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Experimental Investigation of the Proportional Controller - Based Model of DC Servo Motor

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Abstract: ***Direct Current (DC) servo motors or simply DC motors play a significant role in many industrial applications such as manufacturing of plastic, precise positioning of the equipment, and operation of computer - controlled systems. This paper focuses to develop a first - order theoretical model of a DC servo motor with a Proportional (P) controller. The model thus developed is based on the experimentally determined "Gain" and "Time Constant" from a DC motor apparatus operated through a P controller. The theoretical model is then simulated in a MATLAB Simulink environment. Its step response results are compared with those obtained from the experiments with the P controller as an effective means of validation. The comparison showed good agreement. Both the experiment and simulation results reveal that an increase in the Proportional controller gain results in an increase in the motor output at any given time instance and reduction in the time constant under transient conditions. The theoretical model for the DC servo motor with a P controller has proven that application of it in the control systems improves the transient response of the DC servo motor that reflects upon the performance of such systems.***

Keywords: DC servo motor, proportional controller, gain, time constant, Simulink

1. Introduction

Automated control systems technology is a technological development landmark. It is linked to the control of industrial processes, equipment, and their operation without the need of a human operator. The variables that govern the operation, pace, and desired output of all industrial processes should be monitored and controlled. Therefore, such automated control systems applications are nowadays an integral part of all industrial processes [1]. These systems are so frequently used in all industries that a foundation in the servo control mechanism forms a fundamental constituent in the training of a control engineer.

The constant speed regulation of an industrial production drive system is a basic but common industrial application of servo control. An example of it is strip plastic production. The material is fed in the form of a long continuous strip through several workstations. Precise control of the speed at which the strip is fed at each stage is very critical. Another household application of the automated control system is the temperature control of an air conditioner. The air - conditioner is equipped with a temperature adjustment knob to set the desired temperature of the room. A temperature sensor is mounted close to the vaporization unit to constantly monitor the temperature of the room and transmit the data to a controller. As soon as the room temperature drops below the pre - set temperature, the controller ceases the compressor operation to stop the circulation of the coolant in the air - conditioning system. When the temperature rises above the pre - set temperature, the controller lets the compressor start working again to circulate the coolant for cooling purposes.

PID controller is responsible for correcting the resulting error between the actual value and the measured value utilizing a comprehensive feedback loop commonly used in industrial control systems [2]. The computational algorithm consists of three coefficients namely Proportional (P), Integral (I), and Derivative (D). The relative value shows the reaction to the current error, the integrative value commensurate with the continuity of the error. The order of the characters P, I, or D does not necessarily reflect the primacy of the process with the rate of error change [3].

There have been a lot of research studies exploring the characteristics and control of different types of motors using various control systems and techniques such as PID and fuzzy logic controllers. Here, some recent studies are presented related to these controllers. Premkumar and Manikandan [4] proposed and compared the effectiveness of two diverse speed controllers, i.e., fuzzy online gain tunes anti wind up Proportional Integral and Derivative (PID) controller and fuzzy PID supervised online ANFIS controller for brushless DC motor speed control. For comparison purposes, they simulated the DC motor operation using the controllers in MATLAB environment under the constant and variable load conditions and set speed. They found that fuzzy PID controlled online ANFIS perform better under all working situations of the DC motor drive. For the position control of different types of motor drive systems such as induction and DC motors, etc., Parastvand et al. [5] used a model - free method to construct efficient PID controllers. In their work, they demonstrated that frequency response data was adequate to analyze a group of efficient PID controllers that satisfy an H∞ - norm of the complementary sensitivity function.

El - Shimy and Zaid [6] introduced a method of selecting inverter voltage vectors in Direct Torque Controlled (DTC) induction motor involving the use of the fuzzy PID control technology to enhance torque and speed responses while maintaining a steady switching frequency. Fuzzy PID controller was later used by Varshney et al. [7] who applied it to a brushless DC motor under varying load conditions and compared the response with that of a commonly used PID controller. They discovered that using a fuzzy PID controller, the jerk produced during load removal was much reduced. Abdul - Jaleel [8] used a direct synthesis method through two algorithms namely back propagation Artificial Neural Network (ANN) and Particle Swarm Optimization (PSO) to improve the performance or in other words, tune the PID controller for governing the DC servo motor. She discovered that the PSO algorithm outperformed the ANN in terms of improving the PID controller. Tran et al. [9] compared, theoretically and experimentally, the PID and fuzzy logic controllers to regulate the speed of the DC motor. They obtained the theoretical results in MATLAB/Simulink environment and discovered that the fuzzy logic controller outperformed the PID controller when it came to regulating DC motor speed.

To the best of the authors' knowledge, a first - order transfer function of DC servo motor with Proportional (P) controller using experimental methods has not been formulated. The current research presents a novel work of using the experimental methods to investigate different servo motor characteristics, formulating a first - order transfer function of a DC servo motor with P controller, and simulating the function with P controller in the MATLAB Simulink environment for transient response of the servo trainer. The results, thus obtained, are compared with the experiment transient response of the servo trainer.

2. Methodology

The experiments are conducted on a servo control system or servo trainer TQ CE 110, which houses a DC servo motor as shown in Fig.1 (a). The servo trainer is connected to PID analog controller (TQ CE120 controller), shown in Fig.1 (b). It is possible to simulate different characteristics of the operating circuit such as time constant using MATLAB Simulink from which the speed of this motor is controlled by adjusting the control constants and getting the desired response.

The servo trainer CE110 is designed to control DC servo motor position and speed. The device can function with external digital, analog, or other compatible control systems. The present investigation engages only the analog P controller of TQ CE120 to investigate the steady - state error and transient response of the servo trainer.

(a)

(b)

Figure 1: (a) TQ CE 110 Servo Trainer, (b) TQ CE120 Analogue PID Controller

3. Results and Discussion

Real - time experiments are conducted on DC servo motor regulated by the speed control systems. The servo trainer responses are obtained on the computer through the software designed for the trainer system. Necessary servo trainer characteristics such as the gain G1 and time constant T vital in servo trainer response calculations are determined experimentally in the forthcoming sections.

3.1 Motor Drive Input to Speed Sensor Output Gain Characteristics

The steady - state gain characteristics linking the motor drive input voltage to the motor speed sensor output voltage are analyzed by altering the potentiometer input voltage driving the motor in unit steps from 1 V to 9 V and - 1 V to - 9 V and recording the associated motor speed sensor output in Volts while the clutch is disengaged. The schematic of the arrangement is shown in Fig.2.

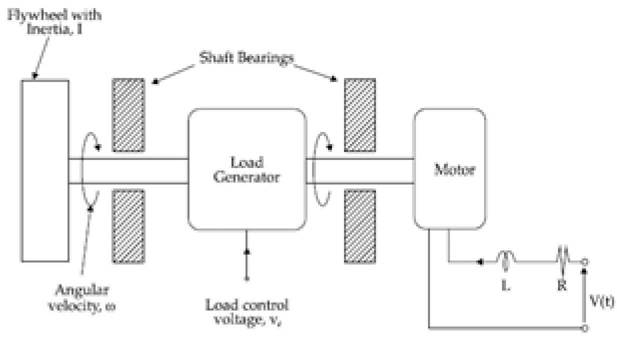

Figure 2: Schematic of the Arrangement Showing the Clutch Disengaged [10]

The procedure is repeated with the clutch engaged, the schematic of which is shown in Fig.3.

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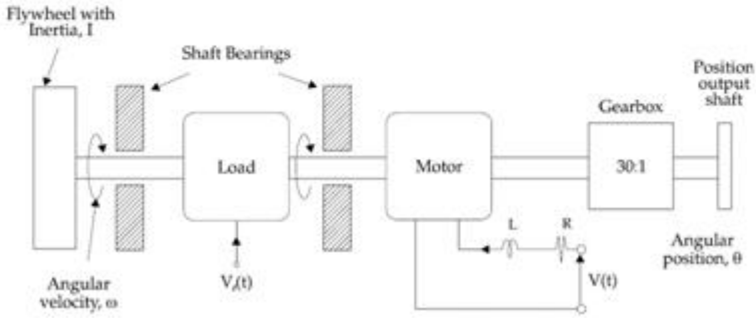


Figure 3: Schematic of the arrangement showing the clutch engaged [10]

Fig.4 is a plot of both (clutch disengaged and clutch engaged) gain characteristics. The gain is obtained by determining the slope of the curves. From the curve representing the gain characteristics with the clutch disengaged, G1 thus obtained is 1.0059 and for that of clutch engaged, G1 is found to be equal to 0.8925. The average gain of the above values is equal to 0.95.

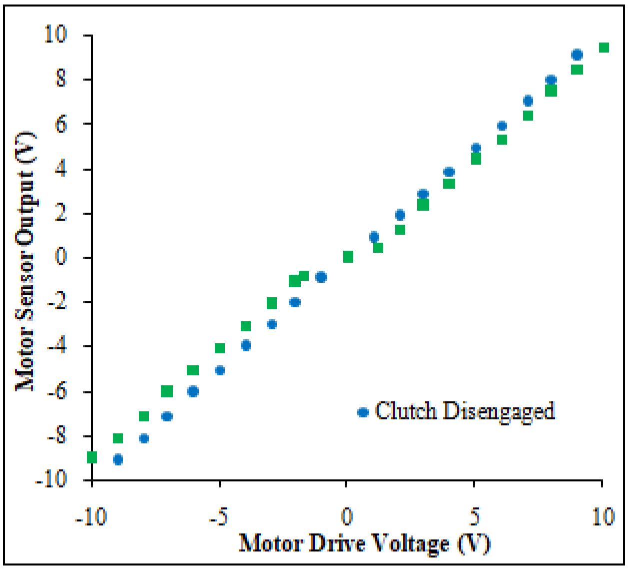
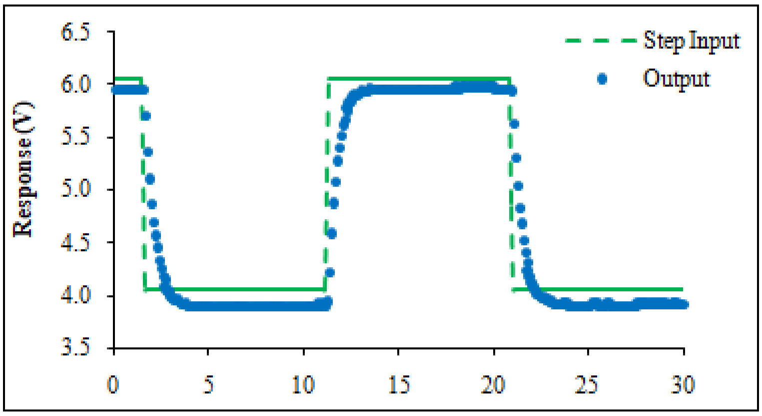


Figure 4: Motor Drive Input to Speed Sensor Output Gain Characteristic

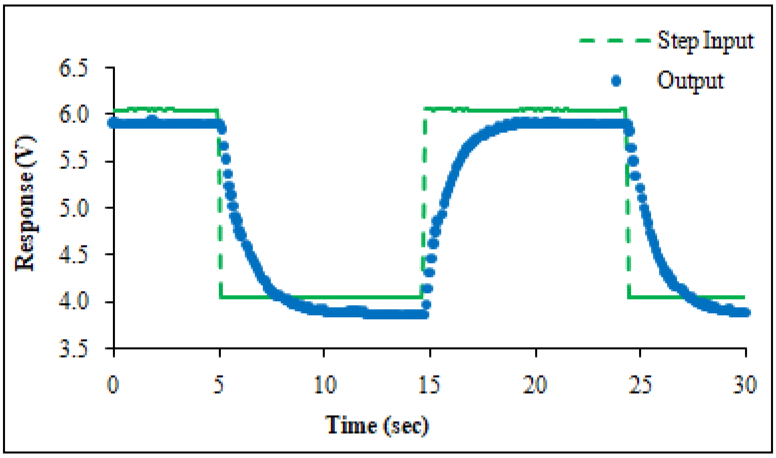
3.2 Time Constant

To determine the time constant of the servo DC motor experimentally, the TecQuipment (TQ) CE110 servo trainer apparatus is connected to the TQ CE120 controller. The clutch for the gear system in the servo trainer is disengaged. To obtain the first set of data for the time constant, only one inertial disc is placed in the servo trainer. This load is assigned the name "small inertial load". Using the CE120 controller's function generator, a square wave with a frequency of 0.05 Hz and a level of 1 V is produced and utilized as a step input to the DC servo motor. It is worth noting that the square wave generates a step shift of 1 V in either direction relative to the operational input of 5 V, resulting in a step amplitude of 2 V from the original steady level of 4 V. The step input data from CE120 and the corresponding speed sensor output data from CE110 are monitored as plots and recorded in the computer through a TQ CE2000 software, which is compatible with the CE110 and CE120 equipment. Once the first set of data for small inertial load is recorded, a second disc is added in CE110 representing the resulting load as "medium inertial load" and the second set of data is recorded. Finally, the third set of data is recorded by adding a third disc, the resulting load represented as "large inertial load".

The first set of experiments is started for small inertial load, i.e., keeping only one inertial disc in the servo trainer. A square wave step input signal is sent to the DC servo motor. Input signal and the corresponding response are recorded for 30 seconds and monitored through the TQ CE2000 software in the form of a plot of step input and motor response in Volts vs time in seconds. Similarly, medium and large inertial loads are applied by placing a second and third inertial disc to the servo trainer, respectively, and the corresponding input and servo motor response data are recorded and monitored with the help of similar plots. These plots with small, medium, and large inertial loads vs time are shown in Figs.5 (a), (b), and (c), respectively.



(a)



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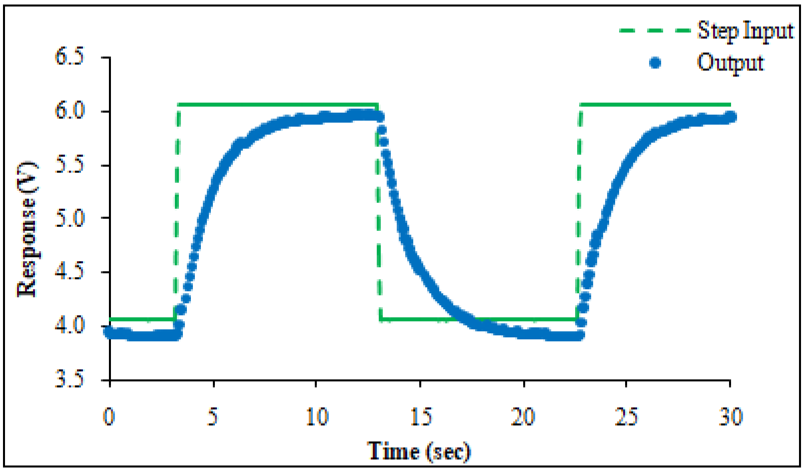

(c)

Figure 5: Step Input and Response for (a) Small Inertial Load (b) Medium Inertial Load, and (c) Large Inertial Load

The time constant *T* of the DC servo motor is calculated based on the concept of the steady - state response using the equation:

$$U \times G_1 = \text{Steady - state value of the response} \quad (1)$$

where *U* is the amplitude of step input and G1 is the proportionality constant or motor gain. The time constant T, according to theory, is the time in seconds the system consumes to attain 63.2 percent of the steady - state response *U* × G1. This concept is adopted to calculate the time constant from the plots using TQ CE2000 software. Figure 6 shows the plot of the step input and response of servo motor vs time pertinent to large inertial load generated in the TQ CE2000 software. The 63.2 % steady - state response is obtained in the software by aligning the bottom edge of a rectangular box with the steady initial horizontal response of the motor while placing the top right vortex of the box on the response curve in such a way that the ceiling horizontal line, which is linked to the rectangular box, is aligned with the maximum steady value of the response curve. The right vertical edge of the box then displays the time constant as shown in Fig.6 for the large inertial load. Similar plots are generated in the same way with small and medium loads. From the plots, the time constant values thus obtained for small, medium, and large inertial loads are 0.56 sec, 1.14 sec, and 1.60 sec, respectively.

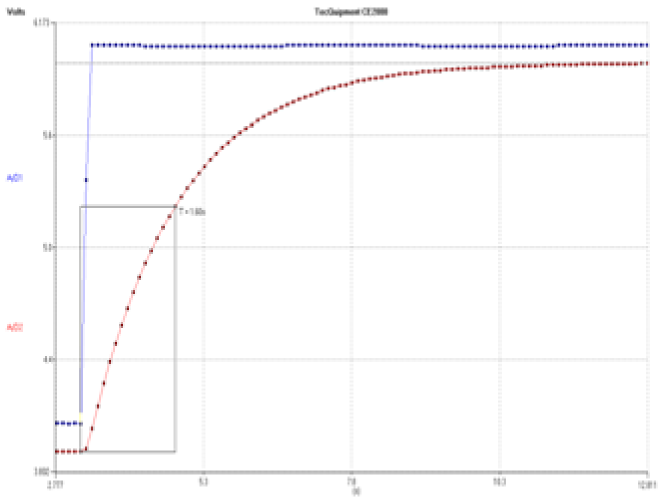

Figure 6: Plot of Steady - State Step Response *vs* Time Generated in TQ CE2000 Software for Large Inertial Load

Fig.7 shows the servo motor output response to step square wave input signal with small, medium, and large inertial loads plotted *vs* time. It can be observed in the figure that the servo motor response time with the small inertial load is the shortest. The Response time increases as the inertial load becomes larger.

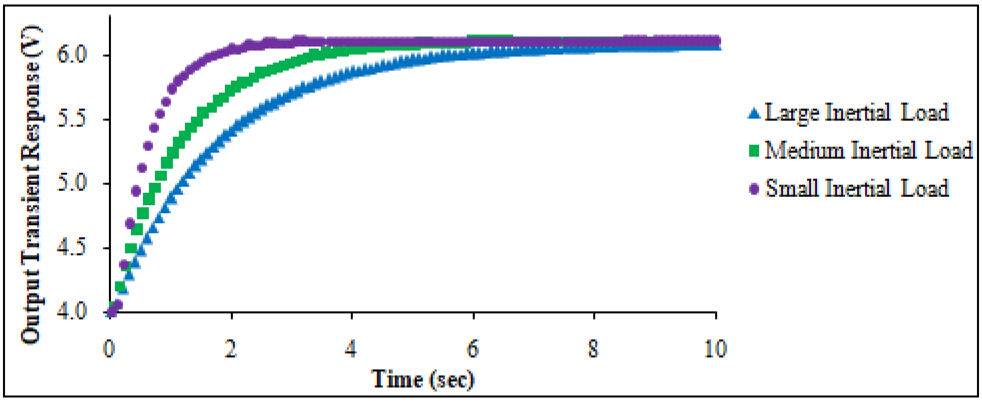

Figure 7: Plot of Servo Motor Steady - State Step Response *vs* Time with Small, Medium, and Large Inertial Loads

3.3. Closed - Loop Transfer Function

By considering the closed - loop transfer function, it is possible to investigate the effect of feedback on the dynamic response of the servo trainer speed controller. From Fig.8, the transfer function expression for the output speed can be written as [10]:

$$y_\omega(s) = \frac{K(s)G_1(s)y_r(s)}{1+K(s)G_1(s)} \qquad (2)$$

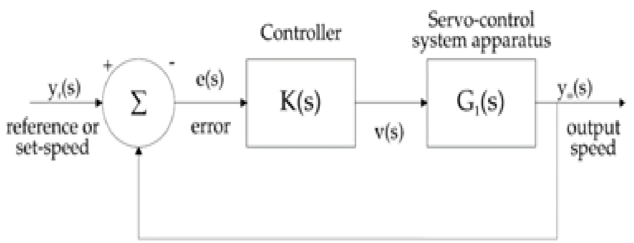

Figure 8: Block Diagram for Velocity Control System [10]

where K is the general notation for controller gain and yr is the potentiometer reference speed signal.

The speed transfer function is given by:

$$G_1(s) = \frac{G_1}{Ts+1} \qquad (3)$$

For Proportional controller, K (s) = k_p is considered. The closed-loop transfer function expression is obtained by combining (2) and (3):

$$y_\omega(s) = \left(\frac{k_pG_1}{Ts+1+k_pG_1}\right) y_r(s), \qquad (4)$$

where k_p is proportional controller gain and y_r (s) is potentiometer reference speed signal transfer function. The above equation can be written as:

$$y_\omega(s) = \frac{G_{cl}}{T_{cl}s+1} y_r(s), \qquad (5)$$

where G_{cl} is the closed-loop gain. T_{cl} is the closed-loop time constant given by [10]:

$$T_{cl} = \frac{T}{1+k_pG_1} \qquad (6)$$

Values of closed-loop time constant T_{cl} are calculated from (6) by substituting the steady-state gain value G_1 = 1.0059 and time constant value for large inertial load T = 1.60, calculated in sections 3.1 and 3.2, respectively. The closed-loop time constant T_{cl} can be expressed as:

$$T_{cl} = \frac{1.60}{1+1.0059k_p} \qquad (7)$$

Finally, the substitution of G_1 and T in (4) yields the final expression of the transfer function of the DC servo motor, expressed as:

$$y_\omega(s) = \left(\frac{1.0059k_p}{1.60s+1+1.0059k_p}\right) y_r(s) \qquad (8)$$

3.4 Transient Response

This section gives an account of the effect of the proportional controller on the closed - loop unsteady behavior of the servo trainer. The controller is characterized by the proportional controller gain k_p. The transient responses of the servo trainer are obtained experimentally for different proportional controller gain values k_p = 0.5, 1, 2, and 4. In addition to this, closed - loop time constants (T_{cl}) are also obtained experimentally and then compared with their theoretical values.

Large inertial load is used in the experiment. The clutch is disengaged and the rear access door is firmly closed. Potentiometer reference speed signal is set to 4 V. Function generator to set to a square wave with a frequency of 0.05 Hz, offset 0 V, level 1. The integral and derivative controller blocks are switched off. The servo trainer is run with the input square wave signal for different values of the proportional controller gain k_p = 0.5, 1, 2, and 4. For each value of k_p, the servo trainer transient response in volt is recorded and real - time plot is obtained in the CE 2000 software. Fig.9 shows typical transient step responses of the servo trainer at the given proportional controller gain values. It can be observed in the figure that increasing the values of k_p results in greater output transient response. From the plot of each k_p, T_{cl} is obtained similarly as explained in section 3.2. The values thus obtained are $T_{cl,\,0.5}$ = 1.16 sec (k_p = 0.5), $T_{cl,\,1}$ = 0.80 sec (k_p = 1), $T_{cl,\,2}$ = 0.56 sec (k_p = 2), and $T_{cl,\,4}$ = 0.37 sec (k_p = 4).

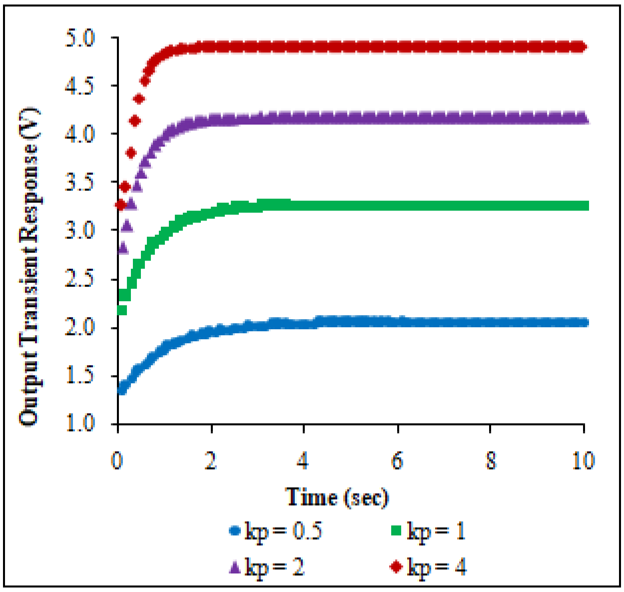

Figure 9: Transient Response of Servo Trainer under Proportional Control of Speed

Finally, the closed - loop time constant values obtained experimentally and theoretically (obtained from (7)) are tabulated against the selected values of proportional controller gain k_p in Table 1.

Table 1: Comparison of Measured Closed - Loop Time Constants with Theoretical Values

Controller Gain (k_p)	***Closed - Loop Time Constant [sec.]***		
	Experimental	*Theoretical*	*% Error*
0.5	1.16	1.1	5.2
1	0.80	0.79	1.2
2	0.56	0.53	5.3
4	0.37	0.32	13.5

Even though time constants measurement from the graph has inherent inaccuracy, the comparison between experimental and theoretical time constants shows good agreement. It can also be noted that at higher values of k_p, the actual and theoretical values of the time constant begins to deviate more because, at higher gain values, the drive amplifier becomes saturated under unsteady conditions.

3.5 Simulation

To simulate the effect of the proportional controller on the closed - loop transient response of the servo trainer, the Simulink toolbox of MATLAB is utilized. The block diagram generated in Simulink comprises of a signal generator, step function, proportional controller, motor servo system, feedback loop, and the output signal. In the block diagram, the servo system is connected with the proportional controller. The error signal, which is the difference between the required and actual system output values, is proportional to the controller output. In other words, a proportional controller's output is equal to the product of the error signal and the proportional gain.

From Fig.10, it is observed that with an increase in the proportional controller gain kp, the time constant decreases. Keeping in mind that the error signal is directly proportional to the time constant, any decrease in the time constant brings down the error as well. Therefore, it can be stated that the proportional controller improves the output by reducing the error. From the plot of each k_p, the closed - loop time constant is obtained similarly as explained in section 3.2. Fig.10 also provides a qualitative comparison of the output transient response between experimental and simulation results for different proportional gain values.

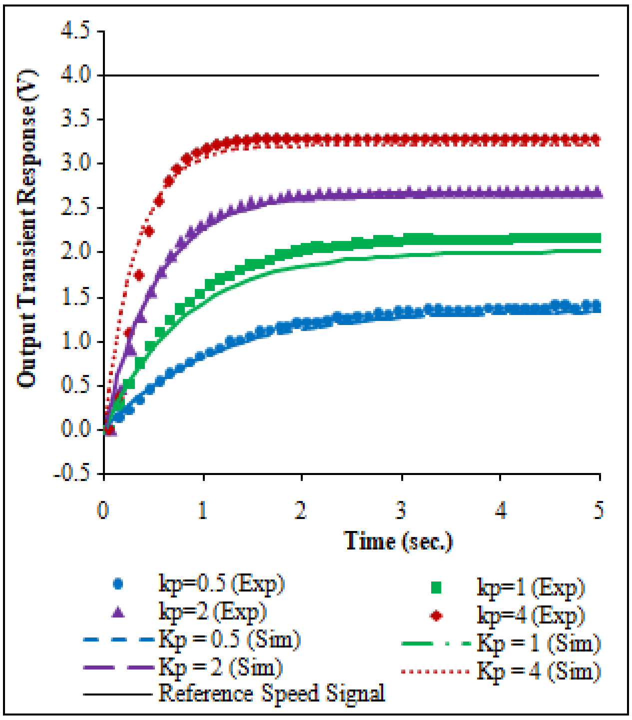

Figure 10: Comparison of Experimental and Simulated Output Transient Responses using MATLAB Simulink Toolbox

Finally, the closed - loop time constant values obtained experimentally and through Simulink are tabulated against the selected values of proportional controller gain kp in Table 2. The actual and simulation values begin to deviate more at higher values of k_p because at higher gain values, the drive amplifier becomes saturated under unsteady conditions.

Table 2: Comparison of Experimental and Simulated Closed - Loop Time Constants using MATLAB Simulink Toolbox

Controller Gain (k_p)	***Closed - Loop Time Constant [sec.]***		
	Experimental	*Simulation*	*% Error*
0.5	1.16	1.108	4.5
1	0.80	0.816	2.0
2	0.56	0.543	3.0
4	0.37	0.332	10.3

In conclusion, we find the advantages of using the proportional controller in reducing the error and decrease the time constant when it is added to the servo motor system. Furthermore, if the proportional controller gain is high, the impact of a load shift on the output will be minimal.

4. Conclusion

The present work gave an account of the DC servo motor characteristics. The work presented the motor drive input to speed sensor output gain characteristics and experimental measurement of the time constant of the DC servo motor. Moreover, the first order DC servo motor transfer function with a Proportional controller was formulated using the experimentally determined values of time constant and steady - state gain. In addition, steady - state errors and unsteady behavior of servo trainer housing the DC servo motor with the proportional controller were also investigated. Finally, the transient response of the servo trainer was simulated and compared with the experimental results.

In the present work, the gain and time constant of the first - order transfer function of the DC servo motor was obtained experimentally. The experimental results showed that the servo trainer (housing the DC motor) output transient response to the step input signal reaches steady - state after some time. The results also show that at a given time, the servo trainer output response increases with proportional controller gain, consequently reducing the closed - loop time constant. The theoretical model with proportional controller thus obtained was simulated using MATLAB Simulink toolbox and compared with the results obtained from experiments for the adequacy of the numerical model. The comparison exhibited good agreement. Hence, the future scope of the current study is that the obtained theoretical and numerical models can be used to analyze the output characteristics of the systems using a proportional controller.

5. Acknowledgments

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Ahmad Jamal obtained his B. S. in Mechanical Engineering in 1998 from the University of Engineering and Technology, Lahore, Pakistan. His M. S. degree in Mechanical Engineering was from King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia in 2002 with a specialization in heat transfer. He secured his Ph. D. degree from McGill University, Montreal, Canada in 2014 in the area of Fluid - Structure Interaction (FSI). His areas of interest are Thermo - Fluid, Fluid - Structure Interactions (FSI), Artificial Intelligence (AI), and Reliability Analysis. He is the author of more than 20 refereed journals and conferences in these diverse areas. His prominent work includes the numerical investigation of natural convection in eccentric annuli. He undertook many research projects in which he investigated, experimentally and theoretically, how a flexible structure interacts with an external axial fluid flow with different degrees of confinement within a closed channel, geometry parameters, and materials; a typical FSI case. His ongoing research includes but is not limited to theoretical and experimental investigation of the system response in external axial fluid flow with different support boundary conditions, eccentricities, and the combined effect of eccentricity and confinement. Other research work includes system response using the PID controller and identifying the rotating machinery faults using Artificial Neural Network (ANN).

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