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1pMU5. Analysis of bow-change strategies
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Abstract One of the most important skills of the accomplished bowed-string player is the smooth bow change. Smooth changes are often necessary in order to keep a phrase flowing, and equally important in situations where the bow is too short for the duration of the given note; the latter requiring a bow change of least possible audibility. The problem arises from the fact that a change of bowing direction requires the rotation of the Helmholtz corner to be reversed, and the phases of the string-velocity frequency components thus to be shifted 180 degrees. In between the two states, there exists no transition that can fully maintain the sound flow without introducing undesirable noises. However, by choosing the right bowing strategy and gesture, the tradeoff between transition time and noise content can be optimized for the purpose. In practice, different players solve this problem in a number of ways. The present study, which is mainly based on numeric simulations, analyzes the sounding outcome of a variety of possible bowing parameters.

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INTRODUCTION

There exists very little scientific literature on bow changes and their acoustical implications, in spite of a large number of violin-family tutorials and physiological analyses discussing the technique. One outstanding exception is the PhD dissertation of C. E. Williams (1985): *Violin bowing skill analysis: the mechanics and acoustics of the change in direction*, University of Melbourne, Australia. Unfortunately, this work is not much quoted, most likely due to its limited availability (the present author had to obtain a microfilm version through the British Library, and copy the 532 pages by hand). More recently another PhD thesis touched on the subject: M. Demoucron (2008), *On the control of virtual violins*, where empirical bow-change parameters were collected in order to create a basis for realistic simulations and synthesis. A good demonstration of bow changes involving string crossings was also presented by E. Schoonderwaldt (2010), in the Vienna-talk proceedings.

However, to get the full picture, analyses of the smooth, quasi inaudible, bow change should involve at least three aspects: (1) *Perception*, e.g., the effect of masking, either by the (sometimes lingering) sound of the previous bow stroke, or by accompanying sounds from other sources. (2) *Acoustical/physical requirements of the string*, the waves of which shall have their orientation rapidly changed 180 degrees. (3) *Bowing gesture*, i.e., a controlled movement of the bow that meets the demands of the two first factors. In the following, these three aspects will be discussed individually.

PERCEPTION

An instant change from a steady state waveform to its “flipped” counterpart (i.e., the waveform that occurs after a bow change has taken place), will produce a very audible “click” or “spike” as many of the frequency components will experience phase discontinuity in the transition. In fact, there is no way to preserve the phase regularity across the seam for all components. The same is even true for a gradual transition, like the ones taking place in smooth bow changes. However, as the bow passes from one velocity through zero, to a velocity of opposite sign, the phase discontinuity (and thus the noise) will occur when the sound level is at its minimum.

Williams writes (page 43): “A smooth bow change is presumably effected by minimizing or disguising the break between strokes and by eliminating or disguising scratchy or extraneous noises at the change. The break between strokes concerns the intensity of sound, while scratchiness or smoothness of sound concerns timbre.”

The present author did the simple experiment of manipulating the attacks of a series of 200 Hz saw-tooth waves, each starting with a linear buildup ramp. When the total buildup time became less than 25 ms, the attack started to sound percussive, leaving the impression of additional high-frequency components. Here timbre and sound intensity intermingle to some extent. This is a well established perceptual phenomenon (see e.g., Caclin 2005).

For the player, this represents a contradiction: A fast buildup in the new bowing direction will leave the impression of a “spike” or “thump” (adding to the noise already produced by the phase discontinuity). However, if another instrument can mask this noise, e.g., an attack of a piano chord, the problem vanishes to a large degree. When the tone is to be played without accompaniment, the task becomes much harder. In William’s data we see that most of the successful smooth bow changes are executed with the second stroke played slightly softer (typically –3 to –6 dB) than the end of the preceding one (see Fig. 1). The relatively fast buildup of the new stroke then falls in its shadow. This leaves the impression of a quickly passing “w” in an otherwise open sonority.

![FIGURE 1](image)

**FIGURE 1.** Sound levels during smooth and rough bow changes, respectively (after Williams). Notice that in the smooth change the sound level does not immediately reach the peak level of the preceding stroke (see text). In the two cases the change including decay and buildup is seen to last approximately 200 to 250 milliseconds. Although not apparent from the plot, the rough change includes a rather noisy interval preceding the new buildup.
I. Galamian (1962) suggests for the violin a slight reduction of the bow force during the change, its main effect most probably being to provide better control of the buildup time, which otherwise might turn out too short and direct. The risk is, however, to lose “grip” of the string in the process. (The idea of “picking up some still ongoing waves” is a wrong one, due to the phase differences already mentioned.) With lower-pitched instruments, buildups are by nature longer lasting, even when the bow force is kept constant. Vibrato will also provide some masking, as it normally (particularly on the violin and viola) contains a certain degree of tremolo (amplitude modulation of 5 to 6 Hz), which might blend in nicely with the level reduction following the bow change described above.

In any case, it is of utmost importance to avoid scratches, i.e., irregular stick-slip patterns of the string, because these easily recognizable sounds strongly interrupt the impression of continuity due to their greater content of high-frequency energy. One should also notice that a soft tone color (like in flautando) demands a slower buildup after the change than does a loud sound with greater brilliance.

To conclude: different situations concerning both the musical situation in terms of timbre, sound level, and the sound environment of the strokes to be spliced, demand different solutions as far as bowing strategy is concerned.

ACOUSTICAL/PHYSICAL REQUIREMENTS OF THE STRING

As has been shown by K. Guettler (2002), to obtain a clean initial buildup of Helmholtz motion in a string when the bow force is held constant, requires a certain acceleration, which cannot be chosen freely, but has to be found within certain limits, dependent on relative bowing position, the mass of the active string length, as well as the bow force itself. The picture gets more complicated when there are already waves present in the string, i.e., remains from a previous stroke. Due to the phase differences, such residual waves are of no help when trying to establish a stroke in the new direction. Figure 2 shows a quite successful (smooth) bow change derived from Williams (1985, p 211):

FIGURE 2: Registration of sound pressure and string velocity under the bow during a smooth bow change (after Williams). Each “spike” in the velocity plot represents a string flyback (slip). In the intermediate transition period, when the string’s contact point is transported from one side to the other, there seems to be some noise in form of irregular slips. The interval [t₁, t₂] lasts here about five nominal periods, after which the slip-stick triggering becomes clean and regular again. Notice also that the maximum bow deceleration preceding the actual change within this interval shows greater magnitude than does the maximum acceleration following it. Williams reported this to be a general feature in smooth changes.

The interval [t₁, t₂] must be quite short in order to make a “good splice”. With “rough changes” this interval between Helmholtz movements is seen to be much longer, and consisting of irregularly triggered (noisy) waves.

Observable from Fig. 2, the maximum deceleration is of greater magnitude than the maximum acceleration that follows bow’s the change of direction. (In fact, generally speaking, simulations show that you can in most cases stop the bow instantly without producing further string slips, provided the normal bow force is kept constant.) The quicker the deceleration, the more the “old” stroke will be masking the new one. However, there is a tradeoff here: The higher the deceleration, the higher the friction-force amplitudes (caused by restoring energy) will be after zero bow velocity is reached. One may think in terms of spectral content here: Higher deceleration implies higher content of high-frequency energy. Although high-frequency energy in practice will fade out more quickly than lower-frequency energy due to the natural damping of the system, what is important here is the friction-force delta between the bow and the string in the immediate continuation, where a stroke in the new direction is being established. Figure 3 shows schematically the requirements of acceleration in a quiet string.
Any attack requires a certain bow acceleration during the $1/\beta$ nominal periods in order to maintain a regular slip-stick triggering from the very beginning, where $\beta$ is the bowing position relative to the active string length. This is not to say that the bow has to keep a constant acceleration during this phase. Velocity functions of the form shown in Eq. (1) will do nicely, as long as the average acceleration complies with the restrictions given by the chosen combination of bow force and position.

In the present situation, however, residual waves with periods $T_0(1 - \beta)$ rotates between the bow and the nut, where $T_0$ denotes the nominal period. When superimposed on the bow’s movement and force buildup in the reverse direction, these may well jeopardize the option of reintroducing a regular, periodic triggering in the new stroke direction. Look at Fig. 4, below:

Four simulated examples of transitions from steady-state bow velocity to zero velocity are presented in Fig. 4. Each function covers 13 nominal periods. In stroke 1, the bow stop is immediate (deceleration surpassing 10 000 cm/s²). Stroke 2 stops with a smooth cosine function, while for strokes 3 and 4, Equation (1) is utilized with the variable “$\sigma$” set to 2 and 3, respectively.

$$v_{\text{Bow}}(\tau) = V_{\text{Bow}} \left[ 1 - \tau^\sigma \right],$$  \hspace{1cm} (1)

where $\tau$ signifies the normalized time ($0 \leq \tau \leq 1$) in the transition interval, while $v_{\text{Bow}}(\tau)$ is the dynamic bow velocity and $V_{\text{Bow}}$ is the static (pre-change) velocity.
This type of function seems to be highly relevant for describing practical bow motions related to the bow change. For the buildup following the change, the variation shown in Eq. (2) seems appropriate:

\[ V_{\text{BOW}}(\tau) = -V_{\text{BOW}} \left[ 1 - (1 - \tau)^{\sigma} \right]. \] (2)

With such a bow-velocity profile, one avoids that the “body” of the new tone is felt to happen at the end of the buildup, as would be the case with a ramp function. For reasons of masking, it is important that the new tone’s “body” arrives as soon as possible after the expiration of the initial stroke. Stroke 2 leaves very little energy in the string, but is probably too slow for practical purposes.

As seen in Fig. 4, the friction-force deltas experienced right after the expiration of the old stroke vary greatly with the magnitude of deceleration: In the simulations 1 through 4, the friction-force deltas some 3 nominal periods after the change came out 458, 104, 193, and 178 mN, respectively. (The 3 periods were added to allow for the string to be brought over to the other side by the bow.) If we look at Fig. 3 once more, the range \( \Delta F_Z \) gives an indirect indication of acceptable friction-force amplitudes during the onset: If we name the friction-force delta \( \Delta F_Y \), we get the approximate requirement \( \Delta F_Y < \Delta F_Z \mu \), where \( \mu \) is the classical friction coefficient, indicating the ratio between maximum static friction force and the bow’s normal force, \( F_Z \). Setting \( \mu \) to a realistic value 0.8, the present demands become \( \Delta F_Z > \Delta F_Y / 0.8 \), i.e., the “white wedge” must provide a \( \Delta F_Z \) range of more than 572, 130, 242, and 223 mN, respectively, in order for the simulated post-change friction-force deltas not to cause premature slips.

A simulated diagram of the type shown in Fig. 3, reveals that the present string-body system simulated with bow force, \( F_Z \), set to 1000 mN, and max. acceleration 120 cm/s², provides a “white-wedge range”, \( \Delta F_Z \), of about 400 mN, which leaves plenty overhead for the superimposed force ripples introduced by strokes 2 through 4. That is, these ripples are not likely to interfere with the new buildup of regular Helmholtz triggering. Fig. 5 shows the friction force and the string velocity under the bow utilizing stroke 2 before the bow change, and a new-stroke buildup following Eq. (2) afterwards, with the acceleration limit set to 120 cm/s² as mentioned above. The result is seen to be very clean.

\[ \text{FIGURE 5: Friction force and string velocity during a clean change of bow direction (simulated). Limiting static friction force is ca. ± 800 mN.} \]

Compared to Williams’ plot in Fig. 2, the number of nominal periods elapsing in the quiet time interval \([t_1, t_2]\), is somewhat greater in the simulation of Fig. 5. The reason might be found in the way the bowing parameters were programmed for our simulations: The bow’s velocity is normally given with no concern to what kind frictional resistance the bow experiences in contact with the string. In the force diagram (left panel) we see that the friction force is rapidly reduced from plus 800 mN to minus 800 mN. A hand-held bow will probably have a certain nonlinear compliance, which will cause some further acceleration as the friction force passes zero—this without introducing much new energy. Simulations based on this consideration show that the \( t_1 - t_2 \) interval can be utterly reduced. In his thesis, Williams (p 210) shows a plot where the transition from down bow to up bow lasts only a couple of nominal periods, which is quite impressing. A high-gauge string will probably do the transition more quickly than a low-gauge ditto, because the transportation distance of the contact point will be less for stiffer strings.
Furthermore, a slight reduction of the bow force at the end of the “old” stroke will contribute to bringing the string closer to its equilibrium, without reducing its amplitude. However, if utilizing such a technique, the bow force needs to be reestablished before the new stroke starts in order to avoid irregular extra slips.

**BOWING GESTURE**

When starting a tone with the bow on the string, a skilled player knows through the string resistance when a first release close to happening. By feel, she also recognizes non-regular slips, i.e., slips more frequent than once per nominal period. Premature slips lower the average friction force quite noticeably, while experience tells how much you can tension the string before it slips back on the bow-hair ribbon. In a quick bow change however, responding to this kind of feedback takes too much time for being very useful in the actual situation. Trial, error, and a standardized gesture seem to be the only way of achieving successful bow changes in practice.

The bow change has been a matter of discussion among major string teachers since before Leopold Mozart. Their philosophies have varied greatly, and with partly contradicting recommendations. There are, however, two very distinct classes: one where the bow is returned in the very same path it took under the preceding stroke, implying that the frog is slowed down before it accelerates in the new direction—and one where the frog is moving with more or less constant speed during the entire change. Figure 6 describes this latter situation, utilizing the stroke parameters discussed above: The left panel shows the chosen bow velocity, while the right panel describes a useful frog’s trajectory, where the frog, holding constant speed, controls the bow’s velocity with respect to the string, simply though choice of path. Had the trajectory been perfectly semicircular, the velocity would have been describing a smooth, symmetric cosine function. With the chosen path, the deceleration is given a greater magnitude than the acceleration that follows.

**FIGURE 6:** By running the frog with constant speed in a suitable path (see right panel), the stroke’s velocity can be quite precisely controlled (left panel).

Provided the two strokes are given the equal velocity magnitude, the vertical component of the frog’s velocity can easily be calculated as

$$V_{\text{VERT}}(t) = -\sqrt{V_{\text{BOW}}^2 - V_{\text{HOR}}^2(t)},$$  \hspace{1cm} (3)

with the minus sign, preceding the square root, indicating that the frog is moved down during the bow change. This is the most common way of performing the change, because it to some extend prevents the bow “pressure” from being released. (When regarding the “string tension transducer signal” of Fig. 2, a slight increase of bow pressure is observed between $t_1$ and $t_2$, where the actual change takes place.) However, the trajectory does not necessarily have to be performed in the vertical plane with respect to the string, one quite often sees players moving the frog in the bowing plane, i.e., along the string length, towards the nut or towards the bridge. The effect is the same either way.

There is also a variation where the bow is moved back and forth in a straight line, while the forearm and wrist are performing the circular movement (see Fig. 7). Changing the bow really close to the frog naturally prevents any manipulation of the frog’s trajectory, so the technique just described comes in handy at that part of the bow.
Apart from being advocated by some distinguished violin teachers in their methods, such rounded or quasi-circular movements were first reported on a more scientific basis by Percival Hodgson (1934) in his book: *Motion Study and Violin Bowing*. When Hodgson’s book met the string-players’ community, it stirred up quite a discussion, as a lot of players disagreed with this circularity concept.

**FIGURE 7**: Controlling the bow velocity by means of a flexible wrist (exaggerated). During the timeline from left to right, the wrist knuckle (marked with a black spot) describes a trajectory not so different from the one showing the frog in Fig. 6. The actual direction change takes place later in the curve, however, namely around the time of the 3rd picture.

All this being said, the circular movement is by no means a prerequisite for making smooth bow changes; the present author has (as a professional double bass player and soloist) only rarely utilized any of the above described circular techniques for changes performed on a single string, but admittedly, it might often make things easier, and above all: it is easier to teach and to visualize. For bow changes involving change of strings, circularity is almost always present, as reported by Schoonderwaldt (2010) and others.

**A FEW, NOT SO CONCLUDING WORDS**

As shown, the issue of “non-perceivable” bow changes comprises several interesting aspects, all of which needing to be subjected to further research in order to find the “ideal” solutions. For the player, it is paramount that the technique be manageable and reliable, with the least possible degree of hazard involved. Over the centuries, different players/teachers have provided quite contrasting recommendations concerning the bow gestures. With modern analytic tools, it not should impossible to sort out which ones have a bearing, and which have not.

**REFERENCES**


