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OPTOPHYSICAL MEASUREMENTS

JITTER MEASUREMENT TECHNIQUE FOR IMAGE-CONVERTER STREAK CAMERAS

M. V. Kanzyuba and V. B. Lebedev

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The phenomenon of jitter is examined in image-converter (electro-optical) streak cameras used for studies of high-speed processes. A method for measuring jitter in streak cameras operating in a linear scan mode for the pulsed optical signal is proposed. An experimental apparatus that realizes this measurement technique is described. This apparatus is used at VNIIOFI to check jitter in commercial image-converter streak cameras for compliance with specifications or the technical requirements of customers.

Keywords: *jitter, measurement, streak (electro-optical) camera.*

Introduction. Image-converter (electro-optical) streak cameras operating in a linear scan (sweep) mode for the pulsed optical signal are essential for studies of various high-speed processes, such as combustion, explosions, shock and detonation waves, the destruction of materials and structures, ballistics, natural and artificial electrical discharges, pulsed radiation, and their interaction with matter, plasma dynamics, phase transitions, and chemical reactions [1–4].

In general, the phenomenon of phase modulation of a received signal (either analog or digital) is referred to as (phase) jitter [5]. In practice, jitter is an instability of a pulsed periodic signal in the form of changes in the time interval (spread) between the specified onset of the period and the subsequent realization of the signal in each period.

In studies of repetitive optical processes with streak cameras operating in a linear scan mode, jitter shows up as a spread in the observed position of the pulsed optical signal in the scan when the streak camera is synchronized with a trigger signal. The main reason for the spread is instability in the timing for the high-voltage scan pulse. Besides the intrinsic jitter of the streak camera, jitter in the trigger for the streak camera relative to the observed process may also contribute. Thus, the jitter in the trigger signal must be eliminated for a correct measurement of the intrinsic jitter of the streak camera when it is triggered.

Jitter can be characterized quantitatively in various ways. The peak-to-peak (full) jitter is defined as the maximum time spread in the position of the pulse in the scan, i.e., the difference in the maximum and minimum delays relative to the onset of the sweep. However, as statistics are accumulated, the full jitter will increase monotonically with increasing sample size and will be influenced by large random fluctuations (overshoots). Thus, it is better to characterize the jitter in terms of a parameter of the statistics of the pulse positions that characterizes the width of the distribution and is independent of the sample size. In a typical practical case, when the distribution of the positions of the pulses is normal or nearly so, jitter is conveniently characterized by the mean square value. Thus, the mean square value of the jitter is the width parameter for a normal distribution, for which the mean square deviation (MSD) of the pulse position is an unbiased estimate.

When a streak camera is run in a regime of accumulating repetitive signals, the value of the jitter is directly determined by the error in measuring the duration of these signals. Thus, the jitter must be measured in all scan ranges of the streak camera.

The jitter relative to the scan duration (the relative jitter) characterizes the quality of the streak camera. The smaller the relative jitter, the higher the quality of the streak camera. The highest relative jitter is attained with the fastest sweep of the streak camera. Thus, as a rule, in their technical specifications for streak cameras, customers impose requirements on the jitter for the fastest scan.

All-Russia Research Institute of Optophysical Measurements (VNIIOFI), Moscow, Russia; e-mail: mkanzyuba@vniiofi.ru. Translated from Izmeritel'naya Tekhnika, No. 10, pp. 33–37, October, 2020. Original article submitted July 2, 2020. Accepted August 2, 2020.

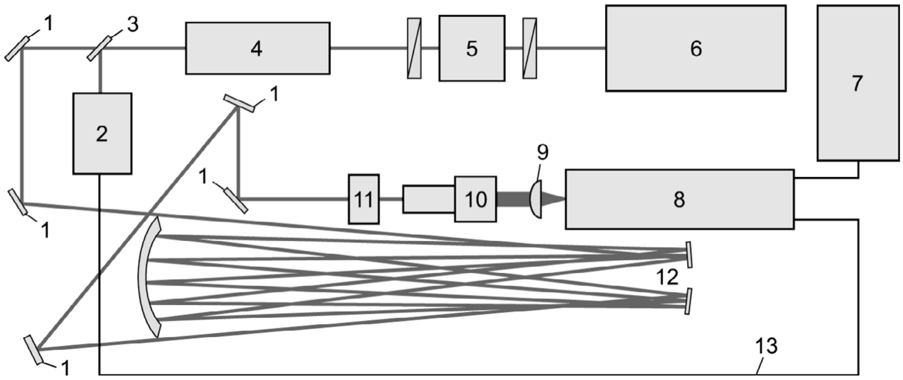

Fig. 1. Schematic of the experimental apparatus for measuring the jitter of an image-converter streak camera: *1*) mirrors; *2*) photodiode; *3*) beam splitter; *4*) second harmonic generator; *5*) electro-optical shutter; *6*) femtosecond laser; *7*) computer; *8*) streak camera; *9*) cylindrical lens; *10*) beam expander; *11*) neutral density filters; *12*) optical delay line; *13*) delay line for trigger signal.

Experimental apparatus. The experimental apparatus developed at VNIIOFI for measuring the jitter of streak cameras employs a direct measurement technique. The jitter of the streak camera is measured by repeated recording of the position of a single short laser pulse in the scan. Here the camera is triggered by an electrical signal from a coaxial photodiode [6, 7] manufactured by VNIIOFI. A beam splitter at the photodiode gathers part of the emission from the recorded laser pulse. In order for an image of the pulse to fall on the scan, it is necessary to synchronize the time of arrival of the laser pulse on the photocathode of the streak camera to the time the laser is fired. An optical delay line is used for synchronization to delay the pulse falling on the camera photocathode along with a delay line for the triggering electrical signal for the photodiode.

Figure 1 is a functional diagram of the experimental apparatus. A femtosecond laser *6* generates a sequence of pulses lasting on the order of 100 fs at a wavelength of 1050 nm with a repetition rate of 70 MHz. An electro-optical shutter *5* separates a single pulse from this sequence. A second harmonic generator *4* transforms the frequency of the laser pulse into the visible range. As a result, the energy of the laser pulse at the wavelength of 525 nm is about 30 nJ. A beam splitter *3* direct part of the radiation onto the photodiode *2*. The electrical pulse from the photodiode serves as a trigger for the streak camera which has a certain operating delay time ("dead time"). The bulk of the radiation passes through an optical delay line *12* consisting of a single spherical and two plane mirrors. The delay is controlled in order for the laser pulse to fall during a scan. It is controlled using a delay line on the electrical trigger signal from the photodiode in the form of a segment *13* of rf cable of the required length. Neutral density filters *11* are used in order to prevent excessive illumination of the photocathode of the streak camera that might lead to distortion of the recorded signals. A beam expander *10* serves to fill the entire length of the slit of the streak camera with light. To prevent reduction of the lighting of the slit after the expander, a cylindrical lens *9* is installed to focus the light on the slit of the streak camera. The images recorded by the streak camera are recorded by a digital television camera built into the streak camera. The images are transferred to a computer *7* for display on a monitor, recording on disk, and subsequent analysis.

Measurement technique. Jitter is measured in the following way. The repetition rate of the laser pulses is adjusted so it does not exceed the maximum allowable trigger frequency of the streak camera. The streak camera is triggered cyclically at the slowest scan rate. The length of the cable between the photodiode and the streak camera is chosen so that an image of the laser pulse is observed in the middle of the scan in the form of a narrow vertical strip. This strip is the temporal instrument function of the streak camera in this scan range. The program for the streak camera is used to record at least 100 successive images of the pulse. This procedure is repeated for the subsequent faster scan ranges. The duration of the most rapid scan of the streak camera with a picosecond time resolution is a fraction of a nanosecond. The operating time of the streak camera in this scan is controlled smoothly by means of small smooth shifts of the photodiode to one or the other side along its optical axis– counter to the beam or in the opposite direction, depending on the required reduction or magnification of the delay in the trigger signal.

The recorded images can be processed manually or using automatic image processing programs. For each image the coordinate t_i of the pulse in the scan, i.e., the time interval from the start of the scan to the time of the maximum signal intensity is determined. The relationship between the coordinate x on the scan expressed in image pixels and the time interval t reckoned from the start of the scan is given in general by the calibration dependence

$$t = \int_0^x k(x)\,dx,$$

where $k(x)$ is the scan coefficient, which depends on the coordinate.

When the nonuniformity of the scan coefficient is negligibly small or if the streak camera program corrects for the nonuniformity in $k(x)$, the relationship between the coordinate of the pulse in the scan in units of time (t_i) and in pixels of the image (x_i) is given by

$$t_i = kx_i,$$

where k is the value of the scan coefficient provided in the operating documentation for the streak camera or determined experimentally [8].

The program for the streak camera may also include a function for automatic transformation of the coordinates from image pixels to units of time when the images are written to a file.

Next, the average t_{avg} and the MSD σ_t of the position of the pulse are calculated using the formulas

$$t_{\text{avg}} = \frac{1}{N}\sum_{i=1}^{N} t_i; \qquad \sigma_t = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(t_i - t_{\text{avg}})^2},$$

where $i = 1, \ldots, N$; N is the number of images being processed.

The result of the measurements of the jitter of the streak camera is the root-mean square (RMS) value of the jitter J_{RMS} in accordance with the above MSD, i.e.,

$$J_{\text{RMS}} = \sigma_t.$$

The standard type A uncertainty of the result of the jitter measurements for the streak camera is calculated using the formula derived for the standard uncertainty estimate of the width parameter of a normal distribution for a finite sample [9]:

$$u_{\text{A}}(J_{\text{RMS}}) = \frac{1}{\sqrt{2(N-1)}}\cdot 100.$$

The standard type B uncertainty of the result of the jitter measurements for the streak camera is calculated taking into account the standard uncertainty of the scan coefficient $u(k)$ given in the operating documentation for the streak camera or found experimentally when measuring the scan coefficient:

$$u_{\text{B}}(J_{\text{RMS}}) = u(k).$$

The combined standard uncertainty of the result of the measurements of the streak camera jitter is calculated using the formula

$$u_c(J_{\text{RMS}}) = \sqrt{u_{\text{A}}^2(J_{\text{RMS}}) + u_{\text{B}}^2(J_{\text{RMS}})}.$$

The expanded uncertainty of the result of the measurements of the streak camera jitter for a coverage factor equal to two is calculated as

$$U(J_{\text{RMS}}) = 2u_c(J_{\text{RMS}}).$$

Measurement of jitter on the KVFSh65.10.000 streak camera. This camera is the prototype of the K016 series of streak cameras manufactured by VNIIOFI and is used as the standard means of measurement of the duration of a laser pulse in the KVFSh65.00.000 system. This device is certified as a national secondary standard for the duration of pulsed laser radiation (registration number 2.1.ZZA.0101.2017 in the federal data base for support of the unity of measurements).

1000 images of a single femtosecond laser pulse were recorded in the fastest scan (0.1 ns/cm) of duration 150 ps of the streak camera. Figure 2 is a histogram of the distribution of the number of images with respect to the coordinate $N(i)$ of the pulse. The distribution has a single maximum and is similar in shape to a normal distribution (indicated by the curve in Fig. 2); this confirms the validity of the jitter estimate in terms of its mean square value.

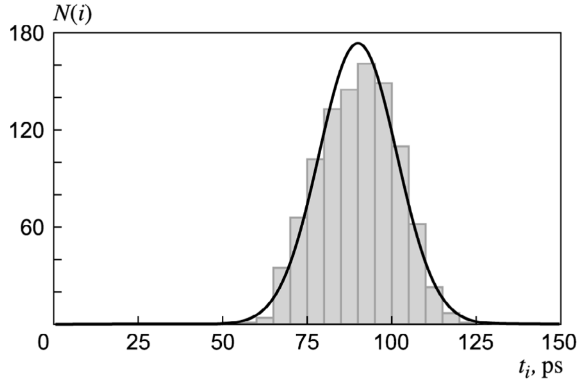

Fig. 2. Histogram of the distribution of the position of a single femtosecond laser pulse in a scan of the KVFSh65.10.000 streak camera; the curve is a plot of a normal distribution with the same values of the mean and root-mean-square deviation.

The result of the measurements of the jitter of the KVFSh65.00.000 streak camera was $J_{\mathrm{RMS}} = 11.5$ ps, which is a factor of 13 times smaller than the duration of the most rapid scan of this streak camera (150 ps). With this jitter the K016 streak camera can be used as a means of measuring the temporal parameters of fast processes accompanied by optical emission, including periodically repeating processes. The calculated uncertainties were $u_{\mathrm{A}}(J_{\mathrm{RMS}}) = 2.24\%$, $u_{\mathrm{B}}(J_{\mathrm{RMS}}) = 2.67\%$, $u_c(J_{\mathrm{RMS}}) = 3.5\%$, $U(J_{\mathrm{RMS}}) = 7\%$.

There are problems, for example, with measuring the duration of low intensity pulses by accumulation of the signal from a set of repetitive pulses that will have to be solved by leveling the jitter. Then, in order to obtain a correct result, it will be necessary to use a program or a programmed instrumentation medium for compensating the jitter built into the design and programming for the streak camera [10].

Conclusion. The technique for measuring jitter developed here is suitable for image-converter streak cameras operating in a linear scan mode for a pulsed optical signal. The experimental apparatus developed here employing the proposed measurement technique is used at VNIIOFI for monitoring the jitter of streak cameras. This method is used to measure the jitter of an image-converter camera, the prototype of the series K016 streak cameras manufactured by VNIIOFI. The K016 streak cameras are intended for measuring the temporal characteristics of optical pulses and are means of measurement of a certified type (registration number 71686-18 in the federal data base for support of the unity of measurements) [11]. The accuracy of the jitter measurements attained by the proposed method is sufficient for evaluating the consistency of the jitter values for commercial streak cameras with the technical specifications of customers.

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