Static and transient modeling of fast moving ball actuator as a display device

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ABSTRACT

FMBA(Fast Moving Ball Actuator), developed as novel electronic-paper display, has already proven its operability and functionality. However, optimization issues related with low operating voltage, high refresh rate, fine pixel and higher display resolution, etc. are still remaining to be improved for a successful commercialization. In order to optimize such issues effectively, static and transient model were developed and verified by comparing the calculated results to the measured. The static model is based on the force balancing equation between the driving and the holding forces while the transient model is developed from Newton's 2nd law by adding the inertia as well as the resistive damping forces caused by the surroundings. With the simplified static model, driving voltage of 30.71 V was obtained, which is reasonably matched to the measured voltage of 40 V. Based on the transient model, also, the transient response of the device can be estimated within reasonable margin. Considering the absence of reliable key parameters of surface roughness, static and dynamic frictional coefficient, and refractive indices, the developed static and transient models account well the experimental results and thus they are expected to contribute further improvements in FMBA.

Keywords: Static model**,** Threshold voltage, Transient model, FMBA, Electronic paper display

1. INTRODUCTION

After the first successful demonstration[1] as novel electronic-paper display device, FMBA has continued its endless improvements[2-4]. Although its operability and functionality as a display device had already proven, optimization issues such as operating voltage, refresh rate, pixel size and display resolution, etc. are still remaining to be improved for a successful commercialization. In order to optimize such issues effectively, clear understanding on its operation principle and the corresponding model should be developed.

In the previous work[5], threshold voltage model was proposed which based on the force balancing between the driving and the holding forces. The proposed threshold voltage model considered all the related forces of Coulomb force, dielectrophoretic (DEP) force, frictional force, and adhesive force caused by van der Waals force, where frictional force consists of vertical Coulomb and DEP forces, buoyance, and gravity. As DEP force, buoyance, and gravity were concluded negligible compared to Coulomb force and van der Waals force, they were omitted from the simplified threshold voltage model. The calculated threshold voltage was matched well to the measured voltage, which verified the proposed threshold voltage model was reasonable. FMBA, however, is not restricted to the so-called "still-cut" image display and therefore its dynamic performances such as switching speed and refresh rate should also be studied for the video display applications.

The transient model as well as the improved static model are presented in this paper. Inertia and damping effects were studied and included in the transient model where the translational and the rotational motions were assumed to be independent. After developing the draft transient model, it was reviewed whether it logically matched with the previously developed static model or not. On this way, the inconsistency in the frictional coefficients used in the static and the transient models and the miscalculation regarding van der Waals force as a normal force not a frictional force were corrected.

2. STATIC MODELING

The previously developed threshold voltage model[5] based on the force balancing condition between all the involved forces shown in Figure 1. In order to consider 3D geometric effect, Coulomb and DEP forces were analyzed through FEM simulations while all the remaining forces were analytically modeled. As DEP force, buoyance, and gravity were negligible compared to the lateral/vertical electrostatic forces and van der Waals force, they were omitted from the simplified threshold voltage model.
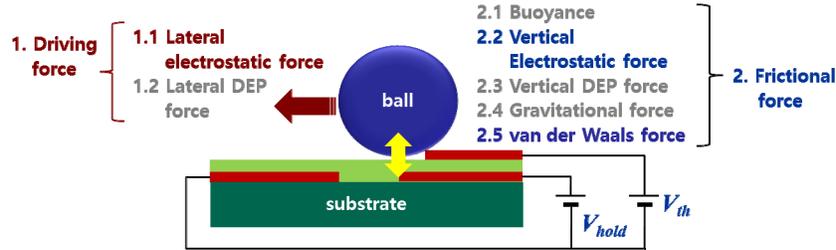

Figure 1. Cross-sectional schematic view of FMBA showing all the involved forces.

The van der Waals force, however, should be treated as a frictional force but it's regarded as a resistive force previously. Such a miscalculation led the static frictional coefficient μ to the under-fitted value of 0.06. The static frictional coefficient of 0.06 was too small to be larger than the dynamic frictional coefficient required in the transient model. In order to fix such a logical inconsistency, the simplified threshold voltage equation was corrected as Equation (1) and the static frictional coefficient was changed as 0.6. With the correction, the threshold voltage V_{th} was calculated as 30.71V, which reasonably matched to the measured voltage of 40 V. Although the difference between the calculated and the measured is increased, it's more consistent logically.

$$V_{th} = \sqrt{\frac{\mu(F_{vdW,1+2} + K_{ev,hold}V_{hold}{}^2) + K_{e,hold}V_{hold}{}^2}{K_{e,drive}}} - K_{e,couple}V_{hold} \tag{1}$$

In Equation (1) of the simplified threshold voltage model, $F_{vdW,1+2}$ is total van der Waals force between the ball and the underlying electrode as well as the underlying dielectric. Also $K_{e,drive}$, $K_{e,couple}$, $K_{e,hold}$, and $K_{ev,hold}$ are coupling parameters explaining the relationships between voltages and corresponding forces as explained in Reference 5.

3. TRANSIENT MODELING

The transient model is generated by combining the translational motion of the moving ball due to the lateral electrostatic driving force as considered in the static model and the rotational motion due to the friction between the moving ball and the underlying substrate surface. Here it's assumed that the translational and the rotational motions are independent. The transient model shown in Equation (2) and (3) includes 1) the inertia and the moment of inertia of the moving ball, 2) added-mass effect due to the surrounding fluid, 3) translational and rotational drag forces, and 4) dynamic frictional force as well as the electrostatic driving force which is defined as a function of the moving ball location and also the applied driving voltage. But the gravity and the buoyance were ignored and the ball was assumed as a rigid body.

$$\rho_s V \frac{dv}{dt} + C_a \rho_f V \frac{dv}{dt} + C_{d,trans}v = F_e - F_{f,translation} \tag{2}$$

$$I\frac{d\omega}{dt} + C_{d,rot}\omega = rF_{f,rolling}$$

(3)

Equation (2) described the translational velocity v as a function of the driving electrostatic force F_e and the translational friction force $F_{f,translation}$, where the inertia was expressed through the ball density ρ_s and volume of the ball V. As the ball is moving in the fluidic surrounding, the added mass effect[6] should be included through the added mass coefficient C_a and fluid density ρ_f and the drag represented through the drag coefficient[7] $C_{d,trans}$ also. In Equation (3) for the angular velocity ω of the rotational motion, I was the moment of inertia of the ball, $C_{d,rot}$ the drag coefficient of the rotational motion[8], r the radius of the ball, and $F_{f,rolling}$ the frictional force causing the rolling motion. The detailed development of the transient model is described in Reference 9.
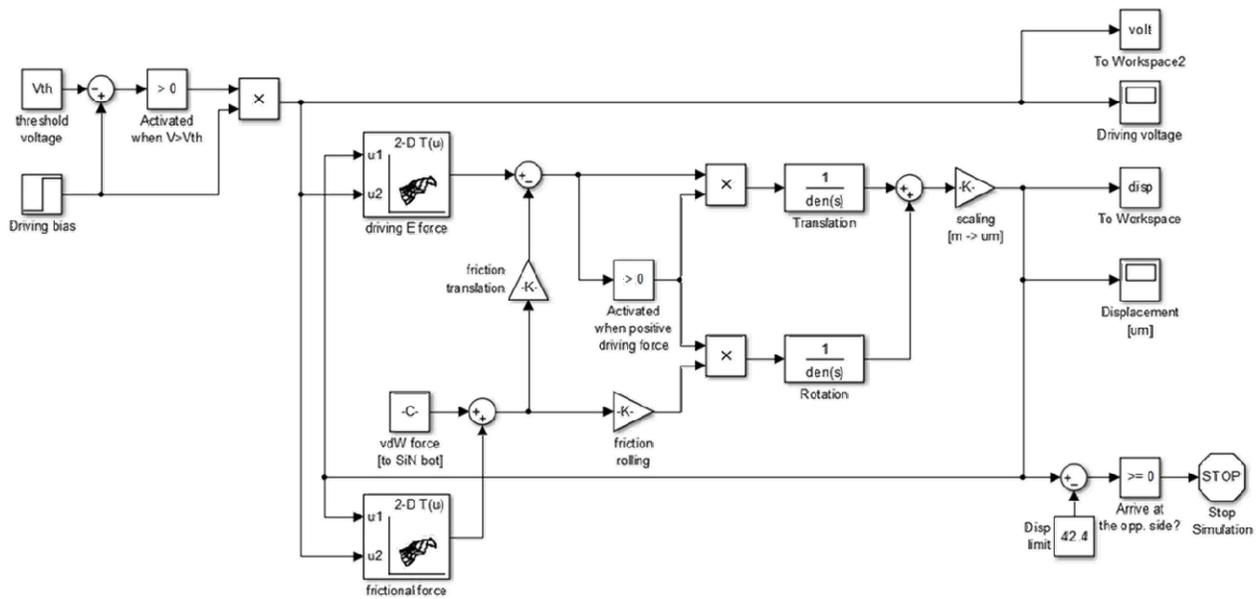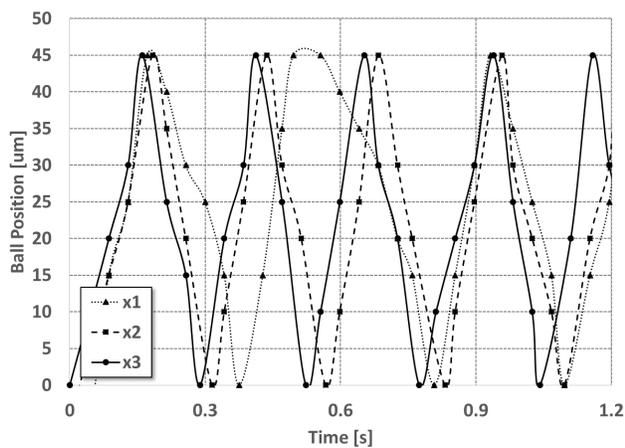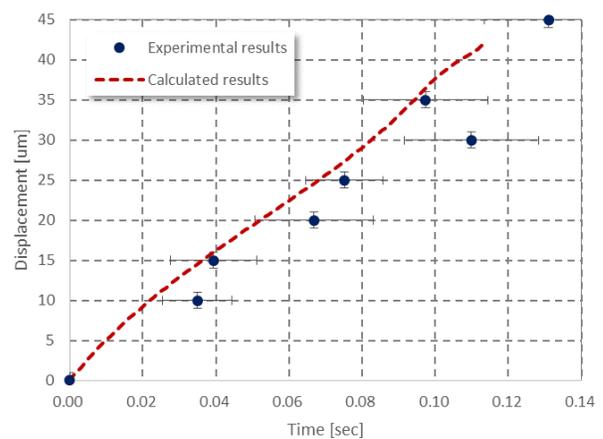

Figure 2. Realization of the developed transient model within MatLab Simulink environment.

(a) Experimental results of the ball locations

(b) Comparing the calculated results to the measured

Figure 3. Verification of the proposed transient model.

The proposed transient model was realized with MatLab Simulink as shown in Figure 2 and its results were compared to the measured results of the moving ball location as a function of time. As shown in Figure 3a, the ball positions were measured through optical inspection while applying the driving bias continuously. In order to obtain the reliable experimental results, 3 different samples were tested and all the measured data were summarized statistically as shown in Figure 3b. The calculated results were matched well with the experimental data including the nonlinear behavior in the ball positions. However, the proposed transient model predicted the faster response than the measured, which is expected due to the larger driving force as the static model resulted out the lower threshold voltage.

4. CONCLUSION

Here the transient model as well as the improved static model of novel display device of fast moving ball actuator were presented with the validation data. Although the expected threshold voltage from the improved static model was lower than the measured, it reflected the operation principle of the device more correctly. Then the transient model based on Newton's 2nd law was developed and realized within MatLab Simulink environment. Two governing equations for the translation and the rotation motions, respectively, were built by including the inertia and the fluidic damping. The calculated transient response was matched well with the measured, which verifies the accuracy of the proposed transient model. Several improvements are still needed to increase the accuracy more but the developed static and transient models can help us to get clear insight on FMBA operation and thus contribute to successful commercialization of FMBA as novel display.

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