A pulsated electromagnet to utilization of intermittent power on miniature mechanical devices

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ABSTRACT
In practice, application of the permanent magnet force is a continuous process without intermittence. One application involves magnetic levitation (maglev) systems in which certain amount of magnetic field force is utilized without presence of any significant intermittence. In some instances, however, a continuously periodically pulsated magnetic field force may be needed controlled with a user-entered frequency input. A steel-alloy-core electromagnet generating a continuously periodic pulsation magnetic force has been designed, built, and operated. A rotational actuator device was set up to demonstrate the effect of the created pulsated magnetic force. User-entered and variable frequency control was demonstrated on the actuator. A control diagram incorporating a current source, a contactor, a PLC (Programmable Logic Controller), and a PC (Personal Computer) was included. The magnitude of the presently generated electromagnet force was compared with that of a permanent NdFeB magnet.

Keywords: Electromagnet design, Periodic pulsation, Continuous pulsation, Periodic force

1. Introduction
In the related research, an ionic pumping action was described (Guha et al., 1966) in which saline ions were forced to move at right angles relative to the magnetic field after developing a current flow under applied electric potential. The force created out of the magnetic field and the current exerted a pressure on the ions. When the applied electric potential was modulated with the frequency, a pumping action was obtained. In the other study (Ramadan et al., 2004), a biological separation system employing micro-electromagnets was presented. Force of an electromagnet without any pulsation was used as a preload support on roll-bearing spindle systems (Hwang and Lee, 2010). In their work, a high-preload and low-speed spindle system applied a high current (high electromagnetic force) while a low-preload and high-speed spindle system applied a low current (low electromagnetic force) to the roll-bearing to conveniently hold the spindle in the designated place. Levitation of a high-temperature-superconductivity bulk was investigated under the DC magnetic field with electromagnets (Yoshida and Matsumoto, 2002). The authors (Yoshida and Matsumoto, 2002) in their work used a constant current which produced a constant magnetic field to raise the bulk. Stability of levitation with air gap was studied (Banerjee et al., 2006). A mathematical
modeling was established for the magnetic field force on the soft ferromagnetic plates (Zhou and Zheng, 1997). Speed control of a motor actuator was demonstrated with the proportional-integral (PI) controller (Hannoun et al., 2011). A grabbing device and an electromagnetic valve operating with twin-coil electromagnetic actuators with an anticipated displacement of 0.2mm was detailed in Kallenbach et al., (1999). The work presented there used a permanent magnet design, hence, a continuously periodic pulsation operation was absent. An electromagnetic membrane extensively utilizing a permanent magnet was proposed as a potential pump (Yin et al., 2007). Under a hybrid system design (a mixture of the permanent magnets and electromagnets), an electromagnet deflection in the excess of 50μm was demonstrated on a membrane with 7mm of diameter under small amounts of constant currents (< 500mA). A pulsed operation of the pumping action was yet needed to be established. A pulsed electromagnet design was described in Krichker et al., (1972), however, there was not any detail about the control part.

Bio particle separation was demonstrated through micro electromagnets (Zheng et al., 2014) and an electromagnet undulator design was outlined (Huse et al., 2014).

A continuously pulsed electromagnet as detailed in this work can find applications in operation of the miniature mechanical devices. Unlike a step motor or variable reluctance motor, present electromagnet design provides a translational electromagnet force. So, it is aimed actually to actuate parts along lines. To accomplish this aim, a control algorithm is needed to be set out. In this paper, a continuous periodic pulsation electromagnet was designed, built, and operated. The pulsed electromagnet design proposed in this work is anticipated to find applications, e.g., as an actuator in operation of the flexible muscles in biomedical systems. The other ones include biomedical switches that selectively close or open flow passages. Engineering subjects may include these devices as potential flow valves in fluids systems. In all of these, sizes of flow passages are expected to be small (2 – 5mm in dimension) and ferromagnetic membranes are expected to have a thickness between 100μm and 1 – 2mm.

The purpose of this paper is to design, build, and operate a continuously periodic pulsation electromagnet. This electromagnet will be used to actuate the parts on miniature mechanical devices with the created small amount of magnetic force. It was seen that miniature-size mechanical device operation with the implementation of a continuously periodically pulsed magnetic force has limited space in the literature. Closing and opening of small flow passages is possible with the present pulsed electromagnet. Only very light-weight parts can be actuated instructions. Specific application areas are bioengineering and miniature mechanical devices. Examples to such aforementioned devices were presented from biological to engineering systems. In addition, small-size ferromagnetic particles can be attracted to this periodically pulsed magnetic force.

This work serves to those engineering applications where the ferromagnetic material thickness is very small and the distance between the electromagnet and actuated part is less than the threshold air gap size (L_d). These are actuated parts having sizes on the order of mms.

2. Theory and design

Strength of a magnetic field (B, [Tesla], [T]) is more intense when the created B travels along a ferromagnetic material. If an air gap (L_a) is present (L_a > 0mm) beyond such a ferromagnetic material, then B tends to wade across the air gap resulting in a net fringing effect. The effect is associated with a decrease on the magnetic field force (F) of the electromagnet in compliance with the well-known formulation, 

\[ F = \left( \frac{1}{2} \right) \left( B^2 / \mu_a \right) A \]

where B is the magnetic field (T), \( \mu_a \) is the magnetic permeability of air (H/m), A is the cross-section area for the core of the electromagnet (m^2), and F is the electromagnet force (a measured quantity) (N). An air gap with a considerable-size between an electromagnet and the object it attracts is viewed as a detrimental weakening the electromagnet force (F \( \propto B^2 \)).
$B$ can be estimated from the Ampere’s law, under the assumption of a uniform $B$ inside the electromagnet core, $B = \mu_c N I / L_c$. In this expression, $\mu_c$ is the magnetic permeability of the core material of the electromagnet ($H/m$), $N$ is the number of copper windings around the electromagnet core (–), $I$ is the current applied to the wire (A), and $L_c$ is the length for the core of the electromagnet (m). In acquiring $B$, a linear material ($\mu_c = \text{constant}$) was considered on the core material of the electromagnet. In this paper, $B$ was assessed from the formulation $F = (1/2)(B^2/\mu_c)A$. Permanent NdFeB magnet (for comparison purposes) and the built electromagnet were shown in Fig. 1. In Fig. 2, a picture showing the actuator device and the components of the control circuit was included.

2.1. Thermal considerations

In order to assess any possible heating by the copper wiring around the electromagnet, an energy balance equation in the form, $\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen} = dE_{sto}/dt$, was written where $\dot{E}_{in} \approx \dot{E}_{out}, \dot{E}_{gen} = I^2 R. R = \rho_0 [1 + \alpha (T - T_0)] L_A / A_w$, and $E_{sto} = \rho c_p A_w L_A T(t)$. In the thermal model, heat generation inside the copper wire without lateral surface cooling was considered initially and this resulting differential equation was solved for $T(t)$

$$T(t) = \frac{1}{\alpha} \left[ \frac{16a_1^2 \rho_0}{\rho^{2/3} d^4 c_p} - 1 \right] + T_0$$

(1)

where $T(t)$ is the copper wire temperature ($K$), $T_0$ is the initial copper wire temperature ($T_0 = 293K$), $\alpha$ is the temperature coefficient ($\alpha = 0.0039K^{-1}$), $I = 4.1A$, $\rho_0 = 1.68 \cdot 10^{-8} \Omega \cdot m$, $\rho = 8,800 kg/m^3$, $d = 2 mm$, $c_p = 420 J/(kg \cdot K)$. $T(t)$ from Eq. (1) presented a flat slope giving a copper-wire temperature of $T = 322.4K (49.3{\degree}C)$ at the end of a 1$h$ of operation ($I = 4.1A$). This highlighted a theoretical upper limit for the wire temperature. An increase on $I$ caused a nonlinear and steeper change on $T(t)$. After incorporating the lateral surface cooling (natural convection) through the protective polyester of 1$m$ thickness with $k = 0.2W/(m \cdot K)$, steady-state temperatures of 294.4$K$ (or 21.3$\degree$C) ($I = 4.1A$) and 296.2$K$ (or 23.1$\degree$C) ($I = 6.7A$) were found. The steady-state solution with the lateral surface cooling further lowered the copper wire temperature. Any radiation effect off the lateral surface was not taken into account as the desirable outcome was to present an upper limit for the copper wire temperature itself. An alteration of $N$ (number of windings) did not cause a change on $T(t)$. $N = 100$ was taken in the present design.

The copper wire (Type: HC GR2 210) used in testing has a safely operation temperature of 453.0$K$ (or 179.9$\degree$C) with a maximum current density of 7$A/(mm^2)$. Although it was calculated for $I = 6.7A$ that the copper wire operation was safe, the cables of the current supply experienced the overheating problem. This overheating problem could be overcome by replacing the currently used supply cables with the ones having a higher maximum current density value.

3. Manufacturing

Assemblage of the actuator device and the electromagnet was shown in Fig. 3. Thin pieces of a ferrous metal (each 1$mm$ thick, 1$cm$ wide, and 7$cm$ long) were glued to the PTFE (polytetrafluoroethylene) shaft which was 1$cm$ in diameter and 27$cm$ in length. Out of these ferrous metals, 1$cm$ sections (out of 7$cm$ total length) were bent at right angles and each ferrous metal was glued to the PTFE shaft from their bent 1$cm$ sections. The ferrous metals glued to the rotational shaft were low-carbon iron with a $\mu$ value in the proximity of $10^{-3} H/m$. The middle section of the PTFE shaft (5$cm$ long) was manufactured in rectangular shape to facilitate holding of the ferrous metals attached to it. Then, the PTFE shaft was put on both two holders from the cylindrical ends and the holders were attached to the base board of the same PTFE material. A PTFE material was preferred on the shaft and holders because of its intrinsic low friction
coefficient. Selection of another material for either the shaft or the holders will, as a result, affect the rotational performance of the rotational actuator device. Hence, the present experimental results may be different on other materials.

In construction of the electromagnet, a steel-alloy (60WCrV8) core electromagnet (\(D = 5cm, L_c = 10cm, \mu_c = 10^{-2} H/m\--\text{an estimate value}\)), a copper wire (\(d = 2mm\)), and thin ferrous metals were used. Table 1 lists the values of the electromagnet parameters.

4. Operational principle

The electromagnet operated with a continuously periodically pulsed current creates a continuously pulsed magnetic force. This exerted magnetic force is felt stronger on the closest ferrous metals creating a stronger pulling effect on the closest ferrous metals. The outcome of the force exertion on the ferrous metals is the creation of a resultant torque about the rotational axis of the shaft. The resultant torque causes the shaft to rotate. Figure 4 sketches the operational principle of the rotational actuator with the electromagnet. This rotational actuator was selected for only demonstration reasons. It was aimed in this paper to actuate small ferromagnetic parts in translational 1D line motion.

The rotation results from the fact that during the current-on stage, the closest ferrous metals are pulled up strongest by the electromagnet force while during the current-off stage, these ferrous metals are not pulled up by the electromagnet force. They simply swing idly. The ferrous metals, yet, hold some residual magnetic field in the current-off stage. Following the current-off stage, the weight imbalance of the ferrous metals and the friction force between the shaft and holders cause the shaft to tend to an equilibrium state. At the end of the current-off stage, current-on stage picks up and ferrous metals are pulled up again by the force of the electromagnet. After the current is completely turned off and a considerable amount of time is elapsed, the rotational actuator will rest at an ultimate resting position. The actuator device cannot support a fail-safe-lock position. The rotational actuator device is set up for the demonstration of effect of a continuously periodic pulsation magnetic force.

In the operation of the rotational actuator device, electromagnet force was exerted to the ferrous metals located on the PTFE shaft only and any interaction of the electromagnet force with any permanent magnet force was absent.

5. Control schematic

A PC installed with an application software was used to instruct the desired on and off times (\(f\)) of the current by directly instructing the PLC via an interconnection cable. PLC ensured, through the contactor, the continuously periodic on and off current times (\(f\)) to the electromagnet.

Control schematic of the continuously periodically pulsed electromagnet was included in Fig.5. Further information related to the PLC set-up can be found at the manufacturer’s website under Instruction Sheet of DVP-SS series. Response time of the PLC was about 10ms at the input and output and input voltage was 24VDC at 5mA with a power consumption of 3.5W.

6. Results and discussion

PLC code and ladder diagram are included in Fig. 6. Possible engineering and biological systems were outlined and can be viewed in Fig. 7. To obtain the results in Fig. 8, a small cluster of ferrous metals was suspended in air under the influence of the electromagnet force. After this, these clusters were weighed. This measuring process provided an assessment of the amount of force exerted by the electromagnet, which had decreased with distance from the electromagnet. That is to say, the exerted force with distance from the electromagnet was measured. This type of experimental measurement was resorted to because almost an
identical electromagnet force was expected to be present on a particular ferrous metal of the rotating shaft at an identical distance. The accuracy (±0.02%) of the electronic scale was shown on the measured points in Fig. 8, however, this level of accuracy was almost indistinguishable on the measurement values. Some experimental values were 1.9424N (l = 4.1A.La = 4mm) and 0.1668N (l = 4.1A.La = 1.9cm). The latter average value of 0.1668N (l = 4.1A.La = 1.9cm) produced a representative estimate for the magnitude of the electromagnet force at an identical distance between the electromagnet and the closest ferrous metals. A measured electromagnet force value was a steady-state value for which both intrinsic and extrinsic factors did not vary. To understand the effect of an extrinsic parameter, e.g., any environmental interference was assumed negligible. In addition, substitution of mediums other than air around the electromagnet will yield different F values. Electromagnet force of Fig. 8 was represented with the following mathematical curve-fit expression

\[ F = 0.368181 \cdot L_a^2 - 2.081920 \cdot L_a + 2.826548 \]  \hspace{1cm} (2)

In Fig. 8, permanent NdFeB magnet force measurements \( L_a[3.8cm, 4.6cm] \) were also included to compare with the magnitude of the created electromagnet force \( L_a[0.4cm, 3.5cm] \). The lap between the \( L_a \) ranges of the two measurements was due to very large pulling force of the permanent NdFeB magnet. Such a large pulling force of the permanent NdFeB magnet did not permit any experimental results to be taken below \( L_a = 3.8cm \). Inclusion of the two types of forces (both electromagnet-created and magnet-created) in Fig. 8 facilitated the comparison of the magnitude of the two magnetic force types. In Fig. 8, \( L_a \) is the air gap and \( R^2 \) is the coefficient of determination of the mathematical curve-fitting through the measurement values. The digits in Eq. (2) were kept because of the small size of the value measured. In terms of the parametric sensitivity of the present electromagnet operation, a variation on \( I \) will cause a variation on \( F \). Although it is seen that force generated by the NdFeB magnet is much greater in its magnitude, it lacks significant pulsation of its force. Present electromagnet can provide pulsed operation. \( F \) of Eq. (2) and Fig. 8 is a single measurement value taken at an \( L_a \) although it is more appropriate to use an integral-average \( F \) value on the ferrous metals when \( L_a \) is not constant. Ferrous metals are not stationary but move (continuously rotate) so that there is no one single value of \( F \). Nature of the \( B \) change with \( L_a \) was presented in Fig. 9. Relating the results of Fig. 8 and the electromagnet force equation, \( F = \left(\frac{1}{2}\right) B^2 / \mu \alpha \delta \alpha \), it was possible to obtain the characteristic of \( B \) over \( L_a \). As it can be seen from Fig. 9, \( B \) is very small when \( L_a \) is large. \( B \) in this figure relates to \( F \) of Fig. 8 via \( L_a \) and \( B \) decays from the electromagnet in a fashion as being inversely proportional to the second or third power of \( L_a \). Like each \( F \) value in Fig. 8, each calculated \( B \) value in Fig. 9 represents a single value although \( F \) and \( B \) values change with the distance between the electromagnet and ferrous metals. That is to say, for \( F \) values in Fig. 8 and \( B \) values in Fig. 9, integral-average values over approximate \( L_a \) may be more suitable.

Torque (\( \vec{T} \)) was estimated from the formula

\[ |\vec{T}| = |\vec{L}_{s-m} \times \vec{F}| \]  \hspace{1cm} (3)

where \( |\vec{T}| \) is the magnitude of the torque vector \( (N \cdot m) \) and \( \vec{L}_{s-m} \) is the vector spanning the shaft axis and the tip of a ferrous metal \( (\vec{L}_{s-m} = 6.5cm) \). \( \vec{L}_{s-m} = 6.5cm \) measures the distance between the tip of a ferrous metal and the shaft axis \( (6cm + 0.5cm = 6.5cm) \). Using Eq. (3) with \( I = 4.1A.N = 100.A = 19.635 \cdot 10^{-4} m^2 \), \( L_c = 10cm \), and \( F = 0.1668N(L_a = 1.9cm), |\vec{T}| \) was calculated as \( |\vec{T}| = 1.0840N \cdot cm \). With \( F = 0.1668N \) \( (L_a = 1.9cm), \mu_\alpha = 1.257 \cdot 10^{-6} H/m, \) and \( A = 19.635 \cdot 10^{-4} m^2 \) \( B \) was 0.01461T. \( B \) calculated for the permanent NdFeB magnet with \( L_a = 3.8cm, L_a = 4.0cm, L_a = 4.1cm, \) and \( L_a = 4.6cm, \) were 0.189869662T, 0.154337921T, 0.140898028T, and 0.12633153T, respectively.

A power conversion efficiency \( (\eta_c) \) was given for the rotational actuator device
\[ \eta_c = \frac{|\vec{T}| \omega}{V_I} \]  

(4)

\( \eta_c \) calculated with Eq. (4) was \( \eta_c = 1.95\% \) with \( V = 3.4V, I = 4.1A, |\vec{T}| = 1.0840N \cdot cm, \) and \( \omega = 25.1rad/s (n = 240rev/min) \). \( \eta_c \) is a non-uniform, non-fixed value and varies with \( |\vec{T}|, \omega, V, \) and \( I \).

A power transmission totaling \( P = |\vec{T}| \omega = 0.2724W \) is possible with the present rotational actuator.

In this paper, a rotational actuator device was selected to visualize the effect of the continuously periodically pulsed magnetic force. Other actuator devices of volumetric or planar geometries, as was illustrated in Fig. 7, can also be proposed.

In the experiments, \( f = 5Hz \) with four ferrous metals attached to the rotating shaft provided the most favorable rotational condition. This condition provided the most uniform \( \omega \) for the shaft. With \( f = 5Hz \), the current times were \( 100ms \) (or \( 0.1s \)) on and \( 100ms \) (or \( 0.1s \)) off. Figure 10 shows the idealized on and off times of the current (I). Changing \( f \) to a value other than \( f = 5Hz \) resulted in either as lower, faster, or no rotation of the shaft depending on the angular positions of the ferrous metals. Although \( f \) control was used to set \( \omega \) of the actuator device, it was nevertheless hard to control \( \omega \) precisely. Setting \( f = 1Hz \) and \( f = 2Hz \) with only two ferrous metals being attached to the rotational shaft generated incomplete partial rotations of the shaft and, finally, at \( f = 3Hz \), the shaft was unable to rotate. In fact, at \( f = 3Hz \), the two ferrous metals were in-line with the electromagnet core axis. Table 2 lists the findings of the experimental observations. The results listed in Table 2 reflect some results from a case study. In the experiments, attempts to stabilize \( \omega \) with \( f \) adjustment resulted in unsteady \( \omega \) values, hence, did not permit a graphical picture of \( |\vec{T}| \) or \( P \) with \( \omega \). Although it is technically possible to increase \( f \) through PLC, beyond \( f = 5Hz \) for example, it is impractical to see the result physically on the contactor: Contactor legs run extremely fast and the contactor operation is too noisy at higher \( f \) values (\( f \gg 5Hz \)). Operation with moderate \( f \) values is relatively smoother.

7. Evaluation of the results

In the present paper, a continuously periodic pulsation electromagnet was designed, built, and operated. The pulsed electromagnet operation was demonstrated on a rotational actuator device. In the operational control circuit of the electromagnet, component number is large so the control circuit can be simplified. Running of the contactor (sudden opening and immediate shutting off of the legs of the contactor) in the control circuit can be too noisy to make it applicable in certain environments especially those where quite operation is desired. Continuous periodic pulsation operation of an electromagnet in translational actuation of parts of miniature mechanical devices was aimed. An intermittent magnetic force was created in small amounts. Electromagnet force is proportional to the number of electromagnet windings (\( N \)), \( F \propto N^2 \). A larger \( F \) is possible with a larger-size electromagnet. Specified value of the maximum current flux on the electromagnet windings as well as on the supply cables is an operation constraining issue. Unlike a variable reluctance motor comprised of a stator and a rotor part, present pulsed design provides actuation in translation order. In addition, compared to a variable reluctance motor, the amounts of \( F \) and \( T \) created with the present electromagnet is substantially smaller. The aim of this paper was to actuate small ferromagnetic parts on miniature mechanical devices. Thus, the required \( F \) and \( T \) are not large values.

In this paper, a continuous periodic pulsation magnetic force was achieved while a continuous a periodic pulsation magnetic force was not present. The rotational actuator device incorporating the pulsed electromagnet was shown to generate enough amounts of magnetic force and resultant torque to initiate and then sustain the axial shaft rotation.

A continuously periodic pulsation magnetic force has several prospects in biological and engineering systems which can take the following forms: A limited flexible muscle, a flow blockage agent, an. AND. or
.OR. switches in fluid flow, a flexible ferromagnetic membrane, etc. After setting a suitable value of \( f \), each application can be actuated with the desired effect. Present amount of the electromagnet force, however, can only actuate small parts on miniature mechanical devices. Large amounts of magnetic force are not intended.

Acknowledgement
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References


Nomenclature

Letters

A : Area ($m^2$)
B : Magnetic field ($T$)
c : Specific heat ($J/(kg \cdot K)$)
D : Core diameter of the electromagnet ($m$)
d : Wire diameter ($m$)
E : Energy ($J$)
F : Force ($N$)
l : Current ($A$)
L : Length ($m$)
N : Number of windings ($-$)
n : Revolution per unit time ($rev/min$)
P : Power ($W$)
R : Resistance ($\Omega$)
R : Correlation coefficient ($\%$)
T : Temperature ($K$)
T : Torque ($N \cdot m$)
t : Time ($s$)
V : Volt ($V$)

Greeks

α : Temperature coefficient ($K^{-1}$)
η : Efficiency ($-$)
μ : Magnetic permeability ($H/m$)
ω : Angular velocity ($rad/s$)
ρ : Density ($kg/m^3$)
ρ : Electrical resistivity ($\Omega \cdot m$)

Subscripts

a : Air gap
c : Conversion, core, cross section
f : Frequency
gen : Generation
in : In
out : Out
p : Constant pressure
s − m : Shaft axis to the tip of a ferrous metal
sto : Storage
w : Wire
0 : Initial, reference, zero

Superscript

2 : Denotes ‘Coefficient of determination (%)’
Others

→ : Vectorial
· : Time rate

Fig. 1. Permanent Neodymium (NdFeB) magnet and electromagnet

Fig. 2. Actuator device, electromagnet and components of the control circuit. *UPS* is short for the “Uninterrupted Power Supply”.
Fig. 3. Assemblage of the actuator device with the electromagnet. Sequence is given with A → B → C. 1- Rotational shaft, 2- Thin ferrous metal, 3-Shaft holder, 4- Electromagnet, 5- Base board.

Fig. 4. Sketch illustrating the operational principle of the present rotational actuator outlined in Figs. 2 and 3.

Fig. 5. Control schematic of the continuously periodically pulsed electromagnet: PLC (Delta Electronics Inc., Model: DVP – 14SS11R2) and Contactor (Schneider Electric, Model: LC1 D80M7).
Fig. 6. a) PLC code, b) Ladder diagram
Fig. 7. Some application areas of the continuously periodic pulsation magnetic force as: a) A flexible muscle, b) An .AND. switch on fluid flow, c) An .OR. switch on fluid flow, d) A flexible ferromagnetic membrane as flow restricting element (as a flow control valve which only partially opens the flow passages). In a) through d), ferromagnetic materials are shown with dark shades.
Fig. 8. Electromagnet force \((F): I = 4.1A, N = 100, A = 19.635 \cdot 10^{-4}m^2, L_c = 10cm\). Permanent NdFeB magnet force: \(A = 19.635 \cdot 10^{-4}m^2, 9cm\) of total height.

Fig. 9. \(B\) over \(L_a\) obtained after substitution of the \(F\) values of Fig. 8 in the electromagnet force equation
\[
F = \frac{1}{2} \left( \frac{B^2}{\mu_a} \right) A.
\]

Fig. 10. Illustration for the idealized on and off times of \(I(A)\)
Table 1. Electromagnet parameters

<table>
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<th>Quantity</th>
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<td>$D$</td>
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<td>$d$</td>
<td>2 mm</td>
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<tr>
<td>$N$</td>
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<td>$\mu_c$ (an estimate value)</td>
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Table 2. Effects of $f$ and number of the ferrous metals on the rotational actuator device performance

<table>
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<tr>
<th>$f$ (Hz)</th>
<th>Number of ferrous metals on the shaft</th>
<th>A constant-$\omega$ shaft rotation</th>
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<td>2</td>
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