$F_d = f [ N - (ma_y + \eta v_y) ]$
MECHANICAL ENGINEERING | RESEARCH ARTICLE

Probing into frictional contact dynamics by ultrasound and electrical simulations

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Abstract: Friction arises in the interface of friction pair, and therefore, it is difficult to detect it. Ultrasonic means, as a NDT, is the correct alternative. This paper introduces a means of detecting dynamic contact and an interpretation of behaviors of dry friction. It has been determined that frictional surfaces have a specific property of dynamic response hardening (DRH). Dynamic response forces and oscillation arise during static–kinetic transition process. While the contact zone of sliding surfaces appears “hard” in motion, it appears “soft” at rest. Consequently, a separation of the surfaces occurs and the real area of contact is decreased as sliding velocity increases. This is the cause of $F-v$ descent phenomenon. When the friction comes to a rest, the remaining process of DRH and micro-oscillation do not disappear instantaneously, instead they gradually return to their original static position. The contact area, therefore, is increased by rest period ($F-T$ ascent characteristics). Based on analogies between a solid unit ($\eta-m-k$) and an R-L-C circuit, the DRH is demonstrated by electrical simulations.

Subjects: Mechanical Engineering, Mechanical Engineering Design, Tribology

Keywords: contact mechanics, dynamics, friction, stick–slip

1. Introduction

In the field of contact mechanics, dynamic friction is a very complex problem. Berman, Ducker, and Israelachvili (1996), Feeny, Guran, Hinrichs, and Popp (1998), Wensrich (2006), Nakano and Maegawa (2009), Thompson and Robbins (1990) and Li (1983) studied the subject on the stick–slip mechanisms. But there are still many issues to be explored. They include how to detect the dynamic contact process, how to explain the mechanism of the stick–slip, how to explain the mechanism of $F-v$ descent characteristics (the real area of contact is significantly decreased with velocity); the $F-T$ ascent characteristics (the contact area increases exponentially with rest period) and the cause of friction vibration (stick–slip).

ABOUT THE AUTHOR

Our group is engaged in ultrasonic applications and tribological studies. We published a book named Ultrasonic Engineering and papers more than 20, over half of which is related to friction mechanisms, friction test methods, and surface dynamic response hardening.

PUBLIC INTEREST STATEMENT

In the field of tribology, four issues are to be explored. They are the mechanism of the difference between static and kinetic friction; the $F-v$ descent characteristics (the real area of contact is significantly decreased with velocity); the $F-T$ ascent characteristics (the contact area increases exponentially with rest period) and the cause of friction vibration (stick–slip). Friction arises in a closed space, and therefore, it is difficult to detect it. This paper presents ultrasonic means, as a NDT, to detect dynamic contact and to show relationships among parameters simultaneously. What’s more, this paper describes the kinetic friction process in a non-traditional way, that is, the friction characteristics are demonstrated by means of electrical simulations.
descent characteristics, and $F-T$ ascent characteristics. The Bowden and Tabor (2001) model of adhesion explains the difference between static and kinetic friction and lays the foundation for the study of adhesive wear. This model cannot explain the kinetic friction process though.

Jin and Yu (1981) and Jin (2013) conducted a study on dynamic response hardening (DRH). Based on previous studies, this paper seeks to discuss the issue by means of DRH and electrical simulations.

2. Experiments
In order to observe the kinetic contact behavior, two experiments were carried out.

2.1. Experiment one: electrical resistance measurement
The friction pair is connected to a bridge arm of a strain gage. It can be seen that there is a considerable V-drop at the time stick–slip occurs (Figure 1(A)). This means that there is a serious decrease in contact area. Figure 1(B) also shows that adhesion occurs and that steel-to-steel is not a perfect match because they easily stick together.

2.2. Experiment two: ultrasonic means
In the process of conducting qualitative analysis, the electrical resistance measurement is an effective way to measure the contact area. However, the study found that the electrical resistance is not proportional to the contact area. Compared with others, ultrasound is an effective means. Ultrasonic waves propagate along a rectilinear direction and reflect at the gap of the interface. Therefore, the ultrasonic energy passing through the contact area is approximately proportional to the contact area. Kendall and Tabor (1971) successfully demonstrated the area of contact between stationary and sliding surfaces by ultrasonic means.

The ultrasonic detection system of the authors is shown in Figure 2. When an ultrasonic generator (1, 3) emits ultrasonic wave beam to the friction pair (8), the ultrasonic energy that transmits through the contact area is received by the probe (7) installed opposite and handled by a signal processor and computer.

In order to synchronize the mechanics and the computer, the synchronize-start signal is obtained from the velocity sensor (4). Therefore, as soon as the upper block moves, the signal representing the contact area (curve A) and the signal of relative velocity (curve V) are recorded simultaneously by the computer.
Figure 3 is the interface circuit. ADC0809 is an analog-to-digital convertor. The computer clock 2 MHz is divided by MM74C74 and provides clock to ADC0809. 74LS12 is used for logical match between the computer and ADC0809. The three amplifiers in LM324 amplify computer starting signal, relative speed and signal of contact area, and connect to ASTB, ADCIN0, and ADCIN1, respectively.

3. Interpretation of experimental results
The test (Figure 2) reveals the three basic phenomena of dry friction. First, $F-v$ descent characteristic, before point B on curve A, the real area of contact is significantly decreased with velocity. Second, $F-T$ ascent characteristic, after point B, the contact area increases exponentially with rest period. Third, bifurcation, in the ascent section or descent section of the relative velocity, the contact area corresponding to the same velocity is different (asymmetry).
3.1. Mechanistic interpretation of DRH

We use Figure 4(A–E) to explain the DRH phenomenon:

(1) As we all know, solid materials are composed of a larger number of elements—mass ($m$), elasticity ($k$), and damping ($\eta$) (Figure 4(A)). When the friction pair is at rest, the load is mainly supported by elastic force (Figure 4(B), the left), and the contact area maximizes. As soon as slider moves, inertial force $ma$ and damping force $\eta \nu \dot{y}$, called dynamic response forces (DRF), appear simultaneously in the new area of contact deformation (Figure 4(B), the right) and share a part of the load while the elastic force is decreased correspondingly. Under the same load, the proportion of DRF is increased with the increase of speed and acceleration (Figure 4(C)). These processes can also be expressed by formulae as follows:

At rest,

$$v_y = 0, a_y = 0, y \neq 0, \quad N = ky_{t \to \infty} \quad (1)$$
In motion,
\[ y \neq 0, \quad v_y \neq 0, \quad a_y \neq 0, \quad N = ky + \eta v_y + ma_y \]  \tag{2}

where \( v_y \) and \( a_y \) are vertical compression speed and acceleration, the latter two forces in Equation 2 are the DRF. It appears in motion and disappears when at rest. DRF detach contact surfaces and result in a decrease in contact area (Figure 4(D)).

(2) Stress distribution: because the elasto-plastic wave at the contact zone is too late to propagate, the kinetically stressed area is smaller than that in static state, and the high stress gradient occurs at the frontier of the contact deformation (Figure 4(E)).

(3) Another origin of \( F-v \) descent characteristics is the micro-oscillation in interface. A solid unit \( (\eta-m-k) \) is in itself inherently a mechanical oscillator. It can easily be excited by friction and vibrate. As we all know, there exist reflected waves and impacts between two mismatching interfaces to separate the contact surfaces. It is similar to a mobile phone in that its oscillation mode moves along the table by itself. Physically, when absorbing kinetic and thermal energy, the boundary molecules vibrate and expand in volume and collide with each other, resulting in the separation forces (Figure 5, the left). When at rest, the molecules calm down (Figure 5, the right). Thus, the real area of contact in vibration is always less than that in static state.

Popov, Starcevic, and Filippov (2010), and Storck, Littmann, Wallaschek, and Mracek (2002), studied the influence of oscillations on friction, especially in the presence of ultrasonic vibrations.

(4) Figure 2 also reveals the nature of bifurcation. Although starting point D and rest point B are both at rest, starting point D corresponds to \( T \to \infty \) and that rest point B corresponds to \( T=0 \), obviously \( A_\infty > A_0 \). After relative rest, the contact area continues to expand and gradually gets close to \( A_\infty \). Like voltage across of a capacitor and current in inductor do not change suddenly, dynamic processes do not end immediately.

3.2. Electrical simulation of DRH
In mechanical tests, it is difficult to measure these forces simultaneously. In general, only the strain is measured by strain gage. Electrical simulation is a virtual test-bed. It is easy to change the parameters and displays the results immediately.

To illustrate DRH vividly, the authors conducted electrical simulation by OrCAD PSpice. As we all know, there is a similarity between a solid unit of Figure 4(A) and a circuit of Figure 6(A). We use the same equations to describe the mechanical and electrical systems.

For a solid unit of Figure 4(A):
\[ N = ky + \eta \frac{dy}{dt} + m \frac{d^2 y}{dt^2} = F_k + F_\eta + F_m \]  \tag{3}
For an R-L-C circuit of Figure 6(A):

\[ U = \frac{1}{c} \int idt + R\frac{di}{dt} = U_c + U_R + U_L \]  

(4)

Here \( N \sim U, k \sim 1/C, \eta \sim R, m \sim L, \nu \sim i, F_k \sim U_c, F_\eta \sim U_R, F_m \sim U_L \). The inductor voltage, the resistance voltage and the capacitor voltage characterize the inertial force, the damping force, and the elastic force, respectively.

3.2.1. Electrical simulation of static–kinetic transition

At the moment of static–kinetic transition, a particle unit at the frontier of contact is compressed suddenly, causing great acceleration and inertial forces to separate two surfaces from contact to a certain degree. This is the reason why friction decreases so quickly at the beginning of static–kinetic transition. This process can be simulated by the transition process of turning on an R-L-C circuit. When an R-L-C circuit is energized, the transition process occurs in the circuit of Figure 6(A). The response is shown in Figure 6(B). Simulation provides three primary results. First, the voltage drops at the beginning in inductor \( V(L_1) \) and resistance \( V(R_1) \) are much larger than the capacitor voltage \( V(C_1) \). This shows that the inertial force and damping force play a large part in balancing external force while elastic force plays a minor role. Second, the proportion of three forces varies with time. It shows that one and the same material at different kinetic stage behaves differently. Third, during static–kinetic transition the influence of acceleration on friction is great.

3.2.2. Simulation of F–v descent characteristics

The F–v relationship can be simulated by the circuit of Figure 7(A). We may use the slope of the pulse rise time to represent the relative velocity and acceleration (compression speed and acceleration) (Figure 7(B)). Simulation results show that capacitor voltage decreases with the decrease in pulse rise time (Figure 7(C)). This is due to the increase in high frequency component, the steeper the slope is, and the greater the inductance is. In other words, as the relative speed and acceleration increases, the impedance of the surface gets close to inertial range, and the contact area is reduced.

The F–v characteristics can also be described by impedance theory of circuit. The filter characteristic is an important property of an R-L-C circuit or its network. It allows the waves by natural frequency to pass...
through the circuit, and prevents waves not of natural frequency from passing through. In fact, friction pairs are filters of mechanical waves, that is, they filter opposite side waves. The increase in sliding speed results in high frequency impacts and vibration in friction pair, and with the increase of velocity, the impedance of contact point increases, the contact deformation decreases and the surface is harder. On impact and high frequency vibration, Baillet, Linck, D’Errico, Laulagnet, and Berthier (2005) also holds the same view, “the kinematic shows the existence of local impacts and sliding at high frequencies.”

3.2.3. Simulation of $F$–$T$ ascent characteristics
As mentioned above, in motion, the load is lifted by $DRF$, accompanied by a decrease in contact area. On the contrary, when at rest, with the disappearance of $DRF$, the contact region would be softened and the load comes down with an increase in contact area. This process can be simulated through
charging process of a capacitor. The simulation circuit is shown in Figure 8. The initial value of contact area, when the slider just stops, can be described by charged value in capacitor \( C_1 \) before that moment. Suppose the initial value of \( C_1 \) is set 3 V here. The process of \( C_1 \) charging from 3 to 5 V supply voltage simulates the \( F-T \) ascent characteristics. \( V(C_1) \) in Figure 6(B) describes a special case in which the initial contact area is equal to zero. This is the whole process of the contact area increasing from zero to the maximum value under the normal pressure.

Based on electrical engineering, the charging process can be expressed as:

\[
V(C_1) = 5V - (5V - 3V)e^{-\frac{T}{\tau}}
\]  

(5)

where \( T \) is rest period, \( \tau \) is time constant (\( RC \)).

By Equation 5, the relationship between friction and rest period can be expressed as:

\[
F(T) = F_{\infty} - (F_{\infty} - F_0)e^{-\frac{T}{\tau}}
\]  

(6)

where \( F_{\infty} \) is the friction when \( T \to \infty \) (\( y_{\infty} \) in Figure 4(A)), \( F_0 \) is the friction when \( T = 0 \) (\( y_0 \) in Figure 4(A)). Equation 6 shows that after relative rest, the contact area increases exponentially with time.

4. Discussion

The formula \( F = fN \) established in Amontons–Coulomb age is a powerful tool for tribology research. However, it has its limitations, that is, it cannot describe the kinetic friction process. Now it can be amended by means of \( DRH \).

The implication of formula \( F = fN \) is that the increase of positive pressure is accompanied by an increase in elastic deformation, contact area, force of the grip and shear resistance, which results in increase of friction. In other words, elastic deformation approximately characterizes the actual contact area and friction.

Multiplying both sides of Equation 1 by \( f \), it becomes the formula of static friction:

\[
fN = fy_{\infty} = F_s
\]  

(7)

By Equation 2, following equation can be derived:

\[
F_d = f[N - (ma_y + \eta y_y)]
\]  

(8)

where \( f \) is coefficient of friction, \( F_s \) is static friction, and \( F_d \) is dynamic friction. Assuming that \( r \) is conversion factor of \( DRF \) in \( y \) direction, then Equation 8 becomes as follows:

\[
F_d = f[N - r(ma_y + \eta y_y)]
\]  

(9)

Equations 8 and 9 show that friction is not only a function of the normal pressure but also a function of \( DRF \).

It should first be pointed out that the inertia force and damping force in the formula refer to the forces produced in the local deformation region. Second, though friction surfaces look smooth, and it seems that there were no vertical motions, but in fact, the variation in speed and acceleration in vertical direction cannot be neglected. Though it is extremely small in quantity, it has a great effect on the friction.
5. Conclusions

(a) The Dynamic Response Hardening in the friction pair is the main cause of $F-v$ descent and $F-T$ ascent characteristics. During static–kinetic transition, DRH and micro-oscillation cause surface separation and decrease in contact area.

(b) The $F-v$ descent phenomenon is the process of lifting up the load by DRF and a decrease in the contact area. And that of the $F-T$ ascent characteristic is the process of the load coming down and an increase in the contact area. The former is the behavior in motion, the latter is the behavior at rest, and the two processes are continuous in time.

(c) Static–dynamic transition is a conversion process between kinetic and potential energy with each other. $F-T$ is the process of storing potential energy in contact area, and $F-v$ is the process of interface obtaining kinetic energy, and causing oscillation and separation.

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