array with N receivers and length L. The array spacing is $\Delta = \lambda/2$. Let place the source in far field zone on the distance $R \geq 2 L^2 / \lambda$.
The point source is moving from point O_1 to point O_2. in parallel to array. Beamforming is performed by acoustical lens or Fourie signal processing. Let us present inhomogeneous medium as the layer of scatters or layer of transparent phase structure $\psi(x)$ with random variations from 0 to 2π and more. If

many intervals of space correlation function of $\psi(x)$ are placed on the length L the incident plane wave on the rear of the layer will be absolutely distorted and angle information will be disappeared after Fourie beamforming. Let's represent point source field as $P(x) = A(x) \exp\{jk\varphi(x)\}$. After the inhomogeneous layer and beamforming the angle space spectrum $\Phi(y)$ is

$$\Phi(y) = \Im\,[P(x)\exp\{jk\psi(x)\}], \qquad (1)$$

where $\Im$ - Fourie-operator, x - array coordinate. Now let form a new function

$$I(y) = |\Im(y)|\,, \qquad (2)$$

and fix $I_1(y)$ and $I_2(y)$ in sequential moments of time t_1 and t_2. In a time $\Delta t = t_2 - t_1$ the point source moved from point 0_1 to point 0_2. As this takes place, the phase structure did not change during this time interval, i.e. $\psi(x,t_1) = \psi(x,t_2)$.

Now let us sum $I_1(y)$ and $I_2(y)$ and take the Fourie-transformation from this sum again. Leaving aside interface mathematical treatments it is easy to show that $|\Phi_1(y)| = |\Phi_2(y + \Delta y)|$ and since

$$\Im u\,[\Phi_2(y + \Delta y)] = \Im u\,[\Phi_1(y)] * \exp(j\Delta y u),$$

$$|G(u)| = |\Im u\,[I_1(y) + I_2(y)| = |\Im u\,[I_1(y)]|$$

$$\sqrt{\{2[1 + \cos(\Delta y\, u]\}}\ , \text{ and}$$

$$|G(u)| = 2\,|\,\Im u[\,I_1(y)]|\,[\,1 + \cos(\Delta y u)]. \qquad (3)$$

From the last relation it is evident that function G(u) is modulated with cosine factor with frequency Δy proportional to the source angle shift α which we want to estimate.

This relation permits to measure only projection of source displacement on x-axis of line array. If we have 2D- array the procedure (3) leads to the occurrence of interference stripes, Naturally the correlation procedure is more preferable algorithm for such processing instead of procedure (3), i.e

$$\text{covar}\,\{I_1\, I_2\} = I_1(y) \otimes I_2(y), \qquad (4)$$

where symbol $\otimes$ means correlation integral.

If the space spectrum of phase function $\psi(x)$ is uniform and many intervals of space correlation of this function are placed on array, correlation procedure (4) gives good results. But if the space spectrum of phase inhomogeneties contains some periodic components the correlation processing can lead to indefinite estimation.

In this connection one can suggest another algorithm of shift estimation. Let us take Fourie - transformation from (2) before their summation, i.e. transfer the shift in phase inclination again:

$$\Lambda_1 = \Im\eta\,[\,|\Phi_1(y)|\,],$$

$$\Lambda_2 = \Im\eta\,[\,|\Phi_2(y)|\,],$$

and form the ratio $B(\eta)$. It is evident that

$$B(\eta) = \Lambda_1(\eta) / \Lambda_2(\eta) = \exp(j\Delta\xi\eta). \qquad (5)$$

The opposite Fourie transformation gives:

$$\text{Div}[\,I_1(y), I_2(y)\,] = \Im\,[\,B(\eta)\,] = \delta(y - \Delta y),$$

i.e. the single peak independent of the type of the function $\psi(x)$, $\psi(x, t_1) = \psi(x, t_2)$.

1. 2D-Ultrasound Underwater Imaging

The High-Speed Ultrasound Lens Camera was used for experiments, [7]. This Camera has 2D- PZT matrix array of 85*85 elements, electron-beam switching, and digital signal post-processing after quadratic signal detection. Operating frequency is 1MHz in continuous mode, frame rate is 24 frames/sec, and angle resolution is about $0{,}9^{0}$ in 36^{0}-sector of view. Sound source was placed on 5 meters from Camera and was moving along quasi-spiral trajectory along XY coordinates. The artificial layer of scatters (special plastic screen) was placed in front of acoustic lens, completely overlapping the lens aperture. The parameters of screen have been preliminary calculated and it was simulated two cases: weak scattering and strong scattering, when phases of HF signals changed stochastically in intervals $(0 - 2\pi)$ in each point of matrix array. The diagram of experiments is shown on Fig.1

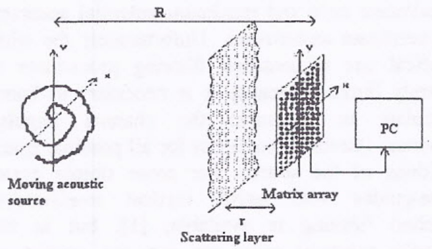
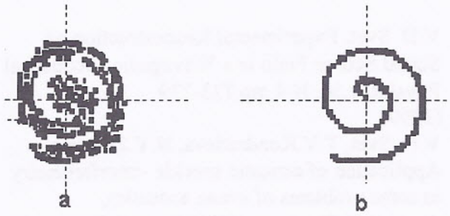


Fig.1 General diagram of experiments

Some results of preliminary computer simulation are shown on the next pictures, Fig 2a,b. (weak scattering) and Fig 3a,b (strong scattering). We used lens beamforming as standard signal processing and correlation speckle-interferometry signal processing to compare the effectiveness of two different approaches. One can see that under weak-scattering the standard beamforming can reconstruct the spiral trajectory of moving source though with bad accuracy. In the case of strong scattering the standard approach is useless, because the signal plane wave is completely exterminated by strong scattering. In the same time speckle-interferometry processing permits to estimate the trajectory with very high accuracy for both types of scattering compatible with the accuracy for free space.



ig 2. *Weak scattering, computer simulation,*
a- 2D beam-forming,
b- speckle-interferometry processing

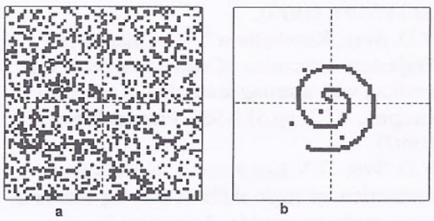


Fig.3 Strong scattering, computer simulation,
a- 2D beam-forming,
b- speckle-interferometry processing

Note that in the case of strong scattering the input plane wave is completely de-correlated behind the scattering layer and traditional beamforming can not reconstruct the image of point source – the angle spectrum became very wide.
Some experimental results are demonstrated on the next Fig.4 a,b and Fig.5 a,b. Practically we did not reproduce the pure spiral trajectory and used horizontal and vertical moving of source.

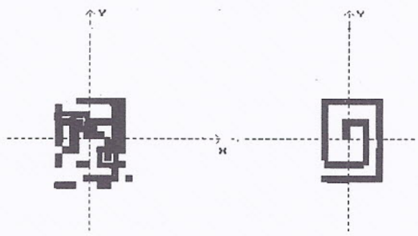


Fig.4 ab. Experimental results, weak scattering,
a- Standard. Imaging (2D-beamforming),
b- Speckle-interferometry processing.

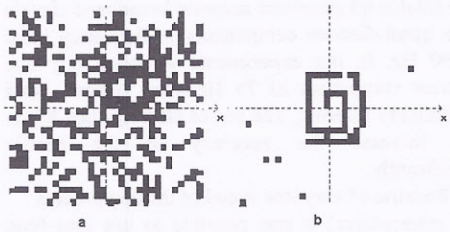


Fig.5a,b. Experimental results, strong scattering.
a-Standard Lens Imaging (2D-beamforming),
b-Speckle-interferometry processing

As one can see the experimental results are in a good agreement with computer simulation data.
Note that all experiments have been performed with sufficient strong signals –input signal/noise ratio was about 10 dB.

2. Estimation of a drilling profile

The estimation of drilling profile is the one of the main goals in prospective geophysics and oil/gas production process. There are two basic approaches to estimate drilling profile.
The first is based on use of the inclinometers lowered down a borehole. These devices are measuring two angles (azimuth and vertical). The main disadvantage of this approach is the necessity to stop drilling process and lift the drilling column with drilling bit every time before estimation of the trajectory. The second approach is based on seismo-acoustical profiling. The drill or rotator bit is the powerful source of low-frequency signals. As a rule one or two crossed seismic-acoustical line arrays are used for the receiving and processing of these signals. It is precisely this case we'll consider below. The geometry of the drilling platform and configuration of 64 –element arrays are shown on the Fig.6

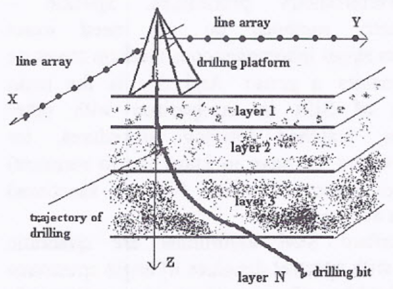


Fig.6. General geometry of drilling process

The rotator bit generates acoustic broadband signals with quasi-discrete components in frequency band 15-90 Hz. In our experiments we used only one discrete component of 75 Hz after narrow- band preliminary filtering. The use of all frequency bands can increase the accuracy of the profile significantly.

Because of very low speed of drilling process (10 meters/hour) it was possible to use long-time averaging of data to decrease the dispersion of estimated trajectory. One of the examples of estimated trajectory in comparison with inclinometer profile is shown on Fig.7.

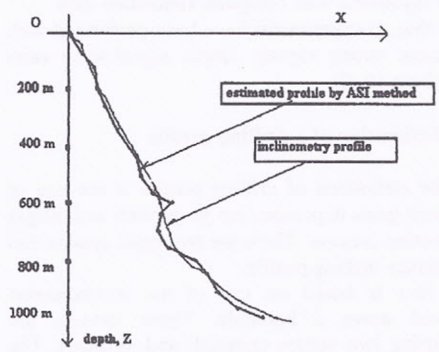


Fig.7 Reconstructed trajectory of drilling profile by speckle –interferometry method in comparison with inclinometer data

One can see that estimated trajectory of drilling by SIM algorithms is very similar to inclinometry data.

3.Conclusion

The performed computer simulation and experiments demonstrated wide capabilities of speckle-interferometry procedures. Speckle – interferometry methods do not need exact information about inhomogeneous medium structure and parameters *a priori*. And this is the main advantage of SIM in comparison with other approaches, matched filtering procedures, for example, where we have to know (or to measure) impulse responses of medium (Green's functions) with phase accuracy.

The described SIM algorithms are quadratic operating with spectral densities of angle spectrums after standard beamforming (focused or unfocused). It is necessary to follow only one condition to apply SIM procedures: the rate of fluctuations and any movements of inhomogeneous medium have to be less than the rate of moving target.

Note that described SIM can estimate only relative coordinates of moving target. Therefore for absolute measuring we have to know the initial point of target placement. For the most practical applications this condition is not very serious.

For absolute coordinate estimation spaced arrays can be used.

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