The expansion of the dynamic range of photodetectors in hydrodynamic research using active optical shutters

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Abstract. The implementation of the method expanding the dynamic range of photodetectors in hydrodynamic experiments based on the use of active optical shutters is presented. A method that allows using modern CMOS cameras as optical radiation receivers and laser emitters as illuminators has been developed. The attenuation coefficients of linearly polarized light on the photodetector has been measured. An experimental estimate of the expansion of the dynamic range in terms of the intensity of the received radiation in the presence of background highlights has been made.

1. Introduction
Methods of hydrodynamic flow visualization are actively developed and improved. One of the fundamental limitations in visualization is the limited dynamic range of photodetectors [1]. The expansion of the dynamic range of photodetectors provides an increase in the quality and quantity of information obtained in physical experiments.

Under conditions of intense background highlights, various approaches are used to expand the dynamic range: control of the photodetector exposure time and illumination intensity [2], introduction of narrow-band optical filtering of the background highlights, and use of narrow wavelength range of illuminator [3].

When solving a number of experimental scientific problems, there is no possibility of reducing the photodetector exposure time interval. For example, in the absence of an external synchronization channel, it is necessary to continuously record a photodetector signal in order not to miss informative intervals in the researched volume [4]. The aim of this work is to create a method for expanding the dynamic range of a photodetector in the absence of external synchronization and in the presence of intense background noise.

2. Method description
When measuring dynamic objects, the intensity of the radiation scattered by the surface of the object can be estimated by the expression:

\[ I(x, y) = k \int_{t_0}^{t_0+T} (A(x, y,t) + N(x, y,t))dt, \]  

where \( t_0 \) is the initial opening time of the photodetector shutter, \( T \) is the photodetector exposure time, \( A(x,y,t) \) is the instantaneous distribution of the intensity of the scattered light on the photoreceiver matrix, \( N(x,y,t) \) is the additional parasitic illumination caused by noise and radiation the surface of the...
measured object (in the case of observation of the heated surface). In the case of using a pulsed source of light radiation, the expression (1) takes the form:

\[ I(x, y) = k \int_{t_0}^{t_0+T} (A(x, y, t)L(t) + N(x, y, t))dt , \]

where \( L(t) \) is the modulation function of the radiation source: \( L(t) = 1 \) if the emitter generates radiation and \( L(t) = 0 \) in other cases.

In conditions of a limited dynamic range, it is important to minimize the level of noise introduced by the \( N(x,y,t) \) term in the final distribution \( I(x,y) \). This can be achieved by reducing the exposure time, or by introducing an additional optical shutter, which provides gating and optical filtering of the radiation falling on the photodetector matrix. Then the expression (2) takes the form:

\[ I(x, y) = k \int_{t_0}^{t_0+T} M(t)(A(x, y, t)L(t) + N(x, y, t))dt , \]

where \( M(t) \) is the modulation function of the optical shutter, which determines the change in the attenuation coefficient of the radiation incident on the photodetector. Laser emitters are often used as an illuminator to visualize hydrodynamic flows. Their advantage over conventional lighting using incandescent bulbs or LEDs is narrowband radiation wavelengths. This allows you to use additional bandpass filtering of the received signal, cutting off interference with a wavelength different from the emitter wavelength. In addition, such an illuminator is easier to modulate in the time domain, which allows visualizing rapidly changing flows.

Optical signal receivers based on CCD (Charge-Coupled Device) and CMOS (Complementary Metal Oxide Semiconductor) technologies are commonly used as photodetectors. The advantage of CMOS technology, compared with CCD, is the absence of the effect of blurring pixels.

Using the CMOS matrix as a receiver entails a limitation on the level of parasitic illumination during the frame exposure time. The frame rate for dynamic processes is selected as high as possible (for consumer photodetectors, it is equal to 30 frames per second with a maximum exposure time of one frame 33 ms). In the case of measuring the hydrodynamic flow, parasitic illumination often occurs, due to the re-reflection of the signal from the optical emitter from the walls. The longer is the frame exposure time, the higher the level of recorded parasitic highlights is, provided that the emitter pulse times are constant. This leads to a decrease in the dynamic range of the receiver in intensity and deterioration of the detail pattern of the flow. Programmatically reducing the exposure time of the photodetector gives a positive effect, but leads to the fact that in some frames there is no useful signal of laser radiation. This occurs as a result of the desynchronization of the frame rate of the camera and laser pulses. In order to reduce the minimum possible exposure time of the webcam without loss of frames, a method of synchronous photodetection of cameras based on active optical shutters was proposed and implemented.

To broaden the dynamic range of the photodetector, it has been proposed to use active liquid crystal (LC) optical shutters [4]. They are based on nematic LC structures oriented along the lines of the electric field and transmitting light of a given polarization. Using the external synchronization scheme of the pulses of the probing illumination and the active optical shutters, you can adjust the exposure time of the receiving image on the photodetector matrix without loss of frames.

In active LC shutters, two optical shutters are used, herewith the direction of the polarization axes of the input linear polarizers is fixed. Optical LC shutters alternately switch between the "open" and "closed" states under the action of the controller signals. In the "open" state, the light penetrates the shutter without significant attenuation. When a switching pulse is applied to the shutter, only light with a certain polarization will penetrate through the shutter without attenuation.
Thus, the method of expanding the dynamic range of photodetectors based on the use of active optical shutters allows implementing a synchronous system of photodetection and significantly expanding the effective dynamic range of the photodetector.

3. Experimental results
To determine the attenuation parameters of linearly polarized light in various states of the optical shutter operation, experimental studies were performed. We used shutters from Samsung glasses SSG-3570CR designed to work with frame rate of 120 Hz. That is, each shutter operates at a frequency of 60 Hz.

![Diagram of the experiment for measuring transmission](image)

**Figure 1.** Diagram of the experiment for measuring transmission: 1 – a source of unpolarized light; 2 – polarizing filter; 3 – active optical shutter; 4 – photodetector.

The light source 1 used a powerful Cree® XLamp™ XR-E709 LED with a luminous flux of up to 100 Lm at a current of 350 mA. Then the light passed through the polarizing filter 2 PF-58. Since the initial luminous flux was weakly polarized, the intensity of the luminous flux after applying the filter decreased about 2 times. Measurements were made of the voltage $U_d$ on the photodetector 4 (photodiode FD-24K) in the absence of an active shutter in the path of light rays and if present in the "open" and "closed" states. The photodiode was shunted with a 1 kΩ resistor. Since the capacity of the photodiode FD-24K in the unbiased state is 25 nF, the limiting frequency of such a scheme is $f_{cut} = 1/(2\pi RC) = 6.4$ kHz. Such a circuit performance is sufficient to measure signals without significant distortion at frequencies up to 100 Hz. In the case of using consumer cameras as an optical signal receiver, it is sufficient to provide a speed of 30 Hz.

The type of signal on the photodetector at a frequency of 30 Hz is shown in Figure 2.

![Graph of the signal on the photodetector](image)

**Figure 2.** The signal on the photodetector at the frequency of the LCD shutter of 30 Hz.
A high signal level means that light travels to the photodetector with minimal attenuation. The noise at the maximum and minimum signal levels is determined by the photodetector noise and averages 0.4 mV. The rise time of the signal front from the state “closed” to the state “open” is determined by the relaxation time of nematic LC structures and does not depend on the rise time of the electrical signal on the plates of the shutter. This time is decisive in the operation of the LC shutters.

As a result of the experiments performed with the light flux attenuation by the LC active optical shutter, the following parameters were obtained:

| Table 1. Obtained parameters of LC active optical shutter. |
|----------------------------------------------------------|
| The attenuation of the luminous flux LC shutter in the "open" state, [%] | 25 |
| The attenuation of the luminous flux of the LC shutter in the "closed" state, [%] | 96 |
| With the frequency of operation of the LC shutter of 30 Hz, the ratio of attenuation between "closed" and "open", [times] | 20 |
| The rise time of the front from the “closed” state to the “open” state in terms of 99.9% of the constant [ms] | 6 |
| The rise time of the front from the state of "open" to the state of "closed" at the level of 99.9% of the constant, [ms] | 0.36 |

The use of active optical shutters allows you to reduce the minimum exposure time to 2 ms. During this time, two liquid crystal lattices of the shutter have time to form a stable structure for transmitting laser radiation with a certain polarization. At other times, the polarization of the liquid crystal lattices is orthogonal and the light passes through such a shutter with a significant attenuation (up to 20 times). This ensures external exposure of the received optical signal and the reduction of spurious illumination. At the same time, the shutter operation is synchronized with the frequency of the illuminator.

An experimental comparison of the image quality on the photodetector was performed using the method of expanding the dynamic range and without it. The ratio of the laser spot brightness on the surface under study visible by photoreceiver to the brightness of the background was estimated. The hardware exposure time was equal to the interframe time and was 50 ms. As a result, it has been found that the use of the method expanding the dynamic range of photodetectors increases the brightness ratio of the laser spot and background visible by the photoreceiver from 2.1 to 15.9 times (Fig. 3). Thus, it is shown that the use of the method expanding the dynamic range of photodetectors and based on the use of active optical shutters increased the image contrast of the observed object more than 7 times.

![Figure 3](image-url) Laser spot observed by a photodetector on the surface under study without widening of the dynamic range (left) and with widening of the dynamic range of the photodetector using active optical shutters (right).
Conclusion
As a result, a method was proposed for expanding the dynamic range of a photodetector in the absence of external synchronization and the presence of intense background noise based on the use of an active optical shutter. Experimental studies aimed at assessing the effectiveness of the proposed method were performed. It is shown that the proposed method provided more than 7 times expansion of the dynamic range of photodetectors in hydrodynamic studies.

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References
[1] Dvoynishnikov S V, Meledin V G / Rivas-Lopez M, Sergiyenko O, Flores-Fuentes, Rodríguez-Quíñonez J C, 2018 pp 49–78. ISBN13: 9781522557517|ISBN10: 1522557512|EISBN13: 9781522557524|DOI: 10.4018/978-1-5225-5751-7
[2] Kabardin I K, Dvoynishnikov S V, Meledin V G, Naumov I V 2016 Journal of Engineering Thermophysics 4 504–8.
[3] Dvoynishnikov S V, Meledin V G, Kulikov D V, Pavlov V A, Rakhmanov V V RU Patent № 2574864, Priority 15.09.2014, registered 15.01.2016
[4] Han J I Sensors. 2013. 13 (12) 16583–90