Contact mechanics modeling of piezo-actuated stick-slip microdrives

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This paper draws a line from early attempts of modeling stick-slip microdrives to open questions from today’s research. As a basis, it contains a collection of substantial investigations on piezo-actuated stick-slip microdrives for nanomanipulation purposes. Friction models showing special characteristics and their mathematical representations are reviewed. It is found that the working properties of stick-slip drives strongly depend on friction characteristics of the contact points between the guiding elements, which is known for years. However, numerous publications in the field of friction and remaining problems — which cannot be explained by known friction models — indicate that there is a demand for even more friction-related research.

Former attempts to model stick-slip drives are based on the so-called LuGre friction model, which is shortly presented. An empirical model called CEIM is also analyzed. It is an adaption of the elastoplastic model. The latter can cover not only the phenomenon “0-amplitude” (described by the authors in recent publications), but also stick-slip based force generation scenarios. Nevertheless, interesting friction characteristics such as the generation of μN forces with stick-slip drives, which are already proven, cannot be covered by known friction models. It is pointed out which characteristics have to be considered.

Keywords: stick-slip drive, actuator, contact mechanics, piezoelectric

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1. Introduction

The stick-slip microdrives have been used widely and effectively in miniaturized micro- and nanoposition and manipulation systems. Their main advantages are the simplification in design and very good working characteristics which offer a theoretically unlimited smooth motion accompanying with a very high resolution of several nanometers working in stepping and scanning mode, respectively. These intrinsic properties have been exploited for many applications in the field of micro- and nanorobotic.

The stick-slip drives were introduced for the first time in the literature by Pohl [1] for the purpose of micropositioning of an object inside the scanning tunneling microscopy. It is simply a one degree of freedom translational stage actuated by a piezoelectric tube using the motion principle called “stick-slip”. The typical components and the principle of the stick-slip drives are briefly illustrated in Fig. 1. The stick-slip principle is carried out by a sequence of a stick-phase and a slip-phase. During the stick-phase with a slow deformation of the piezoelectric element, the runner moves along with the actuator due to the static frictional forces appearing at the contacts between the touching elements of actuator and runner. This phase is followed by the slip-phase, in that the piezoelectric element deforms rapidly in the opposite direction. Because of the inertial force, the runner cannot fully follow this movement and therefore, the runner slides on the guiding system; as a result, a step is performed after a small back-step.

In order to achieve a required simplification in design, a multiple number of piezoelectric actuators are combined to serve usually not only as the actuating elements but also the supporting and guiding system for the runner. However, the consequence of this integration is that the motion characteristics of the drive depend strongly on the dynamic behavior of the whole system, where contact mechanics between actuators and the runner plays an important part.

The contacts in stick-slip microdrives determine mostly their dynamical characteristics such as step length, back-step, and the amplitude, frequency and damping time of the microvibrations which are exerted after the slip-phase. Wear properties and lifetime of stick-slip microdrives are also influenced by the contact mechanics. It is known that stick-
slip microdrives are quite mature and several prototypes developed into commercial products [2]. However, there has done only little research in the domain dealing with an increase of reliability or in deep analysis of tribology aspects.

For this reason, the present paper focuses on several aspects governing the contact mechanics of stick-slip microdrives, in that the up-to-date friction models are deeply analyzed. After the introduction, mechanical models of such devices are presented. The paper reviews attempts to model stick-slip microdrives based on the so-called LuGre friction model, which is the most promising approach for a long time. The elastoplastic friction model, an extension of the LuGre model is also analyzed, which can cover the important phenomenon of 0-amplitude. Moreover, a new friction model called CEIM is discussed, based on the elastoplastic model and enlarging the model capabilities. Finally, the authors present latest results concerning the generation of μ-scale forces using stick-slip drives. The results show that even the sophisticated models presented before fail in achieving similar results. Thus, contact mechanics modeling has to be improved in general.

2. Mechanical modeling

The first extensive attempt to model stick-slip drives was implemented by Breguet [3]. It is the model of a one degree of freedom translational drive using shear piezo-electric actuators. By using the so-called LuGre friction model, the author is successful to obtain essential results from the simulation and measurement. However, the presented model seems to be too simple and does not satisfy in many mechanical aspects, especially the tribology issues. In this paper and for further investigations, we present a new mechanical model which describes the dynamic behavior of a one degree of freedom transitional stick-slip manipulator developed in our division.

Figure 2 shows the actual structure of the manipulator which can be viewed as the runner. The manipulator is integrated into a mobile microrobot to form a four degree of freedom mobile microrobot for the purpose of micro- and nanohandling. A tool (here a gripper) for manipulation task is attached to the runner. In this design, the runner is actuated, supported and guided by six piezoelectric actuators which are arranged in a defined configuration. The preload, which is necessary for the function of the drive, is created by using flexible hinge structures integrated in to the runner.

Generally, the dynamic behavior of the drive depends on the dynamics of each individual actuator and the contact dynamics between actuators and runner. In fact, they exhibit deviations because of their fabrication tolerances and the asymmetric constraint of the runner. The latter makes the dynamic response of each actuator different. Therefore, we propose to model each actuator separately. As a result, the mechanical model of the drive has at least two parts: dynamic modeling of each individual actuator and the dynamic modeling of the runner (rigid-body kinematics).

2.1. Modeling of the actuator

The structure of one of the six actuators in 2-dimensions is shown in Fig. 3(d), which includes three main components: the ruby hemisphere, the glue layer and the laser-structured piezoceramic part. Figure 3(e) shows the mechanical model of the actuator in an actuated position. Here the ruby hemisphere is supported on two columns that act as highly symmetrical piezoelectric actuators. The nominal height of each of actuator is $h_0$ and the skew symmetric displacements are $y_1$ on the left hand side and $y_r$ on the

![Fig. 1. Drive configuration and stick-slip principle: initial position (a), stick phase with slow expansion of the piezoelectric actuator (b), slip phase with rapid contraction of the actuator (c), the deformation of the actuator (d)](image1)

![Fig. 2. The design of the vertically translational manipulator](image2)