Estimation Method of Rotation Characteristic of a Ball for Electrical Twisting Ball Display

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Abstract

Digital paper has been studied as a new medium that appears to offer the advantages of both active displays and paper. A twisting ball display system is a promising candidate technology for digital paper. Dielectric balls with colored hemispheres (black and white) are used as the display elements; each color has a different surface charge. Each ball can be rotated by applying the appropriate electric field. However, obtaining the ideal balls (those that show good rotation characteristics) is a remaining problem. This study proposes a way of clarifying the best ball configuration. Ball mobility is measured in a dielectric liquid under uniform electric fields. Experimental results show a strong relation between the mobility difference between the materials covering the ball and its angular rotation speed.

1. Introduction

The amount of digital information continues to increase with the rapid adoption of the Internet. The concept of Digital Paper[1] suggests that it is an ideal way of allowing this increasing amount of digital information to be read comfortably. This study deals with a twisting ball display system, which is a promising candidate for Digital Paper.

The twisting ball system has the advantages of better stability and shorter response time than, for instance, electrophoretic displays. The principle of the twisting ball display 2)3) is shown Figure 1.

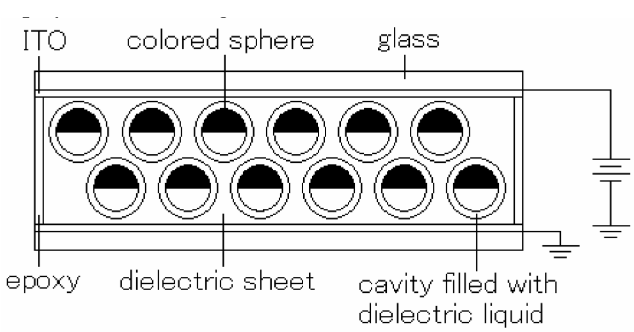

Figure 1. Structure of twisting ball display

It consists of balls with black and white hemispheres that lie in a dielectric-liquid. Individual balls are held in cavities formed in a transparent dielectric polymer sheet. The balls can be rotated by setting electric fields across the sheet. Images are formed by setting the appropriate electric field pattern on the display sheet. The rotation moment for a ball is due to the dipole moment created by the surface electric charge density difference between each hemisphere when an electrical field is applied across the cavity3). Therefore, we need to increase the differences in the surface electric charge densities between the hemispheres to improve the ball's behavior. Prior experiments and analyses have clarified the relation between applied electric field and rotation behavior using enlarged model balls. However, no guide lines on choosing a material pair to cover the hemispheres have been published. We assume that it should be possible to estimate the rotation characteristics from the mobility difference between the different materials used to coat the surfaces of the hemispheres. The following steps were carried out to confirm this hypothesis.

(1) Mobility measurements: the speeds of enlarged scale model balls coated uniformly with different materials were measured at various electric fields.
(2) Rotation speed measurements: rotation speeds of enlarged scale model balls coated with pairs of different materials were measured at various electric fields.
(3) Comparison: the results of (1) and (2) were compared to confirm our hypothesis.

2. Mobility Measurements

2-1.Experimental Method

The experimental apparatus is illustrated in Figure 2. White nylon balls of 3.2 mm diameter were prepared as the enlarged model balls. Various paints were applied uniformly to each ball. Two liquids with different specific gravities were placed in a glass cell as shown in Fig. 2; the ball floated on the horizontal boundary of the two liquids. Migration of the balls from a glass plate to the other was observed when different voltages were applied to the electrodes. The speed of the resulting ball motion was measured from recorded video images. Mobility was calculated from ball speed and applied electric field. Experimental conditions are listed in Table 1.

Table 1. Experimental Conditions

Ball	Nylon Φ 3.2 mm (Specific gravity 1.14)
Dielectric liquid	Hydrocarbon Isoper-G (Specific gravity 0.75) Hydro fluoride PF-5052 (Specific gravity 1.70)
Paints	Vinyl ①, ②, Urethane-Acrylic, Acrylic, Silicone
Measurement apparatus	Digital video camera (30 frames/second)
Applied voltage	3.0kV~5.5kV

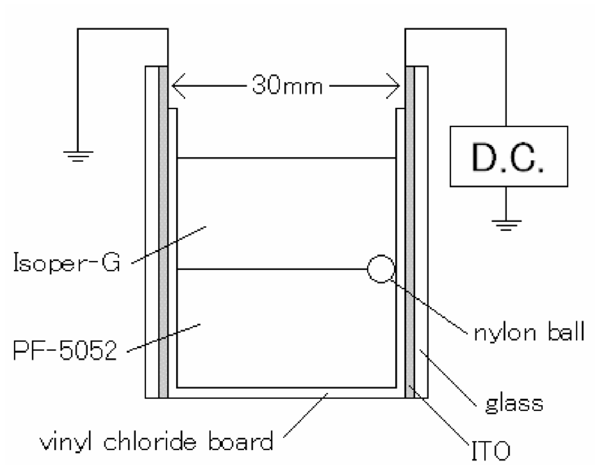

Figure 2. Experimental apparatus for measuring ball mobility

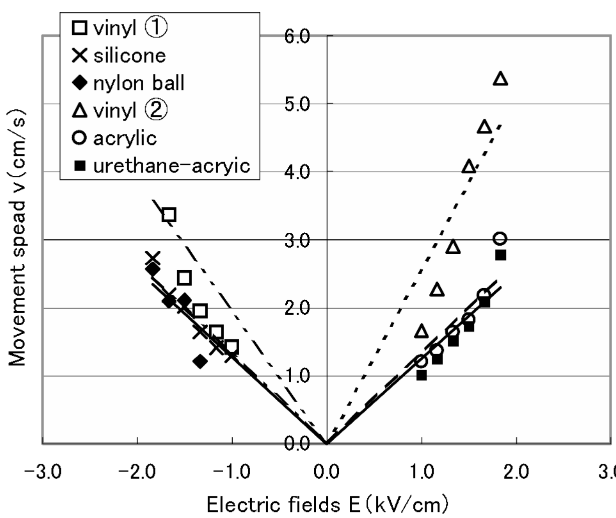

Figure 3. Motion speed of each ball

2-2. Experimental Results

Experimental results are shown Figure 3. Mobility was taken as the inclination of the line fitted to the measured points; mobility values are listed in Table 2.

Table 2. The Mobility of Each Material

Surface materials	Mobility μ ($\times 10^{-7}$ m^2/V*s)
Vinyl ②	+2.55
Acrylic	+1.35
Urethane-acrylic	+1.25
Nylon (without paint)	-1.28
Silicone	-1.34
Vinyl ①	-1.94

3. Observation of Ball Rotation

3-1. Experimental Method

Ball rotation behavior was measured as follows. Various model balls were prepared by painting each hemisphere with a different material; paint pairs were chosen to yield definite mobility differences. The painted balls were placed into the glass cell shown in Figure 4. Angular rotation speeds of the balls were measured when an electric field was applied across the cell. Rotation was divided into three parts as shown in Fig.5: T1, from switch ON till rotation start; T2, from rotation start to 180 degree turn; and T3, from initial 180 degree rotation to cessation of all oscillation. We averaged T2 over five trials to calculate angular speed ω using the formula ω = 180/T2 (degree/second). The experimental conditions were as the same as those shown in Table 1, except the cell width was changed from 30 mm to 6mm. These experiments were intended to confirm the relation between angular speed ω and mobility difference.

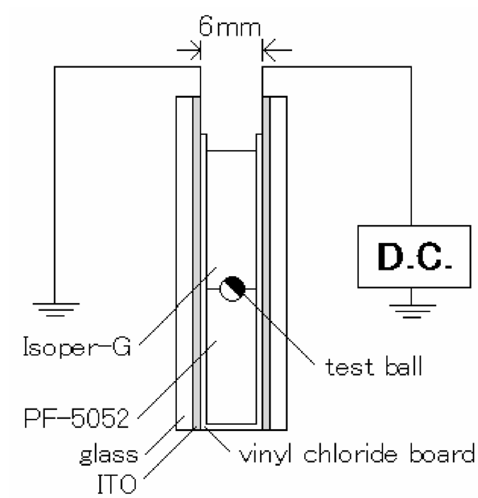

Figure 4. Experimental apparatus for observation of rotation

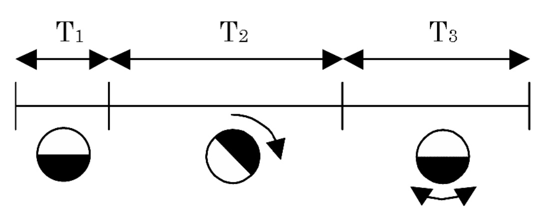

Figure 5. Ball response time divided into three parts

3-2. Experimental Results

The observed rotation behaviors are shown in Table 3 together with the mobility difference Δμ of each material pair. Rotation was observed with five paint pairs. The relation between driving electric field E and angular speed _ is shown in Figure 6 for these five pairs. The relations between driving electric field E and speed ω are shown in Fig.6 for each material pair. We defined the new parameter "angular mobility" as (ω/E); the value of the angular mobility was taken as the inclination of the line fitted to the measured points.

Table 3. Mobility difference Δμ and the rotational behavior of the painted balls

Paint pair	Mobility Δμ ($\times10^{-7}$ $m^2/V*s$)	Rotation behavior
Vinyl②/vinyl①	4.49	O
Vinyl②/silicone	3.88	X
Vinyl②/nylon	3.83	O
acrylic/vinyl①	3.29	O
Urethane-acrylic/vinyl①	3.19	X
Acrylic/silicone	2.68	X
Acrylic/nylon*	2.63	O
Urethane-acrylic/silicone	2.58	X
Urethane-acrylic/nylon*	2.53	X
Vinyl②/urethane-acrylic	1.30	X
Vinyl②/acrylic	1.20	X
Nylon*/vinyl①	0.66	O
Silicone/vinyl①	0.60	X
Acrylic/urethane-acrylic	0.10	X
Nylon*/silicone	0.06	X

*indicates the bare ball material

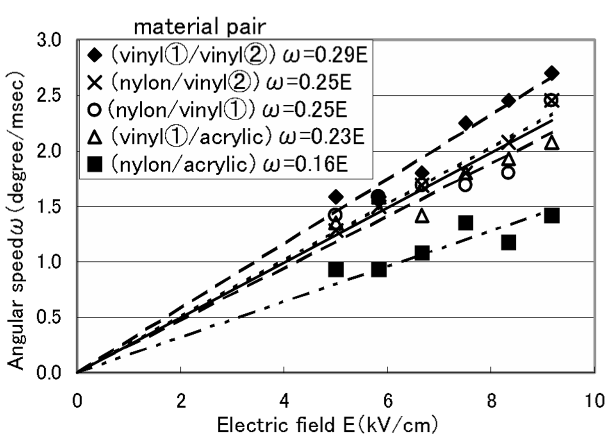

Figure 6. Rotation speed of each ball

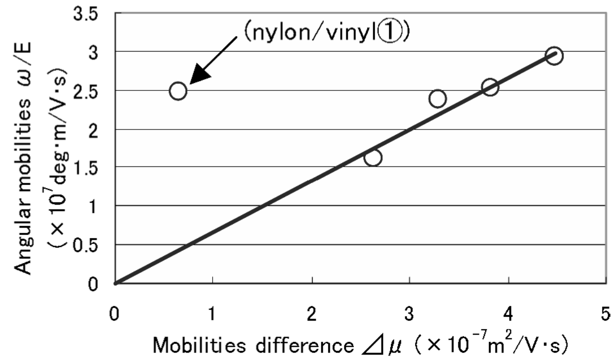

Figure 7. Angular mobility of each ball

4. Discussion

The linear relationship between angular mobility (ω/E) and mobility difference Δμ shown in Fig. 7 indicates that our assumption is reasonable. It is confirmed that the angular mobility of a ball can be estimated from the mobility difference of the material pair used to coat the hemispheres. The only exception in Fig. 7, is the combination of nylon and vinyl①. An explanation for this case is given below. Electrification tendency of various materials is generally given as Table 4.

Table 4. An Electrification Tendency Table

PLUS	**nylon**	small (nylon – acrylic); large (nylon – vinyl chloride)
	silk	
	acrylic	middle (acrylic – vinyl chloride)
	paper	
	black rubber	
	polyethylene	
MINUS	**vinyl chloride (vinyl①)**	

We can find large distance between nylon and vinyl chloride in this table. This large distance means that large potential difference will be given at the boundary of these two materials, when they are contacting each other. A dipole moment for ball rotation can be brought by this potential difference. We have chance to consider other two material pairs out of various tested pairs in our experiments, because we can find acrylics in Table 4. The three cases of material pair (c), (d), (f) have an order of (d)< (c) < (f) on the distance at Table 4. This order is as the same as that of angular mobility for these three pairs.

Fittingness between experimental results and theoretical considerations on causes of ball rotation are listed in Table 5. However, the latter explanation using electrification tendency table has not enough quantitatively, it is useful to give explanation to excepted material pairs from the former explanation using mobility difference of material pair. On the other hand, the former explanation using mobility difference of material pair is generally useful to quantitatively estimate ball motion except minor group of material pairs.

Table 5. Evaluation results on fitness of two methods for ball rotation estimation

Material pairs	Mobility $\Delta\mu$ ($\times 10^{-7}$ $m^2/V*s$)	Distance on the electrification tendency table	Angular Mobility $\Delta\mu$ ($\times 10^{-7}$ $m^2/V*s$)	Fitness evaluation	
				Mobility difference model	Electrification tendency model
(a) vinyl②/vinyl①	4.49	-	2.92	◎	-
(b) vinyl②/nylon	3.83	-	2.51	◎	-
(c) acrylic/vinyl①	3.29	Middle	2.37	◎	O
(d) acrylic/nylon	2.63	Small	1.60	◎	O
(e) nylon/vinyl①	0.66	large	2.48	X	O

5. Summary

Experiments have been carried out for the purpose of creating guidelines for choosing the appropriate material pair for the twisting ball display. Mobility values of enlarged balls whose surfaces were uniformly covered with a single material (paint) were first measured, and ball rotation speeds were then measured on several paint pairs. The results are as follows:

(1) We found a linear relationship between the mobility difference _ of a paint pair and the angular mobility _/E of a ball whose surface was covered with the material pair.

(2) Another explanation was suggested to the exception case for explanation with mobility difference: distance of two materials on the electrification tendency table can bring potential difference on a ball for forming dipole moment for rotation.

6. Reference

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7. Biography

Ryushi Ishikawa was born in 1979. He received his B.S. degree in 2002 from Tokai University. He is expected to receive his M.S. degree from Graduate School of Tokai University in 2004. He is now studying the twisting ball display.