Analyzing the tribology of sound

Using—and sometimes inventing—highly specific testing apparatus, researchers continue to fiddle with the bizarre lubrication properties of rosin.

By Linda Day

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A violin's beautiful tones depend on oscillations that only a slip-stick non-lubricant (the rosin on the bow) can provide—and nearly everything related to this harmonic regime seems quirky or inscrutable.

Violinists and researchers Jim Woodhouse of Cambridge University's Engineering Department in England and Bob Schumacher, with the physics department of Carnegie Mellon University in Pittsburgh, have been working for years to understand and simulate what goes on. If they succeed, computers may throw a little light on why the violin is so hard to play.

At present, nearly everything about the way a violin and its strings vibrate to produce sound is understood well enough for good simulations except for one thing: the interaction of bow and string. And here is where the Woodhouse-Schumacher team may be on the verge of a simulation breakthrough. Or not. To understand how far they've come, you have to start with Helmholtz.

Strange corners

When you draw a rosined bow across a violin string and create a sound that your violin teacher does not object to, something extraordinary happens to the string. Hermann von Helmholtz discovered the resulting waveform about 140 years ago, showing that the string moves in a V shape, two straight-line segments separated by a sharp "Helmholtz corner." What appears to be a smooth vibration is really just the envelope of a moving corner that circulates around one way: When the bowing changes direction, the corner reverses and goes around the other way. For an animated version of this, see the Web article at **http://plus.maths.org/issue31/features/woodhouse/index.html**, since a moving picture is worth even more than the proverbial thousand words.

Sustaining Helmholtz motion depends on the bow's rosin, which possesses unique stick-slip tribological properties. While the Helmholtz corner travels on its long journey to the player's finger and back, the bow is gripping the string so that bow and string move together (sticking) until the Helmholtz corner arrives back at the bow, at which point the rosin gives and the string zips across the bow hairs (sliding). The string sticks again when the corner arrives back from the short journey to the bridge, and the cycle repeats.

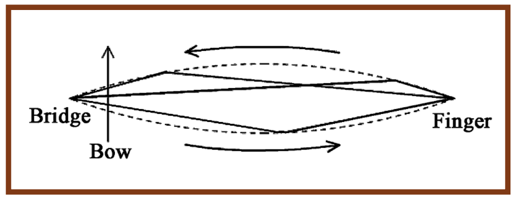

Figure 1. Helmholtz motion of a bowed string. The dashed line shows the envelope of the motion, and the solid lines show three different snapshots of string position at different stages in the cycle. The "Helmholtz corner" circulates in one direction as shown by the arrows. Circulation reverses when the bow changes direction.

Good sound quality relies on achieving Helmholtz motion, which basically depends on three things: the downward force of the bow on the string, the bow position and the bow speed. If the bowing force is too light, the bow slips over the string with only a squeaky 'surface sound' to mark its passing. This is the result of insufficient sticking, which results in two or more episodes of slipping per cycle of vibration. If the bow force is too heavy, it creates chaotic vibrations that produce the raucous graunch of a tortured string.

But it's not enough to get the force right—your bow also has to be moving at the right speed and in the right place on the string because Helmholtz motion also depends on the distance of the bow from the bridge as a fraction of the total length of the string. J.C. Schelleng[1] worked out the math in the early '70s, creating the Schelleng Diagram shown in Figure 2. It shows that if you play near the fingerboard, you have a better chance of sounding good.

OK, so now you can bow with the right force in the right place with the right speed to achieve Helmholtz motion—but how long does it take you to do it? If you want people to stay in the room, you'd better get past the initial transients and into Helmholtz in less than 50 ms. And here's where "playability" comes in.

Professional violinists judge an instrument not only on its sound but also on its

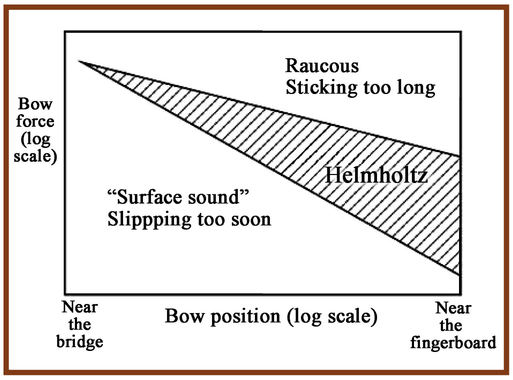

Figure 2. The Schelleng Diagram shows the region of force and position where Helmholtz motion can be achieved.

playability, how quickly and easily the violin moves past the initial transients to achieve Helmholtz motion. "That's what motivates our thread of research, playability," says Woodhouse. "When players are trying instruments, they say things like 'I don't like the sound, but it's very easy to play.' Sound quality is a psychological thing, but playing qualities are more directly related to mechanics and science, which we can measure and understand and hopefully learn to simulate.

"In order to make contact with the things musicians really want to know about, any simulation we develop has to be a really good model," he continues. "It's not enough to get it roughly right. Everything has to do with transients, and those are hard things to get right in theory."

Woodhouse notes that for nearly all other types of frictional vibration like squealing brakes and creaking hinges, the goal is simply to get rid of the noise, and you may not need to understand more than the basic science or common engineering practice. The musical application is unique in its goal to understand and to simulate on a computer every component of Helmholtz motion and related transients: the bow, the violin body vibration, the string and especially the rosin. With a reliable simulation model, many aspects of violin playability could be probed by computer experiment.

Friction fact and fiction

One thing that Schumacher and Woodhouse discovered from researching the tribology of rosin back in the 1980s was that what everyone knew about slip-stick friction was wrong.

"People thought the friction depended on sliding speed," he says. "That follows naturally from the measurements that people do. You've got a pin-on-disk tribometer, you measure the friction force during steady sliding, then you change the speed and measure the friction again. And because that was the data everyone has, people assumed the same thing would happen at high frequencies. It's a concept that is measurement-driven. There is no good reason why that should be true, and as soon as we tested it, we found it wasn't."

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About Jim Woodhouse

Jim Woodhouse received a master's of arts degree in mathematics from Cambridge University in England, in 1972. After receiving his doctorate degree in 1977, he did post-doctoral work on the acoustics of the violin in the department of Applied Mathematics and Theoretical Physics at Cambridge (this work being inspired by a hobby interest in building instruments). He then worked for several years on a variety of structural vibration problems for a consultancy firm before joining the department of engineering at Cambridge in 1985 as a lecturer, and then later as reader and professor. His research interests all involve vibration and musical instruments and have continued to play a major role in his career.

About Bob Schumacher

Bob Schumacher received his undergraduate degree in physics at the University of Nevada, Reno, and his doctorate at the University of Illinois, in 1955. His thesis research was in nuclear magnetic resonance under professor C.P. Slichter. After a brief instructorship at the University of Washington, he joined the faculty of Carnegie Institute of Technology (now Carnegie Mellon University) in 1957. In the mid-'70s, he changed his research interests to musical acoustics, a change that was solidified by a sabbatical at Cambridge University in 1977. His major interests have been simulations of musical oscillators, with particular emphasis on stringed instruments. He has been a professor of physics (emeritus) at Carnegie Mellon University since 1997.

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Figure 3 shows the debunked theory matched up against experimental results. In the theory (the dashed line), friction force increases as sliding velocity decreases until sticking occurs (the vertical line), at which point the friction force can take a range of values. In the experiments (the solid line), force follows a hysteresis loop.

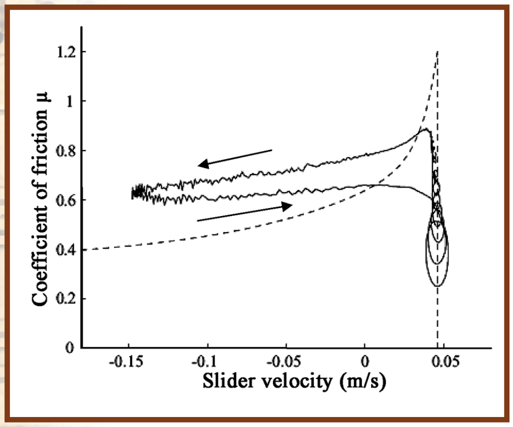

Figure 3. The debunked theory of stick-slip friction (dashed line) shows the coefficient of friction following a smooth curve during sliding, while the vertical portion of the dashed curve shows sticking. The solid line shows what actually happens during a stick-slip vibration. The arrows indicate the direction around the hysteresis loop.

"You can still see a faint shadow of the old curve," says Woodhouse. "There's a vaguely vertical bit on the right, which is sticking, and a slipping bit to the left. But no part of that loop is anywhere near the dashed line. The original model was just wrong. The interaction with the dynamics of the vibrating system changes the friction behavior from the tribometer measurement."

As you might imagine, the experimental technology that produced the hysteresis loop is quite a bit more complex than a pin-on-disk tribometer—dynamic friction force is not so easy to measure directly. The first device used a cantilever with a glued-on wedge of the material to be measured (*see Figure* 4).

To excite the cantilever into stick-slip vibration, it was 'bowed' with a cylindrical rod coated with rosin and pressed against the cantilever by an arrangement of wires and weights. The rod was driven at a steady velocity monitored by a displacement transducer. Vibration of the cantilever was measured using a small accelerometer placed as close as possible to the driving point. The vibration data covered only a few stick-slip cycles over a short time (~ 0.2 sec) and a few millimeters of travel, so that both the normal load and the rod velocity could reasonably be assumed constant.[2]

The cantilever produced interesting data, but it was still a very simple system, a far cry from the complexity of a violin string.

Starting from zero

Meanwhile, Knut Guettler took a leap forward in the study of playability in his dissertation. Guettler taught himself string bass, became one of the world's foremost players, and then, without even a secondary school education, expanded his player's knowledge to a doctorate in music acoustics from the Royal Institute of Technology in Sweden.

As a musician, Guettler realized the value of the new experiments on slip-stick friction but recognized that steady-state experiments could not address playability. In the real world, the bow must start with zero speed (unless you're using the "bouncing bow" technique, which no computer models have yet attempted to simulate). Guettler

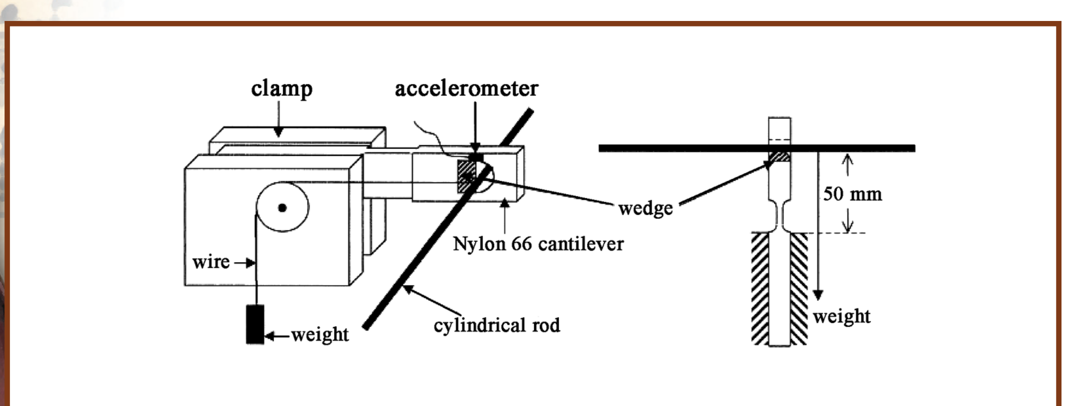

Figure 4. Schematic diagram of the experimental rig. The cross-section is shown to scale.

sought to create a computer simulation based on Woodhouse's mathematics, recognizing that a meaningful simulation would not only require the right equations for the hysteresis, it would also require initial transients that were musically sensible.

As a start in addressing these issues, Guettler studied a family of bow gestures with constant bow force and a velocity that starts at zero and accelerates at a constant rate[2]. Guettler's bowed-string simulations plotted the time taken to achieve Helmholtz motion at a grid of points in the force/acceleration plane. He also sought analytical expressions for the upper and lower bounds of a region containing "perfect transients," combinations of force and acceleration that produce Helmholtz motion right from the start of the note.

Guettler derived four necessary conditions for the production of a perfect transient; in doing so he simplified the real world significantly: He ignored the effects of wave dispersion, torsional motion in the string and temperature, and he treated the ends of the string as dashpots. He also assumed that the bow would contact the string only at one point, that the bow hair was rigid and that the bowing position would be an integer division of the string length.

Guettler's four conditions relate to the way the initial stick-slip events interact with each other—bogglingly complex! We shall sidestep nimbly around them here, but you can get a good explanation in reference [4].[3] Figure 5 presents Guettler's diagrams for six different bow positions defined by the value of β, the bow position as a fraction of the string length. Like the Schelleng Diagram, the Guettler Diagrams show that it's easier to achieve Helmholtz motion quickly (i.e., the white wedge is bigger) when your bow is nearer the fingerboard (i.e., when β, is 1/7 rather than 1/12), and when you use greater bow velocity and force.

How well does Guettler's theory match up with fact? Woodhouse decided to create an experimentally measured Guettler diagram, which would reveal immediately whether the wedge-like region of perfect transients in Figure 5 gives a useful approximation to real behavior. Such an experiment would require a versatile mechanical bowing machine—no human has the required control or patience—so he and a graduate student, Paul Galluzzo, designed the one shown in Figure 6. A linear motor carries a bow, or a rosin-coated Perspex rod, which provides a match to simulation models with a single point of contact.

In the Woodhouse-Galluzzo bowing machine, the bow position is monitored by a digital encoder that tracks the desired trajectory, and the bow force can be tailored to any desired pattern by another feedback controller using a force signal from strain gauges in the machine's "wrist." This computer-controlled robot can produce a wide range of bowing gestures with good accuracy and repeatability. Although it can't cope with "bouncing bow" gestures, for continuous contact its capabilities meet or exceed those of a human player.[4] The string motion in response to a given bowing gesture is monitored using a piezo-electric force sensor built into the bridge of the test instrument, a cello.

At the same time he was testing the bowing machine, Woodhouse also was testing his own simulation models that he hoped would match the machine's results. Figure 7 shows how the results stack up.

Figure 7(c) shows simulation results based on the debunked friction curve model—obviously no match for experimental results. Figure 7(d) shows simulation results for Woodhouse's thermal plastic model. In this model, he treats the rosin as a perfectly plastic solid, which will only deform (i.e., allow slipping) when the shear stress reaches the rosin's

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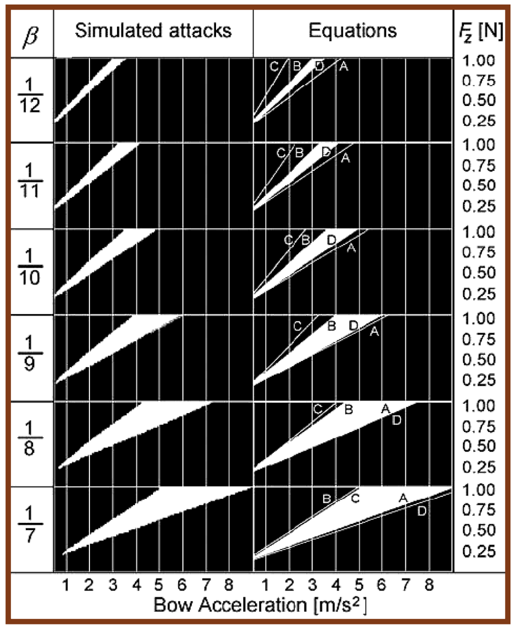

Figure 5. Predicted and simulated regions in the force/acceleration plane where "perfect transients" are possible, reproduced from Reference 4. Right-hand column: the lines labeled 'A', 'B', 'C', 'D' correspond to the four conditions described in that text. The white wedge shows the region satisfying all four conditions. Left-hand column: results of simulations covering the same parameter space, colored so that white pixels correspond to perfect transients. The six rows show results for different values of bow position, ß, expressed as the fractional distance of the bow point from the bridge.

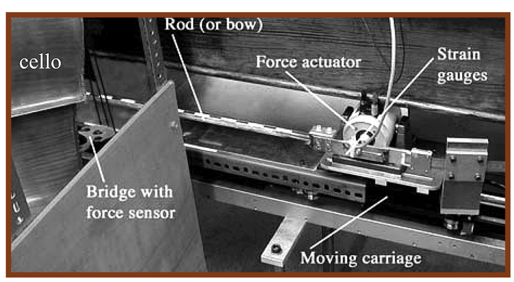

Figure 6. Computer-controlled bowing machine fitted with a rosin-coated Perspex rod to bow a cello.

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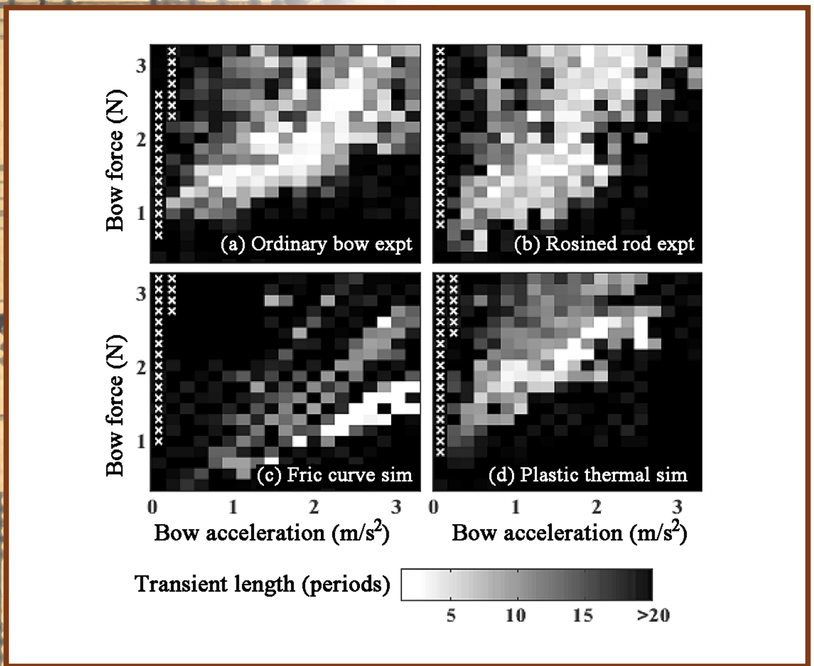

Figure 7. Guettler diagrams for a cello D string. Top row: measured using (a.) a conventional bow and (b.) with a rosin-coated rod. Bottom row: simulated using (c.) the (debunked) friction curve model and (d.) the thermal plastic model, both assuming a single point of contact between bow and string. All four plots correspond to the same bow position ß = 0.0899 (about 1/12): for (a.), this is the center of the bow-hair. (Note: This image is "pixilated" because it is a computer calculation generated from individual pixels, each representing one run of the program).

shear yield strength, which he assumes to be temperature-dependent. Better, but still no cigar.

And now Bob Schumacher enters the picture with a different bowing machine.

Inverse calculations and microscopic wear tracks

Recognizing the need for an experimental system that would measure a wider range of dynamical behavior than the Woodhouse-Galluzzo bowing machine could, Schumacher invented a bowing machine designed to measure friction force and string velocity at the contact point.

"The crucial thing is that you cannot put any kind of mass whatsoever on a string without changing its properties," Schumacher says, "and if you want to know both the force and velocity at the bowing point, that's too much to measure at one place. So I figured that we could get the information we needed by measuring forces at the termination of the string—the bridge and the finger—and then using inverse calculation to back out behavior under the 'bow.' When we finally had this, we wondered why we hadn't thought of it years ago."

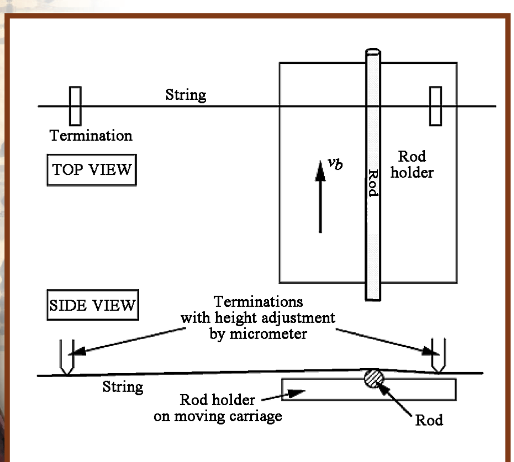

Figure 8. A sketch of the bowed-string apparatus (not to scale). The side view shows rod pressing on string to produce normal force.

Figure 8 shows a schematic of Schumacher's bowing machine. The rosin-coated rod is pressed against a violin E string (a high-tensile steel monofilament), which is mounted on a frame supported on micrometer mounts that allow the normal force of the string on the rod to be adjusted. The rod is mounted on an aluminum plate, and electric heaters on the plate allow the rosin-coated rod to be tested at varying temperatures. The rod and plate are moved by a constant velocity trolley that moves 0.2m at a constant speed 0.2m/s. Acceleration and deceleration occupy about 0.1s, so all runs last slightly longer than 1s. The tension in the string (the note to be played) is adjusted to 650 Hz, giving many hundreds of periods of oscillation in each run.

Piezoelectric force sensors mounted at the string terminations measure the transverse component of the oscillating force exerted by the string, without interfering with the motion of the string. A reconstruction algorithm then combines the forces measured at the two terminations with parameters obtained from plucking experiments to calculate the velocity, v(t), of the center of the string, and the friction force, F(t), at the bowing point.[5]

This novel experimental approach offers important advantages: First, the reconstruction algorithm takes into account all vibration modes of the string so that useful data can be collected over the full audio-frequency bandwidth. And, second, the data gathered provides a sensitive test of which oscillation regime the string chooses under given conditions: A bowed string shows a very rich range of dynamical behavior, both periodic and nonperiodic, all of which can shed light on the underlying frictional constitutive law.[6]

Finally, a friction model that can predict the correct sequence of oscillation regimes during this kind of transient stick-slip test would have a good claim to being convincing. "It's been shown that a skilled violinist can control the length and nature of initial transients with impressive consistency," says Schumacher, "so the inherent variability of frictional interfaces can't be used as an excuse for poor models!"

Figure 9 shows sample data from Schumacher's experiments.

The top graph shows ideal Helmholtz motion, where the velocity of the string relative to the bow is close to zero during the long sticking part of the cycle. The bottom graph shows part of an initial transient with two incidents of sliding per cycle, which produces a "surface" sound. As bowing continues, the second smaller sliding event dies out, and the string attains the desired Helmholtz regime.

The waviness of the flat part of the line illustrates "Schelleng ripples:" "The questions is, is the string really sticking, or does it slip a little bit?" says Schumacher. "The apparatus shows that the bow speed and the string speed during the nominal sticking part are not necessarily the same. But this plot does not prove that sticking is not taking place: the string may be rolling on the bow, or creeping along the bow or a bit of both."

Schumacher's apparatus is capable of extreme detail. In graphs of friction force vs. distance during the sticking phase (for which the debunked theory proposed the smooth line shown in Figure 3), Schumacher's data leads to Figure 10.

When Schumacher plots the data as force vs. velocity (the hysteresis curve), he gets curves that differ dramatically, depending on the temperature of the rosin, but which all show the sticking 'scribble.'

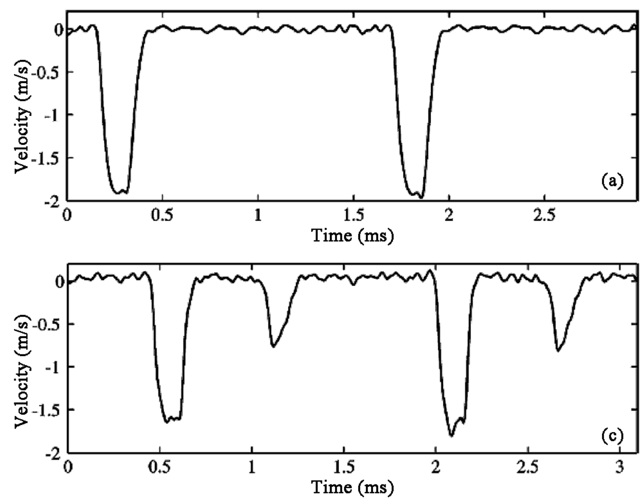

Figure 9. Helmholtz motion (top) and "surface sound" (bottom): The velocity of the string relative to the bow is close to zero during sticking (the longest part of the cycle), and then changes sharply during sliding. The bottom graph shows two incidents of sliding per cycle.

To complement the work with the bowing machine, Schumacher and Woodhouse also examined scanning electron micrographs (SEM) of the wear scar created in the rosined surface after a single bow stroke. Figure 11 (*see page* 38) shows the wear track for two periods of double-slip motion (e.g., Figure 9(b)), plus a close-up view of location D. The string is vertical on the page, and the rosined bow is moving left to right. Each

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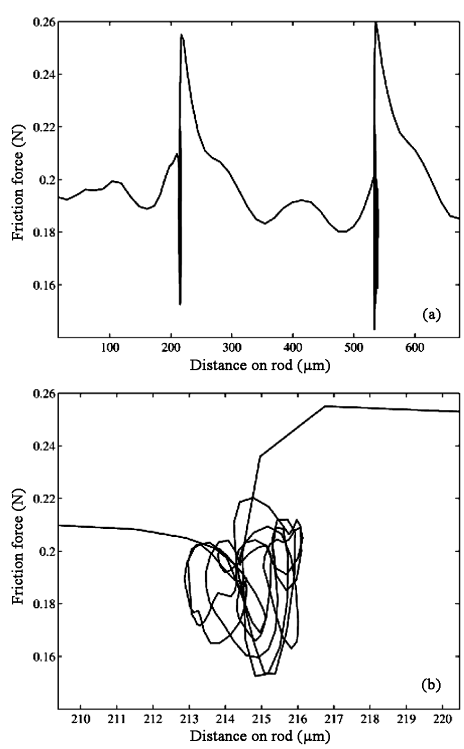

Figure 10. The top graph shows friction force as a function of position on the rod for the Helmholtz motion of Figure 9(a). The bottom graph is an extreme magnification of the first slipping episode shown in the top graph.

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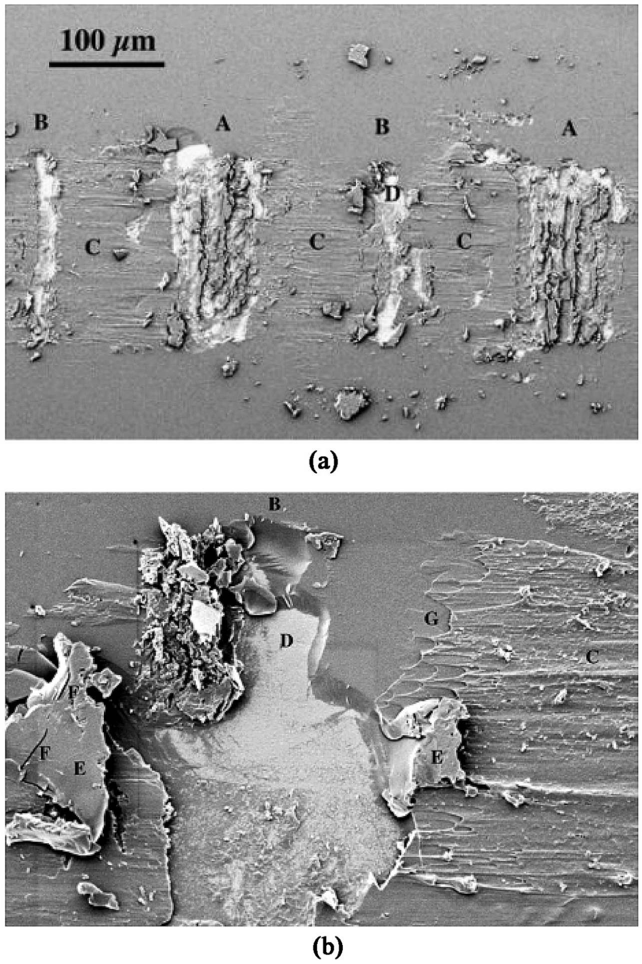

Figure 11. SEM micrograph of wear track on the coated rod, showing approximately two periods of a double-slip motion, and (b) enlarged view of the "D" area shown in (a). (Reprinted with permission from Woodhouse, J., Schumacher, R.T. and Garoff, S., (2000), J. Acoust. Soc. Amer. 108, pp. 357–368. Figure 8(a). Copyright 2000, Acoustical Society of America).

gouge in the rosin's surface represents a single stick, while the mostly intact sections of rosin in between the gouges reflect the slip.

"Each scar is a place where the string has stuck to the bow," Woodhouse explains. "And maybe while it was sticking, it was rolling around a little, which is why it's churned it up a little bit—that could relate to the Schelleng ripples. Then the string lets go, and the rosin breaks in a brittle sort of way, because the string pulls a chunk of it out and leaves a glassy looking fracture.

"It's easy to believe that temperature has been varying a lot during this cycle—the points where it's been sticking and then let go, you can see it failed in a brittle sort of way," Woodhouse adds. "Whereas in between the scars, the little horizontal lines show where rosin has melted on the surface and been pulled out into fingers. You've got to think treacle here. So during slipping, the rosin gets really hot and more or less melts, and during sticking it's had time to cool down a bit and get stronger, until it gets ripped off by brittle breaking."

Woodhouse had included some temperature effects in his first paper (the Guettler Diagrams shown in Figure 7), but this got him to thinking about temperature in a deeper way. "It makes generic sense that temperature is the most important thing," he says. "The most conspicuous thing about rosin is that it's a glassy brittle solid at room temperature, but you only have to hold it in your fingers a few seconds and it goes sticky. Its glass transition temperature is not far above room temperature, which means that all of its properties are varying rapidly with temperature—the effective viscosity changes by orders of magnitude."

Woodhouse explains that in Helmholtz motion, the string spends 90% of the cycle sticking. When it slides, it slides very fast and generates considerable heat. As the rosin heats up, its viscosity goes down and the friction force goes down. At the end of the sliding interval, the friction force is still low, but the string comes back to meet it as the Helmholtz corner comes around and reattaches the string to the bow.

"Then the string sticks again for a relatively long time, during which the heat generated during sliding leaks away into the thickness of the string or into the rod, and the contact layer, which is just a few microns thick, cools down. As it cools, it goes back up the viscosity curve, creating the hysteresis effect," he adds.

"Our first model made a simple attempt to represent that, and it moved in the right direction, but it clearly wasn't fully accurate," Woodhouse says. "What I'm in the middle of at the moment is going for something that's much more physics based. Rather than doing a heat-flow calculation and guessing, I'm trying to do more careful measurements on the rosin as a material and a more thorough heat-flow model, where we actually look at temperature distribution throughout the rosin layer, not just an average temperature. It's work in progress."

In particular, Woodhouse is interested in the formation of shear bands within the rosin. "Having shear bands in the back of my mind, it may be that something similar is happening in our rosin layer," he says. "We start to slide, and we start to shear, and as we shear it gets hot, and if the temperature isn't uniform—say it's a bit warmer in the middle than the edges, which could be heat left over from the previous cycle—then the viscosity is already lower there, and maybe the rosin layer forms one of these shear bands in the middle, within the thickness of the rosin. Then the actual 'break' would take place at the shear band. That's my mental image, that some or all of the rosin is essentially melting and refreezing every cycle. The temperature may be fluctuating as much as 20 degrees every cycle.

"People tend to think that sticking and slipping are two different states," Woodhouse notes, "so somewhere in the computer program should be a switch that says 'If it's sticking, do this, if it's slipping, do that.' I think there won't be two different states: There will be one law incorporating viscosity and temperature that will link into the dynamics of the string to produce stick-slip motion. There will be one model of the material, and the stick-slip friction will arise when you ask how that model behaves if you drive the interface in a particular way."

But for definitive answers, and the ultimate one-law simulation model, we'll have to wait.

"What's endlessly intriguing about the violin problem is the playability question in the background," Woodhouse says. "Once we've got the model, we'll want to use it to look much harder at detailed responses. That makes it a much more challenging problem!" **<<**

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