Onset-transient times

In any acoustical instrument the tone needs a certain time to develop fully. Even if we feed the instrument with a switched-on electronically-made signal of constant amplitude, a certain time will elapse before the instrument responds with the full amplitude. A particularly slow response occurs if the frequency of the input signal is the same as a “very good” resonance (i.e., with low damping) in the instrument. Then the tone-buildup time will be particularly long. For the less responding frequencies (with greater damping) the response time will be considerably shorter. This sounds rather backwards, doesn’t it? The good thing though, is that the amplitudes of the low-damped resonances will be much greater than those of the faster-responding ditto.

The reason behind, is that every resonance will continue building up until the supplied energy equals the losses of the resonating medium. For a lossy medium, this happens fast, and vice versa. In Fig. 1, which shows buildup time (upper panel) and relative radiation (reaching the player’s ear; lower panel) of two violins, we can for the violin plotted with the dark lines easily see the connection between transient duration and body resonances. For the violin plotted with light lines, the picture is not quite that simple, for a good reason: While the response of the first violin (a Francesco Ruggeri) was recorded in an almost anechoic room, the second one (an Antonio Stradivari) was recorded in a normal room, hence the longer response times, particularly visible above 1000 Hz, due to inclusion of the sound buildup of the room itself. For the Stradivarius, the response of the *room* has for a good part been measured in this frequency range. (For some details on radiation measuring techniques, see Appendix B.)

Notice also that generally, the transient time is related to the duration of a nominal period (i.e., the inverse of frequency), meaning that lower frequencies get longer transients, as a rule. This is particularly visible below 1000 Hz for the violin with the dark green/red curves. It has the consequence that low-pitched instruments (e.g., cello and double bass) by nature have longer onset transients than their high-pitch relatives (making them sound late if no special precautions are observed). It also has the consequence for cello and double bass that if they are played on an undamped stage floor with pronounced resonances, their sound buildup of these particular frequencies might appear significantly delayed in the audience.

But now, back to the violins: Fig. 1 represents the response of a series of sine waves, 0.5 Hz apart (for details see Appendix A). In practical life it might be more interesting to see how the instruments (Ruggeri, dark colors—Stradivari light colors) are responding to tones composed of a fundamental and a series of fading partials, like we have in the saw-tooth waves acting on bridges of bowed instruments (where partials are fading out ca –6 dB/octave).

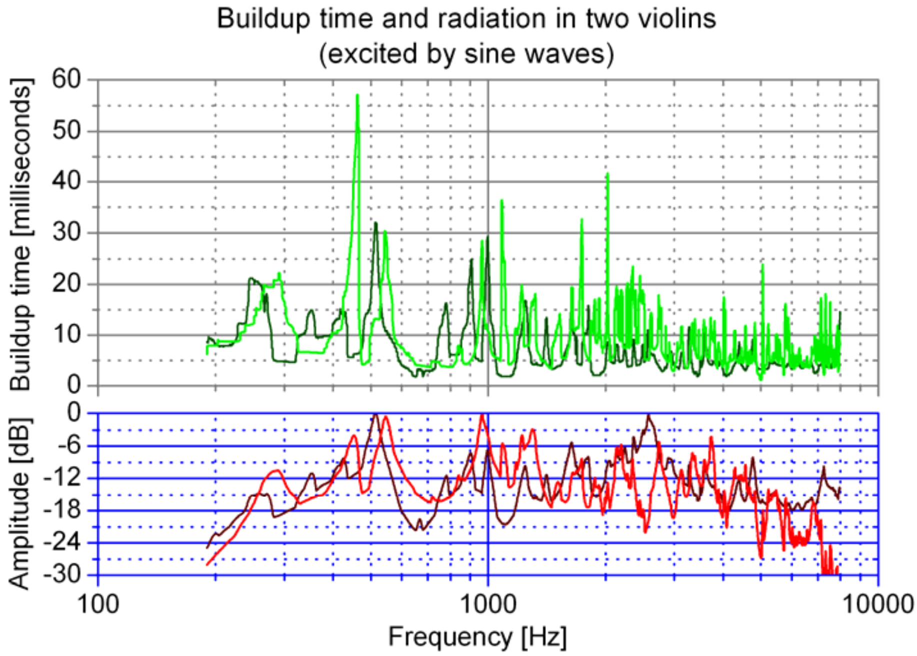

Figure 1: Buildup time compared to radiation (sound pressure) of two violins: dark colors for a Francesco Ruggeri; light colors for an Antonio Stradivari. Notice how the long-lasting transients correspond with major resonances of the violin body. The longer buildup time above 1000 Hz for the Stradivarius is mainly due to the measuring technique (see text).

Fig. 2 shows an analysis of just that, based on the chromatic scale. On the Francesco violin (dark lines), the C_4 and C_5 (with fundamentals 262 and 523 Hz, respectively) appear to be the tones with the longest buildup duration (both about 23 milliseconds), corresponding to major radiation maxima in the lower panel. Similar features can be seen for the Stradivarius, but for slightly higher frequencies. Notice also that in the radiation amplitude panel, the highest level is set to 0 dB for each instrument individually. They can hence not be compared with regard to absolute levels.

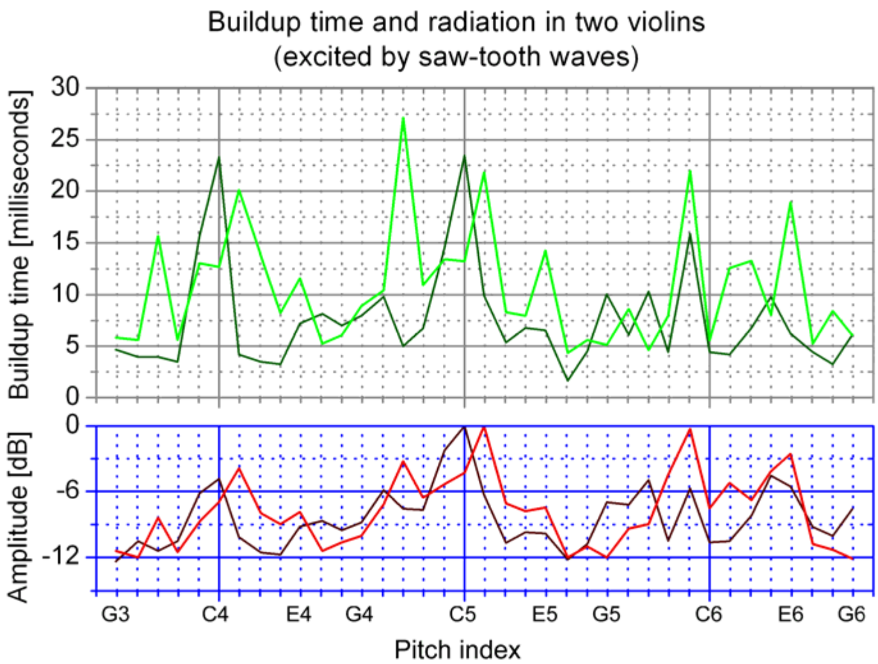

Figure 2: Buildup time compared to radiation of a violin when the input signal is a saw-tooth wave, as comparable to loud playing. Notice that the radiation amplitude is more even now than it was with the pure sine-wave input signal. Also: buildup-time is somewhat shorter in the low-frequency end. Only tones of the chromatic scale were recorded.

When comparing Fig. 1 to Fig. 2, notice that while fundamentals have long buildup durations in Fig. 1, we experience in Fig. 2 a significant shortening when the higher partials are added and the *total energy buildup* is considered. Furthermore, the higher and more quickly responding partials are for a good part masking the onset of the fundamental, making its attack sound more direct. (This is comparable to a technique often applied by organ players, who try to avoid letting large and slowly responding pipes sound alone in the lower register. Octaves as well as octaves of the fifth are often added in the registry to give the impression of a faster attack.) As is clear from the Figs. 1 and 2, when the signal consists of complex tones (i.e., tones with overtones) the amplitude-response curve is also considerably smoother, because the signal is averaged over a large number of resonances and antiresonances.

In sum, the response of a violin is quite fast. Melka (Ref.1) reported that no buildup was longer than 4 milliseconds in pizzicato (where the input signal is rapidly decaying), regardless of pitch. The longest violin onset transients were found when pianissimo was played arco on low strings, where buildups more than a quarter of a second were quite common.

Bowed attacks

However, so far my analyses have only focused on the instrument body's potential for transferring a switched-on signal. In real life a pizzicato is the closest we get to this situation, although in such cases the string's amplitude decays so quickly that we can't really compare it to arco. My own PhD work was mainly focused on bowed-string attacks, their requirements and limitations. One interesting finding was that in order to make a clean start "from the string", with a given bow pressure, a certain bow *acceleration* is required. (One cannot start the tone directly with full bow speed without getting some initial "surface sound".) This acceleration, or rather range of accelerations, is directly related to the *mass of the active string*, being inversely proportional to it. So, there is a limit to how fast you can develop a tone for a given dynamic level. And: the lower the pitch, the slower the buildup. Within reasonable limits, and with the other parameters kept unchanged, you have:

> Maximum acceleration is nearly proportional to
>
> Bow pressure × Frequency/The string's characteristic wave resistance.

(Characteristic wave resistance is described in "Terminology", and practical values are given in "Unpublished : String properties.) An even acceleration implies that the amplitude of the string increases at a steady state, like a ramp. When so, the violin body has to respond, not to a switched-on signal, but to the ramp-like buildup of the string amplitudes. It goes without saying that the total transient time cannot be shorter than this string buildup. Finding out exactly what the duration of the combined transients will be requires quite complex calculations, but if the string buildup is the slowest of the two (which is normally is), the body response does not add significantly to the transient duration.

If you look Fig. 3, which is copied from Fig. 7 of "On the Creation of the Helmholtz Motion in Bowed Strings" (Guettler, 2002 – in the Publication list), with a few pink, and a bright red line added, you will see that clean attacks result from a optimal combination of bow force (i.e., "bow pressure") and bow acceleration (light wedge). The pink lines are added for easy determination of corresponding values at the abscissa and the Y-axis (ordinate). The red line is indicating the maximum bow acceleration that would produce an attack with little or no noise for this particular string-rosin combination. Notice that the "permitted" acceleration is nearly proportional to the bow pressure. The string simulated is a heavy-gauge violin G-string. (Examples of resulting attack sounds can be found at **Videos/Sounds : Sound examples of attacks from creaky to loose/slipping**.)

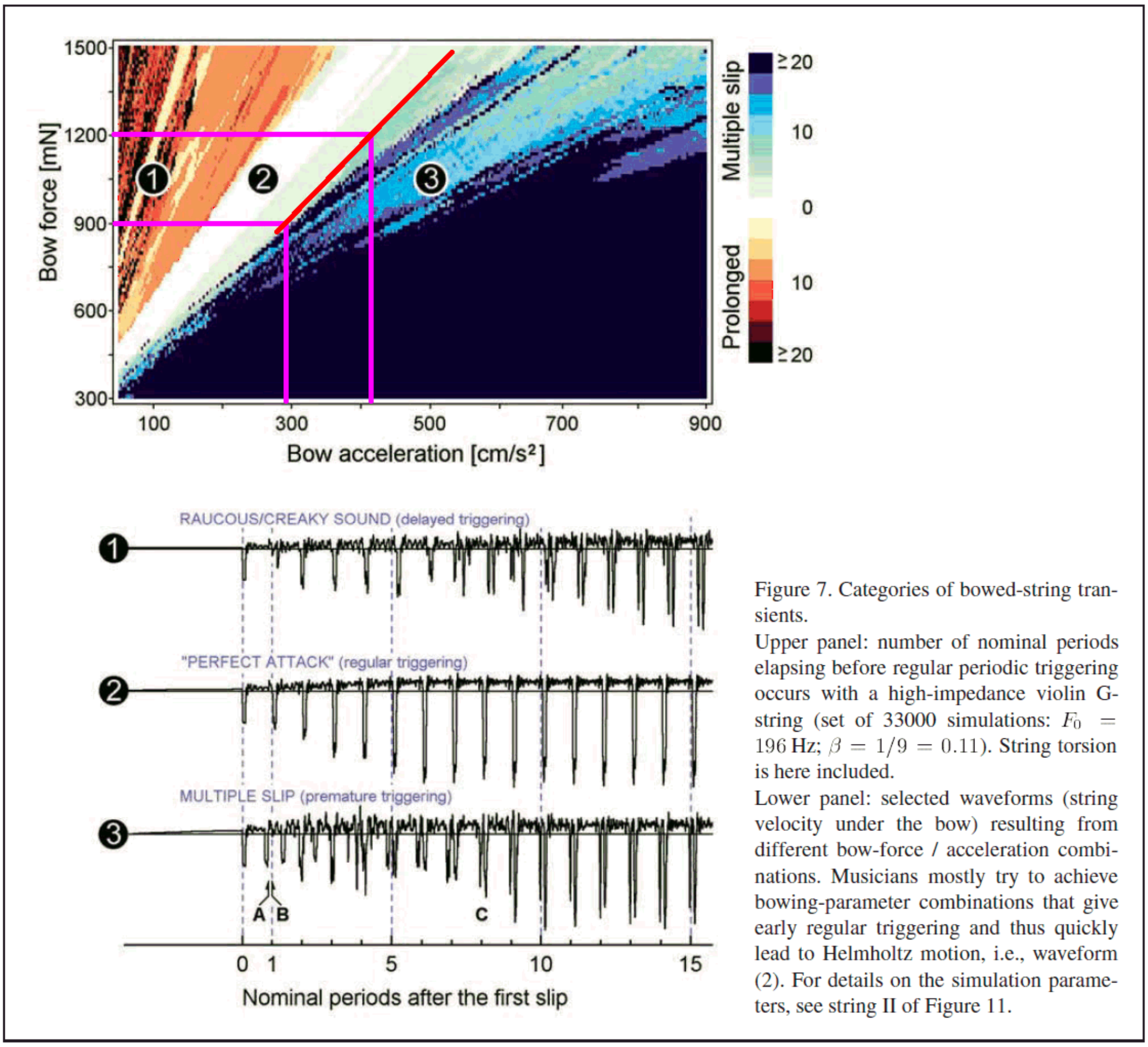

Figure 3: Simulated attacks resulting from a number of bow force (pressure)-acceleration combinations. The clean onsets are found in the light wedge. Orange colors indicate creaky/raucous attacks, while blue indicates scratchy/slipping attacks (from Ref. 2). The red line, following the right side of the wedge, indicates that acceleration producing clean attacks rises nearly proportionally to the bow pressure.

Say, you want to play a note with a bow speed of 20 cm per second. With bow forces of 600 and 900 mN (approx. 60 and 90 gram force), maximum accelerations are 290 and 415 cm/s^2, respectively, according to Fig. 3. This implies corresponding buildup durations of 69 and 48 milliseconds for the string alone, counting from 0% to 100% amplitude, or 55 and 38 milliseconds counting in the conventional way: from 10% to 90% amplitude, as was done in the other examples. (With this custom one avoids the uncertainty caused by background noise and minor fluctuations in the final amplitudes.) To give you an idea what this would sound like, play "**Transient examples"** from the Unpublished page. Here, a series of saw-tooth signals with different onset-transient lengths are played (buildup durations, 0% to 100% amplitude, are prompted). Later you can play "**Ricci"**, which is a tiny (one-tone) excerpt from a performance with Ruggiero Ricci as soloist. His transient time (10-90%) for the A_3 on the G-string is 18 ms, including the response of the violin! Although the tone is a whole step higher than the simulated G_3 of Fig. 3 (and accelerations thus can be increased some 12%), it is pretty obvious that Ricci must have been using greater bow force than has been part of the discussion so far. Higher bow force permits higher acceleration in general. The original sound example here is repeated three times, then three times with the noise removed, and finally three times the noise alone. These sound examples demonstrate that Ricci makes a very clean attack; the intensity is not at all lost when the noise is removed…

When playing the "**Transient examples"**, notice that 50 milliseconds already sounds pretty direct, and from 25 ms the attacks start sounding more and more percussive. Even spiccato/sautillé has a short buildup before the decay, and if well played, the force-acceleration combination will always lie within the light wedge of the relevant diagram. The response time of the instrument itself might be more crucial for the feeling of the player than the actual buildup time perceived by the listener, at least in the violin.

When we move the bow closer to the bridge, the light wedge will become narrower and steeper, implying that the acceleration needs to be reduced, and/or the bow pressure increased (see Fig. 4).

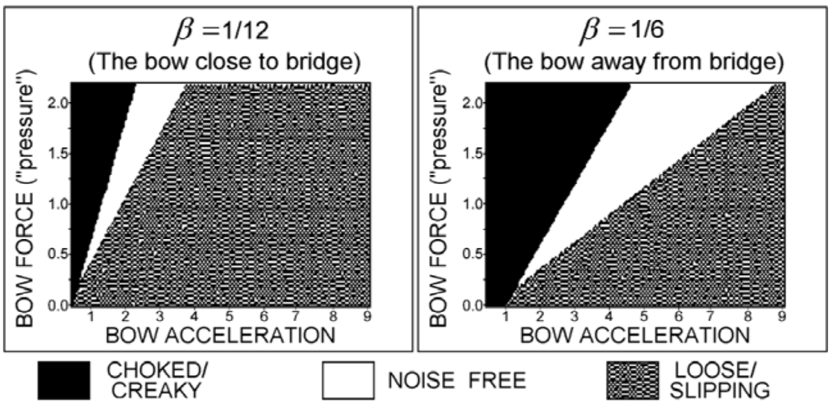

Figure 4: The "clean-attack"/"noise-free" delta gets smaller as the bow is moved towards the bridge. Greater bowing precision is needed to control the attack near the bridge, where the acceleration must be kept steady and low.

We know that when moving the bow closer to the bridge, we can also reduce the final bow speed, so maybe it won't matter that acceleration must be lower? Let us first have a look at Fig. 5, bearing in mind that β expresses the relative bowing position (i.e., ratio of the bow's distance from the bridge β divided by the length of the active string). The relative amplitude is at all times $1 - (1 - 2\beta)^2$, which is the same parabola as the trajectory of the Helmholtz corner.

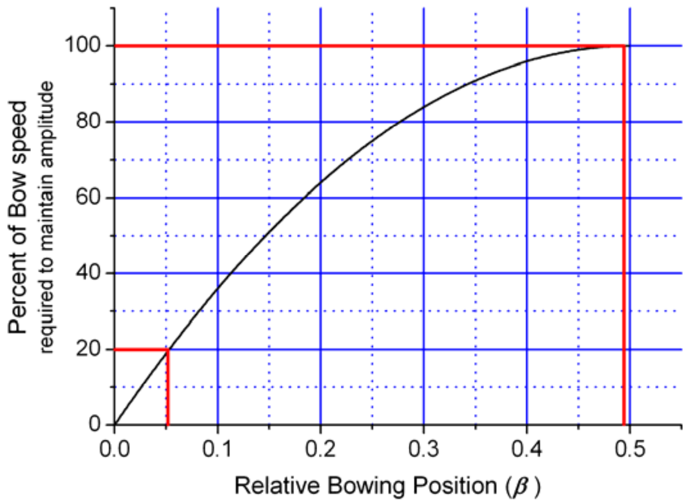

Figure 5: Relation between string amplitude and required bow speed at different relative bowing positions. The relative bowing position β expresses the ratio of the bow's distance from the bridge divided by the active string length. As the bowing position approaches the bridge, the bow speed can be reduced, while still maintaining full amplitude at the string's relative midpoint. E.g., when the bow is positioned with a β of 0.05, the bow speed can be reduced to only 20% of the speed required in the vicinity of the string's midpoint ($\beta \approx 0.5$). (Bowing the string exactly at its midpoint will not result in Helmholtz motion.)

Unfortunately, moving the bow closer to the bridge will not be very helpful as far as quickly reaching the wanted amplitude is concerned. The maximum permitted acceleration falls more rapidly with a decreasing β than does the curve in Fig. 5. However, as the bow is moved towards the bridge, an increase of bow pressure is natural, and will open for greater acceleration again. There is obviously a trade off here. Increasing the bow pressure also provides more brilliant sound, which by itself will be *perceived* as a quicker transient, whether this is a physical reality or not.

The fact that the natural transients of large, low-pitched instruments have longer durations than those of their higher-pitched family members, and that bowed strings in general have longer transients than most winds, should be alerting string players when trying to match their faster-speaking counterparts. One gets a quite good idea of at what time the acceleration expires, and the tone is fully developed, just by watching one's own right-hand wrist: in most cases acceleration does not expire until the angle of the flexing wrist takes a neutral position and follows the arm completely. That instant defines the "body of the attack", i.e., the tone reaching full sound. When playing alone or as soloist with a piano, the very stroke onset may be perceived as the start of the tone, but when the onset is masked by some more quickly responding instruments (like in the example of Fig. 6, below), the end of the bow-acceleration phase defines the rhythm to a large degree.

Figure 6: The opening of Brahms' first symphony. The attacks of the low, repeated quavers of the double basses are largely masked by the timpani and the contra bassoon. However, in the sound example derived from a recording of one of the major European symphony orchestras, the bassists continue to accelerate their bows much longer, with the result that the bass group leaves the impression of lagging one semiquaver behind.

I have chosen a sound example from the opening of Brahms first symphony (played by one of my favorite European orchestras, with a well-known conductor), where the double basses this time sound late, probably because they want to produce as much sound as possible. In the score you see that the bass part has repeating quavers noted C_3, but sounding C_2 on the double bass. Besides that, the bass group adds the octave below, C_1, which has become a tradition after it was discovered that Brahms added the low octave in his four-handed piano edition of the same symphony. In the first sound example, "**Brahms A"**, I have lifted the 30-to-65 Hz frequency band to emphasize the basses, and make the delay effect more audible. In the second example, **"Brahms B"** (the original recording, presented for decency), I think it is still quite obvious what is happening. Rightly, the bass part is marked *pesante* ("heavy", "ponderous"), but I sincerely doubt that Brahms wanted the basses to appear *after* the timpani.

Soft tones with short buildup times

The above discussion on bow force and -acceleration may leave the impression that it is impossible to produce tones in pianissimo with attacks of short duration. This is not true. All you have to do is to start the tones with relatively high bow force (ready on the string *before* its first release), and quickly reduce the bow force while the string is increasing its Helmholtz amplitude. (I.e., high acceleration initially, and lower acceleration as the desired string amplitude is approaching.) In this way accents can be avoided while maintaining very direct onsets. This technique is easiest to perform a little distance away from the frog, where quick changes of bow force can be manipulated with greater ease. Double bassists should learn to master this technique on their lower strings, particularly for playing short (pizzicato-like) notes in piano or pianissimo, as often seen in the classical repertoire. The degree of success is obviously closely related to the timing between bow force and –speed, and takes some practicing to get right.

Pizzicato attacks

One shouldn't think that a discussion on pizzicato attacks could be of much use. But, I hope the sound examples here will make you think otherwise. In the symphonic repertoire there are many places where getting a bass group together on a pizzicato note represents a problem. Mahler's Adagietto of his fifth symphony is one typical example. I have included a recording of the opening bars, brilliantly played by the Chicago Symphony Orchestra, conducted by Daniel Barenboim. Here, the very difficult timing of the double basses' pizzicati is executed with quite impressing precision ("**Pizz Adagietto**").

One trick when playing this movement is to have the whole bass group watch the right arm of the (1st violin) concertmaster, and let her/his bow changes determine the exact time points for pizz execution. But, even more importantly, all bassists should be sure to pluck the string far from the edge of the fingerboard—closer to the middle of the active string. This will make the tone buildup somewhat slower, and with fewer overtones, giving the individual pizzicati much better chances of blending in. The players could amplify this effect by using several fingers for the pizz, shaping the string more rounded at the point of excitation. In the sound example "**Imprecise Pizzicati"**, you will hear a simulation of a bass group in a concert hall playing two different attacks with exactly the same (im-) precision: The attacks (based on recording of one double bass, repeated) are randomly distributed over 250 milliseconds (1/4 of a second). The first pizz is executed close to the middle of the string (but not *at* the midpoint, as this would create a hollow sound); the second one at the end of the fingerboard, more like a jazz pizz. Despite the fact that the timing is identical in both examples, there is little doubt as to which pizz would suit Mahler's fifth the best. For Stravinsky, where the timing is usually less of a problem, and some percussiveness might be appreciated, the second kind would probably quite often be the more appropriate one.

References

Ref. 1: A. Melka, "Klangeinsatz bei Musikinstrumenten" Acustica **23**, 108-117 (1970). See "Library".

Ref. 2: K. Guettler, "On the creation of the Helmholtz motion in the bowed string" Acta Acustica united with Acustica **Vol. 88**, 970-985 (2002).

Appendix A (for the technically minded)

The analyses of Figs. 1 and 2 were performed in the following way: Two impulse-response transfer functions (one for each violin) were calculated from two separate two-channel recordings, where one channel contains the impulsive force signal from a force hammer exciting the violin's bridge, while the other channel contains the resulting sound pressure, recorded with a microphone close to the instrument body (some of the differences in spectral curves between the Ruggerius and the Stradivarius, might be ascribed to different microphone positions as well as the fact that room conditions were very different). In order to obtain a transfer function, one principally divides the spectrum of the microphone signal by the spectrum of the force signal. In order to estimate the different buildup durations, the resulting transfer functions were then convolved with different types of input signals; in the present case: pure sine waves 0.5 Hz apart, and saw-tooth waves a semitone apart. This technique is also utilized in most of the simulated violin-sound examples of the page "Videos/Sounds".

Rise time. Normally, one describes the time interval from 10% to 90% amplitude as the "rise time" or "buildup time". The reason why this particular amplitude-value interval is utilized rather than 0% to 100%, is to avoid background noise triggering a low level start, and ambiguities concerning the max level leaving uncertainty about exactly when the full amplitude was reached. However, when exciting the system with single sine waves, one easily runs into problems, as amplitude will not rise smoothly for some frequencies in the vicinity of strong system resonances. The solution used here for switched-on signals, was to estimate the 10-90% amplitude interval on basis of the shorter 10-50% interval—as well as the true 10-90% amplitude interval—and then select the smaller of the two values. This first estimate was carried out in the following way:

If we set $y = 1 - \exp(-t)$, we can compute the time values t_{10}, t_{50}, and t_{90} from $y = 0.1$, $y = 0.5$, and $y = 0.9$, respectively. We then find that $(t_{90} - t_{10})/ (t_{50} - t_{10}) \approx 3.74$, which means that we *for switched-on signals* (only) can approximate the 10-to-90% buildup duration on basis of the often more reliable 10-to-50% ditto.

Appendix B (on techniques for measuring instrument radiation)

I do by no means claim to be a specialist in measuring radiation of bowed instruments, but I have been participating in such events on a number of occasions, and with different techniques employed. In general, there are two sets of measuring methods: one approximate that measures the *mobility of the instrument's bridge*, and one more accurate that by use of microphone either tries to catch *the radiation of the instrument from different angles around it*, or with the microphone inside the instrument, in which case you only get an approximation of the radiation up to, say, 700 Hz. However, there are challenges connected with all of the above techniques.

Measuring bridge mobility

Over a large frequency range *the bridge mobility* is a fair predictor of a string instrument's radiation. However, it fails to indicate with correct magnitude the radiation of air modes like the Helmholtz mode (often termed A_0—in the vicinity of 270 Hz for the violin, and 230, 120, and 65 for the viola, cello and double bass respectively). In the Helmholtz mode, the inside air is acting like a spring while the air around the *f*-holes acts like a mass; the air is thus itself resonating more than the wood under the bridge. It also fails to indicate with correct magnitude the radiation of wood modes that are moving the bridge vertically, like for instant some important and well radiating modes around 4000 Hz (now referred to as VH, or Vertical Hill, as opposed to the Bridge Hill, BH, which lies some 1.5 to 2 kilo Hz below). However, these lower air modes may well be picked up by an inside microphone during the bridge mobility test, thus filling in some missing spots on the map. This being said, one has to remember that some lateral action of the bridge is a prerequisite for these modes to be excited in the first place, so some sideways action will always be visible. It might also be a good idea to measure the impulse response in the vertical direction to get a more complete picture.

In order to estimate the bridge mobility you have to excite the bridge with a known signal, and measure its resulting movement. The input signal could either be an impact from a force hammer (a device with electrical sensors that indicate the applied force as function of time); a sine sweep (driving the bridge though a certain frequency range by means of a shaker or a combination of coil and magnet); or MLS ("Maximum Length Sequences", a quasi-random signal consisting of pulses of equal amplitude, but varying widths—excited as above). The resulting response of the bridge of the bridge can then be recorded by means of an accelerometer or an optical device (e.g., with laser interferometry). The advantage of the optical method is that it does not load the bridge with any weight like the accelerometer does (a good, lightweight accelerometer weighs some 0.5 grams, causing the bridge resonances to move ever so slightly downwards). If driving the bridge with the combination of a tiny magnet (fixed to the bridge) and a coil (fixed externally, ca 1.5 mm away from the magnet), the laser beam can be pointed at the magnet through the opening of the coil, ensuring identical positions of excitation and response measurements. When utilizing impact hammer and accelerometers, one should preferably avoid hitting the fragile casing of the latter with the hammer, so it is quite common practice to fasten the accelerometer on the treble side of the bridge, and hit the bridge on the bass side.

After having done such a two-channel measurement, some calculation is required to achieve the true impulse response of the bridge. First, whatever dimension the bridge motion is recorded in, it needs to be recalculated to *velocity* (e.g., the accelerometer signal must be "integrated"). Then, because the excitation is never a true impulse (of a certain energy over an infinitesimally short period of time), the velocity signal has to be *deconvolved* by the input signal. This is simply done by dividing the frequency spectrum of the output signal by the frequency spectrum of the input signal, a quite trivial procedure in some programs, like Matlab and others. Then one gets the true response to an impulsive excitation where all the energy is equally distributed over the entire frequency range. At least in theory. In practice you'll need to excite the bridge a number of times (with impact hammer, typically 10 to 12 times—with other methods typically 2 to 3) and subsequently average the energy, in order achieve a reliable result.

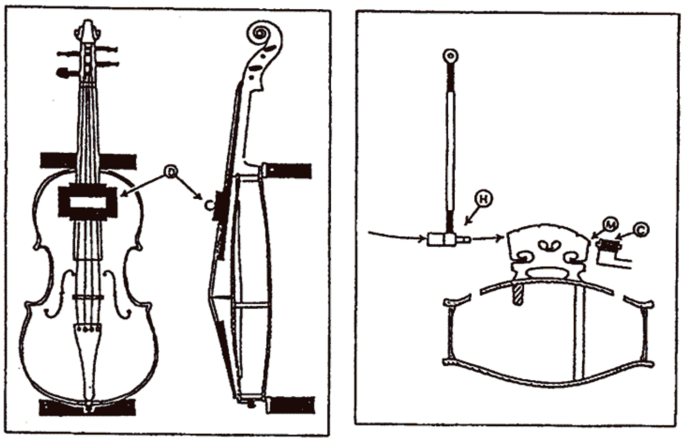

Figure 7.5. Measuring the acosutical properties, bridge vibration sensitivity of a violin by means of impulse excitation (D string damping, H impulse hammer, M magnet, and C electrical coil).

Figure 7: (Fig. 7.5 from Erik Jansson: "Acoustics for violin and guitar makers", see Ref. 3, below) Setup for measurement of bridge mobility by use of impact hammer, small magnet (less than 0.03 grams), and a coil. By this method you avoid most of the problems with wall/ceiling reflections, at the cost of inadequate estimation of air modes and modes where the bridge is moving vertically.

Figure 7 shows the setup used by Erik Jansson for measuring bridge mobility. It is common practice to dampen the strings by soft foam rubber, although some researchers prefer to let the open strings ring, as they often do in real playing.

Measuring radiation with microphone(s)

There are two major obstacles when measuring radiation with microphones: (1) reflections from the walls/floor/ceiling of the room in which the measurements are done; (2) directivity of the radiation from the instrument.

Room reflections can ideally only be adequately dealt with by performing the measurements outdoors, or in an anechoic chamber. The problem arises because disturbing reflections in most cases arrive within a few milliseconds back to the instrument and the near-field microphone. E.g., with walls/ceiling 3 meters away from the instrument on all sides (and carpet on the floor), the reflected signal will hit the instrument after 18 milliseconds only, mixing in with the decay of some of the major resonances of the instrument itself. In order to get the best possible estimate of Q-values, it therefore pays to place the microphone close to the instrument, so that the difference in loudness between the instrument's signal and the reflections becomes as great as possible. The sound pressure diminishes –6 dB every time the distance from the source is doubled. (However, as far as Q-values are concerned, the bridge-mobility method is superior.) A large room would of course have been delaying the return of the reflected signal, but usually large rooms have quite long reverberation times, which mess up the analyses quite a bit. If using a moderately sized room, one should preferably pick a room with book shelves or a lot of cupboards where the doors can be opened. Soft chairs and sofas are good absorbents too.

The Joseph Curtin Rig (Ref. B1), shown in Fig. 8, facilitates controlled measurements of radiation in the so-called "axial plane" (see Fig. 10), i.e., the plane in which the bridge is orientated. The violin is rotated in small steps in order to catch radiation at a number of angles. Indoors, the distance between the microphone and the center of the instrument is typically 20 cm (7.9 inches). Outside, where reflections for a good part are avoided, the distance can be increased somewhat, but the number of angle steps should then be increased proportionally.

Figure 8: Measurement of a violin's radiation by use of the Joseph Curtin rig. In order to avoid wall and ceiling reflections the measurements were performed outside. In the picture, Colin Gough is mounting an additional inside microphone for comparison to the ordinary outside microphone (visible just above his right hand). The rig permits the violin to be rotated horizontally in small steps, while the outside microphone maintains its position. The impact hammer is activated by use of a long camera-trigger cord.

In fact, apart from the lowest modes (the "breathing modes", where the instrument exhibits a significant net expansion/contraction), most modes will be "dipole" or "multipole", meaning that some part(s) of the instrument will be *pushing* on the external air (creating higher local air pressure), while other part(s) of the instrument will be sucking external air in (crating lower local air pressure). Fig. 9 gives an example of what can be happening: While the left side of the box is creating increased air pressure on its outside, the situation is opposite on the right side. This will of course imply a certain degree of cancellation, dependent on the wavelength of the frequency in question, and the distance between the counteractive instrument parts (see video examples in Ref. B2). However, this effect is most noticeable in the so-called "near field" of the instrument (but *if you place the microphone two wavelengths away from the instrument or more, you'll for a good part be avoiding this field*). E.g., in the near field between instrument parts moving in opposite directions, there will be certain points where no radiation of that particular frequency can be measured, while in the far field there will be a measurable radiation proportional to the *net pulsation* of the instrument. The lateral position of the microphone thus becomes less critical.

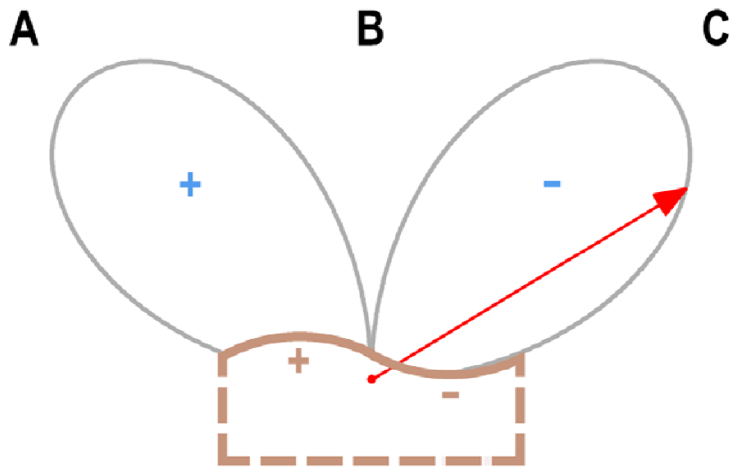

Figure 9: Example of multipole sound-pressure in the near field. While the left side of the box is creating *increased* air pressure on its outside, the situation is opposite on the right side where air is sucked in. The red arrow is indicating the relative pressure magnitude at the different angles. Notice that while microphone positions **A** and **C** both will record maximum sound pressure at that distance, position **B** will record no sound for this particular frequency.

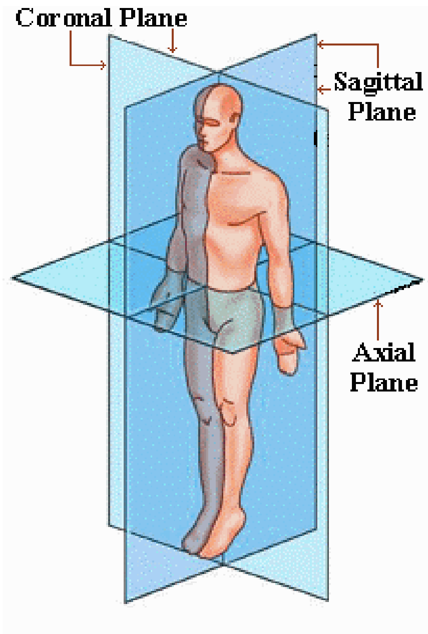

Figure 10: The planes with respect to the human body. (Ref. Spine Universe)

If we estimate modes with frequencies below 650 Hz to have a relatively good net pulsation, we can recommend a microphone distance of minimum 105 cm from the center of the violin (i.e., 2 × 340 m/s divided by 650 Hz = 1.05 m); 340 m/s being the speed of sound in air. In practice, unfortunately, such a distance is only functional in anechoic or very "dead" rooms.

As you can see, there are lots of considerations to balance when you want to measure the radiation of bowed instruments. So far we have only been discussing measurements in the axial plane. A real instrument will, of course, radiate in all planes, so for a more exact measurement of the total radiation, we shall be needing even more microphone positions. Fig. 11 shows such an arrangement: An array of microphones is fastened to a semicircle with a radius great enough to stay clear of the near-field problems. There is no specific demand on distance between the individual microphones, but it still might be a good idea to place them with intervals less than half a wavelength of the highest frequency you want to measure with separation between modes; particularly if you are exciting the instrument with a continuous sound, rather than hammer blows.

Exciting the instrument by loudspeakers

There is one more way of performing radiation measurements that we have not mentioned: Due to the "law of reciprocity", you may well change microphones with loudspeakers, and measure the resulting movement of the bridge, i.e., utilizing the reversed sound path. Sometimes this might be handier, which was the case when Weinreich made his report on "Directional tone color" (Ref. B3), where he also used a gramophone pickup for recording the movements of the bridge.

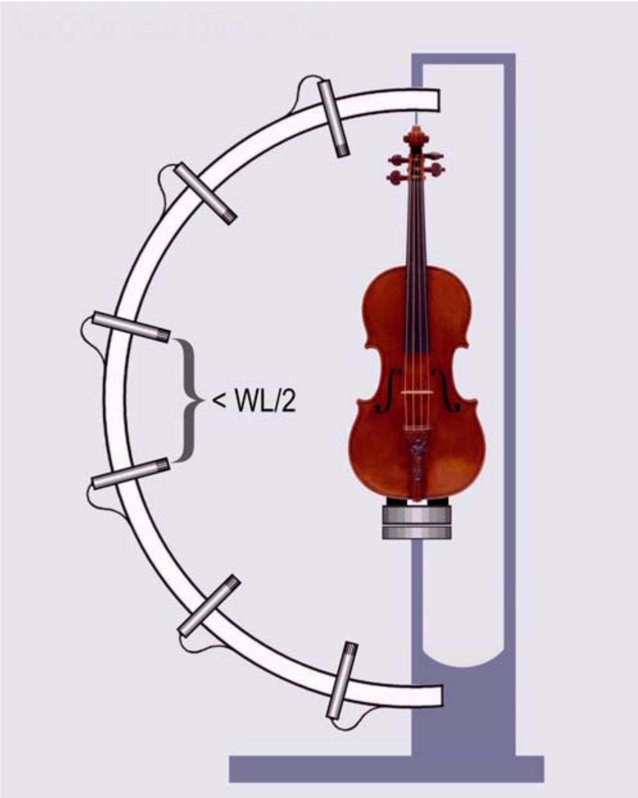

Figure 11: Setup for radiation measurement in an anechoic room. By placing a microphone array in a semicircle, the radiation of an instrument (rotated in steps) can be estimated at all angles. The distance between individual microphones should preferably be less than half the wavelength of the highest frequency where separation of individual modes is desired.

Which technique should be applied?

The technique should always reflect the purpose of the measurements. If you want to compare two instruments with respect to radiation of all relevant frequency ranges (i.e., get the most complete picture of its sound), the microphone setup described in Fig. 11 is undoubtedly the best, but with the most demanding setup, by far. If the purpose is to get an overview in terms of the body structure (i.e., details that might be changed by a violin maker), a measurement of the bridge mobility may be sufficient. E.g., if the important *bridge hill* (frequencies in the vicinity of 2500 Hz) has a weak response, the cause might be that the "island" between the *f*-holes is carved too thin. The Joseph Curtin Rig applied inside an acoustically active room gives a fair estimate of the instrument's response during practical conditions, but is less reliable when it comes to estimates of Q-values and response times of the instrument itself (compare the two violins of Fig. 1, where the J.C. rig was utilized for the Stradivarius, and its response times in the high-frequency range appear to be strongly related to the room, in which the measurements were done). It should also be noted that inside a room with reflecting surfaces, the microphone position is somewhat less critical (an array is not necessary), because most frequencies will bounce back from all sides. The exception is standing waves creating nodes or dead spots. In an anechoic room this problem is eliminated, as there will be no standing waves.

References

B1: http://www.josephcurtinstudios.com/READmeasurerig.htm

B2: This effect is very visible in Terry Borman's animations of Guarneri and Stradivari violins. Visit http://www.bormanviolins.com/animations.asp and click on the frequencies you want to see.

B3: G. Weinreich, "Directional Tone Color" J. Acoust. Soc. Am. **101**(4), 2338-2346 (1997) (see Library).