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BOW NOTES

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1. ABSTRACT

Musicians and bow makers claim with great conviction that they are able to detect differences in timbre between bows. The same is claimed for differences in the playing characteristics. In the string player's repertoire of bowing styles, a variety of bow qualities are asked for, some of which may seem contradicting. In legato playing, for instance, the bow should be tranquil (at least in the bow-force plane normal to the string), ensuring a stable bow-string contact. In contrast: spiccato and ricochet bowing requires the bow to be vigorous in the same plane, facilitating rapid bounces on and off the string. The good bow is said to be capable of both.

Over the last few decades the study of the physics of the bow comprises research on: resonances, modal behavior and static deformation, properties of rosin, bow hair and the stick-slip mechanisms involved, and not of least importance: the bowing parameters utilized in professional playing. The effect of the bow on the string during stick, as linear coupled oscillators, seems formally well established, but a comprehensive model of the bow-string interaction includes several nonlinear elements, the effects of which are not equally well analysed. Although our knowledge about the bow has grown considerably during the last few years, much remains before the physicist can tell the bow maker and the musician in which properties the excellent bow deviates from the average.

2. INTRODUCTION

In this paper, I have sometimes chosen to convey questions and viewpoints of the professional string player (as experienced through my work as a principal philharmonic player, teacher and soloist). Most paragraphs, however, will refer to recent research on the bow - published and unpublished. In the International Symposium on Music Acoustics 1995 (Dourdan, France), A. Askenfelt opened the session on the violin family by giving a comprehensive overview on the violin bow and the interaction with the string [i], with reference to the current state of the related research. When I have now been honored with the request to give a keynote introduction on the bow for ISMA'97, I believe that such a presentation should be supplementary to the one from 1995, rather than repeating all the good works discussed there. This report will therefore to a lesser degree contain numerical data on the physical properties of the bow, but focus on its usage and playing properties.

3. ON THE "NORMAL" BOW STROKES - DÉTACHÉ, TENUTO AND LEGATO

Because a bowed instrument by nature has a much longer transient than the piano or wind instrument, the string student spends much time working on the attack (or "Depart" as Ivan Galamian [ii] preferred to term it), in order to minimize the time required for establishing a full sound. In rapid passages, unless the natural bounce of the stick is exploited as in "spiccato" (from Italian, spiccare: "clearly separated, cut off"), the bow-string contact should be uniform, without quick alterations in the bow force. This is so, whether the stroke be détaché, tenuto or legato ("separated", "sustained", "connected", respectively). The amateur player is usually not able to carry out this, as it takes considerable muscular independency to separate the activity in the two planes (y and z, i. e., bow velocity and bow force). Typically, an erroneous pattern is to start the note with less-than-needed bow force, and continue with exaggerated bow force ("to bring the string into vibrations") before adjusting to the final, better, bow force. However, when playing notes more separated, it is good tradition to both start and end the stroke gently, with less bow force than utilized in the body of the note, provided the bow velocity is modified accordingly and these changes do not happen too abruptly. In "legato, cantabile" ("connected, singing") it is even more urgent to keep the bow force stable in order not to interrupt the fluency of the phrase. By watching the distance between the bow stick and the hair, it is relatively easy to detect changes in the bow force, especially when playing at the middle of the bow. Normal bow forces range between 0.5 and 1.5 N for the violin [iii].

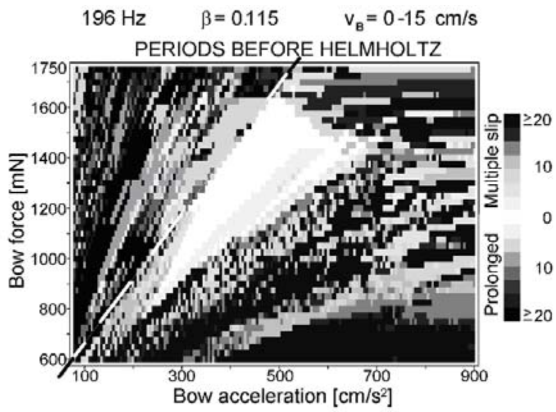
For all bowed instruments, tilting of the bow (i. e., "rolling" the hair ribbon away from the bridge) is normal, but less so on the lower-pitched instruments. Compared to the open-string length of violin, viola, cello and double bass, the width of the bow-hair ribbon is about 2.4-3.7, 2.4-3.5, 1.5-2.6, and 1.4-1.7 percent respectively, when accounting for variations in bow design and differences between the width at the tip and frog.

The term, "détaché" (French: "separated") does not imply "separation between the bow and the string", but "separation between notes" (e. g., as used in "God save the Queen"). If détaché is to be played "on the string", it requires the bow to make sudden stops at the end of each note. Such stops will mute the string (as described in Guettler/Askenfelt this issue [iv]) and facilitate clean and powerful attacks. This muting, however, must happen quickly enough to be masked by the preceding and subsequent notes in order not to reveal the "choking" of the string which inevitably takes place.

Simulations show that for any given (sensible) bow force, there exists a range of bow accelerations that will produce onsets with little or no delay before regular Helmholtz triggering (one slip per nominal period) occurs (see the light triangle of Figure 1). The player controls the maximum bow acceleration partly by choosing the right degree of suppleness in the finger and wrist, etc. Low or steady acceleration calls for greater rigidness in these joints ("loading the bow").

4. ON THE BOUNCING BOW (AND HOW TO STOP IT)

In a "ricochet" stroke (French: "indirectly, rebounding"), the bow gives rotational impacts on the string, while the centre of rotation (near to the players thumb on the frog) is moved forwards or backwards in a straight line. This produces a series of very crisp and rapid attacks (normally 10



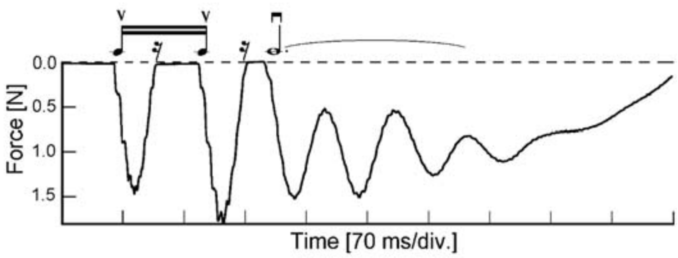


Figure 1:
The number of periods preceding the Helmholtz triggering is an important indicator of perceived quality of the attack. For the open G-string of a violin, the limit for acceptance of pre-Helmholtz transients has been found to be 90 ms (18-19 nominal periods) for onsets with multiple slips (i. e., all attacks shown below the drawn diagonal), for prolonged periods the limit was 50 ms (above the diagonal) [v]. The shown set consists of 7755 simulations, each with a fixed normal bow force and the bow accelerating from 0 to a final value of 15 cm/s. The higher the luminance, the shorter the transient (original graph in colors).

Figure 2:
Contact force in a ricochet stroke (the two first notes): the player throws the bow onto the string, whereafter it rebounces on the string one or more times. Before a long note can be played (here: the 3rd), the player must dampen the rotational mode of the stick as much as possible.

- 20 per second). Only one impulse is given by the player, who starts with the bow at some distance from the string. The bouncing frequency is determined by (a) the firmness of the bow-hand grip, (b) the distance from the frog to the impact point on the bow hair, (c) the perpendicular spring stiffness of the string at the point of bowing - and (d) the height of the bounce above the string. Increasing any of the first three (a through c) implies increasing the bouncing frequency, while increasing (d) implies longer intervals with low acceleration (lower "spring constant"), thus a reduction in the frequency of the nonlinear oscillation. Tilting of the bow lowers the bouncing rate too, since the bow-hair ribbon is more compliant when attacked from the side. In rapid ricochet and spiccato playing, the hairs are played flat on the string.

It takes some experience to execute this technique with rhythmical precision, as the bow grip needs to be constantly adjusted to maintain a constant bounce rate: however, the most difficult part is *to stop the bow from bouncing* when the task is finished if a longer note is supposed to follow.

During the ricochet stroke, the bow must be held firmly enough to let the frog act as an axis. When hitting the string inside or outside of the bow's point of percussion, forces will act back on the frog and the bow hold (moving the frog up or down, respectively). By "catching" this movement (being compliant to it - like when stopping a ball without gripping it), a good part of the rotational energy can be removed from the stick. This is necessary after a series of ricochet notes when the next note is a long one, requiring a more stable bow force. Figure 2 shows a ricochet stroke played with a violin bow on a force transducer. The damping of the rotational mode between the second and third notes is enough to ensure a normal "minimum required bow force". To make the bow tranquil after ending the ricochet series near the point of percussion is more difficult, so ending at this point is usually avoided. Some preliminary experiments show that when holding a mass of 60 grams in a bow-grip, the influence of the hand on the total impedance is only significant in the region below 100 Hz. This probably means that vibrations in the frog above this frequency are not much affected by the hand. Below 20-30 Hz, the impedance of the mass-hand combination was found to be mainly resistive. A more complicated bouncing technique, the spiccato, is described in detail elsewhere in this issue [4],[20].

5. ON BOWING STRAIGHT OR ANGLED WITH RESPECT TO THE STRING

String students are usually instructed to "bow straight on the string", meaning with a perfect angle to it. Should they always do so? From personal experience, I will suggest some examples where perfect-angled bowing is not the best idea:

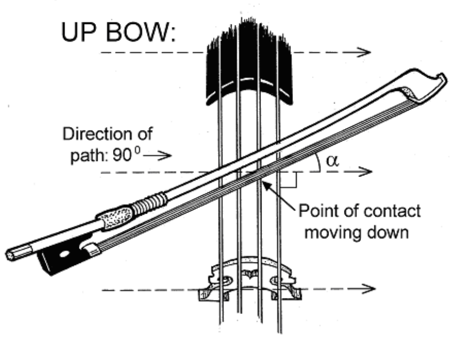


Figure 3:
In certain situations, bowing with an angle to the string gives a better sound.

• When the player wants quickly to move the bow closer to (or farther away from) the bridge during a single stroke, angling of the bow (not to confuse with tilting - see Figure 3, from Guettler [vi]) will reduce the danger of introducing *longitudinal* frictional forces on the string. That is, as long as the *path of bowing* is kept in perfect angle with respect to it. Forces in the string's longitudinal direction, where the string's compliance is small, will easily produce rapid changes between stick and slip - and "scratchy" or "hoarse" sound be inevitable. Due to the greater string lengths, this is even more important on cello and double bass than on the violin. Nevertheless, many violinists use this technique, which was always very visible in Heifetz' playing.

• When trying to make the smoothest possible string crossing, angling may help: in string crossing, the "new" string will be attacked with a constant bow velocity, during which time the bow force will go from zero to the value required for producing a full sound. The (low-compliant) hair will be transferring bow-velocity fluctuations (caused by rapid changes in the frictional force) from the "old" string to the new, where an "imprint" of the old string's time-varying frictional force will be superimposed. This makes it even more difficult to get the new string started. Angling the bow seems however to help. Although we do not yet know, some explanations might be: better damping when the hair-ribbon width on the string is increased; angling involves increased hair and bow-arm compliance, as the arm now works more like a spring where the angle α takes part in the "spring displacement"; the individual bow hairs get a force component from the side, thus changing the average friction (damping) between them. It should also be mentioned that attacks and bow changes on high-impedance strings (particularly in double stops) can be facilitated this way.

• In rapid "arpeggio" (crossing legato or bouncing over three or four strings), angling of the bow improves articulation on low-pitched instruments. On the double bass, the sound of the middle strings tends to disappear when these are bowed straight, but are sounding well in balance when bowed with an angle (even though this implies moving the contact point up and down).

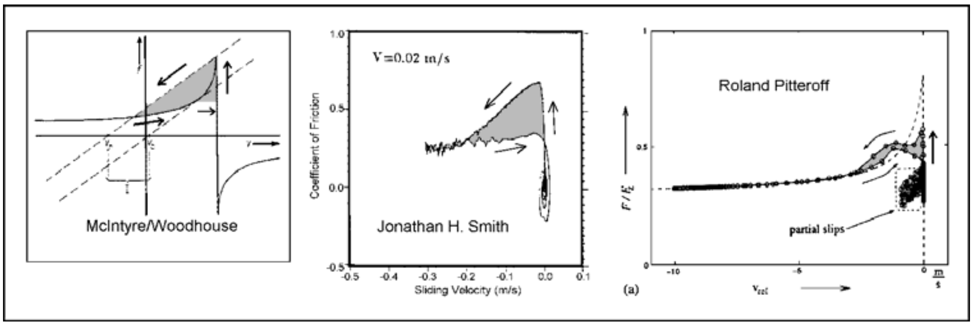


Figure 4:
Three examples of frictional paths (see text).

6. ON FRICTION AND THE BOW-STRING CONTACT

Figure 4 shows the hysteresis paths of three friction models. To the left, the "classical" McIntyre/Woodhouse model [vii], as used in a number of works on bowed-string simulation by these authors, Schumacher [viii] and others. The model is based on Lazarus measurements from 1972 [ix]. Pitch flattening is a consequence of this path. (Shades and arrows are added by me for clarity.) In bowed-string simulations, single-time-step leaps will occur in this path upon departure from, and arrival at static friction.

The middle example is copied from the empirical measurements of friction coefficients in J. H. Smith's doctorate dissertation 1990 [x]. The figure shows the frictional path of a rosined steel rod and a perspex wedge during oscillation. Heating of the rosin during slip, lowers the friction, so that the coefficient remains comparably low when returning to stick (as in the McIntyre/Woodhouse' "mathematical" model). This however, depends to some degree on the relative *driving velocity* (friction levels are increasing with speed), as high velocity leaves less time for heating the adjacent rosin on the bow hair (see also Pickering [xi]). The shown path produces pitch flattening comparable to the McIntyre/Woodhouse model.

The third example is taken from R. Pitteroff's doctorate dissertation 1995 [xii]. A simulation method allowing for finite-width modelling of the contact between bow hair and the string was employed in this work. The programmed friction model is of the McIntyre/Woodhouse type (as indicated with dashed line). However, when calculating the "effective normalised friction" versus the relative velocity averaged over the hair-ribbon width (solid line), the hystereses is significantly less than for the point-bow model. This implies, among other things, that higher bow forces can be employed before pitch flattening occurs.

[Rosins that provide high friction delta are usually considered by the player as "convenient for grabbing the string, but coarse in sound".]

Figure 5 (from Pitteroff) shows the effect of partial slipping during the "static-friction interval" on the bridge-force waveform, as was first examined by M. E. McIntyre et al. [xiii]. The frequency of these small slips is related to the frequency of what L. Cremer calls "secondary waves" [xiv]. This frequency will, together with the harmonic frequencies that have low string-point admittance, be

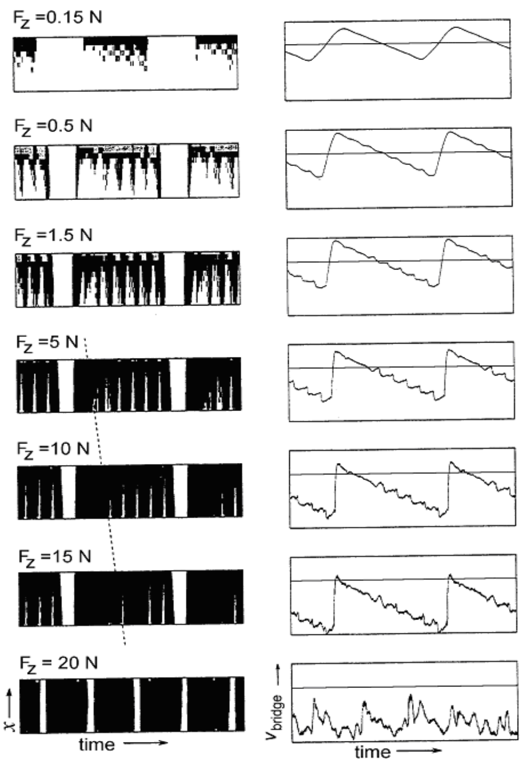


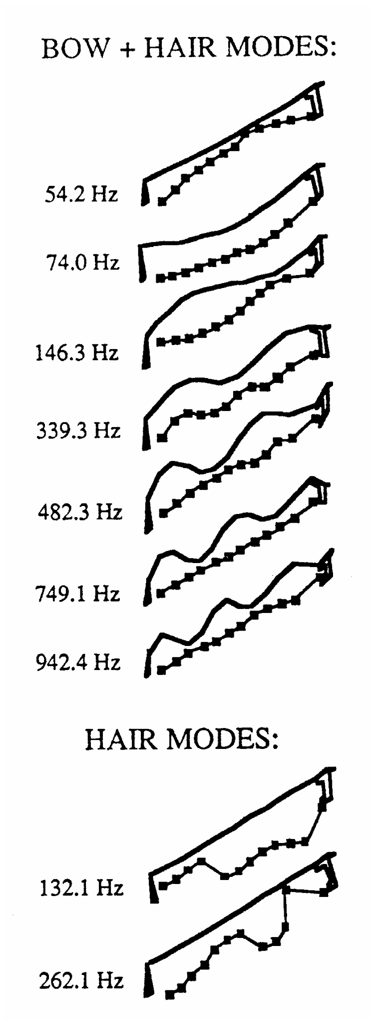
Figure 5:
Friction maps and bridge-force waveforms as functions of bow force (from Pitteroff). White areas in the friction maps (left column) show sliding friction, which happens even during the "static interval" on the bridge side of the hair ribbon.

dominant in the spectrum of frictional force, thus causing fluctuations in the bow-hair velocity and potentially excite bow resonances. The secondary waves are for a good part independent of the string modes, and behave mostly as noise [xv]. Tilting of the bow (i. e., narrowing the hair ribbon in contact with the string) reduces this effect - particularly when being played close to the bridge.

7. ON BOW RESONANCES

The presence of oscillation in the bow hair and their connection with resonances of the bow have been discussed by Schumacher [xvi], Cremer [14], Askenfelt [1],[xvii] and others. Askenfelt found from measurements on nine bow sticks, freely suspended, that the bow modes lie around 60, 160, 300, 500, 750, 1000, 1300 and 1700 Hz, with 0.2-0.6% damping (Q=250-80). These figures have also been in good agreement with other reports [xviii]. Figure 6 shows modal analysis on a violin bow with hair, as measured by G. Bissinger [xix]. In addition to the above mentioned modes, there are resonances strongly related to the bow-string contact point and the propagating speed of the bow hair under tension (2200-2500 m/s).

The bow has also rotational modes where the bow-hold (the frog) is acting as an axis. Dependent on the string's position on the hair ribbon, the lowest mode will start near 6 Hz (at the frog) and end near 30 Hz (at the tip) during a down-bow stroke. For a violin bow excited on the hairs some two cm outside of their midpoint (at "the spiccato point"), the most dominant of these modes are typically found around 13, 130 and 150 Hz. These rotational modes do couple in a nonlinear way, as is discussed in Askenfelt/Guettler this issue [xx]. Figure 7 (lower part) shows how the hair vibrates when excited at the spiccato point (about 40 cm away from the frog), with frequencies near 130 Hz (f_1) and 150 Hz (f_2). One interesting feature is that both these frequencies do also excite the lowest mode (13 Hz), and may even cause the bow to start bouncing at that rate. Rotational modes like these are likely to play an important role for the bow-string contact, whether the player is employing off-string (e. g., spiccato) or on-the-string (e. g., legato) technique.



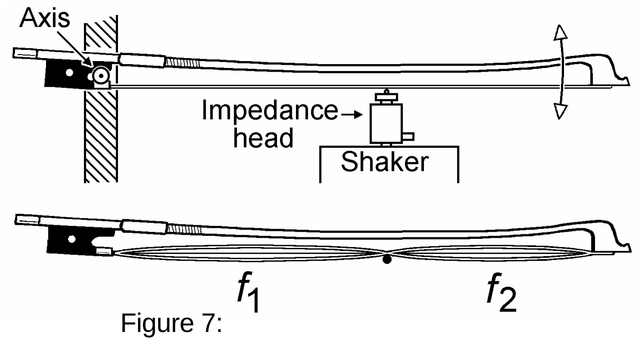


Figure 7:
Examples of transversal "hair modes" on each side of the excitation point.

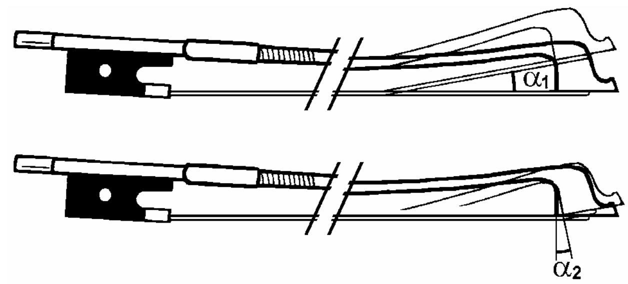


Figure 8:
Examples of bow-head activity (see text).

Figure 6 (left):
Modal analysis of a bow with hair under tension (from Bissinger).

8. ON THE ANGLE OF THE BOW HEAD

When exciting the bow in the rotational plane used for spiccato, ricochet, etc., (i. e., with the axis of rotation through the frog), the outer part of the *bow stick* shows considerable activity around 130-160 Hz [20], dependent on how far away from the frog the bow-hair is excited. During a vivid spiccato, the bow stick nearly touches the bow hair once per attack. Both of these actions cause the outer part of the bow to bend. Dependent on how close to the head the nodes are placed, one will have bending like the upper example in Figure 8, where the hair is lifted, and/or as in the lower example where the hair is stretched. Pitteroff [12] estimates that stretching a ribbon of 200 bow-hairs 1 mm, requires about 60 N. With a height of the head near 20 mm, it should then take only about $\alpha_2 = 0.05^0$ backward rotation to add a force of one Newton to the hair ribbon.

[It is the experience of many string players that certain bows are difficult to control near the tip. They "loose string contact" on the last 10-12 cm.]

9. ON BOW-HAIR FLUCTUATIONS AND INFLUENCE ON THE OUTPUT SPECTRUM

In playing, the bow resonances are normally excited by changes in the frictional force which occur during the entire period, but most significantly during the sticking part, and, in particular at the transitions between stick and slip. The bow resonances will couple to the string resonances and transmit, reflect, and/or absorb some part of the arriving energy, depending on the admittance ratio between the bow and string [xxi].

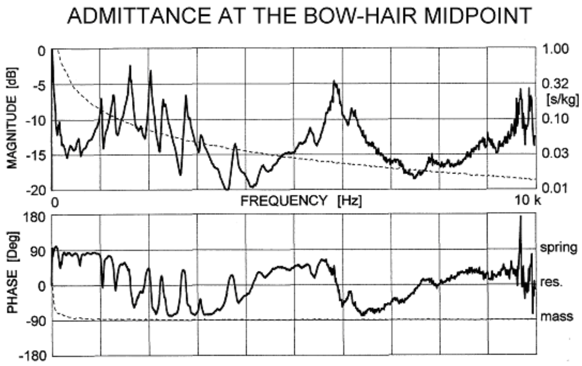


Figure 9 (above):
Input admittance in the longitudinal direction of the bow hair of a student's bow (unsigned) at the midpoint. The dashed line gives the admittance of the freely suspended accelerometer. The bold line gives the compensated bow-hair admittance. (From Askenfelt 1995.) For comparison: the value for the transversal characteristic point admittance for a violin G-string, $1/2Z_0 \approx 1.7$ s/kg, and the longitudinal point impulse admittance of the hair: $1/2Z_{HL} \approx 0.03$ s/kg.

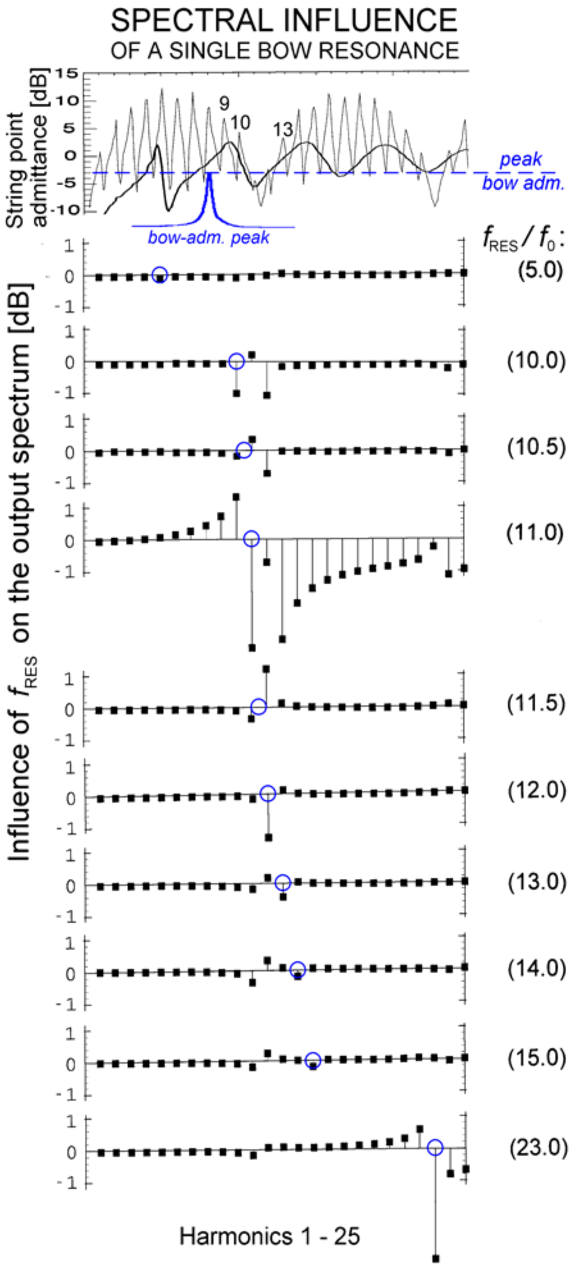


Figure 10 (right):
Simulated influence of a bow resonance on the output bridge spectrum. The upper graph shows transversal (thin line) and torsional (bold line) point admittances for a string with characteristic wave resistances of 370 and 975 g/s, respectively. The fractional bowing point (β) is equal to 0.087 = 1/11.5. The horizontal dashed line shows the peak level of the bow's admittance at its resonance frequency f_{RES}. Below, the difference between the output spectrum of a string bowed with a resonant and a nonresonant bow is shown for 10 different f_{RES}. The relative frequency f_{RES}/f_0 is marked with a circle in each plot. Notice that when f_{RES} exactly matches the frequency of a string harmonic, this harmonic will be lowered in the bridge output spectrum. All simulations were run with the same bow velocity and bow force. The durations of the resulting stick-slip intervals turned out to be identical in all simulations.

Askenfelt [1] has measured bow-hair admittance peaks in the region 0.3 - 1 s/kg. A typical example of the longitudinal bow-hair admittance at the hair's midpoint is shown in Figure 9. To investigate whether the effect of such peaks would be observable in the output spectrum or not, a series of computer simulations was run, where a "heavy gauge" violin G-string (196 Hz) was excited by a bow with a single resonance frequency, f_{RES} [xxii]. The bow was given (through convolution) an admittance peak of 0.5 s/kg (-3 dB), Q-values equal to $f_{RES}/52$, and a minimum admittance of 0.04 s/kg (-14 dB). The fractional bowing point was set to $\beta = 0.087 = 1/11.5$. Spectra of ten bows with different resonance frequencies, as compared to the spectrum of a nonresonant bow, are shown in Figure 10.

The simulations show that for $f_{RES}/f_0 = 5.0$, 13.0, 14.0 and 15.0, the influence is hardly observable, the admittance of the bow being small compared to the point admittances of the string at f_{RES}. However, when f_{RES} is close to a "node frequency", the impedances are better matched, and significant spectral changes are observable. In the present example this occurs when $f_{RES}/f_0 = 11.0$ and 23.0. In practice, some of the most dominant bow-hair resonances are functions of the string's position on the hair ribbon, and thus constantly changing during the stroke. The comforting fact that these sweeps are inaudible to the listener, is in itself an indicator of the marginal transmission to be expected between the longitudinal deflections of the bow-hair velocity and the sound pressure output.

10 CODA

Bowed-string playing comprises a great variety of bowing styles, all of which put specific demands on the qualities of the bow. In order to refine the complex information when searching for the qualities of the exquisite bow design, analyses of its physical properties should reflect a thorough knowledge on how the bow is being manipulated when working at its best. Much of the bow research has focused on resonances of the free bow, with and without hair tension. Of equal importance are the recent analyses of the contact mechanics between the bow and the string. When building the bridge between the bow and the sound output of the instrument, more information on the dynamics in the z-plane, i. e., modulation of the bow force, seems necessary. The activity of the bow in this plane is always a major concern of the player in the search for the excellent bow.

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