Origins and Acoustics of the Modern Pedal Harp

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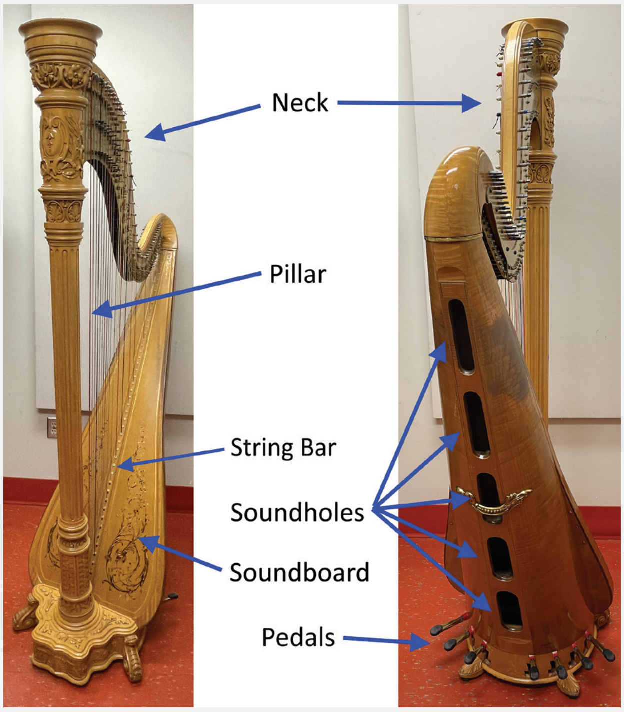
Introduction

Everyone knows what a harp looks like, at least at a distance, and what it sounds like, but few of us have had the chance to get up close and personal with the instrument and to appreciate its complexity and subtleties. Formally, harps are plucked string instruments with many strings arranged in a plane that is perpendicular to that of its soundboard (**Figure 1**). This geometry distinguishes harps from other many-stringed instruments like zithers and lyres, whose strings lie parallel to the soundboard.

Harps have a history going back to at least ancient Egyptian times, and today harps exist in many forms, the most technologically sophisticated of which is the pedal harp, the topic of this article. I concentrate on the pedal harp because it is the harp that concertgoers are most likely to encounter, and it encompasses all the features found in smaller, simpler harps. A general view of the modern pedal harp is shown in **Figure 1**.

Figure 1. *Two views of a pedal harp (Lyon and Healy model 23) showing its basic features. Photographs by C. Waltham.*



A few years ago, I worked with a University of British Columbia (UBC) Vancouver, British Columbia, Canada, music student, Katie Lee, to produce a five-minute video (see bit.ly/3SBGc7X) about the acoustics and mechanical engineering of a pedal harp. It was aimed at those who are not familiar with the instrument. The video takes the viewer on a tour around a pedal harp and ends with a demonstration of the vibrational behavior of the soundbox and a short piece of music played by Hayley Fahrenholtz (see bit.ly/3U2T5IW), who was also then a UBC music student. The images of pedal harps in this article are all of instruments owned by the UBC School of Music. All modern pedal harps have the same basic configuration and differ only in details.

The Anatomy of a Pedal Harp

Walk up to a pedal harp, by which I mean a large instrument of the type found in a symphony orchestra, and it is likely that the first thing you notice is the graceful curve of the neck (**Figure 2**).

The upper part of the neck is made of wood that is varnished or lacquered. Set in this wood is a row of tuning pegs (generally 47) that are turned to tune the strings. The lower part of the neck is faced with brass. In this part, the top row of fittings are the pins that define the vibrating length of each string at the lowest of three possible pitches. Below these are two rows of small *fourchettes* (two-pronged forks) that can be turned to grab a string, shortening its vibrating length to sharpen its

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Figure 2. *Row of tuning pegs (**top**), string pins, and two sets of fourchettes (**bottom**) on the neck of a Salvi Aurora pedal harp. Photograph by C. Waltham.*

pitch by one or two semitones. If the fourchettes are not engaged, the strings are tuned to the pitch a semitone flatter than the white notes of a piano (the A string will play A♭). Engaging the upper fourchette brings the string up to natural pitch (the A string will play A♮). The lower fourchette will raise the pitch one more semitone (the A string will play A#).

Some of the strings are color coded to assist the harpist in finding the right ones. All the Cs are red and the Fs are blue. The lowest pitch strings are wire wound and thick. The highest pitch strings are thin nylon. In between are strings of traditional gut, a natural fiber typically made from sheep or goat intestines. The reason for the choice of gut over much cheaper nylon seems to lie in the way the elasticity of gut under tension differs from that of nylon and the way this difference allows for the production of higher harmonics in the middle pitch range (Woodhouse and Lynch-Aird, 2019). The bottom ends of the strings are connected to the soundboard (also called the table), which forms the front face of the soundbox (**Figure 1**). The string attachment points are reinforced with nylon plugs in the central string bar because the large tension, particularly on the lower strings, would rapidly pull the strings into the wood. The face of the soundboard is spruce with the grain running longitudinally and is often decorated. However, the inside of the soundbox, which can be seen through the soundholes in the back, is spruce with a *horizontal* grain (**Figure 3**).

The soundboard is made up of several parts. The most important parts acoustically are the horizontal slats, made of spruce, 30-80 mm wide, and glued together. These constitute the part of the structure that provides the optimum combination of strength, resonance, and sound radiativity. What you see from the front of the harp is a thin veneer, applied mostly for aesthetic reasons but also to add some additional strength to the soundboard against the outward pull of the strings (Firth and Bell, 1988). It is important to recognize that the total string tension on a harp such as this is on the order of 12 kilonewtons (kN), or over a ton in weight (Waltham, 2010). Thus, the designer of a harp soundbox must contend with two competing requirements: the soundbox must be light and mobile to radiate sound but stiff and strong to resist the string tension.

Moving down from the soundholes, we get to the pedals (**Figure 1**). These and their attendant linkages to the fourchettes are what allows the harpist to handle a change of key in the middle of a piece of music. Each pedal has

Figure 3. *View through a soundhole of a Lyon and Healy Concert Grand pedal harp. The vertical strip of wood down the center holds the string attachments. **Blue knot:** end of an F string; **red knot:** end of a C string. Photograph by C. Waltham.*

Figure 4. *A Lyon and Healy Concert Grand, with University of British Columbia (UBC), Vancouver, British Columbia, Canada, harp professor Elizabeth Volpé Bligh (see bit.ly/47N8OPx). Photograph by C. Waltham, with permission from Volpé Bligh.*

three possible positions: flat, natural, and sharp. The leftmost pedal affects all the D strings, the next pedal to the right affects all the C strings, and so on, through B, E, F, G, and A. The pedals are connected, via a complicated mechanism, to the fourchettes on the neck (**Figure 2**).

The brass plates enclosing the linkages also add to the stiffness of the neck, which helps support it against the large twisting force from all the strings that are all connected on one side of the neck. Between the base and neck, the linkages must pass through the pillar of the harp (**Figure 1**), whose mechanical function is to support the neck against the combined tension of the strings.

Playing the Harp

Harp music is notated like piano music. During playing, the right hand handles the higher strings and the left, the lower. The top of the soundbox sits against the harpist's shoulder (**Figure 4**). The strings are plucked usually between a third and a half the way up from the soundboard. When appropriate, the strings may be plucked *près de la table*, meaning close to the soundboard to give a more extended spectrum. The strings can be plucked with the fleshy part of the fingers or, occasionally for a harder spectrum, with the nails. Because the strings vibrate for a long time, they frequently must be muffled to prevent short notes from blurring together, and there are many techniques for doing this (see bit.ly/48Y62Z2). It is also possible to play harmonics (in the musician's sense of the word) by gently touching the midpoint of the string with the base of the thumb and plucking the string with the thumb. The sound thus produced is ethereal (bit.ly/48C9RDk). Last, the soundbox may be used like a box drum and tapped, knocked, or slapped, producing a wide variety of sounds (see bit.ly/47HoGmC).

A Brief History

The earliest harps were of the "open" or "arch" variety. The frame was L-shaped, with the strings joining the necks and the soundboxes with no pillar to support the structure against the tension of the strings (**Figure 5**). Their sound tables were made of skin or wood (in the case of ancient Egypt, it is not clear which). Open harps continue to be played in various parts of the world and in particular in Africa (Fabre et al., 2023) and Southeast Asia (Williamson, 2010). The first frame harps (i.e., those with pillars) appeared briefly in classical Greece and Italy,

Figure 5. *Various configurations of open harps from Egypt. From Popular Science Monthly vol. 40, in the public domain via Wikimedia Commons.*

but this form was apparently forgotten until it reemerged in northwest Europe around 800 CE (Rensch, 2007).

In the last millennium, there have been three main areas of harp development: string materials, soundbox construction, and pitch-changing mechanisms. The first two tended to go together because better strings meant higher tension, which required stronger soundboxes. Harps need many strings to have a useable pitch range. Moreover, because of the attachment angle, the combined normal force on the soundboard can be enormous, and yet it must be flexible enough to radiate sound. Various sharping mechanisms were developed to be able to play harmonically more complex music without the number of strings proliferating (Rensch, 2007).

Early frame harps had soundboxes carved from single pieces of wood, particularly those from Ireland and the Scottish Highlands (Hadaway, 1980). Irish harps of this period were carved from logs of willow or yew. Strings were variously made of copper, bronze, brass, horsehair, silk, and gut (Firth, 1988). Tensions were low, as was the sound volume, which restricted the instrument to performance in small spaces.

Over the centuries, strings became stronger and more capable of withstanding higher tensions, and soundboxes evolved accordingly. The development of strong glues and improved cutting techniques allowed for the creation of thinner, stronger soundboxes, leading to the composite soundboards we see on pedal harps today.

A well-known example of a small German harp from the end of this early period (1700) is in the Boston Museum of Fine Arts (MFA), Boston, Massachusetts. The museum has published detailed plans of this harp, and I made a replica (**Figure 6**) and later published some of its vibroacoustic properties (Daltrop et al., 2012). This style of instrument is often referred to as "Gothic," the name being inspired by the shape of the neck.

Figure 6. *Replica of the Boston Museum of Fine Arts, Boston, Massachusetts, 1700 German harp made by C. Waltham. Photograph by C. Waltham.*

The instrument is entirely made of maple. It stands 130 cm high and has 36 strings. The lower strings are wrapped nylon and the upper strings are plain nylon. With a one-piece hardwood soundboard, this harp is a quiet instrument. Its pleasant tone can be heard in a sound clip on the Boston MFA website (see bit.ly/40ww42e) in which Nancy Hurrell is playing a replica made by Catherine Campbell of Port Townsend, Washington. However, as was common in this era, brays (**Figure 7**) were added to the soundboard at the string attachment points to boost the sound volume by buzzing against the vibrating string. The effect is an acquired taste (listen to historical harpist Bill Taylor playing a bray harp; available at bit.ly/40C4YXQ).

Figure 7. *Brays on the Waltham's replica of the German harp. The bray height can be lowered (by pushing into the soundboard) to make contact with the vibrating string. Photograph by C. Waltham.*

I have not engaged the brays on my harp (neither are they in the audio clip on the MFA site).

After 1700, more reliable glues and increasingly precise cutting techniques meant that soundboards could be made of multiple shorter pieces, with the wood grain running transversely, the better to withstand the string tension. These shorter pieces could also be made of resonant softwoods like spruce rather than stronger but stiffer hardwoods. As a result, brays disappeared. Music was changing, becoming more chromatic, and harps started appearing with multiple courses of strings, culminating in the Italian and Welsh triple harps of the eighteenth century (Firth, 1989). These harps had two outer courses of "white" notes, with a course of "black" notes in-between (see bit.ly/422eOTj). Apart from being ferociously difficult to play, this arrangement made yet more demands on the strength of the soundboard. Later, harp makers devised various means to allow semitone pitch changes, which allowed a smaller number of strings. In the latter half of the seventeenth century, harp makers in the Austrian Tyrol invented a manual hook mechanism that shortened the vibrating length of the string, raising the pitch a semitone (Rensch, 2007).

However, it was in France at the end of the eighteenth century that *pedal* harps emerged, allowing the sharping mechanism to be operated with the harpist's feet while music was being played (Rensch, 2007). The pedal mechanism developed through two intermediate phases, notably by Parisian makers Georges Cousineau (1733–1800) and François-Joseph Naderman (1781–1835). One was the *crochet* ("hook") in which the string was pulled against a stop. The second was the *béquille* ("crutch") in which two levers pressed on either side of the string. The form of pedal mechanism we see today is due to Strasbourg-born Parisian Sébastien Érard (1752-1831), who invented a device called the *fourchette* ("fork"), as described in **The Anatomy of the Pedal Harp**, where two "prongs" on a rotating disk grab the string. Ultimately, Érard added a second fourchette to each string, which could then be tuned flat. Érard patented this now ubiquitous "double-movement" seven-pedal action in 1810, and most modern pedal harps follow this pattern. (**Figure 8**).

The development of this instrument, whose construction requires precision wood and metalwork, had a lot in

Figure 8. *An 1828 Érard "double-movement" seven-pedal harp. The three positions available to each pedal can be seen at the base of the instrument, as described in* ***The Anatomy of the Pedal Harp.*** *Photograph by C. Waltham, from Kenwood House (Iveagh Bequest) owned by the English Heritage, London, United Kingdom, with permission.*

common with that of the piano, discussed in an earlier article in *Acoustics Today* (Giordano, 2016). Indeed, Érard was also famous for his pianos (Encyclopaedia Britannica, 2023). If the violin is a quintessential product of the Italian Baroque, the harp is a product of revolutionary France in the turbulent years between the end of the eighteenth century and start of the nineteenth. Érard had to cross the English Channel several times to evade the guillotine (he was uncomfortably close to Louis XVI and Marie Antoinette) and then the Continental Blockade. As a result, he set up manufactories in both Paris and London.

Physics and Acoustics of the Harp

The Sound of a Harp

To my knowledge, there has been no formal blind study that shows whether listeners can distinguish the sound of a single plucked harp string, out of context, from that of any other string instrument of the same pitch. However, aspects of the harp's unique geometry and mode of playing suggest how we might be able to recognize its sound. First, harp strings are plucked close to their centers with the fleshy part of the finger, which produces a mellow sound with a spectrum that is stronger in the fundamental and a few low harmonics compared with, say, a guitar string plucked close the bridge, especially if done so with a plectrum (Le Carrou et al., 2007). Readers can compare the guitar with a pedal harp in a delightful sonata for both instruments by Alan Hovhaness (see bit.ly/48XiUOR).

Second, unlike a piano, the rest of the strings of the harp are not damped and are strongly coupled to each other via the flexible soundboard. Thus, when you pluck a particular harp string, all the other harmonically related strings (i.e., octaves, fifths, fourths) will start vibrating. The result has been described picturesquely as a "halo of sound" (Le Carrou et al., 2009) that seems to envelope the instrument and is particularly noticeable as a harp is being tuned (see bit.ly/3O68dBA).

Third, and this is more technical and probably has a more subtle effect, the vibrating string does not simply energize the soundboard with small changes in its attachment angle as it vibrates, which is what happens in a guitar (Houtsma et al., 1975). Instead, the large angle the harp string makes to the soundboard means that changes in the *tension* of the string will also vibrate the soundboard (Waltham, 2010). The distinction is that the string tension changes as the string vibrates but with twice the fundamental frequency of the string, thereby enriching the sound spectrum (and causing some pitch glide). The effect is enhanced by the fact that the pluck amplitude can be large, only limited by the string spacing (about a dozen millimeters). One suspects that this effect is less obvious to the listener than the first two, but it is nonetheless demonstrably present (Woodhouse, 2022).

The Role of the Soundbox

The soundbox of the harp functions as all soundboxes do. Strings on their own do not vibrate enough air to make an appreciable sound, and so they are arranged to transmit their vibrations to a soundboard of much larger area, which then radiates the sound. Making a simple soundboard that will vibrate at the fundamental frequencies of the lowest harp strings would require a piece of wood much too thin to support the tension of the strings. This is also true of guitars and violins, even with the vastly smaller string tensions that these instruments must deal with. However, with the harp, the problem is acute. This is where the soundholes come in. The air in the hole vibrates against the air in the cavity and forms a coupled oscillator with the vibrations of the soundboard wood (Bell, 1997). Then, like all coupled oscillators, these two vibrations combine into two composite vibrations, one of lower frequency than either of the other two and one of higher frequency (Caldersmith, 1978). Although the soundholes allow the soundbox to radiate at a lower frequency than it would without them, harp strings go so low in pitch that a dozen or so of them have lower fundamentals than the soundbox can radiate (Daltrop et al., 2010).

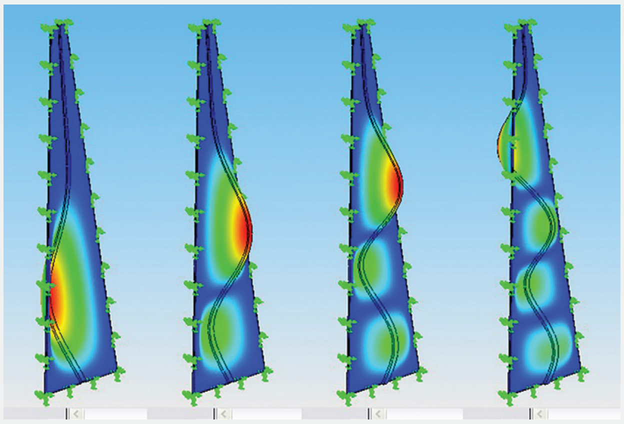

Figure 9. *First four vibration modes of a harp soundboard in a finite-element simulation. The lowest frequency mode is on the* ***left.*** *Figure by C. Waltham.*

Incidentally, this is also true for the G-string on a violin. The rest of the solution comes from the human ear and brain where, if we perceive enough higher harmonics, we mentally fill in the gap of the "missing fundamental" (Fletcher 1924) and do not notice its absence.

The Shape of the Soundboard

The trapezoidal shape of almost all harp soundboards can be explained with a simulation of the first few vibration modes of such a shape (see **Figure 9**). For the lowest frequency mode, the soundboard is vibrating at its wider (bass) end. For higher modes, the region of greatest vibration moves progressively up toward the treble end of the board. It would be nice if this progression in frequency could be matched to the pitches of the strings, but this is not possible because the board frequencies rise arithmetically (e.g., 1, 2, 3, 4), and the string frequencies rise geometrically (e.g., 1, 2, 4, 8). However, individual modes have a fair spread in frequency and strings have many frequencies (fundamental and harmonics) so the chance of a string being completely dead (unable to vibrate the soundboard at any of its frequencies at that particular attachment point) is small.

Harp Music

The pedal harp can handle a wide variety of musical styles, for example, jazz (see bit.ly/48XaPtE) or rock (see bit.ly/3HwTlsd). However, forgive me if I stick with the Western classical canon with which I am most familiar. Even narrowing the field like this, there is a large repertoire of solo harp music written by composers, mostly unknown to nonharpists, who only wrote for the harp (see bit.ly/41YQF09). To single out one such composer, I recommend readers focus on the still living Bernard Andrès (1941–), who's haunting *Elegie Pour la Mort d'un Berger* features many of the playing techniques I have mentioned in ***The Sound of the Harp*** (see bit.ly/3SnLdAP).

In the context of orchestral music, composers need to recognize that, like any plucked string instrument, the harp is quiet compared with bowed instruments. The loudest sound it can make is a glissando (see bit.ly/4bekuhx), and composers frequently use this as the auditory icing on the cake during a dramatic orchestral *tutti,* where everyone is playing at maximum volume. Otherwise, to give the harp prominence, the rest of the orchestra must quiet down. The harp cadenza at the start of the "Valse des Fleurs" from Tchaikovsky's *Nutcracker Suite* is a famous example (see bit.ly/3U48pF9). Harp concerti tend to work the best with a baroque orchestra (see bit.ly/47E5l5S) or, for more modern works, a chamber orchestra scored with a light touch (see bit.ly/3O8c29l).

Smaller Harps

Although full-size pedal harps tend to be alike in size and number of strings, differing largely in the style of decoration, smaller harps abound, often made by amateurs. In fact, for someone wishing to gain experience in instrument making, a small harp is probably the simplest and most satisfying project to start with. The complexities of a pedal

Figure 10. *Detail of sharping levers on a Celtic harp. Figure by E. Volpé Bligh, with permission.*

harp soundbox can be dispensed with and replaced with a box of thin, good-quality plywood. Small harps are known variously as folk harps, Celtic harps, or lap harps (for the smallest). If they have any sharping mechanism at all, it is with small levers mounted on the neck (**Figure 10**). These levers raise the string pitches by a semitone and are usually set at the beginning of a performance, although a dextrous harpist can effect changes midstream when needed by an accidental or a change of key. As with the members of the violin family, the smaller the soundbox, the higher the frequencies of sound radiated, and lever harps tend to have a lighter sound than the larger pedal harps (bit.ly/48UmRnw).

Conclusion

For readers not hitherto familiar with the pedal harp, I hope this article has given a taste of the instrument and its subtleties and complexities and thus increased the enjoyment of the music and respect for the talent of those who play it.

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