8

Stringed Instruments Played with a Bow

8.1 ACOUSTICAL PRINCIPLES

There is an interesting paradox in the operation of a bowed stringed instrument. To produce a sustained sound, the player places the resined hair of the bow against the string and pulls it steadily across the string in one direction. Yet we know that the sound produced corresponds not to a movement in one direction, but rather to a rapid oscillation. Moving the bow smoothly across the open A string of a violin, for example, results in a listener's eardrum being pushed in and pulled out 440 times a second.

We found the same paradox in the behaviour of wind instruments: the player blows a stream of air through the instrument as smoothly as possible to create a steady note, but the note is in fact a rapid fluctuation in the rate of air flow.

In each case, the heart of the instrument contains a mechanism for converting a steady one-directional motion into a controlled oscillation. For wind instruments the mechanism takes various forms: the air jet of the flute, the cane reed of the clarinet or oboe, the lips of the trumpeter. For the bowed strings, the secret lies in the periodic sticking and slipping of the bow hair as it presses against the string.

In Chapter 2 it was explained that, under normal bowing conditions, the stick-slip cycle is synchronized with the fundamental mode of the string, so that the energy imparted by the bow helps to build up a strong periodic vibration of the string. We will return shortly to consider what is meant by 'normal bowing conditions'. It is worth pausing briefly, however, to note an important distinction between the ways in which wind and stringed instruments radiate sound.

The tube of a wind instrument has only one important acoustical function, which is to confine and shape the vibrating air column. When the instrument is played, musically useful sound energy is stored in the standing waves of the air column. This energy is radiated directly into the surrounding atmosphere through the openings in the tube. The strong pressure vibrations in the air column force the walls of the tube to vibrate in sympathy, but in a well-designed instrument these wall vibrations are too small to contribute significantly to the radiated sound.

The musical energy store in a stringed instrument is the vibrating string. Unlike the vibrating air column of the wind instrument, however, the string is very inefficient at communicating its energy directly to the surrounding air. Even if a violin string were bowed with maximum strength by a virtuoso player, it would be inaudible in a concert hall, but for the fact that the string vibrations are coupled through the bridge to the wooden body of the violin.

The body of a stringed instrument has its own natural resonances, and in a good instrument these are carefully designed to respond to the string vibrations in a way which gives a musically satisfactory sound. After discussing the ability of the player to modify the string motion by bowing technique, we shall return to consider the nature of the body resonances and their effect on the radiation of sound.

The bowing action

Stringed instruments played with a bow have for three centuries formed the foundation of the Western European orchestra, and the repertoire of virtuoso solo and chamber music is far larger than that of any other class of non-keyboard instrument. Part of the reason for this predominance lies in the remarkable degree of control which the player can exert by varying the action of the bow. Although we have insufficient space to explore all the subtleties of bowing technique, it is useful to identify the basic principles governing the relationship between bow motion and string vibration.

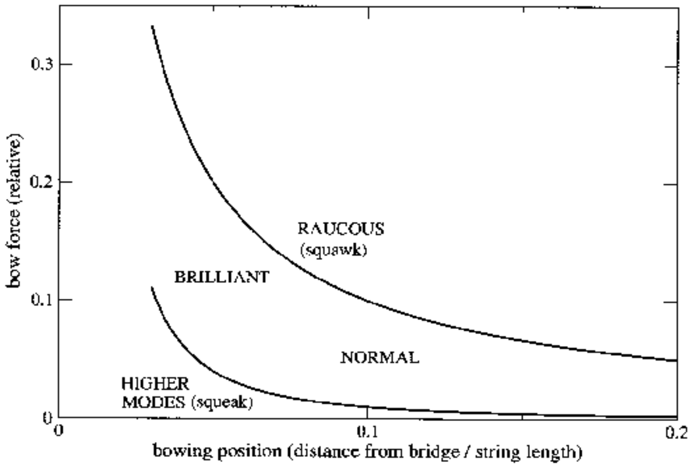
In Chapter 2 we saw that the motion of a bowed string follows a remarkably simple pattern. At any instant, the string has the kinked shape corresponding to two sides of a triangle, the third side being the line joining the fixed end points of the string. During the course of one cycle of vibration the kink forming the apex of this triangle moves along a curved path from one fixed point to the other and back to the first. Some of the shapes adopted by the string during the cycle are drawn in Figure 2.17.

The amplitude of the string motion, defined as the maximum displacement from the position of rest, is largest at the centre of the string. The player controls the loudness of a particular note primarily by varying the amplitude of the string vibration. To achieve the desired amplitude, the player can adjust three aspects of the bowing: the speed with which the bow is pulled across the string, the force with which it is pressed against the string, and the position on the string at which the bow makes contact. It is worth considering the role of each of these variables in turn.

Since the bow hair sticks to the string for a large part of the vibration cycle, it is fairly obvious that, if the position of bow contact on the string is kept unchanged, a greater amplitude of vibration must mean a faster bow speed. An important point to note is that the force between the bow and the string does not come directly into this argument. Pressing harder with the bow will not increase the amplitude of vibration if the other two variables are kept unchanged. The player must nevertheless maintain the bow force within certain limits in order to ensure that the stick–slip cycle remains synchronized with the fundamental mode of the string. If the force becomes too weak, the cycle may jump to one of the higher mode frequencies; if it becomes too strong, the stick–slip motion becomes irregular and the sound degenerates into a raucous squawk.

There is a way in which the player can increase the string amplitude without bowing faster. If the bowing point is moved closer to the bridge end of the string, a given displacement of the bowing point results in a larger amplitude at the centre of the string. In addition, a larger fraction of the cycle time is spent on the 'stick' part of the stick–slip cycle. Both of these effects increase the amplitude achievable with a fixed bowing speed. Thus a long note without a change of bow direction is more easily played close to the bridge.

Bowing near one end of the string does have dangers as well as advantages. The American scientist John Schelleng made a theoretical study of the bow–string interaction, and Figure 8.1 is based on some of his results. Although Schelleng made some simplifying assumptions in his calculations, the curves in Figure 8.1 show at least qualitatively why the player has to exercise careful control over bow force when changing the bowing point.



8.1 The maximum bow force (upper curve) and minimum bow force (lower curve) which result in a musically acceptable sound, shown as a function of the distance of the bowing point from the bridge. Based on a theoretical calculation by John Schelleng

The minimum bow force necessary to avoid jumping to a higher mode (which we can loosely call the 'squeak limit'), and the maximum force which maintains a stable vibration (the 'squawk limit'), both increase steeply as the contact point approaches the bridge. The range of acceptable forces between the two limits also increases, but, more significantly, the ratio of the squawk limit to the squeak limit decreases sharply as the distance of the bowing point from the end of the string is reduced. The diagram in Figure 8.1 suggests that when this distance is a fifth of the string length the maximum bow force is twenty times the minimum; when the distance is one twentieth of the string length both limits are higher, but the maximum force is only five times the minimum. In practice, this means that the inexperienced player finds it much more difficult to avoid either a squeak or a squawk when playing near the bridge. A skilful player, on the other hand, can generate a much louder note near the bridge without quickly running out of bow.

Two other aspects of bowing technique demand at least a brief mention. The foregoing discussion has implied that a change in bow speed, force, or position will alter the amplitude of the string vibration without otherwise changing its pattern. If this were really the whole story, we would expect that altering the bow position would not noticeably change the timbre of the sound. It is a fact of musical experience, however, that bowing nearer to the bridge tends to increase the relative strength of high-frequency components in the sound. More careful study of the bowing process shows that our picture of string motion is oversimplified: a real string excited by a bow of finite width does not have the abrupt kink shown in Figure 2.17. The apex of the triangle is rounded off, to an extent which depends on the bowing position and which in turn affects the timbre of the sound.

We have concentrated our discussion on the steady part of a bowed note, but we cannot leave the topic of bowing technique without remarking on the wide variety of ways in which the player can choose to initiate the sound. The stable vibration patterns shown in Figure 2.17 do not spring into life fully formed, even when the correct combination of bow force, speed, and position have been chosen. For a short time (typically around a fiftieth of a second) various processes compete for control of the string, giving rise to a rich mixture of harmonic and inharmonic frequency components in the attack transient. One of these processes involves the excitation of a set of string modes quite different from the transverse modes which we have previously discussed. These are torsional modes, in which the string rotates around its axis. Recent research has shown that torsional modes can play an important role in the transient behaviour of bowed strings.

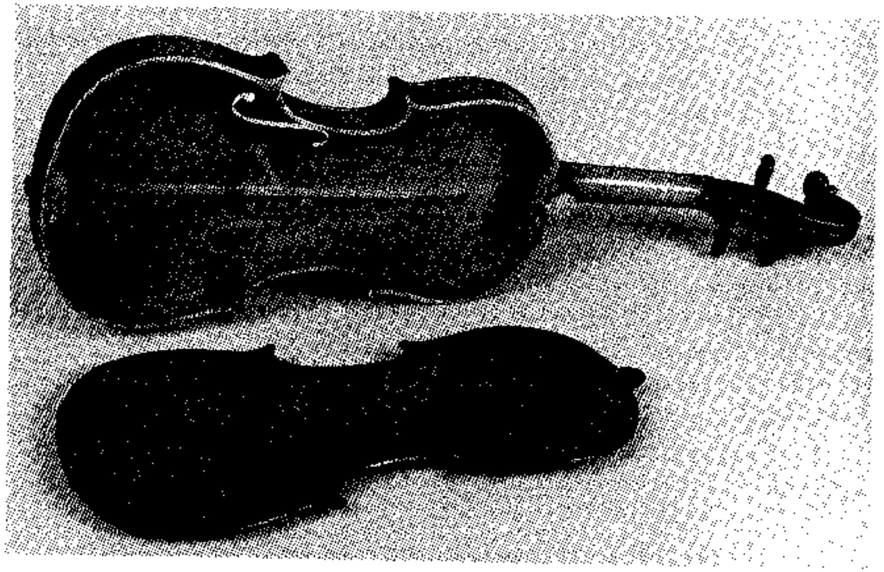
The function of the bridge

If the fixed ends which determine the vibrating length of the string were completely unyielding, waves travelling along the string would be totally reflected at the ends. Powerful standing waves would be set up on the string; these standing waves would have little musical significance, however, since the unyielding supports would be incapable of transmitting any sound energy to the body of the instrument and hence to the ears of the listeners.

On the other hand, we have seen that the kink which travels along the string from the bowing point must be strongly reflected at each end if the stick–slip cycle is to be properly stabilized. Too efficient a transfer of energy from string to body could weaken the reflection of the kink to such an extent that it would be impossible to play a steady note.

In the many different designs of stringed instruments, these competing demands are satisfied in different ways. In the violin, for example, the bridge has two feet which rest on a thin, flexible top plate (Figure 8.2). A slender cylinder of wood called the soundpost is wedged between the top plate and the back plate of the instrument. The top of the soundpost is usually placed just behind the bridge foot at the high-pitch side of the violin. The exact placing of the soundpost has a profound effect on the way in which the instrument plays, to the extent that the French describe this little wooden stick as the 'soul' of the violin.

The proximity of the soundpost to one foot of the bridge means that that side of the bridge is relatively unyielding. The other foot of the bridge, under the low-pitch strings, is more flexibly supported, although the degree of flexibility is modified by the supporting strut known as the bass bar which runs under the top plate parallel to the string direction. This asymmetry in the support of the bridge means that much of the energy transfer from the string to the violin body takes place through a rocking motion of the bridge, which is effectively pivoting on its treble foot.



8.2 Violin with back removed to show bass bar and soundpost. Note that the soundpost is here glued to the underside of the top plate to illustrate its normal position; in the complete instrument is is usually wedged between top and back plates

Body resonances in stringed instruments

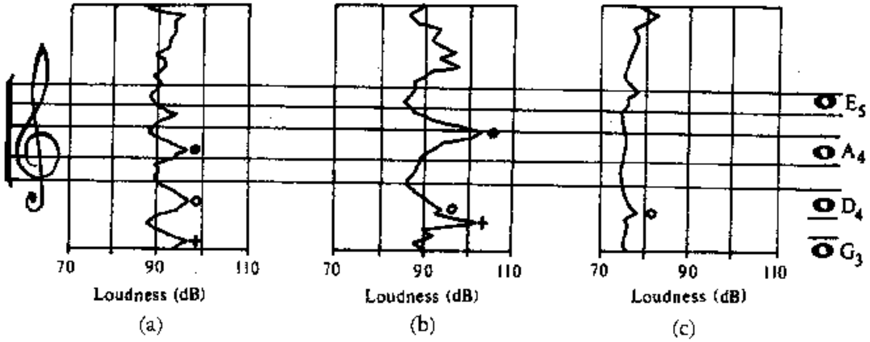
The labours of generations of musical inventors have resulted in a wide variety of body shapes for stringed instruments. The long, thin box of triangular cross section on the tromba marina, the flaring horn projecting from the strohviol: all serve the same basic function, which is to convert the vibrations of the bowed string into a radiated sound wave.

It is sometimes stated that a resonating body amplifies the sound generated by the string. Certainly the sound would be much quieter without the resonator. There is, however, an important distinction to be drawn between the action of a resonating body and that of an electrical pickup and amplifier. The sound output power of an electrically amplified violin can be hundreds of times greater than the maximum power which the bow is capable of feeding to the string: the extra power comes from the electrical supply to the amplifier. There is no source of energy in the wooden body of the violin, and without electrical amplification the power supplied by the bow sets an upper limit to the possible radiated power. The resonating body draws energy rapidly from the string; only if the player is capable of feeding energy into the string at a comparable rate will the potential benefit of the resonance be realized in a louder sound.

Unfortunately, radiation of sound is not the only process which draws energy from the string. Whenever any kind of motion is initiated, frictional forces come into play which dissipate some of the energy of motion. The energy does not disappear completely, but is converted into heat. Friction within the string itself, and in the bridge and body of the instrument, is constantly draining energy from the string vibration, and the bowing process must make up this deficit as well as supplying the sound energy. A good instrument feels easier to play than an unresponsive one partly because a greater proportion of the bow energy goes into sound.

We talk, somewhat loosely, about the 'resonance' of a violin body. In fact, the body of a stringed instrument has many different natural modes of vibration, each mode contributing a resonance with its own characteristic frequency. The first few resonances of the violin body occur at fairly widely separated pitches. Does this mean that only notes at these pitches will be effectively radiated? Fortunately not: the natural modes of the body are broad resonances, in the sense that the response of each extends over a pitch range of several semitones. One of the secrets of designing a good instrument lies in choosing the strength and placing of the body resonances so that they overlap to give the desired response over the whole frequency range of the instrument.

Even an instrument of the highest quality does not respond uniformly at all frequencies. Indeed, much of the individual character of the instrument comes from this very lack of uniformity. This point is illustrated by Figure 8.3, which shows the results of loudness curve measurements on three very different violins. The loudness curve is obtained by bowing the instrument at semitone intervals over its complete playing range; at each pitch, the highest sound level at which the player can produce a sustained note of good tone quality is measured by a sound level meter.



8.3 Loudness curves for three different violins: (a) a Stradivari; (b) an eighteenth-century instrument of second quality; (c) a poor-quality modern instrument. Open circle: 'main air resonance' (MAR); filled circle: 'main wood resonance' (MWR); cross: 'wood prime'. Notes on right show open string pitches. Adapted from Carleen Hutchins

It can come as a considerable surprise to violinists to realize that even an excellent Stradivari can show variations of more than 6 decibels in the loudness curve (Figure 8.3(a)). When playing normally, rather than in a scientific test, the experienced player compensates automatically for such variations. This compensation would be considerably more difficult to achieve on the violin whose loudness curve is shown in Figure 8.3(b), however; in the test, the maximum sound output for the note E_4 was 15 decibels lower than could be achieved at the pitch B_4.

The loudness curve for the Stradivari shows three peaks in sound output at pitches corresponding roughly to those of the three lowest open strings (A_4, D_4, and G_3). The peak near to D_4 is related to the lowest-frequency resonance of the air contained within the cavity of the violin, which is sometimes described as the 'main air resonance'; its frequency is controlled by the volume of the cavity, the flexibility of the walls, and the size of the f-holes cut in the top plate. The pitch of the air resonance can be estimated by blowing across one of the f-holes.

There is a resonance of the wooden body of the violin near in frequency to the first air resonance. Some makers claim that constructing the violin in such a way that this body resonance coincides in frequency with the first air resonance improves the playing properties of the instrument.

There is another important resonance of the wooden body of the violin, sometimes described as the 'main wood resonance', at around 500 Hz. The second air resonance is normally a little lower in frequency. These two resonances combine to give the broad resonance peak around the frequency of the A string (440 Hz).

The third major peak in the loudness curve, known as the 'wood prime', is different in character from the other two, since it does not occur at the pitch of a resonance in the instrument. It is in fact exactly one octave below the wood–air resonance described in the previous paragraph. To understand the origin of the wood prime, we must recall that, when a particular note is played on the violin, the vibration transmitted from the string to the body through the bridge contains not just a single frequency component, but a whole harmonic series of such components. If the note played is A_3, for example, these components will have pitches A_3, A_4, E_5, A_5, and so on. There is no body resonance at the pitch A_3, so the 1st harmonic will not be strongly radiated. The 2nd harmonic, whose pitch is A_4, is however well placed to take advantage of the body resonance at around 440 Hz. As a result, the lowest notes on the violin are strong, with a special timbre characterized by a powerful 2nd harmonic and a relatively weak fundamental.

Although we have used the violin as an example when discussing the role of body resonances, similar principles apply to most other types of acoustically amplified stringed instruments. Without strong body resonances, the energy imparted by the player would remain trapped on the string. A somewhat quirky instrument of the type illustrated by Figure 8.3(b) is still more rewarding to play than the uniform mediocrity of an instrument with no strong resonances, such as that recorded in Figure 8.3(c).

Sound radiation from stringed instruments

The body of a violin or cello does not radiate sound energy with uniform efficiency in all directions. The directional pattern depends on the frequency of the sound; there is no noticeable directionality at low frequencies, while at high frequencies there is a general tendency for sound to be preferentially radiated outwards from the top plate.

When interpreting the musical significance of the directional nature of sound radiation, it is important to bear in mind that a single note played on the violin has many frequency components. Thus when the violinist plays the note A_3, the first two harmonic components have frequencies of 220 Hz and 440 Hz respectively; these will sound as strong behind the player as in front. The 5th harmonic, whose frequency is 1,100 Hz, will in contrast be radiated considerably more strongly in