A Closer Look at the String Player's Bowing Gestures

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ABSTRACT
This presentation seeks to give an overview of present knowledge and theories concerning bowed-string transients and tone coloring. Bowed instruments are quite unique in the way tone production results from a considerable number of physical parameters, many of which are manipulated simultaneously by a single hand: bow "pressure" and speed; the bow's position on the string—as well as the string's position on the bow hair; the bow-hair angle and impact trajectory, to name the most important ones only. However, such complexity makes a two-edged sword since there are often narrow margins between perfection and blunder for the musician trying to get the most out of his/her instrument.

BOW FORCE, POSITION, SPEED, AND THE SCHELLENG DIAGRAM

Both Raman and Schelleng had the musician's perspective in mind when performing some of their most intriguing analyses. While Raman [1] partly collected empirical data by means of his mechanical bowing machine—where the bowing gesture in terms of speed, normal force, and string position were all controllable—Schelleng [2] utilized Raman's theoretical analysis on reflected waves and used the same three parameters for mapping the requirements for maintaining the Helmholtz motion.

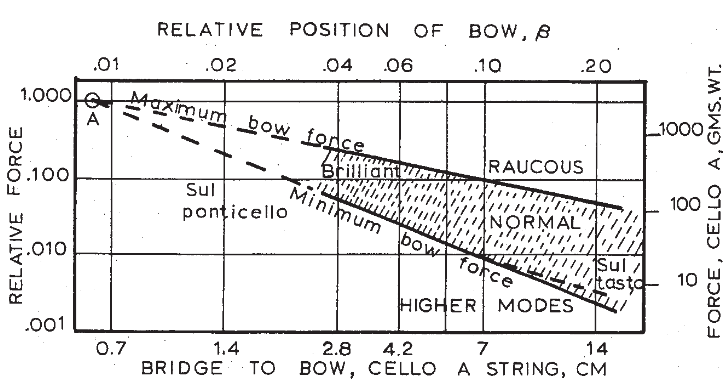
But Schelleng added one more important aspect: *timbre*. At two separate places within the Helmholtz-mode area in his diagram, the expressions "brilliant" and "sul tasto" are marked as indications of timbre. ("Sul tasto" literarily means "by the fingerboard", but is here, presumingly, a reference to soft tone color.)

It is, however, not immediately apparent from the figure whether these timbre differences are caused by change of bowing *position* (the two expressions are marked at different bow positions within the Helmholtz area), or by change of bowing *force* (the expressions are positioned at different values with respect to the ordinate). In the discussion that followed, Schelleng showed how the waveform of the string velocity under the bow is changing with the *bow force*. Later Cremer [3] analyzed this more in depth, and established the theory of "the rounded corner". However, the remaining question is:

Does the timbre change when only the bowing position is changed?

Regard Figure 2: Here the "rounded corner" causes the string release to spread out over a small transition interval before the full negative velocity is reached at slip. Accordingly, a comparable transition takes place at capture. (In practice the transition at capture is often shorter than the one at release.) It can be shown that as long as these *transitions* are independent of the bowing position, the force signal's spectral slope (envelope) will remain entirely unaffected by β (see Fig. 3). However, with the bow speed held constant, moving the bow from one position (1) to another (2) will change the sound level by an approximate factor $\beta_1/\beta_2 \approx \Delta v_2/\Delta v_1$. Adjusting for this, the spectral alterations will generally be related to the low-leveled "node frequencies" of the "old" and "new" bowing positions (i.e., nf_0/β_1, and nf_0/β_2, where $n = 1, 2, 3...$ and f_0 is the fundamental frequency). These will, however, not contribute to an overall raise of higher partials as the bow is moved towards the bridge, although fewer and fewer ("node") partials will be missing as the distance to bridge gets smaller. In Figure 3, spectral differences between simulations with six different β are compared:

Figure 1: Diagram from Schelleng's JASA paper. Given a fixed bow speed, the triangle sets the borders for maintaining Helmholtz motion in a bowed string.



"Quasi 'plastic' friction" is a model where changes of value in the hyperbolic velocity-dependent friction curve are slowed down by a time constant. The spectral tendency illustrated in this figure is, however, seen with a variety of friction models.

How much does the timbre change as function of bow force?

Pickering [4] has shown how each violin strings has an "area of maximum bow-force sensitivity, and that this varies with the string impedance and *the core material*. For a certain light-gauge aluminum A-string with Perlon core, changing the bow force from 200 to 500 mN resulted in a gain of more than 15 dB for the harmonics 5 through 17 (bowing speed and position unaltered). Bowing with a normal force so high that pitch flattening occurs typically produces a shrill sound with no real brilliance, and emphasis on the "near-node" frequencies. This is more so for some string types than others. Nevertheless "excess bow force" (with left-hand pitch compensation in combination with a wide vibrato) is often used in expressive passages, e.g., on the violin G-string.

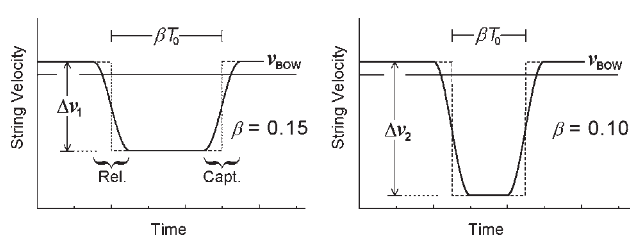
Does the timbre change if only speed is changed?

Yes, it does! And the reason is that changing the bow speed (without changing the bow force) alters the transition characteristics at release/capture. Higher bow speeds give longer slip intervals. When moving the bow towards the bridge, the speed is usually reduced, and that is what causes the noticeable greater brilliance. Increasing the bow "pressure" will of course add to the effect. One should also notice: with a fixed bowing position, when it is musically desirable to maintain tone color best possibly while playing a diminuendo, both force *and speed* should be reduced simultaneously, because reducing the bow force alone would imply softening the tone color.

Double stops

When playing large-interval double stops, the bow force should (normally) be balanced so that the string of lowest sounding pitch feels the greatest "pressure"—regardless of which string "carries the melody". This prevents the pitch of the highest sounding string to be flattened due to its significantly higher *b*. (To count on left-hand compensation is *not* the greatest idea here!)

Figure 2. Example of string velocity under the bow for two different β, but with the same bow speed and identical transition functions from stick to slip and vice versa. (T_0 = the fundamental period; $\Delta v = v_{BOW}/\beta$, while β = ratio between the bow-to-bridge distance and the total string length.)



Keeping the bow force even

In order to achieve an even sound throughout a stroke, the player must actively be changing the fingers' action on the bow stick. Askenfelt [5] writes: "The bow acts as a lever that pivots around an axis roughly through the thumb and the middle finger. This means that gravity contributes a considerable amount to the bow force in bow positions close to the frog, and much less close to the tip. For a normal violin bow, the change could be estimated to be approximately 3 N, provided that the path of the bow is approximately horizontal as when playing on the G-string. The major part of this change occurs within the last third of the bow toward the frog. The compensation is achieved by balancing the bow with the index and little fingers on top of the bow stick on both sides of the pivot point."

CHANGE OF DYNAMICS

Askenfelt further presents measurements of a series of strokes (their transients excluded) where the most accurate player kept *variations* in bow force less than 0.2 N (around 50%) when playing at the dynamic level *piano*, while less than 0.7 N (around 33%) in *forte*. It is interesting to notice that for one of the two players, the *piano* strokes were performed with greater speed in *piano* (29 cm/s at a bow-to-bridge distance 42 mm, and bow force 0.5 N) than in *forte* (21 cm/s, 18 mm, 2.3 N), while for the other player the corresponding figures were 21 cm/s (42 mm, 0.4 N) and 24 cm/s (20 mm, 1.7 N), respectively. The general tendency thus seems to be altering *position and force* rather than *speed* in order to create the major part of the dynamic difference. The dynamic differences produced by the two players during these tests were about 9 dB for each of them. These last figures point at the role of timbre as means for expressing loudness. Remember that raising the bow velocity alone would

Figure 3: Spectral changes as the bow is moved from β = 1/12 to β = 1/7 while keeping other bowing parameters unaltered (the first harmonics normalized to 0 dB). Apart from local deviations, the high-end spectral decay follows the same slope in all the simulations.

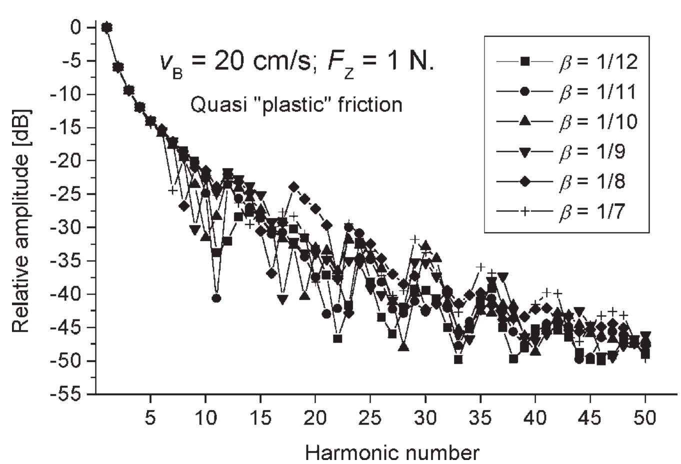


Figure 4: Comparison of (simulated) slip patterns with three different bow speeds. The string velocity is shown relative to the bow velocity in each case. At high bow speeds, transitions from stick to full flyback velocity and back last longer than at lower bow speeds.

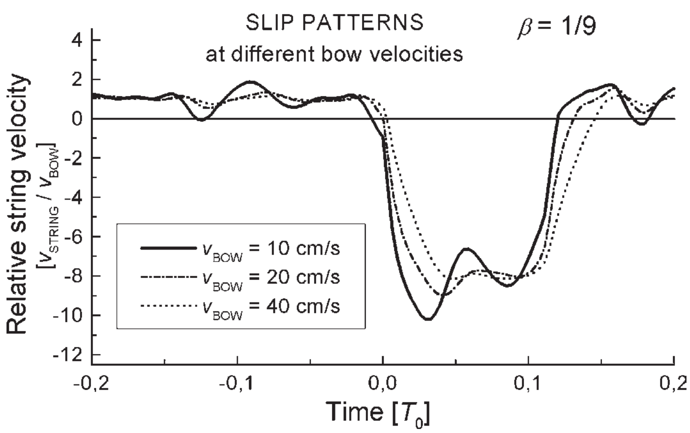
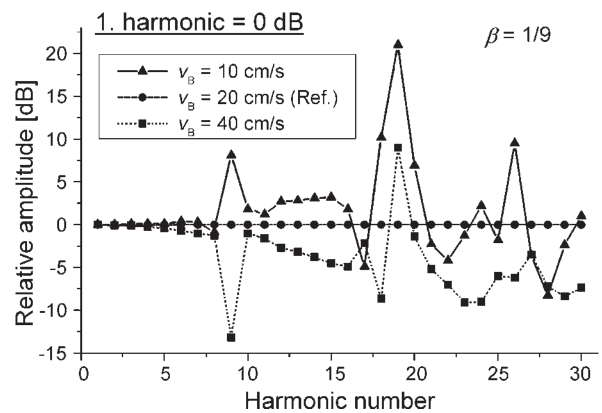


Figure 5: Spectral changes resulting from the different bow speeds utilized in the simulations of Figure 4: The amplitudes of the first harmonics—as well as all harmonics of the reference—are normalized to 0 dB. Reduced bow speed results in brighter sound.



decrease the relative content of high partials, which to some extend would counteract the perception of increased loudness. We shall neither forget that there is a practical side to the choice of bowing position too, as *forte* notes can be played *longer* when bowed close to the bridge, but in the above tests that was not an issue.

Crescendo-diminuendo

The theoretical maximum range of wave energy in the string due to differences in bow force alone is $\pi/\sqrt{6} \approx 2.16$ dB, which reflects the ratio between a true sawtooth- and a pure (1. harmonic) sine wave. This means that by halving β and doubling the bow force, the energy of the signal could be increased up to a maximum of some 8 dB, while the perceived difference in loudness would probably be significantly greater due to the change in timbre. A gradual halving of the β, by the way, is best performed as illustrated in Figure 6 (particularly for instruments with long strings), since this technique prevents introducing longitudinal friction forces during the move.

TILTING THE BOW-HAIR RIBBON

Violinists often claim that tilting the bow provides greater brilliance. Pitteroff [7] found through measurements of string waveforms some indications pointing in this direction. Pitteroff used a bowing machine to ensure identical strokes, while splitting the hair bundle so that larger or smaller widths of hair had contact with the string. In these experiments he found that the slipping intervals became progressively shorter as the hair-ribbon width was decreased, albeit the effect was small (Askenfelt, Schoonderwaldt, and the present author recently repeated this experiment with a thinner string where these spectral effects were quite noticeable). The main reason for violinists to prefer a tilted hair ribbon may, however, be found in the fact that tilting facilitates more gentle stroke onsets resulting from a more gradual string contact. Playing with "all the hairs on the string" could also give rise to noise caused by partial slipping, since the string's velocity relative to the bow will differ across the hair ribbon [7]. Close to the bridge, this might even cause spiky slipping sounds [8].

A pronounced feature of hair-ribbon tilting is the change of frequency for the bow's natural bounce rate, as for instance employed in *ricochet*. In a violin, a normal tilting angle of ca 30° causes the natural bounce rate to drop between 1 and 2 Hz [9]. The point of impact on the string plays a role too, as playing closer to the bridge raises the rate somewhat. For rapid *spiccato*, playing with the hair flat should hence give the best response, while for playing down-stroke ricochet, progressively changing the hair angle from flat to tilted, is sometimes recommendable, as this to some extend counteracts the increased natural bounce rate closer to the tip (see below), making it easier to terminate bouncing at the end of the stroke.

STARTING THE HELMHOLTZ MOTION

In a recent paper [10], the wave buildup of the Helmholtz motion in bowed strings is described. It is shown that in order to start this pattern as quickly as possible, the bow must be *accelerated within certain limits* during the transient, unless substantial loss is present by the nut. That is, under normal conditions the stroke cannot start abruptly, "switched on". The tolerable acceleration values are proportional to the fundamental frequency and inversely proportional string's wave resistance (or, if you prefer: to the string's vibrating mass). Acceleration must also increase with increasing bow force. When starting a bow stroke, the string player has in principle three options at hand:

Figure 6: By angling the bow (∠ = α), the contact point can be moved along the string without introducing longitudinal friction forces. From Guettler/Yorke Edition [6]

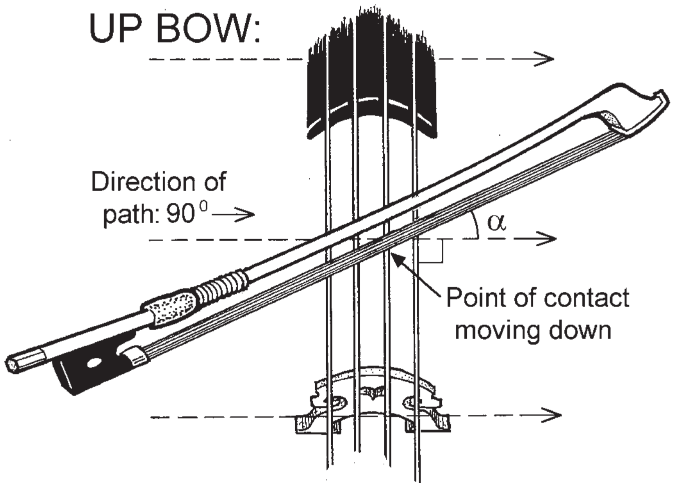
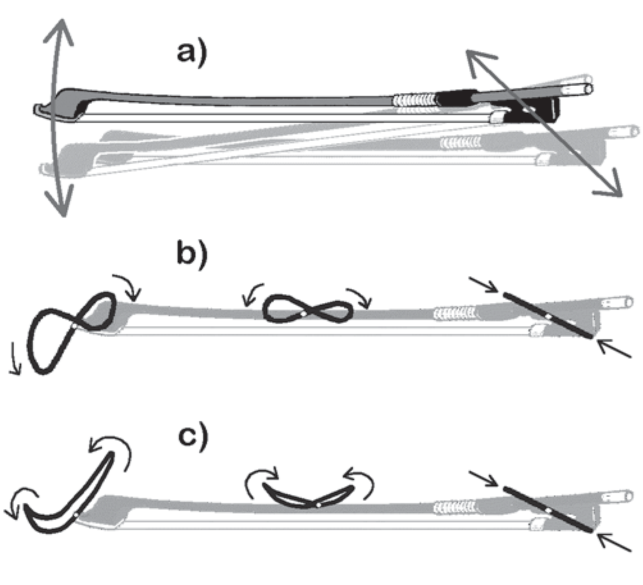


Figure 7: In spiccato and ricochet, the bow-stick rotates around a point near to the thumb on the frog. During a spiccato this point is moved diagonally up and down like shown in panel a), while the rotation (see arrow at the tip) takes place with twice the frequency. In ricochet, the frog is moved in one direction only, forwards or backwards. Panels b) and c) display trajectories resulting from good and bad timing between the two movements during spiccato. Trajectories as shown in panel c) will involve scratchy attacks.



(1) starting the bow "from the air", i.e., with a certain bow speed, but from zero bow force
(2) starting the bow "from the string", i.e., with some bow force, but from zero bow speed
(3) starting the bow from zero bow speed and zero bow force.

The first method is always employed when crossing strings under a slur. Violinists and viola players also frequently utilize it in order to create gentle attacks, particularly at phrase openings.

Nonetheless, in a study performed by Guettler and Askenfelt [11] advanced listeners discriminated strongly against attacks with extensive nonperiodic slip/stick triggering, preferring few or no irregular periods for the transients of "neutral attacks". To facilitate smooth accelerations, many players advocate letting the arm/hand describe a *figure eight* or a narrow *oval* (the bow's contact point on the string remains nearly unaltered) rather than moving the frog back and forth restricted to a perfectly straight line [12]. The movement thus becomes continuous instead of ceasing at the end of each stroke. The small excursions from the straight line could be performed in the z-plane (vertically with respect to the instrument's body), or in the x-plane (parallel to the strings). In skilled smooth bow changes, the bow's deceleration is normally seen to be of greater magnitude than the acceleration that follows. Simulations show that de̲celeration is less likely to produce noise from extra slips than is ac̲celeration of the same magnitude.

Spiccato and Ricochet bowing

Both *spiccato* and *ricochet* involve a combination of rotational and translational movements [13] (see Figure 7). With correct timing between these two movements, very clean attacks can be produced in spiccato, in which case the first release of each stroke takes place just before the normal force reaches its peak. After each jump, the bow should land on the string while still moving in the "old" bowing direction, to ensure a quick noise-free damping of the fading waves of the last stroke before an "on-the-string" bow change takes place. In ricochet, where the orientation of the Helmholtz corner remains unaltered, damping is not required, and clean attacks are hence much easier to achieve. When moving a bow from the frog to the tip, the natural bouncing rate varies from ca 6 to 30 Hz (provided the bow in contact with the string [9]). A fast spiccato is best performed at a point where its natural rate lies one or two Hertz above the driving (spiccato-note) frequency.

PLAYING "HARMONICS" (FLAGEOLET TONES) AND MULTIPHONICS

"*Harmonics*" (i.e., higher-pitched tones produced by touching the string lightly, thus filtering out certain partials) should be excited with bowing parameters suitable for that same pitch *fingered* on the same string (i.e., *stopped* where the highest node of the "harmonic" is situated). The effective β is always relative to the highest node of the "harmonic"—not to the any other node that happens to be fingered. As a rule of thumb, compared to the open string, the bow speed (and the transient acceleration) of a "harmonic" should be increased by a factor $n = f_{HARM}/f_0$, where f_{HARM} and f_0 are the fundamental frequencies of the "harmonic" and the open string, respectively [14].

Multiphonics can be achieved by bowing on the *nut* side of a lightly touched "harmonic" node. Swift changes between the pitches of the open string and the "harmonic" will occur.

UP-BOW VS. DOWN-BOW

Spectral differences between up-bow and down-bow in steady state have been claimed, but not convincingly documented. If any, the main difference lies in the attack transient, where dissimilar dynamic properties at the tip and the frog (e.g., the bouncing rates stated above) play a role in shaping the bow-force envelope. Also, a strong coupling between a mode of the hair in the z-plane and wood-dominated "bouncing modes" of about 130 and 150 Hz [15], might influence the timbre slightly when playing some 40 cm away from the frog, but even here solid documentation of spectral changes is lacking.

AN ADDITIONAL REMARK

To complete the picture, it should finally be mentioned that the player has one more important timbre-shaping device at hand. To be more precise, at the left hand: *the finger pad*. The reflection properties of the finger pad highly influence the output spectral envelope. A soft finger-pad tissue will filter out, or reduce, the higher partials, thus reducing brilliance. It should be enough to mention the timbre difference between open and stopped strings. The finger-tip angle and firmness of pressure might play roles here. On the double bass, vibrato played with two or more fingers is sometimes seen. In those cases the adjacent, lightly touching, "extra fingers" are used mainly to modulate the spectrum, not the fundamental frequency.

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