Modelling and Closed–loop Control System for Magnetorheological Elastomer Linear Actuator

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Abstract. Controlling the actuator in micro to microscale positioning is the challenge in the development of smart material actuator. The design of the existing commercial piezoelectric actuator is limited due to the material properties itself such as brittle which require special packaging and protection in order to avoid creep occurred. Magnetorheological linear actuator representing a relative new class in actuator development. The flexibility in MRE material potentially overcome the limitation of the piezoelectric actuator. This paper presenting the development of closed loop control system including the dynamic model, plant model and PID controller for linear MRE actuator. The control system was successfully developed and the MRE linear actuator able to generate the displacement at certain steady state error.

1. Introduction
The micro component product took place in the development of technology production nowadays. Due to the necessity, the high precision and accuracy of production keep emerging and become high demands. The actuators are closely related to the determination of accuracy and precision in the positioning system in order to achieve high precision and accuracy.

The actuator which uses smart material based was introduced to design the actuator in micro-scale motion [1] including the shape memory alloy, piezoelectric, and magnetorheological materials [2]. The shape memory alloy (SMA) is an alloy that able to restore its original shape after removed the heat [3]. The implementation of SMA as a damper to absorb vibration in the actuator application since their early development in the year 1988 but the operation of the SMA actuator is very complex due to the requirement of both heating and cooling system to produce the displacement.

Thus, piezoelectric material has become the most attractive smart material based for actuator [4] due to its simplicity. The displacement of the piezoelectric actuator deformed by external electric fields [5]. Piezoelectric actuators are promising to create nano-scale displacement [6]. However, the design of the piezoelectric actuator is limited due to the material properties itself such as brittle which require special packaging and protection in order to avoid creep occurred. Therefore, looking for another smart material to overcome the limitation of piezoelectric material is a need.

The magnetorheological (MR) material is also categorised in the smart material group. The displacement of the actuator was varied with magnetic field induced [7].
magnetorheological materials is magnetorheological fluid (MRF) and magnetorheological elastomer (MRE) [8]. The magnetorheological fluid is a type of intelligent fluid in a carrier fluid commonly in oil. The properties of fluid will change to viscoelastic solid when external magnetic was applied. The universal industrial application-based magnetorheological fluid is damper, valve, clutch, and braking system [9].

Besides, the magnetorheological elastomer, which also known as a magnetosensitive elastomer, is the class of solids that consist of the polymer matrix with embedded micro or nano-sized ferromagnetic particle such as carbonyl iron [10]. The mechanical properties can control just like the MRF did when external magnetic was applied. The advantage of MRE had overcome the critical issue in MRF, such as sealing problem, sedimentations, and environment contamination [11]. Additionally, it is expected that the flexibility in MRE material potentially overcome the limitation of the piezoelectric actuator. However, the research regarding of implementation MRE materials in the actuator is remain unclear. Therefore, the objectives of this paper to develop vision closed loop control system for MRE linear actuator including the plant model and PID controller. The signal response was extracted from Arduino serial plotter and replot using Microsoft Excel. The data is needed in the system identification for development of the plant model closed loop control system using MATLAB.

2. Methodology
Figure 1 shows the complete testing setup developed for linear MRE composite actuator using vision-based positioning system.

![Experimental setup](image)

Figure 1. Experimental setup

3. Development of closed loop control system
3.1 Dynamic model of MRE linear actuator
The dynamic model of the linear actuator based on MRE was constructed, and the dynamics response was observed. Before that, the step input was converted to sine waves using the Fourier Transform, as shown in figure 2. The step input was constructed using Arduino in order to produce the displacement response of the MRE linear actuator. Besides, the response time and PWM was set to 200-time frame (8 s) and 250, respectively. This step input was embedded into MD10C motor driver, and then displacement of the MRE actuator was generated.
Meanwhile, figure 3 shows the displacement response of the MRE linear actuator without embedded in the closed-loop control system for different current. This response was recorded using the vision-based positioning system. The graph shows that the response time for steady-state displacement was 5 seconds for 0.34 A, 0.37 A and 4.0 A of currents, respectively. Since the trend of displacement responses were similar to the sine wave input signal regardless of the current. Therefore, this displacement response could be used as an output response in developing the plant model using the system identification tool.

![Figure 3. Displacement responses for 0.34 A, 0.37 A and 4.0 A of current](image)

### 3.2 Plant model for MRE Linear actuator.

A plant is the combination of the process and actuator and commonly referred to with a transfer function. This transfer function was describing the relation between input (sine waves) and output (displacement response) signal of the system. In this work, the transfer function for MRE linear actuator was constructed using system identification tool which available in the MATLAB version R2016b.
Table 1 indicates that the fit percentage for transfer function by varying the number of poles and zeros. The highest fit percentage was 88.56% using 3 and 2 of the number of poles and zero, respectively. This is followed by 80.14% using 3 and 1 the number of poles and zero, respectively. However, the lowest fit percentage measured was 51.59% using 2 and 1 of the number of poles and zero, respectively. The plant models based on the fit percentage and input model (sine waves) was plotted, as shown in figure 4.

Table 1. Fitted parameter.

| Zero | Poles | Best fit (%) |
|------|-------|--------------|
| 1    | 2     | 51.59        |
| 1    | 3     | 80.14        |
| 2    | 3     | 88.56        |

Figure 4. Plant model plots

A mathematical equation was developed to describe the plant model for MRE linear actuator. The degree of the numerator of the mathematical equation indicates the number of zero and the degree dominator indicate the number of poles. Since then, the degree of numerator cannot exceed the degree of the dominator for proper plant model. The equation (1), (2) and (3) represented the mathematical equation of 88.56%, 80.14% and 51.59% fit percentage, respectively. However, the stability of the system unable to describe by using this mathematical equation.

\[
\frac{0.0958 \ s^2 + 0.003642 \ s + 0.001549}{s^3 + 0.3572 \ s^2 + 0.2805 \ s + 0.006333} \quad (1)
\]

\[
\frac{0.0005982 \ s + 0.0001467}{s^3 + 0.1346 \ s^2 + 0.2892 \ s + 0.0005872} \quad (2)
\]
Thus, the number of the pole (x) and zero (o) was plotted, as shown in figure 3.4 in order to observe the stability of the system. The stability of the system was determined to identify the position of the pole and zero in the plot. The system was considered unstable when the plot was in the right half of ‘s’ plane. Since all the plot was in the left half of ‘s’ plane, the system was considered stable. Therefore, 88.56% of the best fit was considered as a plant model for MRE linear actuator, which will use in the evaluation of the closed-loop control system performances.

\[
\frac{0.4123 \, s + 0.03714}{s^2 + 1.753 \, s + 0.1499}
\]  

(3)

Figure 5. Pole and Zero plot

3.3 PID controller
From the best-fitted plant model obtained from previous work, the Proportional-Integral-Derivative controller (PID) was developed to be used as a controller in the closed-loop control system. Therefore, the PID controller was develop using PID tuner in the MATLAB. In the PID tuner, the transfer function was imported to the plant section. The parallel, and time for form and domain, respectively. The PID was tuned until the optimum settling time. The simulation PID controller and without PID controller will be discussed in next sub chapter.

3.4 PID tuner
From the previous work, the constructed plant model of MRE linear actuator was exported to the PID tuner in order to develop the robustness of the closed-loop control system. The PID value was embedded in the plant model to improve the time response and reduce the percentage of the overshoot error in the model. The mathematical equation of the transfer function with PID was described in equation 3.4. This shows that the model of MRE linear actuator was precisely developed and applicable for the actual system.
In figure 6, the transfer function model with and without PID controller was compared in order to observe the amplitude and settling time. The settling time for the PID controller was faster than without a PID controller with the value of 7.87 s and 16.9 s, respectively. Besides that, the amplitude of the PID controller also higher than without the PID controller with the value of 0.6006 and 0.275, respectively. Table 3.3 shows the summary performances of the plant model with and without PID controller. The PID controller has reduced the overshoot response from 12.5 to 7.01. Furthermore, the rise time for the PID system was faster with the value 0.201 s compared to the without PID system, the rise time was 0.391 s.

\[ \frac{0.5083s^2 + 0.01932s + 0.008221}{s^3 + 0.8655s^2 + 0.04737s + 0.01455} \] (4)

According to the results above, the speed of the simulated PID system considers as moderate due to the rise time. Therefore, this control design with PID was possible to be used in the closed-loop control system based on the MRE linear actuator. This is because the high speed will be caused by positioning errors due to the elastic damping but the speed cannot be too low since it is not suitable to be used in the application. Lastly, the closed-loop control system for MRE linear actuator was developed using script code.
in MATLAB. Figure 7 shows the schematic diagram of the complete process. The algorithm of the closed-loop control system was described in Appendix B.

![Figure 7: Closed-loop Control System Diagram](image)

**Figure 7.** Closed-loop Control System Diagram

### 3.5 Closed-loop control system
The closed-loop control system was developed to control the displacement response for MRE linear actuator. This is to test the capability of the PID controller to communicate with the MRE linear actuator in order to produce the desired positioning.

In the evaluation of closed-loop control system for MRE linear actuator, the input displacement magnitude was considered as manipulated input. Figure 8 shows the displacement response of actuator for 10, 20, 30, 40, and 50 μm of displacement magnitude applied to the closed-loop control system.

![Figure 8: Displacement response for difference displacement](image)

**Figure 8.** Displacement response for difference displacement.

The graph shows that displacement response of the MRE linear actuator was increased from 10 μm to 60 μm. However, the settling time was similar with differences input displacement. The displacement rate for the closed-loop control system achieved steady-state was 1.05, 2.61 and 4.63 μm/s, for 10, 20 and 30 μm, respectively. However, the further increment of the input displacement magnitude on the closed-loop control system, the displacement rate remained constant, which was 5.08 μm/s, as shown in figure 3.8.
Figure 9. The displacement response rate for 10, 20, 30, 40, and 50 μm of input magnitude displacement.

On the other hand, it is expected that the displacement response from the control system was similar to the input displacement magnitude. The closed-loop control system accurately generated the 10 μm of the input displacement magnitude. However, there was an error for 20 μm, 30 μm, 40 μm and 50 μm. The highest steady-state errors were 67% obtained from the input displacement of 30 μm. It is followed by 38%, 35%, and 20% for 40 μm, 20 μm and 50 μm, respectively. The steady-state errors were closely related to the magnetic hysteresis of the magnetic materials, which was MRE. Furthermore, the steady-state error increased from 10 μm to 30 μm and then this value was reduced, as shown in figure 3.9. This is because the magnetic density was close to the saturation stage at 60 μm.

Figure 10. The steady-state error rate for 10, 20, 30, 40, and 50 μm of input magnitude displacement.

Lastly, the closed-loop control system was successfully developed for MRE linear actuator, and the performances of the closed-loop control system were summarized in table 3.4. The displacement response was constructed as the input magnitude displacement with steady-state errors. However, the developed system was considered acceptable.
| Displacement (μm) | Settling time (s) | Displacement response rate (μm/s) | Steady State Error (%) |
|------------------|------------------|----------------------------------|------------------------|
| Input            | Output           |                                 |                        |
| 10               | 10               | 12                               | 1.05                   | 0                      |
| 20               | 27               | 12                               | 2.61                   | 35                     |
| 30               | 50               | 12                               | 4.63                   | 67                     |
| 40               | 55               | 12                               | 5.08                   | 38                     |
| 50               | 60               | 12                               | 5.08                   | 20                     |

4. Conclusion
A plant model for the MRE linear actuator was successfully developed using system identification approach. The developed model showed excellent stability with the best-fit percentage of 85.56% from the input response. The system with a PID controller has significantly improved the settling time and amplitude response. The speed of the simulated PID system was moderate, which is suitable to be used in the closed-loop control system for MRE linear actuator. Lastly, the closed-loop control system was successfully developed for the MRE linear actuator. The system was tested with a different magnitude displacement input, and the control system was capable of generating the displacement response with a certain amount of steady-state error.

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