Controlling Stick-Slip Noise Generation with Lubricants

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Tribological contact between plastic or polymer materials can exhibit stick-slip behavior that generates noise. Tribological properties can be influenced by lubricants like bonded coatings, greases, and fluids. In this article, well known theories about polymer friction from the literature will be shown to be useful in developing new lubricants. Theoretical results have been validated with a Ziegler Stick-Slip Test Rig. The test methods presented here are used in the development of lubricants for automotive applications (in the interior of the car, including invisible lubricants developed for Class A surfaces).

Under certain conditions, a sliding motion between two surfaces does not generate a stationary friction force, but the motion alternates periodically between adhesion and sliding. This phenomenon of oscillating friction between two surfaces is referred to as stick-slip. Since stick-slip is a recurring event, it may be perceived as harmonic vibration or noise. Stick-slip effects are a frequent phenomenon in everyday life: when a table is pushed along the floor, its legs may begin to vibrate, as will a wineglass when a wet finger is moved along its rim.[1,8] Stick-slip events in the interior of a car can generate annoying noises. Polymers in particular can have a high static friction coefficient and can exhibit stick-slip in tribological contacts. Tribological properties can be influenced by the use of lubricants.

In this article we show how theories about polymer friction can be used in developing new lubricants. Analytical results will be validated with a stick-slip test rig. The introduced test methods are used in the development of lubricants like oils, greases, fluids and bonded coatings for all applications where friction-induced noise can be present.

Stick-Slip in Theory

Stick-slip can be described as a mechanical system resembling that of spring damper as shown in Figure 1. However, the @damping element is described as a linear function, while the friction force in the form of the Stribeck curve is a discontinuous nonlinear function.[11]

Mathematics Behind Stick-Slip. The spring damper system can be resolved analytically. If, however, the damping element is replaced by a friction pair whose friction force is defined by the Stribeck curve, the differential equation on which this system is based can only be resolved numerically. To set up the differential equation, a mechanical model was chosen based on the literature.[2-5] The behavior of this system is defined by the following differential equation:

$$m\ddot{x} + k\ddot{x} = F_R\left(v_{\text{belt}} - \dot{x}\right) \tag{1}$$

where k is the spring constant and v_{belt} is the belt speed. The lubricant is included in the equation in the form of the friction force defined by the Stribeck curve. To attain a curve with a declining and an increasing branch, the function below was chosen:[1]

$$F_R(v) = \mu \cdot F_N = \left(\text{sgn}(v) \cdot (a_1 + a_2 + a_3) \cdot \exp\left(-abs(v)/a_4\right)\right) \cdot F_N \tag{2}$$

With the parameters $a_1 = 1$, $a_2 = 0.1$, $a_3 = 0.3$ and $a_4 = 0.1$, the resulting friction curve looks like Figure 2. Because a lot of different material pairs in dry and lubricated conditions were examined, no typical values for these parameters could be found. Therefore, the parameter values were chosen arbitrarily. The function of the Stribeck curve obtained from Equation 2 will be subsequently referenced as F_{Stribeck}.

As the condition of the system changes (transition from adhesion to sliding), the differential equations must be solved. MATLAB, for example, offers Solver ode23s. The stiff integration method in the *Octave* freeware program might also be used.[1,7]

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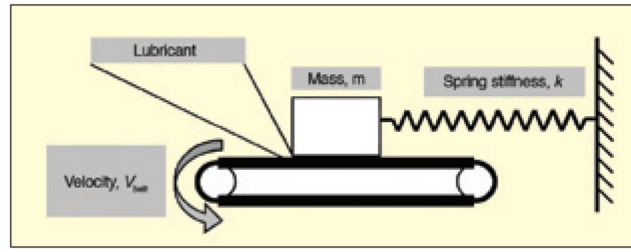

Figure 1. Mechanical model of stick-slip.

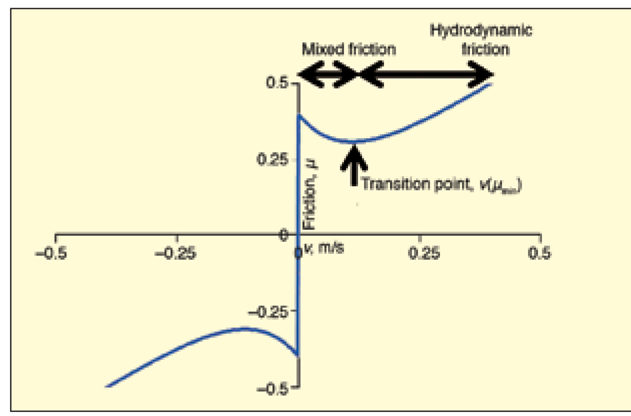

Figure 2. Characteristic of Stribeck curve, $F_{Stribeck}$, with transition point, $v(\mu_{min})$.

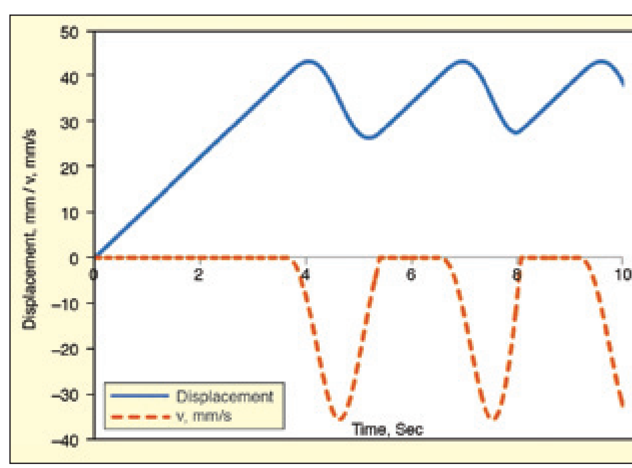

Figure 3. Calculated system behavior of mechanical model in stick-slip regime.

If the differential equation is resolved with parameters bringing the system into the stick-slip regime, the system behavior described by the functions displacement (time), or $s(t)$, and velocity (time), or $v(t)$, is obtained and shown in Figure 3.

Figure 4 illustrates the system's passage through the Stribeck curve in the stick-slip range. Since the spring is tensioned in the stick phase and relieved in the subsequent slip phase, the friction pair (belt and mass, m) will always attain a maximum relative speed that is higher than the speed of the belt, v_{belt}. Interestingly, the relative speed of the friction pair can temporarily pass through the rising branch of the Stribeck curve.

In the declining branch of the Stribeck curve, or the mixed friction regime, oscillation friction occurs. In the increasing branch of the Stribeck curve,

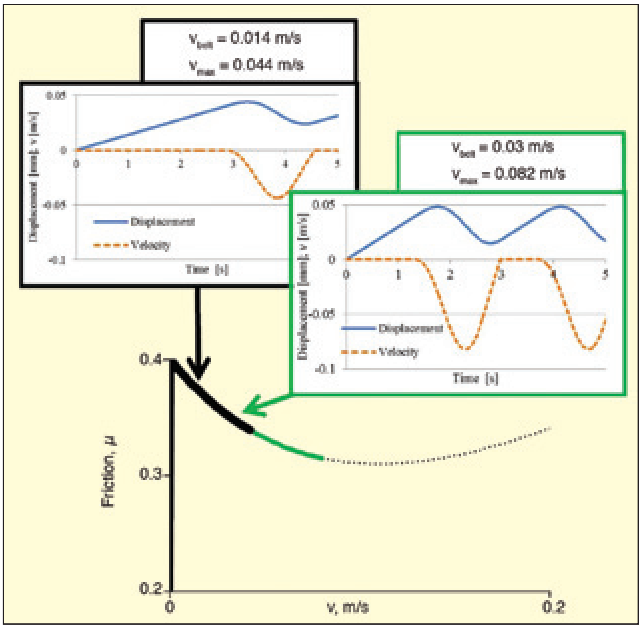

Figure 4. Stribeck curve at different speeds and associated system responses ($v_{belt1} < v_{belt2} < v(\mu_{min})$).

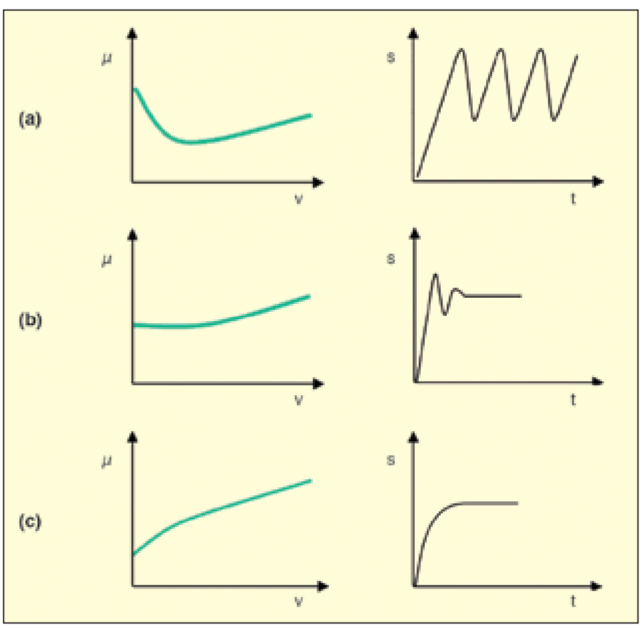

Figure 5. Flat or rising Stribeck curve cannot provoke stick-slip.

however, (the hydrodynamic range) solving the differential equation shows damped oscillation as in the spring-damper system.

The tests allow the conclusion that stick-slip occurs solely in the declining branch of the Stribeck curve (Figure 5a). If the friction force is constant at low speeds or if it rises throughout the speed spectrum, damped oscillation is generated in the system (Figure 5b) or creeping occurs (Figure 5c).

Aside from speed, other parameters can also be changed in this model. In our tests, using a harder spring increased the rigidity of the system. Consequently, the frequency of response functions became higher, showing a smaller amplitude (see Figure 6).

It was surprising to see that with a further increase of the spring's stiffness, the stick-slip-free range was not reached. From practice, on the other hand, it is known that a stiffer link may help to avoid oscillating friction. This leads us to assume that the lubricant is not sufficiently defined by the Stribeck curve described in this section. For this reason, the Stribeck curve was slightly modified in the next section.

Modified Stribeck Curve. Hysteresis effects have been observed during Stribeck curve measurements. An example of such behavior would be a system requiring a high-breakaway force for starting up, while requiring none when slowing down and stopping again. Figure 7 shows three possible Stribeck curves during the slow-down phase of the system.

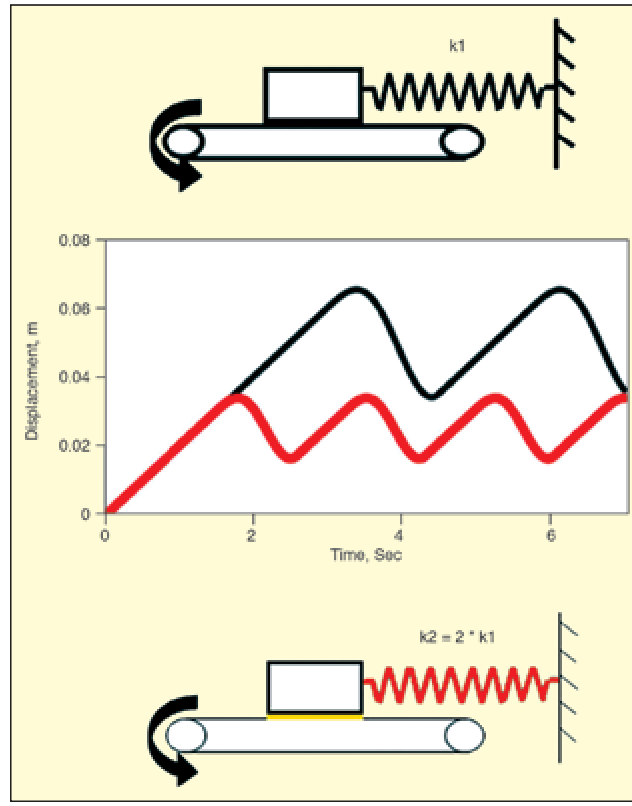

Figure 6. Influence of system rigidity on friction force curve.

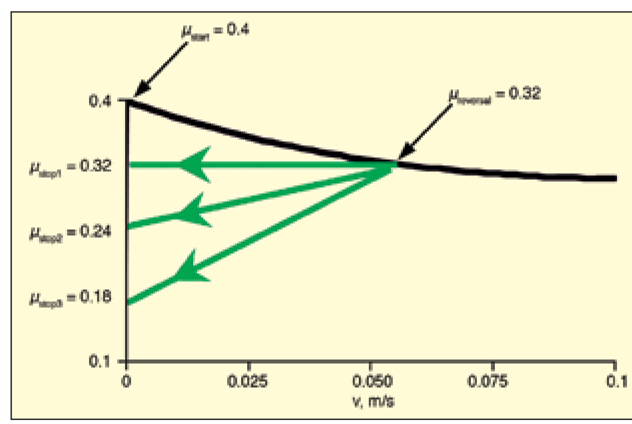

Figure 7. Different possible Stribeck curves during deceleration.

The following calculations were made using the friction coefficients at the breakaway point (μ_{start}), at the reversal point ($\mu_{reversal}$), and finally, just before standstill (μ_{stop}) as the evaluation criterion for stick-slip. To keep things simple, the slowing-down process was assumed to be in a straight line, and the Stribeck curve was assumed to look the same both for accelerating and slowdown past the transition point.

Here is modified coding for the Stribeck curve:

$$\begin{gathered}\text{If } \ddot{x} < 0 \text{ and } \dot{x}(\mu_{min}) \text{ then} \\ F_R = a \cdot x + b \\ \text{else} \\ FR = F_{\text{Stribeck}} \\ \text{endif}\end{gathered} \tag{2a}$$

with parameters a and b being calculated from the values $\mu_{reversal}$, $v(\mu_{reversal})$ and μ_{stop}. The following variations of μ_{stop} have led to the system behavior variants shown in Figure 8

$\mu_{stop1} = \mu_{reversal}$
$\mu_{stop2} = \mu_{start} - 2^*(\mu_{start} - \mu_{reversal})$
$\mu_{stop3} < \mu_{start} - 2^*(\mu_{start} - \mu_{reversal})$

For μ_{stop1}, the system responds in a similar way to Figure 3. If the friction coefficient decreases during slowdown at the same rate as during acceleration (μ_{stop2}), stick-slip turns into a damped vibration. If the value of μ_{stop}

is decreased further, the stationary friction coefficient is reached quickly after breakaway.

These tests have shown that μ_{stop} in relation to $\mu_{reversal}$ influences the generation of oscillation friction in the same way as μ_{start} in relation to $\mu_{reversal}$. Consequently, the following conclusions are reached regarding the stick-slip tendency of the modified Stribeck curve:

$$\text{Value of stick-slip tendency} = (\mu_{start} - \mu_{reversal}) - (\mu_{reversal} - \mu_{stop}) = \mu_{start} - 2 \cdot \mu_{reversal} + \mu_{stop} \quad (3)$$

If the value of the stick-slip tendency is higher than zero, the system is within the stick-slip range. If the value is below zero, no stick-slip occurs. The lower the value, the better the stick-slip characteristics of the tribological system. These conclusions can be drawn without knowledge of the particular system flexibility, because the value of $\mu_{reversal}$ depends on the spring constant k (among other parameters).

This model may also be used to describe the influence of the system rigidity. In the following, μ_{start} and μ_{stop} will be assumed to be constant, only the spring constant k varies. With variation of the spring constant, the passage of the Stribeck curve changes, as shown in Figure 4. The softer the spring, the larger the part of the Stribeck curve is actually covered and the higher the maximum speed. This also means that with a softer spring, $\mu_{reversal}$ becomes smaller in mixed friction, and the term describing the tendency to stick-slip becomes higher. Figure 9 shows that with a harder spring, a transition from stick-slip (black frame) to the stick-slip-free zone (green frame) can be attained. The hypothesis, that μ_{stop} remains constant has not yet been confirmed with physical test data.

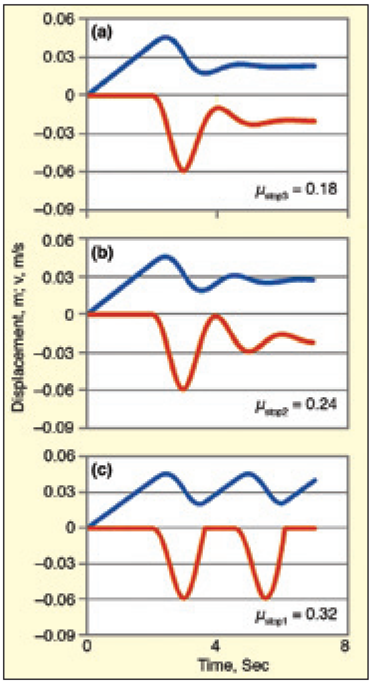

Figure 8. Influence of μ_{stop} on stick-slip behavior.

Static Friction. In the previous section, the negative slope of the Stribeck curve was shown to be responsible for the occurrence of stick-slip. Higher static friction than dynamic friction has the same effect. The static friction in tribological contacts with polymers are affected by the material properties of the polymer. Compared to steel, polymers have a visco-elastic behavior, which means that these have the ability to flow. When two specimens are in contact, there is a nominal area of contact, which is the area of surface overlap, and there is a real contact area that includes surface asperities. Under a normal force, the asperities come closer because of visco-elastic properties, and the real area of contact increases (see Figures 10a and 10b).

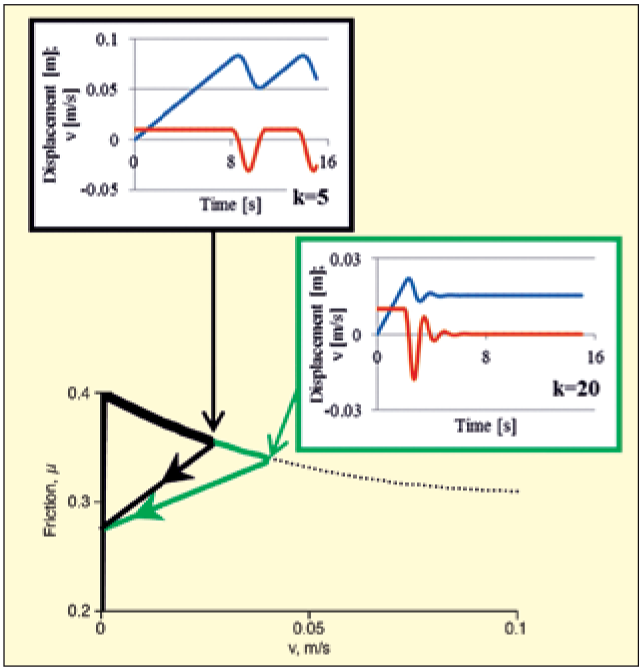

Figure 9. Influence of spring constant on stick-slip behavior.

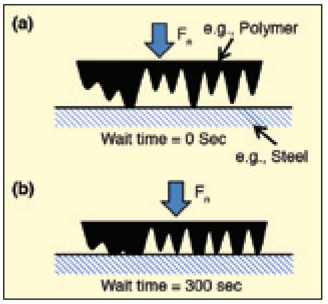

Figure 10. Real area of contact.

The adhesive part of the friction is proportional to the real contact area, so the static friction increases with waiting time. The waiting time defines how long the contact is loaded with a normal force without moving. When the waiting time is plotted on a log scale, increase of the static friction occurs linearly in the diagram (see Figure 11). This happens in a dry and unlubricated contact. A lubricated contact shows the same behavior, because the larger

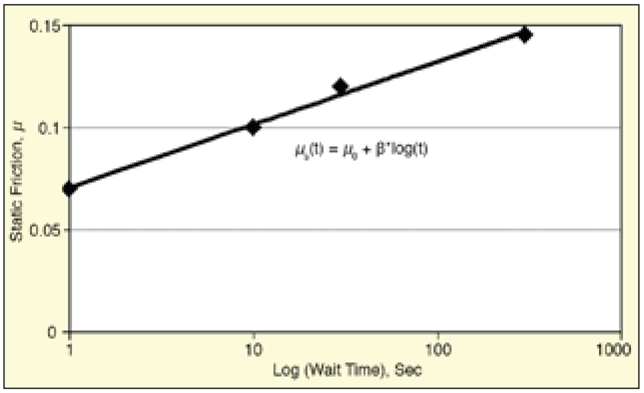

Figure 11. In log-scale diagram, static friction increases linearly.

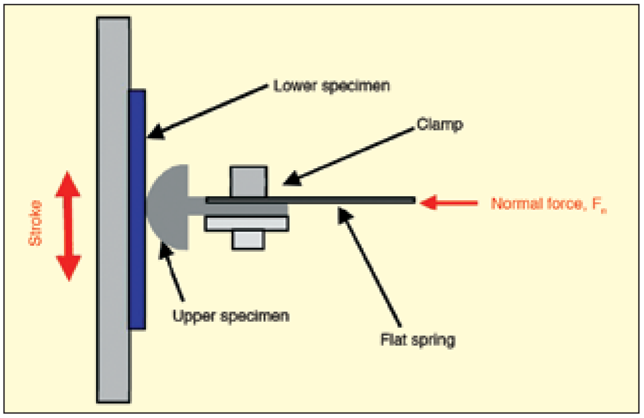

Figure 12. Measurement principle of Ziegler stick-slip test rig.

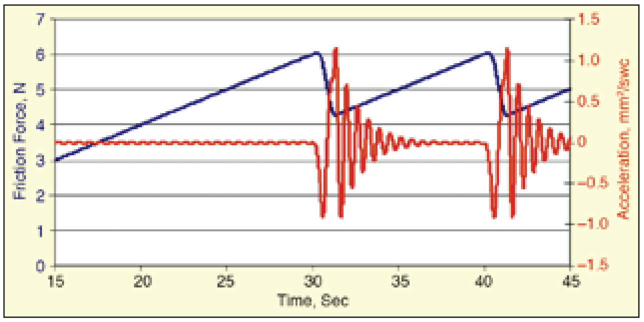

Figure 13. Friction force (in N, left y-axis) and acceleration signal (in mm²/s, right y-axis) in the case of stick-slip.

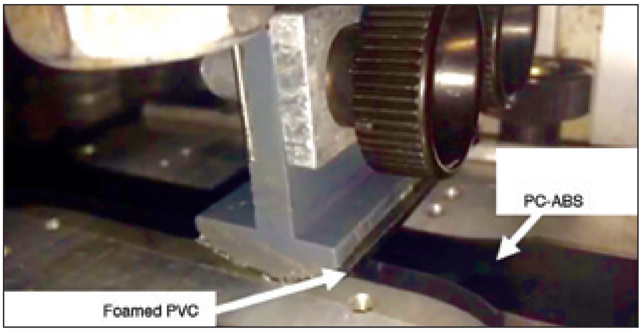

Figure 14. Specimens made of foamed PVC and PC-ABS.

the real area of contact is, the less space for a lubricant is available. In other words, the lubricant is pushed out of the contact zone.

Measurements of Stick-Slip and Static Friction

Ziegler Stick-Slip Test Rig. To examine lubricants according to their stick-slip behavior, the Stick-Slip test rig SSP from Ziegler Instruments is used. A polymer is pressed on a plate (which can be made of steel or a polymer), and is subjected to an oscillating movement. For stick-slip sensitivity assessment, the system flexibility is provided by a flat spring connected between the upper specimen and the loading device (see Figure 12). The test rig measures the friction force and the acceleration of the upper specimen at different loads, speeds, temperatures and humidities. The parameters are listed in Table 1.

Depending on the geometry of the specimen, the load is changed to have a contact pressure that is representative for the application. The manufacturer of the test rig proposes calculating a risk-priority number (RPN) to differentiate bonded coatings according to their stick-slip sensitivity. This works fine for tribological contacts with large differences in stick-slip behavior. Otherwise, measurements of static friction can be compared with dynamic friction.

Noise is not only influenced by the difference of static and dynamic friction, but also by the duration in which sliding friction is reached after overriding the static friction. And this can be evaluated exactly by the acceleration sensor.

When stick-slip occurs, as shown in Figure 13, the acceleration sensors see a signal as a damped oscillation (which describes the vibration of the flat spring). From the acceleration signal, a risk priority number (RPN) is calculated, which describes the risk of noise occurring with the test specimen and lubricant. The RPN is calculated from three parameters:

- Number of sticks, or how often the contact changes between stick and slip.
- Maximum acceleration signal, or the height and loudness of the first static friction.
- Integration of the acceleration signal, or the noise of all stick events that occur in the complete test.

The RPN can have numbers from 1 to 10: 1-3, low noise and no stick-slip (green); 4-5, noise and stick-slip can occur (yellow); 6-10, bad noise and stick-slip behavior (red).

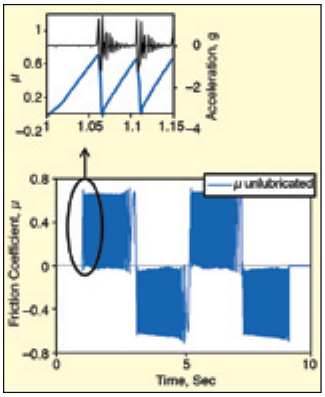

Figure 15. Stick-slip under dry conditions.

Stick-Slip Measurements. In this section, an example of the development of a lubricant is presented. Foamed PVC and PC-ABS, which can be used in the interior of a car, are materials that can generate significant noise when in contact. One solution for this problem is noise tape (or felt tape). Another solution is the use of a fluid, which can be sprayed on surfaces while remaining invisible. With the specimen of Figure 14, the tests are performed at: 10 mm/s; 10N (< 1MPa) and ambient temperature. Normally these tests are done at different temperatures and, especially with elastomers and dry conditions, at different humidities. For this article, only the ambient temperature results are presented, because the full test series is too large.

Table 1. Typical parameters used in stick-slip and static friction measurement.

Velocity, mm/s	Load	Temp., °C	Wait Time, Sec
1	10	30	10
5	20	23	60
10	80	80	300

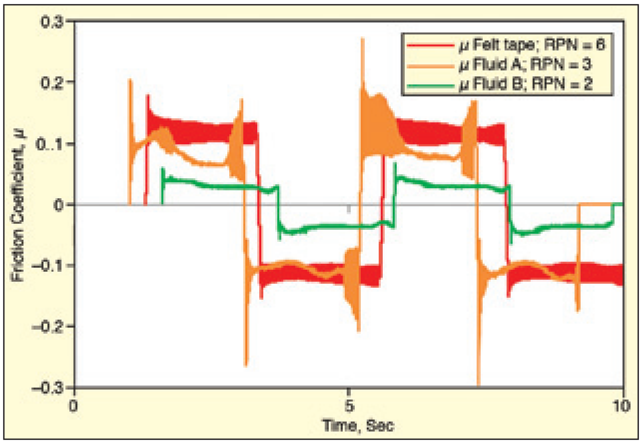

Figure 16. Stick-slip measurement for two fluids and felt tape (different scaling than Figure 15).

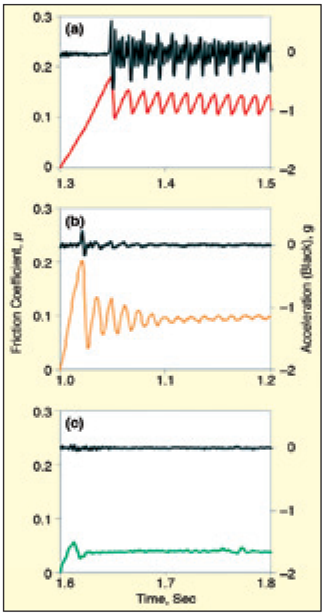

Figure 17. Start of the tests in detail.

Under dry conditions these materials show heavy stick-slip and a high RPN of 7 (see Figure 15). Also the acceleration signals (black line) show high values. To eliminate this heavy stick-slip, two measures were tested. The first one is the use of a felt tape (running against the PC-ABS specimen), and the second is a fluid. Both measures led to a much lower friction than in dry conditions. But lower friction does not mean automatically that the noise generated is lower. In this case, see Figure 16, the friction lowered to less than 50% of the dry condition and also RPNs lowered. But the three measures show different results for stick-slip behavior and noise generation. While the felt tape still shows stick-slip and a high RPN over the whole test, the fluids are able to avoid stick-slip and lower the RPN. Fluid A shows stick-slip only in some sections of the test, and Fluid B is able to avoid the stick-slip completely. The x-axis in Figure 16 is shifted for every test for better visual differentiation. Figure 17 shows the start of the three tests in detail.

Both felt tape and Fluid A show stick-slip. But the acceleration signal of Fluid A is much lower. That means that the generated noise will be lower. The main difference between the two fluids is the viscosity. Fluid B has higher viscosity than Fluid A.

Changing parameters like speed, load and temperature can lead to different results. In this case, parameters were chosen that are critical for stick-slip and are able to differentiate between the different measures.

Static Friction Measurement. An example in this section shows how static friction increases with waiting time (as described previously). For this phenomenon, at least one polymer specimen is needed. In this case, the static friction is measured with a ball made of PA66 sliding against a steel plate (Figure 18). The pressure was approximately 75 MPa, the speed 10mm/s and the temperature ambient.

The waiting times were 10 s, 60 s, 300 s and 1000 s. Therefore, four measurements of the static friction are needed for one lubricant. For the friction coefficient, after 1 second the dynamic friction is used in this diagram. In the upper diagram in Figure 19, the static friction coefficient is plotted against the waiting time. In the lower diagram of Figure 19, the raw data for three static friction measurements are plotted.

With a logarithmic scale of the waiting time-axis, every lubricant shows a linear behavior. Grease A and Grease B show both an equal slope, while the increase of grease C is the lowest. Grease C performs best in this test, because

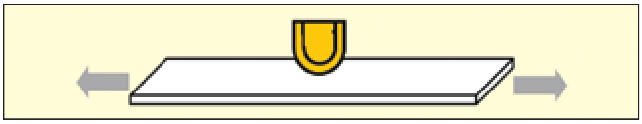

Figure 18. Specimen: ball (POM) and steel plate.

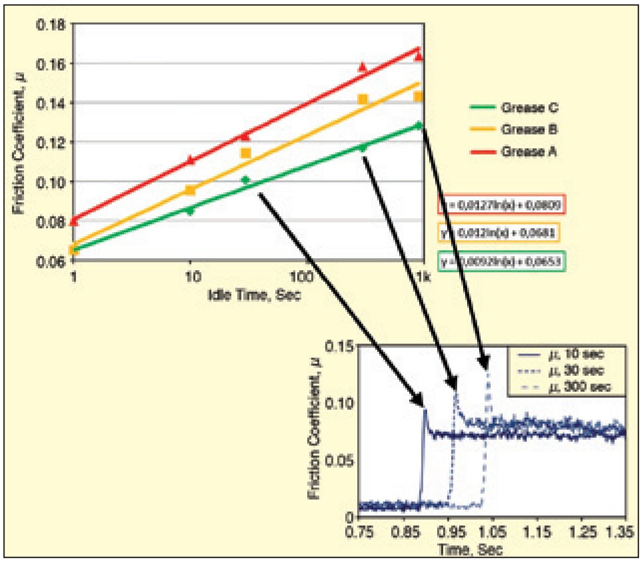

Figure 19. Static friction for various lubricants.

of both the lowest static friction and the lowest slope.

Summary/Conclusions

With the help of polymer friction theories, a model for the occurrence of stick-slip and static friction was developed to understand the tribological mechanisms as a tool to aid in the design of new lubricants. The analytical model developed can account for the influence of stiffness on the occurrence of stick-slip. Tests have to be performed to choose the right lubricant for a noise-critical application. When stick-slip occurs, lubricants (and other solutions like felt tape) can be better differentiated by measuring the acceleration signal as opposed to the friction coefficient between sliding materials.

Stick-slip events can be difficult to reproduce when the stiffness of the test rig is not the same as in the field application. In this case, the static friction coefficient alone can be used to differentiate between lubricants with respect to stick-slip behavior. The test results show that by increasing the viscosity of the lubricant, the potential for stick slip is greatly reduced.

Work is currently in progress to determine whether the theoretical model discussed here correlates with the test results from the Ziegler stick-slip test rig. This is being accomplished by using the Ziegler rig to measure stick-slip properties while varying system rigidity and subsequently determining the friction force during specimen acceleration and deceleration.

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