Archive of Applied Mechanics 71 (2001) 549 – 554 © Springer-Verlag 2001

Sliding friction in the presence of ultrasonic oscillations: superposition of longitudinal oscillations

W. Littmann, H. Storck, J. Wallaschek

Summary It was often observed that friction forces can be reduced significantly if ultrasonic oscillations are superposed to the macroscopic sliding velocity. This phenomenon can be used to improve machining processes by addition of ultrasonic vibration to tools or workpieces, and forms the basis for many processes of ultrasonic machining. On the other hand, ultrasonic vibrations can be used to generate motion. The thrusting force of ultrasonic motors is provided to the rotor through friction. In the present paper, a simple theoretical model for friction in the presence of ultrasonic oscillations is derived theoretically and validated experimentally. The model is capable of predicting the reduction of the macroscopic friction force as a function of the ultrasonic vibration frequency and amplitude and the macroscopic sliding velocity.

Keywords Ultrasonic Vibration, Piezoelectric, Friction, Modeling, Experiment

1
Introduction
Friction contacts in the presence of ultrasonic oscillations have been the subject of numerous theoretical and experimental investigations, [1–5, 7]. The reduction of friction forces by ultrasonic vibrations is used in many processes of ultrasonic machining, [4, 6, 9, 10], and the generation of friction forces by ultrasonic vibrations is used in ultrasonic motors, [11, 12]. Although the effect of a modification of friction characteristics in the presence of ultrasonic vibrations has been well known since long, [8], only qualitative descriptions of their behaviour have been given. To the best of the authors' knowledge, no quantitative analytical models have been derived from first principles until now.

2
Scope of the investigation
A classical set-up for the determination of friction forces is shown in Fig. 1. An object with mass m is put on a plane surface with an angle of inclination θ. If the object is initially at rest, then the friction force between the object and the surface can be determined by observing the object's motion.

For a given angle of inclination θ, the object will not move as long as the so-called static coefficient of friction μ_s is larger than $\tan(\theta)$. If the angle of inclination is high enough, the object will start to move and the so-called coefficient of dynamic friction μ_d is determined as the ratio of friction force

$$F_R = m(g \sin\theta - \ddot{x}) \tag{1}$$

and normal contact force

Received 22 November 2000; accepted for publication 6 February 2001

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The authors express their gratitude to Morgan Electro Ceramics who provided the piezoelectric elements used in the vibrator.

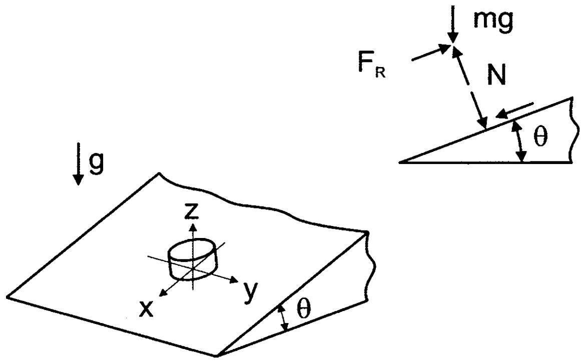

Fig. 1. Classical set-up for the determination of friction forces

$$N = mg\cos\theta \tag{2}$$

as

$$\mu_{\mathrm{d}} = \tan\theta - \frac{\ddot{x}}{g\cos\theta} \quad . \tag{3}$$

It is often observed that the coefficient of dynamic friction is a function of the sliding velocity. In the following, we will investigate, both theoretically and experimentally, how the friction force F_R and the dynamic coefficient of friction μ_{d}, which are observed in the absence of ultrasonic vibration, will be modified by the superposition of ultrasonic vibrations in the longitudinal (x) and transversal (y) directions. In the present paper, we will investigate the case of superposed ultrasonic oscillations in longitudinal directions, see Fig. 2. The superposition of ultrasonic oscillations in transversal direction will be investigated later.

3 Theoretical model for the superposition of ultrasonic oscillations in longitudinal direction

According to Fig. 2, the velocity of the macroscopic base motion is denoted by v_{b} and the superposed ultrasonic vibration results in a velocity

$$\tilde{v}(t) = \hat{v}\cos(\omega t) \tag{4}$$

of the probe mass, which is pressed against the base by a constant normal force N. In the following, $\tilde{F}_R(t)$ will be used to denote the high-frequency time-dependent friction force and $\bar{F}_R$ will be the time-averaged friction force in the case of superposed ultrasonic vibration, while F_R is the friction force observed in the absence of ultrasonic vibration. Introducing the normalized time

$$\tau = \omega t \tag{5}$$

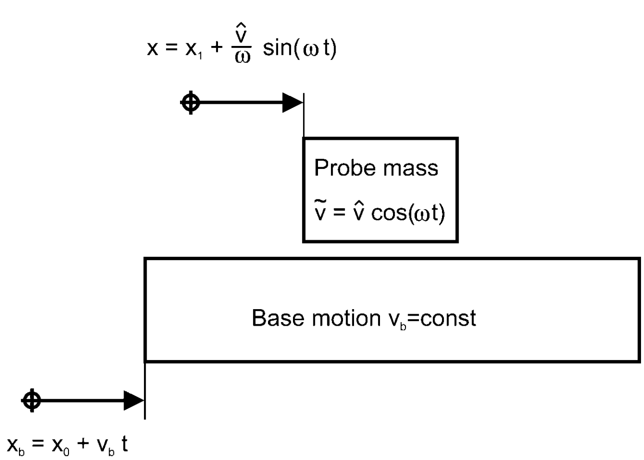

Fig. 2. Contact kinematics The macroscopic base motion is in x-direction and the corresponding velocity is denoted by v_{b}. Ultrasonic vibrations are superposed in longitudinal direction. The corresponding velocity is denoted by $\tilde{v}$

and the dimensionless velocity ratio

$$\zeta = \frac{v_b}{\hat{v}} \tag{6}$$

the average friction force is given by

$$\bar{F}_R = \frac{1}{T}\int_0^T \tilde{F}_R(t)\mathrm{d}t = \frac{1}{2\pi}\int_0^{2\pi} \tilde{F}_R(\tau)\mathrm{d}\tau \tag{7}$$

The net friction force which is observed macroscopically is $\bar{F}_R$, unless a particular high-frequency measurement technique is applied. The effect of "friction reduction by superposed ultrasonic vibrations" can be described quantitatively by the ratio

$$\mu_l = \frac{\bar{F}_R}{F_R} = \frac{\bar{F}_R}{\mu_d N} \tag{8}$$

of the "reduced" friction force $\bar{F}_R$ and the friction force F_R observed in the absence of ultrasonic oscillations. The subscript l is used to indicate that the ultrasonic oscillations are superposed in the longitudinal direction.

Let us consider Coulomb friction. Then the instantaneous friction force $\tilde{F}_R$ is a function of the relative sliding velocity

$$v_{\mathrm{rel}}(\tau) = v_b - \tilde{v}(\tau) = \hat{v}(\zeta - \cos\tau) \tag{9}$$

and the normal force N, which is assumed to be constant. The instantaneous friction force as defined in Fig. 3 is

$$\tilde{F}_R(\tau) = \mu_d N \,\mathrm{sgn}(v_{\mathrm{rel}}(\tau)) = \mu_d N \,\mathrm{sgn}(\zeta - \cos\tau) \ . \tag{10}$$

It is shown in Fig. 4, together with the relative sliding velocity, for one period of the ultrasonic oscillation. The instantaneous friction force can be easily integrated, resulting in the average force

$$\bar{F}_R = \begin{cases} F_R & \text{if} \quad \zeta \geq 1, \\ \frac{2}{\pi}\sin^{-1}(\zeta)\, F_R & \text{if} \quad -1 < \zeta < 1, \\ -F_R & \text{if} \quad \zeta \leq -1 \ . \end{cases} \tag{11}$$

Thus the friction reduction as described by the ratio μ_l is given by

$$\mu_l = \begin{cases} 1 & \text{if} \quad \zeta \geq 1, \\ \frac{2}{\pi}\sin^{-1}(\zeta) & \text{if} \quad -1 < \zeta < 1, \\ -1 & \text{if} \quad \zeta \leq -1 \ . \end{cases} \tag{12}$$

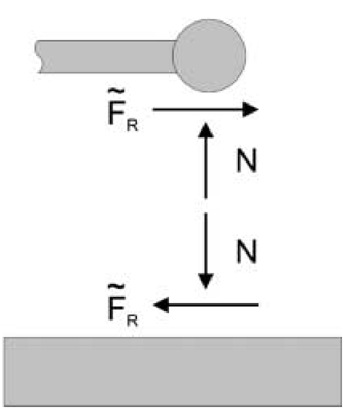

Fig. 3. Instantaneous contact forces

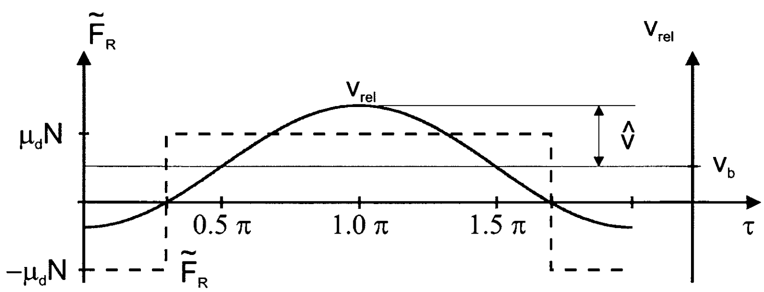

Fig. 4. Instantaneous friction force (left scale) and relative sliding velocity (right scale) over one period

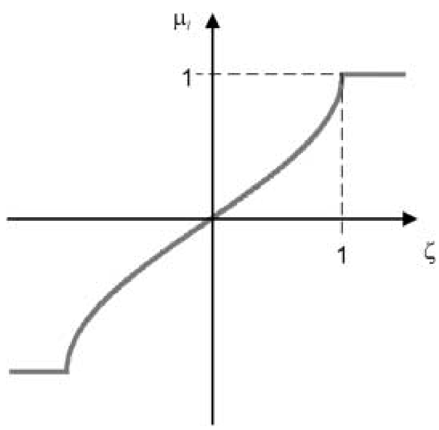

Fig. 5. Friction-reduction function μ_l over velocity ratio ζ

It only depends on the dimensionless velocity ratio ζ. Figure 5 shows μ_l as a function of ζ.

Depending on the ratio of the velocity of the base motion and the velocity amplitude of the superposed ultrasonic oscillation a significant reduction of the friction force can be observed if the velocity of the base motion is small compared to that of the ultrasonic oscillation. For small values of ζ, the nonlinear function $\mu_l(\zeta)$ can be replaced be the linear approximation

$$\mu_l \simeq \frac{2}{\pi}\zeta \ ,$$

which is in perfect agreement with a result obtained by Mitskevich, [5], using a different modelling approach.

4
Experimental investigations

For experimental validation of the theoretical result, a special ultrasonic oscillator and a test rig have been designed. The vibrator is made of steel and is driven piezoelectrically by a sinusodial voltage $\tilde{U}(t)$. It performs longitudinal vibrations ($\lambda/2$-mode) at 60 kHz with maximum oscillation amplitudes of $\hat{\xi} = 0.7\,\mu\text{m}$ leading to an amplitude of velocity of $\hat{v} = 0.26\,\text{m/s}$. The amplitude of vibration can be controlled by the electric power supply. At both ends of the vibrator contacting points have been chosen, Fig. 6. The vibrator is moved on a table track (aluminum) by a pneumatically driven slider with an adaptable base velocity v_b ($v_b = 0.02\ldots0.5\,\text{m/s}$), which is held constant during each experiment. The pushing force between slider and vibrator, which is equal to the average frictional force $\bar{F}_R$ is measured by a force sensor. The test rig is shown in Fig. 7.

The velocities of one endpoint of the oscillator was measured by laseroptical means while moving the slider. The base velocity v_b was measured using light barriers.

The results obtained from the experimental investigations are presented in Fig. 8 together with the theoretical results. They are in very good agreement.

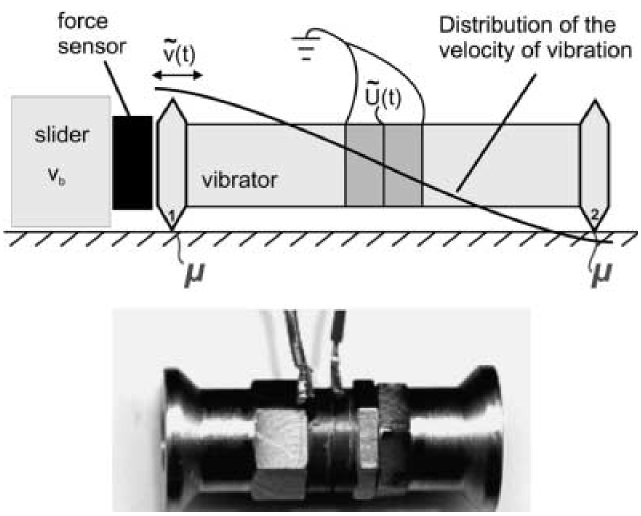

Fig. 6. Sketch and photo of the vibrator used for the experimental investigations

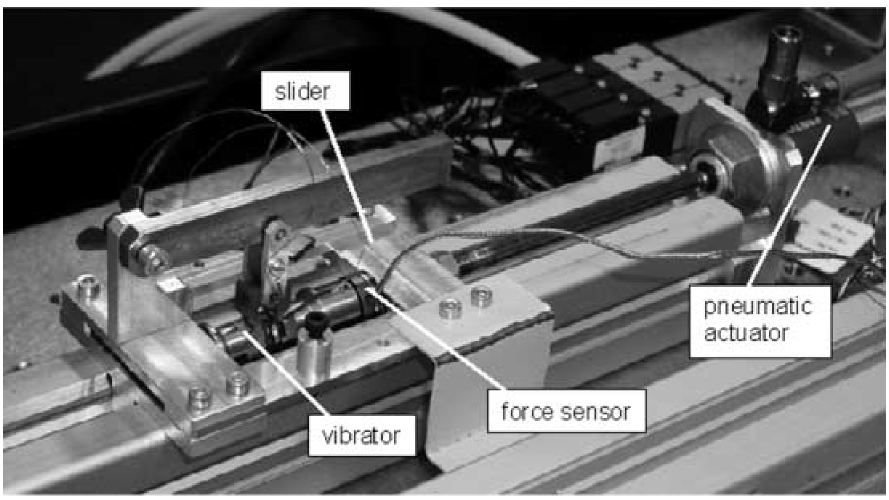

Fig. 7. Test rig for experimental investigations on reduction of friction

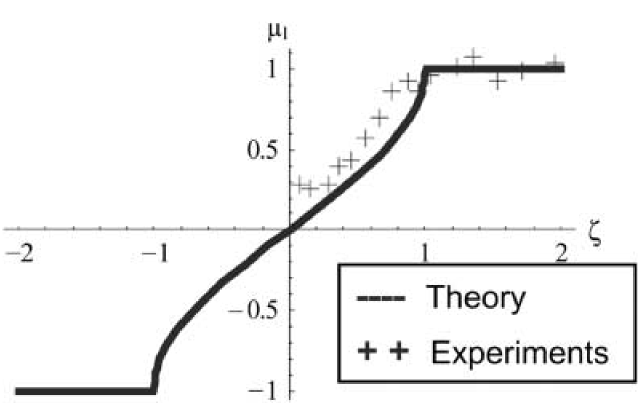

Fig. 8. Experimentally obtained values for friction reduction μ_l over velocity ratio ζ

5
Conclusion

Based on Coulomb's law for sliding, a theoretical explanation for the reduction of friction in the presence of ultrasonic vibrations has been given. It has been shown that the reduction of friction observed in sliding vibrational contact depends on the ratio of the moving velocity to the vibration velocity. The results have been confirmed by experimental investigation with a sliding vibrator moving on a test rig.

References

1. **Adachi, K.; Kato, K.; Saswatani, Y.:** The micro-mechanism of friction drive with ultrasonic wave. Wear 194 (1996) 137–142
2. **Fedaravicius, A.; Tarasevicius, K.; Slyzis, E.:** Investigation of vibrational transportation by controlled dry friction. Mechanika 4 (1997) 27–33
3. **Katoh, K.:** Active control of friction using ultrasonic vibration. Japan J Trib 38 (1993) 1019–1025
4. **Lehfeldt, E.:** Beeinflussung metallischer Reibungsvorgänge durch Schall im 20 kHz-Bereich. Diss RWTH Aachen, 1968
5. **Mitskevich, A.M.:** Motion of a body over a tangentially vibrating surface, taking into account of friction. Sov Phys Acous 13 (1968) 348–351
6. **Onikura, H.; Ohnishi, O.; Feng, J.; Kanda, T.; Morita, T.; Bopp, U.:** Effects of ultrasonic vibration on machining accuracy in microdrilling. Int J Japan Soc Precision Eng 30 (1996) 210–215
7. **Pohlman, R.; Lehfeldt, E.:** Influence of ultrasonic vibration on metallic friction. Ultrasonics 4 (1966) 178–185
8. **Rehbein, P.:** Tribologische Untersuchungen von hochfrequent schwingenden Gleitkontakten für den Einsatz in reibkraftschlüssigen Antrieben. Diss Heinz Nixdorf Institut, Universität Paderborn, HNI-Verlagsschriftenreihe 40, 1998
9. **Siegert, K.; Ulmer, J.:** Reduction of sliding friction in wire and tube drawing with ultrasonic waves. Prod Eng 5 (1998) 9–12
10. **Thoe, T.B.; Aspinwall, D.K.; Wise, M.L.H.:** Review on ultrasonic machining. Int J Mach Tools Manuf 38 (1998) 239–255
11. **Wallaschek, J.:** Contact mechanics of piezoelectric ultrasonic motors. Smart Mat Struct 7 (1998) 369–381
12. **Zharii, O.Y.:** Ultrasonic motor, wave gyro and a snake – what do they have in common? Mechatronics and advanced motion control. Proc of the 3rd Int Heinz Nixdorf Symposium, HNI-Verlagsschriftenreihe 49 (1999) 97–111