Interfacial Friction and Vibration

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ABSTRACT: We explore the effect of vibration on interfacial friction by applying normal and parallel base vibration to a block that rests on an inclined plane. Results show that the block can displace at significant lower angles than the limiting static angle, and that the acceleration level required to cause sliding increases with frequency. Limiting equilibrium analysis is insufficient to explain the observed behavior. Instead, we compute the displacement per cycle and show that (1) the apparent quasi-continuous motion of the block under vibration is the accumulation of successive slip-rest events, and (2) the displacement in every cycle must exceed a threshold displacement in order to cause sliding. The threshold displacement is 0.1 μm for polished granite surfaces; a relation between the threshold displacement and the length scale of surface features is anticipated.

1. INTRODUCTION

Friction is the source of strength in discontinuous systems such as granular materials and non cemented interfaces. Therefore, the fundamental understanding of friction and its control can lead to enhanced construction practices and the development of engineered granular minerals and interfaces.

The history of friction starts with early observations in Mesopotamia [3500 BC] and Egypt [2750 BC]. Theoretical developments begin in the XV century by L. da Vinci [1452-1519 – Italy] and G. Amontons [1663-1705 – France], followed by J.T. Desaguliers [1638-1744 – England], C.A. Coulomb [1736-1806 – France] and J. Leslie [1766-1832 – England] who consider both asperity and adhesion effects on friction. The effects of sliding velocity and lubrication gain relevance in the XX century with the work of W. Hardy and I. Doubleday [1922 – England], P. Bowden [1945-1968 – Tasmanian] and D. Tabor [1968-1981 – Australian]. Molecular dynamic simulations [Alder and Wainwright in 1956 – USA] and the development of the atomic force microscope by G. Binnig, C.F. Quate, and C. Gerber [1986 – Switzerland] bring important new tools for the fundamental study of friction (Note: for a detailed historical review see Santamarina and Díaz-Rodríguez 2003).

Atomistic and engineering scale observations show that friction and noise are interrelated: friction causes noise, and noise or vibration affects friction (Friedman and Levesque 1959; Eaves et al. 1975; Budanov et al. 1980; Serdyuk and Mikityanskii 1986; Tworzydlo and Becker 1991; Skare and Stahl 1992; Adams 1996; Bengisu and Akay 1999; Tomsen 1999; Littmann et al. 2001; Bucher and Wertheim 2001.).

In particular, vibration can reduce the frictional resistance between two sliding surfaces. Theoretical explanations have considered excitation frequency and asperity resonance, local increase in temperature, the ratio between dynamic and static stress, and the ratio between surface roughness characterized by the size of asperities and the vibration displacement amplitude.

More recent dynamic studies of friction include the observation of "stochastic resonance" in frictional systems (whereby the correlation between input and output increases with the addition of noise - Wang and Santamarina, 2003), the enhanced understanding of the dynamics of stick-slip motion between two pure crystalline surfaces separated by a thin liquid film (Thompson and Robbins 1990; Jaeger et al. 1996), and energy dissipation due to the viscoplastic deformation of asperities and the viscous properties of lubricants between surfaces (Oden and Martins 1985; Hunt and Crossley 1975; Wang and Santamarina 2007).

We document herein an experimental and analytical study of vibration-induced changes in interfacial friction. The study places emphasis on the measurement and prediction of the acceleration level required to trigger slippage.

2. EXPERIMENTAL STUDY

2.1 Devices

The experiments involve two polished granite pieces (Fig. 1): one is tilted and serves as the sliding surface; the other piece is the moving block that is placed on the inclined plane (29x36 mm, apparent contact area 10.2 cm^2, weight 27.2 gr). The static friction angle between the two granite blocks is φ=18º.

A minishaker (PCB Piezotronics) is coupled to the lower piece to input base vibration. The sinusoidal input signal is created using a function generator and fed to the shaker through a power amplifier to attain a wide range of frequencies and amplitudes. The vibrations of the base and the moving blocks are monitored with mini-accelerometers (weight 1.9 gr). Instrumentation and peripheral electronics are shown in Fig. 1.

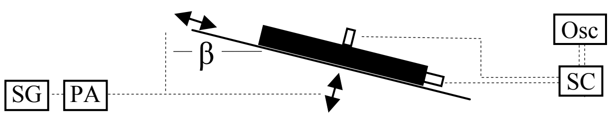

Fig. 1: Test configuration, instrumentation and peripheral electronic devices. Base vibration either normal or parallel to the sliding plane are imposed on any given test. The filled rectangle represents the moving block. Accelerometers are shown as empty rectangles, and the shaker as a double arrow. SG: signal generator. PA: power amplifier. SC: signal conditioner. Osc: Oscilloscope.

2.2 Experimental Results

We study the effect of two base vibration directions: one is normal to the plane, and the other is parallel to the dip vector. The procedure for each measurement follows: (1) select the vibration frequency, (2) increase the amplitude of the imposed vibration until the upper block begins sliding, (3) record the amplitude of the acceleration measured on the sliding block at the verge of sliding. Measurements are repeated for different vibration frequencies and slope angles.

Data gathered for base vibration normal to the base and parallel to the dip vector are shown in Fig. 2. These figures show that (1) the higher the slope angle, the lower the acceleration required to trigger slippage, (2) the acceleration required to cause slippage increases with frequency.

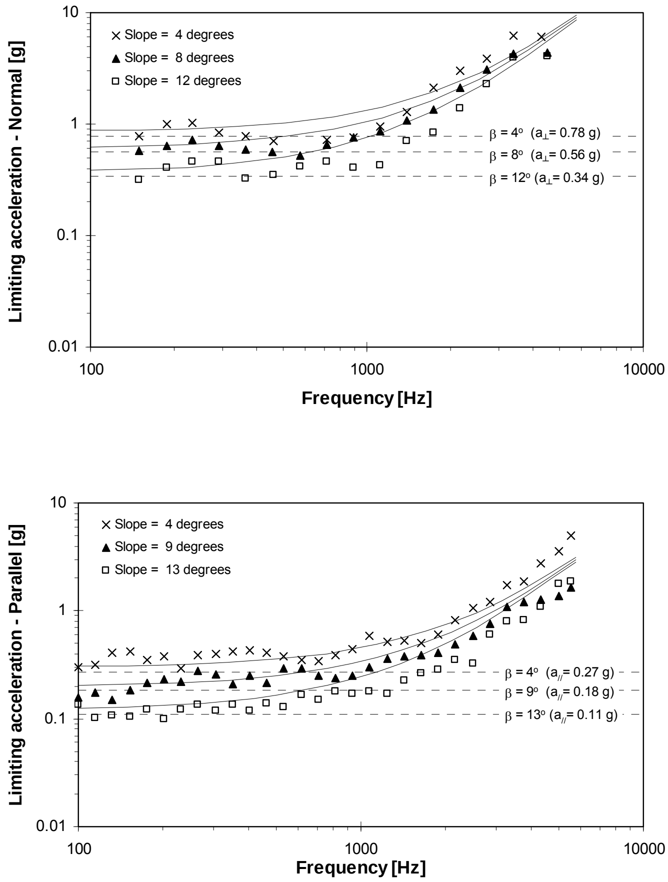

Fig. 2: Acceleration required to bring the block to the verge of slippage for different slope angles and excitation frequencies. (a) Sinusoidal vibration normal to the sliding surface. (b) Sinusoidal vibration parallel to the dip vector. Points represent accelerations measured o n the block. Dashed lines correspond to the limit equilibrium prediction. Solid lines indicate the acceleration that generates a constant relative displacement of 0.1 μm. Note: the granite-to-granite static friction angle is φ=18º.

3. ANALYSES

3.1 Static condition

Consider a block weight W sitting on an inclined plane at angle β (Fig. 3a). Limiting equilibrium requires the balance between the driving and the resisting shear forces $T_{dr}=T_{res}$:

$$T_{dr} = W \sin\beta \quad [1]$$

$$T_{res} = W \cos\beta \tan\varphi \quad [2]$$

In the limit $T_{dr}=T_{res}$, and we conclude that the block will slide when the inclination angle exceeds $\beta=\varphi$.

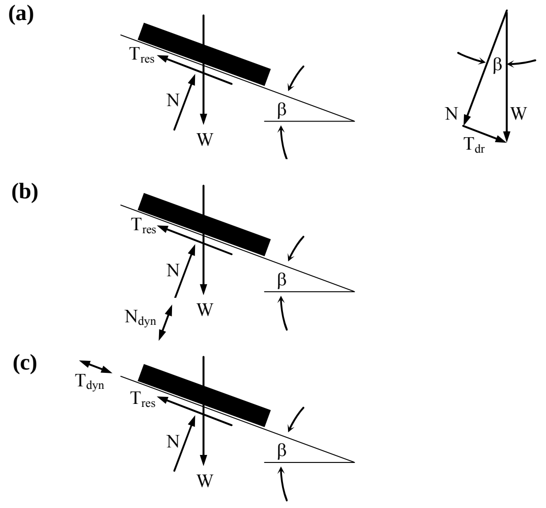

Fig. 3: Forces acting on a block resting on an inclined plane. (a) Static condition. (b) Subjected to base vibration normal to the plane, and (c) parallel to the plane.

3.2 Limiting Equilibrium

Limiting equilibrium must take into account the dynamic force $N_{dyn}(t)$ when vibration normal to the sliding surface is imposed (Fig. 3b). In this case, the driving component T_{dr} is the static one (Eq. 1), but the resistant force varies with time as

$$T_{res} = W\left[\cos\beta + \frac{a_{\perp}}{g}\sin\left(\omega t\right)\right]\tan\phi \qquad [3]$$

The block reaches limiting equilibrium when the resistant force at its minimum becomes equal or lower than the driving force. Then, the normal acceleration $a_{\perp}$ required to bring the block to the verge of slippage is

$$\frac{a_{\perp}}{g} = \left(\tan\varphi - \tan\beta\right)\frac{\cos\beta}{\tan\phi} \qquad [4]$$

Note that the asymptotic value is $a_{\perp}=g$ for $\beta\rightarrow 0$, i.e., the block must loose contact with the base momentarily in every cycle.

The previous analysis is repeated for vibration parallel to the sliding surface (Fig. 3c). In this case, the resistance force T_{res} is the same as in the static case (Eq. 2), but the driving force T_{dr} combines both static and dynamic components:

$$T_{dr} = W\left[\sin\beta + \frac{a_{\|}}{g}\sin\left(\omega t\right)\right] \qquad [5]$$

The block reaches limiting equilibrium when the driving force at its maximum equals or exceeds the resistance force T_{res}. Then, the acceleration of the block parallel to the plane required to bring the block to the verge of slippage $a_{\|}$ is

$$\frac{a_{\|}}{g} = \left(\tan\varphi - \tan\beta\right)\cos\beta \qquad [6]$$

The asymptotic value is $a_{\|}/g=\tan\varphi$ for $\beta\rightarrow 0$, i.e., the dynamic horizontal force imposed on the block must exceed the frictional resistance.

Equations 4 and 6 predict that the acceleration required to cause slippage depends on the slope angle β and the angle of friction between the block and the surface φ, and that the acceleration will increase as the static block stability increases, i.e., as $(\tan\varphi-\tan\beta)$ increases.

Note that $a_{\|}/a_{\perp}=\tan\varphi$. In most cases, $\varphi<45^{o}$, therefore $a_{\|}<a_{\perp}$ and a lower acceleration is needed to cause slippage when the imposed vibration is parallel to the static component.

Limiting accelerations computed with Eq. 4 and 6 are superimposed on Fig. 2. The predicted frequency independent response satisfies experimental results at low frequencies, but deviates from the data at high frequencies. This situation is further analyzed in the following section.

3.3 Displacement Threshold

The block slides for a short lapse of time in every cycle while the vibration level exceeds the limiting equilibrium condition. This situation is captured in Fig. 4 for both vibration normal to the plane and parallel to the dip vector.

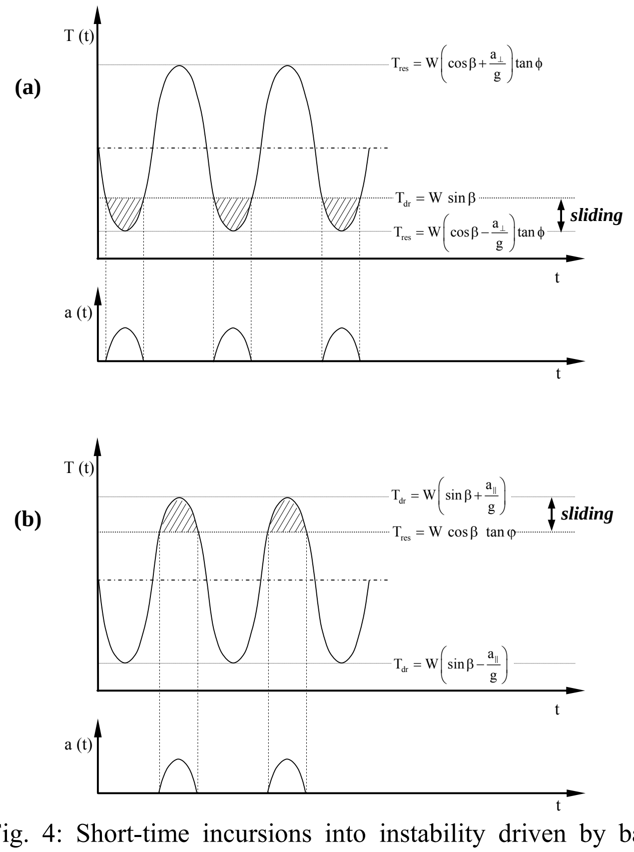

Fig. 4: Short-time incursions into instability driven by base vibration (a) normal to the sliding plane, and (b) parallel to the dip vector. The figure shows the forces acting on the block parallel to the sliding surface in each case. The displacement in each cycle is obtained by integrating the block acceleration.

The duration of the incursion into instability is very short at high frequencies (and low vibration amplitudes), and the integration of the acceleration results in small predicted displacements. Yet, the displacement in each cycle must exceed a minimum "displacement threshold" to allow for block sliding. We anticipate a displacement threshold in all conditions, and this length scale can range from the size of asperities in rough surfaces to the angstrom scale for atomically smooth surfaces.

We compute the displacement of the block by successive integrations of the acceleration, analogous to Newmark's method (see calculated displacements associated to various waveforms in Sarma 1975 and Yegian et al. 1988 and 1991). Results show that the displacement of the sliding block in each cycle of the sinusoidal harmonic vibration is proportional to the amplitude of the acceleration above stability conditions, and inversely proportional to the frequency squared.

We superimpose on Fig. 2 the normal and parallel base accelerations required to cause a certain displacement. This "threshold displacement" is selected to satisfy all the data with a single value: the inverted displacement is 0.1 μm per cycle and it applies to the two datasets obtained with normal and parallel vibrations. Data scatter reflects the difficulties in determining the precise moment and level of acceleration when sliding starts.

4. CONCLUSIONS

Vibration reduces frictional strength and facilitates sliding. The acceleration required to reach limiting equilibrium and trigger sliding increases as the static block stability increases, i.e., as ($\tan\varphi-\tan\beta$) increases.

A lower acceleration is required when vibration is imposed parallel to the sliding plane (i.e., cyclic increase in driving force) than normal to it (i.e., cyclic decrease in normal force).

The observed displacement consists of cumulative slip-rest motions. The displacement in each cycle is proportional (1) to the excess acceleration imposed above the acceleration required for limiting equilibrium, and (2) to the duration of the instability incursion. Experimental, numerical and analytical results show that the displacement in each cycle is inversely proportional to the square of the frequency.

There is a displacement threshold for interface sliding. Single cycle displacements lower than the threshold will not lead to the accumulation of displacement and sliding. We expect the displacement threshold to be a function of interfacial characteristics, such as the geometry of surface asperities.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Adams G. G. (1996). "Self – excited oscillations in sliding with a constant friction coefficient – A simple model", Journal of Tribology, Vol. 118, pp. 819 – 823.

Bengisu M. T. and Akay A. (1999). "Stick – slip oscillations: dynamics of friction and surface", Journal of the Acoustical Society of America, Vol. 105, Issue 1, pp. 194 - 205.

Bucher I. and Wertheim O. (2001). "Reducing friction forces by means of applied vibration", Proceedings of DETC2001, ASME 2001 Design Engineering Technical Conference and Computers and Information in Engineering Conference, Pittsburgh, PA, pp. 2995 – 3000.

Budanov B. V., Kuinov V. S. and Tolstoj D. M. (1980). "Interaction of friction and vibration", Sov. J. Frict. Wear, 1, pp. 79 – 89.

Eaves A. E., Smith A. W., Waterhouse W. J. and Sansome D. H. (1975). "Review of the application of ultrasonic vibrations to deforming metals". Ultrasonics, 13 (4), pp. 162 – 170.

Friedman H. D. and Levesque P. (1959). "Reduction of static friction by sonic vibrations", Journal of Applied Physics, 30, pp. 1572 – 1575.

Hunt K. H. and Crossley F. R. E. (1975). "Coefficient of restitution interpreted as damping in vibroimpact", Journal of Applied Mechanics, June, pp. 440 – 445.

Jaeger H. M., Nagel S. R. and Behringer R. P. (1996). "The physics of granular materials", Physics Today, 49 (4), 32.

Littmann W., Storck H. and Wallaschek J. (2001). "Archive of Applied Mechanics", Vol. 71, No. 8, pp. 549 – 554.

Oden J. T. and Martins J. A. C. (1985). "Models and computational methods for dynamic friction phenomena", Computer Methods in Applied Mechanics and Engineering, 52 pp. 527 – 634.

Santamarina, J.C. and Díaz Rodríguez., A. (2003). "Friction in Soils: Micro and Macroscale Observations", Proceedings of the 12th Panamerican Conference on Soil Mechanics and Geotechnical Engineering, Boston, Massachusetts, Vol. 1, pp. 633 - 638.

Sarma S. K. (1975). "Seismic stability of earth dams and embankments". Geotechnique 25, No. 4, pp. 743 – 761.

Serdyuk L. M. and Mikityanskii V. V. (1986). "Reliability of clamping devices of machine tool fixtures with machining system vibrations", Trenie Iznos Mash. 7 (2), pp. 266 – 275.

Skare T. and Stahl J. E. (1992). "Static and dynamic friction processes under the influence of external vibrations", Wear, 154, pp. 177 – 192.

Thompson P. A. and Robbins M. O. (1990). "Origin of stick-slip motion in boundary lubrication", Science, Vol. 250, Issue 4982, pp. 792 - 794.

Tomsen J. J. (1999). “Using fast vibrations to quench on – induced oscillation”, Journal of Sound and Vibration, Vol. 228, pp. 1079 – 1102.

Tworzydlo W. W. and Becker E. (1991). “Influence of forced vibrations on the static coefficient of friction – numerical modeling”, Wear, 143 pp. 175 – 796.

Wang Y. H. and Santamarina J. C. (2003). “Dynamic coupling effects in frictional geomaterials – stochastic resonance”, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 128, No. 11, pp. 952 – 962.

Wang, Y.H. and Santamarina, J.C. (2007). "Attenuation in sand – an exploratory study on the small-strain behavior and the influence of moisture condensation," *Granular Matter*. Vol. 9, No. 6, pp. 365-376.

Yegian M. K., Marciano E. A. and Ghahraman B. G. (1988). “Integrated seismic risk analysis for earth dams”, Report No. 88-15, Northeastern University, Boston, Massachusetts.

Yegian M. K., Marciano E. and Gharaman V. G. (1991). “Earthquake – induced permanent deformations: probabilistic approach”. Journal of Geotechnical Engineering, ASCE, Vol. 11.