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Modeling and Control of an Air Levitation Ball and Pipe Laboratory Setup

Amirreza Tootchi
Faculty of Mechanical Engineering
University of Guilan
Rasht, Iran
amirreza.tootchi@yahoo.com

Saeed Amirkhani
Faculty of Mechanical Engineering
University of Guilan
Rasht, Iran
amirkhani_saeed@yahoo.com

Ali Chaibakhsh
Faculty of Mechanical Engineering
University of Guilan
Rasht, Iran
chaibakhsh@guilan.ac.ir

***Abstract*—in this paper, design, fabrication, modeling, and control of a low-cost ball and pipe air levitation laboratory system for educational purposes is investigated. Ball and pipe laboratory setup is a dynamic benchmark system, designed to control the position of the ball on a vertical upward airflow that counteracts the gravitational force exerted on the ball without mechanical support. A blower feeds airflow, and the position of the ball is measurable by using an infrared distance meter. In this paper, the design and construction of a ball and pipe system are initially carried out. Detailed mathematical modeling of the process is included, followed by a system parameters identification process, and then a PID control system is developed by establishing a connection between the Arduino circuit and Simulink® real-time toolbox. The performance of the controller represents small overshoot and fast settling time. The system is intended to be used as a benchmark and educational laboratory setup in control systems theory courses. This device would enhance the understandings and skills of students by providing a proper balance between the theoretical concepts and practical knowledge.**

Keywords—Ball and pipe air levitation setup; Arduino; mathematical modeling; system identification; PID controller

I. INTRODUCTION

One of the key elements for a practical approach to the assumptions and theories in control systems is the laboratory setups that can assist students in linking theoretical concepts to their practical application. Accordingly, the gap between industries and universities might reduce if correct simulation and implementation of real processes in laboratories become prevalent. Engineering is a professional work to exploit and improve the essential human resources for achieving more significant benefits. The crucial purpose of engineering education is to prepare students for engineering practice. In particular, to deal with the forces and materials in nature. From the earliest days of engineering education, laboratories have been essential parts of the undergraduate degrees. Indeed, most engineering knowledge and perception are obtained in laboratories. Nowadays, there is a massive collection of accessible and replicable laboratory setups that students can learn new concepts or develop the notions through practicing with setups and implementing the theories on real systems. Student access to laboratory experiments is critical in education because engineering is a practical discipline. Lab experimentation plays a vital role as a way to connect theories and applications. Therefore, more and more universities began to build laboratory setups. Examples include DC motor experiments, coupled tank apparatuses, magnetic suspension control systems, and ball and pipe air levitation systems. Universities give substantial financial support in providing traditional laboratory stands for different fields of science. Advanced learning technologies have emerged to enhance learning, support new inventions and improve interest in engineering studies [1]. Moreover, advancement in technologies and automation are changing the nature of these laboratories, and there is a long-running debate about the value of hands-on versus simulated laboratories. Hands-on advocates emphasize design skills while remote lab advocates focus on conceptual understanding [2]. Laboratory education with a focus on a classroom demonstration device is always beneficial in teaching courses particularly for mechanical, electrical, robotics, control, and biomedical engineering curriculum. Robotics and biomedical engineering laboratory courses using fully equipped with state of the art setups can prepare students for real-world experience with minimal cost and risk. Some affordable laboratory devices for engineering education and prospering theories have already been developed and exploited for different applications [3-8].

Design and analysis of control systems have been of interest and all-important for a long time to researchers and engineers. Due to the development of science, the evolution of technology and complexity of industries, the crucial role of analysis and design of control systems have become more and more worthy over time. Control engineers need to have both an extensive experience in implementing solutions in real plants and processes, and a deep understanding of the mathematics and theories that lie behind these solutions. Therefore, reaching a balance between theoretical intuition and their tangible proofs is a significant challenge in control education.

One type of the devices, which can teach a wide range of algorithms used in control engineering are air levitation ball and pipe laboratory setups. Levitation systems have long been utilized in control system laboratories. Levitation is a process in which an object is floated against gravity by a physical force. Many methods can be used for representing the levitating phenomenon, including magnetic repulsion, viscous liquids, sound waves, and air currents. An exciting example of levitation is based on airflow. Air levitation uses an air stream provided by a blower to obtain the levitating force on a levitator. This phenomenon stems from the Bernoulli principle [9]. The air levitation control system is considered as an interesting and impressive device for educational purpose. Besides, the system is small and straightforward, that is very convenient to be carried from class to class. This kind of laboratory stand can be an environment for implementing a variety of controllers, for instance: PID controller, hybrid controller, predictive controller, fuzzy logic controller, sliding mode controller and others which are used for nonlinear systems [10].

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In the present paper, the goal is to design a low-cost setup with educational functionality, which can increase the accessibility of the control experiences for students and improve the quality of teaching. A primary objective of the ball and pipe air levitation setup is to provide students with a testbed on which they can develop and empirically verify control algorithms. For this purpose, a portable laboratory setup is constructed at the faculty of mechanical engineering at the University of Guilan, followed by a description of the experimental setup. Mathematical modeling of the system is investigated and identification of the model parameters of the system is carried out using the nonlinear least square method. Thereby, the model of the system is identified and validated and a PID controller is designed for the system. In the end, experimental scenarios for teaching the concepts of control lesson through ball and pipe setup is presented.

The paper is organized as follows. Section II introduces the ball and pipe experimental setup. Section III provides an accurate modeling and identification of the system and the mathematical relations behind the process. Validation of the obtained model is included in this section as well. In Section IV, a control strategy for tracking the reference trajectory of the ball is developed. PID control method is adopted for trajectory tracking and position control of the ball. Besides, the suggested control strategies are implemented in both simulation and experimental states and the results are compared in terms of positioning accuracy in this section. In section V, a number of experimental scenarios are introduced for educational purposes. A conclusion puts an end to the paper in Section VI.

II. Experimental Setup

The ball and pipe air levitation laboratory setup (Fig. 1) presented in this paper has a minimalist design in order to be cheap and easy to replicate, rebuild and repair. It is composed of a pipe in which a forced airflow is used to lift a Ping-pong ball and levitate in the desired position. The system is built using the following components as presented in Fig. 1. An infrared sensor, a Plexiglass pipe, a Ping-pong ball, Plexiglass plates, a Fan (Blower), an L298 driver, and a Mega 2560 Arduino board. The device has a variable speed drive which is a 12 V DC fan. Communication between the actuator (fan) and the controller (computer) is handled by the Arduino board which receives position feedback from the infrared sensor. In order to achieve air stream capable of levitating balls with different masses, a fan with high air volume and static pressure was required. A 12V DC fan is inserted into a hole in a flat sheet of Plexiglass, blowing upwards. The fan speed is controlled by pulse width modulation (PWM) signal, and the dual full-bridge L298 driver chip is used in the fan drive circuit. The output voltage of the controller provides the input of a low-cost motor drive, where produces a pulse width modulated signal for fan rotation speed control.

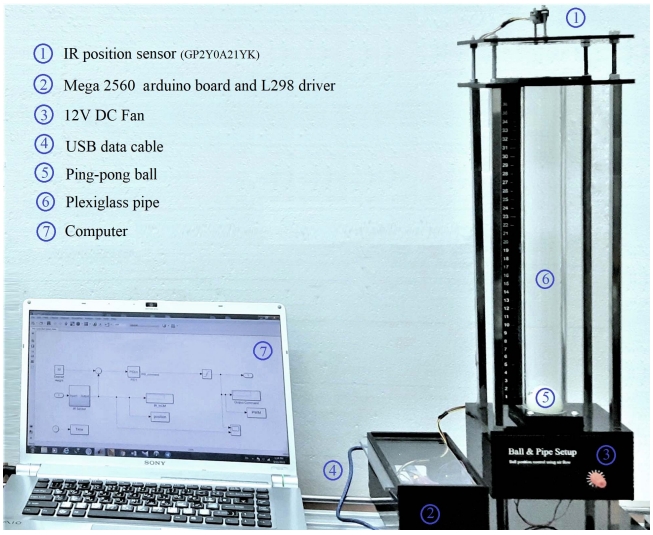

Fig. 1. Ball and Pipe system

The position of the ball is measured with an infrared beam sensor, particularly a Sharp GP2Y0A21YK analog distance sensor, which can obtain measures between 5 and 70 cm with a ranging accuracy that can reach up to 2 mm. Other components of the system are metal bars and a holder for the sensor, which provides a stable position over the pipe. Schematic block diagram of the ball and pipe system under study is shown in Fig. 2.

III. Mathematical Modeling and System Identification

To find a proper solution for a real problem, having exact information in all aspects of the process is impossible. Therefore, a certain representation of the real process takes into account, known as the model of the process. Mathematical models are among the leading models used for investigations and analysis. Formation of mathematical modeling of a system is probably the most crucial phase in the design and analysis of any form of control strategies. An excellent mathematical model provides the designer with all the essential information about the dynamics of the system which in turn, ensures durable design as well as the competence of adopted control theory. The crucial point is that the designed control system itself can be checked on the model before being applied to the real system [8].

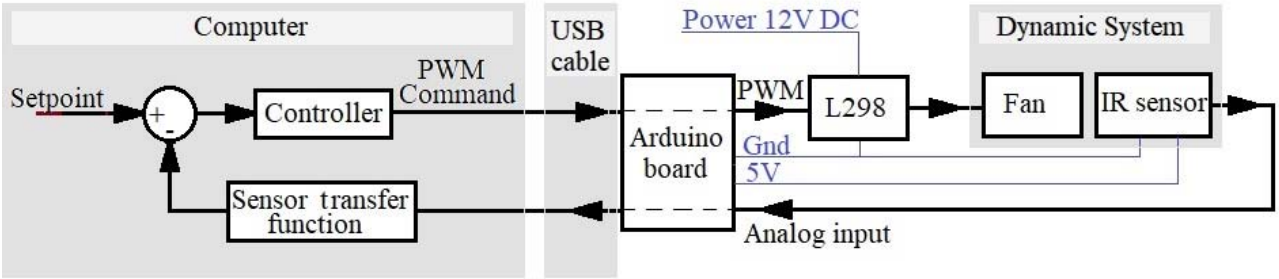

Fig. 2. Schematic block diagram of the system

In the literature, a complete dynamic model of ball and pipe air levitation system based on the physical equations and with several complex phenomena in the system has not been presented in details. Hence, in this paper, detailed modeling is developed to study the mathematical relations behind the process.

The high-speed air hits the bottom of the ball, creating a high-pressure zone under it. This high-pressure air moves over the curved surface of the ball with high velocity, creating a low-pressure zone. If the ball tends to move away from the middle of the stream, the atmospheric air around this low-pressure zone pushes it back to the middle because of its relatively high pressure. Hence, the lateral motion of the ball becomes stable in the middle of the flow. The vertical motion of the ball around this equilibrium point is stable as well, given by the balancing of gravity and the air drag.

A. System model

The mathematical models of the air levitation system are developed in several previous studies, concisely [11, 12]. The system dynamic equations are nonlinear. This is due to the nonlinear description of the air stream, which subjects to the Bernoulli's equation. This equation makes a crucial prediction about the relationship between the pressure and the velocity of a moving ideal fluid:

$$p_1 + 1/2\,\rho v_1^2 + \rho g y_1 = p_2 + 1/2\,\rho v_2^2 + \rho g y_2 \tag{1}$$

where, $1/2\,\rho v^2$ is kinetic energy and $\rho g y$ is gravitational potential energy, p_1 and p_2 are the static pressures of air at the cross-section, ρ is the density of the following air, y_1 and y_2 are the different distances between the ball and the bottom of the pipe, v_1 and v_2 are the mean velocities of fluid flow at the cross-section. Once a fluid moves with high velocity, it has lower pressure than the same fluid at low velocity. In the experiments, one side of the Ping-pong ball is in contact with a low pressure which creates a pressure gradient, the other side of the Ping-pong ball is in contact with a higher pressure which results in the Ping-pong ball being pushed towards the region of low pressure. Placing the ball in the tube allows to achieve higher heights but the Bernoulli principle still works. This is because the tube accumulates the air increasing the speed around the ball and allow the ball to go higher. As air is blown out from the blower, it flows at high speed and this creates a region of low pressure across the top of the pipe. The still air around the ball is at a higher pressure and pushes on the ball and causes it to stay floating.

As it is shown in Eq. (2) and Eq. (3), Newton's second law gives us the dynamic equation for the air levitation ball and pipe system, which has been studied by several previous works [13-15]. Forces acting over the levitating object are the buoyancy force (F_b), drag force (F_d) and weight force of the ball (F_g). Drag force tries to prevent the levitator motion and it is a function of air pressure difference and friction force of air, and Buoyancy is an upward force exerted by a fluid that opposes the weight of a plunged object. Upwards effect of the airflow and the downwards effect of the gravity will induce an up or down motion of the ball (Fig. 3).

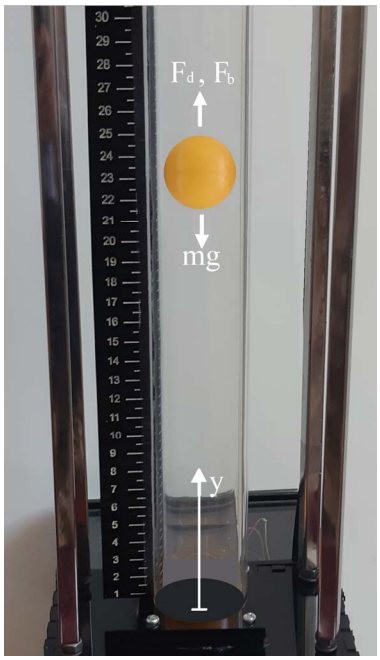

Fig. 3. Schematic representation of forces inserted on the ball

$$m\frac{d^2y}{dt^2} = F_b + F_d - F_g \tag{2}$$

$$F_b = \rho g V_b$$

$$F_d = f(\Delta p, F_f) \tag{3}$$

$$F_g = mg$$

Where Δp is the air pressure difference, ρ is the density of air, g is the gravitational acceleration, m is the mass of the ball, V_b is the ball's volume and F_f is the friction force caused by airflow. The drag coefficient is a term that depends on Reynold's number, which, in turn, depends on the relative velocity of the ball that moves inside the flow, and the velocity of the flow.

$$F_d(\rho, c_d, A, v_f, y) = \tfrac{1}{2} \cdot C_d \cdot \rho \cdot A \cdot (v_f - \dot{y})^2 \tag{4}$$

Where, v_f is the velocity of the air inside the tube, A_b is the ball's area, C_d is the so-called drag coefficient, and y is the position of the ball in the tube. By summarizing and reforming the relations mentioned above, the system's dynamic equations can be obtained by exploiting net force between the airflow force and gravitational force as:

$$m\Delta\ddot{y} = -mg + \tfrac{1}{2} \cdot C_d \cdot \rho \cdot A \cdot (v_f - \dot{y})^2 + \rho g V_b \tag{5}$$

In this study, it is assumed that c_d is constant due to the small velocity of flow. The levitating ball will be in a steady state when it does not move ($\ddot{y} = \dot{y} = 0$). The IR sensor measures the distance between the top of the pipe and the ball. In this way, the sensor provides information about the position of the ball. In the following, v_{eq} defined as airspeed at the equilibrium point ($v_{eq} = v_f - \dot{y}$). Thus, g defines through:

$$g = \frac{C_d \cdot \rho \cdot A}{2(m - \rho V_b)} \cdot v_{eq}^2 \tag{6}$$

Finally, the dynamic equation of the process is expressed as follows:

$$\ddot{y} = g \cdot (\frac{m - \rho V_b}{m})((\frac{v_f - \dot{y}}{v_{eq}})^2 - 1) \quad (7)$$

The system can be modeled either linear or nonlinear. Application of these two states of description depends on the type of control procedures adoption for designing a controller for the setup. Regardless of that, linearization for the system is possible around the equilibrium point by using Taylor's expansion:

$$f(x) \approx f(x_0) + f'(x_0) \cdot (x - x_0) \quad (8)$$

By assuming $x = \frac{v_f - \dot{y}}{v_{eq}}$, and expansion of the relation (7) about the point $x = 1$, it yields to:

$$\ddot{y} = \frac{2 \cdot g}{v_{eq}} (\frac{m - \rho V_b}{m})(v_f - \dot{y} - v_{eq}) \quad (9)$$

Determining the response of a system at an operating point is a critical step in system and controller design. The identification of the process transfer function is carried out in the frequency domain with the open loop tests performed over the system. The system is with one input and one output (SISO). The input signal is wind speed generated by blower and output is an accretion of the position of the ball. Assuming the system is well described by the linearized model, the transfer function between ball position and wind speed is:

$$\frac{y(s)}{v(s)} = \frac{1}{s} \frac{b}{(s+b)} \quad (10)$$

Where $v(s)$ and $y(s)$ are wind speed and increment of ball's position about the equilibrium point, respectively and $b = 2g(m - \rho V_b) / m v_{eq}$. Considering the fan can be modeled as a first-order process, the transfer function between the input voltage and the wind speed is represented as:

$$\frac{v(s)}{u(s)} = \frac{k_v}{\tau s + 1} \quad (11)$$

where *v(s)*, *u(s)*, are wind speed and input voltage, respectively. In addition, k_v is the sensitivity gain that relates the input voltage to the wind speed at steady state, and τ is the time constant of the fan. It should be noted that there be existed a delay in the operator, as well as measurement delay, in the ball and pipe system, which needs to be included in the model. The fan used in this setup has electronic components that can bring out a delay in the time of performing the command. Moreover. A lowpass filter has also been used to reduce the signal noise of the measurement, which results in a delay in the system. It is necessary to mention, the values of these delays are not clear and are estimated at the identification phase. In the present paper, the effect of the two delays is assumed to be T_d, cumulatively.

$$e^{-T_d s} = \frac{1 - T_d s}{T_d s + 1} \quad (12)$$

Finally, the transfer function of the entire system defines as follows:

$$G(s) = \frac{y(s)}{u(s)} = \frac{b.k_v.(1 - T_d s)}{s(s+b)(\tau s + 1)(T_d s + 1)} \quad (13)$$

However, this function does not describe the behavior of the system, solely, due to the limited length of the pipe, it is necessary to add a saturation block after the function. The saturation function has a lower bound of 0 and an upper bound of 40cm. Also, the behavior of the system indicates that the ball does not move with small values of the input, so adding a dead-zone block after the input in the model will make the system performance more precise. In the next section, the nonlinear least square method is adopted to identify the parameters of the presented model.

B. Parameters Identification

Although the physical modeling is an authentic method to obtain a reliable mathematical model of the system for control purposes, there exist numerous unmodeled terms and uncertainties in the system which makes this approach not feasible at least in the context of this work. So, in this work, we decided to ameliorate the model through a system identification procedure. Different open loop tests were performed to identify the system. The idea here is to excite the system with sinewave and square pulse PWM input signals with different frequencies and log the system's output response in the form of ball position curves.

In the obtained data, the input which is in the form of PWM was considered in the range of control input and sampling time was 0.02 seconds. After the data acquisition process, the data preparation process was accomplished and the PWM signal was converted to a voltage.

As described in the previous section, the system model was acquired as shown in Fig. 4. Consequently, four unknown parameters related to G(S) and an unknown parameter related to the upper bound of the dead-zone block, must be obtained.

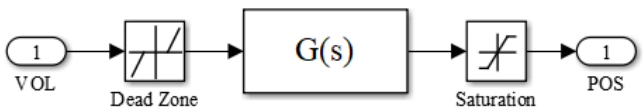

Fig. 4. Model of the system

The known linear least squares error method is widely used in solving linear optimization problems. By modifying the structure of the linear least squares, this method will transform to the nonlinear least squares method which is more flexible and more capable of identifying parameters in nonlinear systems. For the nonlinear least squares method, there are different training algorithms, most notably Gauss-Newton and Levenberg-Marquardt are among them. In this work, identification of unknown parameters of the model was performed using the parameter estimation tools in the MATLAB® Simulink environment, and Levenberg-Marquardt training algorithm was used for this purpose. The results of early attempts to identify the model showed that presence of a pole in the zero point in G(s) reduces the

accuracy of identification, whereas a better result will be achieved by considering the pole in near-zero point. Hence, a slight change was made in the G(s) structure and the identification for the new system was performed.

In Figure 5, the results of the identification process are presented. Figure 5 (top) shows fan voltage open loop input and Figure 5 (bottom) shows the position of the ball. The comparison between real values and the output of the identified model is shown in Figure 5 (bottom). As can be seen, the model output closely follows the real data.

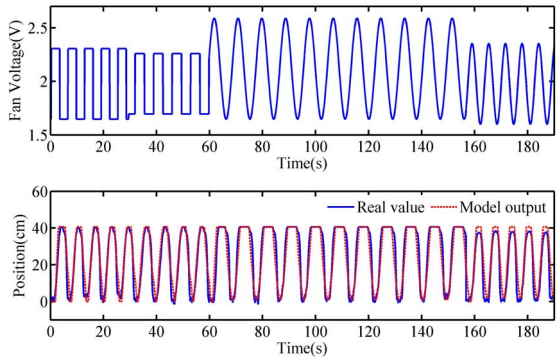

Fig. 5. Input voltage (PWM) and output data (Ball position)

IV. Controller Design

Controlling a system is the perennial monitoring of the system which includes revision and correction in order to gain the control objectives and process as planned. In this paper, the control objective is to impel the ball to track a reference trajectory by regulating the voltage of the blower. The difference between a setpoint and the current position of the ball (position Error) is the input of the controller. The output of the controller will be the control command, sent to the blower driver to control the blower's rotation speed. Eventually, the position of the ball will be variate according to the generated airflow. Proportional-integral-derivative (PID) controller was adopted as a model-free linear type control strategy. The PID controller is favorite for its simple functionality which allows for straightforward operation. The gains of each component need to be tuned for optimal performance [16]. Arduino hardware support package was used to design controller in the Simulink environment of Matlab software. A paradigm was developed to provide communication with the real plant. Fig. 6 shows the implementation of the controller in Simulink environment. It should be noted that the control loop frequency is 50 Hz.

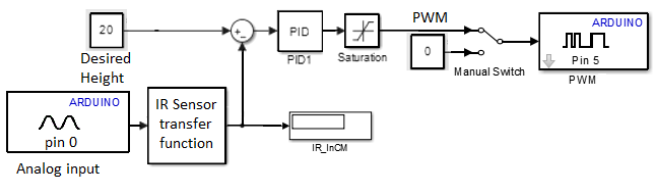

Fig. 6. Implementation of the control system in Simulink environment of Matlab software

In order to tune the parameters of a PID controller, optimization techniques are beneficial. There are various and different methods for optimizing parameters such as genetic algorithms (GA). Furthermore, Matlab includes valuable toolbox for optimizing PID gains which can facilitate the process of parameters tuning. In this paper, MATLAB® toolbox with a trial and error paradigm is used for choosing the best gains of the controller for optimal performance. Finally, the PID controller was designed for the system based on the identified model, taking into account the controller gains $k_p = 0.7$, $k_i = 0.4$, $k_d = 0.5$. According to Fig. 7 and 8, the results obtained for the model and the real system. Fig. 7, shows the result of step trajectory tracking in the presence of the PID controller. The real system oscillation is due to the noise of IR sensor measurement. Zoomed-in images show that model and real system behavior is consistent with acceptable accuracy. Moreover, Fig. 8 shows the result of sinusoidal trajectory tracking. In this figure, the outputs of the model and the real system are consistent as well.

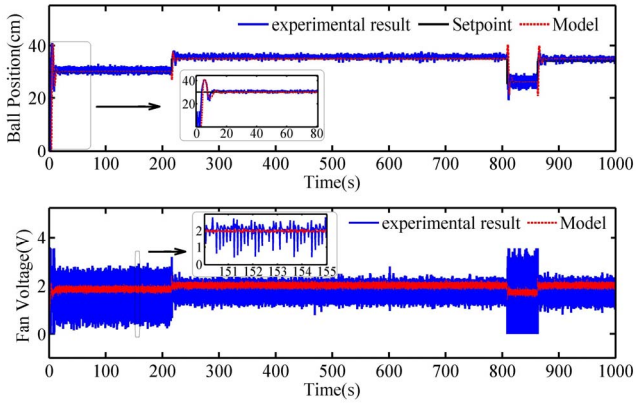

Fig. 7. Step trajectory tracking

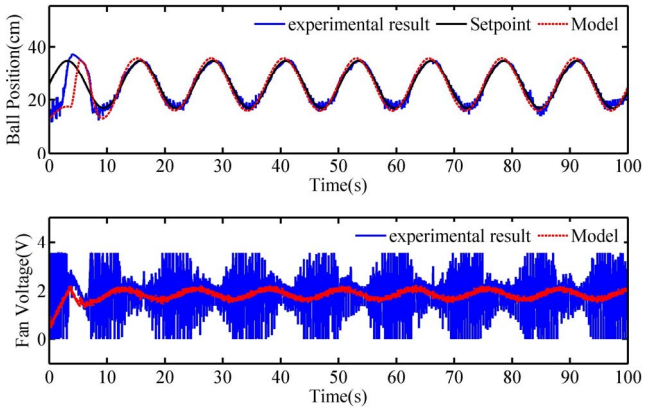

Fig. 8. Sinusoidal trajectory tracking

The results shown in Figures 7 and 8, confirm the model identification results and high accuracy of the designed controller.

V. Educational Scenarios

Ball and pipe laboratory setup is a nonlinear system that can be used as a benchmark system for research and scholarly works to develop control theories. Also, due to its features such as facile and inexpensive construction, suitable controllability, nonlinear dynamics, the feasibility of linear model identification, etc., this system can be a suitable choice for educational purposes. Ball and pip setup, as well as well-known laboratory systems (such as reverse pendulum system, ball and rod system, ball and sheet system, and magnetic floating system), can be used to teach the concepts of control lessons. To achieve this aim,

different experimental scenarios can be designed to give students a deep understanding of the concepts of control. Implementing the ball and pipe system in the Simulink environment of Matlab software makes it easy to work with the device, facilitate controller design or making changes to the control system for students. In the following, several experimental scenarios are introduced with educational objectives.

- Investigating the open loop response of the system
- Design of proportional controller and investigating the closed-loop behavior of the system
- Design of PID controller
- Investigating the effect of each of control gains on performance characteristics such as settling time, overshoot, steady-state error, and stability.
- Investigating the frequency response of the system and draw the Bode plots.
- Investigating delay on the control system
- Investigating the frequency of the control loop on the system behavior.
- Design of state space controller and other types of controllers.
- Investigating the robustness of the control system to parametric and nonparametric uncertainties.

As an example, in order to examine the effect of increasing or decreasing PID controller gains, students can study various states in Table 1 and report their own observations[1].

Table 1. Effect of variation in PID control gains

	Response Time	Overshoot	Steady State Error	Stability
Increase in K_p	↓	↑	↓	↓
Decrease in K_p	↑	↓	↑	↑
Increase in K_i	↓	↑	↓	↓
Decrease in K_i	↑	↓	↑	↑
Increase in K_d	↓	↓	⊘	↑
Decrease in K_d	↑	↑	⊘	↓

VI. Conclusion

The aim of this work is to design, realize and test a ball and pipe laboratory setup for educational purposes in control engineering. The total cost of the laboratory setup provided to the students is under $50. System modeling, parameters identification, model validation using sampled input data and control of this nonlinear process was carried out in this paper. Step and sinusoidal reference trajectories tracking in the presence of the PID controller were investigated. Even though the designed controller is simple, it provides promising results in reference tracking. Finally, several experimental scenarios were introduced with educational objectives. Meeting these objectives made it possible to let the students deepen their knowledge about control systems using real-time hardware and software.

[1] A video clip from the system's operation is uploaded at the following: URL: https://www.youtube.com/watch?v=j1qR7Cu3CrA

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