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Analytical and Experimental Study on Actuation Time of Displacement Amplified Electromagnetic Actuator

Hiroyuki Nabae[1], A. Tugay Karaguzel[2], Gen Endo[1], Koichi Suzumori[1]

Abstract— **This paper introduces an analytical study about a particular electromagnetic actuator design with a displacement amplification mechanism by explaining the physical modelling and formulizing actuation time of the actuator in terms of physical model variables, followed by the experimental study about the actuation time on the same electromagnetic actuator. Aiming to increase the stroke of an electromagnetic actuator, increasing the gap between electromagnet and armatures results with a drastic loss on thrust force. Displacement amplification mechanisms are used to increase the stroke of the actuator without high levels of loss in thrust force. For the same load and the final stroke of the actuator, actuation time can be observed to understand the effect of amplification ratio on the actuator. Using the physical and mathematical modelling of the displacement amplified electromagnetic actuator and formulating the actuation time, simulations are presented revealing the actuation time and amplification ratio relation. In the following section, to verify the simulation results and calculated relationship between amplification ratio and actuation time in practice, the design of the experimental setup and methodology of the experimentation were explained. The results of both simulations and experimentations showed that there is an optimum point to increase the amplification ratio while advancing from actuation time for the same load and final stroke of the actuator. The similarity between simulation and experimentation results proved that the value of this optimum point can be formulized and be found in terms of other variables used to simulate the actuator.**

I. Introduction

Actuators with certain requirements such as durability, fast response, efficiency, and accuracy are needed more and needed with better qualifications to be deployed especially at the utilization areas such as precise industrial applications [1], robotics [2] and high accuracy positioning systems [3]. To be able to enhance the performance, accuracy and reliability of the latest actuator involved technology areas, actuators should be improved such a way. It is only possible by adequately understanding the optimization and improvement possibilities surely resulting by choice of the most appropriate actuator type and development of best design. Although there are couple of options like piezo-electric [4], electro-static, thermal, and electromagnetic actuators, electromagnetic ones are at one step ahead with their rapid movement capability, ability of working under harsh environments and easy to use structures. [5] - [9]. Nevertheless, when it comes to electromagnetic linear actuators which employ a structure utilizing magnetic attraction to generate a force parallel to it, displacement length is an issue to overcome [7].

In the study of [10], a design of a displacement amplified electromagnetic actuator is proposed to cope with displacement issue without facing a serious trade-off with thrust force. Further, this actuator is also expected to have an advantage in fast driving [11]. This feature brings great benefit for many industrial or other usages, but has not been experimentally demonstrated yet. It is, therefore, crucial studies for improvements on electromagnetic actuators that a theoretical background is built and an analysis is conducted to explain the relationship between actuation time and displacement amplification ratio. In order to have a coherent work, both the simulations and experiments should be clearly explained together and experiments should involve the appropriate variables and a reliable design to test and understand the correlation between amplification ratio and actuation time.

In this paper, firstly the theoretical background about the linear electromagnetic actuators and their working principle together with physical modelling process of them are explained to clearly understand the effect of displacement amplification ratio on the actuation time of a working actuator. Then it will proceed with the requirements and after, the design of an experimental setup is presented with the aim practically testing and revealing relation between actuation time and amplification ratio simultaneously comparing this relation with analysis of simulations and calculations. After explaining the design of the setup and methodology of the experimentation process, the results are presented with necessary discussions.

II. Theoretical Analysis on Amplification Ratio-Actuation Time Relation

Before proceeding with any experimental approach to investigate the relationship between displacement amplification and actuation time, providing a theoretical background and explaining the physical modelling process as demonstrated at Fig.1 and Fig.2 are necessary. Since this particular study aims to handle experiment in conjunction with theory, it proceeds with the theoretical roots of it.

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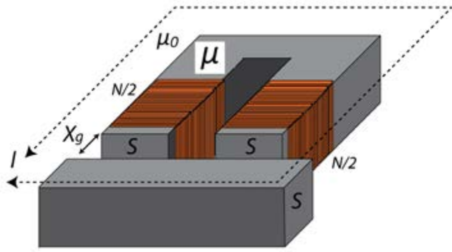


Figure 1. Schematic figure of electromagnetic core

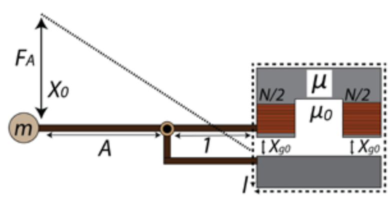


Figure 2. Schematic figure of proposed the principle with a load at the end

This study focuses on an electromagnetic actuator which works on the principle of a magnetic attraction force due to a magnetic flux generated by a winding around an armature and circulating on a closed magnetic circuit. This setup can be simplified to a schematic model carrying two windings on it and including two air gaps to be closed as an actuation. Fig. 1 is showing this simplified demonstration of the analyzed electromagnetic actuator mechanism. It is also effectively illustrating the effect of displacement amplification mechanism. Fig. 1 shows a leverage part on the actuator. In order to conduct a theoretical analysis and various simulations on this actuator system, variables to be considered are also shown at Fig. 1. The air gap length in the system represented as x_g when the total length of magnetic circuit showed with l. The magnetic permeabilities of air and steel showed with μ and μ_o, correspondingly while the cross-sectional area of face is designated by S and total turn number of winding at both sides of U-shaped part is designated by N. Finally, F_G and F_A stands for actuation forces with and without displacement amplification on the system, correspondingly.

As stated and derived previously on the study [2], the resultant magnetic attraction force, acting in the middle point of two air gaps, generated between faces, at this actuator will be;

$$F_A = \frac{aAI^2}{(x+A\bar{x})^2} \tag{1}$$

Where a and $\bar{x}$ representing;

$$a = \frac{S\mu_o N^2}{2} \tag{2}$$

$$\bar{x} = \frac{\mu_o}{\mu} l \tag{3}$$

In order to calculate actuation time of the actuator with a point mass on the end of leverage, the potential energy due to magnetic attraction force between faces of the actuator and the kinetic energy to move the mass, have to be calculated. The potential energy at the very beginning and the representation of the potential energy of the mass at any point along its stroke, will be as follows while the letter x representing the instantaneous position of the mass;

$$U_A = -\int_{\infty}^{x} \frac{-AaI^2}{(x+A\bar{x})^2} \mathrm{d}x = \frac{-q}{x+p} \tag{4}$$

Where p and q representing;

$$p = A\bar{x} \tag{5}$$

$$q = AaI^2 \tag{6}$$

The potential energy difference of the mass at any point;

$$\Delta U_A = \frac{q}{x+p} - \frac{q}{x_0+p} \tag{7}$$

This potential energy difference will transform to kinetic energy of the mass with following equation (8) when $\dot{x}$ representing the instantaneous speed of mass;

$$\frac{m\dot{x}}{2} = \frac{q}{x+p} - \frac{q}{x_0+p} \tag{8}$$

$$x+p = \frac{q}{m(\dot{x}^2+Y^2)} \tag{9}$$

$$Y^2 = \frac{2q}{m(x_0+p)} \tag{10}$$

By knowing and deriving (8), (9) and (10), the final speed of the mass at the end of the stroke will be;

$$\dot{x}_f = -\sqrt{\frac{2q}{mp} - Y^2} \tag{11}$$

In order to proceed, the momentum equation for this system based on moving mass can be written as;

$$F_A \mathrm{d}t = m\mathrm{d}\dot{x} \tag{12}$$

$$\mathrm{d}t = \frac{m\mathrm{d}\dot{x}}{F_A} \tag{13}$$

At this point, by integrating infinitesimal time segment from stationary point to final velocity,

$$T = m \int_0^{\dot{x}_f} -\frac{x+p}{q}\mathrm{d}\dot{x} \tag{14}$$

$$T = -\frac{4q}{m}\int_0^{\dot{x}_f} \frac{\mathrm{d}\dot{x}}{(\dot{x}^2+Y^2)^2} \tag{15}$$

$$T = -\frac{2q}{mY^2}\left\{\frac{\dot{x}_f^2}{\dot{x}_f^2+Y^2} + \int_0^{\dot{x}_f}\frac{\mathrm{d}\dot{x}}{\dot{x}^2+Y^2}\right\} \tag{16}$$

$$T = -\frac{2q}{mY^2}\left\{\frac{\dot{x}_f^2}{\dot{x}_f^2+Y^2} + \frac{1}{Y}\tan^{-1}\left(\frac{\dot{x}_f}{Y}\right)\right\} \tag{17}$$

$$T = \frac{x_0 + A\bar{x}}{I}\sqrt{\frac{m}{2a}}\left\{\sqrt{\frac{\bar{x}x_0}{x_0+A\bar{x}}} + \sqrt{\frac{x_0+A\bar{x}}{A}}\tan^{-1}\left(\frac{x_0}{A\bar{x}}\right)\right\}$$

(18)

When the actuation time T considered, for the positive values of amplification ratio $A > 0$, it is possible to find an optimum point for the relation of T and A, such that it gives $\mathrm{d}T/\mathrm{d}A = 0$. For this condition and a unique numerical solution of (19) leading (20), gives a chance of obtaining a number for optimum A for the known system parameters (21).

$$\tan^{-1}\left(\sqrt{\frac{x_0}{A\bar{x}}}\right) = \frac{\left(\sqrt{\frac{x_0}{A\bar{x}}}\right)^2}{\left\{2-\left(\sqrt{\frac{x_0}{A\bar{x}}}\right)^2\right\}\left\{1+\left(\sqrt{\frac{x_0}{A\bar{x}}}\right)^2\right\}} \tag{19}$$

$$\frac{x_0}{A\bar{x}} \cong 1.1217 \tag{20}$$

$$A_{opt} \cong \frac{x_0}{1.25\bar{x}} \tag{21}$$

The calculation results, which are used to compare experimental data mentioned in the following sections of this paper, are all obtained by using actuation time description given at (18). The actuation time can be obtained by a system using an ON-OFF control which controls the time elapsed between OFF position of the actuator (when the mass is stationary) and the final point of the stroke. Understanding the fact that importance of optimal displacement amplifying ratio (21) is high as the core description of actuation time itself (18) since with the help of $A_{opt,}$ it can be seen that under the conditions for smaller A up to $A_{opt,}$ actuation time decreases with increasing A. When the amplifying ratio passes higher values of A_{opt}, actuation time starts to increase.

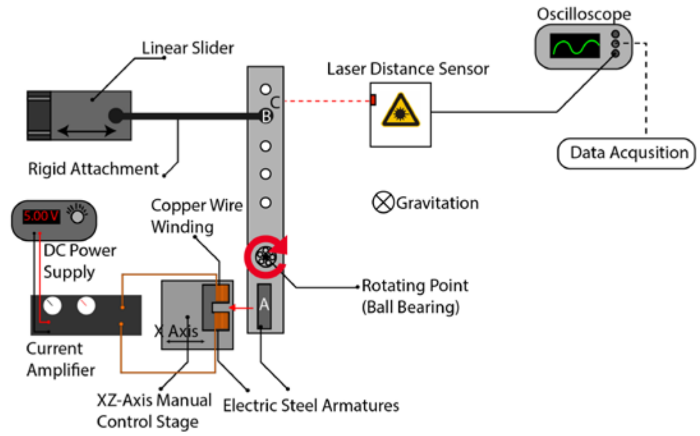


Figure 3. The schematic layout of the experimental setup

III. DESIGN AND METHODOLOGY OF THE EXPERIMENTAL SETUP

According to previous studies, an analytical calculation can be performed to understand the relationship between actuation time and amplification ratio of a displacement amplified electromagnetic actuator. For the purpose of this particular study, an experimental setup should also be built to compare theoretical and practical results. The setup used for this study, is demonstrated at Fig. 2. The most crucial point is to isolate as much variables as possible from the system that, are not involved in the simulations. When it comes to the requirements of the experimental setup, there exist some necessary points. Firstly, in order to act the system with different amplification ratios, amplification ratio of the system should be easily changed. Secondly, in order to keep the total stroke length constant among different amplification ratios, the gap between magnetic armatures should be accurately adjusted. Finally, in order to monitor the mass to be traveled, highly precise and reliable distance sensing element should be employed in the setup.

In this study, the design shown in the Fig.2 was employed. For the sake of simplicity and clarity of the results, a very basic displacement amplification mechanism was employed in the setup, a lever-like structure, fabricated from polyacetal. The magnetic attraction force which provides motion to the mass is obtained from two armatures, cut out from 20 electrical steel (50H270, Nippon Steel & Sumitomo Metal) plates of 0.5-mm thickness, stacked one upon another. The U-shaped armature had 200 wire turns in total, to flow a current in order to magnetize the armature. This armature was placed on a two-

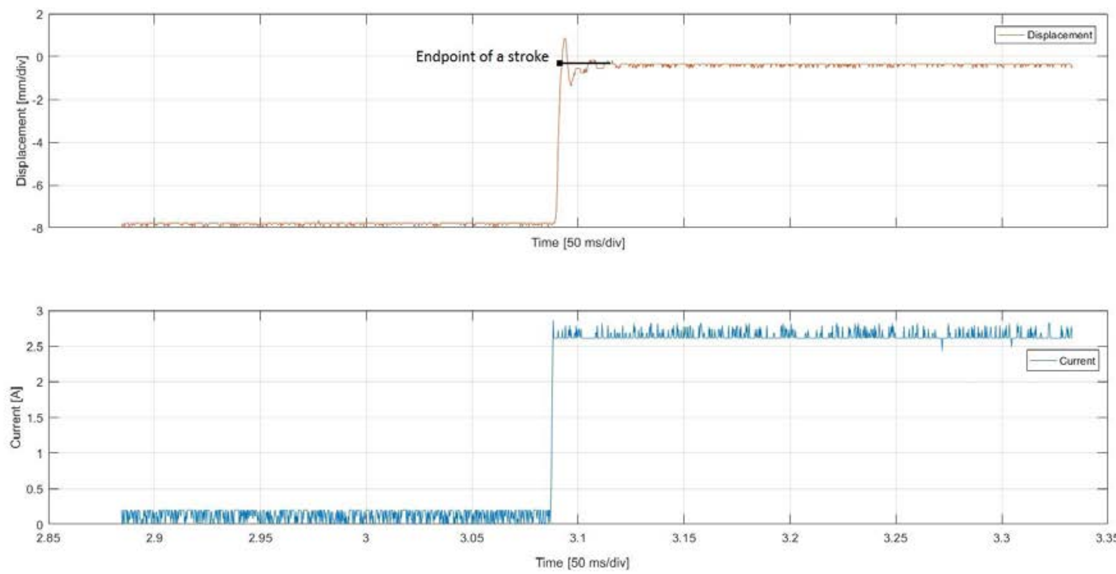


Figure 4. Displacement versus Actuation Time, 2.5A, A=1.54 A and Current versus Time, 2.5A, A = 1.5

axis (XZ) manual linear control stage, on the purpose of changing the gap between electrical steel parts accurately. The lever-like part which was free to rotate around a rotating point (obtained by using a ball bearing), had another steel part on it at one side of rotating point, designated with point A at Fig.2. At the opposite side, there are pre-defined points to attach the load to be displaced (Fig.3, point B). It is important to note here that the setup was constructed horizontally with the aim of eliminating gravitational effect on the system. The mass to be traveled under the effect of magnetic force, was placed on a linear guide.

The displacement measurement was done by a laser displacement sensor (LKG32, Keyence Corporation), focused on a particular point (Fig.3, point C), which had a distance of 83 mm to rotating point of the lever. The position of point C was monitored from the same point throughout the experiment. In order to change amplification ratio, the point where the mass was attached should be changed. Therefore, the point where the laser displacement sensor was focused on, should be change at every trial. In order to avoid this, the lever part was assumed to be ideally stiff with the bending moment on it, and the stroke of every point was calculated by using simply the ratio between the focus point of sensor (83 mm from rotating point) and the distance between attaching point of mass and rotating point.

The current which ran through copper wire winding was supplied and controlled by a DC power supply (Takasago Corp., EX-750L2) and a current amplifier (Takasago Corp., BWS 120-2.5) connected to it. The system was tested on current control mode of this current amplifier on constant current in order to apply a step input to the system. Also, the current was sensed by a Current Probe (Tektronix, TCPA300) which was connected to copper winding. All the displacement and current data were recorded with a digital storage oscilloscope (Agilent Technologies, DSO-X 2004A) and then analyzed with MATLAB-R2016A.

In order to obtain reliable result and deeper understanding on the subject, 5 different amplification ratios were used and the same experimentation process was repeated at 4 different current level. Since there will also be a simulation part for this study, variables were obtained as accurate as possible for this simulation. Table 1 briefly shows the variables for simulations and the values picked for the experimental setup for those variables.

The current flowing on the copper windings, which is the input of the system, was given to the system as a step input as much as possible. That means, the measurement is held on a ON-OFF controlled actuation process. Since the main idea behind this experiment is to observe the relationship between amplification ratio and actuation time, the mass load and stroke length were constant for the system for all measurements. For this reason, the air gap between armatures was adjusted such that the stroke length will be the same with other trials at different amplification ratios. At a current level

TABLE I. PARAMETERS USED IN SIMULATION

Parameter	**Symbol**	**Value**
Facing cross section area of armatures	S	1.6 x 10^{-4} [m^2]
Magnetic Permeability of Electric Steel	μ	450 μ_0 [H/m]
Magnetic Permeability of Air	μ_0	4π x 10^{-7} [H/m]
Turn number of copper winding	N	200 [turn]
Length of the magnetic circuit	l	0.11 [m]
Travel distance of mass	x_o	0.00039 [m]
Mass to be traveled	m	0.2 [kg]
Current on winding	I	1, 1.5, 2, 2.5 [A]
Amplification Ratio	A	0.77, 1.15, 1.54, 1.92, 2.31

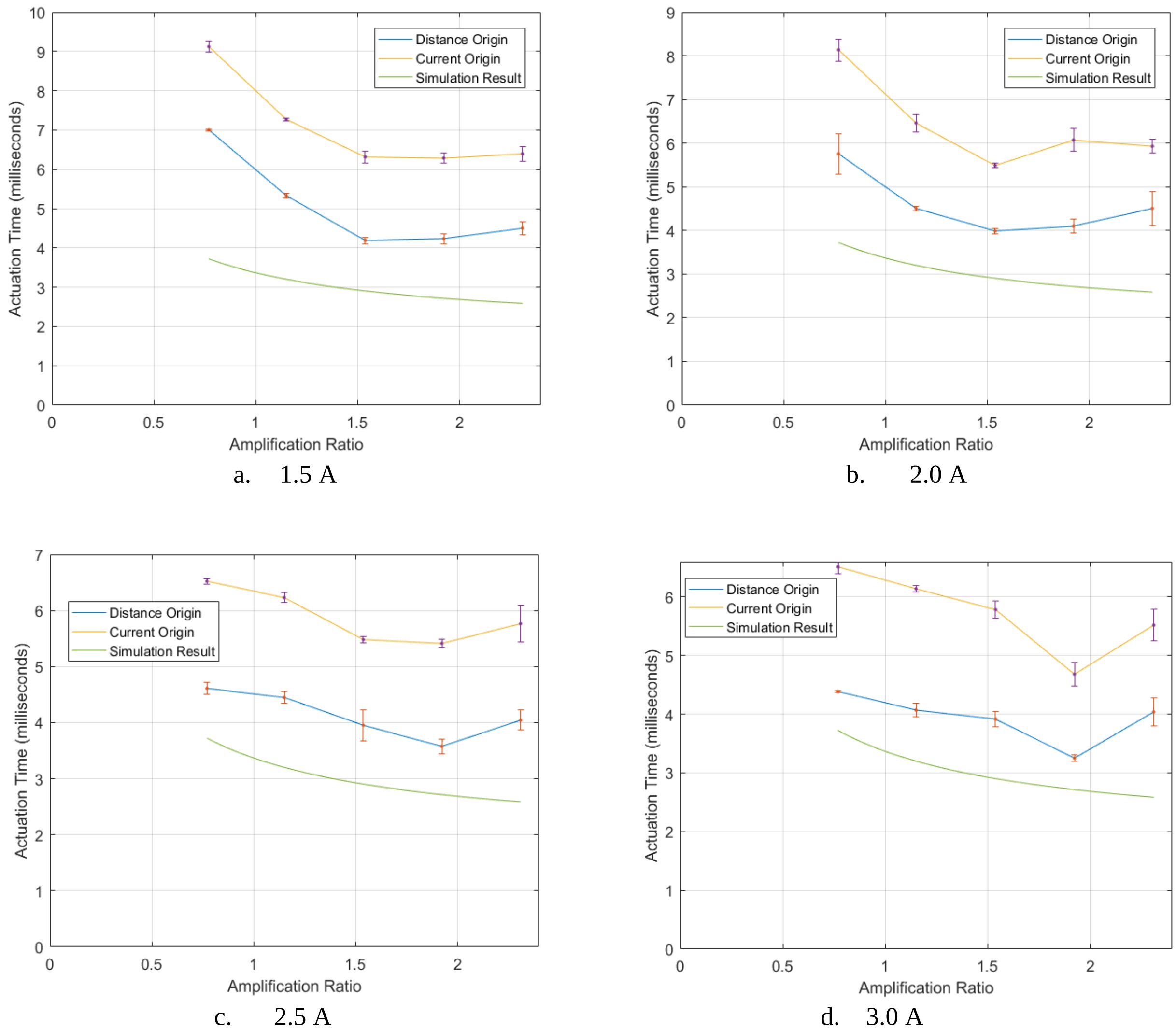


Figure 5: Actuation Time vs Amplification Ratio

of 1.5 A, for 5 different amplification ratios, the actuation process was repeated 3 times at every data point for data reliability. Then, the same process is repeated for 2.0, 2.5 and 3.0 A current levels. All the measurement results were recorded, then analyzed, tabulated and plotted by using a MATLAB program. Fig.4 represents a sample output for a trial at 2.5 Amperes, and amplification ratio of 1.54.

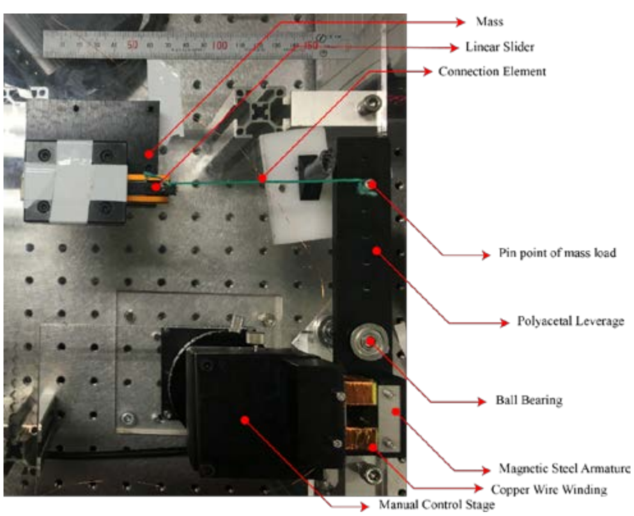
In order to see the actuation time and amplification ratio relationship more clearly, the tabulated data can be plotted as Actuation Time vs Amplification Ratio plots, for different current levels. Also for the sake of a convenient presentation, these plots involve the same plot of simulation result. In the plots, there are 2 different actuation time description; Current Origin and Distance Origin. As a brief explanation, distance origin stands for the time elapsed from the time where the mass starts its travel until the end of stroke where current origin stands for the time elapsed from when the current starts to rise until the end of stroke. The time difference between current origin actuation time and distance origin actuation time mainly caused by the delay on the system. This delay involves several errors majorly inductance of the coils and damping effect on the moving parts of the system. This will surely help to have a deeper understanding and a brief comparison between theory and practice at first look. Following graphs in Fig.4 consist of these plots.

IV. Discussion and Conclusion

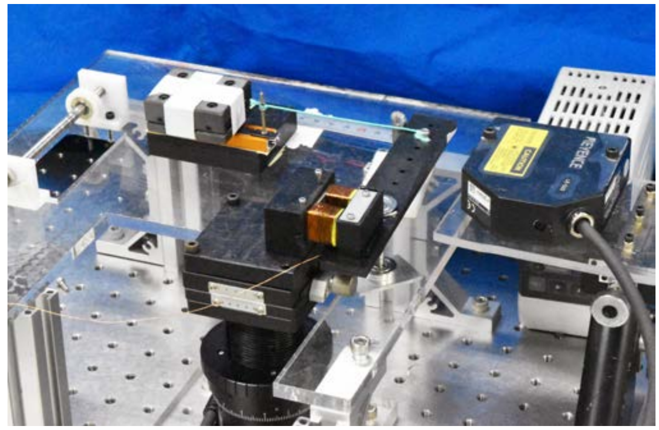
It is a great advantage to see theoretical predictions and practical measurements about the relationship between actuation time and amplification ratio side by side so as to construct a further understanding on displacement amplified electromagnetic actuators. As the analysis in Section II, the results shown in this paper give a brief idea about the effect of amplification mechanisms. As a general trend in the actuation time, it can be seen at Fig.4, with the increasing amplification ratio, there is distinct decrease in the average actuation time values. Moreover, as revealed by experimental results plotted as Fig.4, with a further increase on amplification ratio, this decrement on the actuation time slows down at first, then become reversed. This increasing behavior is noticeable at the figures of experimental results but with different optimal A value, which is depending on the current flowing through the coils. A similar behavior also can be observed at simulation results, with the further increase on amplification ratio, the decrement of actuation time slows down. Fig.4 shows that both the simulation and experimental results allow one to understand and compare theory and practice. In addition, the above mentioned behavioral similarity that makes it possible to have a deeper understanding on amplification mechanism, also improves the confidence for optimizing the ratio for displacement amplification mechanisms. The plots of experimental results at Fig.4 also includes the standard errors which are vital elements of this study. In those figures, the actuation time decrements before the critical A and similarly its increments afterwards, are both much higher than standard error values of data points, which implies that the behavioral relationship between increasing amplification ratio and actuation time showed in this paper which is the final objective of this study, is surely realized. It should be noted that only the variables which takes place in the formulations and simulation, are arranged and adjusted in the experiment setup (Table 1). In order to improve the similarity between theory and practice and to have better and more reliable results, the variables involved in the simulations and adjusted in the experimental setup can be increased.

It is most likely that better optimized electromagnetic actuators will take place in the industrial and research aimed fields with improved efficiency and reliability. The actuators with well-designed amplification mechanisms which are already the pioneering options for precise and small requirements, will be hopefully emerge as outcomes of the research studies in this field. Having a better optimization, deeper understanding and robust control with less unknown and uncertainty on electromagnetic actuators, needs for those small actuators will certainly be satisfied better in the near future.

APPENDIX



A. Overview of the system layout



B. Photo of the experimental setup

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