euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016

www.euspen.eu

Equi-force contour analysis in electronic papers using charged particles

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Abstract

In this paper, a new concept of euqi-force contour is introduced to theoretically optimize the particle parameters used in electronic papers. This analysis is based on a ratio of electric force to mechanical force. Electrical force is consisted of coulomb force and imaginary force. One dominant force among mechanical forces is van der Waals force. From my point of view, a concept of equi-force contour has been rarely reported especially in researches on electronic papers. Equi-force contour analysis for a particle pair is numerically conducted by analysing forces acting on the charged particles. According to particle diameter and electric field strength, the equi-force contour is divided into three regions including mechanical adhesion, electrostatic adhesion and electrostatic removal. From electrical removal region, the minimum electric field strength related to particle diameter is theoretically obtained for particle transition. This equi-force contour analysis constructed a theoretical basis to extract the optimum conditions for particle transition such as particle diameter and electric field

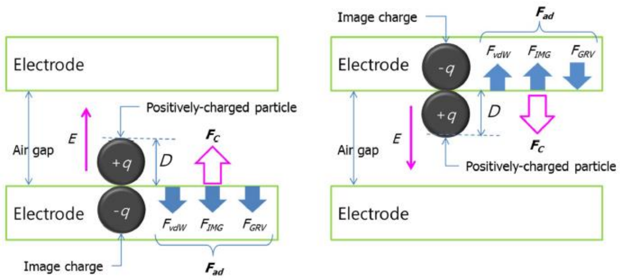
Equi-force contour, electronic paper, charged particle, particle transition, charged particle adhesion, charged particle

1. Introduction

Electronic-paper (e-paper) is one of the most feasible flexible displays because of its main advantages (e.g., low power consumption, clear readability under sunlight, light weight, and flexibility). So, much research has been concentrated on the realization of e-paper with various technologies [1,2]. Among them, electrophoretic display [1] based on charged particles and electric field represents the strong feasibility. However, there are little studies of theoretical analysis to comprehend the operation principle for e-paper. The aim of this paper is to give the theoretical model for the particle transition in e-paper, and to optimize the particle parameters by using a new concept of equi-force contour. In this experiments, equi-force contour analysis is conducted for a particle pair. In equi-force contour, three different regions for each particle will be discussed.

2. Theory

2.1. Basic model for electrophoretic electronic-papers



(a) (b)

Figure 1. Adhesion and detachment forces when a positively-charged particle is (a) on bottom electrode and (b) under top electrode.

Figure 1 shows a basic model about electrophoretic electronic papers when a positively-charged particle is on bottom electrode and under top electrode. The basic model is composed of four forces; electrostatic image force (F_{IMG}), van der Waals force (F_{vdW}), gravitational force (F_{GRV}), and Coulomb force (F_C). Equation 1 shows the net adhesion force (F_{ad}) acting on the charged particle when the charged particle with radius (R) and charge (q) exists under the uniform electric field (E) between parallel electrodes with air gap (L). However, in our interesting range of particle diameter and a ratio of charge to mass, a gravitational force is not a dominant factor. So, F_{ad} can expressed as;

$$F_{ad} = \begin{cases} F_{vdW} + F_{IMG} \cdots\cdots \text{ for top electrode} \\ F_{vdW} + F_{IMG} \cdots \text{for bottom electrode} \end{cases} \quad \text{(Equation 1)}$$

where F_{vdW} and F_{IMG} can be written respectively as;

$$F_{vdW} = -\frac{A_{132}}{12} \cdot \left\{ \frac{2}{z_0} - \frac{2R}{z_0^2+1} + \frac{1}{z_0+2R} - \frac{2R}{(z_0+2R)^2} \right\} \quad \text{(Equation 2)}$$

where A_{132} is Hamarker's constant and z_0 is minimum distance between particle and electrode.

$$F_{IMG} = -\frac{q^2}{4\pi \cdot \epsilon_0 \cdot (2R)^2} \quad \text{(Equation 3)}$$

where ϵ_0 is a permittivity of air or vacuum and q is an amount of charge of each particle. In the other hand, F_C is a main detachment force and can be express as;

$$F_C = q \cdot E \quad \text{(Equation 4)}$$

where E is electric field strength. Table 1 shows several constants for force calculation.

Table 1 Constants for force calculation

Constant name	Symbol	Value	Unit
Hamaker's constant	A_{132}	$4.5 \cdot 10^{-20}$	J
Air permittivity	ϵ_0	$8.854 \cdot 10^{-12}$	F/m
Minimum distance	z_0	40·10-9	m

2.2. Equi-force contour

From our numerical simulations, F_{vdW} has been found to be proportional to particle radius, and F_{IMG} has been known to be proportional to square of q and to be inversely proportional to square of R. In addition, F_C is proportional to q when E is uniform. As a result, variation of particle radius has an effect on q, F_{vdW}, and F_C. Therefore, in order to analyse direct effect of R on adhesion and detachment forces for a given ratio of charge to mass, we use equi-force contour (f) which is a ratio of electric force (F_{IMG} and F_C) to mechanical force (F_{vdW}). It can be written as;

$$f = \frac{Electrical\ force}{Mechanical\ force} = \frac{F_C - F_{IMG}}{F_{vdW}} \qquad \text{(Equation 5)}$$

From Equation 5, the numerator (F_C- F_{IMG}) is positive when F_C is bigger than F_{IMG}. It means that the particle can be electrically detached, which is defined as electrostatic removal. On the contrary to this, when F_C is smaller than F_{IMG}, the numerator is negative. It means that the particle cannot be electrically detached, which is defined as electrostatic adhesion. In the other hand, if the denominator (F_{vdW}) is extremely bigger than the nominator (F_C- F_{IMG}), f gets to be close to zero. It means that F_{vdW} is too big to detach the particle electrostatically, which is defined as mechanical adhesion. In addition, when both F_C- F_{IMG} and F_{vdW} is same, a value of f can be +1 or -1. Consequently, the particle can be transferred between parallel electrodes only when f is bigger than +1.

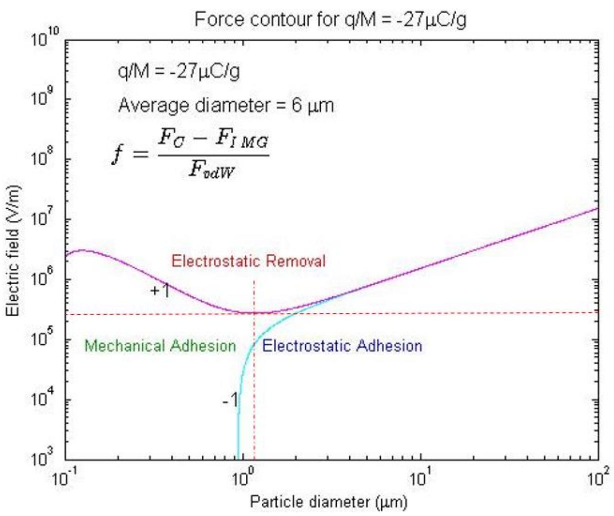
Table 2 shows simulation parameters about particles, where q/M is a ration of charge to mass and its unit is micro-charge/gram.

Table 2 Parameters about particles

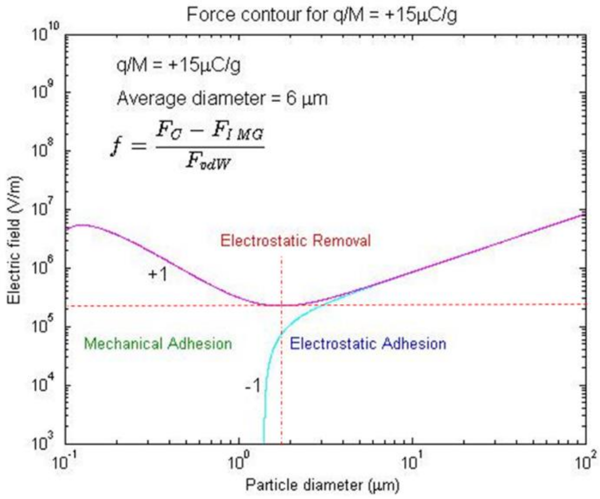
Type	Symbol	Value	Unit
A particle pair	q/M	-27	μC/g
	q/M	+15	μC/g

3. Simulation results

Simulations about black and white particles has been conducted and their results are shown in Figure 3 (a) and (b), respectively. Three divided regions are also marked: electrostatic removal, electrostatic adhesion, and mechanical adhesion. In both graphs, a dotted horizontal line and an alternate long and short dash line are drawn. The former means minimum point of $f = +1$ and the latter means a specific particle diameter at minimum point of the dotted horizontal line. In Figure 3 (a), optimum diameter is about 1.2 ㎛ and one bigger than $2.8 \cdot 10^5$ (V/m) in electric field strength is required for electrostatic removal at this diameter electrical field strength. In Figure 3 (b), in the same manner, optimum diameter is about 1.8 ㎛ and one bigger than $2.2 \cdot 10^5$ (V/m) is necessary.



(a)



(b)

Figure 3. Equi-force contour graph of (a) the particle of -27 μC/g and of (b) the particle of +15 μC/g.

4. Conclusion

In this paper, a new equi-force contour analysis is adopted to find optimum diameter and required electric field strength for given a ratio of charge to mass. In this simulation, two charged particle are used and their equi-force contour are drawn and important factors are extracted; optimum diameter and electric field strength. The optimum diameter is important for particle manufacturing process and the electric field strength is also significant for an electronic-paper driving scheme. These key parameters can be concurrently determined in equi-force contour graph. We expect that this concept and its simulation results will contribute to the advancement of electronic-paper technology.

References

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