Experimental Study on a Condition of Rotating a Magnetic Ball by Applying the Pulse Magnetic Field

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Abstract

This paper describes a simulative experiment using a large scale model of a twisting ball magnetic display. One hemisphere of the magnetic ball with the diameter of 6mm is magnetized to "North" and colored white. The other hemisphere is magnetized to "South" and colored black. The electromagnet generates the pulse magnetic field to rotate the magnetic ball by applying the pulse current. As a half rotation is made, the visible color of the ball is inversed. Relationship between the pulse width and the amplitude of the current is studied. As the amplitude of the current is increased, the probability of rotation is increased. Finally the probability reaches 100%. As the pulse width is increased, the amplitude to rotate the ball is decreased. As a result, the following relationship is obtained. As the pulse width becomes one tenth, the correspondent amplitude for rotating the ball becomes double. For example, if the pulse width is 500ms, the correspondent amplitude is 0.3A. And as the pulse width is 50ms, the correspondent amplitude is 0.6A. This relationship is expressed by the following equation. $I_n/I_0 = (T_n/T_0)^{-\log 2}$, where I_n/I_0 is the ratio of the amplitude compared with the initial amplitude and T_n/T_0 is the ratio of the pulse width compared with the initial pulse width. It is also found that as the pulse width becomes one tenth, the correspondent electric energy becomes 0.4 times. This relationship is expressed by the following equation. $W_n/W_0 = (T_n/T_0)^{-\log 0.4} = (T_n/T_0)^{\log 2.5}$, where W_n/W_0 is the ratio of the electric energy. As a result it is found that a current with shorter width and higher amplitude is more effective than a current with longer pulse width and lower amplitude.

Introduction

Various kinds of technologies for an electronic paper have been studied. A magnetic display using twisting magnetic ball is one of such technologies.[1] It is notable in the points that it has a wide visual field angle, that it does not require maintaining energy, that it has portability, that it is gentle for eyes because of reflectiveness and so on.

The author et al. has studied the factors affecting the rotation of the magnetic ball by a simulative experiment using a large scale model.[2,3] In this paper pulse magnetic field is applied to rotate the magnetic ball and the relationship between the pulse width and the amplitude of the current of the electromagnet for rotating a magnetic ball is studied.

Method of Study

Figure 1 shows a schematic diagram of the experimental apparatus. A pulse signal is generated from a function generator and it is provided to a control input of a DC power supply. The power supply provides an electromagnet with an exciting current. The electromagnet generates magnetic field by the current. A magnetic ball which is a permanent magnet is located under the electromagnet and it is rotated by the magnetic field generated by the electromagnet.

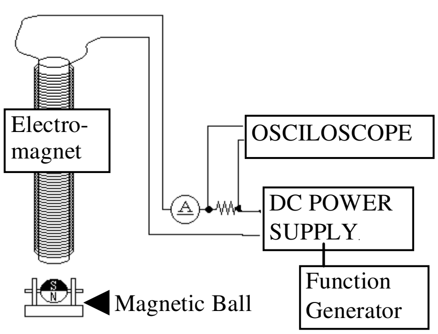

Figure 1. Schematic diagram of the experimental apparatus

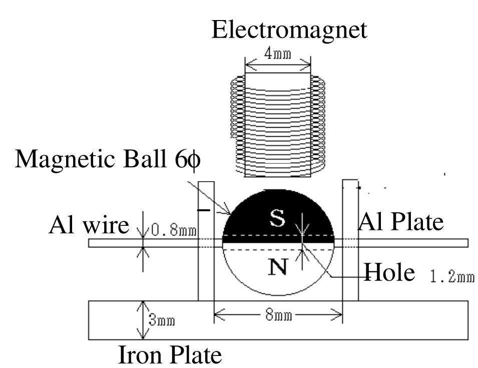

Figure 2. Arrangement of the electromagnet and the magnetic ball

Figure 2 shows an arrangement of the electromagnet and the magnetic ball in detail. One hemisphere of the magnetic ball is magnetized to "North" and colored white. The other hemisphere is magnetized to "South" and colored black. If half rotation is achieved, the visible color is inversed. An iron plate is positioned under the magnetic ball. It functions to stop rotating ball and hold the rotated state. In order to simplify the rotation condition, an aluminum wire is provided as a rotation axis through the center hole of the magnetic ball. The relative position between the magnetic ball and the electromagnet is adjusted by the three dimensional stage.

The experimental conditions are as follows.

- Magnetic ball: 6mmϕ, 12mT, Ferrite
- Electromagnet
  - Core: electromagnetic soft iron, 6mmϕ, 130mm long
  - Coils: enameled wire, 0.4mmϕ, 500turns, L=2.0mH, R=1.3Ω
- Whole circuit
  - L=2.0mH, R=2.4Ω, τ=0.83ms
- Iron plate: 3mm thick, electromagnetic soft iron
- Pulse width of the exciting current: 5-500ms
- Amplitude of the current: 0-1A
- Vertical distance between the magnetic ball and the electromagnet: 0-3mm
- Horizontal distance: 0-2mm

The Results of the Experiment

Table 1 shows one of the results of the experiment that indicates relationship between the current and rotation probability with a parameter of the pulse width. The sign of circle shows the ball rotated successfully and the sign of x shows it did not rotate successfully. They were measured 10 times for each current and the probability is the average of the successful number. For example, as the exciting current of 0.02A was applied to the coils of the electromagnet, all of the trials were unsuccessful. Then, the probability of rotation was 0%. As the current of 0.08A was applied, three of the ten trials were successful. Then, the probability of rotation was 30%. As the current of 0.28A was applied, all trials were successful. Then, the probability of rotation was 100%.

Figure 3 shows one of the graphs that indicates relationship between the exciting current and rotation probability with a parameter of the pulse width. As the amplitude of the current increases, the rotation probability of rotation increases, although this tendency is unstable in the smaller amplitude regions.

In addition, as the pulse width decreases, the amplitude of the current to rotate the magnetic ball increases. In other words, if the shorter pulse is applied, the higher amplitude is required to rotate the magnetic ball.

Table 2 shows one of the results of the experiment that indicates relationship between the pulse width and the exciting amplitude of the current at the 100% probability. Table 2 tells that as the pulse width becomes one tenth, the correspondent amplitude of the current for rotating the ball becomes double. For example, if the pulse width is 500ms, the amplitude is 0.22A. If the pulse width is 50ms, which is 1/10 times of 500ms, the amplitude is 0.48A, which is almost the double of 0.22A. And if the pulse width is 5ms, which is 1/10 times of 50ms, the amplitude is 0.96A, which is the double of 0.48A.

Table 1. Relationship between the amplitude of the current and rotation probability

Amplitude (A)	Number of the measurement								Prob. (%)
	1	2	3	4	…	8	9	10	
0.02	×	×	×	×	…	×	×	×	0
0.04	×	×	×	×	…	O	×	×	10
0.08	O	×	×	O	…	O	×	×	30
0.12	×	O	×	O	…	O	O	×	40
0.14	×	O	O	O	…	×	O	×	50
0.18	O	O	×	O	…	O	O	O	70
0.20	O	O	×	O	…	×	O	O	80
0.24	O	O	O	O	…	O	O	O	90
0.28	O	O	O	O	…	O	O	O	100
0.32	O	O	O	O	…	O	O	O	100

O:rotated, ×: did not rotate

Pulse width: 500ms, Vertical distance: 3mm,
Horizontal distance: 1mm

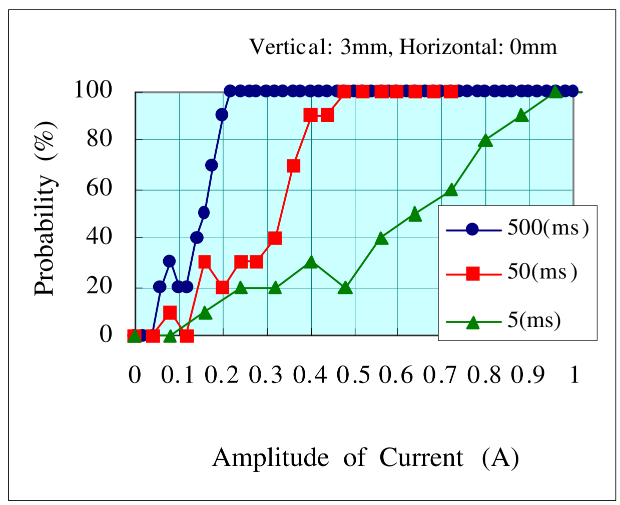

Figure 3. Relationship between the exciting current and rotation probability

Figure 4 shows one of the graphs that indicates relationship between the pulse width and amplitude of the current at the 100% probability. Both axes take common logarithm scale. They show straight lines with the slope of about -0.3.

Table 3 shows experimental equations according to Figure 4. All of them indicate that the amplitude is proportional to about the –0.3 rd power of the pulse width.

Table 2. Relationship between the pulse width and the amplitude of the current at the 100% probability

Vertical distance: 3mm			
Pulse Width	Amplitude of Current (A)		
(ms)	H.d: 0mm	H.d.:1mm	H.d:2mm
500	0.22	0.28	0.26
167	0.32	0.40	0.40
50	0.48	0.60	0.60
16.7	0.64	0.80	0.80
5	0.96	1.04	1.04

H.d.: Horizontal distance

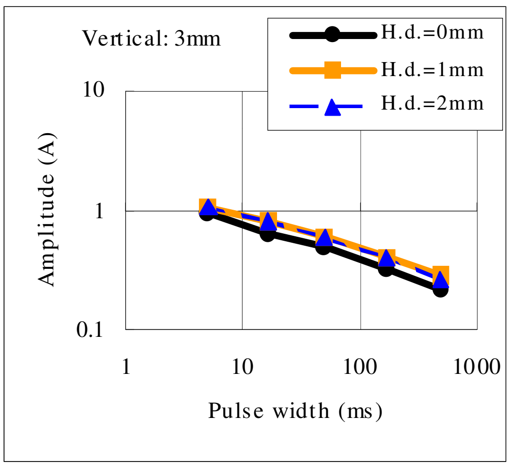

Figure 4. Relationship between the pulse width and the amplitude of the current at the 100% probability

Studies

Relationship Between the Pulse Width and the Amplitude of the Current

Now the equation is studied that expresses relationship between 1/10 times of the pulse width and the double of the amplitude. Table 4 shows relationship between 1/10 times of T_n/T_o and the double of I_n/I_o. Here, T_n and I_n mean the present pulse width and the present amplitude respectively and T_o and I_o mean those at the initial state. Then T_n/T_o means the ratio of the pulse width to the initial state and I_n/I_o means the ratio of the present amplitude to the initial state.

These relationships are expressed as follows.

$$T_n/T_o = 10^{-n} \quad (1)$$

$$I_n/I_o = 2^n \quad (2)$$

Common logarithm is applied to the both sides. Then the following equations are obtained respectively.

$$\log(T_n/T_o) = -n \quad (3)$$

$$\log(I_n/I_o) = n\log 2 \quad (4)$$

These equations are simultaneous equations. If "n" is erased from the equations (3) and (4), then the following equation is obtained.

$$I_n/I_o = (T_n/T_o)^{-\log 2} = (T_n/T_o)^{-0.301} \quad (5)$$

This equation indicates that the amplitude I is proportional to the -log2 (= -0.301) power of the pulse width T. This is coincident with the experimental results.

Table 3. Experimental equations of the relationship between the pulse width and the amplitude of the current at the 100% probability

Horizontal (mm)	Vertical distance (mm)	
	1	3
0	$I=1.60T^{-0.32}$	$I=1.32T^{-0.26}$
1	$I=1.61T^{-0.29}$	$I=2.10T^{-0.31}$
2	$I=1.70T^{-0.30}$	$I=2.10T^{-0.31}$

I: amplitude *T*: pulse width

Table 4. Relationship between 1/10 times of the pulse width and the double of the amplitude

n	T_n/T_o	I_n/I_o
0	$1=10^0$	$1=2^0$
1	10^{-1}	2^1
2	10^{-2}	2^2
⋮	⋮	⋮
n	10^{-n}	2^n

Table 5. Relationship between 10 times of the pulse width and the half of the amplitude

n	T_n/T_o	I_n/I_o
0	$1=10^0$	$1=2^0$
1	10^1	2^{-1}
2	10^2	2^{-2}
⋮	⋮	⋮
n	10^n	2^{-n}

This relationship is also described that if the pulse width becomes 10 times, the corresponding amplitude becomes half as shown in Table 5.

Relationship Between the Pulse Width and the Electric Power

Now electric power used for rotating the magnetic ball is studied. Electric energy is expressed as the product of electric power and the pulse width.

The initial electric energy W_0 is expressed as follows,

$$W_0=RI_0^2\times T_0 \quad (6)$$

where R: resistance of the coils, I_0: initial amplitude, T_0: initial pulse width.

Table 6. Relationship between 1/10 times of the pulse width and 0.4 times of the electric energy.

n	T_n/T_o	I_n/I_o
0	$1=10^0$	$1=0.4^0$
1	10^{-1}	0.4^1
2	10^{-2}	$(0.4)^2$
⋮	⋮	⋮
n	10^{-n}	$(0.4)^n$

Table 7. Relationship between 10 times of the pulse width and 2.5 times of the electric energy

n	T_n/T_o	I_n/I_o
0	$1=10^0$	$1=2.5^0$
1	10^{-1}	2.5^1
2	10^{-2}	$(2.5)^2$
⋮	⋮	⋮
n	10^{-n}	$(2.5)^n$

Then, if the pulse width becomes 1/10 times of the initial state and the corresponding amplitude becomes double, the electric energy W_1 is expressed as follows,

$$W_1= R\,(2I_0)^2\times 10^{-1}T_0=0.4\,W_0 \quad (7)$$

That means the electric power W_1 becomes 0.4 times of the initial electric power W_0.

Then if the pulse width T_2 becomes further 1/10 times of T_1 and the corresponding amplitude I_2 becomes the double of I_1, the electric energy W_2 is expressed as follows,

$$W_2= R\,(2I_1)^2\times 10^{-1}T_1=R\,(4I_0)^2\times 10^{-2}T_0$$
$$=0.16\,W_0=(0.4)^2\,W_0 \quad (8)$$

That means the electric power W_2 becomes further 0.4 times of the preceding electric power W_1. This relationship is shown in Table 6. It means that if the pulse width T_n becomes 1/10 times of the preceding pulse width $T_{(n-1)}$ and the corresponding electric power W_n becomes 0.4 times of the preceding electric power $W_{(n-1)}$.

This relationship is also described that if the pulse width is 10 times, the electric energy becomes 2.5 times as shown in Table 7. The following equation is obtained by the same way as introducing the above equation (5).

$$W_n/W_0= (T_n/T_o)^{-\log 0.4}= (T_n/T_o)^{\log 2.5}= (\,T_n/\,T_o)^{0.398} \quad (9)$$

Figure 5 shows this relationship.

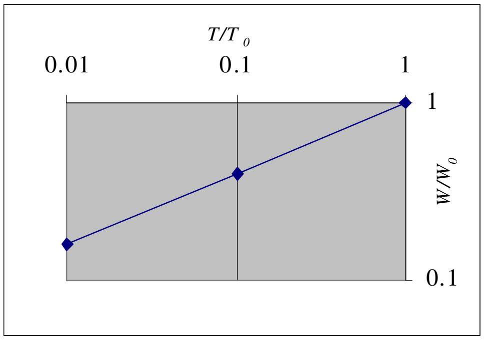

Figure 5. Relationship between pulse width and electric energy

That means that it is more effective to employ shorter pulse width with higher amplitude than longer pulse with lower amplitude from the view point of electric energy efficiency.

Conclusion

A simulative experiment was done using a large scale model of a twisting ball magnetic display. The relationship between the pulse width and the amplitude of the current provided to the exciting coil of the electric magnet for rotating the ball was studied. The results are as follows.

a) If the pulse width becomes one tenth, the correspondent amplitude of the current for rotating the magnetic ball becomes double. This relationship is also described that if the pulse width becomes ten times, the correspondent amplitude becomes half. This relationship is expressed that the amplitude of the current is proportional to –log2 (=-0.301) power of the pulse width.

b) If the pulse width becomes one tenth, the electric energy for rotating the magnetic ball becomes 0.4 times. This relationship is also described that if the pulse width becomes ten times, the electric energy becomes 2.5 times. This relationship is expressed that the electric energy is proportional to –log0.4 (= log2.5=0.398) power of the pulse width.

c) From the view point of electric energy efficiency it is more effective to employ a current with shorter pulse width and higher amplitude than that with longer pulse width and lower amplitude.

References

1. L. L .Lee, IEEE Trans. on Elect. Devices, Vol. ED-22, No9, pg. 758. (1975)
2. T. Daita and N. Kokaji, Proceedings of Japan Hardcopy 2001, ISJ, pg.127.

3. T. Daita and N. Kokaji, Technical report of IIEEJ, 01-07-03, pg.13. (2002)

Biography

Norio Kokaji received the B.E. and Ph.D. degrees from Tohoku University, Japan in 1965 and 1991, respectively. He joined Hitachi Koki Co., Ltd. and Iwatsu Electric Co., Ltd., in 1965 and 1969, respectively. Since 1997 he has been a professor of Meisei University. His work has primarily focused on R&D of digital printing technology, especially magnetography. His works include almost the whole areas of magnetography using longitudinal recording. His recent interest is also in R&D of magnetic display.