The Violin Bow in Action—“A Sound-Sculpturing Wand”

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Abstract. The aim of this paper is to give an overview over bow-string interactions related to a number of different sonorities and articulations. The violin bow has incredible potential for variation in the production of tone color, texture, dynamics, articulation, and envelope, so this presentation can merely provide insight to a limited selection of characteristic categories and their underlying principles. Special focus is set on the manipulation of the bow as seen from the player’s perspective: the gestures and their effect on sound and the string’s waveform.

1 The Helmholtz Motion

The reader is supposed to possess some knowledge of the Helmholtz motion and the principles behind it (Helmholtz, 1862). A brief remainder is given in this first section for completeness.

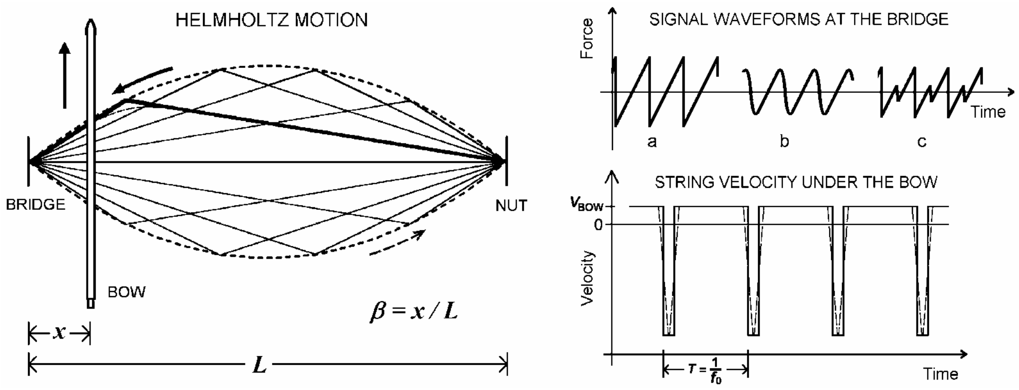

Figure 1: Bowed-string waveforms during idealized Helmholtz motion. Left panel shows the trajectory of a string composed of two straight lines joined in a rotating corner. When the corner passes the bow on its way to the bridge, friction goes from static (“stick”) to sliding (“slip”). When passing again towards the nut, static friction is recovered. The resulting force signal at the bridge is shown in upper-right panel a), while b) shows the signal when the rotating corner is rounded (smeared out) by losses and string stiffness. Lower-right panel shows the corresponding string motions under the bow (v_{BOW} being the bow’s velocity). The orientation of rotation is reversed when the bow changes direction. Upper-right panel c) shows the signal when *two* corners, giving *two* slip intervals, are present, i.e., a non-Helmholtzian movement.

The Helmholtz motion, with the string slipping once per nominal period, is but one of many stable waveforms the string can take during steady-state bowing. It is, however the waveform providing the fullest sound with the most complete set of overtones, and is therefore the most commonly utilized bowed-string pattern in classical Western music. Based on analyses by Raman (1920-1921), Schelleng (1973) was able to define boundaries for the Helmholtz-motion regime in terms of (relative) bow force and contact position on the string, with the bow speed held constant (see Fig. 2). The bow force is furthermore function of friction coefficients and system losses.

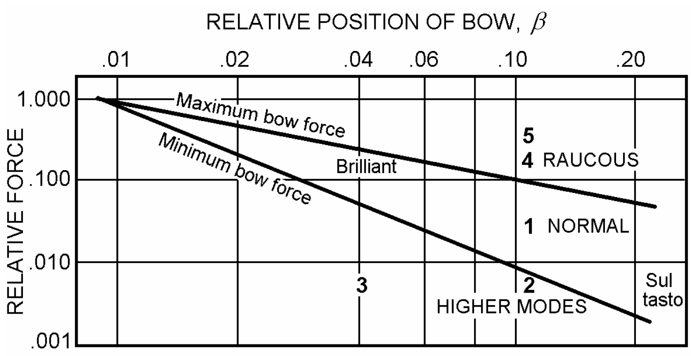

Figure 2: The Schelleng diagram. Within the wedge Helmholtz motion reigns with one slip per nominal period. Below it, more slips are produced and the nominal fundamental is weakened or absent (higher modes prevail). Above the wedge unstable waveforms are usually seen (raucous), with the exception of *ALF*, a peculiar phenomenon, where delayed but regular triggering lowers the pitch below the string's natural first mode. The bold numbers of the diagram point to parameter combinations discussed in the next section.

2 Five Characteristic Regimes

In the following we shall discuss five important regimes, all definable within the space of the Schelleng diagram. In Fig. 2 they are marked with bold numbers **1** through **5**. Generally, the three most important bowing parameters are: (1) *bow force*, F_Z—i.e., the contact force between bow hair and string, (2) *bow speed*, v_{BOW}—i.e., the speed of bow across the string in normal-angle direction, and (3) the *bow's relative position on the string*, β—i.e., the ratio between distance from bridge and the total length of the moving string (see left panel of Fig. 1). In the Schelleng diagram v_{BOW} is held constant. The effect of increasing/decreasing v_{BOW} would be to translate the diagram up/down in absolute force values. Since higher relative force produces greater brilliance, a reduction of speed pulls in the same direction.

The parameter combinations explored have all β equal to 1/9 except for combination "**3**", which has $\beta = 1/24$. All illustrations of section 2 are produced through numerical simulations of a bowed-string system, but resemble well waveforms obtainable through measurements of actual playing. The nominal fundamental frequency is 196 Hz (musical pitch G_3) for all simulations.

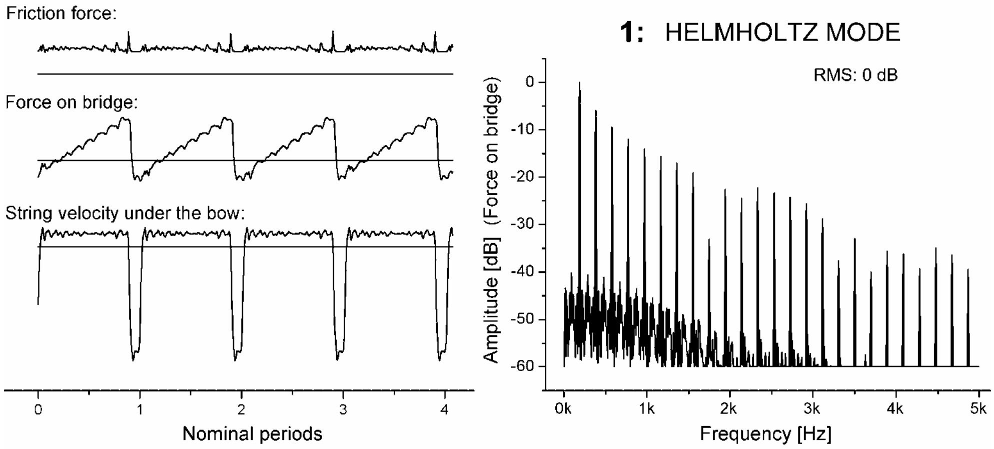

Figure 3: Waveforms and spectrum resulting from Helmholtz mode.

2.1 The Helmholtz mode

The Helmholtz mode is defined by one stick and one slip interval per nominal period. Figure 3 gives an example of signals at the bridge and under the bow, resulting from the parameter combination marked "**1**" in Figure 2. A β of 1/9 implies a spectral reduction of the 9th harmonic (ideally also all integer multiples of the $1/\beta$ harmonic). Due to substantial rounding of the Helmholtz corner, the spectrum in Figure 3 shows a slope steeper than –6 dB per octave, which is the slope of a perfect saw-tooth signal. The rounding determines the spectral roll-off frequency, but the corner is sharpened every time it passes the bow—*how much* depends on the relative force, F_Z. Here F_Z is only some 20-25% of maximum, so the periodic sharpening is quite moderate.

Every time the string slips on the bow-hair ribbon, noise caused by small irregularities in the rosin is produced. (In Figures 3 through 5—showing results from a numeric simulations—noise has been added for spectral realism.) To a lesser degree stochastic noise is produced also during the stick interval, caused by minor partial slips across the hair ribbon. Normally the slip interval occupies an approximate fraction β of the fundamental period. However, with low bow force the ratio may expand beyond that, giving the tone a "breathy" character (as used in *flautando*).

2.2 The "Harmonic" mode

Regard the position of the bold number "**2**" in the diagram of Figure 2, placed in an area termed "higher modes" by Schelleng. In the present situation the dominating mode is the second harmonic (see Figure 4). In spite of an unchanged bow speed, the force on bridge drops 8 dB RMS relative to the Helmholtz mode just discussed. This reduction is caused by the periodic extra slip seen in the plot "String velocity under the bow". As can be seen, the slips are not separated by stick intervals of equal duration, nor speed; hence the 1st harmonic is not completely suppressed. Since we have two slips per nominal period, there are two kinks rotating on the string, both rounded. The sound lacks "core" and "brilliance", and is a bit "faint" due to the many weak partials.

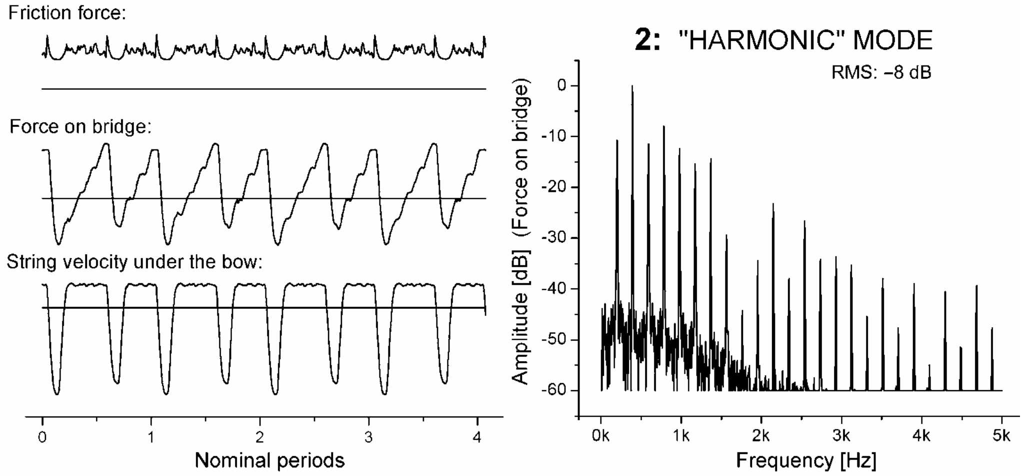

Figure 4: Example of "higher modes" 1: Emphasis on the 2nd harmonic.

2.3 The "Ponticello" mode

Position "**3**" of the diagram points to a bow force equal to the one just discussed, but this time with the relative bowing position, β, reduced to 1/24. That is not much more than one cm away from the bridge on a violin's open G-string. *Sul ponticello* (literarily: "on the little bridge") requests a bow played close to the bridge with insufficient bow force for maintaining a Helmholtz mode. The effect is shown in Figure 5, where no less than seven slips per nominal period are counted in the lower-left panel. This corresponds with the dominating seventh harmonic in the spectrum. In general, ponticello signals are periodic with emphasis on high partials, giving a "glassy" impression. Still bowed with the same speed, the RMS has dropped to –11 dB. In principle ponticello could be produced further away from the bridge, but then with considerably lower bow force, resulting in a substantially weaker sound. Ponticello is traditionally played tremolo (i.e., with rapidly changing bow directions), but is in contemporary music more and more often employed for sustained notes. Which one of the harmonics comes out as the dominating one, largely depends on the bow speed and the contact position on the string.

2.4 The "Raucous" mode

The fourth parameter combination is referred to as *raucous* (seen as number **4** in the uppermost area of Figure 2). The corresponding wave- and spectral plots show an irregular (non-periodic) signal, producing mainly noise. Spectrum show peaks in the vicinity of $n\, f_0\, /\beta = n \cdot 196 \cdot 9$ Hz (n = 1, 2, 3,…), that is 1764, 3528, 5292 Hz, etc. This because the transfer function, force on bridge divided by string velocity at the bowing point, favors these frequencies, which on the other hand show very high string-point impedances. However, whenever high bow force is utilized, a certain hysteresis (pitch flattening) takes place, which makes excitation of "near node frequencies" quite possible. Compared to the initial Helmholtz-mode, the RMS output is +12 dB, and the sound raucous and sometimes creaky.

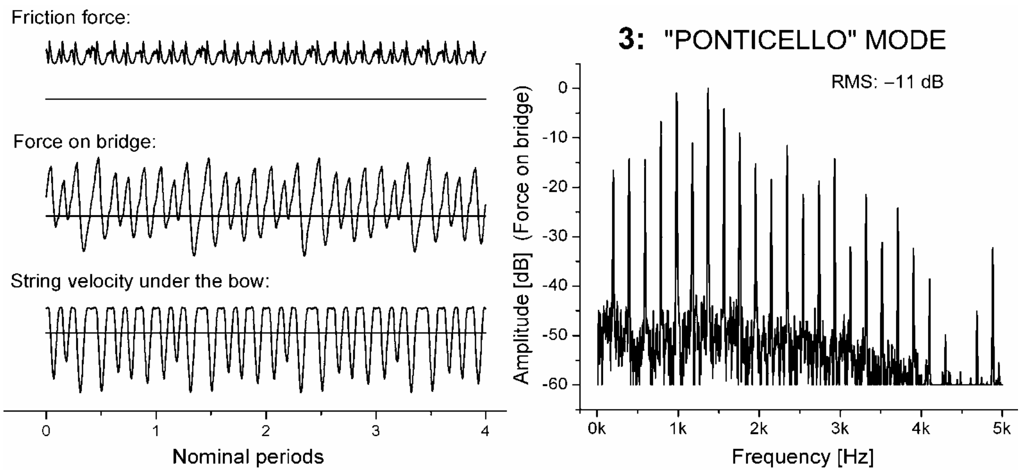

Figure 5: Example of "higher modes" 2: Emphasis on the 7th harmonic.

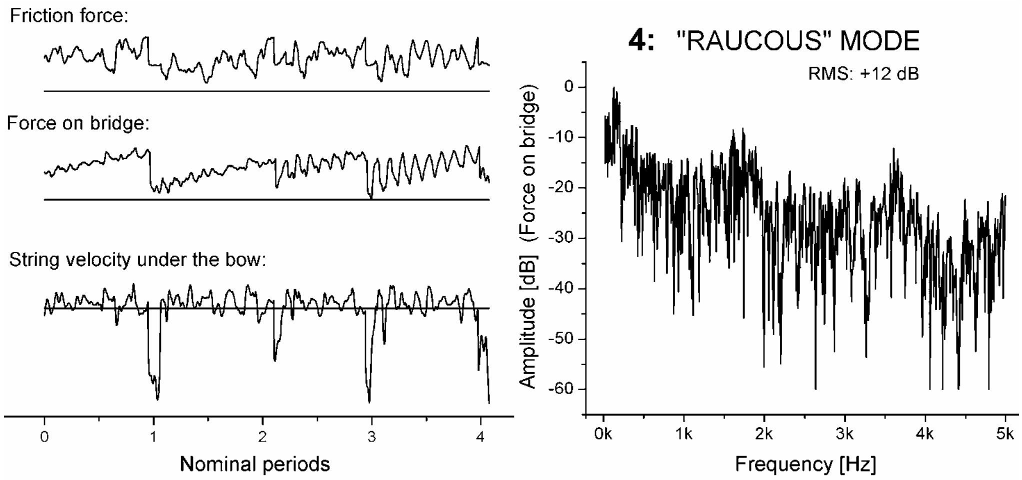

Figure 6: Example of "raucous mode".

2.5 The "ALF" (Anomalous Low Frequency) mode

If increasing the bow force even more (see **5** in Figure 2), *anomalous low frequencies* might occur. ALF is created when triggering of the string release fails at the ordinary point of time, but succeeds on a regularly basis at a later stage. In these cases the Helmholtz corner, reflected at the bow, takes one or more "extra turns". There are two sets of such frequencies: one related to transverse triggering, and one related to torsional triggering (Guettler 1994, Hanson 1994). Typical lowering musical intervals are third, octave, and octave plus fifth. Figure 7 gives example of the octave. Also here the node frequencies are emphasized. The RMS is +15 dB with respect to the Helmholtz mode of Figure 3; the sound is rather stressed and lacking sonority.

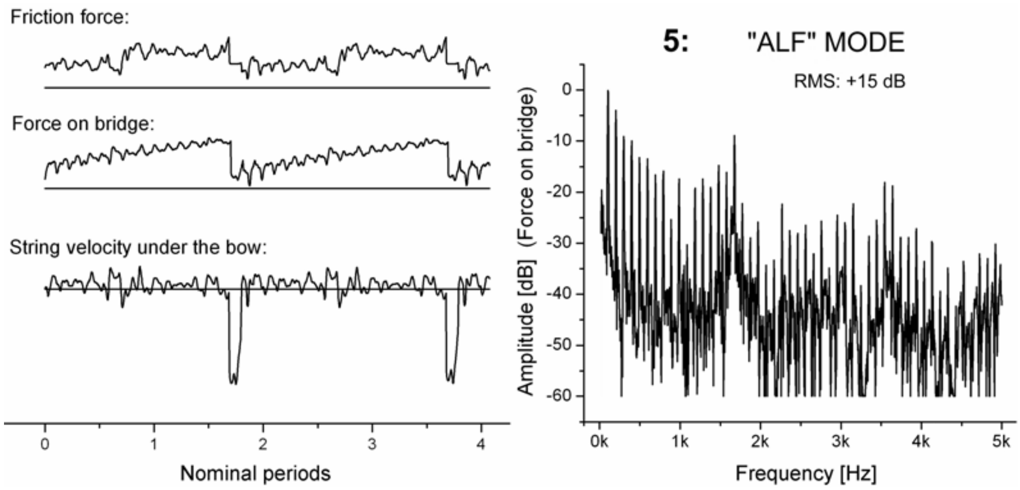

Figure 7: Example of frequency halving through “Anomalous Low Frequency” (ALF).

3 “Harmonics” (Flageolet tones)

“*Harmonics*” is another steady-state mode that cannot be placed on the Schelleng diagram directly. In *harmonics* the player dampens the string lightly with the finger pad at one or more points. All frequencies not having a node there are suppressed. The remaining ones form a new fundamental with a full set of overtones, with exception/reduction of frequencies $n\, f_0\, h/\beta$, where h is the ratio between the new fundamental and f_0. The waveforms are similar to those of the Helmholtz mode, but will be seen on the string as a series of h small rotating corners, lined up. Since there will be rounding of all of these, but only one place for sharpening, *harmonics* tend to have less energy in higher partials than normal tones. Bow speed should be increased nearly h times compared to normal playing if force and bowing position are kept unaltered.

“Multiphonics” can be mimicked by bowing the string on the nut side of the lightly touching finger. Quick alterations between the frequencies of the open string and those of the more restricting *harmonic* will result. For more information on *harmonics* read Guettler (2002A).

4 The starting Transients

So far only steady-state signals have been discussed. Similar regimes exist also during tone onsets. In most cases regular triggering from the very beginning is preferred. Strategies differ substantially between instruments of different sizes (double bass to violin): Transient duration is by nature proportional to the inverse of the frequency, implying that transients last twice as long when playing one octave below, provided comparable Q-values. (The buildup time in a violin body is approximately 18 ms; string buildup is normally lasting considerably longer.) While cello and bass players might want to start the tone with the bow “on the string”, violin and viola players usually prefer starting the stroke “off the string” and make a gentle landing; the latter to avoid hard attacks caused by a too quick tone buildup. Cello and bass players can produce gentle attacks *on the string* because of the instruments intrinsic slowness. As far as transient duration goes: *slow* is perceived as soft and gentle, while *quick* is perceived as hard, especially when high partials are present, what they mostly are in bowed tones. The violinist would thus often start a singing phrase by *gradually* establishing bow force, although by doing so some of the initial cycles might turn out to be of the "harmonic" (multi-slip) kind. A diagram in the spirit of Schelleng has been put up by the present author for relevant bowing parameters during the attack. See figure 8, which consists of two diagrams of different β. The parameter space is *bow force* versus *bow acceleration*. Acceleration is required if wanting to start "Helmholtz triggering", i.e., periodic slip triggering once per fundamental period, right from the start.

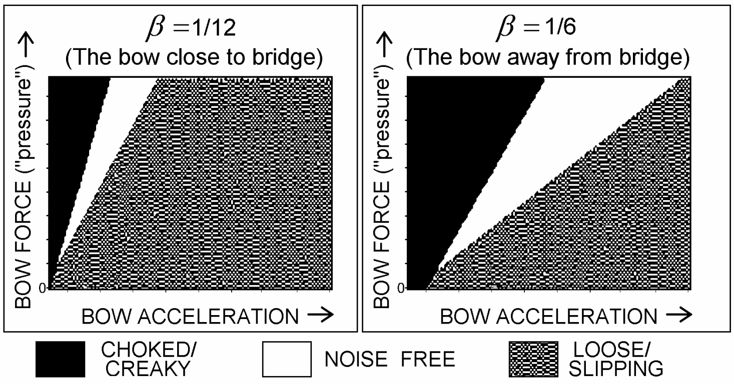

Figure 9: Two diagrams for different β showing relation between bowing force/acceleration and output waveform (both axes linear). The white wedge represents Helmholtz triggering from the very first cycle. In the black area slips are delayed. In the marbled area they occur prematurely; both black and marbled areas are producing characteristic noises.

The diagram is based on a simple resistive-boundary model similar to the one Schelleng used for his diagram. For discussion on the underlying calculations see Guettler (2002B). In the black areas transient waveforms are resembling those of the regimes: *raucous*, *ALF*, or *"pitch flattened"* (the latter with a moderate prolongation of regular periods); in the marbled areas *harmonic* modes of one kind or another will prevail for a good part of the transient. Whether that be musically acceptable or not relies on the musical context. As can be appreciated from the two diagrams of Figure 9, bringing the bow closer to the bridge narrows the range of acceptable accelerations when aiming at a clean tone onset. The required acceleration is also inversely proportional to the mass of the vibrating string and the nominal frequency, implying that in a musical piece individual pitches should be treated uniquely, or at least the acceleration being adjusted to some degree.

In the following subsections some characteristic bow techniques will be discussed. Notice that the player always has to compensate for a changing bow force as the contact point is moved along the hair ribbon. A violin bow weighs around 60 grams and has its center of gravity some 19 cm in front of the player's thumb, which more or less acts like an axis. The player's index finger gives a positive torque some 6 cm in front of the thumb, while the little finger gives a negative torque some 4.5 cm behind it, when needed. To maintain a bow force of 0.5 N in a horizontal stroke from frog to tip, the player must start with a (negative) torque of about –0.11 Nm and then gradually increase it to +0.21 Nm. That is: starting with a little-finger force of 2.5 N while ending with a force of 3.5 N by the index finger. A *crescendo* is hence most conveniently executed as an up-bow: starting slowly with low bow force at the tip, and ending with high speed and ditto force by the frog. If wanting to bring the bow nearer to the bridge during a crescendo (thus saving bow length), a slight angling of the bow with respect to the stroke's normal perfect-angle orientation (i.e., moving the frog slightly closer to the bridge plane during up-bow) will automatically bring the contact point nearer without introducing longitudinal forces, which would otherwise tend to interfere with the regular slip-stick action.

4.1 Détaché

In détaché (from French: "separated") the bow is moved back and forth—normally without any release of the bow force—so that tones are fully sounding with individual clearly audible attacks (but usually unaccented). National anthems (e.g., "God Save the Queen") are typically played détaché. Most attacks would be found inside the white wedges of Fig. 9. That is, the sound building up quickly without noticeable noise. When played *forte* or *mezzo forte* ("loud" or "medium loud") the bow acceleration will typically follow the middle part of the white wedge in Figure 9; for a *fortissimo* ("very loud") both the bow force and relative acceleration will be higher; if not compensating acceleration by bowing nearer to the bridge.

4.2 Martelé

In martelé (from French: "hammered") each bow stroke starts on the string with high bow force, causing the initial periods between slips to become slightly prolonged (pitch flattened compared to the nominal frequency); sometimes even irregular (raucous). As long as this transient last less than some 20–30 ms, the attack does not sound noisy: only heavily accented. The tone typically continues with a *diminuendo* (fade) executed with release of the bow force while maintaining the speed. Martelé is quite often performed as a series of down-bows.

Examples: The aggressive repeated chords of Strawinsky's The rite of spring, number [13] (Dances of the young girls), and Paganini's Moses fantasy on the G-string, the second variation.

4.3 Spiccato and ricochet

In these "off-string" bow techniques the bow bounces off the string between tones, moving rotationally around a point near the thumb/frog. In *spiccato* (from Italian: "spiccare", clearly separated, cut off) the bow is thrown onto the string for each individual attack whilst the frog axis is moving diagonally (down-up) with respect to the bowing plane. The up-bow attack comes mainly as a rotational rebound following the down bow, thus requiring minimal finger action. In "*ricochet*", (from French: "indirectly", "rebounding") several successive tones are performed in one throw and one bowing direction—only the first note actively initiated, the others rebounding while the frog axis is translated in the bowing plane without wobbling, forward or backwards. Frog wobbling tends to dampen the rotational resonances of the bow. Between attacks the string should be freely ringing in ricochet, as opposed to spiccato, where they should be well damped:

While the Helmholtz-corner rotation will continue in ricochet (the corner merely "refreshed" at each new attack), the rotation has to be reversed for each new stroke in spiccato.

The bow's natural bouncing rate *increases* with: (a) the string's distance from frog; (b) the firmness of the bow grip – and *decreases* with: (c) the bow's distance from the bridge; (d) the tilt of the bow hairs with respect to the string. A very rapid spiccato is therefore most easily performed with the bow's hair flat on the string—not too far from the bridge. To obtain regular stick-slip triggering from each tone onset the (rotational) bounce must be well timed with respect to transitional movement of the frog axis (moving with half that frequency). For each new attack the first slip should only happen when the bow force is close to its maximum.

Example of spiccato (or sometimes referred to as sautillé): Finale of Tchaikovsky's violin concerto, *Allegro vivacissimo*. Example of ricochet: Paganini caprice no. 5, *Agitato* (original bowing consisting of three notes down followed by one up).

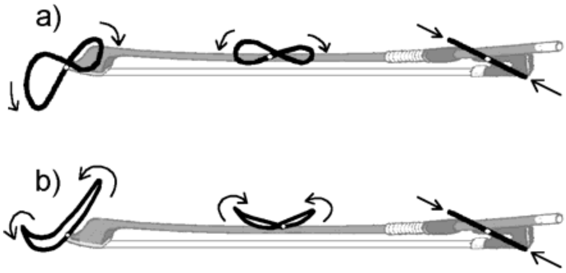

Figure 10: Trajectories of good (a) and a bad (b) spiccato. The timing between the translational component (seen at the frog) and a rotational component twice that frequency is crucial for obtaining a crisp clean spiccato. (From Guettler & Askenfelt 1998.)

4.4 Flautando

In *flautando* (from Italian: "flutelike") a relatively high bow speed and large β are combined with low bow force—usually inside the Helmholtz regime. The result is a long slipping interval (most often exceeding the ratio β of the nominal period), during which noise is created due to stochastic variations of the friction force. The resulting "breathy" sound resembles that of the flute. It is of uttermost importance that the bow's acceleration be kept low during attacks and bow changes, to avoid any accent or perceived change of tone color.

5 Utilizing Bow Dynamics for Envelope Shaping

In section 4 the use of "intrinsic torque" was discussed in connection with an up-bow crescendo. There are many similar cases where the bow dynamics helps shaping the envelope. *Tied staccato* and *flying staccato* are two typical examples: a rapid series of crisp notes executed in one bowing direction—*on* or *off* the string, respectively. In both cases the mass of the bow works against the springiness of the string and the player's grip, aiding synchronization and regularity of a horizontal oscillation determining the rate of attacks.

The player's choice of a stroke's starting point is strongly connected to the bow's natural bouncing rate (see Guettler: "Some Physical Properties of the Modern Violin Bow" for another lecture of this course). Close to the frog, bow force cannot be as quickly reduced as is possible further out on the hair ribbon; any loud attack will sound "meaty". It is also difficult to make a soft tone fade gently out with an up-bow close to the frog; such endings are usually played towards the tip, where the contribution of gravity is much less noticeable.

Violinists usually tilt the bow-hair ribbon (rolling the stick away from the bridge) some 30º with respect to the string. This reduces the effect of any small bowing inconsistency, but more importantly: it facilitates gentle attacks and in particular attacks close to the bridge; a modest increase in brilliance is also noticeable (Schoonderwaldt et. al, 2003). Pitteroff & Woodhouse (1998) showed through simulations how correct tilting actually increases the safety margins for the Helmholtz mode in the violin. In spiccato of a moderate tempo, tilting will make the attacks gentler and the tones longer lasting; without tilting attacks will sound percussive and be of shorter duration. When playing a down-bow ricochet, the bow's natural bouncing rate will increase as you approach the tip. If, however, the music calls for steady rhythm and tones of equal character, it would be a good idea to: (a) progressively relax the bow grip for keeping the bouncing rate down; (b) start the stroke with flat hair and gradually tilt the bow hair to avoid notes to become progressively shorter. Tilting also lowers the natural bouncing frequency, so the bow does not need high jumps for keeping the rhythm. When you can do it, the result is magic!

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