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Decomposition of stiffness and friction tangential contact forces during periodic motion

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ABSTRACT

The purpose of this paper is to introduce techniques used in experimental analysis and simulation of the internal resistance force in mechanical contact. We are presenting an idea and a method to separate the internal resistance into two force parts, the spring stiffness and the dissipative friction. This separation is based on the proven dependency for the projections of the phase angle between the displacement and acceleration of the periodic motion. By combining the Hilbert transform analysis with the phase relations of the simultaneously measured applied force and the vibration response we are able to estimate the nonlinear separated spring stiffness and dissipative friction force parts in the contact interference. Theoretical analysis and experimental measurements are presented as well as simulated verification results.

1. Introduction

For stage control applications, involving point to point positioning, friction analysis, modeling and compensation can be very important. The tighter the requirements for the precision and the settling time, the more important becomes the understanding and operation of the friction mechanism. Along with dissipation friction, an elastic behavior in frictional contacts is directly observed, e.g. in pointing systems and high-precision machine tools [1].

1.1. Internal resisting force

Friction is generally described as the resistance to tangential motion when a body slides against a surface. It is well-known that during the motion and depending on system parameters, the body may continuously move or it may come to a stop during parts of each cycle. Thus there could be two main possible motions: stick (pre-sliding regime when the velocity of the body is close to zero) or slip (sliding regime when the velocity takes essential values) [2,3].

It is also well-known that after applying an external force, the system initially reacts as a spring and the mass moves a small distance till it reaches a steady state [4]. Much work has been done in the past to understand the behavior of mechanical contact systems. The main purpose of the following short literature review is to gain more insight into the available elastic-frictional contact models and their differences.

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1.1.1. Static models of friction

Basic resistance friction models were first suggested. In these models, the friction force depends solely on the velocity and can be described as an algebraic function of the velocity. These models are the simplest viscous damping element friction proportional to relative velocity (physically justified for lubricated contacts) and the sliding friction element as a dry or Coulomb damping proportional to the normal force. The experiments of the sliding lubricated surface showed the typical form of the resistance force, for a particular critical relative velocity [5].

When the relative velocity is close to zero the friction force cannot be described as a function of velocity alone. Karnopp [4] proposed different sets of conditions for the description in the stick, slip and transition phase in the small neighborhood of zero velocity.

1.1.2. Dynamic models of friction

In the suggested dynamic resistance models, small pre-sliding displacements appear, at which the friction force is also a function of the displacement. Dahl assumed that friction force is not only a function of the velocity but of displacement as well [4,6]. The Dahl-type friction-stiffness combination model [7], particularly the LuGre model [8], overcomes the need to have two structures in the friction model. A single state variable qualitatively models the state of elastic deformation in the contact for small displacements. The modified Leuven integrated friction model further improves the LuGre model by including pre-sliding hysteresis with nonlocal memory [9]. The elasto-plastic friction model [6] provided a modification that solved this position-drift issue with the LuGre model. The generalized Maxwell slip model (GMS) [10,11], as a further development of the modified Leuven model, explains two possible motions for the block: stick (velocity of block equals velocity of base) or slip (velocity of block different from velocity of base).

The models mentioned so far are all empirical models based on heuristic approach. From another point of view, there are also the so called physics or mechanical-motivated resistance force models, which describe friction on physical levels of atomic-molecular and tectonic-plate level [12].

1.1.3. Elasto-plastic and crack-like detachment in contact

Under appropriate contact conditions a strong connection exists between the frictional sliding response and the material elasto-plastic properties [6]. Following the elastoplastic deformation [6], motion in a friction contact can be characterized by three regimes: purely elastic displacement; mixed elastic and plastic displacement; and, purely plastic displacement. Another proposed two-state dynamic friction model with elasto-plasticity combines two nonlinear state variables: one independent and one dependent friction states which capture the pre-sliding hysteresis and transient sliding response [13].

Recent studies have shown that the transition from static to dynamic friction (i.e. from stick to slip) is mediated by collective motion along the interface that is embodied by rapid crack-like detachment fronts [14]. The dynamic evolution of the frictional strength is closely linked to the rapid processes of contact detachment and subsequent reattachment that are precipitated by these fronts. This evolution enables the mean (slow) motion of frictionally sliding bodies. The rapid fracture process is a distinct process that significantly modifies the character of the interface, sets the stage for slip to take place and actively enables the ensuing slip dynamics [14].

1.2. Suggested view of friction

1.2.1. Friction as mechanism of damping

A harmonic external force F_{external} applied to the mass can generate a steady-state vibration response $x(t)$ representing the sustained forced vibrations. The power, P, (the rate of work) done by the external force, $F_{\text{external}}(t) = F_A \cos \omega t$, on the forced vibration, $x(t) = A\cos(\omega t - \alpha)$, by definition is a product,

$$P = F_{\text{external}}(t)\dot{x}(t) = -F_A \cos \omega t A\omega \sin(\omega t - \alpha) = 1/2F_A A\omega[\sin \alpha + \sin(2\omega t + \alpha)], \tag{1}$$

where α is the phase angle between the driven object position and the applied force. The constant part, $1/2F_A A\omega \sin \alpha$, is an active power, while the oscillation with doubled frequency part, $1/2F_A A\omega \sin(2\omega t + \alpha)$, is an idle power.

The mechanical work is done when a force overcomes a resistance and it moves through a distance. Thus the average work W, done by the force during a time interval, T, over a cycle, is

$$W = \int_0^T P dt = 1/\omega \int_0^{2\pi} P d(\omega t) = \pi F_A A \sin a \tag{2}$$

and is not affected by the idle power. The produced mechanical work is the amount of dissipation energy transferred by an applied force in one period of vibration. The loss of the energy dissipated in each cycle due to resistance is made up by the energy supplied through the external force to maintain the steady forced vibration. Thus, only the part of the resistance force, shifted in phase relative to the motion, controls the energy dissipation in contact. This part arising from the relative motion is a well-known source of energy dissipation and is the dissipative friction force.