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Development of New Algorithm in the Method of a Resonant Vibrating Target for Large Scanning Speeds

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Abstract—The work is devoted to the study of scanning the transverse profile of a beam using a vibrating wire. A new algorithm has been developed that allows the use of a resonant vibrating target method for high scanning speeds. The method is based on the idea of measuring secondary/reflected particles/radiation generated from the interaction of the beam particles with the wire material, synchronously with the frequency of the wire oscillation. The proposed algorithm for using a differential signal with sign inversion on consecutive measurements from half-periods of wire oscillations is generalized for the case when the scanning speed is much higher than the average speed of the wire oscillation.

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1. INTRODUCTION

The basis of traditional scanning methods is a quite simple idea of simultaneously measuring the position of the scanning beam of wire and the signal from this wire [1]. Scanners with a separate system for detecting secondary particles/radiation are used [2]. Usually this system is located at a sufficiently large distance from the location of the wire, and in addition to the useful signal from the wire, it is registering a sufficiently large background of particles and radiation scattered as a result of other processes. Scanners, that are registering the current of secondary charges generated in the wire as a result of the interaction of the beam particles with the wire material, have the advantage of concentrating the measuring setup in one node, but require measuring small currents (up to pA) by analog methods [3]. Increasing the scanning speed is one of the actual tasks [4].

In [5–6], it was proposed to use the frequency of the vibrating wire as a measuring signal, depending on its temperature, which in turn monitors the density distribution of particles in the beam. The method is more sensitive than the previous two, however, due to the thermal principle of operation, it has inertia (i.e., measurement time in a fixed position of the wire is, at best, a fraction of a second). In [7], a series of reflections from a vibrating wire during one half-period was used to measure the profile of thin beams. The transverse beam size is of the order of the wire oscillations amplitude.

In [8–9], it was proposed to use a vibrating wire as a target wire, and measure the scattered/reflected particles/photons synchronously (resonantly) with the wire oscillations. The pairwise measurement of these particles/photons in the extreme positions of the wire during its oscillation allows using the procedure of differentiation of this signal, which cuts off the constant component of the background. In [9], it was emphasized that in order to isolate the spatial component of the distribution of the beam being measured, a consecutive use of the differentiation procedure with sign inversion at each half-period of oscillations is required. As a result, temporary background fluctuations are also cut off. This method was called the resonant method of a vibrating wire. In [9] there is a limit on the scanning speed ν_s, which is derived from the condition that the scanning speed is much less than the average speed of the wire on its half period $\nu_w = 4AF$, where A is the amplitude of the wire oscillations (the maximum displacement of the center point of the wire from its equilibrium position), F is the oscillation frequency of the wire (it is assumed that the wire oscillates at the first harmonic).

2. THEORETICAL MODEL

In this paper, a method has been developed that allows scanning at speeds much higher than the average speed of a wire ν_w during its oscillation. The method was tested on a model beam.

For distinctness, the process of scanning a laser beam is considered. This assumption does not limit the application of the method, but further allows the use of the terms ‘reflected photons’ and ‘beam photons’ without loss of generality.

2.1. Slow Scanning of the Laser Beam ($\nu_s \le \nu_w$)

Consider scanning a laser beam in the case when the scanning speed is less than the average speed of the wire during its oscillation.

Taking into account that the wire in the process of oscillation makes two movements simultaneously – uniform and vibrational, for the position of the center of the vibrating wire in the direction x we use the formula:

$$x_w = \nu_s * t + A * \cos(2\pi F t), \tag{1}$$

where the term $\nu_s * t$ describes the motion of the projections of the wires points on the scan axis x trace through the center of the wire (it is assumed that the wire is perpendicular to this axis). In the following, the motion of the projections of the wire's fixed points will be called the motion of the scanner.

We introduce the parameter of the period of oscillations of the wire $T = 1/F$ and, accordingly, the set of measurement points in time through each half-period:

$$t_i = iT/2, i = 0,1,2.... \tag{2}$$

The corresponding center positions of the wire are written as

$$x_w^i = i\nu_s T/2 \pm A, \tag{3}$$

where the ‘+’ sign is taken for even i and the ‘−‘ sign for odd i.

The idea of resonant scanning is to measure the reflected photons of the beam in the limiting positions of the wire during its oscillation.

Let $P(x)$ is the photon distribution of the beam. Then the number of measured reflected photons is written in the form:

$$S_i = k * P(x_w^i) = k * P(i\nu_s T/2 \pm A), \tag{4}$$

where the ‘+’ sign is taken for even i and the ‘−‘ sign for odd i, a constant coefficient k determines the proportionality between the number of photons falling on the wire and reflected from the wire. Since we are interested only in relative measurements of the profile without loss of generality, in the future, let us assume that $k=1$. By consecutive measurements of the number of reflected photons, one can find the local value of the profile gradient in the form

$$G_i = (P(x_w^i) - P(x_w^{i-1}) / (x_w^i - x_w^{i-1}), \quad (5).$$

if $x_w^i > x_w^{i-1}$, and

$$G_i = (P(x_w^{i-1}) - P(x_w^i) / (x_w^{i-1} - x_w^i), \quad (6)$$

if $x_w^{i-1} > x_w^i$.

The fact that both cases are possible are shown in fig. 1, where values from time x_w^i (i index's) are presented. The model parameters are as follows: ν_s = 10 mm/s, A = 0.05 mm, F = 1000 Hz, so the average speed of the wire is 200 mm/s. As seen, consecutive positions of the wire on half periods oscillate with a small increase in the average value.

Figure 1 shows the movement of the center of a vibrating wire at a speed lower than the average speed of the wire.

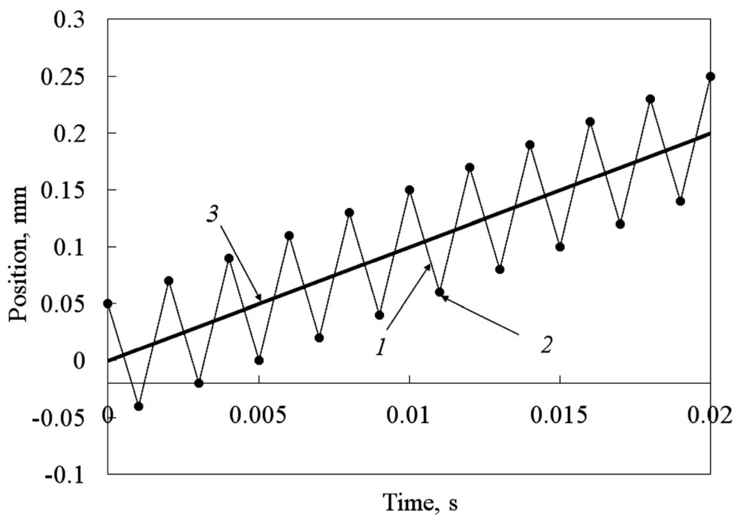

Fig. 1. Time dependence of the vibrating wire center: broken line *1* – connects circles, *2* – positions of maximum deviations of the wire, straight line *3* – scanner position.

As can be seen from the figure, the consecutive positions of the wire increase non-monotonously. Formulas (5, 6) rewrite in the form

$$G_{\rm i} = (S_{\rm i} - S_{\rm i-1}) / (\nu_s T/2 + 2A) = (P(i\nu_s T/2 + A) - P((i-1)\nu_s T/2 - A)) / (\nu_s T/2 + 2A), \quad (7)$$

for even i and

$$G_{\rm i} = -(S_{\rm i} - S_{\rm i-1}) / (-\nu_s T/2 + 2A) = (P((i-1)\nu_s T/2 + A) - P(i\nu_s T/2 - A)) / (-\nu_s T/2 + 2A), \quad (8)$$

for odd i.

If $\nu_s T/2 << 2A$ (the condition that the scanning speed is much less than the average speed of the wire in its half period) formulas (7, 8) can be simplified

$$G_{\rm i} = (S_{\rm i} - S_{\rm i-1}) / 2A = (P(i\nu_s T/2 + A) - P((i-1)\nu_s T/2 - A)) / 2A, \quad (9)$$

for even i and

$$G_{\rm i} = -(S_{\rm i} - S_{\rm i-1}) / 2A = (P((i-1)\nu_s T/2 + A) - P(i\nu_s T/2 - A)) / 2A, \quad (10)$$

for odd i.

According to the consecutive values of the beam gradient, by integrating (actually by summation over the index i), the initial beam profile is found.

Let us demonstrate the process using the example of a slow scan of a model beam. The distribution of photons in the transverse direction x is given by the formula

$$P(x) = 1 + \cos(\pi(1 + x / x_0)) \text{, for } 0 \le x \le 2x_0, \tag{11}$$

where $2x_0$ is the beam half width.

In the sequel, we will use different ratios of scanning speeds and wire vibrations. It is more convenient to do this by changing the amplitude of oscillations of the wire, while maintaining the frequency of oscillations of the wire and the type of photon beam profile, as well as the scanning speed. This will save the number of measurement points, which will make it possible to compare configurations of different ratios of speeds.

The figure shows that the integrated differential signal with inversion of the sign (formulas (9, 10)) practically coincides with the initial distribution.

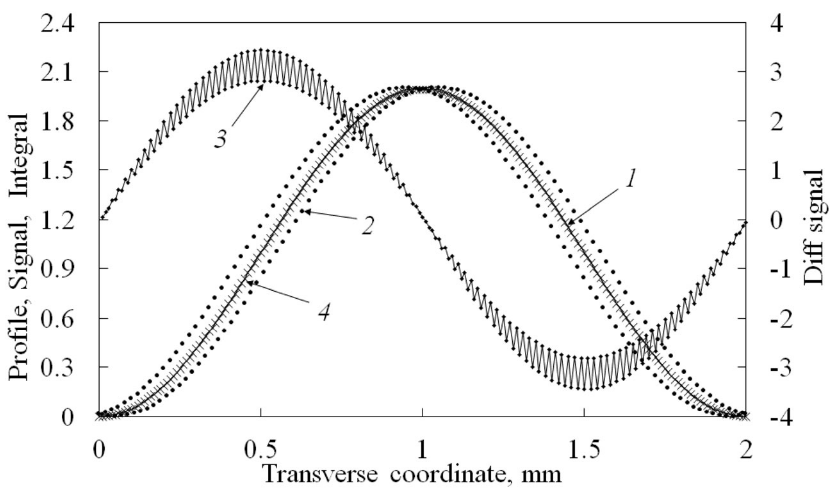

Fig. 2. Slow scanning of a photon beam by vibrating wire. Solid line *1* – beam profile, circles *2* – consecutive measurements over the half period of wire oscillations, *3* – differential signal, crosses *4* – integrated differential signal.

Let us give an example of an experiment on slow scanning of a laser beam. Scanning was carried out using a pendulum with a shoulder of ≈ 1 m, on which a sensor with a vibrating wire was fixed. The laser and photodiode were fixed on a separate platform so that when a wire intersected a laser beam, some of the photons reflected from the wire would fall into the photodiode aperture. However, the photons of the laser beam reflected from other parts of the sensor and the external background from artificial light also fell on the photodiode. In the previous processing of the mathematical model (see Fig. 2) it was assumed that the scan is performed at a constant speed. Figure 3 shows the photodiode measurements corresponding to two consecutive passages of a laser beam by a wire. A differential signal is also presented here. In the case of a pendulum, this is not so: the pendulum reaches its limit position and begins to move in the opposite direction, and the speed of movement is not constant. Figure 3 shows a simple summation of the differential signal without taking this into account.

In the graph of the signal from the photodiode is clearly visible 50 Hz – component of the lighting. It is also seen that the differential signal completely cuts off this component, as well as the central plateau of the signal from the photodiode, which is related with photons reflected from the mechanical elements of the sensor (from the non-vibrating wire). Figure 3 also presents the summation of the differential signal – a necessary step before the reconstruction of the laser beam profile. It is seen that the profile of the laser beam on the second scan is inverted due to the fact that the scanning speed has changed its sign. The drift of the sum signal is due to the fact that the summation does not take into account the change in the scanning speed. For more information about the profile recovery procedure with slow nonuniform scanning, see [9].

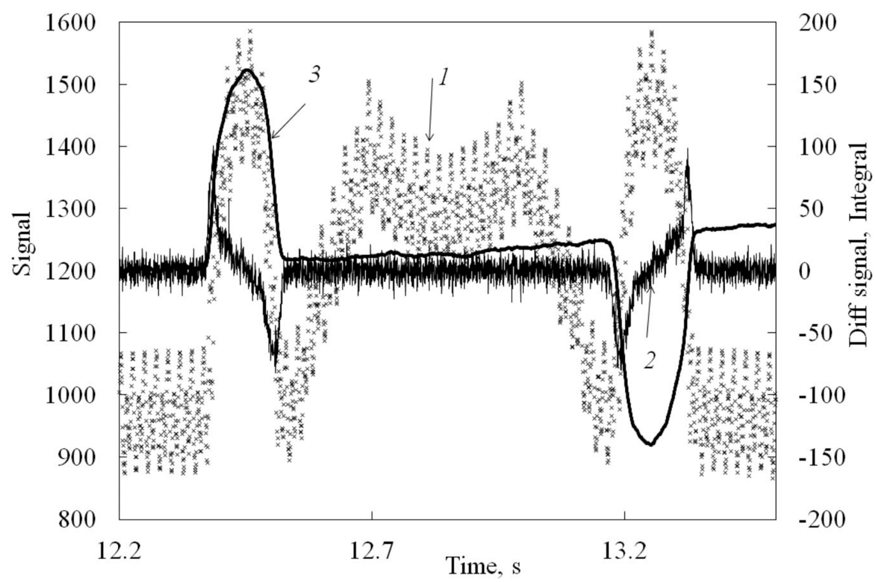

Fig. 3. Results of scanning a laser beam with a scanner mounted on the shoulder of a pendulum. Crosses *1* – photodiode measurement, *2* – differential signal, solid line *3* – summation of the differential signal.

2.2. Fast Scanning of a Laser Beam ($\nu_s \geq \nu_w$)

Previous results were obtained on the basis of approximate formulas (9, 10). However, the exact formulas (7, 8) can be used only under the condition $\nu_s < \nu_w$, since the denominator in the formula decreases and can even be zeroed out. Figure 4 shows several graphs of the center point of a moving wire depending on the oscillations amplitude. In the case of A = 0.005 mm, the average oscillation velocity of the wire ν_w is compared with the scanning speed ν_s = 10 mm/s and at the half period, when the wire moves against the scanning movement, the center positions of the wire at the beginning and at the end of the half period coincide. This corresponds to zeroing the denominator in the formula (8). In the case when $\nu_s \geq \nu_w$ the position of the center of the wire monotonously increases during scanning, approaching the graph of the wire's fixed point position (in Fig. 4, this is the graph corresponding to A = 0.002 mm, with ν_w = 4 mm/s).

For the case, when $\nu_s \geq \nu_w$, it is proposed to continue using formulas (9, 10) with sign inversion on consecutive half-periods, although the total differential signal is far from the real beam gradient. Further it is proposed to integrate the differential signal generated in this way and, finally, apply the current average integral signal procedure over two consecutive points. Mathematically, it all looks like this – a differential signal is calculated as

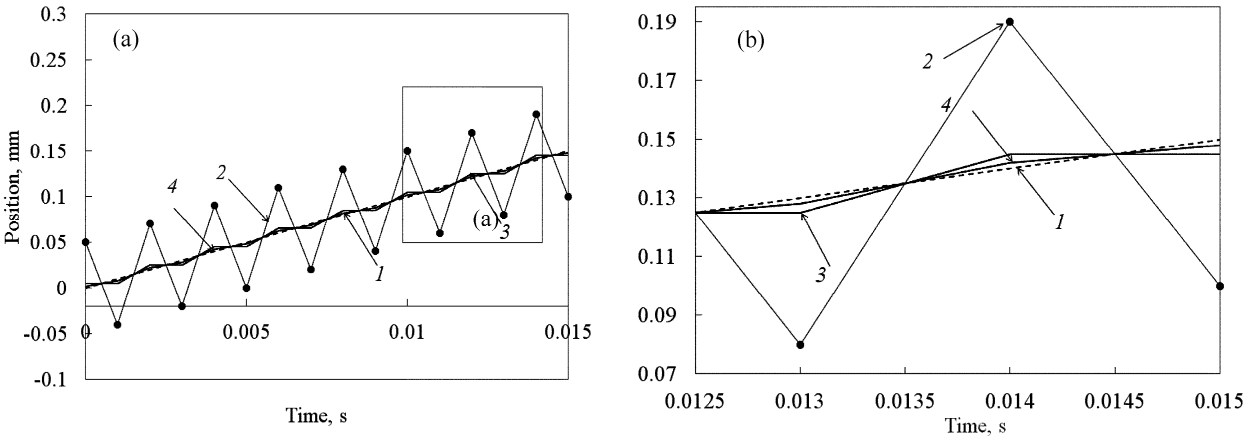

Fig. 4. (a) The positions of the scanner and the center of the vibrating wire on consecutive half-periods of oscillations for different amplitudes: dashed line *1* – scanner position, *2*, *3* and *4* – position of the wire with amplitudes of vibration A = 0.05 mm (slow motion), A = 0.005 mm (scanner speed equal to the wire's movement speed) and A = 0.002 mm (scanner speed is 2.5 times higher than the speed of the wire), respectively. (b) Fragment on an enlarged scale.

$$G_i = (S_{i-1} - S_i)/2A, \quad i = 1,3,5...,$$
$$G_i = (S_i - S_{i-1})/2A, \quad i = 2,4,6.... \tag{12}$$

Next, the integral signal is calculated.

$$I_{\rm i} = I_{\rm i\text{-}1} + \Delta_{\rm s} G_{\rm i}, i = 1,2,3,..., \tag{13}$$

where the $\Delta_{\rm s} = \nu_{\rm s} T/2$ is a displacement of the scanner during the half period of wire oscillations. As a result, the current average of the integral signal is calculated by two consecutive points.

$$\overline{I}_{\rm i} = (I_{\rm i} + I_{\rm i\text{-}1})/2, i = 1,2,3,.... \tag{14}$$

The result of the procedures (12–14) with amplitude A = 0.001 mm is shown in Fig. 5.

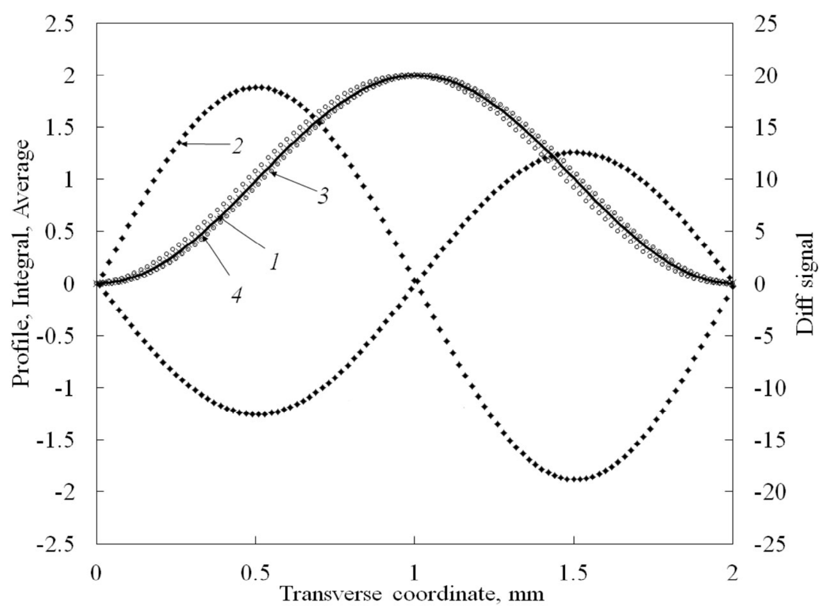

Fig. 5. Reconstruction of the beam profile with amplitude A = 0.001 mm. Solid line *1* – photon beam profile, rhombs *2* – differential signal, circles *3* – integrated differential signal, crosses *4* – signal averaged from signal *3*.

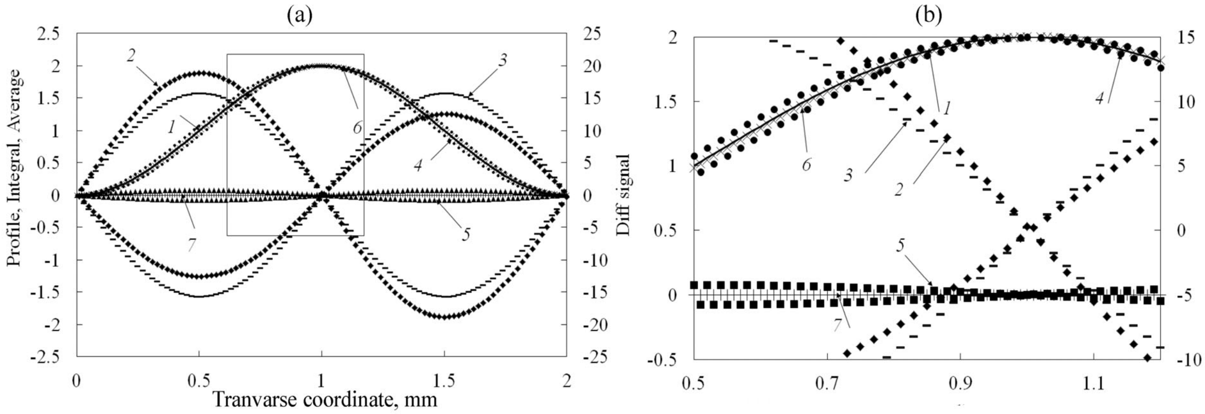

Fig. 6. (a) Reconstruction of the beam profile with amplitude A = 0.001 mm and use of the algorithm to a non-vibrating wire. The solid line *1* is the photon beam profile, rhombs *2* and hyphens *3* are differential signals from a vibrating and non-vibrating wire, respectively, circles *4* and triangles *5* are integrated signals of *2* and *3*, oblique crosses *6* and straight crosses *7* are signals averaged from *4* and *5*. (b) Fragment on an enlarged scale.

In Fig. 6, the results of applying the algorithm (12–14) to the position of the scanner are added to the previous result. As can be seen from the figure, the result is zero.

The method can also be applied at a much higher ratio of speeds: ν_s = 10 mm/s, ν_w = 0.2 mm/s (see Fig. 7). The results of applying the algorithm (12–14) to the motion of a non-vibrating wire (of the scanner) are also presented.

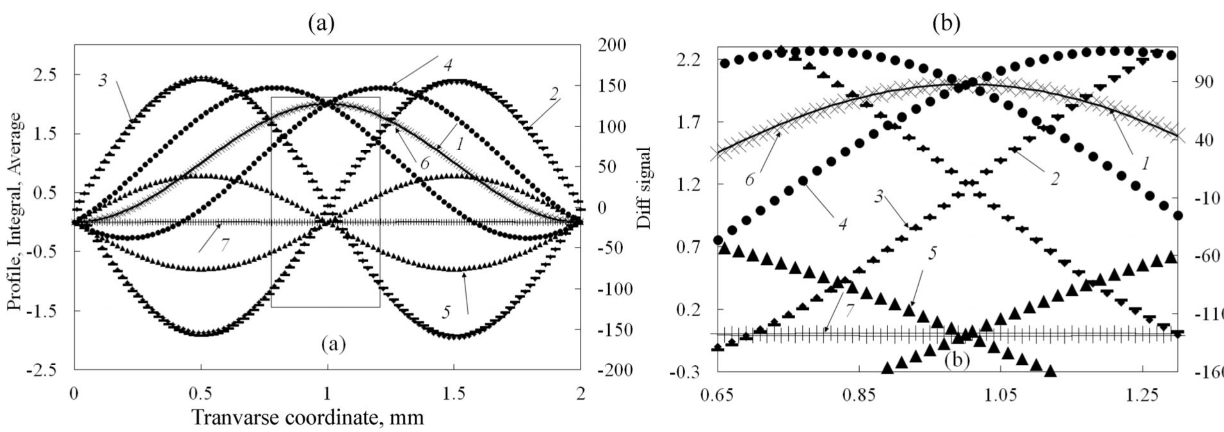

Fig. 7. (a) Reconstruction of the beam profile with amplitude A = 0.0001 mm and use of the algorithm to a non-vibrating wire. The solid line *1* is the photon beam profile, rhombs *2* and hyphens *3* are differential signals from a vibrating and non-vibrating wire, respectively, circles *4* and triangles *5* are integrated signals of *2* and *3*, oblique crosses *6* and straight crosses *7* are signals averaged from *4* and *5*. (b) Fragment on an enlarged scale.

2.3. Model with Background

We introduce into our model a time-dependent background that is uniform within the photodiode aperture. Mathematically, this means that instead of (4) you should use the formula of the form

$$S_i = P(x_w(t_i)) + \Phi(t_i)\,. \tag{15}$$

In our models, we fixed a scan speed of 10 mm/s. The whole process of scanning a beam with a width of 2 mm lasts 0.2 s. Consider a background with two oscillations during this time.

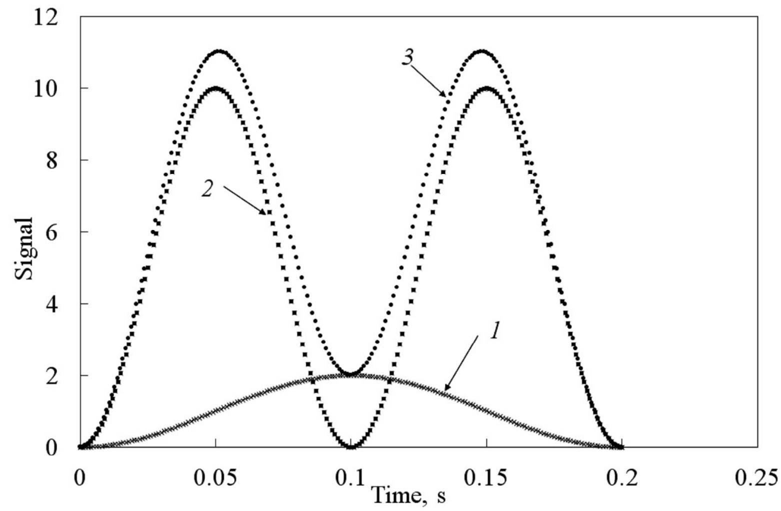

Fig. 8. The dependence of the readings of the photodiode on time: crosses *1* – reflections from the vibrating wire, squares *2* – background, circles *3* – full signal from the photodiode.

$$\Phi(t) = B(1 + \cos(\pi(1 + 4t / t_0))) \, , \tag{16}$$

where $t_0 = 2x_0 / \nu_s$ is the scan time, and $2B$ is the maximum background value.

Figure 8 shows the summary signal from the photodiode containing a component of reflections from a vibrating wire with amplitude $A = 0.001$ and a large background.

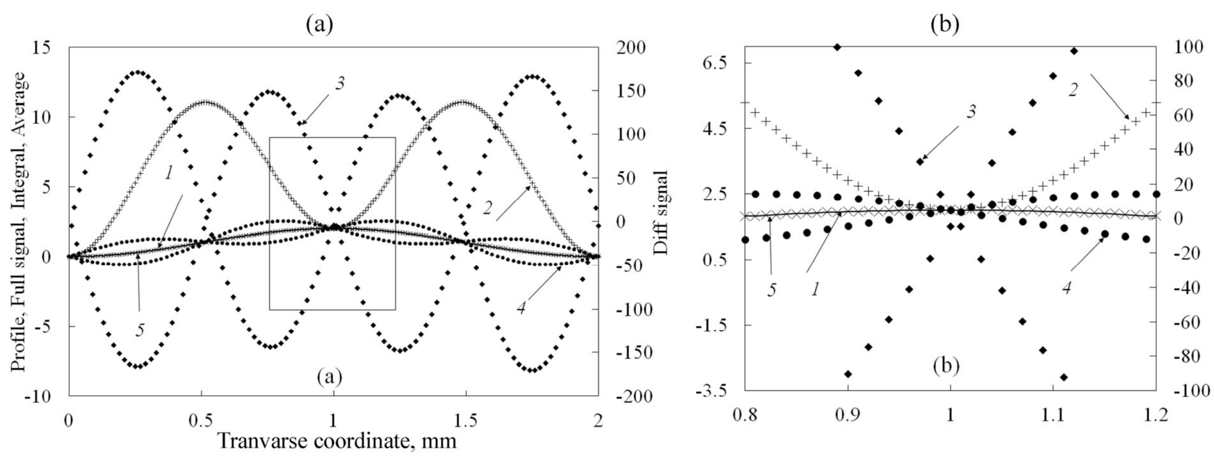

Fig. 9. (a) Profile reconstruction with amplitude A = 0.001 mm in the presence of background. Solid line *1* – photon beam profile, straight crosses *2* – full signal from photodiode, rhombs *3* – differential signal, circles *4* – integrated differential signal, oblique crosses *5* – signal averaged from signal *4*. (b) Fragment on an enlarged scale.

The process of profile extraction by the algorithm (12–14) is depicted in Fig. 9.

If the ratio of scanning speed and wire speed is increased (amplitude A = 0.0001 mm), the averaging from the integral signal (triangles in Fig. 10) is not yet imposed on the beam profile. Another averaging of this signal over the current average, similar to (14), restores the beam profile with good accuracy.

Figure 11 shows the case when photons reflected from the vibrating wire are not falling on the photodiode (the first term to the right in the formula (15) is absent).

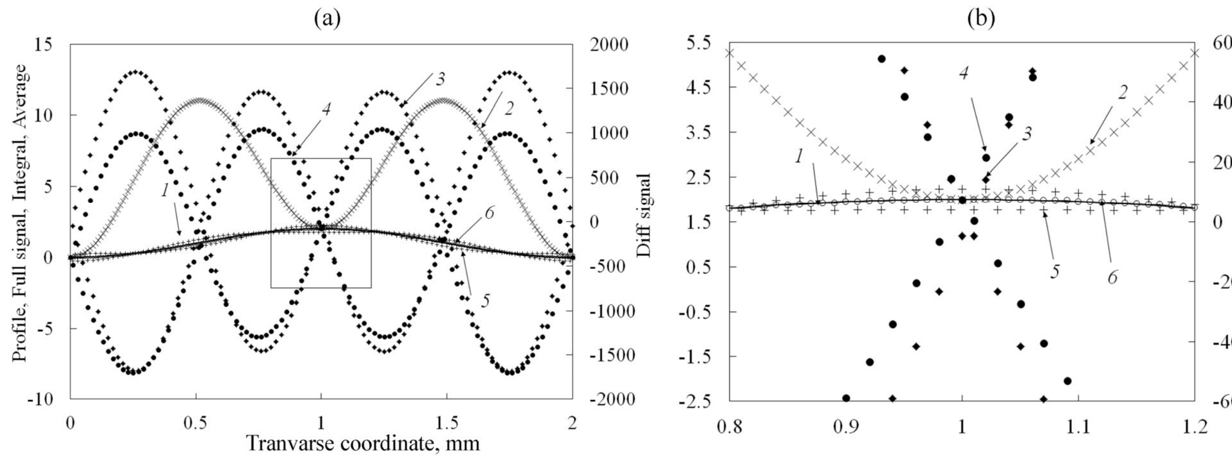

Fig. 10. (a) Profile reconstruction with amplitude $A = 0.0001$ mm in the presence of background. Solid line *1* – photon beam profile, oblique crosses *2* – full signal from photodiode, rhombs *3* – differential signal, circles *4* – integrated differential signal, straight crosses *5* – signal averaged from signal *4*, hollow circles *6* – second averaging of the signal *4*. (b) Fragment on an enlarged scale.

As follows from Fig. 11, the background does not make any contribution to the final resulting signal, which once again confirms the exceptional ability of the algorithm to filter out only the useful signal resulting from the interaction with the vibrating wire.

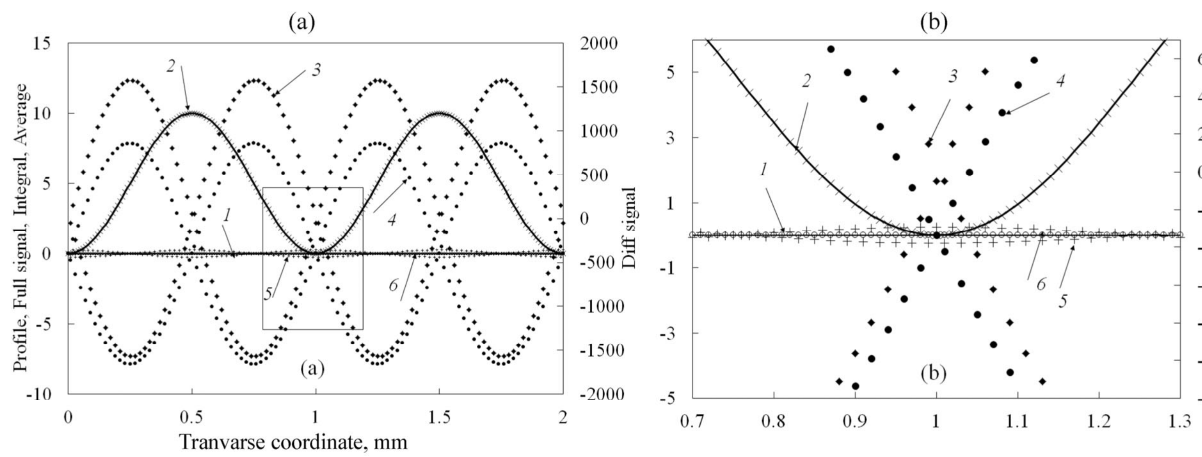

Fig. 11. (a) Applying of beam reconstruction algorithm to background. Solid line *1* – photon beam profile, oblique, crosses *2* – full signal from photodiode, rhombs *3* – differential signal, circles *4* – integrated differential signal, straight crosses *5* – signal averaged from signal *4*, hollow circles *6* – second averaged signal. (b) Fragment on an enlarged scale.

3. CONCLUSION

A new algorithm has been developed in the case when the scanning speed is much greater than the average wire oscillation speed. The method allows significantly reducing the beam scanning time. The algorithm for using this method has been applied in the presence of the backgrounds of the reflection of the laser beam from the scanner structure and external unstable radiation.

The possibility of reducing the amplitude of the vibrating wire is also useful from the point of view of increasing the vibrations stability.

The proposed algorithm is quite universal and can be used to measure the profiles of charged particle beams, neutrons and electromagnetic radiation in a wide range of the spectrum.

In the case of accelerator beam profiling, it may be necessary to use high-energy particle detectors (scintillator plus photomultiplier tube). However, given the high degree of selectivity of the proposed scheme, it is possible that photodiodes can be used for the X-ray range.

The method can be useful for detecting objects containing constituent parts oscillating with a known frequency, for example, propellers.

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