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Measurement of hydrodynamic flow velocity by laser Doppler anemometer with different types of photodetectors

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Abstract. The potential applications of three distinct photodetector types in laser Doppler anemometers for the measurement of hydrodynamic flow pulsations have been investigated. Laser Doppler anemometers with a classical vacuum photomultiplier tube, a multipixel silicon photomultiplier and a photomultiplier based on microchannel plates were used in the experiments. The main criteria for evaluating the quality of the Doppler signal were determined and analyzed for measuring the hydrodynamic flow velocity pulsations. The range of flow pulsations was from 1 to 50 Hz. In all experiments, laser Doppler anemometers demonstrated satisfactory performance when measuring pulsations up to 10 Hz. At frequencies from 10 to 50 Hz, the optimal results were achieved with laser Doppler anemometers employing photodetectors based on a silicon multipixel photomultiplier and a vacuum photomultiplier tube.

1 Introduction

The measurement of flow velocity pulsations is an urgent task in various fields of science and technology. These measurements provide information on the dynamic characteristics of the flow, which is important for understanding and optimizing processes in various systems. In fluid dynamics, velocity pulsations can affect the efficiency of hydraulic machines such as pumps and turbines. In aerodynamics, velocity pulsations are important for the design and operation of aircraft. In process engineering, the presence of velocity pulsations can result in the generation of vibration and noise within equipment, which must be considered during the design of structures.

In recent years, the issue has become increasingly pressing due to the construction of a significant number of wind farms. The study of the impact of pulsation characteristics of the flow enables the comprehension of the influence of the flow behind one turbine on the operation of subsequent turbines [1]. Similarly, in hydroelectric power plants, the necessity for optimization of suction pipes is evident in order to reduce the problems associated with the growth of vortex bundle pulsations and plate failure [2-3].

There are numerous methods for the diagnosis of pulsations in flows, including thermoanemometry, the measurement of pressure pulsations on the walls and inside the flow, tracking imaging, laser Doppler anemometry (LDA), ultrasonic Doppler anemometry, strain

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gauge, and others. Each of these experimental methods has its own advantages and limitations, and the choice of method depends on factors such as flow characteristics, the required spatial and temporal resolution of the measurement results, and ease of use.

The most accurate non-invasive method for determining flow velocity pulsations is the LDA method.

This paper is devoted to the specifics of operation of different types of photodetectors in LDA in the context of studying pulsation flows.

The laser Doppler anemometer is a device that measures the velocity of particles that scatter light (bubbles, special light-scattering particles, and natural light scatterers) within a fluid flow. In the presence of flow velocity pulsations, the measured velocity will take the form of a periodic function (Figure 1). It is evident that the greater the number of particles per second detected, the more accurate the pulsation frequency measurement and the value of the measured pulsation frequency may be.

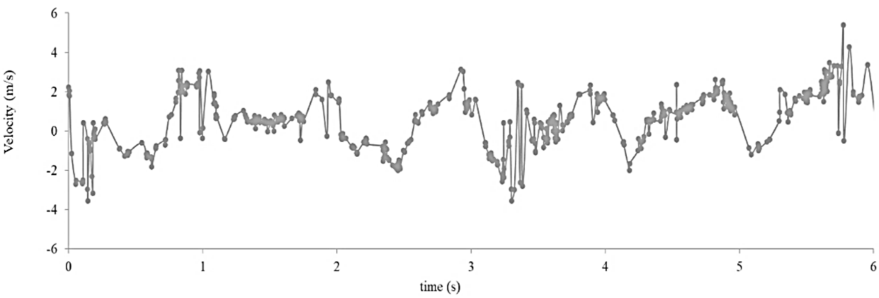

Fig. 1. Flow velocity with periodic pulsations.

Given that particles traverse the measurement area at random intervals, it is necessary to oversample velocity data for an equidistant time distribution in order to achieve reliable determination of pulsation frequency. It is imperative that the discrete Fourier transform be performed only after the aforementioned oversampling of the measurement results.

Significant advancements have been made in the development of various photodetector types for use in laser Doppler anemometers [4-5]. However, there are notable differences in the operational characteristics of different types of photomultiplier tubes (PMTs). One distinguishing feature of a microchannel plate photomultiplier (MCP-PMT) is its large photocathode area. When a light-scattering particle crosses the rays within the measurement area, all types of PMTs "see" the light scattered by the particle.

However, if the particle crosses the rays outside the measurement area, due to the limited receiving aperture, the multi-pixel silicon photomultiplier tube (Si-PM) will not "see" it, because the scattered light will not enter the receiving area. Nevertheless, it is important for MCP-PMTs to use as much of the photocathode surface as possible. In the event that a particle passes outside the measuring area, the PMT will register this parasitic signal, which will result in the generation of additional noise.

The objective of this study is to evaluate the performance of LDA with different types of PEU in the diagnosis of pulsation flows. The quality of LDA performance will be evaluated based on the following criteria: the number of registered particles per unit time, the resolution of pulsation frequencies in the range from 1 to 50 Hz, and the standard deviations (RMS) of the velocity measurement result for different pulsation frequencies.

2 Experimental setup

Three types of photodetectors were used as photodetectors (Figure 2): the classical vacuum dynode PMT Hamamatsu type R6358-10, Si-PM KETEK PM3325-WB, and MCP-PMT CJSC "EKRAN FEP" 6776 with two consecutive microchannel plates. All three photodetectors have high gain ~10^6 and sufficient responsiveness for operation in LDA with carrier frequency offset by 80 MHz.

a) b) c)

Fig. 2. Types of photodetectors used in the experiments as part of the LDA: classical PMT (a), MCP-PMT (b) and Si-PM (c).

Each PMT, along with its associated power supplies, was installed as a photodetector within the experimental LDA LAD-05M.

A pulsating alternating flow from the rotor blades immersed in water was selected as the test object. The velocity of the flow was measured at different rotor speeds (Ω) from 30 to 1500 rpm. The rotational frequency was set approximately by means of a potentiometer, and the video recording was used to reconstruct it in order to determine the frequency more accurately. The error of this method was approximately 10%. Nevertheless, this estimation is sufficient for the purposes of evaluating the performance of photodetectors in these experiments.

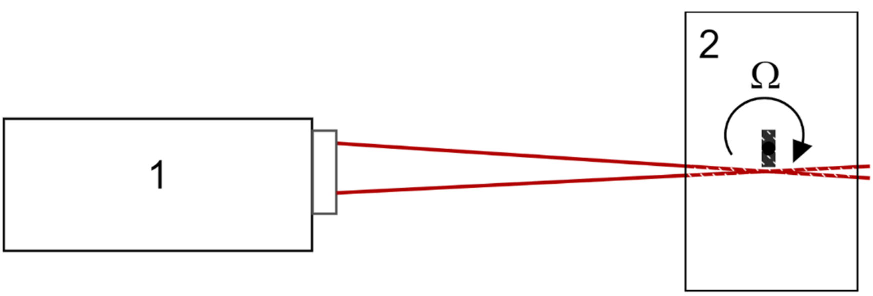

Fig. 3. Schematic diagram of the experimental setup.

The scheme of the experiment is presented in Figure 3. Laser Doppler anemometer 1 measures the velocity of rotating dynamic flow in a rectangular container 2 with transparent walls. The flow rotation was realized by rotating the rotor with an impeller containing two blades. The velocity measurement point was located at a distance of 3 mm from the blade edge. Each measurement lasted 60 seconds. During this time, sufficient statistics was collected to estimate the RMS and plot the velocity pulsation spectrum.

It can be reasonably assumed that the expected velocity pulsation frequency should be equal to twice the rotor speed, given that a rotor screw with two blades was used.

Figure 4 demonstrates the pulsation spectrum for LDA with a Si-PM photodetector at a rotor speed of approximately 800 rpm. The primary flow pulsation frequency is 27.6 Hz, with a second harmonic frequency of 55.2 Hz also visible. The ratio of the maximum in the peak to the average intensity is greater than 40 times.

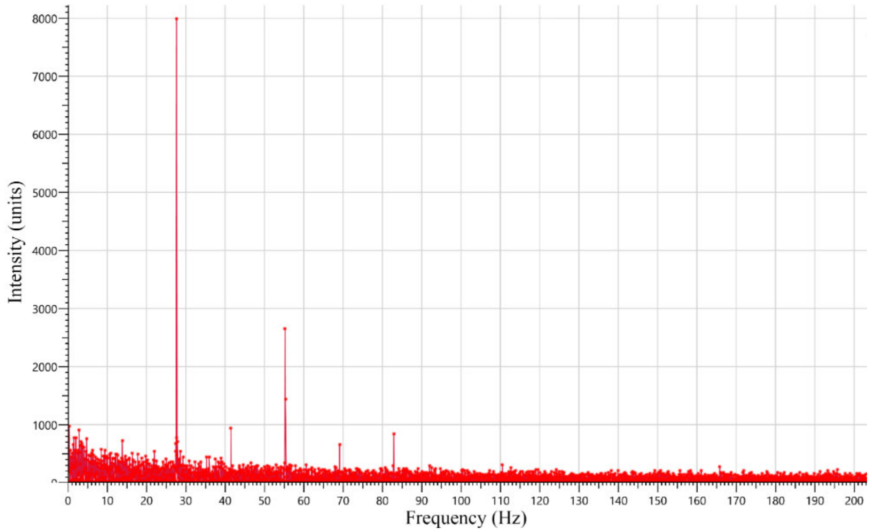

Fig. 4. Spectrum of velocity pulsations at a rotational speed of 800 rpm.

3 Results and discussion

A series of experiments were performed to measure the hydrodynamic flow velocity with pulsations by laser Doppler anemometers with different kinds of photodetectors.

LDA with vacuum PMT and Si-PM measured pulsation frequencies in the range from 1 to 50.5 Hz. However, the LDA with MCP-PMT did not allow measuring pulsation frequencies higher than 10 Hz. The data on the measured pulsations for different types of PMTs are summarized in Table 1.

Table 1. Targeted and measured pulsation frequencies.

Video frequency, Hz	Vacuum PMT frequency, Hz	Si-PM frequency, Hz	MCP-PMT frequency, Hz
1.0	1.0	1.1	1.3
1.8	1.8	1.8	1.7
3.5	3.6	3.6	3.8
7.0	7.1	7.2	6.7
12.1	12.4	12.0	-
31.0	31.3	30.1	-
50.5	53.3	52.6	-

The discrepancy between the measured and specified pulsation frequencies is less than 10%, which is consistent with the precision of the pulsation frequency setting. Despite the inability to resolve the pulsation frequency beyond 7 Hz in the MCP-PMT, the RMS of velocity pulsations could be accurately measured across the entire range. As illustrated in Figure 5, the RMS velocity pulsations exhibited a positive correlation with increasing pulsation frequencies for all tested types. The frequency axis is given in logarithmic scale. The maximum RMS velocity values were recorded under identical conditions for MCP-PMT, while the minimum values were recorded for Si-PM.

Another key factor in the operation of photodetectors as part of LDA is the ratio of signal amplitude to pedestal amplitude, which is known as contrast. A reduction in this value will result in an increased error in determining the Doppler frequency.

The average contrast in all experiments for all PMTs was calculated. The value of this ratio was 2.7 times for the vacuum FES, 0.9 times for the Si PM, and 1.4 times for the MCP-PMT. The best signal contrast was observed for the vacuum PMT, and the worst for the silicon photomultiplier.

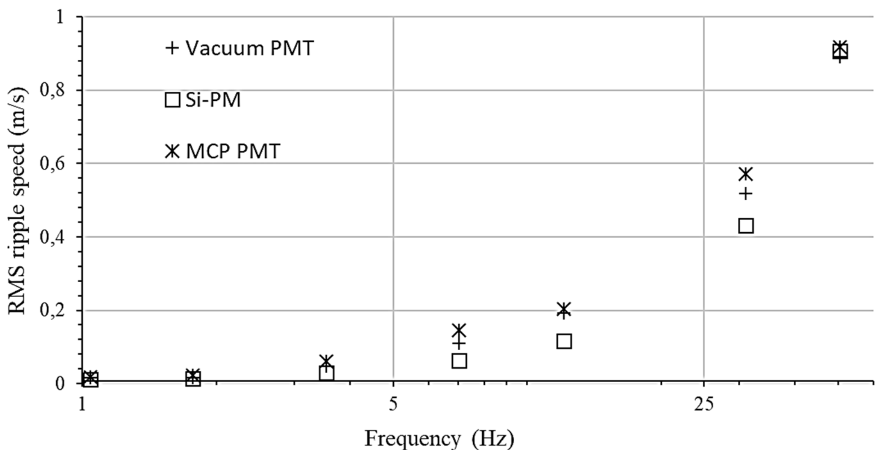

Fig. 5. RMS of velocity pulsations for three types of photodetectors.

Another parameter that influences the resolution of pulsations is the number of registered valid particles per second. This parameter characterizes the quality of the signal registered by LDA. Table 2 provides a summary of the data for all experiments.

Table 2. The number of recorded credible particles per second.

Video frequency, Hz	Vacuum PMT, particles/s	Si-PM, particles/s	MCP-PMT, particles/s
1.0	102	310	65
1.8	156	564	40
3.5	207	879	55
7.0	283	1264	60
12.1	302	1579	70
31.0	312	1393	113
50.5	407	2065	136

As illustrated in the preceding data, the highest number of particles per second was observed in the Si-PM group. In contrast, the lowest value was observed in the MCP-PMT group. From the data for MCP-PMT presented in Tables 1 and 2, it can be seen that if the ratio of the number of particles per second to the pulsation frequency is greater than 8.5, the frequency is determined correctly. When this parameter is reduced to values below 6, the pulsation frequency is not detected. It appears that the number 6 is a critical parameter for this value in the case of non-uniformly time-distributed flow rate data.

4 Conclusion

During the performed experiments on studying the features of LDA operation with different types of photodetectors in diagnostics of hydrodynamic flow with pulsations, it was found that all types of photodetectors showed good results in the tasks of measuring pulsations up to 10 Hz.

However, for tasks with pulsation frequencies greater than 10 Hz, the use of MCP-PMT does not effectively measure the pulsation parameters. This may be due to a combination of two factors:

- High intrinsic noise of the MCP-PMT;
- Excessive sensitivity of MCP-PMT to spurious illumination due to high quantum efficiency.

As a result of these factors, the algorithm used in LDA to determine the Doppler frequency by the center of mass method does not allow confidently detect signals with high noise level, because the number of registered reliable particles per unit time is significantly lower than when using the other two types of photodetectors.

Further research is required to study the pulsations of aerodynamic flows, as these can reach tens of kilohertz. Nevertheless, it can already be stated that LDA with Si-PMs as a photodetector is a promising direction of development of laser Doppler anemometry, and the use of MCP-PMT for hydrodynamic flows is not a reasonable solution.

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