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Designing a device for measuring the velocity of liquid flowing in open channels

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Abstract

Water flow systems in open channels are designed according to certain levels. Flow rate increases in open channels can bring many disasters. Therefore, it is necessary to routinely measure flow in open channels. In addition to rivers and streams, open channels are used in many areas in city life. If open channels are not checked regularly, floods may occur in sudden rains and human life may be endangered. Practical problems like measurement, control and linearization of mechanical outputs can be solved within the context of function generation problem. In this work, an exemplary design associated with the measurement of water velocities in open channels and the resulting apparatus has been shown. To test its performance, velocities have been compared with those obtained by the constructed prototype. The results have been observed to be consistent with each other.

1. Introduction

Mechanism is a mechanical arrangement that is used to transfer motion and force or used to advance the points of an object on certain trajectories [1]. In the design of lever mechanisms, it is desirable that the rotational, oscillating and sliding movements of the output lever be a function of time, or a function of the movement of the input lever. For example; high temperature, pressure, toxic gas and chemicals, working under excessive loads, in unfavorable and dangerous environments for human health, in control events such as performing the measurement and inspection function with a remote control [2] or, on a conveyor line, while the conveyor is in motion, a motion programming event such as bottle closing, returning, taking the next cap is made possible by solving the lever mechanisms within the scope of function generation [3]. The linearization of nonlinear mechanical outputs is also considered within the scope of function synthesis [4].

Water is the most important element of food production, and the easiest and most cost-efficient way to transport it through open-channel [5]. An open channel is a waterway, canal or conduit in which a liquid flow with a free surface [6]. Open channels had created by nature conditions or built by humans. Open channels are used in rain water channels and wastewater treatment plants. Measuring the velocity of liquid flowing in open channels are routinely made on many rivers in the world to provide information on flow. Velocity measurements are made in open channels due to needs such as protecting clean water resources, recording the processes in the industrial area, and taking precautionary measures against adverse natural events such as sudden floods.

In recent years, new theoretical approaches have been studied for the measurement of flow velocity in open channels, which is an old problem. A sharp crested triangular weir was recently studied based on two theoretical models, a weir theory (Model I) and critical flow approach (Model II) [7]. Flow measurement using a triangular broad crested weir theory and experimental validation studied recently [8]. Theorical approach studied based on the application of dimensionless energy equation applied between a section taken in the approach channel and the weir under critical flow conditions [9,10].

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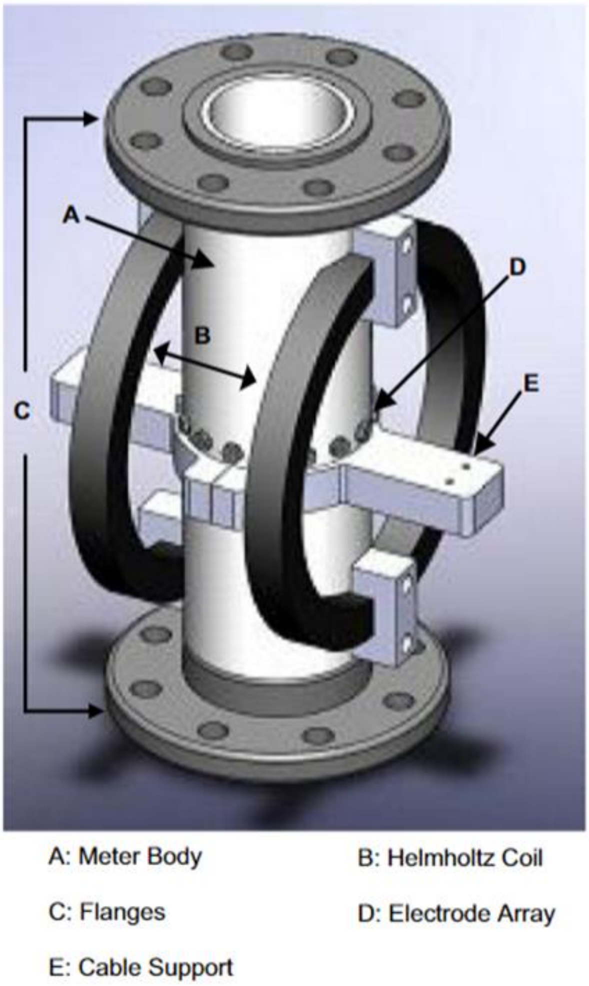


Figure 1. Electromagnetic flow meter setup design [11]

Leeungculsatien and Lucas [11] designed an electromagnetic flow meter. Electromagnetic flow meters (EMFM) which had shown in Fig.1. widely using in industries for measuring velocity of liquid flows.

Goal et al. [12] studied open channel flow measurement of water by using width contraction shown in Fig. 2. Experiments on that study were conducted on sharp edged constricted flow meters having four types of width constrictions namely 2:1, 1.5:1, 1:1 and 90º in the direction of flow. The device having contraction 2:1 is the most efficient one as it allows maximum critical submergence [12].

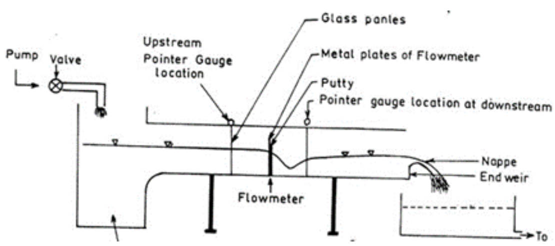


Figure 2. Experimental setup for open channel flow measurement of water by using width contraction [12]

Bolognesi et. al. [13] studied measurement of surface velocity in open channels using a lightweight remotely piloted aircraft system (RPAS) shown in Fig. 3. The RPAS was used both with ground control points (GCPs) for orientation of the photographic images and without GCPs. The data analysis showed that the RPAS provides valid results even without GCPs [13].

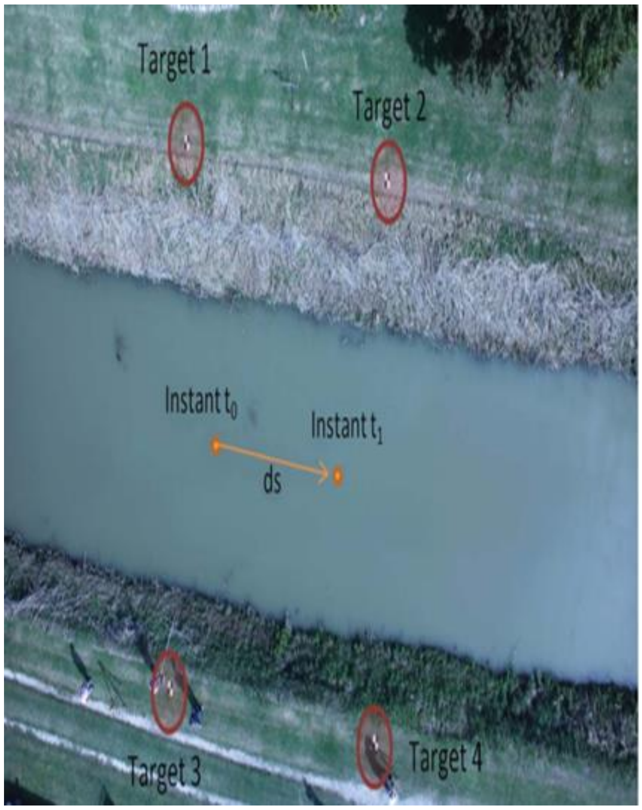


Figure 3. Layout of the test site for surface velocity measurement using the RPAS (Fossa Masi channel) [13]

Figuérez et al. [14] studied an enhanced treatment of boundary conditions for 2D Reynolds Averaged Navier–Stokes (RANS) streamwise velocity models in open channel flow. Results suggest that the influence of the free surface boundary layer has a significant impact on the results for both the streamwise velocity and boundary shear stress in windy conditions [14].

In this study, an exemplary application associated with the measurement of water velocities in open channels has been shown, and the resulting apparatus has been constructed and tested under laboratory conditions.

2. Method

There are too many 4 and 6 bar mechanism designs to produce a desired function. It is possible to obtain different designs that produce the desired function by changing the design parameters that require arbitrary selection or by choosing the method applied in the design differently. This means that we have a better chance of meeting certain criteria required from the mechanism. For example, if it is important to achieve very low structural errors, the mechanisms that best meet these criteria are selected from among the designs. If the dimensions of the mechanism are required to be compatible with each other, appropriate designs are selected.

In order to produce different designs that will produce the same function with the program packages in this study, the data in the program input set must be changed systematically. While doing this, it may be necessary to play with the parameters that affect the design results the most. In this study, the program dataset was modified to select the mechanisms that best met the structural error and size criteria.

In practice, problems such as measurement, control, linearization of non-linear mechanical outputs can be considered within the scope of function synthesis. An example application of measuring the average flow rate of water in an open channel, which is one of such problems encountered in practice, tested under laboratory conditions.

In order to measure the water flow rate in an open channel, a device that converts the water velocity to angular displacement must be selected and the functional relationship between the water velocity and the angular displacement must be found experimentally or theoretically. For this, a suspension arm with a spherical object and mass m on it, as shown in Fig. 4.

When the spherical object at the end of the suspension arm seen in Fig. 4 is immersed in water, the water hitting the sphere at a certain speed creates a force proportional to the cross-sectional area of the sphere. The moment created with respect to point O is balanced by the mass m on the suspension arm and the weight of the suspension hair. In order to eliminate the effect of buoyancy, which causes instabilities in the system, the weight of the spherical body is chosen equal to the buoyancy force. According to these, the force created by the water velocity on the sphere is written as:

$$F= C_d \frac{V^2}{2} A \qquad (1)$$

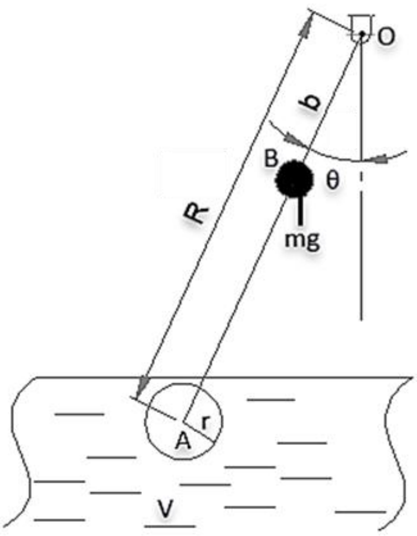


Figure 4. A device for measuring the water flow rate in an open channel

When the force balance is written with respect to the O point of the suspension arm under the influence of (1) force (C_d: Drag coefficient, A: cross-sectional area of the sphere, V: Velocity in equation (1)), the relationship between the water flow rate and the angle (θ) of the suspension arm with the horizontal becomes as follows:

$$V=k\sqrt{Tan}\,\theta,\ k=\sqrt{\frac{2bmg}{RC_4\pi r^2\rho}} \qquad (2)$$

The constant k in equation (2) is a quantity dependent on the density of water and the mass and geometry of the suspension arm. Equation (2) does not include all parameters that affect the event in the measurement of water flow rate. For example, bearing frictions, axial misalignments arising from manufacturing, and additional forces occurring on the part of the suspension arm that enters the water do not cover. Instead of (2) equation, it would be more realistic to establish the relationship between θ angle and velocity at certain water velocities experimentally in laboratory facilities.

For this reason, by establishing the apparatus in Fig. 4, another apparatus with a pump, in which different flows are obtained in rectangular and open channels used as an experiment set in the laboratory, was used in order to determine the angle (θ) velocity (V) relationship. In the setup, different flow rates are provided by creating a dam at different heights in front of the channel and changing the depth of the flow.

In the setup of the assembly shown in Fig. 4, the selection of dimensions and the determination of the balancing mass m were made by taking into account the available possibilities. According to these, a hollow spherical object made of light plastic material with a radius of r=2 cm available in the market was added to the end of a selected b=21 cm long suspension arm. The inside of the spherical body is completely filled with water, eliminating the effect of the buoyancy of the water. The mass m added to the suspension arm was determined experimentally in such a way that the ball cannot come out of the water when the suspension arm is immersed in the water in the channel at the maximum flow rate. The different water flow rates obtained in the experiments were determined by means of a water velocity measuring instrument called "MULINE" with a rotating propeller. Water gage was used to immerse the suspension arm perpendicular to the flow. The results of a series of experiments carried out in the laboratory under these conditions are presented in Table (Table 1).

As can be seen in Table (Table 1), the maximum velocity value of 29.4 cm/sec is obtained against the deflection of the pendulum arm of maximum 16 degrees. For two degrees of deviation, the velocity is 12.64 cm/s. Accordingly, the working range of the velocity measuring device to be made will vary between 12 cm/s and 30 cm/s.

Table 1. Experimental water flow velocity (V) and suspension arm deviation angle (θ) values

θ (°)	θ (rad)	Velocity(V) cm/min
2	0.0349	12.64
4	0.0698	15.82
5	0.0873	18.00
8	0.1396	21.65
10	0.1745	24.30
16	0.2792	29.40

The suitability of a quadratic polynomial for the relationship between angle (θ) and velocity (V) in Table 1 was demonstrated by the least squares method. Accordingly, the quadratic polynomial obtained with the help of the values in table (Table 1) is as follows: [15].

$$V=-138.50\Theta^2 + 112.60\,\Theta+8.90 \quad (3)$$

The graph consisting of the expression in equation (3) and the experimental results (Table 1) is shown in Fig. 5. As seen in the graph, all experimental points are very close to the curve in expression (3). Therefore, (3) the velocity (V) angle (Θ) relation is appropriate.

For the design of the 4-bar mechanism that will produce the function in the expression (3), a computer program package containing the "SUBREGION" method [16] was used. Theoretical statements regarding the design of the 4-bar mechanism with the subregion method within the scope of function synthesis are presented in this study. Accordingly, the inputs and outputs of the computer program package used for the design are as follows.

Here, DPS, DAL, respectively, the amount of rotation of the input and output arm, X0, XN is the first and last value of the definition range of the generated function, PS0, in degrees, the angle of the input arm that starts the calculations, the allowed error in E solution, N required for numerical integration, an even integer greater than 2 , the number of intervals, the upper bound integer entering an NI sequential solving technique, the inputs PJ0 and (Pj(k),k=1,2,3,4,5) are the lower range limits used in the subregion method in degrees.

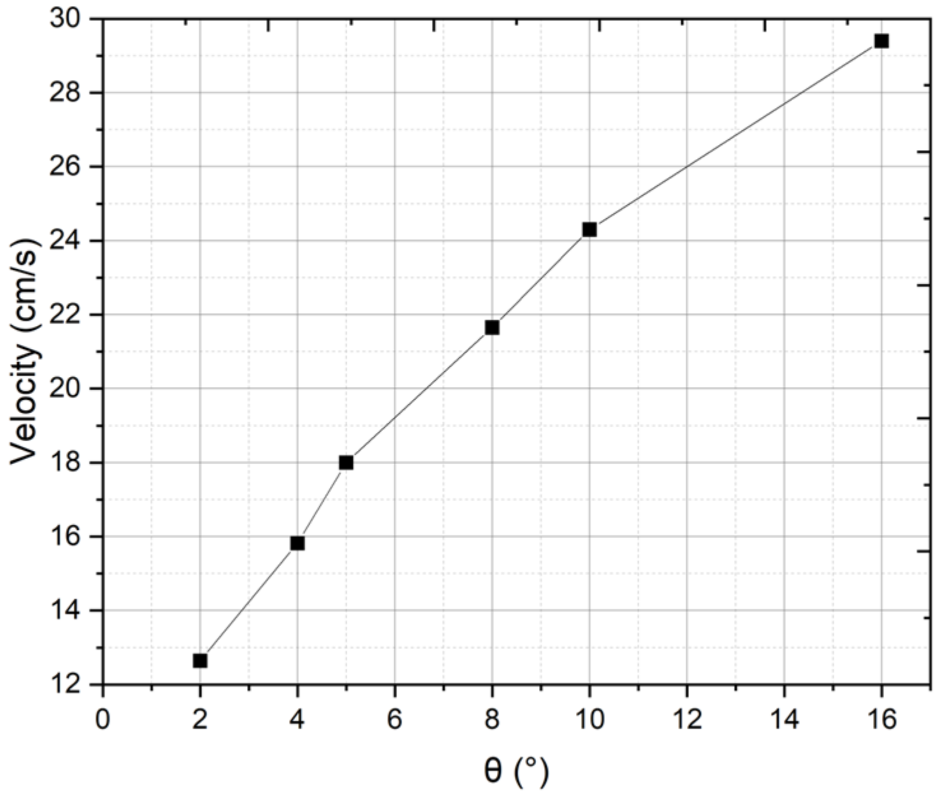


Figure 5. Variation of water flow velocity with respect to suspension arm deviation angle Θ

Design results from the program:

Input arm starting angle	$\psi_0 = 354.8°$
Output arm starting angle	$\alpha_0 = 76.50°$
Input arm length	$x_1 = 0.8124$
Connecting rod length	$x_2 = 0.6767$
Output arm length	$x_3 = 0.5396$
Fixed arm length	$x_6 = 1$

2.1. Application of Subregion Method to 4-Bar Mechanism in Function Synthesis

The common point of many analytical methods developed is to consider the difference (error) between the desired function and the function produced by the mechanism as the objective function and to minimize this error in a certain operating range. Therefore, the idea of optimization is present in many of the methods. Methods have different names according to the mathematical approaches used in minimizing the objective function (error function). The most used ones are; The exact point method [17], the subregion method [18], the Galerkin method [1], the least squares method [19] can be counted.

The equation of motion that connects the input arm rotation angle (ψ) of a 4-bar mechanism to the output arm rotation angle α can be written as follows using Fig. 6:

$$G\,(x_i, \psi, \alpha) = 0,\ i = 1,\ldots\ldots,5 \quad (4)$$

Here, xi are the unknown kinematic quantities, which are used in the function synthesis design of the 4-bar mechanism and are maximum 5 [20]. These dimensions are the arm lengths as x_1, x_2, x_3 and the starting angles of the entry and exit arm ($x_4 = \psi_0$, $x5 = \alpha_0$).

For the design of the 4-bar mechanism to produce a continuous function of the form Y=f(X), $X_0 \le X \le X_n$, (4) the equation of motion $\psi_0 \le \psi \le \psi_n$ by dividing it into 5 subregions, in each subdomain the integral of (1) if the condition of being zero is written [21],

$$\int_{\psi k-1}^{\psi k} G(X_i, \psi, \alpha) d_\psi = 0, \text{ i, k=1,.......,5} \quad (5)$$

In the expression (5), called the subregion method, (ψ_{k-1},ψ_k)'s indicate the sub-region boundaries within the (ψ0,ψn) range of motion.

By establishing a linear relationship between the mechanism and the independent and dependent variables (ψ,α) ,(Y,X) of the mechanism and the produced function, and substituting the integral in the equation (5), the set of nonlinear equations with 5 unknowns is found as follows.

$$Z_2 d_k + Z_3 C_k + Z_1 I_k - J_k = 0, \text{ k=1,.......,5} \quad (6)$$

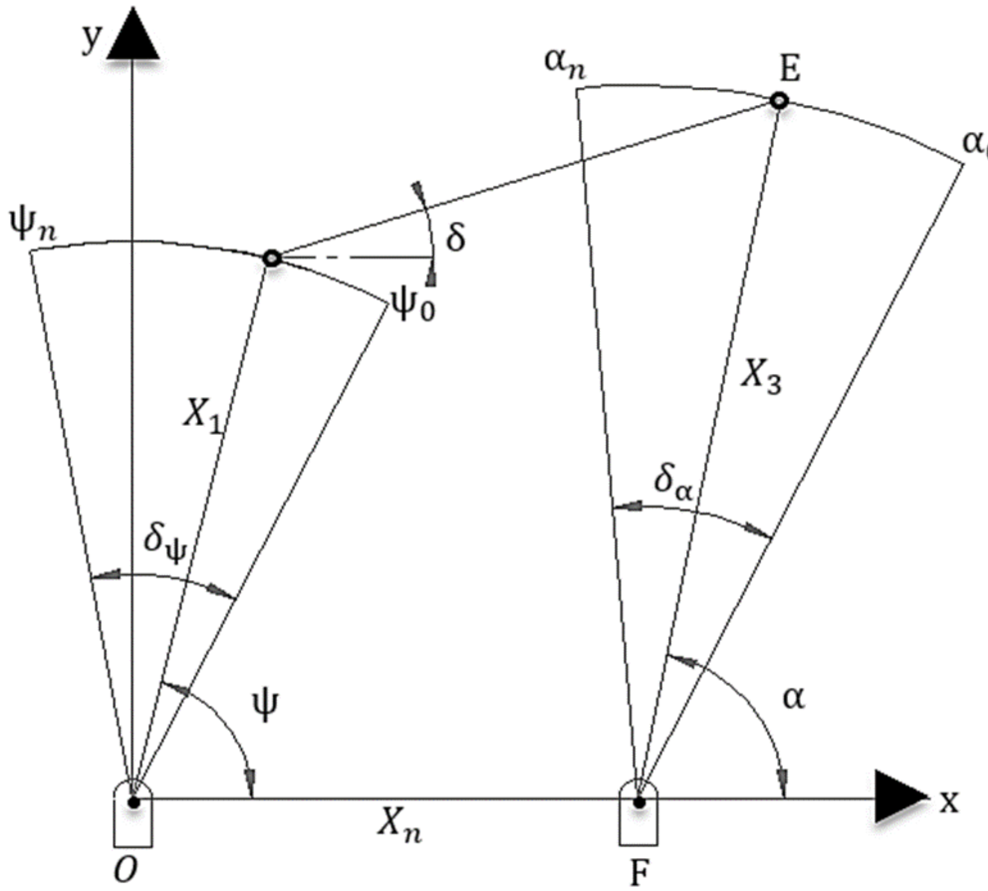


Figure 6. Function synthesis parameters of the 4-bar mechanism

Here, $Z_1 = 1/x_1$, $Z_2 = (1+x_1^2 + x_3^2 - x_2^2)/(x_1 x_3)$ $Z_3 = 1/x_3$; d_k , C_k , I_k , J_k , ψ_0 , α_0 are the coefficients depending on the unknown input and output arm initial angles. If the set of equations (6) is solved using sequential iteration methods for 5 unknown parameters, the 4-bar mechanism is designed to produce the desired function.

3. Designing Velocity Measuring Setup

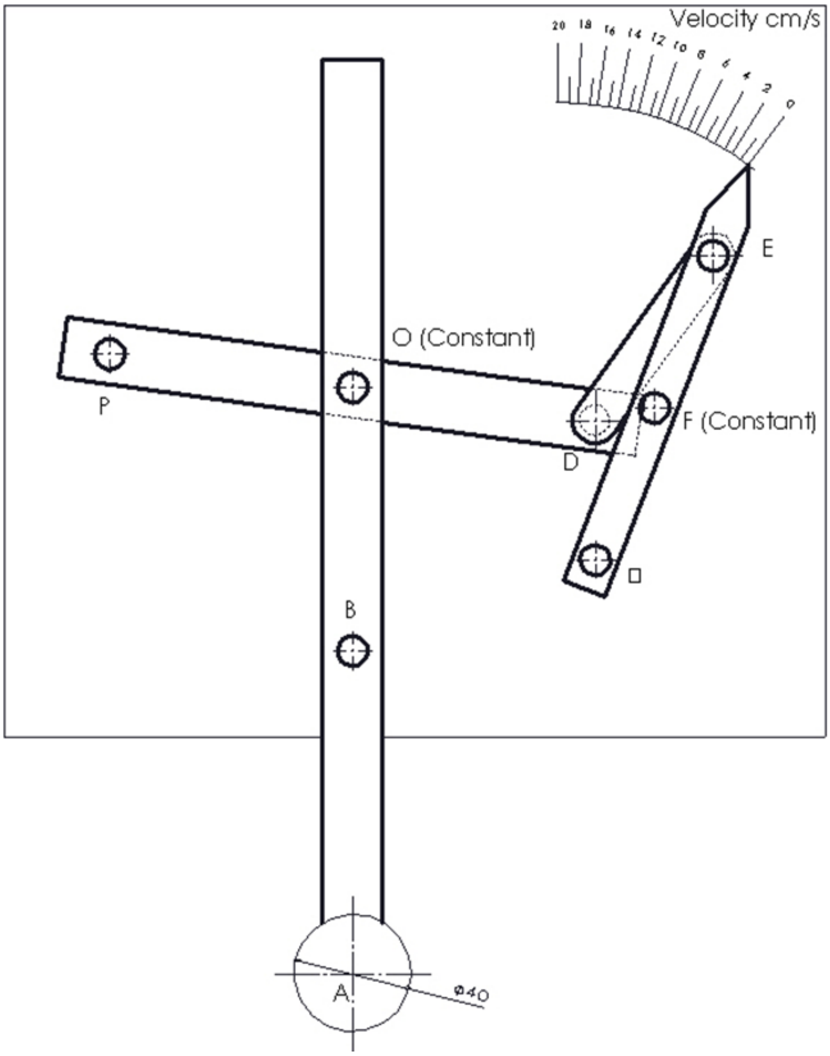
It is seen that the 4-bar mechanism size ratios obtained as a result of the design are suitable for production. These dimensions were found as a result of the body (fixed arm) length assuming 1 unit. For this reason, the mechanism lengths can be changed as desired in accordance with the purpose.

In this study, when the body length is taken as 10 cm, the appropriate design values are obtained by multiplying the other dimensions by 10. As a result of the 4-bar design formed under these dimensions, the structural error distribution, which is the difference between the function produced by the mechanism and the function given in the expression (3), is examined.

The 4-bar mechanism was designed in accordance with the results of the design, and the pendulum arm in Fig. 4 was mounted, and the velocity measuring device in Fig. 7 was obtained. In the design of the 4-bar mechanism, the inlet and outlet arms are statically balanced with the help of additional masses (P and Q). Thus, the effect of additional moments on the pendulum arm due to the mechanism's own weight is eliminated. Thanks to a linearly calibrated angle dial, the velocity values measured from the output arm of the 4-bar mechanism are shown. In Fig. 7, OD = 8.1 cm, DE = 6.7 cm, EF = 5.4 cm, OF = 10 cm, and the diameter of sphere A is 4 cm.

4. Conclusion

In order to test this setup, measurements were made at various velocities in the open channel available in the laboratory with the other velocity measuring instrument “MULINE” and the values obtained were compared. As a result, it was determined that the relative error between the "MULINE" and the velocity measuring device produced in Fig. 7 and the measured velocities did not exceed 2%.



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Author contributions

Hüseyin Mutlu: Methodology, **Emre Kaygusuz:** Writing-Original draft preparation, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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