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SPECTRA OF ULTRASOUND DOPPLER RESPONSE USING PLANE-WAVECOMPOUNDING TECHNIQUE

Introduction. ***Within the framework of a simple model of the sensitivity function, the Doppler spectra are considered for different ways of generating response signals using plane wave compounding.***

Methods. ***A Doppler spectrum is obtained for coherent compounding of signals received at different steering angles of waves during their period of changing. Compared to traditional diagnostic systems, the Doppler spectrum width is increased only by limiting the duration of the signals. There is no additional increase in the spectrum width if the compound signals are formed by adding with cyclic permutation, in which signals from each new wave angle are compounded.***

Results. ***When a Doppler signal is formed directly from Doppler signals at different steering angles, the spectral width increases both in comparison with the traditional method of sensing with stationary focused ultrasound fields and with the case of coherent signal compounding.***

Conclusions. ***The obtained increase in the spectral width has an intrinsic physical meaning. The increase in width is connected with a dynamic change in the Doppler angle, which increases the interval of apparent projections of the velocities of motion of inhomogeneities along the direction of transmitting of a plane wave without inclination.***

Keywords: ***ultrasound; Doppler spectrum, plane wave compounding, synthetic aperture method, spectral dispersion, projection of the inhomogeneity velocity.***

Iintroduction

The general idea behind synthetic aperture in ultrasound diagnostics is that the ultrasound response is recorded by all elements of the ultrasound transducer for a sequence of different emitted wave fields. The response for each point in space is then identified as a complex value for the different fields, which is coherently summed, resulting in a high-resolution image due to the focusing at each point in space (Trots et al., 2011, p. 3).Using the synthetic aperture method, it is possible to implement imaging methods that use plane waves with different propagation directions or wave fronts with different spatial configurations (Golfetto et al., 2021, p. 1105; Montaldo et al., 2009, p. 489; Sheina, Kiselov, & Barannik, 2020, p. 5). Moreover, it is necessary to optimise the parameters that characterise the quality of images obtained using aperture synthesis (Provost et al., 2015, p. 1467). There are experimental works on new techniques within the plane wave compounding method that allow to improve image quality in terms of lateral resolution and contrast-to-noise ratio for two-dimensional images (Zheng et al., 2018, p. 495) and for Doppler technique (Shen, & Chu, 2021, p. 4856). The effect of the movement of ultrasonic scatterers and the ways to correct this impact were investigated in (Hyun, & Dahl, 2020, p. 1323).

The calculations have been implemented within the framework of the continuum model of the biological medium and the low-frequency Doppler signal under the pulsed mode of ultrasound.

Methods

Emission depends on the motion of the density inhomogeneities and compressibility. It also depends on the complex sensitivity function over the emission-receiving field which may also depend on time.

$$G_p'(\vec{r}) = G_t(\vec{r},t)G_r(\vec{r},t)b\left(T_1 - \frac{x'}{c_0} - \frac{x' cos\Phi(t)}{c_0}\right). \quad (1)$$

The time dependence is caused by small deviations of the wave vector from the wave vector of plane waves without inclination (Sheina, & Barannik, 2022, p. 116).

In the case of the synthetic aperture technology, it is possible to generate an ultrasonic Doppler response signal directly from discrete signal values from different sequential angles of revolution of the wave vector. For a given range of angles Φ, the ultrasonic Doppler response signals are registered for a limited period of time, after which the registration procedure is repeated periodically. Then the power spectrum of the Doppler signal is equal to:

$$S(\omega_p) = \frac{k^4}{(2\pi)^3}\sum_{j=-\infty}^{\infty}\int d\vec{q}C(\vec{q},\omega_p - \omega_j)\left|G(\vec{q}+2\vec{k},\omega_j)\right|^2, \quad (2)$$

where $\omega_p = 2\pi p/T$ is the Fourier expansion variable, and T is the period of repeating a given set of deflection angles. There is another way to generate an ultrasonic Doppler signal. Discrete values are obtained by coherent compounding of complex signal values at different angles of rotation for the entire period of angle change T. Then the spectrum can be written as follows:

$$S(\omega_p) = T^2\frac{k^4}{(2\pi)^3}\int d\vec{q}C(\vec{q},\omega_p)\left|G(\vec{q}+2\vec{k},0)\right|^2, \quad (3)$$

$$G(\vec{q}+2\vec{k},0) = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} G(\vec{q}+2\vec{k},t+t')dt'. \quad (4)$$

Within the framework of our model, it follows from (3) that in this case the sensitivity function is independent of frequency. To reduce the effect of the rectangular window on the calculated spectra Gaussian weighting window are used.

Results

In the case of the synthetic aperture technology, it is possible to generate an ultrasonic Doppler response signal directly from discrete signal values from different sequential angles of revolution of the wave vector. For a given range of angles Φ, the ultrasonic Doppler response signals are registered for a limited period of time, after which the registration procedure is repeated periodically and formula for the Doppler spectrum:

$$S(\omega_p) = \nu\left\langle(\tilde{\beta} - \tilde{\rho})^2\right\rangle T^{-1}k^4\frac{\pi^3 a^3}{4}\sqrt{\frac{T_W^2 a^2}{a^2+T_W^2 V^2}}\exp\left\{-\frac{T_W^2 a^2}{a^2+T_W^2 V^2}\frac{(\omega_p-\omega_d)^2}{4}\right\}. \quad (5)$$

Then the dispersion of the Doppler frequency spectrum equal to $\sigma^2 = 2\left(\frac{1}{T_W^2} + \frac{V^2}{a^2}\right)$.

There is another way to generate an ultrasonic Doppler signal. Discrete values are obtained by coherent compounding of complex signal values at different angles of rotation for the entire period of angle change T. The final expression for the ultrasonic Doppler response spectrum

$$S(\omega_p) = \left\langle(\tilde{\beta} - \tilde{\rho})^2\right\rangle k^4 T^{-2} T_W^2\frac{\pi^2 a^4}{8}\sqrt{\frac{\pi}{2a^2+T_W^2 V^2}}\exp\left\{-\frac{T_W^2 a^2(\omega_p-\omega_d)^2}{4(2a^2+T_W^2 V^2)}\right\}. \quad (6)$$

Then the dispersion of this Doppler spectrum can be written as follows $\sigma^2 = 2\left(\frac{2}{T_W^2} + \frac{V^2}{a^2}\right)$ and it is greater than the dispersion of the previous spectrum (5) by $\Delta\sigma^2 = 2/T_W^2$.

The reason for the increase in the width of the Doppler spectrum when forming a signal from Doppler signal counts obtained at different steering angles is the change in the projection of the motion velocity onto the direction of the current wave vector due to a change in the Doppler angle, as shown in Fig 1. This situation can be interpreted as a movement with acceleration:

$$V_{x'} = V\cos\vartheta(t) = V\cos(\vartheta \mp \Phi) =$$
$$V(\cos\vartheta\cos\Phi \pm \sin\vartheta\sin\Phi) \cong V\cos\vartheta \pm V\sin\vartheta\frac{\Phi_{\max}}{T_w}t\,. \quad (7)$$

Aceleration is inversely proportional to the time T_w. It is clear that both during acceleration and deceleration, the range of velocities during time T for a given range of angles is the same, so the width of the spectrum cannot depend on the sign of the acceleration. Because of this, in dispersion of the spectrum (6), compared to dispersion of spectrum (5), there is a quadratic acceleration term in the form of $2/T_W^2$.

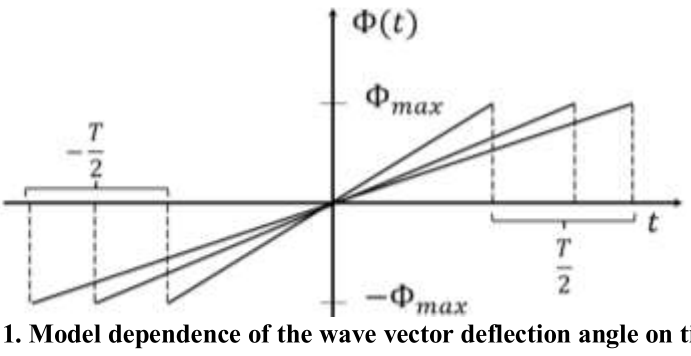

Fig. 1. Model dependence of the wave vector deflection angle on time

From Fig. 1, it is easy to see that the larger T and, accordingly, T_w, the smaller the acceleration at a given range of angles $\Phi_{\max}$, the smaller the range of velocities and, accordingly, the additional dispersion of the Doppler frequency spectrum. Obviously, such terms can be neglected when the strong inequality $1/T_W^2 \ll V^2/a^2$ is satisfied.

Discussion and conclusions

The technology of plane wave compounding uses a periodic repetition of the sequence of waves with different inclinations. Therefore, a periodic extension of all time-dependent physical parameters naturally occurs, which leads to a limitation of the duration of ultrasonic Doppler response signals. The influence of limiting the duration of the response signals and its apodisation by weight windows on the spectral properties of the correlator of inhomogeneity motion and the spectrum of the sensitivity function of the ultrasonic system is determined. In contrast to the spectrum of the correlation function, the width of the sensitivity function spectrum depends on both the size of the measuring volume and the duration of the signals. Within the framework of a simple model of the sensitivity function, the Doppler spectra are considered for different ways of forming response signals using plane wave compounding. A Doppler spectrum is obtained by coherent compounding of signals received at different angles of inclination of waves during their repetition period. Compared to traditional diagnostic systems, the Doppler spectrum width is increased only by limiting the duration of the signals. There is no additional increase in the spectrum width if the compound signals are formed by accumulation with cyclic permutation, in which signals from each new wave angle are added. When forming a Doppler signal directly from Doppler signals at different inclination angles, the spectral width increases both in comparison with the traditional method of sensing with stationary focused ultrasonic fields and with the case of coherent signal accumulation. In terms of the internal physical meaning, the invented increase in the spectral width is connected with a dynamic change in the Doppler angle, which increases the interval of apparent projections of the velocities of motion of inhomogeneities along the direction of transmitting of a plane wave without inclination.

Authors' contribution: Evgen Barannik developed the theoretical formalism; both Evgen Barannik and Mykhailo Hrytsenko authors contributed to the final version of the manuscript and the analytic calculations. Evgen Barannik supervised the project.

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СПЕКТРИ СИГНАЛІВ УЛЬТРАЗВУКОВОГО ДОППЛЕРІВСЬКОГО ВІДГУКУ ПРИ ВИКОРИСТАННІ ТЕХНОЛОГІЇ КОМПАУНДИНГУ ПЛАСКИХ ХВИЛЬ

Вступ. ***В останні роки в ультразвуковій діагностиці все більш досліджуваним і вживаним у медичній практиці стали різні варіанти технології синтезованої апертури. Головною перевагою таких методів є підвищення роздільної здатності зображення за рахунок динамічного фокусування під дією випромінювання ультразвуку.***

Методи. ***Розвиток методів когерентного компаундингу сигналів ультразвукового відгуку дозволив покращити спектральні оцінки у спектральній допплерографії порівняно з традиційними допплерівськими методиками. Метою роботи є винайдення й аналіз допплерівських спектрів та його ширини з використанням технології синтезованої апертури, а саме, компаундингу пласких хвиль різними способами формування допплерівських сигналів відгуку.***

Результати. ***У межах простої моделі функції чутливості розглянуто допплерівські спектри за різних способів формування сигналів відгуку з використанням компаундінгу пласких хвиль. Винайдено допплерівський спектр при когерентному компаундінгу сигналів, отриманих за різних кутів нахилу хвиль***

протягом періоду їх повторення. Встановлено, що у процесі формування допплерівського сигналу безпосередньо з допплерівських сигналів, отриманих під різними ракурсами зондування пласкими хвилями, ширина спектра збільшується, як порівняно з традиційним методом зондування стаціонарними сфокусованими ультразвуковими полями, так і у випадку когерентного накопичення сигналів.

Висновки. ***За внутрішнім фізичним змістом винайдено збільшення ширини спектра, пов'язане з динамічною зміною допплерівського кута, яке збільшує інтервал позірних проєкцій швидкостей руху неоднорідностей уздовж напрямку випромінювання пласкої хвилі без нахилу. Додаткового вивчення потребує вплив нелінійних членів залежно від часу відхилення хвильового вектора від вектора хвиль без нахилу.***

Ключові слова: ***ультразвук, допплерівський спектр, метод синтезованої апертури, компаудинг пласких хвиль, дисперсія спектра; швидкість руху неоднорідностей.***

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