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On the kinematics of spiccato bowing

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Abstract
A skilled string performer is able to play a series of spiccato notes (short strokes played by a bouncing bow) with each onset showing little or no aperiodic motion before a regular slip/stick pattern (Helmholtz motion) is triggered. Kinematic analysis reveals that a well-behaving 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. The complex movement of the bow stick can be decomposed into a translational and a rotational motion. Within one full cycle of the translational motion (down-up bow), giving two notes, the bow describes two periods of rotational motion. The axis of rotation is close to the finger grip at the frog. This paper discusses the relation between the quality of the spiccato and the phase lag between the two components of bow motion.

Introduction

Spiccato (from Italian *spiccare*: "clearly separated, cut off") is a bowing technique 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 much longer, freely decaying "tails." This effect was not easily achieved until François Tourte (1747-1835) designed a bow with concave curvature of the stick. This 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. A very precise timing in the bow control is also imperative. In fact, the quality of the rapid spiccato differs greatly even among professional string players of today.

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

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

$$\begin{cases} f_z = C_2 + C_3\cos\left(\frac{\pi}{15T_o}t - \alpha\right) & \text{for } f_z \geq 0 \text{ else} \\ f_z = 0 \end{cases}$$

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

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

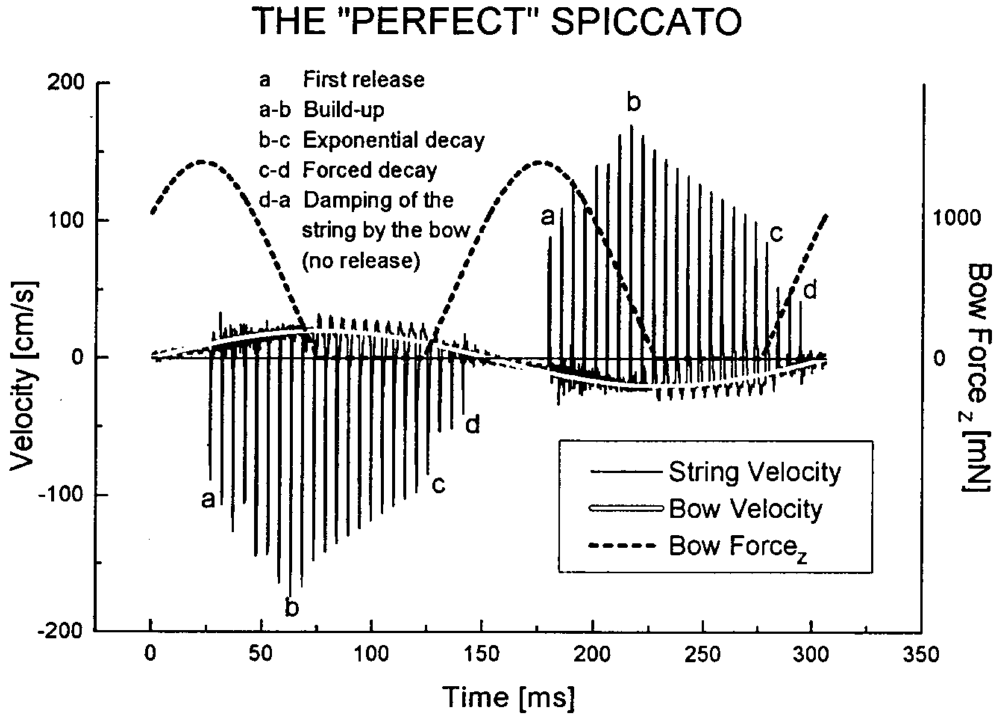

Figure 1. The "perfect" spiccato can be subdivided in four phases (see text). Simulation of rapid spiccato on an open violin G-string.

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 centre 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 co-ordination of these two components, as will be illustrated in the next section.

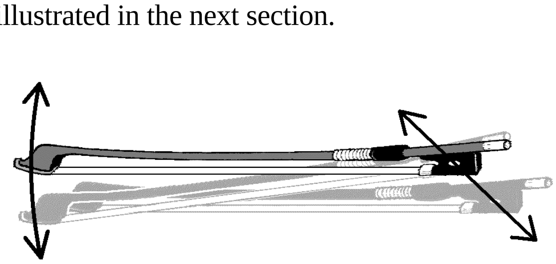

Figure 2. During spiccato, the movement of the bow can be decomposed into a translational and a rotational motion. The centre of rotation lies close to the player's thumb at the frog.

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 build-up 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 build-up 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

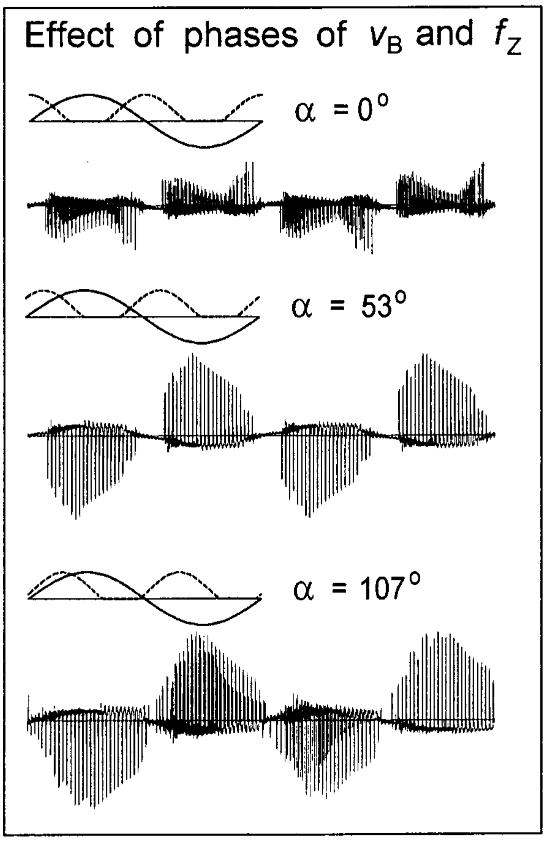

Figure 3. Computer simulations of spiccato with three different phase lags (α = 0, 53°, and 107°) of the bow force (dashed line) relative to the bow-velocity (white line). Only the middle case produces a "perfect" spiccato.

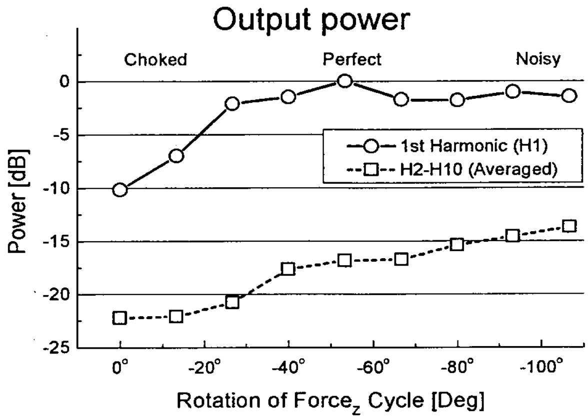

Figure 4. Power output obtained in nine spiccato simulations with different timing between bow velocity and bow force. Each simulation consisted of 30 notes. The values are given as the arithmetic average of the decibel values of harmonics 2 through 20 (squares) compared to the power of the 1st harmonic (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).

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 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 produced perfect attacks for all 30 notes.

The margins in α relative to the "optimal" 53° seemed rather narrow. With α = 40° , there was only one noisy attack, while all cases with α > 53° gave many noisy attacks appearing randomly. For cases with α < 53°, all notes sounded choked, but less so as the "optimal" lag of 53° 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 1st-harmonic power, while α = 107° gives the highest average power for the partials.

The results of the simulations do not imply that α = 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 (α = 53°, see Fig. 1), this leaves f_Z with a relatively wide marginal of about ± 20 - 30° (cycle deg) around its peak value, during which the initial periods must be triggered. In Fig. 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).

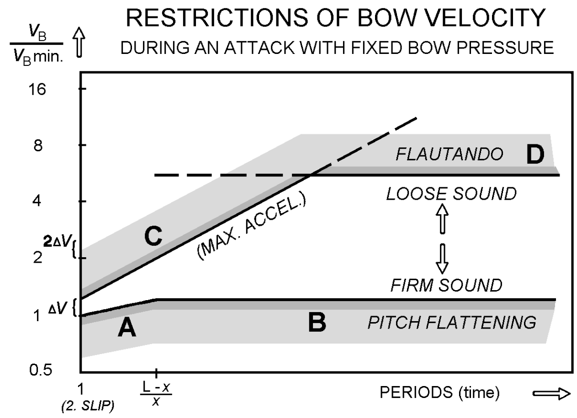

Figure 5. During an attack with fixed bow force f_Z the bow velocity should follow a path inside the frame A through D in order to trigger a Helmholtz motion as quickly as possible. At the onset, only a narrow range in bow velocities will produce Helmholtz triggering (one flyback per period). After a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

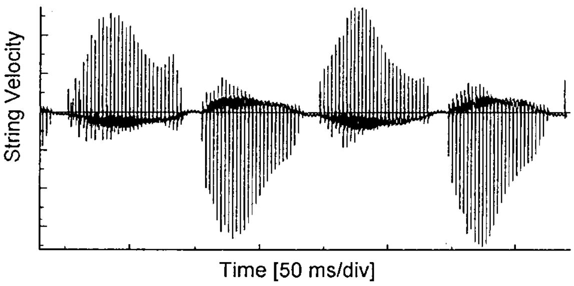

Figure 6. String velocity at the bow recorded during a rapid spiccato on a stopped violin D-string (note E_4) at a rate of 11 notes/s (sixteenth notes at M.M. = 160 beats/min). The patterns compare well to the cases obtained in the simulations. All four attacks are nearly perfect. Notice the quiet intervals 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 sizeable series of spiccato notes with little or no onset noise

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 Fig. 6 analysed in the same manner as in Fig. 1. In the interval (a-b), the ripple is growing due to a quick build-up 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 an absolutely necessary condition for torsional-transversal transformation to occur (Cremer, 1984). After (d), static friction reigns and the bow damps all remaining string vibrations efficiently.

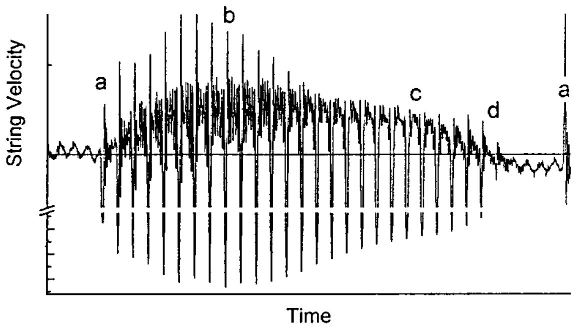

Figure 7. Some information on the bow force can be extracted from the ripple in the string velocity signal. The second note in Fig. 6 is displayed (fundamental period T_o = 3.0 ms.) Using the same markings as in Fig. 1, the letters (a) through (d) have been placed where the interpretation of the ripple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

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 high-quality spiccato, the midpoint of the stick will always describe a lying numeral eight (the infinity symbol) like the example in Fig. 8(a). The bow will then be approaching 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 Fig. 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 Fig. 8(b) compared to (a).

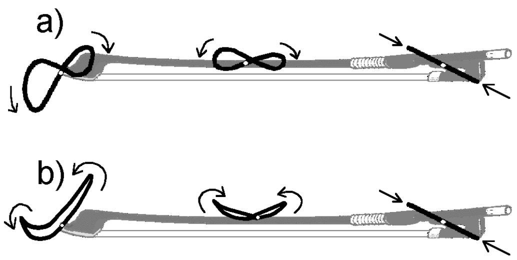

Figure 8. An easy visual way to confirm the phase relation between the translational and the rotational movement during a rapid spiccato is to put a small white mark on the middle of the bow stick and observe the motion pattern. Of the two cases shown here, only (a) will produce a crisp sound. In (b), 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.

Conclusions

A well-performed rapid spiccato can be modelled 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 build-up," starting with an initially high bow force combined with an increasing bow velocity, followed by a rapid decrease in bow 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 co-ordination of the rotational and translational components of the bow motion is necessary for such a perfect spiccato.

Acknowledgements

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