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DC motor PID control system for tamarind turmeric herb packaging on rotary cup sealer machine

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Abstract

The end of this research is to find PID tuning value on the packaging automation process using the PID method. By finding the most suitable PID tuning value, a fast packaging process is obtained. Herbal ingredients in herbs that are left in the open for a long time tend to be damaged more quickly. So after the production process ends, the herbs must be packaged quickly. With the packaging automation method, the product can be hygienic and does not spoil quickly. One of the most widely and easy-to-use for automation methods in the industry is the PID control method because it can accelerate the system response, stabilize the system to match the setpoint and minimize overshoot. This study will discuss how the design of the PID control system using DC motor transfer function modeling in Matlab and the Second Ziegler-Nichols PID tuning method, the effect of the load on the motor response, and the effect of PID on the production speed. The system was tested with PID tuning values are Kp = 12, Ki = 12,506, Kd = 0.0028785, speed motor 24 RPM and a load of 3,160 Kg produces a good output response are delay time = 0.502 s, rise time = 0.804 s, settling time = 4.023 s, peak time = 133.084 s, Overshoot = 0.125% and Steady State Error = 0%. The effect of PID control on production speed is 83% faster than manual production and 29% faster than systems without PID.

1. Introduction

The packaging machine often used by large industries is the conveyor method, but this method cannot be applied to MSMEs (micro, small and medium enterprises) because it is expensive and requires large electrical power. This condition forces MSMEs to use manual cup sealer machines without continuous automatics. Manual packaging takes a long time and requires several workers so that the productivity of small industries decreases. Based on this background, this research makes a Single Line Automatic Rotary Cup Sealer Machine for MSMEs which has a rotary packaging method with 6 holes automatically continuously. By adopting the working method of beverage packaging machines using straight conveyors, the method is changed to circular or rotary. Machines with the rotary method utilizes the rotation of a DC motor to move cups. However, the dynamic change of beverage load makes the DC motor speed unstable. When all the cups are filled with a drink in the six holes, the speed of the DC motor becomes slow and tends to be unstable. One of the most widely and easy-to-use for automation methods in the industry is the PID control method because it can accelerate the system response, stabilize the system to match the setpoint, and minimize overshoot. The faster the cup is moved, the faster other production processes such as filling and pressing can be done automatically.

In the previous study, the use of PID control was implemented on a quadcopter as an Unmanned Aerial Vehicle (UAV) [1], Multiple motor synchronization [2], Control of Twin Rotor MIMO System [3], BLDC Motor [4][5], 2DOF Rotary Torsion Plant [6][7], Unmanned Agricultural Vehicle [8], Active Magnetic Bearing Rotor System [9], DC Motor Speed Control [10][11] and Marine Diesel Control Speed [12]. The PID control system starts with finding the motor characteristics using transfer function modeling. Where each DC motor will have different characteristics and calculation results of the transfer function [13][14][15][16]. The transfer function will become a plan that will be controlled by the PID Control System in MATLAB [17].The process of tuning the constant value on the PID control can be done by trial error or using the Rule-based tuning method, namely: Ziegler-Nichols [18][19][20][21][22], Chien, Hrones and Reswick [23], Cohen-Coon [24], Kappa-tau, and Lambda. With the tuning, it can be observed the results of the closed loop system response on MATLAB and the tool directly.

From previous research, it can be ascertained that PID control can increase the speed of the DC motor according to the setpoint. Although there have been many studies discussing the PID system on DC motors that provide a PID tuning value with a certain value. The PID tuning value is not suitable to be implemented in the DC motor used in this study. Different types of DC motors and the invention of new engine mechanical designs for Single Line Automatic Rotary Cup Sealer Machine require further research. So in this study will be discussed about DC motor transfer function modeling in Matlab with the Second Ziegler-Nichols tuning method to obtain the PID constant control value. The effect of the load on the DC motor output response, the effect of using a PID control system on a system that works periodically, and the effect of using PID control on production speed in a home industry for tamarind turmeric herb.

2. Research Method

2.1 Tamarind Turmeric Herb Packaging on Single Line Automatic Rotary Cup Sealer Machine

Single Line Automatic Rotary Cup Sealer Machine is a machine designed to carry out the packaging process of tamarid turmeric herb automatically. This machine is targeted for liquid tamarind turmeric herb products packaged in 160 ml cups. This machine can drop the glass, fill the herbal medicine in the cup, transfer the glass, press the packaging, and roll the plastic automatically. The cup transfer method used in this research is the rotary method using a DC motor rotation. DC motor shaft will be connected to a circular iron that has 6 holes. Each hole has a size of 8 cm. The hole will accommodate the cup that must be moved so the filling process and pressing can be carried out. When the herbal medicine filling process is carried out continuously, there will be an increase in the load at 160 ml for each glass that was rotated by a DC motor. Increasing the load will affect the speed of the motor used. So we need a control that can accelerate the speed of the DC motor even though there is a change in load, namely the PID control system for DC Motor speed. The PID tuning value from previous research is not suitable to be implemented in the DC motor used in this study. Different types of DC motors and the invention of new engine mechanical designs for Single Line Automatic Rotary Cup Sealer Machine require further research. The mechanical design to be implemented by the PID control system is shown in Figure 1.

Figure 1. Design of Single Line Automatic Rotary Cup Sealer Machine

2.2 PID Control

A stable system that can maintain the setpoint and is not affected by disturbances such as loads is very necessary for the packaging process of tamarind turmeric herb in liquid form. The liquid will spill more easily if the motor rotation is too fast, the DC motor rotation is unstable and the system gets overshoots. So that the design of the PID control system is very necessary. PID (Proportional Integral Derivative) control is a controller to determine the precision of an instrumentation system with the characteristics of feedback on the system. PID components consist of 3 types, namely Proportional, Integral, and Derivative. All three can be used together or separately, depending on the needs of the controller [18]. PID controllers are very often used in industrial control systems. The transfer function Gc(s) of the PID controller is shown in the Equation 1.

$$Gc(s) = Kp\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{1}$$

With Kp = Proportional Gain, Ti = Integral Time and Td = Derivative Time. If e(t) is the input to the PID controller, the equation of the PID controller can be expressed in Equation 2.

$$u(t) = Kp\ [e(t) + \frac{1}{T_i}\int_{-\infty}^{t} e(t)dt + T_d \frac{de(t)}{dt}] \tag{2}$$

Constants Kp, Ti and Td are the parameters of the controller. It can be seen in the Equation 3.

$$Gc(s) = Kp + \frac{Ki}{s} + K_d s \tag{3}$$

With Kp = Proportional Gain, Ti = Integral Gain and Td = Derivative Gain. In this case Kp, Ki and Kp become the parameters of the control device.

For this reason, to produce output with a fast rise time and small error, it is possible to combine these three control actions into a PID control action. PID (Proportional Integral Derivative) controller parameters are always based on a review of the regulated characteristics (plant). Thus, however complex a plant is, the behavior of the plant must be known before the PID parameter search is carried out. The design of the PID control system begins with knowing the characteristics of the motor by knowing the transfer function modeling on the DC motor used. The results of the transfer function calculation will be simulated using the Matlab application to determine the best PID tuning value using the Second Ziegler-Nichols method. So, we can get the value of Kp, Ki, and Kd which can be implemented directly on the tool. The PID method is designed using a closed-loop system to control the speed of a DC motor in the cup transfer process. The block diagram of the designed control system is shown in Figure 2.

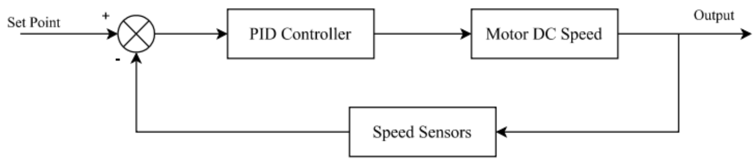

Figure 2. Control Block Diagram

Setpoint is the speed value given to the system to produce a speed according to the speed that is read. The speed data will be processed by the controller to be used as a comparison with the setpoint value and then the control results are implemented in the system. PID is used to adjust the rotation of the DC motor on the tamarind turmeric herb packaging device according to the input feedback and the optocoupler sensor that is read on the cup transfer. The plant regulated by the PID Controller is the DC Motor speed. Where the motor driver will adjust the rotation of the DC motor according to the PID Controller command. Speed sensors are used to detect or measure the speed of a DC motor when moving the cup and as feedback in a closed-loop system. The output of the system is a stable motor speed, then the reading of the optocoupler speed sensor will be adjusted to the setpoint value of the speed value specified via the keypad.

Then the working principle of controlling the speed of the Cup transfer motor on the Single Line Automatic Rotary Cup Sealer Machine is to enter the setpoint value for the desired rotational speed of the Cup transfer motor on the keypad. After the setpoint value is entered, Arduino will process the data by comparing the reading of the DC motor rotation speed variable by the optocoupler sensor with the setpoint value to be determined. PID control in arduino is used to control the rotation of the DC motor based on a predetermined setpoint. The LCD is used as a display when entering the setpoint and the achieved DC motor rotational speed. The comparison of the rotational speed variable and the setpoint will produce an error that makes Arduino issue a signal to control the DC motor's rotational speed. Changes in the rotational speed of the DC motor are carried out automatically with PID control by taking into account the speed measured by the sensor.

2.3 DC Motor Transfer Function Modeling System in Matlab

DC motors can be modeled by a combination of electrical structures and mechanical structures. The electrical structure is a model of the electrical circuit of the armature winding, namely the resistance connected in series with the impedance of the armature winding. The mechanical structure is the moment of inertia in the rotor and the load and friction caused by mechanical movement. A common actuator in a control system is a DC motor. It directly provides rotary motion and, coupled with wheels or drums and cables can provide translational motion [25]. By knowing the characteristics of the motor used in the form of a transfer function, we can perform a simulation to find the best PID tuning values. The schematic circuit for the DC motor model is shown in Figure 3.

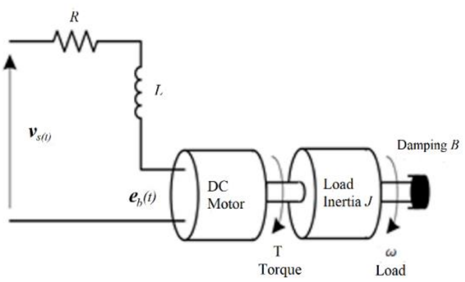

Figure 3. DC Motor Model

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From an electric circuit, a voltage equation can be made according to Kirchhoff's voltage law as stated by Equation 4.

$$V_s(t) = Ri_a(t) + L\frac{di_a(t)}{dt} + e_b(t) \tag{4}$$

With R : Armature Winding Resistance (Ω), L : Armature Winding Impedance (H), $i_a(t)$: Armature Curent (A), $e_b(t)$: Induced Voltage in Armature (V) and $V_s(t)$: Motor Terminal Voltage (V). $e_b(t)$ is the induced voltage which depends on the rotation angle ω(t), expressed by the Equation 5.

$$e_b(t) = k_1 \emptyset \frac{60}{2\pi}\omega(t) \tag{5}$$

With description :
k_1 : Motor dimension constant
Ø : Motor Pole Magnetic Flux (Wb)
$\frac{60}{2\pi}\omega(t)$: Motor rotation (rpm)
$\omega(t)$: Rotor angular speed (rad/s)

If the poles of the motor are permanent magnets, then Ø constant so that the Equation (5) can be rearranged into the Equation 6, with the opponent's EMF (Back EMF) proportional to the spin [26].

$$e_b(t) = K\omega(t) \tag{6}$$

For armature constant $K = k_1 \emptyset \frac{60}{2\pi}$. By substituting the Equation 5 with Equation 6, we can get Equation 7.

$$V_s(t) = Ri_a(t) + L\frac{di_a(t)}{dt} + K\omega(t) \tag{7}$$

For a mechanical structure that refers to Newton's law, the torsion equation is obtained as Equation 8.

$$\tau(t) = J\frac{d\omega(t)}{dt} + B\omega(t) = Ki_a(t) \tag{8}$$

With description:
J : Motor Moment of Inertia (kg.m^2/s^2)
B : Mechanical system damping constant (Nms)

Equation 7 and Equation 8 are transformed in Laplace form assuming all initial conditions are equal to zero, we get Equation 9.

$$V_s(s) = (R + sL)I_a(s) + K\omega(s) \tag{9}$$

So that it is obtained $I_a(s)$ as follows, shown in the Equation 10 and value $T(s)$ shown in the Equation 11.

$$I_a(s) = \frac{V_s(s) - K\omega(s)}{R + sL} \tag{10}$$

$$T(s) = (B + sJ)\omega(s) = Ki_a(t) \tag{11}$$

From Equation 11 it is obtained that the angular velocity $\omega(s)$ is shown in Equation 12.

$$\omega(s) = \frac{KI_a(s)}{(B + sJ)} \tag{12}$$

Next, by substituting the Equation 10 to Equation 12, we get the transfer function between the input voltage $V_s(s)$ and armature current output $i_a(s)$ shown in the Equation 13.

$$\frac{I_a(s)}{V_s(s)} = \frac{Js + B}{(Js + B)(Ls + R) + K^2} \quad \left[\frac{rad/sec}{V}\right] \tag{13}$$

The DC Motor Transfer Function modeling system in Matlab is known in Equation (*13*). The DC motor that will be controlled using PID control is a Cup transfer DC motor. So that calculations can be done to find the required quantities, including:

a. Inertia Moment (J)
The value of the Inertia Moment (J) can be seen in the datasheet 750 g.cm^2 or 0.000075 kgm^2.

b. Mechanical System Damping Constant (b)
Mechanical System Damping Constant (b) can be calculated using Equation 14 and Equation 15. Where Equation 14 is used to calculate the motor torque and Equation 15 is used to calculate the Damping Constant of the Mechanical System (b).

$$T = A \times K \tag{14}$$

With Description are T = DC Motor Torque (N), A = No-Load Motor Current (A), K= Konstanta Armatur (Nm/A)

$$b = \frac{T}{W} \tag{15}$$

With Description are b = Mechanical System Damping Constant (Nm/s), T= DC Motor Torque (N) and W = Velocity (rad/s). Velocity (W) value is obtained from the conversion of the motor speed value of 24 rpm into rad/s. So that the value of $2{,}617994\ rad/s$. From the calculation in Equation 15 obtained the value of $b = 0{,}020987\ Nm/s$

c. Armature Constant (K)
The value of the Mechanical System Damping Constant (B) can be seen in the datasheet 0.0306 Nm/A.

d. Armature Winding Resistance (R)
The value of the Armature Winding Resistance (R) can be seen in the datasheet is 0.25 Ω.

e. Armature Winding Impedance (L)
The value of the Armature Winding Impedance (L) can be seen in the datasheet is 0,6 mH or 0.0006 H.

After getting the calculations at points a, b, c, and e to find the characteristics of the GR 63x55 type dc motor used. Then the characteristics and specifications of DC motors are as follows:

- DC Motor Speed : 24 rpm
- Input Voltage : 12 Volt
- Input DC Current : 8,3 A
- Inertia Moment (J) : 0.000075 kgm^2
- Mechanical System Damping Constant (b) : $0{,}020987\ Nm/s$
- Armature Constant (K) : 0.0306 Nm/A
- Armature Winding Resistance (R) : 0.25 Ω
- Armature Winding Impedance (L) : 0.0006 H

After calculating each required quantity, the transfer function value of the DC motor used in Equation 16 is obtained

$$\frac{I_a(s)}{V_s(s)} = \frac{0{,}0306}{4{,}5e^{-8}s^2 + 2{,}534e^{-5}s + 0{,}003683} \left[\frac{rad/sec}{V}\right] \tag{16}$$

2.4 Tunning PID Control Using Second Ziegler-Nichols Oscillation Method

In the previous sub-chapter, the transfer function calculation has been carried out as shown in Equation 16. So, the next step is to design the Second Ziegler-Nichols PID control. In the plant oscillation method, it is arranged serially with the PID controller. By using Simulink in Matlab, the system can be designed as shown in Figure 4.

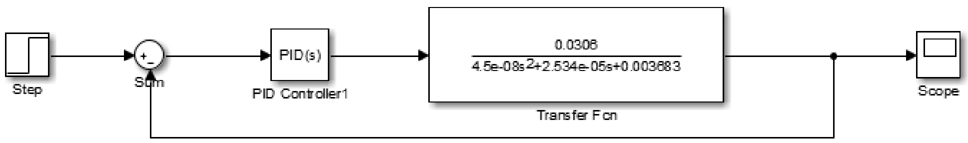

Figure 4. Second Ziegler-Nichols PID System on Simulink

Initially, the Ti worth is about to time and therefore the Td worth is about to zero (Ti =∞ and Td = 0). Then the worth of Kp is accrued step by step from zero to a essential value of Kcr, this may end in a reaction within the system which will oscillate ceaselessly [27]. From the ceaselessly isolated output, the essential gains of Kcr and Pcr is determined, as shown in Figure 5.

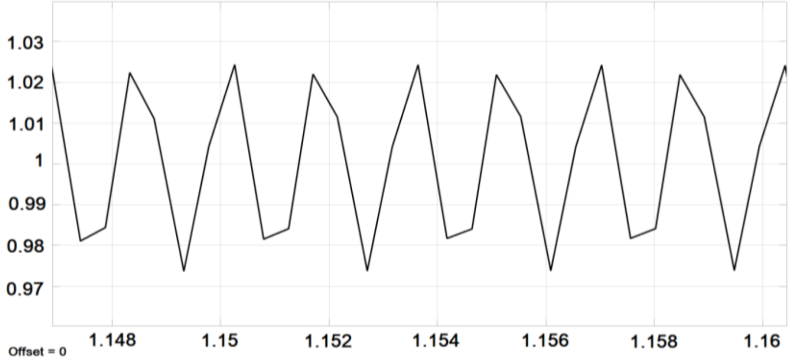

Figure 5. Continuous Oscillation with Period Pcr

Figure 5 is obtained when the Kcr value is 20, so the Pcr value obtained is Pcr = 1.919ms = 0.001919s. Adjustment of Kp, Ti and Td values based on the formula shown in Table 1.

Table 1. Second Ziegler-Nichols Rule

Controller Type	Kp	Ti	Td
P	$0{,}5\ Kcr$	∞	0
PI	$0{,}45\ Kcr$	$0{,}5\ Pcr$	0
PID	$0{,}6\ Kcr$	$0{,}5\ Pcr$	$0{,}125\ Pcr$

Based on Table 1, we can know the values of Kp = 12, Ti = 0,0009595 and Td = 0,0002398. The values of Ki and Kd are obtained according to Equation 17 and Equation 18.

$$K_i = \frac{K_p}{T_i} \quad (17)$$

With Description are K_i = Integral Constant, K_p = Proportional Constant and T_i = Integral Time.

$$K_d = K_p \times T_d \quad (18)$$

With Description are K_d = Differential Constant, K_p = Proportional Constant and T_d = Derivative Time. So, it can be concluded that the design of the PID system using the Second Ziegler-Nichols method obtained the value of Kp = 12, Ki = 12.506 and Kd = 0,0028785.

3. Results and Discussion

3.1 PID control Simulation and Machine Testing

Table 2. PID Control Simulation and Machine Testing

No	Response Performance	Simulation on Matlab		Machine Test Load (Kg)		
		Without PID Control	With PID Control	3	3,160	3,320
1.	Delay Time (td)	0,001 s	0,0005 s	0,502 s	0,512 s	0,514 s
2.	Rise Time (tr)	0,002 s	0,001 s	0,804 s	0,819 s	0,823 s
3.	Settling Time (ts)	0,025 s	0,01 s	4,023 s	2,082 s	2,059 s
4.	Peak Time (tp)	0,004 s	0,0011 s	133,084 s	56,459 s	113,895 s
5.	Error Steady State (%Ess)	11%	0 %	0%	0%	0%
6.	Overshoot Maximal (Mp)	19,6 %	56%	0,125 %	0,125 %	0,125 %

The experiment was carried out in 2 stages are Simulation on Matlab and Machine Test. Simulation result is obtained by simulating transfer function calculation and the PID tuning value using Simulink in the Matlab application. A plan is arranged in such a way as shown in Figure 5 and then simulated with a certain time sampling. By getting figure in scope, we can analyze Delay Time (td), Rise Time (tr), Settling Time (ts), Peak Time (tp), Error Steady State (%Ess), and Maximum Overshoot (Mp). The results of simulation matlab are likened to the ideal condition of a no-load system plan.With the ideal condition, Table 2 shows that the system without PID control never reaches the set point value with a steady state error that is 11%. Table 2 shows if system using PID control can reach the setpoint value, 60% faster system response to reach steady state point because the system without PID can only reach the steady state point at 0.002s.

Machine Test are obtained by measuring the speed of the DC motor using the optocoupler speed sensor and then displayed by sampling a certain time on the Arduino application for 38 seconds or 1 cycle of DC Motor rotation. The data is then converted into a graphic form using Microsoft Excel. The obtained image is then analyzed the parameter inside table. Table 2 shows the speed of the cup shifting DC motor can be maintained at a setpoint of 24 RPM despite system disturbances and even though the system works periodically with a steady state error that is 0%. When the condition of the DC Motor receives a load of 3 Kg (iron plate weight), the system is faster towards the setpoint value of the motor speed was indicated by the value of the rise time are 0,804 s. The rise time value will be slightly longer when the load is 3.160 Kg (iron plate weight and a herb cup) and 3.320 Kg (iron plate weight and two herb cup). The three experiments have the same highest overshoot at the value of 0,125%. PID Control Implementation on the machine proves that the system can maintain the setpoint value, speed up the response and reduce the overshoot value. The addition of the load will affect the response speed in reaching the setpoint, but the difference is not significant.

From previous research [28], it can be ascertained that PID control can increase the speed of the DC motor according to the setpoint. Although there have been many studies discussing the PID system on DC motors that provide a PID tuning value are Ki=4.77554, Kp = 1.3640 and Kd= 0.02499 produces a higher overshoot value of 1.8% in no-load conditions. So that the response obtained in this study is much better.

3.2 PID control Effect on Production Speed

Production speed measurements were carried out in 5 experiments under 3 operating conditions are manual operation, automatic without PID control, and automatic PID control. The tool is operated and the results are calculated for 2 hours. Then the speed is calculated to be cups/hour so that the results are shown in Table 3. Tool performance in accelerating the Tamarind Turmeric Herb Packaging process is very good with an average of 696 cups/hour. So, it can be calculated the tool performance is 83% faster than manual packaging. Manual packaging only produces an average of 116 cups/hour. This is happened because of fluctuating production conditions such as reduced number of workers, work interruptions, and worker fatigue levels.Table 3 also shows the effect of PID control on the speed of the production process, providing 29% faster performance compared to a system without PID which can only produce herbs an average of 494 cups/hour. This is because the influence of the load can affect the rise time value of the DC motor to reach the setpoint. The PID control method can accelerate the system response, stabilize the system to match the setpoint, and minimize overshoot. A system that has this capability can avoid all disturbances that can slow down the speed of a DC motor. The smoother the DC motor rotates, the faster the production activities of the turmeric and tamarind herbal medicine will be. So it is very possible if PID control is used to speed up production.

Table 3. Production Speed Test

No	Operating Conditions	Production Speed (cups/hour)					Average Speed (cups/hour)
		Experiment					
		1	2	3	4	5	
1.	Manual	106	133	112	94	126	116
2.	Automatic (Without PID Control)	515	526	450	474	505	494
3.	Automatic (With PID Control)	687	702	695	708	692	696

4. Conclusion

The results of the PID control design using the value of Kp = 12, Ki = 12,506 and Kd = 0.0028785 as a Cup transfer speed control produces a good response in periodic system because it can maintain the speed according to the specified setpoint, which is 24 RPM and accelerate the initial response in loaded 3,160 Kg, the system response has a delay time = 0.502 s, rise time = 0.804 s, settling time = 4.023 s, peak time = 133.084 s, Overshoot = 0.125% and Steady State Error = 0%. The increase in the load on the system can affect the initial time for the system to reach the setpoint. Effect of PID control on Production speed in Single Line Automatic Rotary Cup Sealer Machine is 83% faster than manual production and 29% faster than systems without PID. So, it can prove that the PID system can be implemented on a system that works periodically, accelerating system response, reducing oscillations, and accelerating production.

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