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Development and Performance of an Auger Type-Metering Device for Variable Rate Fertilizer Applicator

Abdul Azis S, Radite P.A. Setiawan, Wawan Hermawan, Tineke Mandang

Abstract -- A new fertilizer metering system for variable rate fertilizer applicator (VRFA) was designed to get a better performance of the metering device. The auger-type metering device was considered to have a better performance compared to the edge-cell type and other types. The objectives of this study were to do performance test and analysis of the auger-type metering device which was controlled using a proportional–integral–derivative (PID) controller. The auger was rotated by a DC motor, and the motor speed was controlled using a PID controller. The PID tuning was conducted using Internal Model Control (IMC) with Tustin model approach. The first test was conducted to get a calibration equation by measuring the fertilizer discharge at a particular set-point of DC motor speed. The metering device performance test was conducted using stair-step response method. The results obtained showed that the fertilizer discharge has a linear relationship with the motor speed (R2 = 0.998). Stair-step response test results showed that the system can follow any set-point given, either on the step up or step down.

Index Terms— Auger metering device, fertilizer applicator, IMC tuning, PID controller, stair-step response, variable rate.

1 Introduction

Fertilization is one of the stages of paddy rice production with a high enough cost. The production cost per planting season per hectare for wetland cultivation in Indonesia reaches 1.3 million rupiahs or about 10.40% of total production cost [1]. If it is converted to the amount of fertilizer requirement for every ton of grain produced, the rice crops require 17.5 kg of N (equivalent to 39 kg of Urea), P as much as 3 kg (equivalent to 9 kg of SP-36) and K as much as 17 kg (equivalent 34 kg of KCl) [2].

Fertilizing method of paddy fields in Indonesia is still using the manual method by hand broadcasting. This method produces un-uniform fertilization application, both dosage and dispersion pattern. It has impact on the amount of fertilizer used couldn't be predicted and potentially has a negative impact on the soil and environment.

Variable rate fertilizer applicator (VRFA) in the precision farming system is one of technology that can give the right application of fertilization according to land condition and plant needs, both amount and way to applying [4]. Precision farming is a sustainable technology through an information technology approach (GIS, GPS, and VRT) to produce food and fiber [5]. It can improve production efficiency, reduce environmental pollution from agrochemical and increase farmers profits by reducing the use of fertilizers, pesticides, and irrigation [6], reducing the number of nutrients (fertilizers) given to plants so as to benefit the environment [7]. The using of VRFA technology can reduce the pollution that caused by the using of uncontrolled inputs. The technology can also convert conventional technology using electronic control systems [8], improve input efficiency, reduce costs, environment-friendly and produce more uniform crops, both in terms of yield and quality at the same time [9]. One of the precision agricultural indicators was to reduce the use of N fertilizers and improve the efficiency of their use through the identification of site-specific management zones [10].

The VRFA technology includes three main aspects of right dosage, right location and the right time. The right dose would be achieved by using variable rate fertilizer technology (VRFT), right location requires GPS technology, and right time requires soil testing and yield monitors [11]. VRFT is one of the important components of precision agricultural technology [6]. It is an easily adopted component of site-specific management (SSM) technology that can give a treatment of different production inputs on land based on prescription maps or sensor scanning [9].

VRT control incorporates the microcontroller technology as the sensor data receiver, GIS prescription data, and the desired instruction via the hardware and software interface and calculates the desired application rate using a formula or algorithm [12].

PID controls have reliability in response speed, reduced steady state error and isolation. The determination of KP, KI and KD constants was done through tuning PID using internal model control method with Tustin model approach. PID control with IMC method has been used in magnetic levitation system [13], controlling superheated steam temperature [14], unstable system control [15]. The using of PID tuning technique with IMC method can minimize error by comparing the output process with the output of predicted result by using inverse model so that it can be used to optimize PID control [16]. IMC explicitly provides strategies using models from controlled processes to develop appropriate controllers [13].

- Abdul Azis, Phd.Student in Bogor Agricultural University and Lecturer in Hasanuddin University, Indonesi. E-mail : abadzakwaan@gmail.com
- Radite. PA. Seiawan. E-mail: Lecturer in Bogor Agriculture University, Indonesia. Email: iwan_radit@yahoo.com
- Wawan Hermawan, Lecturer in Bogor Agriculture University, Indonesia. Email: wawanfateta@yahoo.com
- Tineke Mandang, Lecturer in Bogor Agriculture University, Indonesia. Email: tineke_mandang_2003@yahoo.com

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One important component of VRFT is a metering device that works to discharge fertilizer from the hopper. There are several types of device metering, such as star-wheel feed, rotating bottom plate, auger-type, loose-fitting auger, edge-cell vertical rotor and belt-type metering device [3].

Auger type metering device has a better performance than other types in terms of easy to control of its rotation and able to avoid the accumulation and compaction of fertilizer in rotor gap as is generally occurred in edge-cell type. This metering system needs to be designed, calibrated and tested its performance, before being applied in a precision fertilizer applicator machine. Therefore, the purpose of this study was to test the performance of auger-type metering device controlled by PID controller, with stair-step response method.

2 RESEARCH METHODS

2.1 Materials And Equipments

In this study, NPK fertilizer with size distribution of 4.76; 2.83; 2.0; 1.41 and less than 1:41 mm of 4%, 54%, 29%, 11% and 1% respectively was used. Its angle of repose was 320. An ARM-Cortex microcontroller types STM32F401 Nucleo was used to control the speed of a DC motor for driving the metering device. It is based on STM32F401RE minimum system with 512k flash, 96k RAM and operates on the 32-bit channel. EMS 30A H-Bridge module was used to drive the DC motor speed that can drive two directions of continuous current up to 30 A at 5.5 Volts to 36 Volts and can operate at frequencies up to 20 kHz PWM. A powerful 12V brushed DC motor with a 100:1 metal gearbox and an integrated quadrature encoder that provides a resolution of 64 counts per revolution of the motor shaft, 220 oz-in (16 kg-cm) torsions was used.

2.2 DESIGN OF METERING DEVICE

Auger and hopper (Fig. 1(a) and 1(b)) were made from stainless and acrylic materials respectively. The dimension of the auger was determined by the formula [8]:

$$Q_t = \pi/4\,({d_{sf}}^2 - {d_{ss}}^2)\, l_P n \quad (1)$$

(a) (b) (c)

Fig. 1 Auger design (a), metering device design (b), and DC motor placement in metering (c)

where: Qt, dsf, dss, lP, and n are the theoretically volumetric capacity, outside diameter, shaft diameter, pitch length and rotational speed respectively. If fertilization dosage, the working width of tool and plant spacing were assumed to be 250 kg/Ha/season, 3 flow plant and 25 cm respectively, by using Eq. 1, it would be obtained the outside diameter, shaft diameter, pitch length, and pitch width of 30 mm, 15 mm, 10 mm and 1.5 mm, respectively. A DC motor was connected on one side of the auger shaft (Fig. 1(c)) as a driving force of the metering device.

2.3 PID Tuning

Controlling the dose of fertilization was done by controlling the rotation speed of the DC motor that attached to the metering device as shown in Fig. 1(c). DC motor speed was controlled by an ARM-cortex STM32F401RE-based control system using PID control. PID tuning step was done to determine the constants of KP, KI, and KD using IMC method with Tustin model approach. The transfer function of a DC motor used a first-order equation model with time delay function [17]:

$$G_P(S) = k/(\tau s + 1)\, e^{-ds} \quad (2)$$

Where: k, d, and τ are gain, time delay, and time constant. To get the simulation equation of control, then the following Tustin model approach with model equation was used [18]:

$$S = 2/T\ (1 - Z^{-1})/(1 + Z^{-1}) \quad (3)$$

Further, a simulation model was obtained [19]:

$$C_n = (k(r_{(n-d/T)} - r_{(n-1-d/T)}) - (1 - 2\tau/T)\, C_{(n-1)})/((1 + 2\tau/T)) \quad (4)$$

Where: Cn and Cn-1, k, τ, T, are current and previous control values, constant of gain, the time constant, time sampling, respectively. r(n-d/T), and r(n-1-d/T) are time delay function of current and previous processes.

The simulation model of Eq. 3 was used to determine control parameters. PID tuning process was done by direct testing with step response method. This method was done by controlling the DC motor in open loop with PWM value of 100 (20%) for 20 seconds with sampling period of 0.2 second. DC motor speed data was measured by an encoder that was installed at the motor shaft. Measurement data was sent to the laptop computer via a serial line and displayed using a Tera-term software. Then it was processed using Eq. 3 and was optimized using a solver device to obtain the control parameters. These three control parameters are used to determine the PID constants using equations [19]:

$$K_P = 1/K\ [(\tau + 0.5d)/(T + 0.5d)] \quad (4)$$
$$K_I = \tau + 0.5d \quad (5)$$
$$K_D = (\tau.d)/(2\tau + d) \quad (6)$$

Further, test performance of PID constants was conducted by controlling the speed of DC motor using a close-loop with set-point of 700 rpm and 1500 rpm. To control the speed of DC motor the following PID control equation was used [20]:

$$C_n = C_{n-1} + K_P\left[(e_n - e_{n-1}) + K_I T K e_n - K_D\left(\frac{e_n - 2e_{n-1} - e_{n-2}}{T^2}\right)\right] \quad (7)$$

where: Cn, En, t, KP, KI, and KD are the controlled values, an error of process, the time sampling and PID constants (proportional, integral and derivative), respectively.

2.4 Calibration test of Metering Device

A calibration test was done to determine the relationship between DC motor speed and mass of fertilizer discharge from the metering device. The calibration process was performed by controlling the speed of the DC motor in close loop with set-point of 700, 900, 1100, 1300, 1500, 1700, 1900 and 2100 rpm respectively for 20 seconds and 0.2 seconds sampling period. Fertilizers discharge was accommodated in a container placed on the top of the digital scales. This scales connected to the laptop computer via serial RS232, so that the data of fertilizer mass could be recorded and displayed in real time. Each set-point treatment was done in three replications.

2.5 Performance Test of Metering Device

A stair-step response method was used on the performance test to know the performance of the metering device by changing set-point suddenly. This method was conducted by controlling the DC motors speeds using a close-loop control to follow the resemble ladder patterns set-point, either step up or step down. Testing was conducted with and without fertilizer. In testing without fertilizer, DC motors was controlled with set-point of 0, 800, 1100, 1400, 1700, 2000 0, 2000, 1700, 1400, 1100, 800, and 0 rpm, respectively. The data of motor speed and operation time were obtained during the test. The test using fertilizer was conducted using set-points of 0, 1158, 1334, 1512, 1691, 1869, 0, 1869, 1691, 1512, 1334, 1158, and 0 rpm, respectively. The data of motor speed, operation time and fertilizer discharge were obtained during this test.

3 RESULT AND DISCUSSION

3.1 PID Tuning

The result of step response and the simulation model was shown in Fig. 2. The graph with dot line is a result of step response test, whereas solid line is simulation model result. The graph trend of the simulation model in Fig. 2 followed the trend of testing result. This indicates that the built model is able to follow the characteristics of the DC motor. From the simulation and optimization results, it was obtained that the control parameters were 674.95; 0.36; 0.1 respectively. Further, using equations (4), (5) and (6) could be obtained the constants of KP, KI, and KD of 0.4013; 0.0988 and 0.0176, respectively.

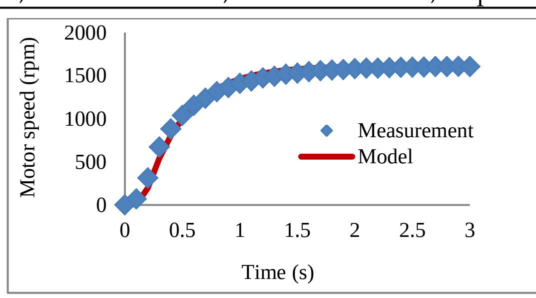


Fig. 2 The test result of step response and control parameters simulations

Fig. 3 showed the results of DC motor speed control at set-point of 700 rpm. The graph showed that the PID constants are reliable enough to control the performance of the DC motor that it is marked by the quick motor response and short time delay. There was a high overshoot of 72.14% at t = 0.4 seconds and it decreased to 13.57% at t = 1.2 seconds. Overshoot was only happened lasts for 1.2 seconds. After that, oscillation occurred around the set-point with the highest oscillation of 6.43% at t = 1.8 seconds, then it decreased to 2.86% at t = 4

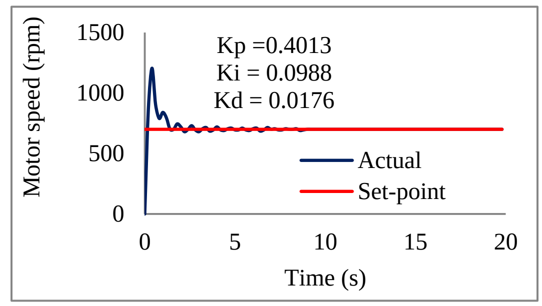
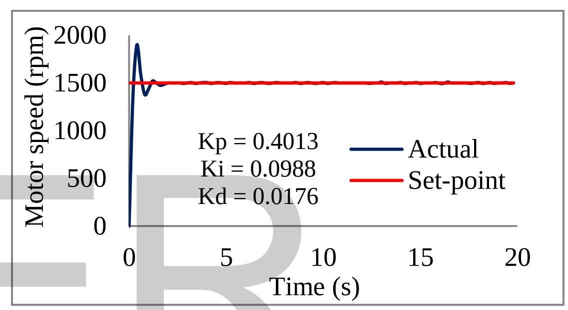


Fig. 3 The results test of PID constants with set-point of 700 rpm (a), set-point of 1500 rpm (b)

seconds and decreased by 1% for 4.6 seconds. The oscillation took place for 7 seconds. After that, the motor speed became constant at the set-point value.



(a) (b)

Fig. 4 The results test of PID constants with set-point of 700 rpm (a), set-point of 1500 rpm (b)

Testing result of PID constants at 1500 rpm was shown in Fig. 4. The test results showed that the motor response wascquick and occurred overshoot was smaller than that of the previous test. The highest overshoot was 26.67% at t = 0.4 seconds.

3.2 Calibration Result of the Metering Device

A calibration was done to find out the correlation between DC motor speeds and the mass of fertilizer discharge from the metering device. The calibration result of metering was shown in Fig. 5. The X-axis represents the speed of a DC motor in

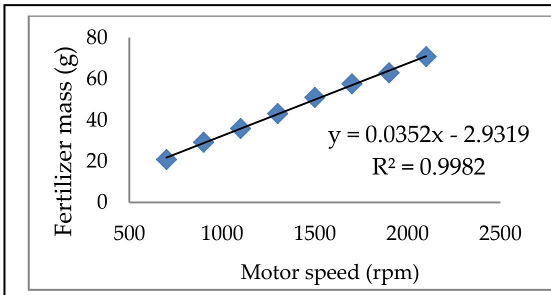


Fig. 5 The calibration result between motor speed and fertilizer discharge

units of rpm, whereas the Y-axis is the mass of the fertilizer discharge in grams. The calibration graph showed that between the DC motor speed and the mass of the fertilizer discharge from the metering device is linearly correlated with the correlation equation and the coefficient of determination of y = 0.035x - 2.931 and R^2 = 0.998, respectively. These results indicated that controlling the dose of fertilization can be done by controlling the speed of the DC motor attached to the auger shaft.

3.3 Performance of the Metering Device

The result of the performance test of the metering device without fertilizer was shown in Fig. 5. DC motors speed followed every set-point changes, either for step up or step down with the rapid response. From the graph, it could also be seen that there were overshoots and oscillation. The highest overshoot occurred at t = 175 seconds, both at set-point of 700 rpm and 2000 rpm. This was due to the position of the previous motor condition from the stationary position, so that the rapid

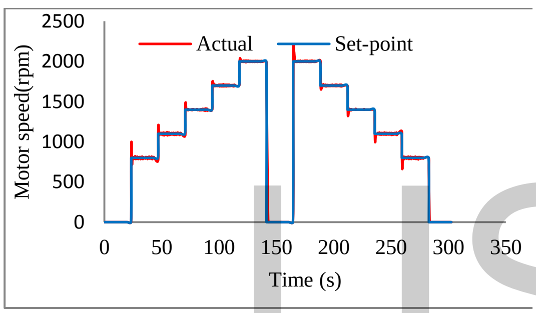


Fig. 5 The test result of stair-step response without fertilizer

response caused the motor speed to pass through the set-point value. In addition, the role of proportional controls will accelerate the system response but will leave overshoot and oscillation. Oscillations were caused by a time delay that occurred on the system. The greater the KP value, the greater the control action for a certain error value, so that the system's chance to pass the set-point value will be greater [21].

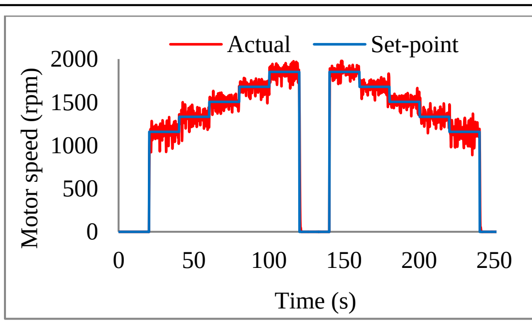


Fig. 6 The test result of stair-step response with fertilizer

The result of stair-step response test using fertilizer is shown in Fig. 6. The test results showed that in general the system could respond and follow the given set-point, either step-up or step-down, but there was occurred overshoot and oscillation significantly. The conditions were caused by several things, such as the DC motor power was not strong enough to overcome the fertilizer burden, the size of fertilizer was not uniform namely ranging from 1.41 mm to 4.76 mm and the auger pitch length only 10 mm so that the fertilizer compaction was easy to occur when the large size fertilizers was accumulated on the auger pitch.

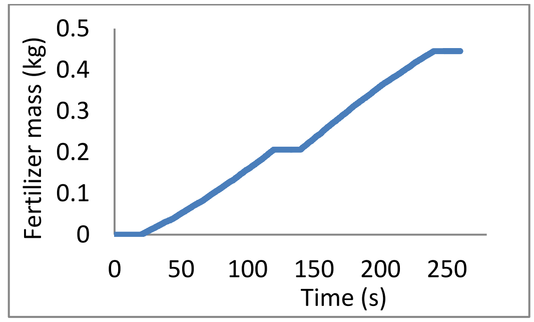


Fig. 7 The test result of stair-step response with fertilizer

In Fig. 7, the mass of the fertilizer discharge followed the DC motor speed pattern. Mass of fertilizer was not increased at both t = 0 – 20 seconds and t = 120 – 140 seconds. The increase of the mass of fertilizer from t = 20 seconds to t = 120 seconds was preceded by a slow increase then significant increase (step-up). This was in contrast to the mass increase from t = 140 seconds to t = 240 seconds, where initially, the mass increase significantly then slowly. Maximum mass of fertilizer for 260 seconds testing achieved to 0.5019 kg.

4 CONCLUSION

The auger-type metering device which was controlled using a proportional–integral–derivative (PID) controller has been developped and tested. The performance test results obtained showed that the fertilizer discharge from the metering device has a linear relationship with the motor speed (R^2 = 0.998). Stair-step response test results showed that the system can quickly follow any set-point given, either on the step up or step down.

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