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Sensitivity analysis of nanoparticles manipulation based on different friction models

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ABSTRACT

The advent of miniaturization and transition from the macro world to the micro/nano world has brought into existence materials with more ratio of area to volume. In transition from the macro world to the micro/nano world, surface forces such as friction and adhesion that were formerly less significant or even negligible are under solemn scrutiny. In this respect, various friction models have been developed by numerous researchers in an effort to model the governing conditions in the micro/nano manipulation. In this paper, nanoparticle displacement dynamic modeling and simulation in AFM-based manipulation is addressed using advanced friction models in the nano scale including HK and LuGre which are both on the basis of true contact surface. Moreover, the effect of accurate modeling on the process of manipulation is compared with the results of the previous model. In addition, critical force and time variations by using different friction models are analyzed under the influence of model parameters. Previous research entailed a simplification of nanoparticles manipulation modeling using modified Coulomb friction model and assuming apparent contact surface while in reality, true contact surface is much less than apparent contact surface due to the raggedness of surfaces. This causes a significant decrease in friction force and hence manipulation critical parameters. Implementing an accurate friction model upgrades the precision of the prior less complex models. Simulation results show that the predicted critical force necessary for the initiation of particle movement by HK and LuGre models are reduced by 15.87% and 22.22% respectively and the critical time by 50% and 75% respectively compared to Coulomb model.

1. Introduction

The Atomic Force Microscope (AFM) has been very much sought after as a fundamental tool for displacing nanoparticles and building desired objects made of atoms and molecules [1,2]. Manipulation modeling is a major tool for precise and controlled displacement of nano/micro scale particles and objects. Since, with the size reduction and transition from a macro world to a world of micro/nano, the ratio of area to volume has increased for the materials involved, and surface forces such as friction and adhesion become more significant [3], therefore, different friction models have been presented that take into consideration, the real conditions of motion on a nano scale. The manipulation and the friction models are fundamentally interdependent. In fact, the success of the manipulation model in predicting the experimental results depends, to a large extent, on the accuracy of the applied friction.

In recent decades, many studies have been undertaken on the subject of accurate modeling of nanomanipulation based on the application of an AFM probe as a nanomanipulator [4–8]. The initial model for driving of nanoparticles and the reaction forces applied on the particle has been presented by Falvo; however, surface adhesion forces have been ignored in this model [9]. Then, to consider the surface adhesion factor, a control system was devised by Sitti for driving of nanoparticles by applying the JKR contact theory, which was aimed at controlling the particle displacement semi-automatically [10]. To speed up the manipulation, Zhou et al. [11] have used moment analysis of forces exerted on a microsphere. Rifai et al. [12] have introduced a nanomanipulation model which includes the dynamic couple of the micro-cantilever lift and the AFM piezotube operator tension. Also, Sumer and Sitti [13] have investigated the slip and roll of micro/nano particles and the critical conditions of boundary transition from slip to roll. Tafazzoli and Sitti, by applying the JKR contact theory, have offered a model [14,15] which simulates the dynamic behavior of a particle while it is driven on the substrate. Korayem and Zakeri have further developed the dynamic model and investigated the changes of critical force and time in nanoparticle manipulation based on the changes of geometric parameters and material [16].

Because of a major role it plays in the modeling of mechanical systems, friction has caught the attention of the researchers

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in recent decades [17]. In fact, the macro-tribologic behaviors of materials, because of differences of friction and grinding processes, cannot be easily associated with their nano-tribologic behaviors [18]. It has become obvious through FFM measurements that the friction laws for nano-scale single protrusions differ from those of the macroscopic scale. The main results of several FFM tests have confirmed that the friction force on the scale of nano behaves in a saw tooth manner commonly known as stick–slip [19–22] and the nano-scale friction strongly depends on velocity [23,24]. In addition, the physics of the sticking phase is different from that of the slipping [21].

It should be noted that most of the nanomanipulation models presented in research articles have the drawback of being essentially dependent on the Coulomb friction model and this model is incapable of estimating the pre–slip conditions and creating the stick–slip movement. The new research has made it possible to gain a deeper understanding of friction on the atomic scale and it has been made possible through the analyses of contacts between single asperities [25–27].

Therefore, to study friction and to explain its dependency on scale, different methods have been proposed. Some researchers have suggested the expressions: “the effects of scale on friction” or the “principles of scaled friction” [3]. A comprehensive nano-scale friction model capable of simulating the dynamic of the stick–slip phenomenon, will allow a more precise design of nanomanipulation models. Scale dependency of the friction force has been investigated by Hurtado and Kim (HK) [28,29]. The HK model provides a term for the friction stress behavior in a large spectrum of contact levels including the nano-scale contacts [30]. On the other hand, the LuGre friction model [31] is able to reproduce the 2-D stick–slip phenomenon with the lattice period, and it also possesses appropriate computational properties which makes it suitable for process control [32,33]. So, the type of friction model used in the process influences the dynamic behaviors of the nanoparticle and nanomanipulator, and therefore, should be taken into consideration in the precise modeling of nanomanipulation.

In this paper, first, the appropriate friction models applicable for micro/nano scales are studied and then the manipulation process is defined. Subsequently, the dynamic equations pertaining to manipulation of nanoparticles are presented and finally, the dynamic equations of the system are simulated by using the more precise friction models, and the obtained results are analyzed by comparing them with those of the previous studies.

2. Micro/nano scale friction models

Researchers have always focused on friction, due to the important role it plays in modeling of the mechanical systems. The fundamental laws of friction have been put forth several centuries ago by Da Vinci, Amontons, and Coulomb. With growing need for manufacturing fine instruments on the micro/nano scale, friction studies have gained a new dimension [34]. Investigation of friction on atomic scale has been made possible through the analyses of contacts between single protrusions, and it has been demonstrated that the friction laws for single protrusions are different from those of the macroscopic scale [18–20]. The results from various experiments have confirmed that the friction force on the scale of nano behaves in a saw tooth fashion commonly known as stick–slip [22–24,21]. Fujisawa et al. [35,36] after a series of experiments showed that this phenomenon has a periodic relation with the atomic lattice configuration of the sample surface and is dependent on the surface scan direction. As a result, the scanning instrument’s tip sticks to separate adhesion points and its movement in lower velocities becomes periodic.

For definition, the friction force (F) is the tangential force resisting the relative movements of two surfaces which are pressed together by the vertical force (P). This notion of a dry friction between two objects in touch was presented by Amonton in 1699 and by Coulomb in 1875. The Amontons–Coulomb friction principle states that during sliding, the ratio of the friction force to the vertical force remains constant; this ratio is called the coefficient of kinetic friction. Similarly, the coefficient of static friction constitutes the ratio of the maximum friction force to the vertical force. The friction coefficient μ expresses the law of friction as:

$$\mu = \frac{F}{P} \tag{1}$$

Experimental results show that the static friction is usually larger than the dynamic one. With the advancement of science, and because of the inability of the existing models in predicting the friction behaviors of systems, extensive studies have been carried out on the subject, which have led to the development of more exact models. Friction, in general, is known as the resistance against the movement of the protrusions of one surface over those of another surface [37]. Bliman and Sorine [38,39] have presented a group of experimentally based dynamic models of friction in which friction is only a function of route and does not depend on motion velocity of the system. Haessig and Friedland [40] have offered the bristle friction model that simulates the behavior of microscopic contact points between surfaces and in it the number of contact points and their positions are generated randomly. This model, because of its complexity, is not used very much for simulations. The Dahl model [41] has been developed for the purpose of simulating the control of frictional systems. This model represents a general case of the Coulomb friction. The mentioned models do not account for the effects of stiction and Stribeck, which are velocity-dependent phenomena and important in the estimation of micro/nano scale frictions; these effects were later added to the said models in subsequent research works. Hurtado and Kim presented the HK model based on the Coulomb friction model considering the stiction effect, and finally, Canudas de Wit et al. presented the LuGre model developed from the Dahl model, which includes the Stribeck and stiction effects. Thus, in this article, to increase the precision of nanoparticle manipulation models of previous research works that were based on the Coulomb model [10–16], the HK and LuGre models have been used; in the following sections, these models are discussed in more details.

2.1. HK friction model

The Hurtado and Kim developed a single-asperity nano contact model incorporated into a multi-asperity model for contact and friction which includes the effect of asperity adhesion forces using the Maugis–Dugdale model. In their investigation, the dimensionless shear stress is a function of the dimensionless contact radius and is approximated by [30]:

$$\log\,\bar{\tau}_f = \begin{cases} \log\,\bar{\tau}_{f1} & \bar{a} < \bar{a}_1 \\ M\,\log\,\bar{a} + B & \bar{a}_1 < \bar{a} < \bar{a}_2 \\ \log\,\bar{\tau}_{f2} & \bar{a} > \bar{a}_2 \end{cases} \tag{2}$$

where the left and right limits of region-2 are $(\bar{a}_1, \bar{\tau}_f)$ and $(\bar{a}_2, \bar{\tau}_{f_2})$ respectively. The constant parameters in the above equation are:

$$M = \frac{-\log(\bar{\tau}_{f_1}/\bar{\tau}_{f_2})}{\log(\bar{a}_2/\bar{a}_1)}$$

$$B = \frac{\log(\bar{\tau}_{f_1})\,\log(\bar{a}_2) - \log(\bar{\tau}_{f_2})\,\log(\bar{a}_1)}{\log(\bar{a}_2/\bar{a}_1)} \tag{3}$$