

# Proceedings of The Institute of Acoustics

## FRICTION CHARACTERISTICS AND THE BOWED STRING

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The quality of a violin does not only depend on the sound it makes, as perceived by a distant listener. It also depends very significantly on the "feel" to the player. This rather vague term is intended to cover at least two different (but doubtless related) aspects of behaviour. First, some instruments may be a lot more tolerant of minor errors in bowing than others. Second, the available range of both tone and dynamic can vary considerably between different instruments. On the whole, players prefer docile instruments with a large expressive range.

Both these aspects of "feel" depend on variation among instruments of the details of the bow-string interaction. This realisation goes back to the early days of bowed-string research, and major contributions to our knowledge have been made by Raman [1], Saunders [2], Schelleng [3] and Cremer and his students [4]. The simplest relevant problem to study is that of steady bowing, although we must never lose sight of the importance in practice of transients of various kinds. When a player produces a steady note, he is almost invariably trying to sustain the string in the "Helmholtz motion" [5], in which a "kink" shuttles up and down the string, triggering transitions between sticking and slipping at the bow. The player controls three main parameters during such a steady note: bow speed, bow position on the string, and normal force between bow and string (often called "bow pressure"). The region in this parameter space within which the Helmholtz motion is possible has been described by Schelleng [3], with his well-known diagram which is reproduced below as Figure 1.

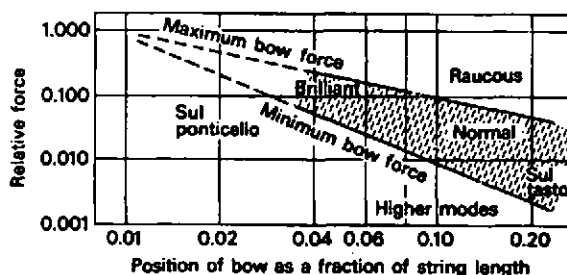


Figure 1. Schelleng's diagram showing the region of bowing parameter space in which the Helmholtz motion can be obtained.

# Proceedings of The Institute of Acoustics

## FRICITION AND THE BOWED STRING

To go beyond this level of analysis requires more careful modelling of bowed string motion. Such modelling is now quite well understood in principle, and has produced musically-interesting predictions which have stood up well to experimental tests [5,6,7]. There are two independent aspects of these models: the linear behaviour of the string and instrument body (and also of the bow) measured at the bowed point, and the non-linear behaviour of friction at the bow-string contact. Progress in understanding the underlying problem is currently held up by a lack of experimental information about both aspects.

There are many facets of the linear vibration behaviour which are insufficiently well measured. Perhaps the most important relate to the torsional behaviour of the string - as Cremer has pointed out [8], torsional motion provides the most significant loss mechanism for the string motion, particularly during starting transients, to the extent that without it, the violin would probably not be playable at all! Other important questions concern the dynamics of the bow, and the nature of the influence of body vibration on the string. There are indeed many challenges for the ingenious experimentalist in such problems. However, these are not the subject of this paper.

We are concerned mainly with the other area, the frictional behaviour at the bow-string contact. Up to now, it has been conventional to suppose that the frictional force between bow and string is given by a simple functional relation, of the kind sketched in Figure 2. The vertical portion of the curve corresponds to sticking, when the force can take any value between two limits with no relative velocity. When there is relative sliding between the surfaces, the force is assumed to depend on the instantaneous sliding velocity as indicated by the other portions of the curve. For this model to make sense, Friedlander [9] and Keller [10] both pointed out that the slope of the curve must be positive, at least within the range of achievable bow speeds, as sketched.

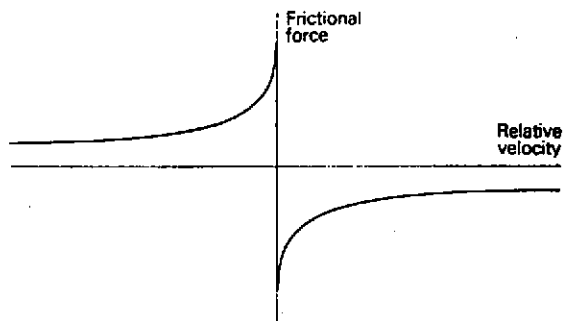


Figure 2. A friction curve, of the general kind usually assumed.

# Proceedings of The Institute of Acoustics

## FRICTION AND THE BOWED STRING

It is not easy to discover any rational justification for this model of frictional behaviour. Current understanding of the tribology of contacting bodies gives no convincing reason why the force should depend only on the instantaneous sliding velocity, and not on any aspects of the history of the motion. The model perhaps has its origin in the well-known fact that the static coefficient of friction is usually greater than "the" dynamic coefficient of friction. The easiest way to incorporate this observation within a mathematical model is to make the force a simple function of sliding velocity as indicated above.

If this model is believed, it is natural to measure the friction curve by enforcing steady sliding at a range of relative speeds, and determining the force used [11]. Such measurements do not, of course, provide any test of the underlying assumption that friction is governed by a simple curve. The measurements are interpreted from this assumption, and if the assumption were not correct, the results would have to be reinterpreted.

It would be better to measure the frictional behaviour during a stick-slip oscillation, to see whether the friction-curve model is in fact supported or whether it should be replaced with something more sophisticated. The simplest approach, at least on paper, is to take a simple harmonic oscillator and excite it by bowing, as sketched in Figure 3. Knowing the mass, spring strength and damping coefficient of the oscillator, one can readily deduce the force which is applied at the contact point at each instant from observations of the motion of the mass. One can then use a computer to plot the instantaneous force against the instantaneous sliding velocity through several cycles of the oscillation, and see whether a simple curve does or does not appear on the screen.



Figure 3. Schematic diagram of an approach to measuring the friction-velocity characteristics during a stick-slip oscillation.

# Proceedings of The Institute of Acoustics

## FRICION AND THE BOWED STRING

Such measurements have been employed in other areas of contact mechanics [12], but apparently not to the problem relevant here, where rosin is used to facilitate the stick-slip oscillations. In most other applications, for example friction between brake pads and their discs, the aim is to eliminate any stick-slip oscillations. That is not, of course, the aim here (it can be achieved quite easily by rubbing candle wax rather than rosin on the bow, but this does not go down very well with the owner of the bow). As in many such problems, musical acoustics requires us to ask more searching questions than is generally necessary for the vibration-control engineer. We are interested in the details of the stick-slip motion, since the clues to our problem of "feel" lie there.

To perform measurements of the kind just described proves to be harder than the simple description just given would imply. The biggest problem is to make a simple harmonic oscillator, which does not have any higher modes of vibration within the frequency range of interest. The point here is that stick-slip oscillations involve very rapid changes at the moments of capture and release, so that frequencies much higher than the basic oscillation frequency will tend to be excited. One either has to design these higher modes out, or allow for them in the processing of the data. Some preliminary attempts in this direction have been made, but efforts still continue.

A typical set of results so far is shown in Figure 4. We do not see a simple friction curve, but a hysteresis loop. During sticking the force builds up to a high level, then falls rapidly as sliding starts. At the end of sliding, by contrast, the force only climbs to a more modest level before the transition back to sticking, at least if these measurements are to be believed. There are many possibilities for the interpretation of such results. Perhaps we can preserve a "friction curve" model of sorts, but generalised to allow hysteresis cycles. On the other hand, perhaps what really matters is the time since slipping starts, so that we would obtain entirely different results at other oscillation frequencies. Perhaps the "flash temperatures" at the contact are the important thing, since rosin is very temperature sensitive. Perhaps the behaviour varies significantly with the normal force between bow and vibrator, or with humidity, or with bow speed.....

If such measurements can be perfected so that systematic answers to at least some of these questions can be obtained, one could then ask what the implication might be for bowed-string motion. This requires not just observations of the frictional behaviour, but a mathematical model of that behaviour. Here another difficulty can be anticipated. While it would be easy enough to fit a given set of measurements to a model of some kind, how could we tell whether this is the right model? The problem is analogous to the earlier one, where steady sliding measurements could not tell us anything about the validity of the friction curve model, since that model was assumed in interpreting the measurements.

To answer this problem, we need to find more than one independent type of measurement. One would then use one set of measurements to calibrate a given model, then use the model to predict the outcome of the other measurements, then compare those predictions with results. Some ideas for such independent

# Proceedings of The Institute of Acoustics

## FRICTION AND THE BOWED STRING

measurements will be discussed.

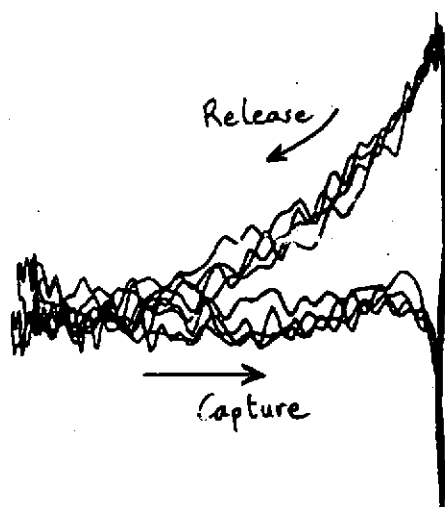


Figure 4. A preliminary attempt to measure the friction-velocity characteristic by the method described in the text. Velocity is plotted horizontally and force vertically, in the same sense as in Fig. 3.

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# Proceedings of The Institute of Acoustics

## FRICTION AND THE BOWED STRING

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