ON THE KINEMATICS OF SPICCATO AND RICOCHET BOWING

Knut Guettler
Norwegian State Academy of Music
P.O. Box 5190 Majorstua
N-0302 Oslo, NORWAY.
knut.guettler@nmh.no

Anders Askenfelt
Dept. of Speech, Music and Hearing
Royal Institute of Technology
SE-100 44 Stockholm, SWEDEN
andersa@speech.kth.se

A skilled string performer is able to play a series of spiccato and ricochet notes—short notes played with a bouncing bow—with each onset showing little or no aperiodic motion before a regular slip-stick pattern (Helmholtz motion) is triggered. The motion of the bow stick can be decomposed into a translational component and a rotational component with the axis of rotation close to the finger grip at the frog. In spiccato, the bow describes two periods of rotational motion for each complete cycle of the translational motion (down-up bow), giving two notes. Simulations reveal that in a well-performed, crisp spiccato the bow gives nearly vertical impacts on the string, and that the first slip of each note takes place when the normal bow force is near its maximum.

In ricochet, the bow is thrown onto the string in order to create a series of short, crisp notes in one single bow stroke. The player terminates the ricochet stroke by damping the rotational component. This is done by loosening the bow grip and being compliant to the reaction forces acting back on the frog.

Spiccato (from Italian spiccare: "clearly separated, cut off") and ricochet (French: "indirectly rebounding") are bowing techniques in which the player lets the bow bounce on the string —once per note—in order to create a series of notes with quick, crisp attacks followed by freely decaying "tails." This effect was not easily achieved until François Tourte (1747-1835) designed a bow with concave curvature of the stick. The new design was quite opposite to the earliest musical bows which had a convex shape (bending away from the hair). In order to produce a crisp spiccato the bow force must be "switched on and off" very quickly. The Tourte bow can manage this well because it does not tend to fold or collapse in contrast to the older types. However, a stiff bow alone is not enough to produce good-quality spiccato or ricochet. In spiccato, a precise timing in the bow control is imperative as will be discussed in the following. In fact, the quality of the rapid spiccato differs greatly even among professional string players of today. In ricochet, the difficulty lies primarily in stopping the bouncing when the series of notes should end. The action of the bow in spiccato and ricochet are considered to be of major importance when ranking bows.

The Phases Of A "Perfect" Spiccato

Figure 1 shows a computer-simulated "perfect" spiccato as performed on an open violin G-string (196 Hz). The main control parameters, the bow velocity v_B, and the bow force f_Z are shown together with the obtained string velocity at the point of excitation. The time history of v_B is defined as a sine function (v_B positive for down-bows and negative for up-bows), and f_Z as a half-rectified cosine function with an offset. The frequency of f_Z is twice the frequency of v_B.

The bow velocity and bow force were defined as

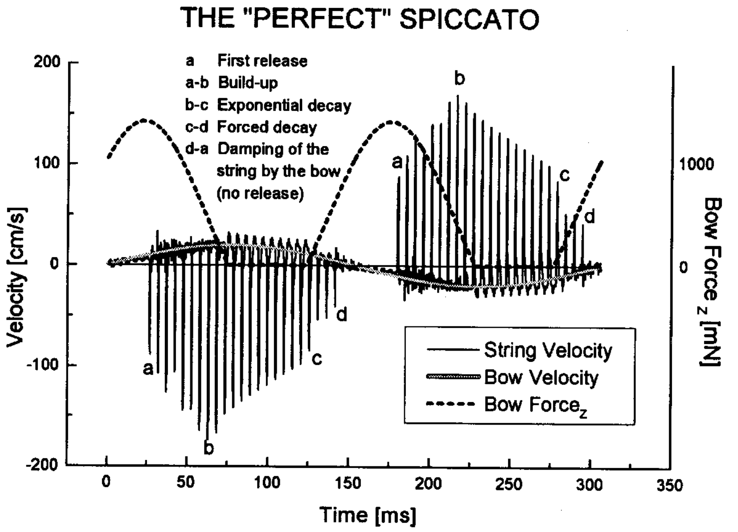
$$v_B = C_1 \sin\left(\frac{\pi}{30T_0}t\right)$$

$$\begin{cases} f_z = C_2 + C_3 \cos\left(\dfrac{\pi}{15T_0}t - \alpha\right) & \text{for positive values} \\ f_z = 0 & \text{else} \end{cases}$$

where T_0 is the fundamental period of the string. A maximum of 30 nominal periods is thus possible for each bow stroke. For $\alpha = 0$ the note starts with full force and zero velocity. As α is increased the buildup in force is successively delayed, making it follow the increase in bow velocity closer and closer (see Figure 3). At a lag of $\alpha = 112°$ they will depart from zero simultaneously.

Each note in Figure 1 can be subdivided into five phases (intervals a-b, b-c, etc.), all of which are necessary for pro-

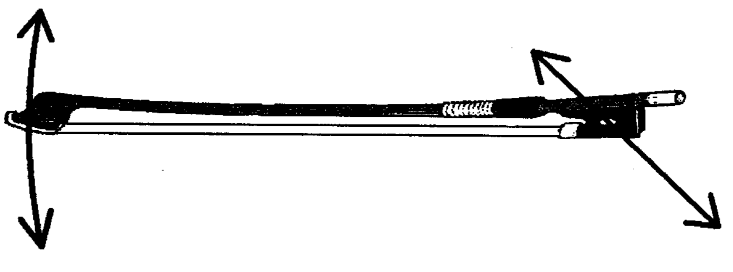
Figure 1 ▪ Simulation of rapid spiccato on an open violin G-string showing the bow velocity (white line) and bow force (dashed line) together with the obtained string velocity. The "perfect" spiccato can be subdivided into four phases (see text).



ducing a crisp spiccato with clean attacks. After the initial release at (a), the string velocity curve shows regular Helmholtz triggering with one single slip per period. During the interval (a-b), the string amplitude builds up quickly until, at (b), the bow force has dropped so much that the string motion starts a free, exponential decay. The decay rate is determined by the internal damping of the string and the losses at the terminations. This state lasts until (c), where f_Z starts rising again, increasing the frictional force. Due to the lowered v_B the bow is now braking the string, forcing a quick decay of the string velocity. At (d), the limiting static frictional force is high enough to prevent the string from slipping as the velocity passes zero and changes direction. This silent part prepares the next string release which will take place in the opposite direction.

Figure 2 shows the two components of the bow motion which are necessary to create the desired combination of v_B and f_Z. The straight arrow at the frog indicates a translational movement with the frequency of v_B. At the tip, a rotational movement is indicated. The center of this rotation lies somewhere at the frog, close to the position of the player's thumb. The frequency of the rotational motion is that of f_Z, twice the frequency of the translational motion. For the player, the challenge lies in the phase coordination of these two components, as will be illustrated in the next section.

Figure 2 ▪ In spiccato, the motion of the bow can be decomposed into a translational and a rotational component. The center of rotation lies close to the player's thumb at the frog.



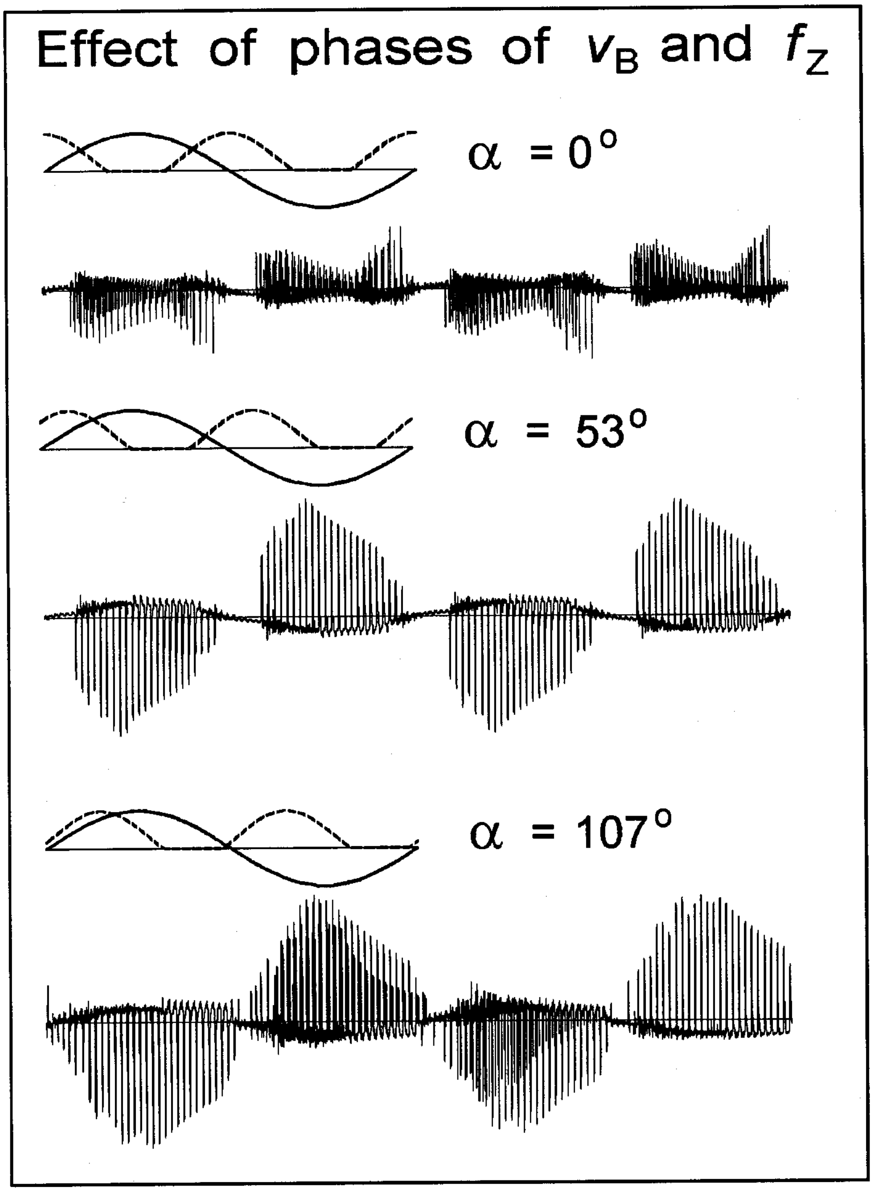
Evaluation Of The Phase Lag

Three simulated cases of spiccato with different amount of phase lag (α) between bow velocity and bow force are compared in Figure 3. In the upper graph, the force function is applied without any lag ($\alpha = 0$). This leads to a situation where the bow force decreases far too early so that when maximum velocity is reached, the force has already gone down to zero. Further, the force starts its second increase long before v_B has descended to a low value. In all, this results in a double buildup of each note. The string amplitude will never reach a high value and the perceptual impression is a "choked" spiccato.

In the middle graph, f_Z is given a lag of 53° compared to the velocity. This produces the "perfect" spiccato which was shown in Figure 1. In the lower graph the lag is 107°. Of the four notes in this latter series, two are "scratchy" with multiple flybacks attacks and irregular and poorly defined onsets (#2 and #3). The two remaining notes show clearly longer buildup times than in the perfect case. The explanation should primarily be sought in the lack of forced damping which precedes the initial slips in the perfect case (middle graph). For large lags as in this latter case ($\alpha = 107°$), remaining Helmholtz components from the preceding note with high amplitudes and "wrong" (opposite) phase orientation are still present on the string when v_B changes sign.

The graphs in Figure 3 were taken from a simulation series with nine sets—each consisting of 30 notes—in which α was changed from 0° to 107° in steps of 13°. The force on the bridge was taken as the output of the simulation, and convolved with a transfer function, relating the radiated sound to the bridge force. This transfer function was obtained by recording a force impact on a violin bridge and the resulting sound

Figure 3 ■ Computer simulations of spiccato with three different phase lags ($\alpha = 0$, 53°, and 107°) between bow force (clipped cosine, dashed line) and bow velocity (sine function, full line). Only the middle case produces a "perfect" spiccato.



pressure at a distance of 30 cm from the violin body. This convolution gave a signal with the characteristics of the sound of a real violin, and the quality of the spiccato could then be judged by listening. Out of the nine simulation sets, only one case ($\alpha = 53°$) produced perfect attacks for all 30 notes.

The margins in α relative to the "optimal" 53° seemed rather narrow. With $\alpha = 40°$ there was only one noisy attack, while all cases with $\alpha > 53°$ gave many noisy attacks appearing randomly. For cases with $\alpha < 53°$ all notes sounded choked, but less so as the optimal lag was approached.

Figure 4 shows an estimation of the output power, given as the arithmetic average of the decibel values of harmonics 2 through 20 compared to the power of the 1st harmonic. Not surprisingly, the "perfect" spiccato gives the highest 1^{st}-harmonic power, while $\alpha = 107°$ gives the highest average power for the partials.

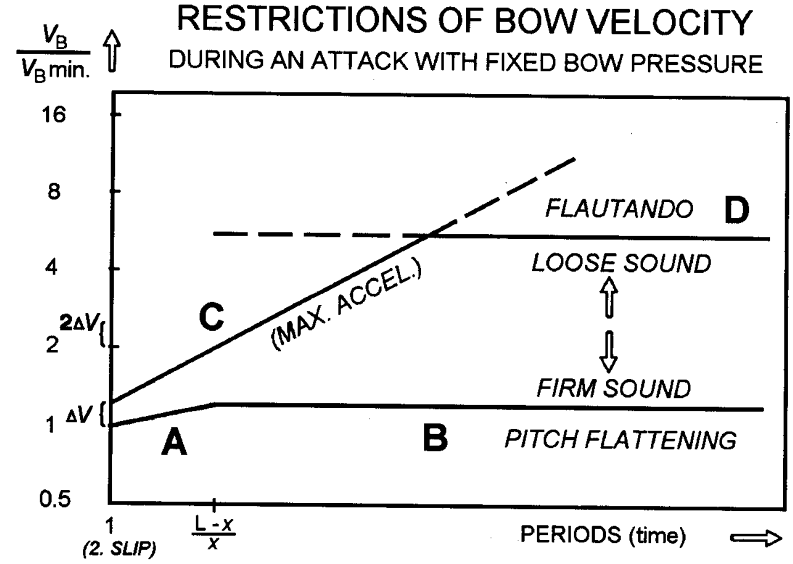
The results of the simulations do not imply that $\alpha = 53°$ is a magic figure. The "magic" lies elsewhere. A perfect attack requires a few initial periods with a gradually increasing v_B combined with a f_Z that does not change too rapidly, say, less than 5 - 7 % per nominal period. With the force-velocity lag of the perfect case ($\alpha = 53°$, see Figure 1), this leaves f_Z with a marginal of about ± 20-30° (cycle deg) around its peak value, during which the initial periods must be triggered. In Figure 1, the first release occurred 9° after the force maximum. With a slightly higher v_B the first release would have occurred earlier, but perfect attacks might still have been produced. Figure 5 shows conditions for perfect onsets when f_Z is kept constant (Guettler 1992).

Measurements Of Spiccato Bowing

Figure 6 shows a recording of the string velocity during rapid spiccato performed on a stopped violin D-string by a professional string player. The repetition rate is close to 11 notes/s, corresponding to sixteenth notes at metronome tempo M.M. = 160 beats/min. The measurements were done by applying a miniature magnet close to the bowing point and recording the voltage across the string. The three last notes in the figure are perfect in timing and triggering, while the first one displays a premature increase of the bow force, causing a few periods to grow in amplitude again. In between the notes "quiet" areas exist.

Without direct measurements, some information on the magnitude of the bow force can be gained by observing the ripple in the string velocity signal. Due to the relatively low Q-values of the torsional string modes, the ripple (which mainly consists of transformed torsional waves) will fade away quickly when the bow leaves the string. Figure 7 shows the second note in Figure 6 analyzed in the same manner as in Figure 1. In the interval (a-b) the ripple is growing due to a quick buildup of flybacks (Schumacher 1979). In the interval (b-c) the ripple is decaying exponentially, which means that f_Z is zero, or close to zero. Between (c) and (d), where the bow is braking the string, the ripple grows again despite of that the transversal amplitude is still decreasing. The presence of ripple is nevertheless an indication of bow-string contact because this seems to be a necessary condition for torsional-transversal transformation to occur (Cremer 1984). After (d) static friction reigns and the bow damps all remaining string vibrations efficiently.

Figure 5 ▪ During an attack with fixed bow force f_Z the bow velocity should follow a path inside the frame A through D in order to trigger a Helmholtz motion as quickly as possible. At the onset, only a narrow range in bow velocities will produce Helmholtz triggering (one flyback per period). After a few periods the tolerance for changes in bow velocity and bow force is much greater (Guettler, 1992).



Visual Feedback To The Player

The easiest way to determine the phase conditions while performing a rapid spiccato is to put small, white marks on the bow stick and observe the patterns they create. Figure 8 shows two of several possible cases. During a crisp, "perfect" spiccato, the midpoint of the stick will always describe a lying numeral eight (the infinity symbol) like the example in Figure 8(a). The bow will then make contact with the string at the end of each stroke and a forced decay will take place. If the pattern is shaped like a V or a U as in Figure 8(b), the attacks are always noisy because the bow is off the string when the changes in bowing direction take place. The rotational motion is delayed 108° in Figure 8(b) compared to (a).

The Ricochet—And How To Stop It

In the ricochet, the bow gives a whole series of rotational impacts on the string during each stroke, while the centre of rotation (near the player's thumb on the frog) is moved at normal bow speed in a straight line. This produces series of fast and short notes (typically 10 15 notes/s) with crisp and rapid attacks. Only one impulse for the whole series is given by the player, who starts with the bow at some distance above the string.

The bounce rate is determined by the moment of inertia of the bow together with the spring constants during "flight" and string contact, respectively (Askenfelt and Guettler 1998). The player's controls of the bounce rate are: (1) the firmness (stiffness) of the bow-hand grip, (2) the distance from the frog to the impact point on the bow hair, (3) the distance from the bridge to the impact point on the string, and (4) the bouncing height above the string. Increasing any of the first three parameters gives increasing bounce frequency due to increased spring constants during flight (1), and during string contact (2-3), respectively. Increasing (4) gives longer "flight" intervals and a reduction in the bounce frequency. The restoring mo-

Figure 4 ▪ Power output obtained in nine spiccato simulations with different timing between bow velocity and bow force. Each simulation consisted of 30 notes. The values are given as the arithmetic average of the decibel values of harmonics 2 through 20 (squares) compared to the power of the 1st harmonic (circles). The last three simulations on the right-hand (noisy) side included many "scratchy" attacks that appeared randomly in spite of the consistent control of the bowing parameters (bow velocity and bow force).

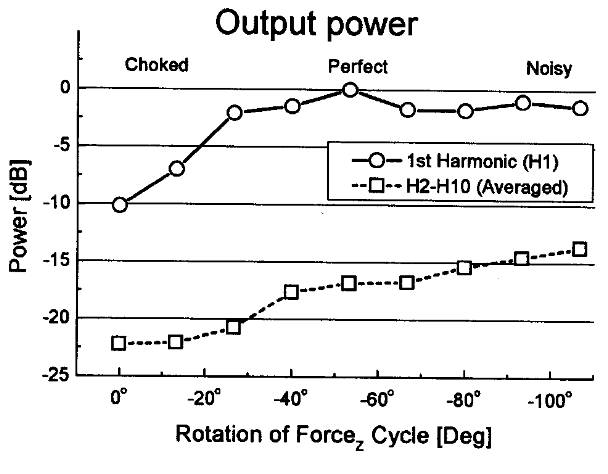
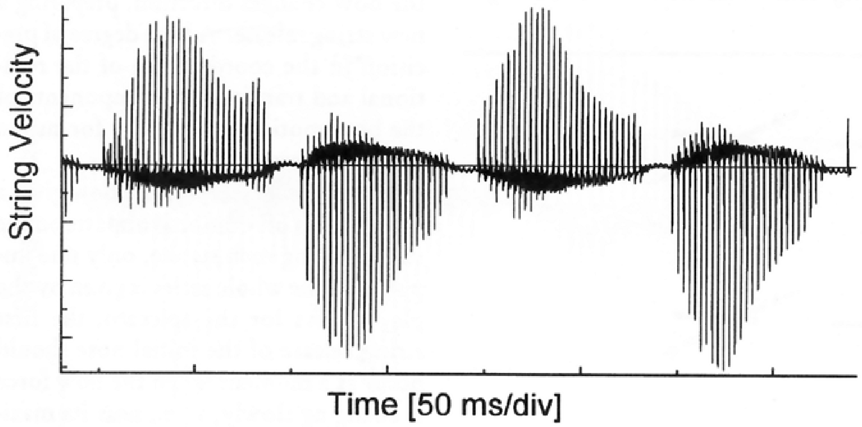


Figure 6 ▪ String velocity at the bow recorded during a rapid spiccato on a stopped violin D-string (note F4) at a rate of 11 notes/s (sixteenth notes at M.M. = 160 beats/min). The patterns compare well to the cases obtained in the simulations. All four attacks are nearly perfect. Notice the quiet intervals between notes. In the first note the bow has returned a little too early after the "exponential decay," causing the amplitude to rise again. A good professional player is capable of producing a sizable series of spiccato notes with little or no onset noise.



ment during flight, supplied by the player's bow grip (cello/ bass) in combination with gravity (violin), does not increase proportionally to the bounce height. Tilting the bow lowers the bounce rate as well, since the bow-hair ribbon is more compliant when attacked from the side. Rapid ricochet and spiccato must always be played with the bow hair flat on the string.

It takes some experience to perform the ricochet with rhythmical precision. In order to maintain a constant bounce rate, the bow grip needs to be constantly adjusted as the distance from the frog changes during the stroke. The most difficult part, however, is to stop the bouncing in due time at the end of the stroke. This can be done by changing the supporting conditions at the frog. During the ricochet, the bow must be held firmly enough to let the frog act as an almost fixed axis. The rotational motion of the bow generates reaction forces at the axis of rotation which try to move the frog up or down, and these must be balanced by the bow grip. The sign of the reaction forces (up or down) depends on whether the bow hits the string inside or outside the point of percussion (Askenfelt and Guettler 1998). By loosening the bow grip at the end of the ricochet stroke and letting the frog and hand move a little like stopping a ball by a compliant hand and arm without gripping it a good part of the rotational energy can be removed from the bow. This technique is necessary when a longer note follows after a series of ricochet notes, the longer note requiring a relatively stable bow force.

Figure 9 shows a ricochet stroke consisting of two short notes followed by a long note played with a violin bow on a force transducer as a substitute to the string. The damping of the rotational component after the second ricochet note is high enough to ensure a reasonably stable bow force for the long note. Note that the bow force continues to vary with the "ricochet rate" also during the long note but it does not fall below the critical minimum-required-bow-force limit.

The conditions when playing on the force transducer do not appear to be very different from normal playing. The player reported that the "feel" of the bow was similar to normal playing on a string, although lacking the grip of a compliant string in the bowing direction. Also, the magnitude of the contact force seems reasonable, as judged from the minimum distance between bow stick and hair observed in this experiment and the corresponding distance in normal playing.

It is difficult to make the bow settle when ending a ricochet stroke near the point of percussion, as the reaction forces acting back on the frog approaches zero for this contact point. Ending a ricochet stroke in this part of the bow (about 1/3 from the tip for a violin bow) is therefore usually avoided when a long note follows. If for some reason this is not possible, a quick tilting of the bow may facilitate the termina-

Figure 7 ▪ Some information on the bow force can be extracted from the ripple in the string velocity signal. The second note in Figure 6 is displayed (fundamental period $T_0 = 3.0$ ms.) Using the same markings as in Figure 1, the letters (a) through (d) have been placed where the interpretation of the ripple signal makes changes in bow force plausible (see text).

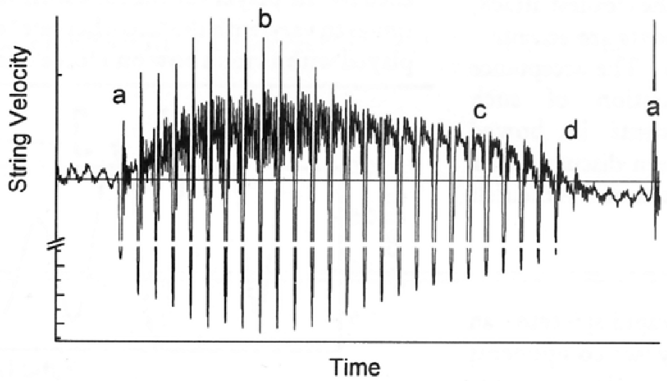
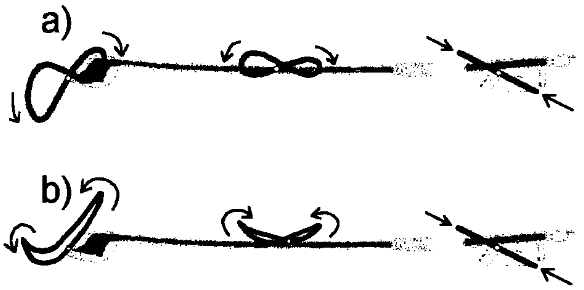


Figure 8 ▪ An easy visual way to confirm the phase relation between the translational and the rotational movement during a rapid spiccato is to put a small white mark on the middle of the bow stick and observe the motion pattern. Of the two cases shown here, only (a) will produce a crisp sound. In (b), where the rotational motion is delayed 108° compared to (a), the attacks will be noisy because the change of bowing direction takes place when the bow is off the string. When the bow returns to the string, remaining Helmholtz components of high amplitudes and "wrong" (opposite) phase orientation will still be present. In (a) the hair has contact with the string during the bow change and mutes these waves. The figures are drawn out of proportions for clarity.



tion of the bouncing.

For the same reason as in spiccato, the first string release in the initial ricochet note should occur when the bow force is changing slowly, i.e. near a maximum in bow force, but the following notes may have an earlier first release provided that the (decaying) string amplitude is sufficiently high. The fact that the bowing direction (and thus the rotational direction of the Helmholtz corner) remains unchanged for all notes in a ricochet stroke makes the start easier for the latter notes. Figure 10 illustrates this point. A forced muting of the string between notes in ricochet like in spiccato is thus neither necessary nor desirable.

Although an onset of note with a perfectly periodic Helmholtz motion from the first period gives the cleanest attack, short aperiodic transients are accepted, even by professionals. The acceptance limits for the duration of such pre-Helmholtz transients in bowed string attacks have been discussed in a separate study (Guettler and Askenfelt 1997).

CONCLUSIONS

A well-performed rapid spiccato can be modeled using only two components of bow motion; a translational component giving a sinusoidal bow velocity, and a rotational motion giving a bow force varying as a half-rectified cosine, with a phase lag relative to the velocity. The rotational component has the same frequency as repetition rate of the notes, while the translational component has only half that frequency.

A crisp spiccato with little or no attack noise can be separated into four parts: (1) "the buildup," starting with an initially high bow force combined with an increasing bow velocity, followed by a rapid decrease in force after a few initial periods; (2) "the exponential decay," with decreasing bow velocity and low or no bow force; (3) "the forced decay," with the bow still moving (slowly) in the old direction while the bow force builds up again, the effect being that the string amplitudes are quickly reduced; (4) "the muting of the string," during which the bow force is high enough to prevent the string from slipping while the bow changes direction, preparing a new string release. A high degree of precision in the coordination of the rotational and translational components of the bow motion is necessary for such a perfect spiccato.

In the ricochet, where the bow gives a whole series of rotational impacts on the string during each stroke, only one impulse for the whole series is given by the player. As for the spiccato, the first string release of the initial note should occur at a moment when the bow force is changing slowly, i. e., near its maximum value. Since all subsequent notes are played with the Helmholtz corner rotating in the same direction, forced muting of the string between notes is unnecessary. The bouncing can be terminated by the loosening the bow grip somewhat and letting the frog and hand follow in the direction of the reaction forces that are acting back on the axis of rotation. ■CASJ

Figure 9 ▪ Contact force in a ricochet stroke consisting of two short notes (up-bow) followed by a long note (down-bow). The player throws the bow onto the string and the bow rebounds twice before the rotational component is dampened by the player for the following long note. Observe that the bow force continues to vary with the "ricochet rate" also during the long note. The example was played with a violin bow on a force transducer.

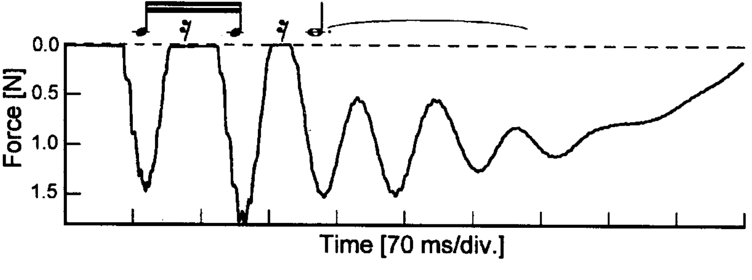
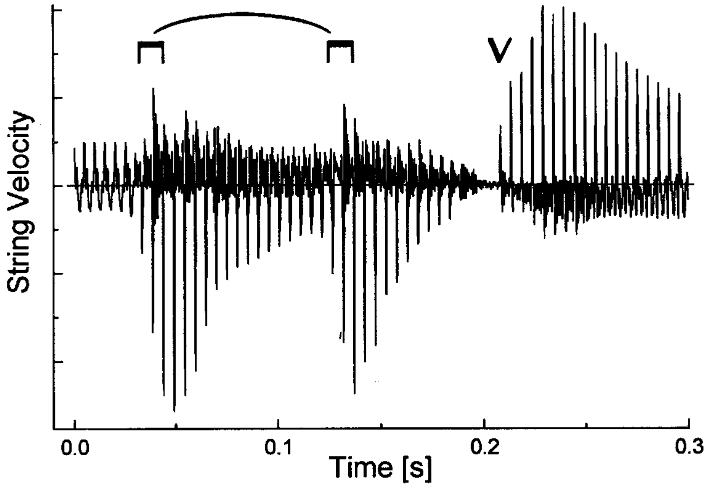


Figure 10 ■ Example of excellent attacks in ricochet (the two first notes), followed by a perfect spiccato-attacked note. The figure shows the string velocity close to the bowing point, measured on a violin G-string. Note that a decaying string vibration (mainly fundamental) is present at the onset of the first note, and that the first release of the ricochet notes (both down-bow) are synchronized with this signal. Before the third note (up-bow) is played the string is muted by the bow, as in spiccato.



ACKNOWLEDGMENTS

The authors are indebted to the Wenner-Gren Foundation and the Swedish Natural Science Foundation (NFR) for supporting this work.

REFERENCES

Askenfelt, A. and K. Guettler, 1998. "The bouncing bow: an experimental study" *CAS Journal* (November): 3 - 8.

Cremer, L. 1981. *The Physics of the Violin*, (Cambridge:MIT Press, 1984, English translation by J. Allen of *Physik der Geige*, Stuttgart, Hirzel Verlag): Ch. 6.

Guettler, K. 1992. "The bowed string computer simulated Some characteristic features of the attack", *CASJ*, Vol. 2, No. 2 (Series II): 22-26.

Guettler, K. and A. Askenfelt. 1997. "Acceptance limits for the duration of pre-Helmholtz transients in bowed string attacks," *J. Acoust. Soc. Am.* Vol. 101, No. 5: 2903-2913.

Schumacher, R. T. 1979. "Self-sustained oscillations of the bowed string," *Acustica* 43: 109-120.