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Design and implementation of a stroboscope with high brightness white LEDs for measurement of rotational speed

Miroljub Pešić
Department of Measurements
University of Niš, Faculty of Electronic Engineering
Niš, Serbia
miroljub.pesic@elfak.ni.ac.rs,
orcid.org/0009-0006-1909-6972

Milan Dinčić
Department of Measurements
University of Niš, Faculty of Electronic Engineering
Niš, Serbia
milan.dincic@elfak.ni.ac.rs,
orcid.org/0000-0001-7508-0277

Milica Stojanović
Department of Measurements
University of Niš, Faculty of Electronic Engineering
Niš, Serbia
milica.stojanovic@elfak.ni.ac.rs,
orcid.org/0009-0000-5528-3675

Jelena Đorđević Kozarov
Department of Measurements
University of Niš, Faculty of Electronic Engineering
Niš, Serbia
kozarov@elfak.ni.ac.rs, orcid.org/0000-0002-6941-4098

Aleksandar Jocić
Department of Measurements
University of Niš, Faculty of Electronic Engineering
Niš, Serbia
aleksandar.jocic@elfak.ni.ac.rs,
orcid.org/0009-0009-7869-8473

Dragan Živanović
Department of Measurements
University of Niš, Faculty of Electronic Engineering
Niš, Serbia
dragan.zivanovic@elfak.ni.ac.rs,
orcid.org/0000-0002-9880-2305

***Abstract*—The measurement of angular velocity in rotating systems holds significant importance, especially in industrial applications. Various methods, both contact and non-contact, have been developed for determining angular velocity. This paper presents a notable contribution in the form of the design and implementation of a stroboscopic system characterized by the capability to fine adjustment the frequency of stroboscopic pulses using a multi-turn potentiometer, along with minimal energy consumption and low implementation cost, owing to the utilization of widely available components. To evaluate the performance of the stroboscope, a rotating system based on a DC motor was designed and implemented, whereas the rotation speed is controlled by a PWM signal. Additionally, to verify the accuracy of the measurements obtained with the implemented stroboscope, an angular velocity measurement system based on a photointerrupter was also developed.**

Keywords*—stroboscope, angular velocity measurement, non-contact measurement, generation of the PWM pulses

I. Introduction

Angular velocity is defined as the angle that an object rotates per unit time. Rotation represents one of the fundamental motions common in machines, including motors, gears, and various types of wheels. Precise control over rotation is important for maintaining optimal machine performance, as many mechanical malfunctions stem from issues related to rotary motion. Therefore, the measurement of angular velocity holds significant importance.

Measuring devices for measuring speed of rotation are tachometers (Greek: tachos = speed, metron = measure). According to the principle of measuring, tachometers can be mechanical, electrical, magnetic, inductive, photoelectric, stroboscopic. In the contact-type instrument, probe or sensor tachometric comes into contact with rotating parts. The advantage of non-contact methods of angular velocity measurement lies in the fact that object is not affected directly during measurement [1]-[6].

The stroboscopic effect is a visual phenomenon that occurs when a movement is presented as a series of samples. A periodic movement repeats at equal time intervals, that is, it returns to the same position after complete a specific period. If a pulse of light illuminates a periodically moving object always when it is in a single position, the object appears stopped and the movement frozen. The stroboscopic effect was discovered in the 1830s and can be observed when there is a synchronization between the frequency of light flashes and the frequency of movement [2].

The stroboscope is a device used for measuring the angular velocity (i.e., frequency) of a rotating element, based on the stroboscopic effect. Assuming that a disk is rotating at a frequency f_x which needs to be measured, with one marker on the disk. The stroboscope consists of a lamp that emits short periodic light pulses (stroboscopic pulses) illuminating the rotating disk, whereby the frequency of the stroboscopic light pulses can be adjusted and measured, thus being known at any given time. An important element of the measurement process is the human observer who observes the disk illuminated by the light pulses of the lamp. The stroboscope offers many advantages over other types of tachometers. It absorbs no power from the device which speed is being measured and can thus be used with delicate mechanisms. It is fast enough to catch the highest-speed motion. It can be aimed at machine parts inaccessible to other tachometers and it is much more accurate than most mechanical tachometers (the Stroboscope measures speeds to within one percent) [1]-[3].

The stroboscope applications cover many areas, including industry, education, medicine, movies, party illumination and optical illusion. This device can be applied in the measurement of bullet speed, torque measurement, investigation of loudspeaker operation through oscillation analysis, lead shot manufacturing inspection, because in the fabrication process there is the solidification of molten lead in free fall, allowing the observation the size and shape of the pellets. It can also be applied to television frequency measurement, fluorescent tubes,

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and light bulbs [8]. In medicine the stroboscopic effect is applied in the area of laryngology, assisting in diagnosis of vocal cord problems, through the study of the vocal cord vibration [9]. In [10] the stroboscope is applied to excite fluorophores, as an illumination system for fluorescence microscopy. Besides that, the stroboscopic effect can be found in movies because it consists of joining several successively displayed images with a constant velocity. The effect can be observed, as an instance, in situations where car wheels or airplane propellers appear to be rotating in the opposite direction, this is because the frequency of rotation of these equipment is independent of frequency at which images are displayed [11].

In the industry the stroboscope is commonly applied as a measurement instrument, monitoring operation and determining the velocity and frequency of rotational machines without physical contact. Also used in inspections and quality assessment of propellers, motors, shafts, gears, pulleys, chains, sprockets, textile processes, in terms of balancing, slip and vibration measurement. In addition to assisting in the identification and troubleshooting of high-speed machines, because it provides slow-motion visualization of the movement. Due to progress in the design of electronics and sensors, some machinery as the stroboscope remains a simple and reliable backup tool to verify the correct operation of permanently installed sensors.

Commercial devices for stroboscopic measurement of angular velocity typically have an RC generator of relatively low frequency (up to several hundred Hz) with a precisely calibrated scale for frequency reading as their starting block. Industrial flash guns are used for illuminating the rotating object, providing higher illumination and longer lifespan. The flash gun is powered by a relatively high DC voltage (up to several hundred V) generated by a separate circuit. The flash gun itself is housed in a glass enclosure resembling an electronic tube, containing gas at lower pressure. A special circuit triggers and rapidly discharges a large capacitor through the flash bulb in sync with the generator frequency, generating a short burst of light (shorter than ms) of high brightness. The problem here is the procurement of a specialized flash gun, as well as the generation of high DC voltage for powering the flash gun itself.

Instead, the authors of this paper propose to realize the stroboscope using stroboscopic LED diodes with a diameter of 5 mm, which emit white light of relatively high brightness. This significantly simplifies the entire device, and the cost of the electronic components used is very low compared to commercial devices. This paper introduces an advancement in stroboscopic technology with the implementation of a highly adaptable system. The implemented stroboscopic system is distinguished by its ability to finely adjust the frequency of stroboscopic pulses using a multi-turn potentiometer. This feature allows for precise control over the illumination frequency, enhancing the system's versatility and usability.

To assess the performance of the stroboscope, a rotating system based on a DC motor was designed and implemented. In this setup, the rotation speed of the system is regulated by a PWM signal, providing a reliable means of controlling the rotational dynamics.

Furthermore, to validate the accuracy of the measurements obtained using the stroboscopic system, a secondary angular velocity measurement system based on a photointerrupter was developed. This additional verification mechanism ensures the reliability and precision of the stroboscopic measurements, bolstering confidence in the system's effectiveness and utility in practical applications.

II. Stroboscopic Method for Measurement of the Angular Velocity

The principle of measuring rotation frequency using a stroboscope is as follows: a rotating disk with a marker is illuminated by short light pulses generated by a lamp as shown in Fig. 1. At a certain moment, a short light pulse illuminates the disk, and the observer sees the marker in a certain position [3].

For the visualization of the phenomenon, the light pulse length must be short enough compared with the disk rotation, otherwise, image freezing may not be detected. If the illumination frequency f_s is bigger than the frequency of the disk f_x, the disk will appear to move backward, if f_x is bigger than f_s., the disk will appear to move forward, and if the frequencies coincide, the disk will appear to be stationary [2].

The stationary visualization of a rotate movement can also be observed if the flashes velocity are multiples or submultiples of the rotation velocity. In those cases, the motion will also appears to be stopped, but the difference will be the amount of markers that will be seen. Considering one marker on the rotating machine, if the both frequencies are equal, then, the next light pulse will be emitted precisely at the moment when the disk completes a full revolution, and the observer will see the marker again in the same position as before, and this frequency is called fundamental frequency. If the flashing rate is twice the fundamental velocity of the machine, or also called second harmonic, two markers will be seen in a distance of 180 degrees. If the flashing rate is three times the fundamental velocity of the machine, third harmonic, three markers will be seen in a distance of 120 degrees and so on. Then, if the light blinks at twice the object's rotation velocity, when it is halfway through its rotation another flash of light will illuminate it causing the effect of two markers. For this reason, to avoid errors measurements, it is recommended to start the velocity measurements at a high flash rate or the instrument's maximum flash rate, and then slow down until only one marker is seen [2], [3].

To determine the rotational frequency of the disk f_x, the following procedure is employed. Firstly, the frequency of light pulses is adjusted until the impression that the disk is stationary is achieved, denoted as frequency f_s. The frequency is then decreased until the disk appears to be illusory stationary again,

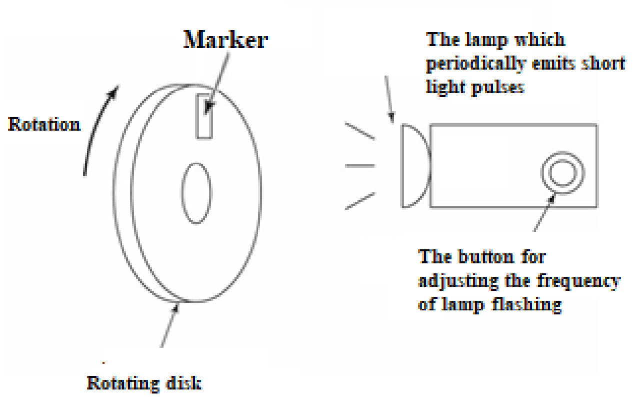

Fig. 1 Measurement of the angular velocity by stroboscope

and denoted as frequency f_{s1}. For these two frequencies, the following holds [3]:

$$f_x = \frac{f_s f_{s1}}{f_s - f_{s1}}. \quad (1)$$

III. Design, Implementation and Testing of a Stroboscopic System

In the following text, the practical implementation of an electronic circuit for generating light pulses, a rotating system based on a DC motor with variable rotational speed, and a circuit for verifying the accuracy of the implemented stroboscopic method will be explained.

A. *The design and implementation of an electronic circuit for generating light pulses*

The rotating disk is illuminated by a lamp consisting of 9 LED diodes with short periodic light pulses. White light of high brightness is emitted by the LED diodes. A basic schematic diagram of the electronic circuit for generating short periodic light pulses is shown in Fig. 2. In order for the LED diodes to emit such pulses, they must be stimulated by the same type of electrical signal, i.e., a periodic pulse signal with short pulses. Furthermore, precise frequency modulation of this pulse signal must be enabled to allow adjustment of the light pulse frequency.

The application of the 74HC132 [12] circuit for generating square pulses is shown in Fig. 2. The circuit is supplied with voltage V_{CC}=5 V. This component represents an inverter with Schmitt triggers at each of its two inputs. Capacitor C is alternately charged and discharged. When a high voltage (logical 1) is present at the output of the circuit, the capacitor is charged through resistor R until the voltage across it, V_C, reaches the upper Schmitt trigger threshold V_{T+}; at this point, the output voltage transitions to a low state (logical 0), and the capacitor discharges through resistor R until the voltage across it reaches the lower Schmitt trigger threshold V_{T-}, causing the output to transition back to logical 1, and the capacitor begins charging again.

To generate pulse signals in the circuit shown in Fig. 3, a variable resistor (potentiometer) has been inserted into the path for charging and discharging the capacitor, enabling the frequency of the generated pulse signal to be altered by changing the resistance, in accordance with the equation:

$$f_{out} = \frac{1.51}{RC}. \quad (2)$$

The multi-turn linear potentiometer P = 100 kΩ with a slider having 10 turns enables fine and precise adjustment of the

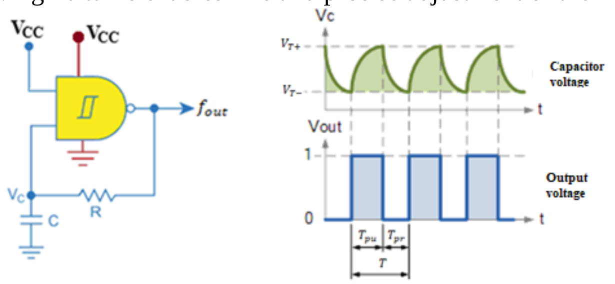

Fig. 2 Pulse generator circuit for stroboscope frequency control

stroboscopic pulse frequency f_s within a range of approximately 6.5 Hz to approximately 195 Hz, allowing for the obtainment of an image of the marker to be illusory stationary on the rotating disk.

In the circuit diagram shown in Fig. 3, an output (via a transistor) is provided for the measurement of the generated pulses frequency. Additionally, a 74HC132, NI logic circuit configurate to work as inverter, has been incorporated into the circuit as a buffer.

In the previously described section of the circuit, rectangular pulses were obtained, the frequency of which can be adjusted. However, the issue arises due to the duty cycle of these pulse signals being approximately 50 %, whereas very short duration pulses (i.e., pulse signals with a very small duty cycle) are required for illuminating the disk. This change in the duty cycle can be achieved by the application of a monostable multivibrator (MMV) realized using the NE555 [13] timer. The MMV is triggered by the falling edges of short negative pulses of frequency f_s obtained by differentiating the input pulse signal (using a differentiator consisting of a 3.3 nF capacitor and a 10 kΩ resistor). With each trigger pulse, the MMV transitions from its stable state, causing the capacitor C_x to charge through the resistor R_x until the voltage across the capacitor reaches a value of $2V_{CC}/3$, at which point the MMV returns to its stable state and remains there until the next trigger pulse. Positive periodic pulses are generated at the Q output of the MMV, with a frequency equal to the frequency of the trigger pulses (which is essentially the frequency of the rectangular pulses f_s adjusted by the potentiometer P), while the pulse duration equals the charging time of the capacitor and can be controlled by choosing values for R_x and C_x according to the formula:

$$\Delta t = R_x C_x \ln 3 \approx 1.1 R_x C_x. \quad (3)$$

By choosing appropriate values for R_x and C_x, pulses of very short duration can be obtained, and the pulse frequency f_s is adjusted by potentiometer P. In this process, the duration of the pulses is constant and independent of the frequency. Specifically, in this circuit, a resistor R_x of approximately 15.4 kΩ and a capacitor C_x of approximately 10 nF were utilized, resulting in a pulse duration of $\Delta t \approx 169.4$ µs. The pulse duration Δt must not be too long to prevent "blurring" of markers on the rotating object.

The output Q excites the low power N-MOSFET BS170, which then drives 9 LED diodes that emit high-intensity white light. The threshold voltage for such LED diodes is approximately 3.16 V. The current passing through each of the LED diodes is approximately 24.9 mA and is only allowed to flow during the pulse duration Δt.

B. *The design and implementation of a rotating system based on a DC motor with variable rotation speed*

In order to test the operation of the stroboscope, a rotating system based on a DC motor with brushes, which speed can be adjusted, was created. The DC motor is powered by a voltage in the form of pulse width modulation (PWM), whereby the motor's rotation speed is controlled by the width of the pulses. The rotation speed actually depends on the average voltage supply, so if the pulses are narrow (i.e., the duty cycle is small),

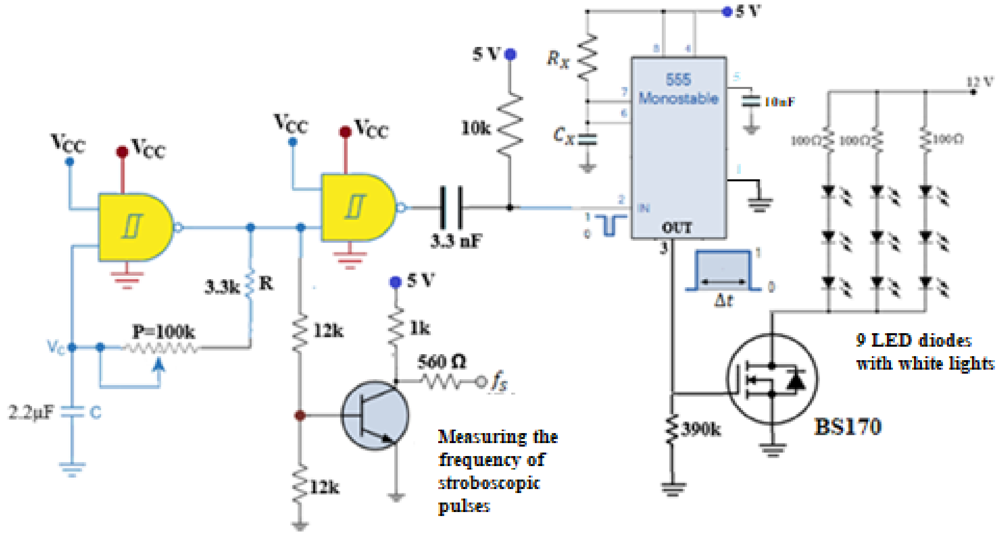

Fig. 3 The electrical circuit for generating short periodic stroboscopic pulses

the average voltage supply is low, resulting in slower motor rotation. Conversely, if the pulses are wider (i.e., if the duty cycle is larger), the average voltage supply is higher, causing the motor to rotate faster.

The PWM signal generation circuit is based on the logic component 74HC132, as shown in Fig. 2. However, this circuit cannot be directly used for PWM signal generation because the duty cycle of the rectangular waveforms is constant (approximately 50 %) and cannot be adjusted. Therefore, this circuit must be modified to enable the adjustment of the duty cycle of the generated pulse signal. The issue arises because the paths for charging and discharging the capacitor overlap (both charging and discharging occur through resistor R), resulting in approximately equal charging and discharging times of the capacitor.

The complete circuit diagram of the circuit for generating PWM signals is shown in Fig. 4. This circuit is based on the circuit from Fig. 2 for generating rectangular pulses, but now includes two commutating diodes, D_1 and D_2, which are used to separate the paths for charging and discharging the capacitor. Additionally, there is a potentiometer consisting of resistances P_1 and P_2, which values can be adjusted (as P_1 increases, P_2 decreases, and vice versa). The charging path of the capacitor is through resistor R, diode D_1, and a part P_1 of potentiometer, while the discharging path of the capacitor is through a portion P_2 of potentiometer, diode D_2, and resistor R. By adjusting the values of P_1 and P_2, the resistances in the charging and discharging paths of the capacitor can be adjusted, thereby regulating the duration of charging and discharging of the capacitor, i.e., the duration of logic 1 and logic 0, thus adjusting the duty cycle of the PWM signal. This enables adjustment of the duty cycle of the PWM signal over a wide range, from approximately 2 % to about 98 %. In the implemented circuit, a PWM signal frequency of about 111 Hz was achieved. Another 74HC132 inverter was added to the circuit as a buffer, i.e., to prevent the output section of the circuit with the transistor from affecting the input section of the circuit that generates the pulses; the output of this inverter generates the inverted PWM signal ($\overline{\text{PWM}}$). This signal drives the MOSFET power transistor that operates the DC motor VTHD01. This is essentially a small hobby drill brushed DC motor used for rotating a disk with a marker. By adjusting the duty cycle ($\overline{\text{PWM}}$) signal, the speed of rotation of the DC motor is regulated. The VTHD01 motor, when powered at 12 V, consumes a current of approximately 0.42 A for a maximum duty cycle of the PWM signal of 100 %. The 1N4007 diode connected in parallel with the DC motor is called a flywheel diode, which eliminates voltage spikes that occur when the current through the rotor winding of the DC motor is interrupted (the stator being a permanent magnet). This protects the power transistor from voltage breakdown. Such a circuit can also be realized with the integrated timer circuit NE555, also using two commutating diodes. A bipolar transistor can be used as the power transistor instead of a MOSFET transistor.

C. The circuit for verifying the accuracy of the implemented stroboscopic system

In order to verify the accuracy of rotational frequency measurements using a stroboscope, another method of rotational frequency measurement was implemented, employing a two-bladed propeller rotating at the same speed as the disk, with its blades interrupting the infrared light in the LTH301-07 photointerrupter. The electrical circuit diagram of this measurement circuit is shown in Fig. 5. When the light ray is interrupted, the collector of the phototransistor is in a logical state 1 (the phototransistor is in cut-off state), and the output of the entire circuit is in a logical state 0. For an uninterrupted light ray, the circuit output has a logical state 1. As the propeller interrupts the infrared light beam twice during one revolution, the circuit output is a square wave signal with a frequency of $2f_x$.

D. Testing of the implemented stroboscope

To test the implemented stroboscope, the complete angular velocity measurement system was established, as depicted in Fig. 6. This system comprises the stroboscope outlined in section A and a rotating disk with a marker mounted on the shaft driven by a DC motor which rotation speed is controlled by PWM pulses, as described in section B. Additionally, there is a verification system based on a photointerrupter and a two-blade propeller described in section C.

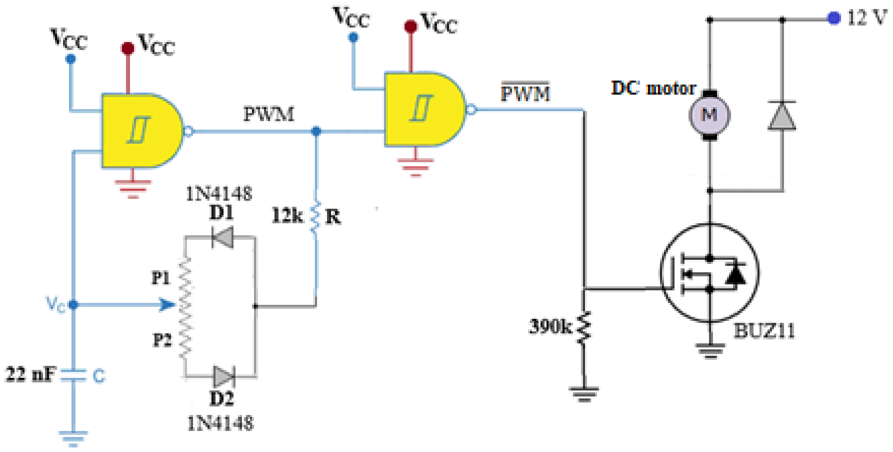

Fig. 4 The complete electrical scheme for generating PWM signals

An aspect to be taken into consideration is the duration of the stroboscopic pulses Δt by which the LED diode is triggered to illuminate the rotating disk with a marker.

The marker was drawn with a width of Δl = 8 mm. The diameter of the disk is $2r_D = R_D$ =11.96 cm. The maximum rotation frequency of the disk is achieved when the DC motor VTHD01 is directly supplied with +12 V, resulting in a motor current of approximately 0.42 A (with a PWM duty cycle of 100 %). Using an electronic circuit with a photointerrupter, the rotation frequency of f_{xmax} = 152.5 Hz was measured (i.e., 9150 revolutions per minute). The time taken for the marker to pass over, Δt_M, is defined as the duration during which the marker, in rotation, goes from its starting point to its end point relative to an imaginary fixed point

$$\Delta t_{Mmin} = \frac{1}{f_{xmax}} \frac{\Delta l}{R_D \pi}. \quad (4)$$

For previously listed values of Δl, R_D and f_{xmax}, and using (4), Δt_{Mmin} ≅139,6 μs was calculated. The flight time is longer at lower rotation frequencies. It is evident that for the length of the quasi-stable state Δt at the output of the monostable multivibrator, which is the duration of the stroboscope pulse for illuminating the rotating disk, a value of Δt_{Mmin} should be selected. Of course, a value greater than Δt_{Mmin} can be adopted, but not excessively greater. Only in this way a clear image of the illusory stationary marker can be obtained, which does not appear "smeared". As said before, a value of Δt ≅169.4 μs was adopted by choosing values for R_x and C_x.

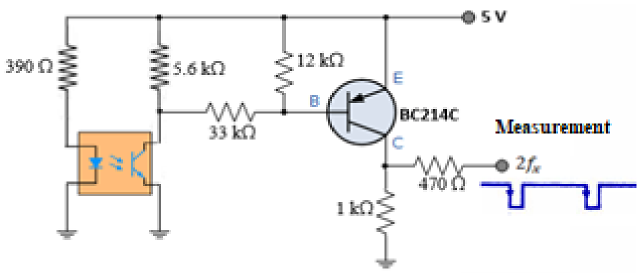

Fig. 5 The electrical circuit for measuring rotational speed using a photointerrupter and a two-blade propeller

For a 7.5 V average supply PWM signal, frequencies f_s = 98.37 rpm and f_{s1} = 49.28 rpm are determined. Based on (1), the rotation frequency is calculated, f_x = 96.7 rpm. The system with a photointerrupter measured the frequency f=193 rpm, i.e. f_x = 96.5 rpm , which confirms the accuracy of the implemented stroboscope.

IV. Conclusion

The advantage of this implemented stroboscope, compared to commercial strobes available on the market, lies in the use of readily available and cost-effective components. Additionally, the paper introduces a circuit for altering the duty cycle factor of the generated PWM signal, achieved by separating the paths for capacitor charging and discharging through the inclusion of a potentiometer in the circuit. This modification enables the adjustment of the DC motor rotation speed. The paper also introduces the control circuit that enables the verification of the accuracy of rotational frequency measurements using a stroboscope, where another method of rotational frequency measurement was implemented, employing a two-bladed propeller rotating at the same speed as the disk, with its blades interrupting the infrared light in the photointerrupter.

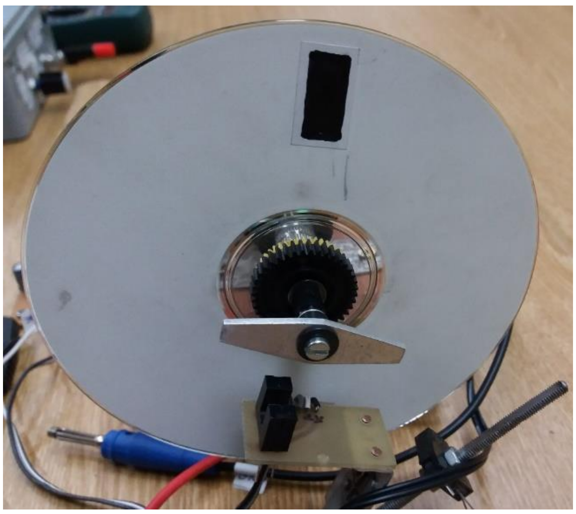

Fig. 6 Rotating disk with marker, two-bladed propeller and photointerapter

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