Chapter 8
Harpsichord and Clavichord

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8.1 Introduction

While plucked string instruments such as harps are known to have been used in many parts of the world for several thousand years, the idea of using a keyboard to control the plucking action does not seem to have developed until the late fourteenth century, with an instrument similar to what we now know as the harpsichord. These early keyboard instruments were represented in paintings, carvings, and written descriptions from the time. Most of the development of the harpsichord, however, took place in the sixteenth and seventeenth centuries in Italy, Flanders, Germany, and England.

Italian harpsichords generally had the functional instrument enclosed in a decorative case and had a rather different string scaling from the others, giving them a longer and narrower shape. The harpsichords developed a little later in Flanders, particularly by the Ruckers family, had a single, more solid case and, because of different string scaling, were a little broader in shape. These instruments soon became popular and were exported all over the world. Excellent accounts of this history and of the distinctions between instruments from different countries have been given by Hubbard (1965), Russell (1973), and Kottick (1987, 2003), while both Kottick and Zuckermann (1969) relate these traditions to the harpsichord revival in the second half of the twentieth century.

The clavichord, which is a more personal instrument, has received much less attention, but good historical and practical descriptions are given by Russell (1973), Neupert (1965), Brauchli (1998), and Vermeij (2004). A general technical discussion of harpsichords and clavichords has been given by Fletcher and Rossing (1998) based upon detailed separate studies of the two modern instruments by Fletcher (1977) and Thwaites and Fletcher (1981), and more recently by Kottick et al. (1985, 1991).

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In this chapter, we shall be concerned with the design, construction, and acoustic performance of harpsichords and clavichords, rather than their historical development, though the instruments on which we report measurements and design details are modern instruments based upon classic models from the seventeenth and eighteenth centuries. Because there is an important distinction between the sound production mechanisms of harpsichords and clavichords, they will be considered separately.

8.2 The Harpsichord

8.2.1 General Design

A typical harpsichord by a modern maker is shown in Fig. 8.1. As will be discussed later, it may have either one or two keyboards. In many earlier harpsichords, as with other keyboard instruments, the naturals were often covered with dark wood and the chromatic keys with light-colored material such as bone or ivory. Many instrument makers, however, used the current configuration with white naturals and black chromatic keys. As in a modern grand piano, the lid serves the dual purpose of keeping dust out when closed and directing the sound towards the audience when open. The whole case is of wood, and the string tension is supported by a set of wooden braces running between the sides. The pattern of these braces varies according to different national traditions (Kottick 2003). There are also ribs glued to the underside of the thin soundboard to stiffen it, and the bottom of the case is closed with a wooden panel.

In addition to the standard harpsichord where the strings run straight away from the player, there are two smaller versions using the same plucking action. One, known as the virginal, generally had a rectangular case with the strings running nearly parallel to the keyboard, with the bass strings toward the front, but other shapes were also made. Another, known as the spinet, has a triangular case with the strings running obliquely to the keyboard, which is on one of the longer sides, and with the bass strings at the back. Many variants of these instruments were also made, such as a so-called “mother and child” virginal with an inset smaller, or even a rectangular double harpsichord with the two instruments in a single rectangular case and the players facing each other (Kottick 2003).

The basis of harpsichord operation is simply a mechanization of the plucking action of the harp, or perhaps the psaltery, in which there is a set of taut strings, each tuned to the pitch of a different note, clamped rigidly at one end and coupled to a light soundboard at the other, as in almost all string instruments. The function of the soundboard is crucial, since a vibrating string by itself radiates hardly any sound. The questions of importance are thus the material and mounting of the strings, their support and coupling to the soundboard, the mechanics of the keyboard and the plucking action, and the overall design. It is also important to understand what

Fig. 8.1 A modern Flemish harpsichord by Carey Beebe based on classical instruments by the seventeenth-century Antwerp maker Andreas Ruckers. The keyboard compass has been extended down to G_1 in the bass and up to D_6 in the treble. Note the traditional painted decoration on the soundboard, and printed papers lining the case and lid. The small protrusions on the right-hand side (cheek) enable the player to reach around and engage or disengage either of the two sets of jacks by sliding the appropriate register on or off

controls the sound quality and how this can be modified for particular musical purposes (Fletcher 1977).

Figure 8.2 gives more details of the construction of a harpsichord such as that shown in Fig. 8.1. Each metal string is wound around a tuning pin, which is secured in a solid wooden block, the *wrestplank*. The string then runs at an angle past a thin brass pin on a wooden bridge (the *nut*). Before reaching its other end, it passes over a bridge mounted on the soundboard, being held in place by passing at an angle

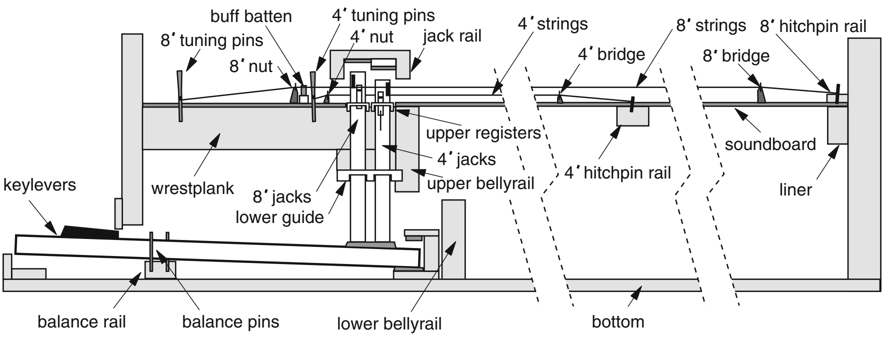

Fig. 8.2 Cross-section of the harpsichord action. Each jack passes through a slotted upper register and a lower guide, and the player can manipulate the upper register to move the whole set of jacks so the quills are just out of range of normal plucking contact with the strings and they do not sound

around another small brass pin. The bridge serves to transfer the force of the vibrating string to the soundboard and cause it to vibrate in sympathy. The *choir* of full-length unison-pitch strings (also called *8-foot* or $8'$ strings by analogy with the 8-foot stops of an organ, this being the length of the longest pipe C_2) are then secured to *hitchpins* in the *hitchpin rail* at the inside perimeter of the heavy case, while half-length ($4'$) octave strings are anchored through the soundboard into a curved wooden support on its underside.

As shown in Figs. 8.2 and 8.3, each key has resting upon it a *jack* for each choir. The jack body contains a tongue, so arranged that it can be pivoted backward against a thin spring – originally a hog bristle but these days often a thin wire or plastic monofilament – but cannot pass forward through the jack. Protruding from the tongue is a thin flexible quill, originally made from the spine of a crow or raven feather but now more usually of Delrin or Celcon, which are hard but flexible industrial polymers. Each jack also has a protruding felt damper that normally rests in contact with the wire and so inhibits its vibration. When the key is depressed, this raises the jack so that the damper is lifted off the string and the quill displaces the string until it bends sufficiently for the string to slip off, after which the string vibrates freely. When the player's finger is removed from the key, the jack returns by gravity, the tongue is deflected backward so that the quill flips easily under the string, and the felt damper stifles the vibration so that the sound ceases in a fraction of a second.

The "feel" of the keyboard action depends upon the mass, length, and pivot position of the key, the stiffness of the plucking quill, and the distance of the plucked string from the face of the jack. A short distance here will give a relatively stiff action but strong string excitation, while a greater distance with a longer quill gives a lighter action and a softer sound. Careful adjustments are therefore very important. The jacks for a whole choir of strings are positioned accurately by passing through slots in a narrow wooden register just below the strings and a lower guide running across the instrument above the rear of the keys, as shown in Figs. 8.2 and 8.3. A harpsichord usually has more than one choir of strings, and

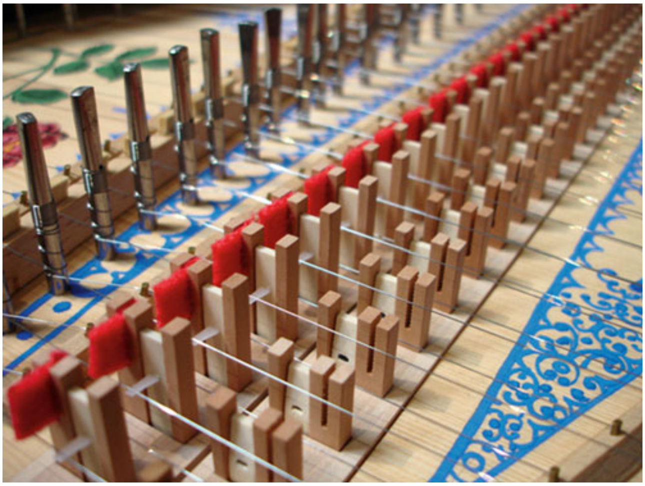

Fig. 8.3 Close-up of the action of the Flemish-style harpsichord shown in Fig. 8.1. In this instrument there are the traditional two choirs of strings, the shorter 4′ choir, for which the tuning pins can be seen, being tuned an octave above the other 8′ choir, for which the tuning pins are out of sight to the left. Both sets of jacks are visible because the jackrail has been removed. The set of leather pads of the buff stop that can be moved into contact with the 8′ strings just beside their nut is visible behind the 4′ tuning pins

separate choirs can be activated at will by moving the appropriate upper register a little along its length so that the quills of that set either pluck or pass by the strings. Some modern instruments have a pedal mechanism to accomplish this so that changes can be made rapidly while playing.

8.2.2 Plucked Strings

As was discussed in Chap. 2, the fundamental vibration frequency f, and thus the musical pitch of a string, depends upon its length, diameter, and tension, as well as the material from which it is made, the relation being

$$f = \frac{1}{2L}\left(\frac{T}{m}\right)^{1/2} \tag{8.1}$$

where L is the string length, T its tension, and m its mass per unit length. Harpsichord strings differ from those of most other plucked string instruments in being made of metal, usually iron or brass. Because these materials are much heavier than gut or nylon, metal strings must be held at a higher tension for a given length, but because of this greater tension they can be made thinner and still produce the same sound output. Metal strings can sustain this higher tension stress and also retain their tension more stably than do the softer materials. The other difference is that, while soft materials such as gut or nylon tend to absorb internally the higher frequencies of the string vibration so as to give a "mellow" sound, this does not happen nearly as much for metals, so that the sound can be much "brighter."

If all the strings were the same diameter and brought to the same tension, then it would be necessary to double their length for each octave decrease of pitch. For the five-octave range of a large harpsichord this would give a length change of a factor of 32, which is not practical, so the strings of the lower octaves are made more nearly of equal length, their diameter increased, and their material changed to make them even heavier. The upper strings are normally made of mild steel, generally referred to as *iron*, and the lower ones of brass, which is more dense but cannot support as much tension. Many instruments use two different brass alloys – red brass, which is 90% copper and 10% zinc for the extreme bass, and yellow brass, which is 70% copper and 30% zinc up into the tenor region. Typical scaling parameters for a modern version of a classical Ruckers harpsichord are shown in Fig. 8.4, while the string composition and diameter variation are shown in Fig. 8.5.

Another major design feature to be considered before we examine mechanical design is the position at which each string is plucked. What is important is not so much the vibration of the string itself, because it radiates only a very small amount of sound directly, but rather the force that the vibrating string applies through the bridge to the soundboard, and this depends greatly on the position of the plucking

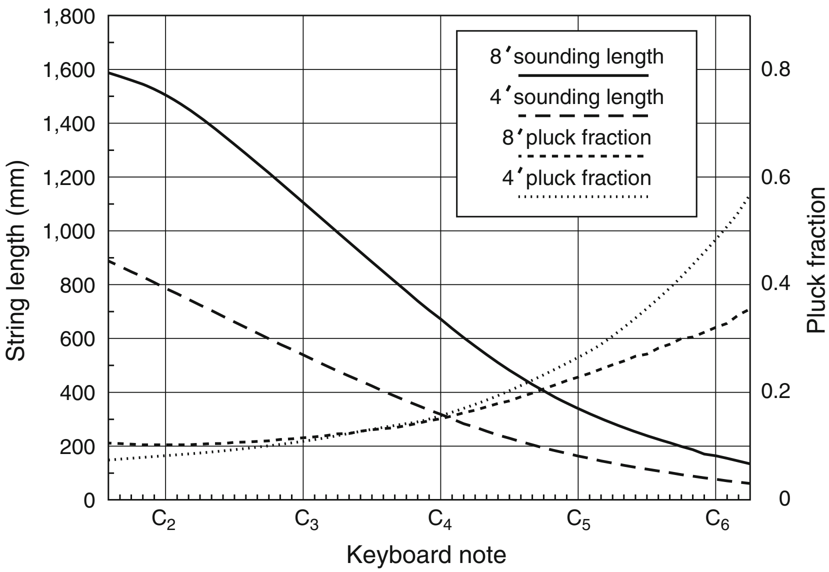

Fig. 8.4 Scaling of (**a**) string sounding length, (**b**) plucking position, and (**c**) string diameter for the 8′ and 4′ string choirs of the modern-reproduction Ruckers harpsichord of Fig. 8.1. The pluck fraction gives the position of the plucking point from the nut relative to the total sounding length of the string involved

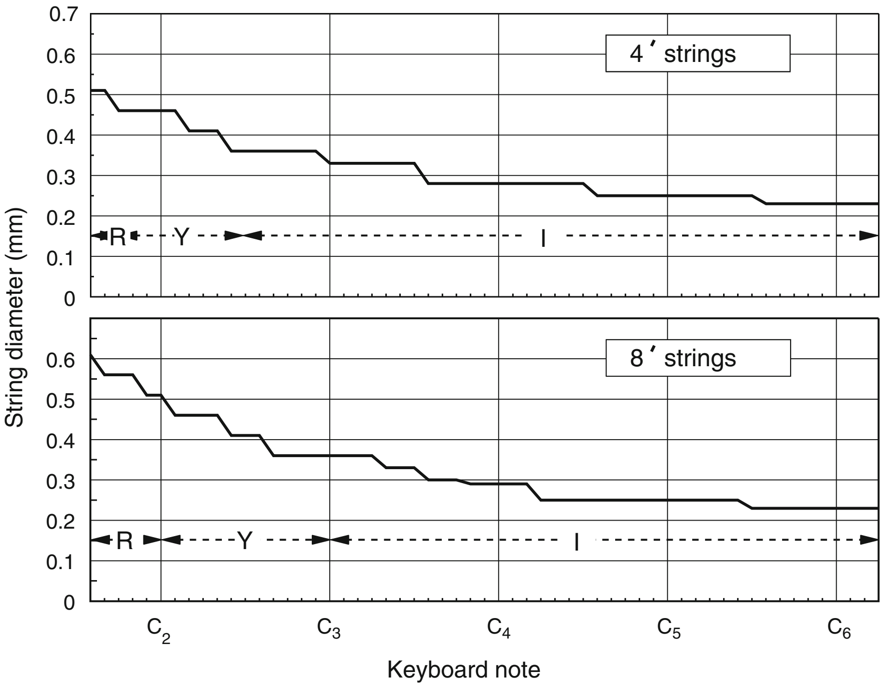

Fig. 8.5 Scaling of string diameter and composition for the 8′ and 4′ string choirs of the modern-reproduction Ruckers harpsichord of Fig. 8.1. The symbols *R*, *Y*, and *I* denote *red brass*, *yellow brass*, and *iron*, respectively

point. If a string is plucked at a position $1/n$ of its length from one end, the shape with time of this repetitive force on the bridge, which is near the remote end of the string, is a strong downward force for a fraction $1/n$ of a period followed by a much weaker upward force for the remainder of the period, as shown in Fig. 8.6. Harmonics below the nth are all strong; the nth harmonic is missing; and harmonics above the nth decrease in amplitude with increasing frequency, as shown in the lower panels of Fig. 8.6.

The perceived tone quality of the radiated sound depends on the relative amplitudes of the lower harmonics, perhaps up to the eighth, which is three octaves above the fundamental. A string plucked at a moderate fraction of its length from the end, as in (a) and (b) of Fig. 8.6, will sound *mellow* because the amplitudes of its harmonics fall rapidly with increasing frequency, but quite loud because of the high amplitude of the fundamental. A string plucked at a very small fraction of its length from one end, as in (c) and (d), will have a relatively *bright* sound because many harmonics are as prominent as the fundamental, though it will not be as loud because all these amplitudes are lower.

Most harpsichords have more than one choir of strings and these are plucked at different points to take advantage of this effect and give tonal variety to the sound.

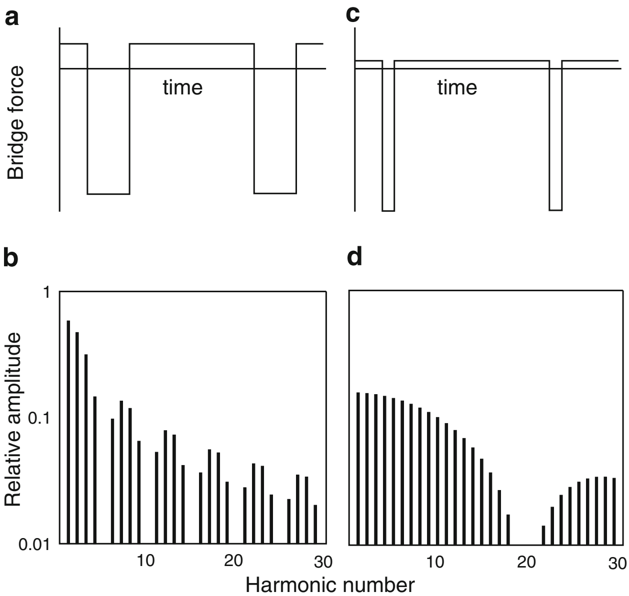

Fig. 8.6 (**a**) Time evolution of the force acting on the bridge for a string plucked at one-fifth of its length from the nut end. (**b**) Spectrum of the force exerted on the bridge for this plucking position. (**c**) Time evolution of the force acting on the bridge for a string plucked one-twentieth of the distance from the nut. (**d**) Spectrum of the force exerted on the bridge for this plucking position

A choir plucked very close to the nut constitutes a *lute stop* and has a bright and nasal but generally softer sound, because the quill is unable to displace the string by more than a small distance at this point. In a well-designed harpsichord, however, the strings of even a single choir are not all plucked at the same fraction of their length, but over a designed range, as shown in Fig. 8.4, so as to give an appropriate balance to the sound throughout its compass.

8.2.3 Soundboard and Radiation

When a string vibrates, it exerts a force through the bridge on the soundboard causing it to vibrate as well, though with much smaller amplitude than that of the string. It is this vibration of the soundboard that transfers the sound to the air, because it is able to actually displace the air, in contrast to the string which simply moves through it. The exact shape and amplitude of the vibrations of the soundboard are therefore very important in determining the overall sound quality of the instrument, just as they are for the body of a violin. The soundboard itself is usually made from spruce, of which popular varieties for musical instruments are Norway spruce (*Picea abies*) or Engelmann spruce (*Picea engelmannii*).

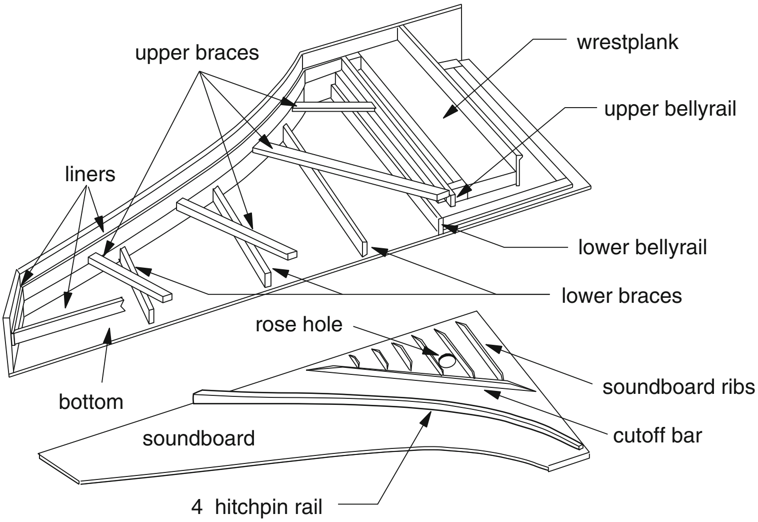

Fig. 8.7 Exploded view of the structure of a typical Flemish harpsichord such as the one studied here. The soundboard is stiffened by wooden ribs glued to its under surface, while the whole case is strengthened by frames at its *top* and *bottom* to support the string tension (from an original by The Paris Workshop)

The soundboard is assembled so that the wood grain runs in the long direction at right angles to the keyboard. It is typically only about 3 mm thick and is thinned slightly in some areas, particularly in the treble corner. The acoustic and vibrational properties of these wood species have been discussed in detail by Bucur (1995), their main advantages relating to low density, high stiffness, and low internal damping. Glued to its underside in a particular pattern are light ribs, as shown in Fig. 8.7, which stiffen the soundboard and raise the frequencies of some of its resonances. The rib positions also influence the shapes of the vibrational modes of the soundboard and thus affect its radiation efficiency. Mounted in a hole cut in the soundboard near its bass end is a small decorated emblem or *rose*. Its main function is an identification of the maker, but it also combines with the larger spaces above the keys to provide an acoustic vent to the air cavity under the soundboard, with effects to be described below.

The shapes of the vibrational modes of the soundboard are determined by its overall shape and by its stiffness distribution, which is strongly influenced by grain direction, wood being 10–20 times as stiff along the grain as it is across, as well as by the ribs and bridges attached to it. In its lowest mode, the soundboard simply vibrates in and out like the lowest mode of a drumhead, while at higher frequencies the mode shapes divide it into progressively smaller areas, each one of which vibrates in anti-phase to its neighbors. Sketches of some of these mode shapes have been given by Savage et al. (1992).

The impedance of the air between the soundboard and the bottom of the case is also important. At low frequencies it is simply compressed and flows to some extent out through the rose hole and the spaces above the keys, either in-phase or out-of-phase with the overall motion of the soundboard, thus modifying the resonance frequencies and splitting the low-frequency drumhead resonance into two. The lower of these two resonances, with the enclosed air flowing out through the apertures while the soundboard moves inwards, is the lowest resonance of the whole instrument, typically near 30 Hz, and determines the *fullness* of its bass response, while the upper resonance is important at a slightly higher frequency. At higher frequencies, where the largest dimension of the cavity is comparable to or greater than the sound wavelength, there can be resonances within the air itself and these will couple to the higher modes of the soundboard. Of course, all these resonances overlap to some extent because of vibrational and acoustic losses. The whole situation is very complicated, and a detailed study by Savage et al. (1992) identifies 36 vibrational modes below 600 Hz. There will be many more above this frequency.

If the design of the soundboard and case has been well developed, then these resonances will be fairly evenly distributed over the audible frequency range, so that there are no very pronounced maxima or minima in the sound output. The resonant response of the soundboard does, however, influence the overall sound quality of the harpsichord and varies from one maker to another. As a general rule, a large harpsichord can be expected to have a fuller bass sound than a small one, simply because large structures generally have resonances of lower frequency and radiate them more efficiently than do smaller structures. Finally, the nature of the wood used to make the soundboard is also important, since its internal damping influences both the general shape of the response at high frequencies and also the prominence of the resonances (Kottick et al. 1991).

8.2.4 Acoustic Balance

Sound balance is an important feature of the sound of a musical instrument. This has three major components: initial loudness, decay time, and tonal quality. Because music written specially for an available instrument of the period is likely to explore its full compass and resources, it is desirable that the initial loudness of all the notes should be nearly the same. On instruments such as the pianoforte the performer can adjust the relative loudness of individual notes, but this is not possible on the harpsichord, so uniform loudness should be built into the instrument design. This is a matter of case and soundboard design, string length and diameter, and pluck mechanics as discussed above. Long experience allowed instrument makers to develop appropriate designs for all these things well before the advent of acoustic analysis, and the result is that their harpsichords, along with good modern instruments, have nearly constant initial loudness across the whole four and a half octave compass from G_1 to D_6. For the Ruckers instrument of Fig. 8.1, the measured sound pressure level at a distance of 2 m for a rapidly repeated short scale passage was 70 ± 5 dB(A) over the whole compass for the 8′ string choir and 68 ± 3 dB(A) for the 4′ choir. When combined, the level was 72 ± 5 dB(A).

To evaluate these figures we should note that the "A" means the reference level has been adjusted over the whole frequency range to approximately match the sensitivity of human hearing. For comparison, we should also note that measurements of similar scale-patterns played *mezzoforte* on a piano give a level of about 80 dB(A), but the pianist has control over at least the range from 70 to 90 dB(A). These figures will be compared with those for the clavichord later on.

The second important feature of sound quality is the decay time of the sound when a note is played and the key is held down. This time depends on the amount of energy stored in the string by its initial displacement and the rate at which this energy is dissipated. A set of measurements on the modern-reproduction Ruckers harpsichord is shown in Fig. 8.8. The decay time decreases steadily with rising pitch, the total variation being more than a factor of two over the keyboard compass in the case of the 8′ choir and nearly a factor of four in the case of the 4′ choir. The slope is very close to $(1/\text{frequency})^{0.25}$ for the 8′ choir and has the much steeper slope $(1/\text{frequency})^{0.45}$ for the 4′ choir. Such a result is appropriate, because low notes in music are generally played more slowly than high notes, and a longer decay time is generally desirable to give "fullness" to the sound.

A note on the harpsichord, or any other *acoustic* musical instrument, is, however, not simply a copy of a lower note transformed to a higher frequency. This is because

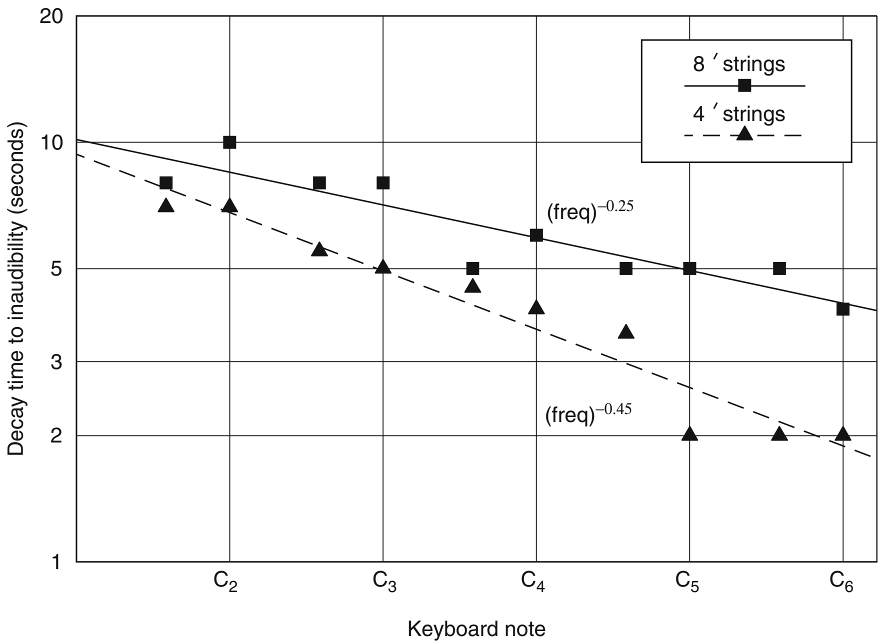

Fig. 8.8 Measured decay time to inaudibility as a function of pitch for a selection of notes played on the reproduction Ruckers instrument of Fig. 8.1

of the difference in string diameter, plucking point, soundboard response, and radiation efficiency. These features contribute to the complex musical nature of the sound compared with the *synthetic* sound of many simple electronic imitations.

In considering the design of harpsichords and other string instruments, it is important to realize that only a few percent of the energy stored in the vibrating string is radiated as sound. Most of it is dissipated in viscous losses from the motion of the string through the air and in losses to the material of the soundboard. To maximize the radiated sound level, it is important to have a soundboard that is as large as possible and to ensure that it is made of a material and in a way that minimizes internal losses. Most aspects of the design and construction are now a matter of tradition, but modern studies of the acoustics of wood (Bucur 1995) can reveal why the decisions that were made in the past are essentially correct.

The third aspect of tone quality is the tonal balance over the entire compass of the instrument. In a four and a half octave harpsichord such as the one examined here, the fundamental frequency of the 8′ choir ranges from about 46 Hz in the bass to about 1.1 kHz in the treble if the instrument is tuned to standard *Baroque* pitch $A_4 = 415$ Hz. Remembering that human hearing sensitivity decreases below about 500 Hz, the bass notes might be expected to sound very weak. This is corrected by the fact that the lower strings have a much shorter fractional plucking length than the higher strings, as shown in Fig. 8.4, and thus have much greater harmonic development up to about the tenth harmonic than do the higher strings. At the other end of the range, the extreme treble strings are plucked proportionally much further from the end and so have much less harmonic development. This tends to equalize the subjective loudness of the sound and to give a balanced quality over the whole compass.

8.2.5 Design Extensions

The discussion above has been concerned with basic aspects of harpsichord design and operation, but there are several extensions to the basic instrument that are important. Most of these aim to give the performer greater influence over the nature of the sound and to provide subtle variants of the basic tone quality. Some of these have been mentioned before, but it is helpful to consider them together.

A simple addition found on many instruments consists of a batten with a set of small felt or leather pads glued to its upper surface, which is able to slide against the 8′ nut as shown in Figs. 8.2 and 8.3. This is known as the *buff stop*. The effect of the pads is to damp dramatically the upper harmonics of the string vibration, and thus of the radiated sound, to produce a very mellow quality such as can be expected from the gut strings of an early lute or guitar. This addition is rare in Italian harpsichords, but is found in most other instruments.

A development that has already been displayed in Fig. 8.3 and discussed above is the incorporation of a second (4′) choir of strings tuned an octave above the main unison or 8′ choir. Some very large modern harpsichords have gone even further in this direction and incorporate a sub-octave 16′ string choir, something few original instruments had. Again, because it is not practical to double the string length, the solution is to use nearly the same lengths and tensions as the standard 8′ strings, but to double the string diameter so as to increase the mass per unit string length m by a factor of four, thus halving the frequency, as given by (8.1). Because of limits to the size of the soundboard, the bass strings of this set do not have a strong fundamental, but provide extra harmonics in between all those of the 8′ choir. This gives an overall rich and almost "orchestral" sound that can be impressive in appropriate musical compositions. Incorporation of a 16′ string set, however, causes other problems and it is unusual now even on modern instruments.

Considerable emphasis has been placed in the discussion upon the importance of choice of plucking point in determining the harmonic development and thus the subjective brightness of the sound. The first and simplest way to accomplish this is to have a second choir of strings, also at unison pitch but plucked closer to the nut so as to give a sound that is not so loud but has much more harmonic development, as illustrated in Fig. 8.6. The choirs would then be described according to their plucking position, for example, "front 8-foot" plucking closest to the player and "back 8-foot" closer to the middle of the instrument. An additional set plucking very close to the nut would be called the lute stop, as already discussed.

While it is possible to have the additional string choirs in these examples plucked by a set of jacks operated from the same keyboard as the standard set and to turn each set on or off by moving the appropriate register, this creates difficulties for the performer if it is desired, as it often is, to have short interpolated phrases with different sound quality. The solution is to have a second keyboard, located just above and behind the first as in an organ, which plucks the second set of strings. It is then easy for the performer to shift hands from one keyboard to the other to produce tonal contrast effects. The builder is not, however, limited to one set of strings for each keyboard but can have several sets in much the same way as is done for the stops of a pipe organ. The instrument then becomes very versatile and tonally flexible. Some quite early Flemish instruments were made with two keyboards, but surprisingly in those days the aim was not to produce different tone colors but rather to transpose the notes upward by a perfect fourth.

If an additional keyboard can be considered, then why not a pedalboard as well? Indeed, some classical harpsichords show signs of having had this feature, probably largely because it then made them good substitutes for a pipe organ, as far as practice was concerned, and of a size and cost that organists could reasonably manage for their homes. The pedalboard could operate either with a *pull-down* mechanism for the keyboard notes, or with its own set of strings. This addition does not appear to have carried over to the present day, with few makers interested in such complexities, but such instruments were built in the middle of the twentieth century.

In addition to these relatively minor but important additions to the standard simple harpsichord, there have been some much more adventurous developments. Some of these simply involved changing the overall shape of the instrument. The spinet has already been mentioned and also the virginal. These were, for the most part, simply adaptations to make the instrument fit more easily into a small living room, but some were much more adventurous. Chief among these were a combination of a harpsichord and a fortepiano, often with separate keyboards, and the claviorganum, which was a combination of a harpsichord and a pipe organ. This latter instrument was probably never really popular because of the tuning problems when combining strings with pipes: as the temperature rises, the organ goes sharp but the harpsichord strings go flat. Detailed specifications of some of these instruments from the 1500s and 1700s are given by Hubbard (1965) and by Kottick (2003).

8.3 The Clavichord

8.3.1 General Design

The clavichord is sometimes seen as a very close relation of the harpsichord, partly because they developed over the same period and by the late eighteenth century most musicians probably had at least one of each instrument in their homes, but the basic acoustics of the two instruments is really very different. General descriptions of the clavichord have been given by Russell (1973), Neupert (1965), and Brauchli (1998), while the first technical study of which we are aware is that by Thwaites and Fletcher (1981). The surviving instruments of the Bavarian clavichord maker Christian Hubert have been the subject of a detailed study by Vermeij (2004).

Figure 8.9 shows a typical double-fretted clavichord, the meaning of the term *fretted* to be explained presently. It is a quite small instrument, only about a meter long, and is designed to be placed on a table for playing. The best modern versions

Fig. 8.9 Modern version of a typical double-fretted clavichord made in the eighteenth century by the Bavarian maker Christian Hubert. An unfretted instrument looks very similar but is usually larger, while a triple-fretted instrument is usually smaller

are all essentially copies of instruments built more than 200 years ago. The keyboard compass is typically just over four octaves from C_2 to D_6. The reason the clavichord has not developed into a concert instrument is that the sound it produces is very quiet – typically less than about 50 dB(A) at 2 m – so that it is best used for personal performances or, at most, with a solo instrument such as the recorder.

The brass strings of this clavichord, of which there are 74 arranged as 37 pairs, run at a small angle to the long spine side of the case where they are fixed to rigid hitchpins. The strings run over a wooden bridge mounted on a thin soundboard, as shown in Fig. 8.10, to their termination at individual tuning pins. The soundboard itself, as shown in Fig. 8.9, covers less than one-third of the area of the instrument and is vented through one or more small apertures, called the *mouseholes*, cut in the bellyrail. The combination of enclosed volume and aperture dimensions influences the frequency of the lowest or Helmholtz resonance of the cavity, which is typically around 150 Hz. The effect of this resonance is to enhance the lower frequencies produced by the string vibrations in the same way as does the body cavity of a cello, vented through the f-holes, or the vented box of a bass loudspeaker. As with the harpsichord soundboard discussed before, there are complex resonances of even the simple clavichord soundboard and these are coupled to sound waves in the air enclosed in the cavity. More details are given in the references listed (Brauchli 1998; Fletcher and Rossing 1998; Thwaites and Fletcher 1981). The fact that each note is produced by a pair of strings tuned to the same pitch obviously increases the loudness, but has another effect that will be discussed presently.

We come now to the meaning of the term fretted in describing the clavichord. Because the vibrating length of the string is determined by the distance between the

Fig. 8.10 Detail of action of the reproduction Hubert clavichord. Each key is pivoted on the balance rail and, when it is depressed, the brass tangent at its distal end strikes the pair of strings corresponding to that note. The listing cloth is clearly visible

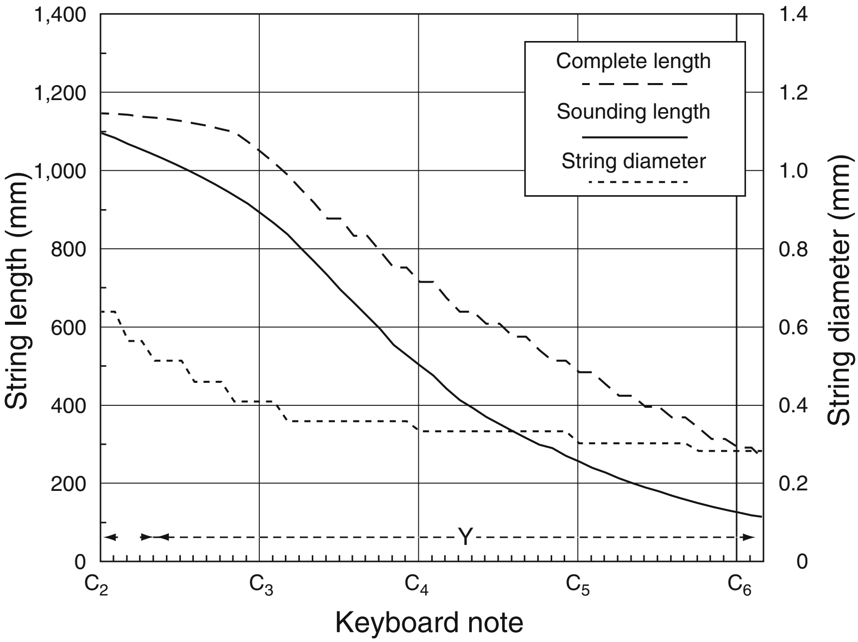

Fig. 8.11 Measured string lengths and diameters for the reproduction classical double-fretted clavichord of Fig. 8.9. Strings from C_2 to F#$_2$ are of *red brass* (R) and all other strings are of *yellow brass* (Y)

tangent impact point and the bridge, it is clearly possible to play more than one note on a given pair of strings, provided this is not attempted simultaneously. This multiple use of strings is termed fretting; it has essentially no effect on performance provided that note pairs that are never used simultaneously, such as C and C#, are combined on the same string pair. This results in a small and economical instrument, which can be made even smaller by triple-fretting the strings. Not all clavichords use this design technique, however, and many larger unfretted instruments were made with independent string pairs for each note. Such instruments have a larger soundboard, thus often leading to a stronger bass sound.

Figure 8.11 gives details of string lengths and diameters for a modern version designed by D. Jacques Way and Marc Ducornet after an original double-fretted clavichord by the Bavarian maker Christian Gottlob Hubert. The lowest seven pairs of strings, covering the range from C_2 to F#$_2$, are unfretted and made from red brass, though the original probably used over-wrapped strings, while the higher strings are yellow brass and fretted from about an octave above this for the remainder of the compass. The *overall length* is the total length between the hitchpin at the left end of the instrument, including the damped length between the pin and the impact point of the tangent, and the bridge, while the "sounding length" is just that from the impact point of the tangent to the bridge.

8.3.2 String Excitation in the Clavichord

The action of a clavichord is very different from that of a harpsichord, although the key lever is mounted on a pinned balance rail just as shown in Fig. 8.2. Each key lever has near its distal end a "tangent" made from a thin brass plate and so arranged that it strikes a pair of strings towards one end, as shown in Fig. 8.10. Importantly, the tangent then remains in contact with the string, holding it in a slightly displaced position, until the key is released. The tangent impact sets the string into vibration, but only the longer section of the string continues to vibrate because the shorter section is damped by the *listing cloth* twined between the strings. This is very different from the fortepiano or pianoforte action, in which a relatively heavy felt-covered hammer strikes and then quickly rebounds from the string which is firmly mounted at both its ends. The excitation of the clavichord string is much less than that of a string hit by a sharp hammer because the excitation consists simply of displacing one end of the string over a time of about 10 ms and holding it in the displaced position. Relatively little energy is transferred to the string during this process compared with that in a strike and rebound of the piano, or the pluck of the harpsichord.

Unlike the harpsichord, this action gives the clavichord player direct dynamic control over the sound by varying the speed at which the key strikes the string and the force exerted while the sound is sustained. Because of these variables, the actual string excitation in a clavichord is more difficult to analyze than the vibration of a harpsichord string. The displacement of 1–2 mm caused by the key action typically takes about 10 ms, during which time a displacement wave has been able to travel some distance along the string. The displacement of the tangent then becomes steady and the string vibrates under the influence of its initial displacement and velocity distribution. Analysis shows that the force on the bridge typically has a spectrum that falls fairly smoothly at about 8 dB/octave (Thwaites and Fletcher 1981). Because the displacement of the string by the tangent increases its tension by a small amount, the player can even create a slight pitch vibrato effect, called *Bebung* in German, by varying the finger force exerted on the key.

The loudness and tone quality of the clavichord sound depends greatly on soundboard material and thickness, as well as on its size and the dimensions of the mousehole(s). The sound level at a 2-m distance for the reproduction Hubert instrument is a very quiet 50 dB(A), fairly uniformly across the compass. The decay time to inaudibility, which is also important for sound quality, is around 4 s over most of the compass, but decreases to less than 3 s in the top octave, measured at the same 2-m distance in a fairly quiet environment. Very similar measurements were earlier reported for a modern version of a triple-fretted instrument (Thwaites and Fletcher 1981).

The fact that each note is produced by two strings tuned to the same pitch has a very subtle effect that was carried on to the pianoforte. Vibration of the two strings is not independent, because they both run over the bridge that is not completely rigid. While the strings are nominally tuned to the same frequency and struck in the same way, there are always slight differences, and the slight bridge motion tends to couple the vibrations of the two strings, adding further complications (Weinreich 1977). When the strings are moving in the same direction, the force on the bridge is large and the radiated sound is greatest, but it decays quickly. When the strings vibrate in opposite directions, the force on the bridge is small and the sound is quiet, but it decays slowly, taking as long as 4 s to reach inaudibility. The total sound of the instrument therefore has a relatively loud onset, which decays quickly to a more sustained quieter sound, the total effect to a listener at close range being of clarity combined with mellowness.

8.4 Keyboard Tuning

There are two important features of keyboard tuning. The first is the overall pitch, which is generally specified by giving the frequency of A_4, and the frequencies of the individual notes within an octave span. Most modern musical instruments are tuned to standard pitch of $A_4 = 440$ Hz, though there are minor variations such as 442 Hz for the Boston Symphony Orchestra. In earlier times, however, there was no such standardization, and today we regard A392 as French Baroque pitch, A415 as Baroque pitch, A430 as the Classical pitch used by Mozart, and A466 as Renaissance pitch. (These nominal frequencies have, however, with the exception of A430, been adjusted slightly to conform to notes of the normal A440 scale so that they can be reached by simple transposition.) Changes in overall pitch can also have the effect of changing the perceived tone quality of a performance because of the slightly different prominence of harmonics and also the slightly different decay times. Both the instruments examined in detail above were tuned to A415.

The second feature concerns the exact tuning of notes within the octave. Most musical instruments allow the performer at least some control over the pitch of the individual note being played, but this is not true of keyboard instruments. It is therefore important that the strings of the instrument be tuned to exactly the desired frequencies, and this raises important problems. Each note produced by a musical instrument has a fundamental accompanied by a whole set of overtones of higher frequencies. In a stringed instrument, provided the strings are very thin and tightened to a high tension and that the supports at each end of the string are very nearly rigid, the overtone frequencies will be almost exact integer multiples of the frequency of the fundamental, and are then called *harmonics* – the nth harmonic having frequency n times that of the fundamental. (It should be noted that scientific and musical terminologies are in disagreement here, since musicians often confusingly refer to the first overtone, which has frequency twice that of the fundamental, as the *first harmonic*, whereas it is scientifically the second. In this chapter we adhere to the scientific terminology.)

The tuning of the keyboard is required to produce combinations of notes that sound pleasant, rather than rough. If one of the harmonics of the first note has a frequency very close to that of some harmonic of the second note, then this will produce fluctuating *beats* in the sound. A very slow beat is not unpleasant, but rapid beats make the interval sound rough. The aim therefore is to tune the notes of the keyboard to eliminate fast beats as much as possible. This initially resulted in the classic "Pythagorean" tuning, in which octaves were tuned to the frequency ratio 2:1 and perfect fifths to the similarly acoustically pure ratio 3:2. It might appear to be possible to tune the whole keyboard by following the "cycle of fifths" C, G, D,. . ., F, C, but unfortunately the final C (really B#) is substantially sharper than would be found by stepping up pure octaves from the initial C, which is a discrepancy known as the *Pythagorean comma*. This is clear from arithmetic, because 3/2 raised to the power of 12 to complete the cycle of fifths is certainly not an integer, which it needs to be to match 2 raised to the power of 7, which brings one to the same note reached by octave intervals. The error, allowing for octave transpositions, is $(3/2)^{19} - 1$, which is about 1.4%, or about a quarter of a semitone, because one semitone is a frequency change of about 5.9%.

There is, however, another problem that arose when musicians began to use major thirds in their compositions several centuries ago. A *just* major third has a frequency ratio 5/4, which is smooth and pleasant. A Pythagorean major third, however, tuned for example by the sequence of four perfectly tuned fifths CGDAE and a two-octave jump downward, has a frequency ratio 81:64, which is far from being simple, so that the Pythagorean major third has a rather different and somewhat "sharp" sound. This discrepancy between a Pythagorean major third and the just ratio of 5/4 is called the *syntonic comma* and is a frequency difference of about 1.25%, or about a fifth of a semitone.

Is it possible to tune a keyboard exactly? Unfortunately arithmetic defeats us once again, and it is not possible to devise a tuning with both exact fifths and thirds in all keys when there are only 12 distinct pitches available in the keyboard octave. A once-popular tuning called *quarter-comma meantone* tunes all the fifths flat by a quarter of the syntonic comma, which is not very much. This gives perfectly in-tune thirds in several useful keys, but several keys are completely unusable and there are no enharmonic equivalents available – each note has only one name, G-sharp or A-flat, for example, and must be tuned as such (Kottick 1987; Haynes 2002; Barbour 1951; Lubenow and Meyn 2007; Sethares 1998).

While meantone tunings were commonly used from the beginning of the sixteenth through to the middle of the nineteenth century, some innovative musicians or theoreticians devised better compromises, sometimes known now as *well temperaments*, which allowed music to be played in any key (Barbour 1951; Lubenow and Meyn 2007; Sethares 1998). Two of the most successful of these were Werckmeister III from the early 1700s and the later Kirnberger III of 1771, Kirnberger having studied under Bach. Bach probably used a slightly different temperament of his own for his famous "48 Preludes and Fugues" of *Das wohltemperirte Clavier* and perhaps encoded details on the title page (Lubenow and Meyn 2007), but in each of these temperaments all keys sound pleasant but subtly different.

The modern solution to all these dilemmas is the total compromise known as equal temperament (Sethares 1998) in which all keys sound equally out of tune. In this temperament all the fifths are tuned flat by about 0.1% to eliminate the

Pythagorean comma, so that all semitone intervals are exactly equal, with frequency ratio $2^{1/12}$ or about 1.0595. The major thirds are still considerably sharp, with a ratio about 1.26 instead of 1.25, which is about one-sixth of a semitone mistuning, but all keys are now exactly equivalent, which is a great advantage for more modern music. Equal temperament might be tolerable with the mellow tone of the modern piano, but it sounds very harsh with the high harmonic content of the plucked strings of the harpsichord. Some harpsichordists use equal temperament for simplicity or because of familiarity, but classical music sounds better and more authentic in an appropriate tuning, and these are enjoying a revival.

There is one further thing related to tuning that should be mentioned. The requirement that the strings of a musical instrument be thin and under high tension ensures that the prime restoring force on a displaced string is that of tension, rather than that of string stiffness. This is true for the harpsichord and clavichord, but not for the piano, which uses much thicker strings. This leads to *inharmonicity*, where the overtone frequencies are all stretched a little bit above those of true harmonics. The octaves on a piano must be tuned to a frequency ratio a little greater than two, so that there are no prominent beats and the interval sounds "in tune." The result is that the tuning of a grand piano is stretched by about half a semitone across the whole keyboard range, though not quite uniformly because of the variation in string length and diameter, so that this does not help with reconciling the Pythagorean comma. This problem does not occur to any significant extent with the harpsichord or clavichord because of their relatively very thin strings. As well as covering possible tunings for standard harmonic sounds, an excellent and interesting analysis of possible tunings for sounds with extremely inharmonic overtones has been given in a book by Sethares (1998), though this extension fortunately has no real relevance to harpsichords!

8.5 Conclusion

The harpsichord and the clavichord were, between them, responsible for the development of nearly all "Western" keyboard music before the advent of the piano. (The exception is music written for the organ, which has a very different background.) As musical tastes changed, these two instruments were largely superseded by the piano in the late eighteenth and early nineteenth centuries, and it seemed that they might disappear forever. Things changed dramatically, however, by the first half of the twentieth century when there was a revival of interest in performing music in traditional style on original instruments, and there is no doubt that performances of great works such as Bach's *Brandenburg Concerto No. 5* sound entirely different and less appropriate when the harpsichord is replaced by a piano. Modern makers of traditional keyboard instruments are active in many areas of the world, and the changes that they have made, such as the substitution of Delrin or Celcon for the natural crow feather quills, have been with the aim of making the instrument more reliable rather than of introducing any fundamental changes to the success of the historic instrument. Long may this revival continue!

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