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Acousto-optic wavelet processing of bioelectric signals

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Wavelet analysis is one of the most efficient methods of the informative signals characteristics investigation. First shown the possibility of informative signals wavelet processing by means of the acousto-optic processor with time integration. The possibility of the realization of both power spectrum calculation and performance of wavelet transform of bioelectric signals in the real time mode has been proved. The analysis is listed which describes its operation in different modes.

Keywords: wavelet analysis, bioelectric signals, acousto-optic processors, time integration

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Recently the wavelet analysis has found wide application in the practice of theoretical and applied research. In this field, the best development was gained by numerical methods for the wavelet analysis implementation. However, tasks needing processing of informative signals in the real-time mode are often met. This has become possible due to the development of correlation-type optical wavelet processors equipped with a set of wavelet filters [1–4]. In this case, the procedures of optical processing imply either holographic recording mainly by the dynamic holography methods [2] or image recording by using spatial light modulators of various types [3,4].

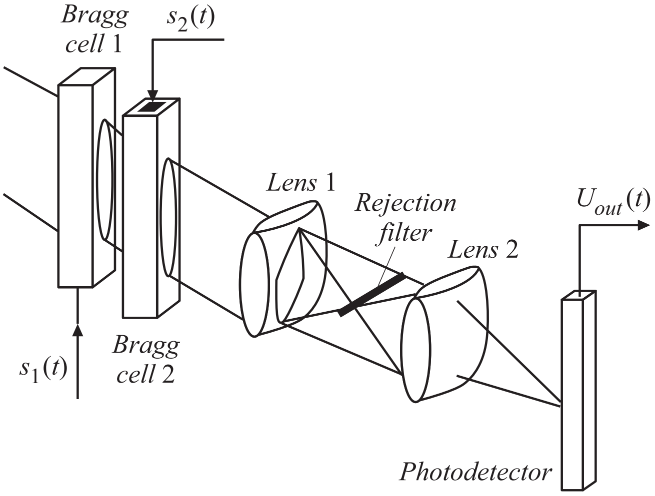
The acousto-optic (AO) wavelet-analysis techniques were for the first time proposed for optical image processing devices in nondestructive analysis of products [5]. Here the acousto-optic modulator plays an auxiliary role of the data input into the optical processor that performs the wavelet transform.

The definition and solution of the task this study is devoted to were caused by the necessity of informational support of experimental investigations of evolution of artificial pathologies of experimental animals based on the original method of instrumental high-resolution electrophysiology, which are performed in our laboratory „Radio and optoelectronic devices for early detection of the living system pathologies“ of IAIM RAS jointly with physiologists of the Institute for Experimental Medicine of the Almazov Federal Center [6]. It has become necessary to perform real-time calculation of the power spectrum and wavelet transform of the bioelectric signals (BES) under study, which is possible under the specific experimental conditions only by using inertia-free AO processors.

Since ordinary AO devices process signals of the frequencies of about tens and hundreds of megahertz, their use to analyze low-frequency BES required implementation of specific signal processing methods [7], for instance, those employing an acousto-optic spectrum analyzer with time integration for real-time calculation of the power spectrum of the considered signals [8]. The optical scheme of such a device is given in the figure.

This optical scheme comprises two oppositely oriented Bragg cells one of which is fed with a linear frequency-modulated signal (LFM signal) modulated in amplitude by informative signal $s_1(t)$, while the other is fed with a reference LFM signal $s_2(t)$ with a rectangular envelope. Lenses perform the optical Fourier transform, and the rejection filter eliminates the zero diffraction order. The multicomponent linear photoreceiver provides the charge accumulation and generates the output signal.

Since the wavelet analysis based on acousto-optics has not been performed so far, searching for the ways of its realization became necessary. The wavelet transform itself is by definition a convolution of the analyzed function of time $s_1(t)$ and function of the mother wavelet $s_2(t)$ expressible



Optical scheme of the acousto-optic spectrum analyzer with time integration.

as

$$W_f(a,b)=\frac{1}{\sqrt{|a|}}\int_{-\infty}^{\infty}s_1(t)s_2^*\left(\frac{t-b}{a}\right)dt, \tag{1}$$

where a and b are the parameters determining the scale and time shift of function $s_2(t)$ with respect to informative signal $s_1(t)$ (symbol * designates complex conjugation) [9]. It was found out that the first who proposed convolution using the AO processor with time integration was R.M. Montgomery who protected his technical solution by the USA patent [10]. The scheme of the Montgomery's convolver was considered and justified in [11,12]. It appeared to be identical to the scheme presented in the figure.

As per [11], the resulting light intensity I_d in the plane of the multicomponent linear photoreceiver may be represented as follows:

$$\begin{aligned}I_d(x,t)&=\left|i(1/2)\tilde{s}_1\left(t-\frac{x}{v}\right)+i(1/2)\tilde{s}_2\left(t+\frac{x}{v}-T_a\right)\right|^2\\&=\frac{1}{4}\left|\tilde{s}_1\left(t-\frac{x}{v}\right)\right|^2+\frac{1}{4}\left|\tilde{s}_2\left(t+\frac{x}{v}-T_a\right)\right|^2\\&+\frac{1}{2}\mathrm{Re}\left\{\tilde{s}_1^*\left(t-\frac{x}{v}\right)\tilde{s}_2\left(t+\frac{x}{v}-T_a\right)\right\},\end{aligned} \tag{2}$$

where $\tilde{s}$ is the complex analytical signal, x is the coordinate in the Bragg cells and in photoreceiver, v is the sound speed in the acoustic duct medium, T_a is the time aperture of the Bragg cell. At the photoreceiver output, a charge is formed which is proportional to the incident light energy over the light exposure time and is limited by the permissible linear array integration time. This energy is

$$\begin{aligned}E(x)&=\frac{1}{4}\int_T\left[\mathrm{Re}\tilde{s}_1^*\left(t-\frac{x}{v}\right)\right]^2dt\\&+\frac{1}{4}\int_T\left[\mathrm{Re}\tilde{s}_2\left(t+\frac{x}{v}-T_a\right)\right]^2dt\\&+\frac{1}{2}\mathrm{Re}\left\{\int_T\tilde{s}_1^*\left(t-\frac{x}{v}\right)\tilde{s}_2\left(t+\frac{x}{v}-T_a\right)dt\right\}.\end{aligned} \tag{3}$$

The first two terms of equation (3) are constant in the case of sufficiently long integration time T, while the third term is the convolution of functions $s_1(t)$ and $s_2(t)$.

The above presented data allowed us to propose the use of the convolver with time integration [10,11] to perform the wavelet-transform of informative signal $s_1(t)$ as its convolution with its mother wavelet $s_2(t)$.

The scheme of the AO processor with time integration identical to that given in the figure was proposed in [13] for obtaining the spectrum of informative signal $s_1(t)$. The operating procedure of this scheme is considered in details in [14]. That paper describes LFM signals similar to those in the scheme presented in the figure, which are fed to the Bragg cells:

$$\begin{aligned}s_1'(t)&=\left[1+s_1(t)\right]\cos\left(\Omega_0t+0.5\gamma t^2\right),\\s_2'(t)&=\cos\left(\Omega_0t+0.5\gamma t^2\right),\end{aligned} \tag{4}$$

where $s_1'(t)$ represents the LFM signal with initial frequency Ω_0 and frequency modulation steep γ, which is modulated in amplitude by informative signal $s_1(t)$; $s_2'(t)$ is the reference LFM signal with a rectangular envelope. Paper [14] also shows that complex envelopes of those signals have the following form:

$$\dot{u}_{s_1'}(t)=\left[1+s_1(t)\right]\exp(i0.5\gamma t^2),\ \ \dot{u}_{s_2'}(t)=\exp(i0.5\gamma t^2). \tag{5}$$

As in the case of the convolver, at the photoreceiver output a charge proportional to the incident light energy is generated. By filtering out the constant pedestal, it is possible to distinguish the signal component of the charge accumulated in the photoreceiver [14]:

$$\begin{aligned}Q(x)&=\mathrm{Re}\left\{A\exp(i2K_0x)\int_{L/v}^{L/v+T}\dot{u}_{s_1'}\left(t-\frac{x}{v}\right)\dot{u}_{s_2'}^*\left(t+\frac{x}{v}\right)dt\right\}\\&=\mathrm{Re}\left\{A\exp(i2K_0x)\int_{L/v}^{L/v+T}s_1\left(t+\frac{x}{v}\right)\exp\left(-i\frac{2\gamma xt}{v}\right)dt\right\},\end{aligned} \tag{6}$$

where $K_0=\Omega_0/v$, L is the dimension of the acousto-optic cell linear aperture. Relation (6) demonstrates that the signal accumulated at the photoreceiver (its distribution over coordinate x) is the spectrum of signal $s_1(t)$ at the spatial carrier frequency. Thus, the considered scheme forms the informative signal $s_1(t)$ spectrum when appropriate signals are fed to it.

The Montgomery's convolver [10,11] implies the input of radio frequency signals $s_1(t)$ and $s_2(t)$ into two respective Bragg cells for their convolution, which allowed us to propose realization of wavelet transform of the informative signal (3). Based on this, it is possible to perform the bioelectric signal wavelet processing by using amplitude modulation of the radio frequency carriers in the both Bragg cells (see the figure) by the informative BES and its mother wavelet. In this case, similarly to (5) and (6), the output signal of the wavelet processor−convolver may be presented as

$$Q(x)=\mathrm{Re}\left\{A\exp(i2K_0x)\int_{L/v}^{L/v+T}s_1\left(t+\frac{x}{v}\right)s_2\left(t-\frac{x}{v}\right)dt\right\}+C, \tag{7}$$

where C is the variable-amplitude pedestal. Hence, when radio frequency carrier signals are used, the charge accumulated at the CCD linear array provides information on the signal $s_1(t)$ wavelet transform by the mother wavelet $s_2(t)$.

Finally, this study has proved the possibility of using a single AO-processor with time integration (see the figure) to calculate both the information signal $s_1(t)$ wavelet transform and power spectrum.

Thus, this paper showed for the first time the possibility of wavelet processing of informative signals at the acousto-optic processor with time integration and also justified both the real-time spectrum calculation and performance of BES wavelet transform by using this processor with feeding different signals to its inputs. This may be quite interesting for many practical applications.

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Conflict of interests

The authors declare that they have no conflict of interests.

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