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Estimation of Rotation Behavior of Balls for a Twisting Ball Display by Mobility Measurements

Ryushi Ishikawa
Department of Electro-Photo-Optics, Faculty of Engineering, Tokai University, 1117 Kitakaname, Hiratsuka-shi, Kanagawa-ken 259-1292, Japan

Makoto Omodani▲
Department of Electro-Photo-Optics, Faculty of Engineering, Tokai University, 1117 Kitakaname, Hiratsuka-shi, Kanagawa-ken 259-1292, Japan
and Tokai University Future Science and Technology Joint Research Center, 1117 Kitakaname, Hiratsuka-shi, Kanagawa-ken 259-1292, Japan
E-mail: Omodni@keyaki.cc.u-tokai.ac.jp

Shuichi Maeda
Advanced Technology Research Laboratory, Oji Paper Company, 1-10-6 Shinonome, Koto-ku, Tokyo 135-8558, Japan

Abstract. *Electronic 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 Electronic 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. © 2006 Society for Imaging Science and Technology.*
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INTRODUCTION

The amount of digital information continues to increase with the rapid adoption of the Internet. The concept of Electronic 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 Electronic 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[2–4] is shown Fig. 1. 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 cavity.[5,6] 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;[8,9]
(2) Rotation speed measurements: Rotation speeds of enlarged scale model balls coated with pairs of different materials were measured at various electric fields;[7,8]

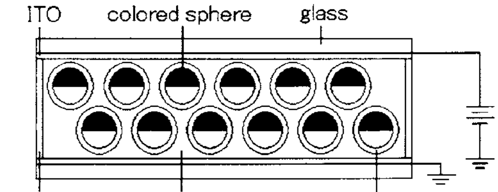

Figure 1. Structure of twisting ball display.

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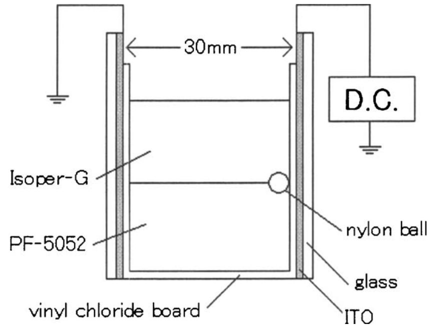

Figure 2. Experimental apparatus for measuring ball mobility.

(3) Comparison: The results of tasks (1) and (2) were compared to confirm our hypothesis.[8,9]

MOBILITY MEASUREMENTS

Experimental Method

Table I. Experimental conditions.

Ball	Nylon Φ3.2 mm
	(Specific gravity 1.14)
Dielectric-liquid	Hydrocarbon Isoper-G(Specific gravity 0.75)
	Hydro fluoride PF-5052(Specific gravity 1.70)
Paints	Vinyl①,②, Urethane-Acrylic, Acrylic, Silicone
Measurement apparatus	Digital video camera (30 frames/second)
Applied voltage	3.0–5.5 kV

The experimental apparatus is illustrated in Fig. 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 I. Source of paint materials are listed in Table II.

Experimental Results

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

OBSERVATION OF BALL ROTATION

Experimental Method

Ball rotation behavior was measured as follows. Various model balls were prepared by painting each hemisphere with

Table II. Source of paint materials.

Paints	Manufacturer	Item
Vinyl①	Tamiya Inc.	Tamiya color for polycarbonate
Vinyl①	Teranisi chemical Industry	Magic ink.
Acrylic	Asahipen Corp.	Creative life spray
Silicone	Nippe home products	Heat resistant spray
Urethane-Acrylic	Nippe home products	Urethane for building

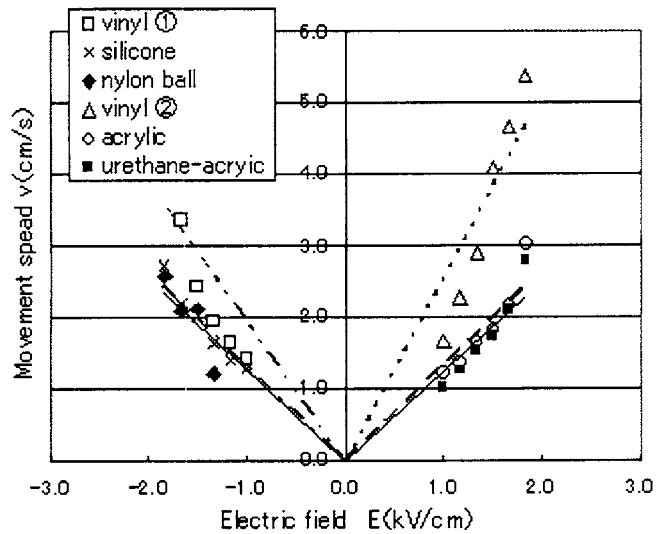

Figure 3. Motion speed of each ball.

Table III. Mobility of each material.

Surface materials	Mobility μ($\times 10^{-7}$ $m^2/V\cdot s$)
Vinyl②	+2.55
Acrylic	+1.35
Urethane-acrylic	+1.25
Nylon (without paint)	−1.28
Silicone	−1.34
Vinyl①	−1.94

a different material; paint pairs were chosen to yield definite mobility differences. The painted balls were placed into the glass cell shown in Fig. 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 until rotation start; $T2$, from rotation start to 180 degree turn; and $T3$, from initial 180

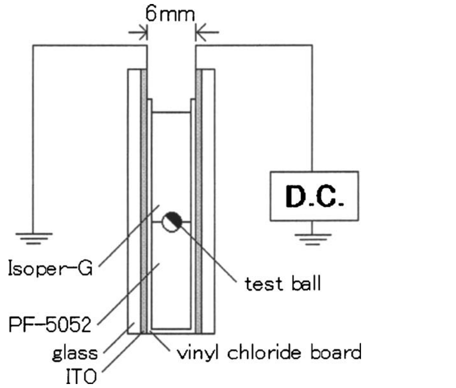

Figure 4. Experimental apparatus for observation of rotation.

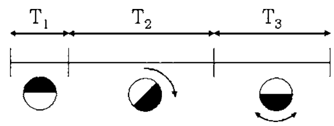

Figure 5. Ball response time divided into three parts.

degree rotation to cessation of all oscillation. We averaged $T2$ over five trials to calculate angular speed ω using the formula $\omega = 180/T2$ (deg/s). The experimental conditions were as the same as those shown in Table I, except the cell width was changed from 30 to 6 mm. These experiments were intended to confirm the relation between angular speed ω and mobility difference.

Experimental Results

The observed rotation behaviors are shown in Table IV together with the mobility difference $\Delta\mu$ of each material pair. Rotation was observed with five paint pairs. The relations between driving electric field E and angular speed ω are shown in Fig. 6 for these five pairs. 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.

Measured angular mobility (ω/E) and mobility difference $\Delta\mu$ of the rotated ball are summarized in Table V.

The linear relationship between angular mobility (ω/E) and mobility difference $\Delta\mu$ shown in Fig. 7 indicates that our assumption is reasonable. It confirms 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 vinyl.①

DISCUSSION

The former explanation using mobility difference of material pair is generally useful to quantitatively estimate ball motion except in the case of one sample of material pairs. It is a residual theme why the combination of (nylon and vinyl①) does not agree with the linear relationship for the other material pairs. We have to investigate the reason of disagreement between the characteristics of the separated and combined states of these two materials. We now expect that the solution might be found when we precisely consider the contact potential difference for two different materials on a ball.

Table IV. Mobility difference $\Delta\mu$ and the rotational behavior of the painted balls.

Paint pair	Mobility $\Delta\mu$ ($\times 10^{-7}$ m^2/V·s)	Rotation behavior
Vinyl②/Vinyl①	4.49	○
Vinyl②/silicone	3.88	×
Vinyl②/nylon[a]	3.83	○
acrylic/Vinyl①	3.29	○
urethane-acrylic/Vinyl①	3.19	×
acrylic/silicone	2.68	×
acrylic/nylon[a]	2.63	○
urethane-acrylic/silicone	2.58	×
urethane-acrylic/nylon[a]	2.53	×
Vinyl②/urethane-acrylic	1.30	×
Vinyl②/acrylic	1.20	×
nylon[a]/Vinyl①	0.66	○
silicone/Vinyl①	0.60	×
acrylic/urethane-acrylic	0.10	×
nylon[a]/silicone	0.06	×

[a]*Indicates the bare ball material.*

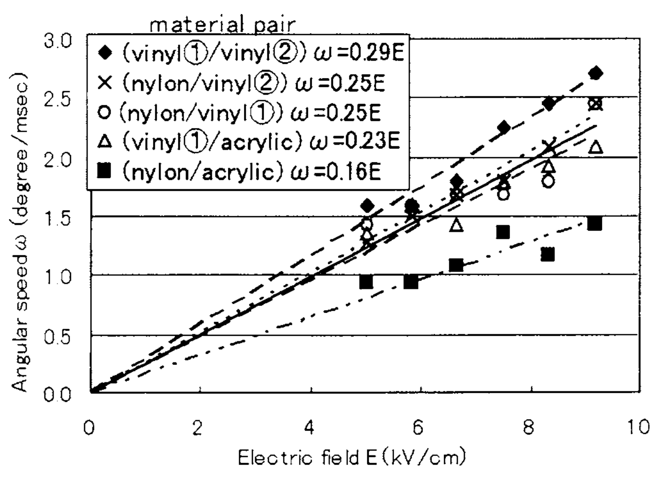

Figure 6. Rotation speed of each ball.

It is well-known that when the radius of a cavity sphere is sufficiently large the dragging moment, N, is written as

Table V. Mobility difference and angular mobility of the balls.

Material pairs	Mobility difference $\Delta\mu$ ($\times 10^{-7}$ $m^2/V\cdot s$)	Angular mobility ω/E ($\times 10^{-3}$ $deg\cdot m/V\cdot s$)
(a) Vinyl② /Vinyl①	4.49	2.92
(b) Vinyl② /nylon	3.83	2.51
(c) acrylic/Vinyl①	3.29	2.37
(d) acrylic/nylon	2.63	1.60
(e) nylon/Vinyl①	0.66	2.48

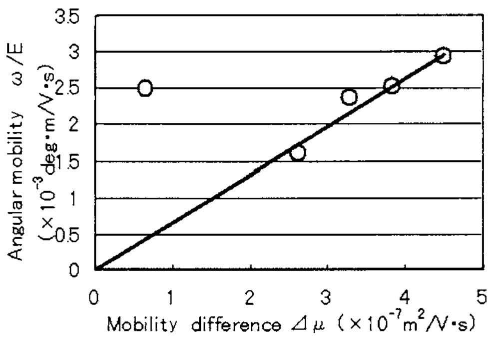

Figure 7. Angular mobility of each ball.

$$N = 8\pi S R^3 \omega, \tag{1}$$

where R is the ball radius; ω is the angular speed of the ball, and S is the viscosity resistance of the liquid. We note that Eq. (1) was cited in '*Hydrodynamics*' by Lamb[10] and the calculations were carried out in detail in that reference.

One of our previous papers[6] has already reported that the driving moment of the ball in an electric field (Fig. 8) is written as

$$M = \left(\frac{8}{3}\right)\sigma R^3 E \sin\theta, \tag{2}$$

where σ is the difference in the surface electric charge densities of the hemispheres of the ball, E is the external electric field and θ is the angle of the boundary between hemispheres off the perpendicular to the electric field. (When $\theta = 0$, the boundary between hemispheres is perpendicular to the electric field.)

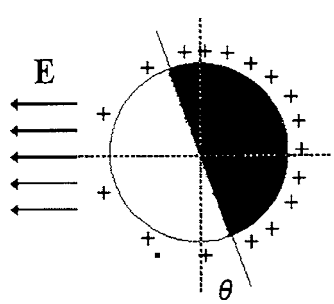

Figure 8. Cross sectional view of a ball in an electric field.

Assuming that the inertia moment of the ball can be ignored when the mass of the ball is relatively small, we find that N is equal to M. Therefore,

$$\left(\frac{8}{3}\right)\sigma R^3 E \sin\theta = 8\pi S R^3 \omega, \tag{3}$$

and

$$\omega = \frac{\sigma E}{3\pi S}\sin\theta. \tag{4}$$

Equation (3) suggests that the angular speed of the ball has a minimum of 0 when $\theta = 0°$ and reaches the maximum of $\sigma E/(3\pi S)$ when $\theta = 180°$ during its half rotation.

Although this approximation might be too rough, assuming that the average of angular speed (ω_0) can be centered between the minimum and maximum above, we write ω_0 as:

$$\omega_0 = \frac{\sigma E}{6\pi S}. \tag{5}$$

On the other hand, it is well known that Stoke's drag, F_1, for a ball in a liquid is written as[10],

$$F_1 = 6\pi S R v, \tag{6}$$

where v is the velocity of the ball.

When the electric charge is q, the Coulomb force, F_2, due to the presence of an electric field is written as

$$F_2 = qE. \tag{7}$$

When the density of electric charge is given as σ, q of a ball is written as

$$q = 4\pi R^2 \sigma. \tag{8}$$

Therefore,

$$F_2 = 4\pi R^2 \sigma E. \tag{9}$$

When the velocity of the ball is constant, considering F_1 to be equal to F_2, we write

$$6\pi S R v = 4\pi R^2 \sigma E \tag{10}$$

and

$$\frac{v}{E} = \frac{2R}{3S}\sigma, \tag{11}$$

From the definition of mobility, μ

$$\mu = v/E. \tag{12}$$

Then,

$$\mu = \frac{2R}{3S}\sigma. \tag{13}$$

When the radius of two balls is R_0, the surface electric charge densities of them are σ_1 and σ_2, respectively, and the mobilities of them are μ_1 and μ_2, respectively,

$$\mu_1 = \frac{2R_0}{3S}\sigma_1, \tag{14}$$

$$\mu_2 = \frac{2R_0}{3S}\sigma_2. \tag{15}$$

Therefore,

$$\mu_1 - \mu_2 = \frac{2R_0}{3S}(\sigma_1 - \sigma_2). \tag{16}$$

with

$$\mu_1 - \mu_2 = \Delta\mu. \tag{17}$$

Equation (16) can be rearranged as

$$\sigma_1 - \sigma_2 = \frac{3S}{2R_0}\Delta\mu. \tag{18}$$

In the case of a ball for which the two hemispheres of the ball are combined together, the hemispheres of the ball can be considered to have the surface electric charge densities of $\sigma_1/2$ and $\sigma_2/2$, respectively. Therefore, the difference in the surface electric charge densities of the hemispheres, is written as

$$\sigma = \frac{\sigma_1 - \sigma_2}{2} = \frac{3S}{4R_0}\Delta\mu. \tag{19}$$

By substituting Eq. (19) into Eq. (5),

$$\frac{\omega_0}{E} = \frac{1}{8\pi R_0}\Delta\mu. \tag{20}$$

These theoretical discussion suggest that the angular speed of a ball, ω, can be predicted by the difference in experimentally obtained mobilites of two balls using an enlarged model and Eq. (20) suggests that ω/E is independent of the radius of the ball. Equation (20) also suggests that ω/E is proportional to $\Delta\mu$, and this theoretical result explains the liner relationship between $\Delta\mu$ and (ω_0/E) in Fig. 7.

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. We found a linear relationship between the mobility difference $\Delta\mu$ of a paint pair and the angular mobility ω/E of a ball whose surface was covered with the material pair.

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