

The effect of frequency of vibration and humidity on the stick–slip amplitude

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Abstract This work examines the variation of stick–slip amplitude with the variation of frequency of vibration and relative humidity on a mild steel disc. A pin-on-disc machine, developed by the authors, capable of vibrating the disc at different frequency is used for the experiments. During the experiments, normal load, speed, relative humidity and frequency of vibration were varied. The results reveal that, depending on the conditions, a different stick–slip behavior can arise in the same system. It is found that the rate of reduction of stick–slip amplitude has a particular relationship with the frequency of vibration and the relative humidity. It is also observed that the transition from irregular to regular stick–slip behavior is load dependent, while the transition from irregular to smooth sliding is load independent.

Keywords Stick–slip amplitude ·
Frequency of vibration · Relative humidity

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1 Introduction

The phenomenon of stick–slip motion occurs if there is an intermittent change between static and dynamic friction which results in a very robust limit cycle that creates noise, wear, damage, and diminishes accuracy. When two surfaces are rubbed against each other at a constant driving velocity or force the surfaces themselves do not move at constant velocity, i.e. smoothly but intermittently, and when this occurs the measured friction force is not also constant. An understanding of stick–slip is of great practical importance in tribology (Rabinowics 1995). Stick–slip motion is a very common phenomenon and is also the cause of sound generation (the sound of violin string, a squeaking door, or the chatter of machinery), sensory perception, earthquakes, granular flow, non-uniform fluid flow such as the spurting flow of polymeric liquids, etc.

Stick–slip vibrations are present in many kinds of engineering systems and everyday life and are attributed to surfaces sliding with friction. Stick–slip vibrations might be acceptable in applications provided their amplitudes are sufficiently small (Popp and Rudolph 2004). It is always desired to cure or at least to reduce the severity of vibration amplitude of stick–slip motion.

Mainly, there are four different models of stick–slip friction: Rough surfaces or surface topology model (McClelland 1989, 1990; Meyer et al. 1998), distance-dependent or creep model (Hymann et al.

1954; Sampson et al. 1943), velocity dependent friction model (Carlson and Langer 1989; Nasuno et al. 1997), and phase transition model (Thompson and Robbins 1990; Robbins and Thompson 1991; Person 1994). The first three mechanisms may be considered traditional or classical mechanisms or models; the fourth is essentially the same as the freezing-melting phase-transition model.

It is known that the dynamic behavior in several fields of science with dry friction is nonlinear because of Colomb's laws (Abdo and Al-Rawahi 2008; Bowden and Tabor 1954). The static friction force is the force necessary to start sliding or a constraining force during sticking (stick regime) while the kinetic friction force is the force necessary to keep sliding at a constant velocity (slip regime). If the static friction force is larger than the kinetic one, or that the kinetic friction force drops rapidly at small speed, the sliding surfaces alternately switch between sticking and slipping in more regular or irregular fashion. This unstable motion is repeated in rapid succession until the slide reaches a certain velocity called the critical speed (Kenmoe and Kofane 2007). To describe the static and kinetic friction in more detail both coefficients can be assumed to be dependent on other parameters such as applied load, speed, humidity, time and temperature.

During smooth sliding, the shearing surfaces move relative to each other at the same constant interfacial velocity as the driving velocity. The measured friction forces are then different at any instant due to the finite inertia, compliance, and relaxation time(s) of the system (Gourdon and Israelachvili 2003). When describing intermittent friction, individual stick-slip events are referred to as "spikes" which have various shapes (Ruths et al. 2005).

Researchers have found the effect of applied load and speed on stick-slip motion (Gourdon and Israelachvili 2003; Kang et al. 2009; Popp and Rudolph 2004). However, the effect of the frequency of vibration and humidity on the stick-slip motion and the combine effect of the applied load and speed are yet to be investigated. Therefore, in this paper a mechanism leading to stick-slip motion is introduced and an attempt is made to investigate the simultaneous effect of frequency of vibration and humidity on stick-slip behavior and amplitude with the variation of applied load and speed.

2 The experimental setup

Series of tests are performed on an in house made pin-on-disc machine shown in Fig. 1. Modifications on the previously developed pin-on-disc machine (Abdo and Alyahmadi 2009) are carried out in order to make it suitable for stick-slip testing. The constructed pin-on-disc machine mainly consists of two motors, carriage with a handle, spindle, arrangement to generate vertical vibration and sensors. The machine is connected to a custom PC, which has the capability to control the motion of spindle and lower shaft, data acquisition and has a display unit (monitor).

The carriage consists of an arm and its holder that is designed with a facility of carrying dead weights. Therefore, the desired normal force will act on the specimen through the pin. The pin can move freely on the rotating surface (disc specimen). The disc specimen is attached to the spindle that is screwed to a long vertical shaft. The structure of the machine is composed of four square supporting plates and a base plate. There are four columns passing through the plates to provide rigidity to the main structure. The base is fixed to the ground for safety purposes and to increase the rigidity of the structure as well. There is a compound V-pulley between the first and the second supporting plate to transmit rotation to the upper shaft from the upper motor. Another compound V-Pulley is fixed between the fourth plate and the base to transmit rotation to the lower shaft from the lower motor. To rotate the shafts two motors of

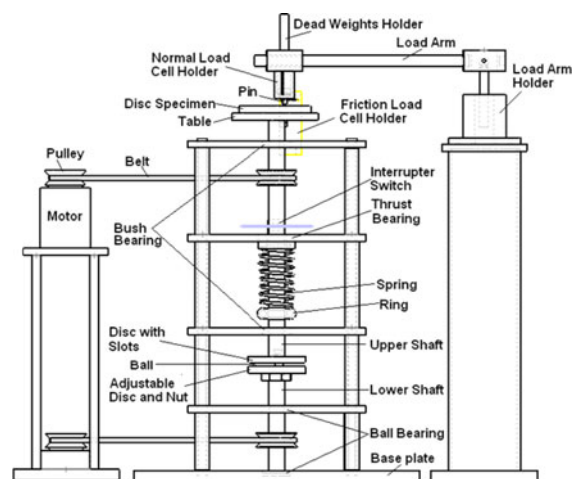


Fig. 1 Schematic of the pin-on-disc machine

one-horsepower each are mounted vertically on two separate bases having rubber damper. These separate bases were used to reduce the affect of vibration of the motors, which may be transmitted to the main structure.

The machine has a linear vertical and horizontal motion system for positioning the pin and a rotational motion control system that controls the spindle speed by controlling the upper motor velocity. The pin is attached directly to the friction and load sensors; the latter provides feedback about the force versus displacement servo-loop. The upper vertical shaft passes through two close-fit bush bearings which are rigidity fixed with two-square plates such that the shaft can move only axially and any radial movement of the rotating shaft is restrained by the bush. The lower shaft passes through two ball bearings which are fixed with the base and fourth plate.

A compression spring is fitted with the shaft between the first and the second supporting plates in order to restrain any vertical movement of the shaft. There are two circular plates in the lower part of the machine. One is fixed to the bottom of the upper shaft and the other is fixed to the top of the lower shaft. The upper circular plate has number of slots on its lower surface. The lower circular plate has a spherical ball extended from its upper surface. For stick–slip measurements, the lower shaft is allowed to rotate with higher rotational velocity than the upper shaft so that the ball slides over the slots. The pin-on-disc apparatus is designed so it has the capability of vibrating the disc at different frequencies and amplitudes. Due to the spring action the shaft and the disc specimen vibrates. The mode of vibration generated is approximately sinusoidal. The amplitude of vibration is controlled by adjusting height of the nut that is attached to the circular plate and to the lower shaft as shown in Fig. 1. The frequency of vibration is controlled by controlling the rotational relative velocity of the shafts and the number of slots on the lower surface of the upper plate. The rotational velocity of the shafts are controlled and programmed to have different values.

Machine able mild steel discs are used to perform the tests. The surface topography of the discs is controlled. The Mahr profilometer is used to obtain the profile of mild steel discs. The profile measurement consists of 512 traces with trace taken over a 10 mm long distance. The 512 traces are separated so

as to occupy a width of 1.25 mm, providing a reasonable aspect ratio for the sampled area.

To rotate the shafts two motors of one-horsepower each are mounted vertically on two separate bases having rubber damper. This separate base were arranged to reduce the affect of vibration of the motors, which may transmit to the main structure.

The whole set-up was placed inside a chamber whose relative humidity can be adjusted by supplying requisite amount of moisture. A hydrometer was used to measure the relative humidity of the chamber.

3 Experimental measurements and control

The apparatus is equipped with control features to regulate normal applied load and relative velocity. Appropriate sensors with an integrated data acquisition system provide measurement of normal and tangential load on the specimen. The tests are performed at various spindle speed and normal applied load ranging from 0.7 to 7 N. The frictional forces F_s , F_k are recorded from which the friction amplitudes, stick–slip amplitudes, are computed. An interrupter switch is utilized to measure the speed of the spindle by attaching a metallic disc with one slot to the shaft.

A PI controller was designed in order to control the spindle speed and obtaining the transfer function, and was used to terminate the effect of the load and to obtain the constant desired speed. Since changing the armature voltage is a practical method to control the speed of the shaft, Pulse Width Modulation (PWM) is used to change the applied voltage by switching the motor ON or OFF with a high frequency. PWM technique uses a square waveform with a variable duty cycle. The duty cycle is adjusted depending on the error in the speed. Since the time is too small, the motor was not able to recognize the transient between ON and OFF and was only taken the average voltage in that time. To switch ON and OFF the motor, a Power MOSFET is used. However, the speed of the spindle is measured via the interrupter switch and the signal is fed-back to the PC through the data acquisition card directly to the PI-controller in order to take an action of decreasing or increasing the speed. The block diagram of speed control system is shown in Fig. 2.

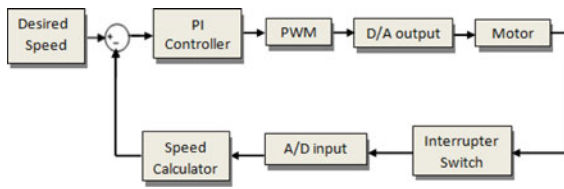


Fig. 2 Block diagram of speed control system

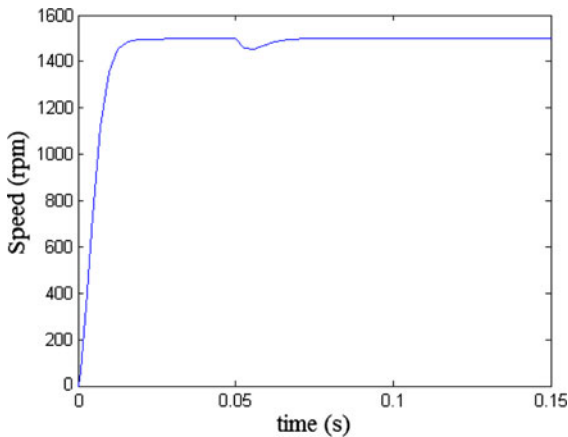


Fig. 3 Motor's response (speed) after applying a load

To test the controller and the speed, a load is applied and as it is shown in Fig. 3 the speed drops down due to the applied load and it goes back to the desired speed due to the PI-controller.

4 Results and discussion

There are different measures and techniques that are useful in avoiding stick–slip motion. An increase in external damping can compensate the negative damping induced by decreasing friction characteristics. An addition of external excitation can be applied either as a harmonic base excitation or as a harmonic force excitation of the mass. This excitation can break up the robust stick–slip limit cycle. In this work we show how stick–slip motion can be avoided by introducing an external frequency of vibration, i.e. significant reduction of the stick–slip amplitude.

4.1 Effect of speed and applied load on stick–slip amplitude

The stick–slip motion behavior under various applied load ranging from 0.7 to 7 N, the speed varies from 0

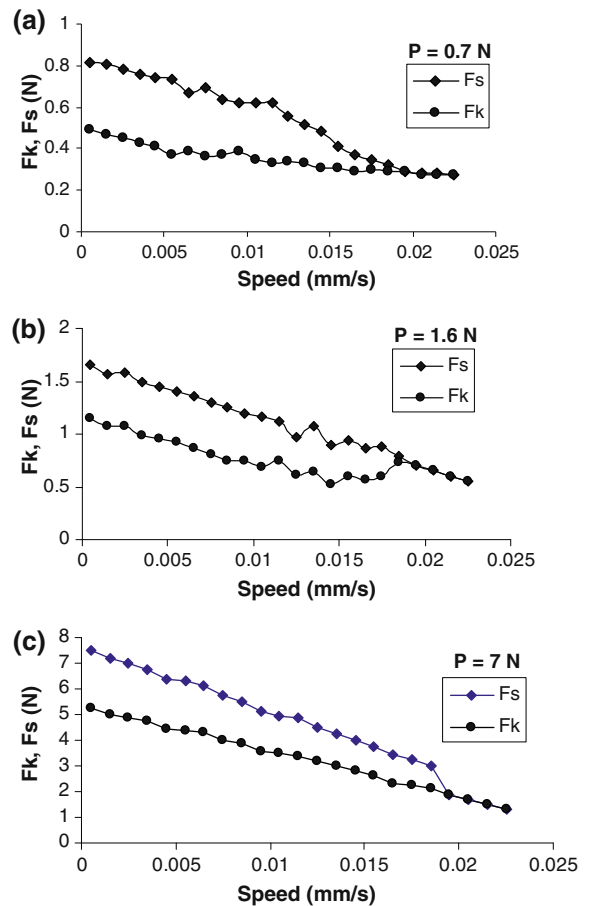


Fig. 4 Variation of friction forces with speed at different applied loads and relative humidity of 30%

to 0.023 mm/s and with relative humidity at 30, 50, and 75% are investigated. Figure 4a–c shows the variation of friction forces with speed at applied loads of 0.7, 1.6, and 7 N measured under steady-state conditions and relative humidity of 30%, i.e. friction traces no longer changes with time. Steady-state is reached at about 150 s. The difference between the static and the kinetic friction forces in Fig. 4 represents the stick–slip friction forces amplitude, $\Delta F = F_s - F_k$.

Figure 4a–c shows that there was regular stick–slip at low speed below a certain critical speed, $V_c^{(1)}$, followed by intermittent stick–slip that disappeared above a certain critical speed, $V_c^{(2)}$, above which the sliding was smooth. This type of behavior is common to systems where the friction–velocity curve has a negative slope. The details of transition from regular to intermittent stick–slip at $V = V_c^{(1)}$ and then to

smooth sliding at $V = V_c^{(2)}$ can be very different. Here, $V_c^{(2)}$ is largely independent of the load, P , but $V_c^{(1)}$ is load dependent. That is the higher the applied load the shorter the regular stick–slip amplitude range and the longer the irregular stick–slip amplitude range. This is the same as previously measured by (Gourdon and Israelachvili 2003) for low load while the dependent of critical speed $V_c^{(1)}$ on the load was not established in their work.

In the smooth sliding regime, the kinetic friction forces continue to slightly decreases with increasing speed, indicative of continue shear thinning. It is noteworthy to indicate that the transition from stick–slip to smooth sliding is believed to require that the slope of intrinsic friction force–velocity curve is negative. However, the inertia and the compliance of the pin-on-disc machine, e.g., the stiffness of the friction force measuring the pin, determine the critical speed and other feature of the transition.

4.2 Effect of relative humidity on stick–slip amplitude

Figure 5a and b shows the variation of friction forces with speed and relative humidity of 50 and 75% at an applied load of $P = 0.7$ N. The behaviors show a

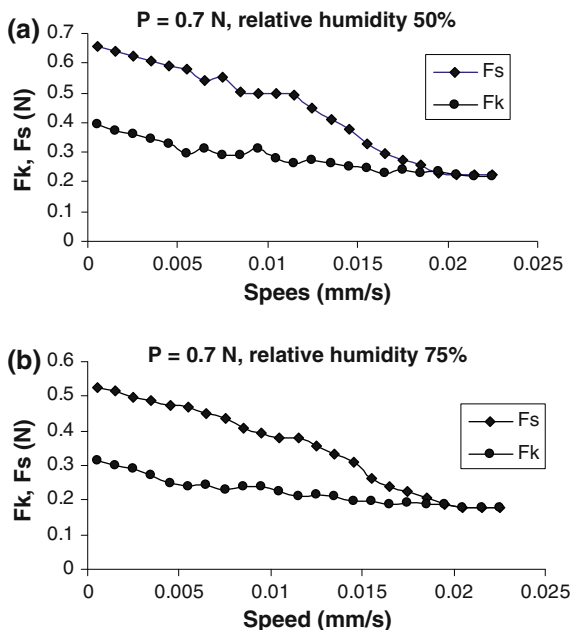


Fig. 5 Variation of stick–slip motion with speed and relative humidity at applied load of 0.7 N

trend similar to that of 30% relative humidity. The decrease of friction forces with the increases of the relative humidity might be associated with plugging because of roughening and trapped wear particles. In general there is a tendency for surface roughening to increase as the humidity is decreased. The details of transition from regular to intermittent stick–slip at $V = V_c^{(1)}$ and then to smooth sliding at $V = V_c^{(2)}$ at relative humidity of 50 and 75% are similar to that at relative humidity of 30%. As it is in the case of relative humidity of 30%, the critical speed $V_c^{(1)}$ is applied load dependent and $V_c^{(2)}$ is applied load independent at both relative humidity of 50 and 75%.

4.3 Effect of frequency of vibration to smooth sliding transition

In this section the effect of frequency of vibration on the stick–slip amplitude is investigated. Figure 6a shows the variation of the measured stick–slip amplitude with time at constant applied load of 2.0 N, different speeds of 0.005, 0.012, and 0.022 mm/s, and relative humidity of 30%. As shown in Fig. 6a, in the region of $V < V_c^{(1)}$ the stick–slip motion is characterized by roughly constant amplitude. Then, the stick–slip progressing through an irregular regime, $V_c^{(1)} < V < V_c^{(2)}$, characterized by a gradually decreasing stick–slip amplitude and an increasing erratic periodicity until it disappeared abruptly at the smooth sliding regime, $V > V_c^{(2)}$. The stick–slip transition from regular to intermittent at $V = V_c^{(1)}$ is applied load dependent and from intermittent to smooth at $V = V_c^{(2)}$ is applied load independent. It is noteworthy to mention that the experiments were repeated using different speeds within the irregular and regular regions and the results showed similar trends as the one in Fig. 6a.

To observe the effect of frequency of vibration on the stick–slip amplitude, different experiments were carried out. For this purpose experiments were performed at the vibration of 50, 80, 110, 140, and 170 Hz. Figure 6b shows the reduction of the stick–slip amplitude is to about 70% at 170 Hz.

Figure 7 presents the percentage reduction of stick–slip amplitude as a function of frequency of vibration and relative humidity. From the curves of Fig. 7 it is observed that the percentage reduction increase from 5 to 70% with the increase of vibration from 50 to 170 Hz. As the frequency increases the

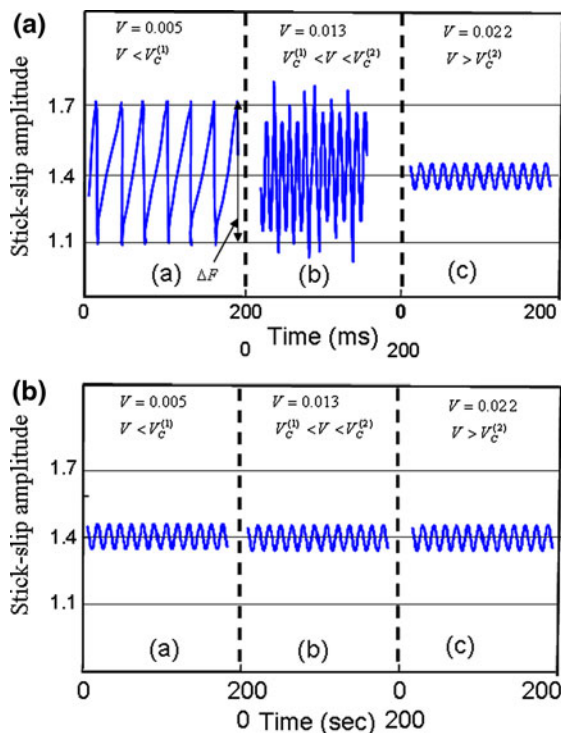


Fig. 6 Stick-slip amplitude as a function of time at applied load of 2 N. **a** No excitation frequency **b** with excitation frequency of 170 Hz

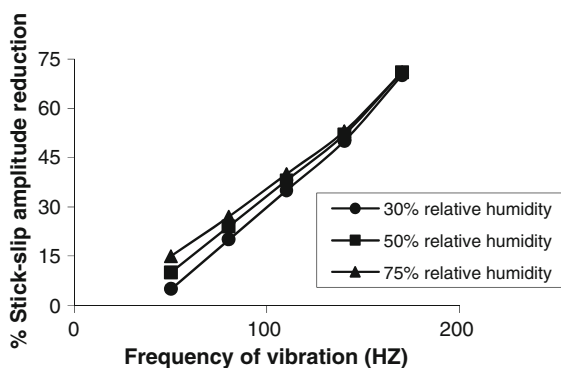


Fig. 7 Percentage reduction of stick-slip amplitude as a function of frequency of vibration with relative humidity

momentary load reduction during vibration increases which may result in higher separation of contact surfaces and that may cause the stick-slip amplitude reduction, i.e. the higher the frequency of vibration the higher the separation of rubbing surfaces. From Fig. 7 it is also observed that there is a humidity effect on stick-slip amplitude at low frequency of vibration but on high frequency of vibration there is

no effect of humidity on the reduction of stick-slip amplitude.

5 Conclusions

A pin-on-disc machine was developed to study the stick-slip motion. The presence of vibration affects the stick-slip amplitude. The value of stick-slip amplitude decreases with the increase of frequency of vibration. The percentage reduction of stick-slip amplitude was increased from 5 to 70% with the increase of frequency of vibration from 50 to 170 Hz. The transition from regular to intermittent stick-slip motion is load dependent while the transition from intermittent to smooth sliding is load independent. Relative humidity has an effect on stick-slip amplitude at low frequency of vibration but there is no effect of relative humidity on reduction of stick-slip amplitude at high frequency of vibration.

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