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Modeling and Simulation of Electrostatic Attraction Force for Climbing Robots on the Conductive Wall Material

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***Abstract*-Electrostatic adhesion technology having good application prospects on wall climbing robots has been extensively investigated in recent years. In this paper, an accurate analytical model that is derived from ideal the parallel-plate capacitor consisting of two different dielectric layers in series has been developed by the Maxwell stress tensor formulation for the electrostatic attraction force between a conductive material wall and the flexible electrodes pad. The analytical model of the adhesion force is verified through comparing the calculation results with the simulation data by the ANSYS finite element technique. And the computation results are demonstrated to be good agreement with the simulation data. The parameters such as electrodes geometrical properties, applied high voltage magnitude and so on, affect the electrostatics adhesion force also been revealed in this paper.**

Index Terms – Electrostatic adhesion force; plate capacitor; wall climbing robot.

I. Introduction

Wall climbing robots has the capacity of travelling in complicated three-dimensional environments, such as the vertical walls, the ceiling, and cages, and performing various tasks including of security reconnaissance, structure inspection, testing and cleaning for instance[1,2,3]. Furthermore it has been an important research branch in the mobile robots and lots of works have been carried out so far. The attachment and movement mechanisms are the most key technologies for the wall climbing robots. To design a robot, the selection of adhesion mechanisms is one of the most significant aspects. The conventional available attachment methods are mainly based on the negative air pressure or magnetic force[4,5,6,7,8,9]. However, both of them have limitations in some cases. Air pressure adhesion needs air pump, Venturi tube or fan either on-board or external to it, which often leads to the large and heavy robots and noise, and this method works only on smooth and nonporous surfaces and can't work in vacuum environment. On the other hand, magnetic adhesion can work only on ferromagnetic walls though it can be realized by a rather simply structure and can produce a high attraction force.

Recently, bio-inspired adhesion approaches have been proposed as alternatives. A dry adhesion pad with thousands of the artificial tiny setae mimicking gecko's feet utilizes Van der Waals force to attach various wall materials with no residue left behind[10,11,12]. However, the artificial tiny setae are very sensitive to dust and moisture on the wall, which may lead to adhesion failure. In addition, fabrication of these fine elastomeric structures at micro level using nanotechnology is very expensive until now[13,14]. Another biomimetic approach that has been recently pursued is the use of an array of micro-spines to scale vertical walls that have some inherent surface roughness[15,16]. While this approach ensures good mechanical contact and is mostly independent of material contaminants or dust on a surface, it is difficult to climb on smooth surfaces with this method. The adhesion approach has become a bottleneck of development and application of wall climbing robots, so there has been a sustained interest in pursuing novel adhesion methods, which can benefit from simplicity, robust, light-weight and working stability of the robots.

More recently, electrostatic adhesion technology having been widely used in the clothing, semiconductor, solar panel, and flat-panel display industries, has shown significant potential in the application for the wall climbing robots[13,14,17]. Electrostatic adhesion mechanism utilizes electrostatic forces produced by an electrostatic adhesion voltage, which is applied to the electrodes embedded in the electrostatic adhesion pad. When the pad is positioned near the wall surface, the electric field, which is set up by the voltages between the electrodes, can polarize opposite charges on the wall surface and thus causing electrostatic adhesion force between the electrode pad and the surface of wall materials. Through previous researches, electrostatic adhesion possesses several advantages over other existing adhesion techniques for wall climbing robots, including robust clamping over a variety of surfaces (rough or smooth, conductive or insulating), workable on dusty and wet surface, low power consumption, electrically controllable clamping and unclamping, non-damaging nature, a simple structure, lightweight, and quiet operation[18].

However, the principle of electrostatic force generation for semiconductors or conductive materials is different from that of dielectrics. And the main purpose of this paper is to explore an accurate mathematical model of the electrostatic adhesion force on the conductive wall material. As mentioned in the literatures 14,17,19, the new electrode patterns, such as inter-digital electrodes, concentric circles or square spiral,

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possessing many boundaries having potential difference can be utilized for attracting to the dielectrics alternatively. Although the mathematical model in this paper is derived based on the conductive materials, it is still helpful for the optimum design of the electrodes pad for attraction to the dielectric materials.

Section II and III provide the modeling by deriving from force on the plate of a flat capacitor with two different dielectric layers in series and present the results of electrostatic adhesion force through the mathematic model and compared with the simulation data using ANSYS finite element software, and various parameters affecting adhesion force will also be discussed. Finally, the conclusion remarks is given in Section IV

II. Modeling and Calculation of Electrostatic Adhesion Force

Electrostatic fields, like the magnetic counterparts, can be used to provide an attraction force, known as electroadhesion[20]. Though the electrostatic force is generally relatively weaker than the similar magnetic force, and the significant force still can be created with an appropriate choice of the electrode adhesion pad's parameters.

A. Working Principle of the Electrostatic Adhesion Pads

As introduced in 13, 14, 17, the electroadhesion pads consist of a homogeneous and isotropic dielectric medium bearing conductive electrodes on its surface. As previously mentioned, the electrodes can have various patterns. Electrostatic adhesion technique, which is associated with Johnsen-Rahbek effect, makes use of electrostatic forces that are created between electro-adhesive pads and conductive or non-conductive materials, when a high voltage potential is applied to electrodes, as shown in Fig. 1. Electrons are free to travel in conductive materials, thus the negative electrons migrate under the positive electrodes and electron holes are created under the negative electrodes. This arrangement is similar to a set of capacitor. In non-conductive substrates, the electric field polarizes the substrate, which develops an electrostatic adhesive force[19,20].

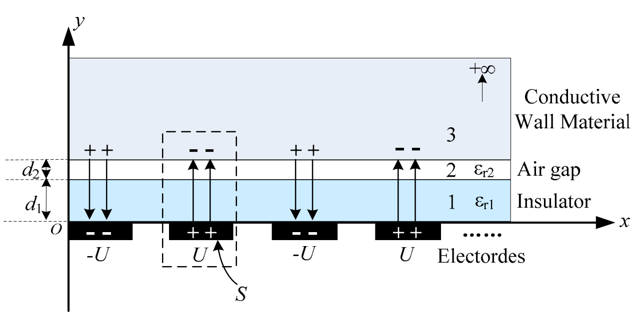

Fig. 1 The cross-section of an electrostatic adhesive pad with the insulating material in light blue and electrodes in black.

The conceptual diagram of electrostatic adhesion is illustrated in Fig. 1. The insulating layer of the pad and the air gap between pad and wall material prevent dielectric breakdown, otherwise resulting in the high short-circuit currents and drop of voltage[14,21]. The high voltage $\pm U$ are applied to the electrodes with each area of S. The insulating material thickness is d_1, and the relatively dielectric constant is ε_{r1}. And the thickness of air gap between the adhesion pad and wall substrate is d_2, and the relatively dielectric permittivity is ε_{r2}. However, the thickness of the wall material is infinite contrast to the pad.

B. Modeling of the Electrostatic Adhesion Force

And now, if the interaction between one electrode of adhesion pad and the conductive wall material is taken into consideration, neglecting the edge effect, a parallel plate capacitor model with two different dielectrics in series constitutes the basic theory to derive the electrostatic force, as shown in Fig. 2.

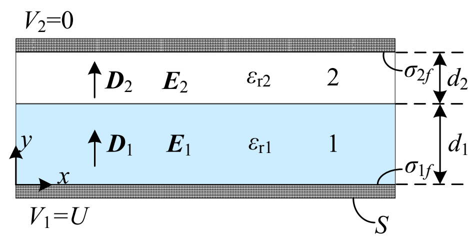

Fig. 2 A flat capacitor containing two layers of different dielectrics in series, the boundary surface between the dielectrics is parallel with the conductive plates.

Electrostatic adhesion force $\boldsymbol{F}$ acting on electrode in the electric field with electric field intensity $\boldsymbol{E}$ can be obtained by integrating the force density $\boldsymbol{f}$ with respect to any volume of it[22]. The Maxwell stress tensor in the presence of dielectric materials is represented as[23]

$$\boldsymbol{T}_{ij} = \varepsilon E_i E_j - \frac{1}{2}\varepsilon E_k E_k \delta_{ij} = \begin{bmatrix} \frac{\varepsilon}{2}(E_x^2 - E_y^2) & \varepsilon E_x E_y \\ \varepsilon E_y E_x & \frac{\varepsilon}{2}(E_y^2 - E_x^2) \end{bmatrix} \tag{1}$$

where $\boldsymbol{T}_{ij}$, ε and δ_{ij} represent the Maxwell stress tensor, dielectric permittivity and Kronecker delta, respectively. Then, the y-directional force can be written as follows.

$$F_y = \int_V f_y dV = \int_V (\nabla \cdot \boldsymbol{T}_{yy}) dV = \oint_S \boldsymbol{T}_{yy} dA \tag{2}$$

In Fig. 2, it can be seen that discontinuity in $\boldsymbol{T}_{yy}$ across the interface of dielectric materials and this will give us the traction acting on the surface of different materials as the jump $\langle \boldsymbol{T}_{yy} \rangle$, which is denoted by[24]

$$\left\langle \boldsymbol{T}_{yy} \right\rangle = \boldsymbol{T}_{yy}^{+} - \boldsymbol{T}_{yy}^{-} \tag{3}$$

where *plus* and *minus* notations indicate the values slightly above the surface in the y direction, or below the surface respectively.

The parallel plate capacitor model with two different dielectric layers in series is shown in Fig. 2. When a high voltage U is applied to the under plate (electrode) of the capacitor, the upper plate is induced to have opposite electric charges. Since the charges on the plates of the capacitor is in static equilibrium, the free surface charge densities σ_{1f} and σ_{2f} equal to each other as σ_f. In addition, there is no free charge on the boundary surface and the normal components of the electric displacement vector $\boldsymbol{D}$ are equal on both side of the surface ($\boldsymbol{D}_1$, $\boldsymbol{D}_2$) between the different dielectrics by applying the Gauss's electric flux theorem[25]. Thus, one can easily verify that the magnitude of total electrical field density is given by $\boldsymbol{E} = E(y)\hat{\mathbf{y}}$, with

$$E(y) = \begin{cases} 0, & y < 0 \\ \dfrac{\sigma_f}{\varepsilon_{r1}\varepsilon_0}, & 0 < y < d_1 \\ \dfrac{\sigma_f}{\varepsilon_{r2}\varepsilon_0}, & d_1 < y < d_1 + d_2 \\ 0, & d_1 + d_2 < y \end{cases} \tag{4}$$

where σ_f is the free surface charge density on the conductive plates, ε_{r1} and ε_{r2} are the relative dielectric permittivity of the insulating material and air, respectively. And the Maxwell stress tensor component can be expressed as

$$T_{yy}(y) = \begin{cases} 0, & y < 0 \\ \dfrac{\sigma_f^2}{2\varepsilon_{r1}\varepsilon_0}, & 0 < y < d_1 \\ \dfrac{\sigma_f^2}{2\varepsilon_{r2}\varepsilon_0} & d_1 < y < d_1 + d_2 \\ 0 & d_1 + d_2 < y \end{cases} \tag{5}$$

Because the potential difference is controlled rather than the surface charges in the electrostatic adhesion applications, equation (4) must be operated by integration along the y direction to derive σ_f using the formula as following:

$$U = \int_0^{d_1+d_2} E dy \tag{6}$$

And then,

$$\sigma_f = \frac{\varepsilon_{r1}\varepsilon_{r2}\varepsilon_0 U}{\varepsilon_{r1}d_2 + \varepsilon_{r2}d_1} \tag{7}$$

The electrostatic surface pressure will be derived first by(3), (5) and (7), the electrostatic pressure acting on the under plate i.e. electrode top-side of the capacitor as:

$$\begin{aligned} p_1 &= T_{yy}(0)^+ - T_{yy}(0)^- \\ &= \frac{\varepsilon_{r1}\varepsilon_{r2}^2\varepsilon_0 U^2}{2(\varepsilon_{r1}d_2 + \varepsilon_{r2}d_1)^2} \end{aligned} \tag{8}$$

And for the pressure acting on the surface of the two dielectrics is derived as:

$$\begin{aligned} p_2 &= T_{yy}(d_1)^+ - T_{yy}(d_1)^- \\ &= \frac{\varepsilon_{r1}\varepsilon_{r2}\varepsilon_0(\varepsilon_{r1} - \varepsilon_{r2})U^2}{2(\varepsilon_{r1}d_2 + \varepsilon_{r2}d_1)^2} \end{aligned} \tag{9}$$

Then the electrostatic pressure acting on back-surface of the upper plate of the capacitor (the conductive wall material) is represented as following equation:

$$\begin{aligned} p_3 &= T_{yy}(d_1 + d_2)^+ - T_{yy}(d_1 + d_2)^- \\ &= -\frac{\varepsilon_{r2}\varepsilon_{r1}^2\varepsilon_0 U^2}{2(\varepsilon_{r1}d_2 + \varepsilon_{r2}d_1)^2} \end{aligned} \tag{10}$$

where the negative sign indicates that the electrostatic force is opposite to the normal direction i.e. y-direction. It should be note that the hydrostatic force has been neglected during force formula derivation that may be present in the dielectric owing to its tendency to expand or contract in an electric field[25].

In the same fashion, for the case d_2 or d_1 equal to zero as shown in Fig. 2, then, equations (8) and (10) degrade into the basic pressure formulas of the parallel plate capacitor with only one layer of dielectric, that is,

$$p = \frac{\varepsilon_r\varepsilon_0 V^2}{2d^2} \tag{11}$$

where d represents the distance of d_1 or d_2, and the dielectric constant ε_r represents ε_{r1} or ε_{r2}, respectively.

The advantage of the calculation method revealed above is obviously that it can compute the resultant electrostatic force upon any boundary layer easily. Therefore, the resultant electrostatic adhesion force for the wall climbing robot which the electrode should be suffered can be derived by (8) multiplying by the electrode area S.

$$\boldsymbol{F}_e = p_1 \cdot S = \frac{\varepsilon_{r1}\varepsilon_{r2}^2\varepsilon_0 U^2 S}{2(\varepsilon_{r1}d_2 + \varepsilon_{r2}d_1)^2} \tag{12}$$

And the electrostatic adhesion force for the wall material can be computed by (10) multiplying by the area S expressed as:

$$\boldsymbol{F}_w = p_3 \cdot S = -\frac{\varepsilon_{r2}\varepsilon_{r1}^2\varepsilon_0 U^2 S}{2(\varepsilon_{r1}d_2 + \varepsilon_{r2}d_1)^2} \tag{13}$$

Let $k = \varepsilon_{r1}/\varepsilon_{r2}$, then

$$\frac{F_w}{F_e} = k = \frac{\varepsilon_{r1}}{\varepsilon_{r2}} \tag{14}$$

From (12)-(14), it is indicated that the electrostatic adhesion force is greater on the plate which is covered with the dielectric of less permittivity. Thus, for the case of mentioned above, the adhesion force acting on the wall material is k (> 0) times greater than that of electrode.

As introduced previously, the electrostatic attractive force is much weaker. From the above(12), it can be seen that the adhesion force upon the electrode is directly proportional to the square of power supply and inversely proportional to the square of the thickness of the insulator and air gap. For this reason, to improve the force, the electrostatic adhesion pads often use the kV power supply and reduce the thickness of the dielectrics layer bearing the electrodes to micron level. And these parameters will all be discussed in the part III.

C. Material for Electrostatic Adhesion Pad

And now, the materials should be determined for the electrostatic adhesion pad. Copper is customarily selected for electrode material. The insulating material is chosen based on the mechanical elongation properties [26]. Here three conventional insulating materials are selected for simulation and analysis, as listed in Table I with the respective electrical features. For the PE material with the dielectric strength of 20kV/mm, if the thickness d_1 is set at 50μm, then the applied power U must not exceed 1kV, otherwise electrical breakdown will occur.

Table I
The electric properties of the insulating materials

Name	Relative Permittivity	Dielectric Strength [kV/mm]
Polyethylene (PE)	2.2	20
Polypropylene (PP)	2.2	24
Polyimide (PI)	3.5	150

For the case of the mono-polar type electrostatic adhesion pad, the Fig. 3 of electrostatic adhesion force versus the relative dielectric constant ε_{r1} of insulating materials is computed by (12), with the typical input parameters: S=2×60 (mm^2), the thickness d_1=50μm, air gap d_2=5μm, dielectric constant of air ε_{r2}=1, the applied voltage U=1kV.

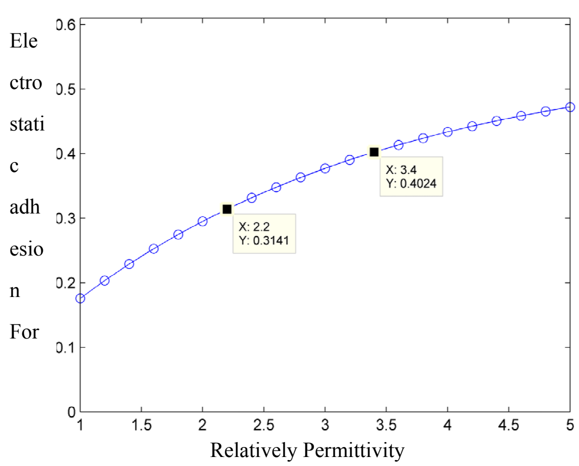

Fig. 3 The electrostatic adhesion force verses the relative permittivity of the insulator material.

As shown in the graph above, the electrostatic force is enhanced with the increase of the relative dielectric constant when other parameters are fixed. Thus, the Polyimide materiel is more suitable for the manufacture of the electrostatic adhesion pad, for the reason that PI has larger value of relative permittivity and margin for the applied high voltage. And the following analysis and simulation is based on the PI material.

III. Results of Finite Element Analysis and Discussion

This part the electrostatic adhesion force, analyzed by the FE commercial software ANSYS 12, is compared with the computation results using(12). The finite element electrostatic analysis makes use of the P-method to indicate the conductive wall material surface on which the electrostatic force distribution is to be calculated when setting the Maxwell Force Flags (MXWF). And the 20-node, Solid 128 element is selected for the analysis. And 0 volt boundary condition is applied on the lower surface of the wall material as shown in Fig. 1.

The electrostatic adhesion force generated by the electrode pad above depends on many parameters, including the applied voltage, the thickness of the air layer and insulating layer, the permittivity of the insulator which has been analysis in section II, as shown in(12). In addition, atmospheric humidity and the electric conductivity of the wall and insulating material also can influence the electrostatic adhesion force to some extent[13]. And next, the simulation is performed using the ANSYS 12 to verify the calculation model established above.

A. *Excitation Voltage*

The effect of the excitation voltage on the electrostatic adhesion force is fist analyzed by keeping other parameter constant. As illustrated in Fig. 4, the force improvement with increase of the driving voltage has a relation of quadric parabola. Therefore, a larger adhesion force can be achieved through the method of increasing excitation voltage, in the case of that the insulting layer is under electrical safety.

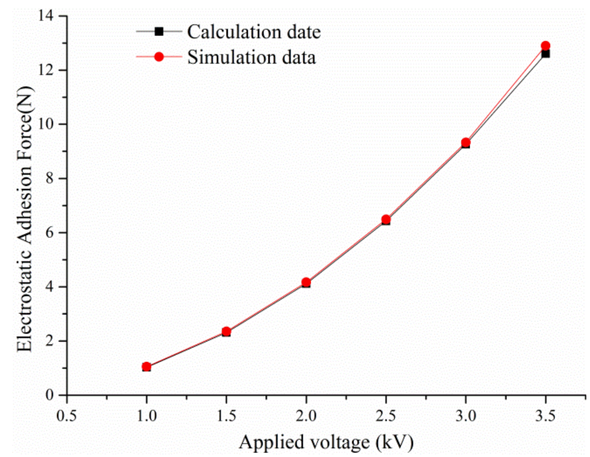

Fig. 4. Excitation voltage versus the electrostatic adhesion force with the input parameters: d_1=25um, d_2=5um, ε_1=3.5ε_0, ε_2=ε_0=8.854×10^{-12}(F/m), S=2×60 (mm^2).

B. *Thickness of the Air Gap*

Due to the roughness of the wall surface, the electrode pad can't contact the wall completely perfect, which leads to the existence of an air gap between the electrode pad and the wall material. And to simplify the adhesion model, the thickness of the air layer is assumed to be uniform. The adhesion force varies from 11.3 N to 1.3 N with the thickness increase of the air layer from 0.25μm to 15μm, as exposed in Fig. 5. The results indicate that it too difficult to get sufficient adhesion force in the rough wall, so the flexibility of electrode pad should be improved to make a perfect contact with the wall obtaining a stronger adhesion force, as shown in 13 and 17.

C. *Thickness of the Insulating Layer*

The thickness of the insulator can't be made too small to prevent it breakdown. On the other hand, the electric field will be weakened as the thickness increases, which will cause the electrostatic adhesion force decrease. Fig. 6 reveals the electrostatic adhesion force decreases from 10N to 0.36N with the thickness of the insulating layer varies from 10μm to 130μm. It's obvious that the thickness of insulating layer has a profound effect on the electrostatic adhesion force. And the thinner the insulating material is, the greater adhesion force will achieve.

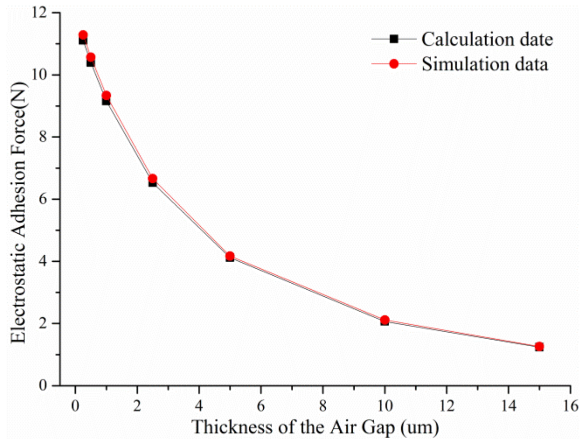

Fig. 5 Thickness of air gap affects the adhesion force with the unchanged parameters: d_1=25um, ε_1=3.5ε_0, ε_2=ε_0=8.854×10^{-12}(F/m), S=2×60 (mm^2), U=1kV.

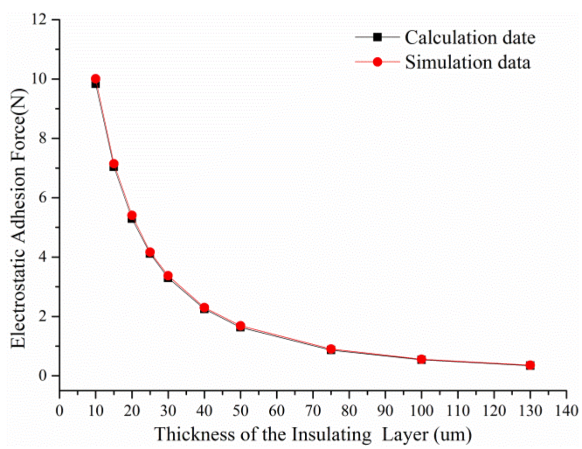

Fig. 6 Thickness of insulator influence on the adhesion force with the unchanged parameters: d_2=5um, ε_1=3.5ε_0, ε_2=ε_0=8.854×10^{-12}(F/m), S=2×60 (mm^2), U=1kV.

D. *Comparison with the reported experimental data*

The calculation and simulation results are also compared with the reported experimental data in [17]. In the literature, the bi-polar type electrostatic adhesion pad is fabricated with each area of 50×120 mm^2. And the thickness of insulating material Polyimide is 75μm. However, the thickness of air layer hasn't been taken into account in the analysis model utilized in the literature bringing about that the computation results are much larger than the experimental data. Thus, 5μm thickness of air layer is considered in the analysis model for the bi-polar type adhesion pad for new calculation and simulation. As shown in Fig. 7, the AC high voltages are applied from 0.5kV to 2kV, and a very good agreement is found among the calculation data, simulation data and experimental data, which indicates that the calculation method for the adhesion force on the conductive wall material presented in this paper is correct. Although the adhesion model is derived under the specific condition, this is also of significance to the electrostatic adhesion pad designing.

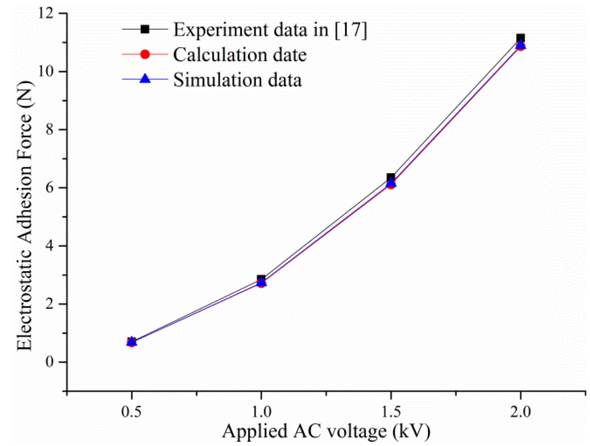

Fig. 7 The comparison among the calculation data, simulation data and experimental data, with the parameters: d_1=75um, d_2=5um, ε_1=3.5ε_0, ε_2=ε_0=8.854×10^{-12}(F/m), S=120 (cm^2).

IV. CONCLUSION AND FUTURE WORK

In this paper, an accurate analysis model of electrostatic adhesion force on the conductive wall material is established for the wall climbing robot. The model is derived from the parallel plate capacitor utilizing the Maxwell stress tensor and with the advantage of that the electrostatic adhesion force can be expressed for each interface of dielectric materials. And the computation results are established to be good agreement with the simulation data. The influence factors affect the adhesion force is also analyzed and discussed in detailed. The future work will focus on the mathematical models for electrode patterns working on the dielectric materials by solving the Laplace equation. And the electrostatic adhesion pad configuration will be optimized according to the adhesion force model, then manufactured and tested on different wall materials.

ACKNOWLEDGMENTS

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