TEST Engineering & Management

May – June 2020
ISSN: 0193-4120 Page No. 1398 - 1404

The Performance Analysis of PID Controller for Rehabilitation by Using Dynamic Model

Rupal Roy, MM Rashid*, Maidul Islam, Julkar Nayen, Anik Paul, Norsinnira Zainul Azlan

Article Info
Volume 83
Page Number: 1398 - 1404
Publication Issue:
May - June 2020

Article History
***Article Received**: 11August 2019*
***Revised**: 18November 2019*
***Accepted**: 23January 2020*
***Publication**: 10 May2020*

Abstract:

This work investigates the performance of 2DOF (degree of freedom) PID (Proportional Integral Derivative) controller on upper limb rehabilitation robots in order to control elbow flexion and extension with a range of 0 to 115 degree. As simple PID is not able to ensure always promising performance like 0% overshoot with fast rise time and settling time while such a performance from the controller is inevitable for patient's safety and convenience, PID has been modified and renamed as 2DOF PID controller. A new algorithm has been adopted to design 2DOF PID controller. This work has been carried out in simulation in order to measure the initial performance of the system before moving to hardware implementation. MATLAB & Simulink environment has been considered for simulation work. Sinusoidal trajectory is considered to evaluate the performance of the controller. However, the controller performance is satisfactory as both rising time and settling time have been found less than 1 second and overshoot and undershoot have exhibited zero percent.

***Keywords:** PID controller, Upper limb Rehabilitation robot, Elbow Movement.*

I. INTRODUCTION

The applications of exoskeleton robots are soaring up dramatically because of their functionalities and to reach the demand of the users or patients. In several areas where extensive amount of additional force is required to perform any onerous job, these robots have become very popular such as medical [3-5], military [6, 7], industrial [8-10] and consumer [11, 12]. The main function of these robots are to enhance the muscle energy of upper limb or lower limb in an extensive amount in a mechanical form [2].

The exoskeleton robots can be classified into four different types according to their support on the muscles of human body [13]. Lower limb includes several body part such as incorporates hips, thigh, knee and ankle muscles [14] and that's why the supporting exoskeletons are named as Lower limb exoskeleton. Similarly, upper limb exoskeleton supports the shoulder and elbow muscles [15], upper and lower integrated exoskeleton supports both upper limb and lower limb [16]. The fourth type of exoskeleton robots are such type of robots that can be used to support any other part of the body, for instance finger muscles [17].

In literature, researchers show their interest on shoulder, elbow or both together when they want to pay attention specifically on upper limb exoskeleton robot. As these robots are electro-mechanical machine, they require a suitable controller that will assist them to work smoothly, accurately and precisely. As a result, a group of researchers show their interest on different type of control algorithms such as linear, linear and learning based control.

Wen Yu et al consider a linear controller, model-free PID based impedance controller to operate another exoskeleton robot, EXO-UL7 where the parameters are chosen based on human impedance properties [19]. M H Rahman et al introduces with a physio-therapeutic robot, ETS-MARSE in order to overcome the impairment of upper extremity that is controlled by a nonlinear controller, Sliding Mode Control [18]. Apart from that, Hang Su et al propose a learning based controller, electromyogram (EMG) based neural network control approach to control with high accuracy, the motion of the upper limb exoskeleton in accordance with wearer's motion intention [20].

This work introduces a new type of PID, 2DOF PID controller with a view to controlling an existing upper limb exoskeleton system. The main function of this exoskeleton prototype to offer physio-therapy to

May – June 2020
ISSN: 0193-4120 Page No. 1398 - 1404

the patients who suffer from elbow impairment. In this work, the performance of 2DOF PID controller is investigated for its flexion and extension movements with the controller in simulation environment, MATLAB & Simulink where sinusoidal trajectory has been considered as the trajectory. This controller can be implemented on the prototype after satisfactory performance from the simulation work.

II. ANALYSYING REHABILITATION TECHNIQUE

The exoskeleton to move with similar trajectories of the natural human movement trajectories so that it safeguards the movements are comfortable and accurate for the user. From the survey of non-compulsory movements. The derivative of the acceleration can be written as the third order derivative of position x (t):

$$Jerk\ \dddot{x}\ (t) = \frac{d^3x(t)}{dt^3} \qquad (1)$$

A parameter for smoothness can be accomplished for a trajectory x that starts at time t_i and finishes at time t_f.

$$\int_{t_i}^{t_f} (\dddot{x}(t))^2 dt \qquad (2)$$

Minimum jerk trajectory for an end-effector from one point to another is achieved by reducing the integral of squared jerks over time. This lets to the reducing of the function (3).

$$I(x) = \frac{1}{2}\int_o^T (\dddot{x}_t)^2 dt \qquad (3)$$

Here, T= Final time at which target position
x_T = velocity
$\dot{x}_T$ = acceleration
$\ddot{x}_T$ = need to be achieved
x_0 = Initial conditions: initial position
$\dot{x}_0$ = initial velocity
$\ddot{x}_0$ = initial acceleration

The minimum of this function is achieved upon utilizing calculus of variations. Firstly, equation (4) is defined for a trajectory x where δ is a random function such that $\delta_0 = \delta_T = 0, \dot{\delta}_0 = \dot{\delta}_T = 0, \ddot{\delta}_0 = \ddot{\delta}_T = 0$.

$$h(\epsilon, t) = x\ (t) + \epsilon\ \delta(t) \qquad (4)$$

Suppose,

$$F\ (\epsilon) = \frac{1}{2}\int_a^b (\dddot{h})^2 dt \qquad (5)$$

Limiting condition for the trajectory x to reduce I is given as the following:

$$\left.\frac{dF(\epsilon)}{d\epsilon}\right|_{\epsilon=0} = 0 \qquad (6)$$

Integrating by parts,

$$\int_0^T \dddot{x}_t \dddot{\delta}_t dt = \dddot{x}_t \ddot{\delta}_t \Big|_0^T - \int_0^T x_t^{|4|} \ddot{\delta}_t dt \qquad (7)$$

Integrating by parts again

$$-\int_0^T \dddot{x}_t \ddot{\delta}_t dt = -x_t^{|4|} \dot{\delta}_t \Big|_0^T + \int_0^T x_t^{|5|} \dot{\delta}_t dt \quad (8)$$

To maintain the condition in equation (8), the following equation (9) is required,

$$\int_0^T x_t^{|6|} \delta_t dt = 0 \qquad (9)$$

It must satisfy for any random function δ therefore for all t ∈ $(0, T)$

$$x_t^{|6|} = 0 \qquad (10)$$

It means, when the sixth-time derivative of the trajectory function x becomes zero, the minimum trajectory occurs. The well-established solution for this equation is a quantic polynomial i.e., a fifth-order polynomial (11) in which six constants a_0, a_1, a_2, a_3, a_4 *and* a_5 are to be determined.

$$x(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \quad (11)$$

$$\dot{x}(t) = a_1 + 2a_2 t + 3a_3 t^2 + 4a_4 t^3 + 5a_5 t^4 \quad (12)$$

$$\ddot{x}(t) = 2a_2 + 6a_3 t + 12a_4 t^2 + 20a_5 t^3 \quad (13)$$

The first three constants are determined when we take the initial conditions t=0

$$a_0 = x_o \qquad (14)$$

$$a_1 = \dot{x}_0 \qquad (15)$$

$$a_2 = \frac{1}{2}\ddot{x}_0 \qquad (16)$$

The last three constants are obtained when we take the final condition t=T

$$x_T = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + a_5 T^5 \quad (17)$$

$$\dot{x}(T) = a_1 + 2a_2 T + 3a_3 T^2 + 4a_4 T^3 + 5a_5 T^4 \quad (18)$$

$$\ddot{x}(T) = 2a_2 + 6a_3T + 12a_4T^2 + 20a_5T^3 \quad (19)$$

In matrix from

$$\begin{bmatrix} x_T - a_0 - a_1T - a_2T^2 \\ \dot{x}_T - a_1 - 2a_2T \\ \ddot{x}_T - 2a_2 \end{bmatrix} = \begin{bmatrix} T^3 & T^4 & T^5 \\ 3T^2 & 4T^4 & 5T^5 \\ 6T & 12T^2 & 20T^3 \end{bmatrix} \begin{bmatrix} a_3 \\ a_4 \\ a_5 \end{bmatrix} \quad (20)$$

$$\begin{bmatrix} a_3 \\ a_4 \\ a_5 \end{bmatrix} = \begin{bmatrix} T^3 & T^4 & T^5 \\ 3T^2 & 4T^4 & 5T^5 \\ 6T & 12T^2 & 20T^3 \end{bmatrix}^{-1} \begin{bmatrix} x_T - a_0 - a_1T - a_2T^2 \\ \dot{x}_T - a_1 - 2a_2T \\ \ddot{x}_T - 2a_2 \end{bmatrix} \quad (21)$$

III. DYNAMIC MODEL

The dynamic equations of motion for exoskeleton mounted on the Newton-Euler method which is utilized to get the equations of motion for each joint of the exoskeleton. Here, τ_a is the actuation torque produces by the motor unit, τi is the torque produced by inertia, τ_g is the torque due to gravitational forces, τ_f is the friction torque due to the user's limb movements as shown in equation (22).

$$\tau_a = \tau_i + \tau_g + \tau_f \quad (22)$$

Torque generated by Coriolis and centrifugal effects is smaller due to the exoskeleton drives at low velocities and can be negligible

The torque output of the brushless DC motors used in the exoskeleton joints According to the equation (23).

$$\tau_m = k_i i \quad (23)$$

Here, τ_m = the output result of torque of the motor

k_t = torque constant

I = electric current

The torque constants for each joint motor in the proposed exoskeleton are given. The gearbox connected to each motor helps so that the output torque is higher when there is lower output velocity. The resulting torque of the gearbox is given.

$$\tau_a = \eta r \tau_m \quad (24)$$

Output toque of the gearbox can be measured using the following Eqn.

$$\tau_a = k_r \tau_m \quad (25)$$

$$k_r = \eta r \quad (26)$$

Here, k_r= gearbox reduction constant

To find the output torque using Equation,

$$\tau_a = k_r k_t i \quad (27)$$

The inertial torque an exoskeleton consummates which is calculated by the following Equation (28),

$$\tau_i = \sum_S^N I_S \times \propto \quad (28)$$

Here, I_S= inertia tensor of the segment s at the joint coordinate system

α = angular acceleration of the joint

N= total number of segments acting on the joint

The parameters regarding inertia of the exoskeleton and the segments of the upper limb are illustrated in.

Table. 1. Joint upper limb angle (Degrees)

Joint	Range	
Shoulder	q1 q2 q3	$(-25^0,80^0)$ $(-140^0,25^0)$ $(-70^0,80^0)$
Elbow	q4	(00,115)
Forearm	q5	$(-90^0,90^0)$

The mass, center of mass and inertia tensor at the center of mass for every robotic segment are achieved from a CAD model of the 5-DOF exoskeleton in SolidWorks. Values of a regular adult are achieved from the literature for the parameters of the human upper limb parts (3). The wrist joint is supposed to be rigid at the normal anatomical position in the model is shown in figure

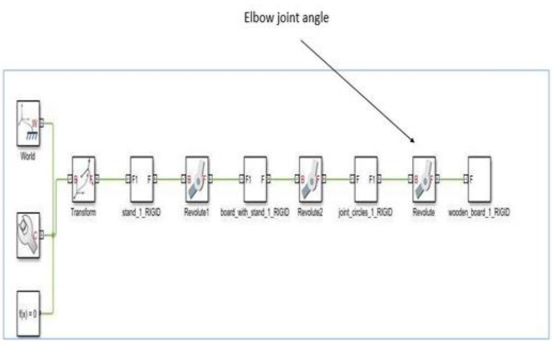

Figure.1. Simulink design of elboe joint angle

The figure shows Simulink block diagram of the revolution of the intertie tensor is achieved by using a homogeneity transformation and the elbow joint angle the figure illustrates the function of the elbow joint model which is the segment and the corresponding arm increases rapidly. Compared to the segment itself, the arm movement is less intensive. On the contrary, accelerations that the forearm produces may not be well designed as movements are certain, it can also contribute a part of the estimation error between the joint coordinate system which is shown in equation

$$I_R = R I_m R^T \tag{29}$$

Here, I_R= inertia tensor that rotated into the orientation of the joint coordinate system
I_m= inertia tensor at the segment's center of mass in the segment's coordinate system
R= rotation matrix related to the segment coordinate system to the joint coordinate system

Now, translation of the inertia tensor includes utilizing the parallel axis theorem (30),

$$I_T = I_m + m[(P_m^T P_m)I_3 - P_m P_m^T] \tag{30}$$

Here, IT= inertia tensor that translated into the origin of the joint coordinate system
m = mass of the segment
Pm= displacement vector from the center of mass of the segment to the origin of the joint coordinate system
I3= the 3×3 identity matrix
Finally, the inertia tensor of a segment regarding the joint coordinate system can be achieved by applying rotation first and then the translation:

$$I_s = R I_m R^T + m[(P_m^T P_m)I_3 - P_m P_m^T] \tag{31}$$

By combining the equation with the function of the elbow joint, which proposes the movement of the upper limb in the Figure 2, the algorithm seems to work well with extremely low deflection accuracy and a high movement estimate, demonstrating the feasibility and effectiveness of the proposed capture and motion analysis algorithm.

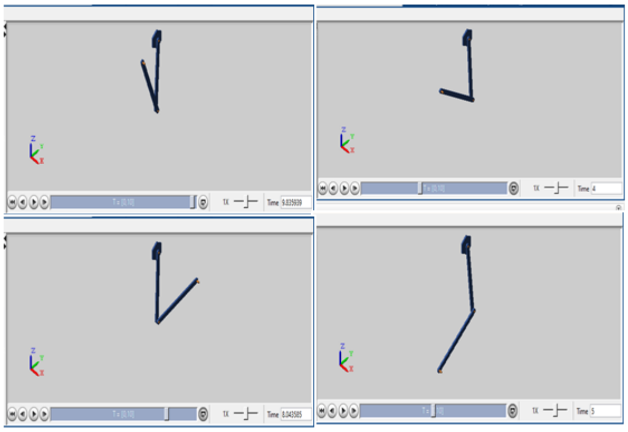

Figure. 2. Dynamic Model of human upper extremity

The movement of the segment which is the misalignment of coordinate frames. Although the source of the coordinate frame is not completely compatible with the global framework used in the proposed model, it can also bring some difference in the estimate between the common function. The proposed upper limb motion capture algorithm has been extensively tested by different movements of the four subjects. The precision of the proposed movement design of the upper end was taken into account in the exterior design.

IV. CONTROLLER DESIGN:

For this experiment, 2DOF PID controller has been considered in order to obtain some extra advantages like unwanted disturbances and smoothing the signal appropriately. This PID controller is named as 2DOF because additional algorithms improve the signals before reaching at proportional and derivative part of the controller. The adopted algorithm has been mentioned as followed.

$$P(b.r - y) + I\frac{1}{s}(r - y) + D\frac{N}{1 + N\frac{1}{s}}(c.r - y)$$

Here, P = Proportional gain
I= Integral
D= Derivative
N= Filter coefficient
b = Set point weight for proportional part
c= Set point weight for derivative part

May – June 2020
ISSN: 0193-4120 Page No. 1398 - 1404

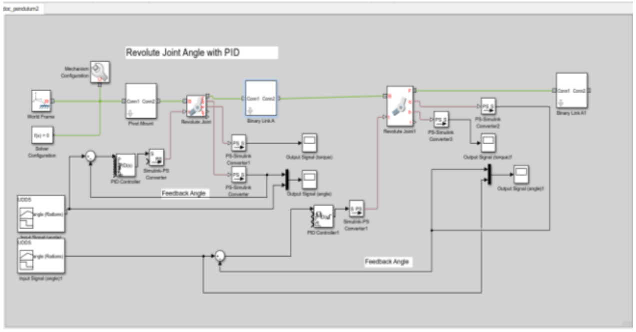

Figure. 3. Siulink model of Elbow Exeskeleton

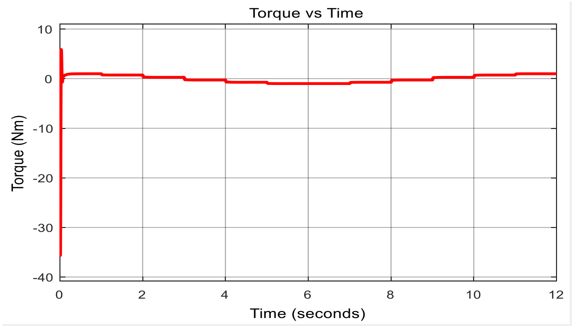

Figure. 4. Torue vs time

V. Simulation Results:

Choosing a suitable gain or weight is a difficult job to find out manually and that's why Simulink Tuning environment has been adopted to choose suitable gains and weights in order to design the controller properly. The controller parameters have been mentioned as follows.

Table 2. Controller parameters

Controller Parameters	Value
P	100
I	9
D	4
N	100
b	1
c	1

Table 3. Controller Performance

Rise Time	0.0168 Seconds
Settling Time	0.1736 Seconds
Overshoot	0%
Undershoot	0%

Table 3 demonstrated the performance of the controller that is quite satisfactory. Here, rise time and settling time is less than 0.5 seconds and overshoot is 0% and undershoot 0% that made the system considerably adjustable with a patient without any jerk or delay.

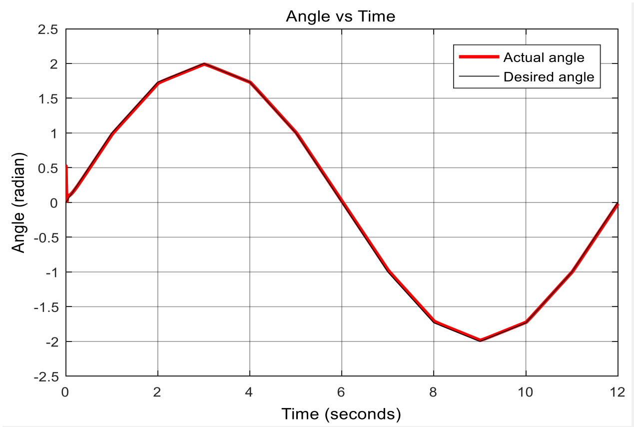

Figure. 5. Upper limb moving angle vs time

VI. CONCLUSION

Upper limb rehabilitation is one of significant research areas in order to design a proper controller. In this work, a 2DOF PID controller has been introduced to operate upper limb. Concurrently, the controller has been validated using hardware performance.

Initially, a proper state-of-art has been proceeded in order to find out the research gaps. Consequently, problem statement guides towards objectives and the main objective of this work is to design and development of a controller. More specifically, in this work, the elbow flexion and extension is a 1 DOF movement and here, 2DOF PID controller has been considered in order to control this 1DOF movement. Specifically, this 2DOF PID offers some advantages like filter specially when there is a possibility of the system to influence by disturbances.

In order to design PID sinusoidal wave have been considered in Simulink environment. In addition, MATLAB signal tuning feature help to choose proper gains and successfully, an overshoot free and short rise time with settling time have been ensured for this controller.

REFERENCES

[1] A. Riani, T. Madani, A. Benallegue, and K. Djouani, “Control Engineering Practice Adaptive integral terminal sliding mode control for upper-limb rehabilitation exoskeleton,” Control Eng. Pract., vol. 75, no. November 2017, pp. 108–116, 2018.

[2] T. G. Sugar et al., “Design and Control of RUPERT : A Device for Robotic Upper Extremity Repetitive Therapy,” vol. 15, no. 3, pp. 336–346, 2007.

[3] C. Yang, J. Zhang, Y. Chen, Y. Dong, and Y. Zhang, "A review of exoskeleton-type systems and their key technologies," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 222, no. 8, pp. 1599-1612, 2008.

[4] C. Carignan and M. Liszka, “Design of an Arm Exoskeleton with Scapula Motion for Shoulder Rehabilitation,” pp. 524–531, 2005.

[5] G. Bao *et al.*, "Academic Review and Perspectives on Robotic Exoskeletons," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 27, no. 11, pp. 2294-2304, 2019.

[6] H. Kazerooni, K. M. Fearing, and W. Y.-W. Tung, "Exoskeleton support mechanism for a medical exoskeleton," ed: Google Patents, 2019

[7] H. A. Almeida *et al.*, "Additive Manufacturing Systems for Medical Applications: Case Studies," in *Additive Manufacturing–Developments in Training and Education*: Springer, 2019, pp. 187-209.

[8] H. P. Crowell, J.-H. Park, C. A. Haynes, J. M. Neugebauer, and A. C. Boynton, "Design, Evaluation, and Research Challenges Relevant to Exoskeletons and Exosuits: A 26-Year Perspective From the US Army Research Laboratory," *IISE Transactions on Occupational Ergonomics and Human Factors*, pp. 1-14, 2019.

[9] K. Kawaharazuka, S. Makino, M. Kawamura, Y. Asano, K. Okada, and M. Inaba, “Online Learning of Joint-Muscle Mapping using Vision in Tendon-driven Musculoskeletal,” vol. 3766, no. c, pp. 1–8, 2018.

[10] M. B. Näf, A. S. Koopman, S. Baltrusch, C. Rodriguez-Guerrero, B. Vanderborght, and D. Lefeber, "Passive back support exoskeleton improves range of motion using flexible beams," *Frontiers in Robotics and AI*, vol. 5, p. 72, 2018.

[11] C. J. Walsh, K. Endo, and H. Herr, "A quasi-passive leg exoskeleton for load-carrying augmentation," *International Journal of Humanoid Robotics*, vol. 4, no. 03, pp. 487-506, 2007.

[12] M. Fontana, R. Vertechy, S. Marcheschi, F. Salsedo, and M. Bergamasco, "The body extender: A full-body exoskeleton for the transport and handling of heavy loads," *IEEE Robotics & Automation Magazine*, vol. 21, no. 4, pp. 34-44, 2014.

[13] J. M. Adarraga, "Safety and control exoskeleton for snow skiing," ed: Google Patents, 2011.

[14] Z. Li, H. Xie, W. Li, and Z. Yao, "Proceeding of human exoskeleton technology and discussions on future research," *Chinese Journal of Mechanical Engineering*, vol. 27, no. 3, pp. 437-447, 2014.

[15] H. Lee, W. Kim, J. Han, and C. Han, "The technical trend of the exoskeleton robot system for human power assistance," *International Journal of Precision Engineering and Manufacturing*, vol. 13, no. 8, pp. 1491-1497, 2012.

[16] A. J. Young and D. P. Ferris, "State of the art and future directions for lower limb robotic exoskeletons," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 25, no. 2, pp. 171-182, 2016.

[17] G. Fazekas, M. Horvath, T. Troznai, and A. Toth, "Robot-mediated upper limb physiotherapy for patients with spastic hemiparesis: a preliminary study," *Journal of rehabilitation medicine*, vol. 39, no. 7, pp. 580-582, 2007.

[18] T. Takubo *et al.*, "Integrated limb mechanism robot ASTERISK," *Journal of Robotics and Mechatronics*, vol. 18, no. 2, pp. 203-214, 2006.

[19] P. Agarwal, J. Fox, Y. Yun, M. K. O’Malley, and A. D. Deshpande, "An index finger exoskeleton with series elastic actuation for rehabilitation: Design, control and performance characterization," *The International Journal of Robotics Research*, vol. 34, no. 14, pp. 1747-1772, 2015.

[20] M. H. Rahman, M. Saad, J. P. Kenné, and P. S. Archambault, "Nonlinear sliding mode control implementation of an upper limb exoskeleton robot to provide passive rehabilitation therapy," in *International Conference on Intelligent Robotics and Applications*, 2012, pp. 52-62: Springer.

[21] Q. Wu, X. Wang, F. Du, and R. Xi, “Modeling and position control of a therapeutic exoskeleton targeting upper extremity rehabilitation,” vol. 0, no. 0, pp. 1–14, 2016.

AUTHORS PROFILE

Rupal Roy, Mechatronics Engineering, International Islamic University, Kuala Lumpur, Malaysia, rupal.roy@live.iium.edu.my.

MM Rashid*, Mechatronics Engineering, International Islamic University, Kuala Lumpur, Malaysia, mahbub96@gmail.com

Maidul Islam, Mechanical Engineering, International Islamic University, Kuala Lumpur, Malaysia, mislam.dipu@gmail.com

Author-4
Photo

Julkar Nayen, Mechatronics Engineering, International Islamic University, Kuala Lumpur, Malaysia, md.julkarnayen@gmail.com

Anik Paul, Mechanical Engineering, Chittagong University of Engineering & Technology, Bangladesh, anikcuet09@gmail.com

Norsinnira Zainul Azlan, Mechatronics Engineering, International Islamic University, Kuala Lumpur, Malaysia, sinnira@iium.edu.my