

Chapter 22

Electric Guitar and Violin

Colin Gough

Almost all the instruments described in this book have their origins in historical cultures dating back over many centuries. In contrast, the electric guitar and violin are clearly twentieth-century innovations. They are products of the electronics age following invention of the rectifying thermionic valve (tube) by John Ambrose Fleming in 1904, the amplifying triode valve (tube) by Lee de Forest in 1907, and the vacuum-filled amplifying valve (tube) by Irving Langmuir in 1915. By 1916, such valves were already being used in radio receivers, and important advances were being made in microphone, amplifier, and loudspeaker design. This, and the increasingly wide distribution of mains electricity in the 1920s, provided the technology and infrastructure for the development of the electric guitar and violin and their lower-pitched relations – the bass guitar, viola, cello, and string-bass. Although we focus here on the electric guitar and violin, almost everything discussed in this chapter is also relevant to their lower-pitched relations.

In the first section, we briefly describe the emergence of the electric violin and guitar within the context of early acoustic recordings, and radio and public performances, in which conventional acoustic stringed instruments such as the guitar and violin were placed at a huge disadvantage compared to the much louder wind and brass sections of big band groups and orchestras. We then describe in a little more detail the early innovations, which led to today's familiar shapes and sounds of today's electric violin and guitar. The third section describes the design and influence on the sound of magnetic and piezoelectric pickups, with a brief interlude on some of the special effects that characterize the sounds of many guitarists and pop music groups of the 1960s and onward. We conclude by describing the use of the electric violin in advancing our understanding of the acoustics of the traditional violin and especially those factors in the perceived sound and quality that can be related to the damped, multiresonant, filtering action of the violin shell.

There are a number of publications describing the history and design of the electric guitar and violin (Bacon 2006; Evans 1977; Graesser and Holliman 1998;

C. Gough (✉)
44 School Road, Birmingham B13 9SN, UK
e-mail: profgough@googlemail.com

T.D. Rossing (ed.), *The Science of String Instruments*,
DOI 10.1007/978-1-4419-7110-4_22, © Springer Science+Business Media, LLC 2010

393

Submitted text

Almost all the instruments described in this book have their origins in historical cultures dating back over many centuries. In contrast, the electric guitar and violin are clearly 20th century innovations. They are products of the electronics age following Fleming's 1904 invention of the rectifying thermionic valve, the amplifying triode valve by deForest in 1907, and the vacuum-filled amplifying valve by Langmuir in 1915. By 1916 such valves were already being used in radio receivers and important advances were being made in microphone, amplifier and loudspeaker design. This, and the increasingly wide distribution of mains electricity in the 1920's, provided the technology and infra-structure for the development of the electric guitar and violin and their lower pitched relations – the bass-guitar, viola, cello and string-bass. Although we focus on the electric guitar and violin, almost everything discussed in this chapter is also relevant to their lower pitched relations.

In the first section, we briefly describe the emergence of the electric violin and guitar within the context of early acoustic recordings, radio and public performances, in which conventional acoustic stringed instruments like the guitar and violin were placed at a huge disadvantage compared to the much louder wind and brass sections of big band groups and orchestras. We then describe in a little more detail the early innovations, which led to today's familiar shapes and sounds of today's electric violin and guitar. The third section describes the design and influence on the sound of magnetic and piezo-electric pickups, with a brief interlude on some of the special effects that characterise the sounds of many guitarists and pop-groups of the 1960's and onwards. We conclude by describing the use of the electric violin in advancing our understanding of the acoustics of the traditional violin and especially those factors in the perceived sound and quality that can be related to the damped, multi-resonant, filtering action of the violin shell.

There are a number of publications describing the history and design of the electric violin guitar and violin [1,4, 9, 17, 18] and a wealth of information available on the web [e.g. www.digitalviolin.com]. Most of the important innovations were made by designers working for commercial companies - mostly in America - with freely downloadable patent applications[www.google.com/patents] providing details of important developments. These will be frequently referenced in the form [Charles Chew 1885/7 US 358542] - an early patent for a silent, stick-like, practice violin, similar in shape to many modern electric violins, where the application and awarding dates are both indicated.

X.2.1 Historical Background

In acoustic recordings – before 1925 – all the energy required to cut the grooves in the recorded discs had to be supplied by the sound of the performer's voice or instrument. This placed stringed instruments like the violin and guitar at a major disadvantage relative to much louder wind and brass instruments - see, for example, Day [2] for a fascinating account of such problems. This led to several attempts to develop louder stringed instruments, including the use of steel-cored strings and the use of additional acoustic resonators and horns attached to stringed instruments. Several of those active in such innovations were later at the forefront of the development of electric instruments and many of the early designs retained features of these earlier instruments.

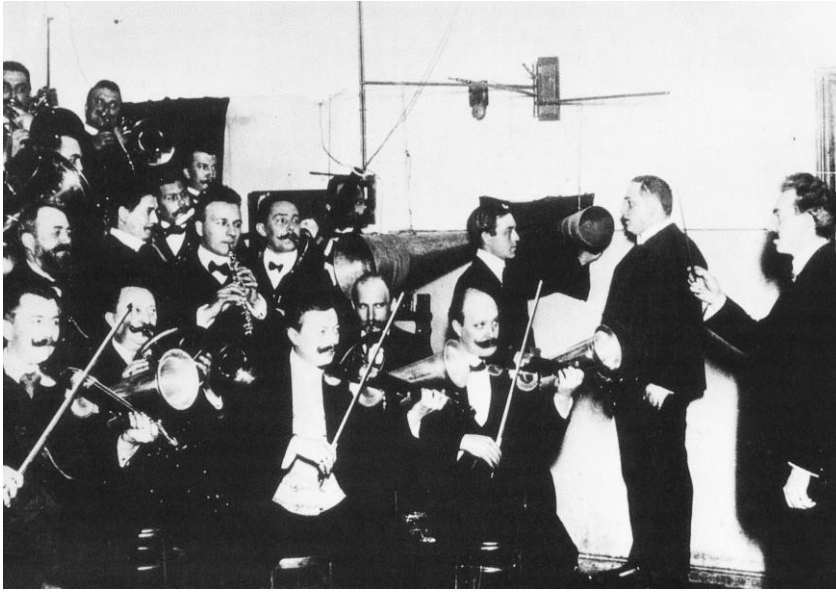


Fig. 1 shows a typical 1911 recording session in Berlin, with a pair of recording horns driving a single cutting head - one horn for the singer and the other for the orchestra. The violinists are all playing solid-body Stroh violins [10] with acoustic horns attached. In early orchestral recordings, saxophones were often used to boost the sound of the violas, while tubas replaced the cello and double-base [2].

Fig 1. 1911 acoustic recording session in Berlin with all the violinists playing Stroh violins.

The electric guitar and violin were developed in the late 20's and early 30's, with most of the technology used today already established, at least in rudimentary form, by the early 40's. The first electric guitars used a magnetic pickup on all-metal, Hawaiian-style, guitars – instruments with steel-cored strings played across the lap. The use of magnetic pick-ups on Spanish-style, hollow-bodied, guitars initially proved troublesome – with problems from distortions, overtones and acoustic feedback. To circumvent many of these problems, Les Paul, Paul Bigsby and Leo Fender in the early 40's pioneered the use of solid-bodied wooden guitars using compact magnetic pickups very similar to those in use today.

By the late 30's and early 40's the electric guitar and violin had become firmly established in jazz- and big-band groups – and were features in bands like Bert Lynn's All-Electric Orchestra, with the whole string section playing electric instruments (see photographs in Smith [18, p15]). By 1940, the outstanding jazz guitarist Charley Christian, playing and recording with the Benny Goodman Band, had established the electric guitar as an instrument with its own unique voice. Christian played on the Gibson ES-150 Spanish guitar, with a state-of-art magnetic pickup that still remains popular amongst jazz guitarists and is still known as the Charley Christian pickup.

There was a slight hiatus in the development of electric instruments in the war years, but by the 1950-60's, several commercial companies were producing a wide range of solid-bodied electric guitars, which were defining the distinctive sounds of popular music - and of rock and rock-and-roll in particular - and later variants like punk and heavy metal.

It took somewhat longer for the electric violin to be widely adopted into popular musical culture, though today almost every pop group includes an array of electric violins and often cellos and string-basses in the backing group.

The electric guitar - and to a lesser extent the electric violin – first transformed and now defines the sounds of popular music. The electric guitar is commercially the most successful of all musical instruments in the Western World – and almost certainly outstrips the sales all other stringed instruments put together. We now trace the development of the electric guitar and violin in a little more detail.

X.2.2 The electric guitar

In 1923, Lloyd Loar of the Gibson Mandolin-Guitar Company demonstrated what appears to have been the first electric guitar. The electric signal was generated by a modified carbon-granule microphone, which sensed the vibrations of the bridge induced by the plucked strings. However, the output was rather erratic and particularly susceptible to humidity. Unsurprisingly, attempts to market it in 1929 by the Stromberg-Voisinet Company were unsuccessful.

Arguably the most important figure in the development of both electric guitars and violins was George Beauchamp, a Texan born violinist and Hawaiian guitar player. In 1926, in a collaboration with five Dopyera brothers, he set up the National Guitar Company, with the initial aim of producing acoustic Hawaiian guitars with an array of hollow metallic resonators attached to the bridge [Smith 1987]. The Dopyera brothers had previously manufactured banjos, but these were declining in popularity by the early 1920's. The early National instruments were Hawaiian-style guitars with cast aluminium bodies. They were manufactured by the Rickenbacker Company, which by 1925 were producing as many as fifty guitar bodies a day. National ultimately produced two types of guitars - a conventionally shaped guitar with a round neck, mostly used by blues musicians, and a Hawaiian style instrument with a flat neck

George Beauchamp, in collaboration with Paul Barth, developed a more compact magnetic pickup (Barth 1941/43, US 2310606), which sensed the vibrations of the strings directly – the forerunner of all magnetic pickups in use today. An earlier version is included in his 1934 patent application (Beauchamp 1934/37, US 2089171) for the banjo-style Hawaiian guitar, shown in Fig.2a. The pickup used a pair of horseshoe magnets, with pole-pieces under each string to concentrate the magnetic field into these regions. A single large coil, wound around the six pole-pieces, sensed the changes in magnetic flux as the plucked strings vibrated towards and away from the ends of the pole pieces. Magnetic pickups rely on the strings being magnetic, so cannot be used with gut or nylon strung acoustic instruments.

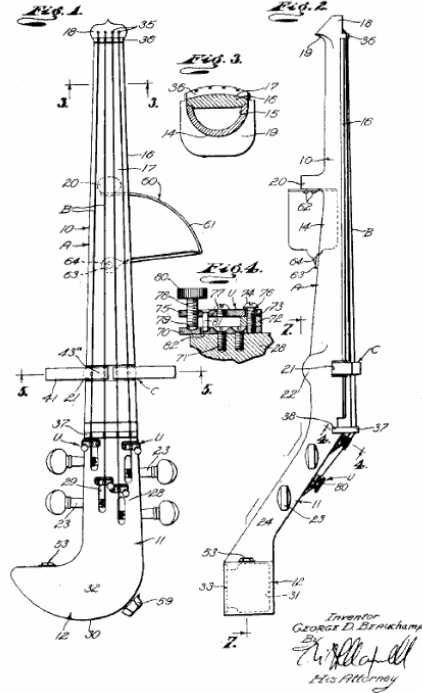
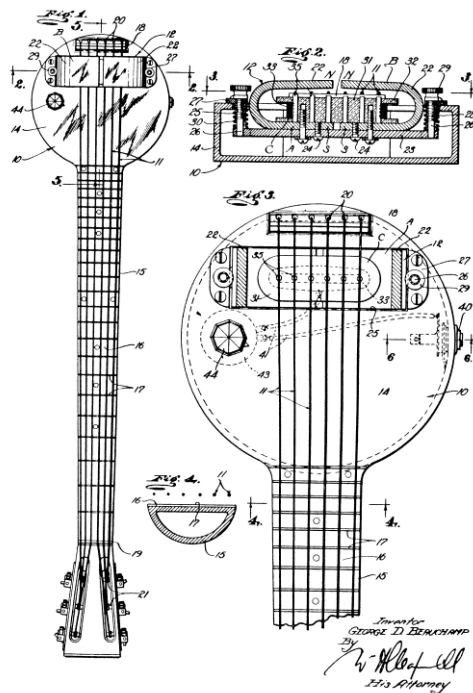


Fig.2 Beauchamp's patent applications for (a) the "Frying Pan" guitar and (b) electric violin.

Beauchamp and his colleagues subsequently formed the "Ro-Pat-In Corp" to manufacture electric guitars and by 1932 were marketing both the "Frying Pan" model illustrated in Fig.2a, and a more conventionally-shaped wooden model, the "electro Spanish guitar". In 1934, the company was renamed the Electro String Instrument Corporation and the guitars referred to as "Rickenbacker Electros". By 1936, the company was also manufacturing electric mandolins, bass viols, violins, cellos and violas, in addition to guitars.

The next significant development was a very much more compact, single-coil, magnetic pickup designed by Walter Fuller for the Gibson Company (Miller 1938/39, US 2145490). It was originally developed in 1935 for the EH-150, Hawaiian-style, electric guitar, and was subsequently used on the 1936 ES-150 hollow-bodied wooden guitar, which is still considered one of the best sounding electric jazz guitars [18]. In 1946 Gibson introduced their first solid-body electric guitar using a newly designed P-90 magnetic pickup, and in 1957 introduced the humbucker pickup – designed to eliminate pickup from mains power supplies - which is widely used on many modern instruments.

By 1937 a number of companies in addition to Gibson and Rickenbacker - National-Dobro, Epiphone, Tutmark and Audiovox - were also manufacturing a wide range of electric instruments, including easily portable, upright, electric string basses.



Fig.3 Modern replicas of famous guitars of the late 1950's by three of the most influential American electric guitar manufacturers. Famous players using such instruments are also indicated.

Since 1929, the famous guitar player Les Paul had been experimenting with solid-bodied electric guitars at week-ends [18]. In 1941 he produced "the Log", with the strings and magnetic pickups mounted on a solid length of 4x4" wood. This allowed the plucked string to ring for very long times, since very little energy is transferred to the body at the bridge. However, it was left to two of his friends, Leo Fender and Paul Bigsby, to be credited with the first "modern-style" solid-body guitars [18]. Fender quickly set up the Fender Electrical Instrument Company - to patent and manufacture such instruments (Fender 1951/51, US Des. 164,227). Their instruments also incorporated a vibrato- or tremolo-arm attachment originally developed by Bigsby[18] and the subject of a later patent by Fender (Fender 1954/56, 2741146). By 1948 Fender had introduced its "Broadcaster" guitar, renamed the "Telecaster" in 1950. In 1952, Gibson introduced their first solid-body guitar, designed in consultation with Les Paul after whom it was named, while Fender introduced its three-pickup "Stratocaster" guitar in 1953 [18].

Modern replicas of some of these famous instruments are shown in Fig. 3. Such instruments became the Stradivari and Guarneri instruments of the burgeoning world of leading rock bands and the iconic artists of the 1950's and early 60's. Original electric guitars have fetched very high prices in the sale rooms, with a Fender Composite Stratocaster of ~1956/7, played by Eric Clapton, sold for \$959,500 in 2004 at a charity auction Christie's in New York. A Fender Stratocaster played by Jimi Hendrix at the Woodstock Festival is believed to have been sold privately for considerably more [The Sunday Times, December 12, 2004].

The subsequent development of electric guitars included many futuristic designs including instruments with double necks - initially by Semie Moseley in 1954 followed by Gibson in 1958. The use of solid wooden bodies led to guitars with completely differently shaped bodies,

like Gibson's Flying V (1957) and Explorer (1958) models. Smith [18] illustrates the development of electric guitars with many photographs and details of historically important instruments.

The emergence of rock music and rock-and-roll in the 60's led to an explosive growth in the electric guitar market and the development of ever-louder amplifiers and special effects, which helped create the distinctive sounds of such artists and groups as the Beatles, the Rolling Stones, Jimi Hendrix, Les Paul, Eric Clapton, the Cream, the Who, the Yardbirds, Jeff Beck, Led Zeppelin, Traffic, the Doors and many others.

The innovative companies responsible for the initial development of the electric guitar - Gibson, Rickenbacker and Fender - remain amongst the most prominent makers today, though they face increasing competition from many rivals, especially from the Far East. In addition, there are a large number of individual craftsmen creating custom-designed instruments, no longer constrained by traditional designs.

Future developments in consumer electronics and computing will undoubtedly lead to major advances in the ease with which such instruments can be played and the sounds manipulated. Gibson already market a "Robotic" guitar with a computer-controlled tuning system - alongside other electronic refinements. Wireless connectivity is removing the need for cables between the instrument, amplifier and sound system. Inexpensive computer-controlled boxes already exist in the research laboratory, and will undoubtedly be commercialised in the near future, that will enable sounds to be transformed in almost any conceivable way.

X. 2.3 The electric violin

The development of the electric violin followed similar lines to that of the electric guitar with many of the same innovators and companies involved. Accounts of the early development of the electric violin are included in many of the earlier references cited for the guitar [4, 18], and Graesser and Holliman [9], which also includes many fine photographs and detailed descriptions of modern, hand-crafted, instruments.

The first known reference to an electric violin appears in an article written for Radio News, Vol. 8, No. 10, April 1927. It describes the amplification of a conventional violin using a carbon button microphone located close to the treble foot of the bridge, with a battery-driven amplifier and loudspeaker. The editor remarks that "it has been found possible to make the leading violin louder than an entire orchestra by attaching a small microphone to the violin itself and amplifying it to such a degree that the violin will over-shadow a 50-piece orchestra without difficulty".

In 1928, Victor Pfeil patented the first, solid-bodied, electric violin (Pfeil 1928/32, US 181717). The strings were mounted on a stick-like object, with the string vibrations sensed by the rocking motion of the bridge induced by the string vibrations. An iron lever was attached to the underside of the rocking bridge, forcing the lever to move between the poles of a magnet and inducing a voltage in a surrounding coil. A patent in the following year (Eisenberg 1929/33, US 1900489), using a similar rocking-bridge pickup, describes a skeletal-frame body, similar in shape to many modern-day, mass-marketed, electric violins. In France, Gabriel Dimitru also patented a rather similarly instrument [France (Seine), Brevet d'Invention (686,683)]. However, the first electric violin to be commercially marketed was almost certainly

the Vivi-tone violin designed by Lloyd Loar (1933/35, US 2020842) for the Acousti-Lectric Company of Kalamazoo. It also used a rocking bridge magnetic pickup.

At around the same time, the Rickenbacker Guitar Company introduced the “Electro” violin designed by George Beauchamp (1936/38, US 2130174) illustrated in Figs.2b and 4a. The violin used steel strings mounted on a solid bakelite body shaped rather like a short hockey stick. It had no peg-box or scroll, but had tuning pegs mounted on the near-side of the bridge close to the chin, with additional fine-tuning adjusters on each string. An electromagnetic pick-up, with a rather large pair of protruding hose-shoe magnets, was used to sense the string vibrations at about $1/7^{\text{th}}$ of the string length from the bridge. Many features of this initial patent predate supposedly “innovative” features of several modern instruments.

A later Electro model replaced the bakelite body with a hollow metal tube (Beauchamp 1940/43, US 2310199), to which a conventional neck and scroll were attached. This made for a very light string-bass, Fig. 4b. In this later model, the magnetic pickup was located close to the bridge - less in the way of the bow. Smith [18, p15] includes 1939/40 photos of Bert Lyn’s All Electric Orchestra all using Beauchamp’s electric violin, cello and bass instruments (and guitar).



Fig. 4 An early Rickenbacker (a) “Electro” violin (1936) and (b) string-bass (1943) of the later design, both designed by Beauchamp.

The next major advance was made by Hugo Benioff, a geophysicist, who was already famous for designing seismographs around the world, which he used to map the sliding motion of tectonic plates over each other in the resulting areas of intense seismic activity now known as “Benioff zones”. He also measured the strain across the St Andreas fault using a large piezo-electric crystal. Benioff applied his exceptional instrumentation skills to the design and

development of piezo-electric transducers for the violin and cello (Benioff 1938/40, US 2222057) and piano (Benioff 1959/62, US 3049958). In collaboration with the Baldwin Piano Company, he developed a conventionally-strung piano without a soundboard, using instead piezo-pickups at the end of each string to sense and then electronically amplify the string vibrations. A highly acclaimed recital on such an instrument was given by Rosalind Tureck in Carnegie Hall. But to his dismay, the collaboration was terminated, when the company accountants claimed the piano would cost over \$100,000 to manufacture.

On June 13th 1938, the New York Times reported that “after many years of research, Benioff had invented a *Seismographic* electric violin, astonishing musicians by the depth, volume and clarity of its tones”. Many leading musicians tested the instrument and “without exception pronounced Dr Benioff’s invention superior in tone to the orthodox counterparts”. Benioff used a pair of piezoelectric crystals mounted on either side of short and relatively thin, vertical cantilevers, supporting each string. The bending of each cantilever induced a voltage in the piezo-crystals proportional to the force acting on them from the vibrating string. This innovation was the forerunner of the wide range of piezoelectric bridge transducers in common use today and of the later multi-string piezoelectric pickups by Max Mathews [1988/89, US 4860625] and Richard Barbera [1987/89, US 4867027] in particular.

Unlike the electric guitar, the electric violin never became a major commercial success until well towards the end of the 20th century, despite its occasional use in dance and jazz bands in the intervening period. But today, there is scarcely a pop singer or group that does not include an array of electric violins in its backing section. Moreover, the electric violin has a modest presence in classical music, with several leading violinists, like Nigel Kennedy and Vanessa May, and the cellist Yo-Yo Ma, frequently featuring electric instruments in their performances and recordings, often with music specially written for such instruments by leading composers.

One of the attractions of electric instruments is the ease with which additional strings can be added to increase the playing range, with 5- or 6-string violins and cellos commonplace. In addition, electric instruments no longer need to have the large bodies required to radiate sound efficiently. They can therefore be far more robust and compact than their traditional counterparts. Compact electric string basses are particularly popular in many jazz, rock and pop-groups.



David Bruce-Johnson
Violectra



Andy Holliman
The Griffin



John Jordon
Royal Paulownia



Nicholas Tipney
Voyager bass

Fig.5. Three hand-crafted modern electric violins and one bass.

Many companies world-wide now produce electric violins, cellos and basses in addition to guitars. There are also a large number of excellent makers of hand-crafted, custom-designed, instruments. A small selection of such instruments, illustrating the creativity in design afforded by solid bodied instruments, is shown in Fig.5.

There is also a rapidly expanding market for colourful and inexpensive “student-quality” electric violins, which are easier to bow than conventional instruments and can be electronically filtered to give a much more encouraging, less grating, sound than generally produced by a beginner learning to play on a small-sized violin. Moreover the violin can be played silently and listened to through headphones, without distracting the rest of the family or neighbours. A strong argument can be made for beginners to start learning on such instruments until they gained the necessary skills to make an acceptable sound on a conventional acoustic instrument.

X.3 Acoustic, magnetic and piezo pickups

There are currently three main types of pickup used to convert the vibrations of the plucked or bowed strings into electrical signals – acoustic, magnetic and piezo-electric. Each pickup imparts its own characteristics to the amplified sound of the instrument, which is also dependent on the location of the pickup, amplification and subsequent electronic processing, as described in this section.

X.3.1 Acoustic pickups

The easiest way to amplify the sound of a conventional acoustic instrument is to mount a small microphone close to the body, or sometimes even inside the instrument. Alternatively, one can affix an inexpensive thin-film piezo pickup (available as an encapsulated device) to a vibrating surface of the instrument. In both cases, the sound will be somewhat different from the normal

radiated sound, because any microphone or transducer will be sensitive to the air or plate vibrations in the immediately locality of its mounting position, rather than experiencing the sound or vibrations of the instrument as a whole. However, such transducers can easily be attached to an acoustic guitar, violin, cello or bass, without any significant modification, other than requiring some way to attach a lead or wireless connection to the amplifying electronics. A player can therefore easily switch between playing the instrument normally or with electric amplification. The instrument also feels perfectly natural to play and the sound quality remains to a large extent determined by the acoustic properties of the instrument itself – unless significantly changed by subsequent audio signal processing.

A potential problem with any such pickup is acoustic feedback, resulting in the familiar howls of many a public address system when the amplifier gain is too high. Contact film pickups are less susceptible to such problems than microphones. However, contact pickups are more susceptible to microphonics (spurious signals) from accidental hitting or tapping the body of the instrument.

X.3.2 Magnetic pick-ups

From the earliest days of the guitar, magnetic pickups have been used to sense the vibrations of the plucked strings directly. Magnetic pickups were also initially used for the electric violin – sensing the bowed- string induced rocking motion of the bridge. Major advances in design and magnet technology have led the much more compact types of magnetic pickup in wide use on guitars today. In contrast, most electric violins now use piezo pickups attached to or encapsulated in the bridge.

A magnetic pickup works by sensing the vibrations of a plucked steel string vibrating close to one end of a magnetised iron rod or pole. The vibrations change the amount flux passing through the pole piece. This induces a voltage in the surrounding multi-turn coil, which is then amplified and filtered as appropriate. The geometry is illustrated schematically in Fig. 6a. Provided the string vibrations are not too large, the induced voltage will be proportional to the vertical velocity of the wire, assuming the string is located immediately above the pole piece. Any transverse motion will induce a much weaker pick-up at twice the string frequency, since the induced signal will be the same whether the string moves to the left or right.

The stronger the magnetizing field, the larger will be the induced signal. Modern magnets are usually complex alloys of iron, with small additions of aluminium, cobalt and nickel to improve their hysteretic magnetic properties. Professor Errede at the University of Illinois at Urbana—Champaign has published detailed measurements on several hundred commercial magnetic pickups [3]. Typical magnetic field at the ends of the pole pieces are ~ 600-800 G for a fully-magnetised AlNiCo-III alloy, ~ 900-1100 G for an AlNiCo-V alloy, and ~ 800-1100 G for modern ceramic materials.

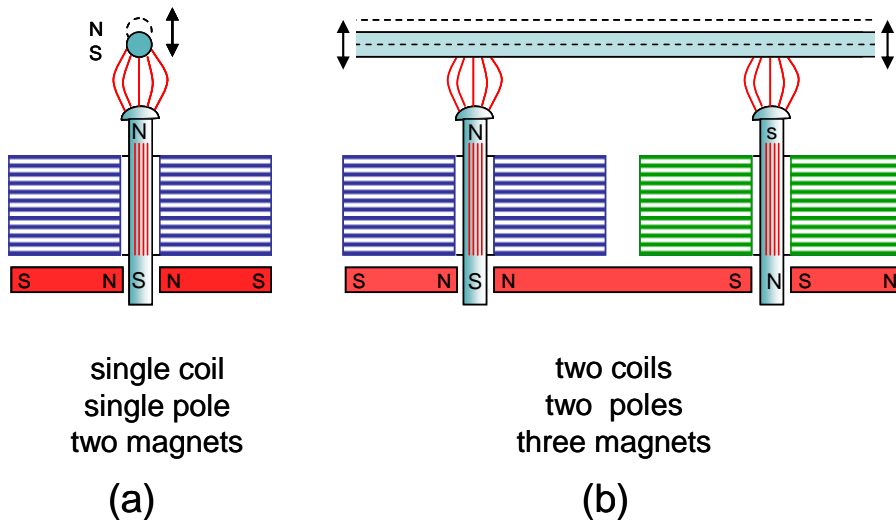


Figure 6 (a) Single pole pickup illustrated transverse to length of steel string, and (b) the Gibson “super-humbucking” pole configuration, with the coils surrounding the poles to the left and right wound in opposite directions to eliminate mains pick-up.

Magnetic pickups can clearly only be used with steel strings. The inharmonicity of solid steel strings - resulting from their finite rigidity - immediately introduces a much more “metallic”, longer-ringing, sound than the sound of gut strings on an acoustic instrument.

Magnetic pickups also have a peak in their output at a resonant frequency $f_o = (1/2\pi)\sqrt{1/LC}$ and a significantly reduced response at higher frequencies. This results from the large inductance L (typically several henries) and capacitance C between the very large number of coil windings. Resonances for single coil pickups are typically in the range 5-10 kHz, with a quality factor $Q \sim 4-8$, the latter limited by the large resistance of the coils $\sim 5-10 \text{ k}\Omega$. All such parameters are strongly design- and, to some extent, frequency-dependent [3]. Different pickups therefore produce different sounds, so the choice of which magnetic pickup to use can be a highly charged subjective issue. The relatively high impedance (reactive and resistive) of the coil winding requires the use of an amplifier with an input impedance of at least $1 \text{ M}\Omega$, if the output signal is not to be attenuated significantly, especially at high frequencies.

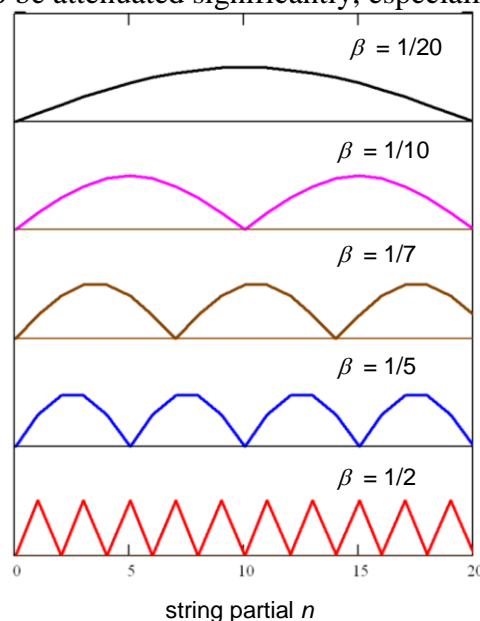


Figure 7. The dependence of the sensitivity of the n -th partial of a plucked note for a magnetic pickup located at a fractional length β of the vibrating string from the bridge.

The sound produced by a magnetic pickup also depends on their position along the length of the vibrating string, illustrated schematically in Fig.7. If, for example, the pickup were to be placed at the centre of the string, it would only be sensitive to the odd partials of the plucked string, since all the even partials would have a node at that point. Likewise, if the pickup is located at a fractional distance β along the string, there will be no output from the $1/\beta$ -th partial or any of its multiples, but will have maxima in between, as illustrated.

Sets of pick-ups at different lengths along the string therefore produce different sounds. Transducers close to the bridge will give a relatively low output for the lower partials, but will retain a strong output with no significant “drop-out” across the audio frequency range resulting in a bright sound. Conversely, transducers near the end of the fingerboard will have a much stronger output for the lowest partials, but a marked attenuation of some of the acoustically important higher partials, resulting in a more mellow tone. A set of pickups located in between will give an intermediate sound quality. By varying the combination of signals from pickups at different positions along the length of the string, the player has considerable control over the kinds of sound produced. Typical pickup positions for modern instruments can clearly be seen in Fig.3.

A potential problem with magnetic pickups is “hum” from nearby mains power supplies. Non-linearity in mains power transformers and other electrical equipment generates magnetic pickup at multiples of the 50/60Hz supply frequency - well into the audio range. Such pickup can usually be eliminated by the use of what are termed “humbucking” coils patented in 1955 by Seth Lover for Gibson [1955/59, US 2896491]. This involves the use of two closely-spaced pickups along the string with their outputs added, but with their sensing coils wound in opposite directions, so that external pick in one is cancelled by the other. A schematic diagram illustrating one such coil and polarising magnet configuration is shown in Fig. 6b. This accounts for the familiar double row of poles of humbucking coil pickups on the Gibson and Rickenbacker instruments in Fig. 3.

Because humbucking coils systems use two pickup coils, they have a larger inductance and stray capacity than single coil pickups. This results in a lower resonant frequency and high-frequency cut-off than single-coil pickups, resulting in a somewhat mellower tone. They also have a slightly different frequency response because they sense the motions at different points along the string. The use of single or double coil pick-ups and their placing along the string results in marked degree of flexibility in the design of pickups for the electric guitar, which accounts for the different sounds of commercial instruments.

X.3.3 Special sound effects

Almost all electric guitars have easily operated volume and tone controls on the instrument itself. The tone controls are often just simple CR- filters attenuating or enhancing the bass and treble responses. However, with the increasing sophistication of audio processing technology, computer-controlled software and audio digital signal processors, the sound can now be transformed in almost any conceivable way.

In the 1960's, it became fashionable to include additional sound “effects” - for example, by introducing a controlled amount of distortion resulting from clipping the tops off of the waveforms – giving the sound an additional buzz, edge and impact .

Other popular effects involved the use of:

- phasers – where the pickup signal is divided into two paths. In one path the phases of the various partials is changed. When the two signals are recombined, additional “notches” or zeroes in the output spectrum occur, when the amplitudes and phases of particular partials cancel. By varying the phase changes with time (e.g. driven by a low frequency electric oscillator) a number of interesting sounds can be produced.
- flangers – are essentially phasers in which the filter characteristics are determined by delaying one signal relative to the other. This produces a distinctive sound quality, which can again be varied electronically. Feedback can also be incorporated to obtain interesting reverberation effects.
- wah-wah – used by Leo Fender as early as 1945, involves feeding the guitar sound through a filter with a formant structure similar to that of the human voice. By modifying the strengths and positions of such formants with a foot pedal, the plucked strings can be made to mimic the wah-wah sound of the human voice. The intensity of the sound can be used to control the formants to obtain other interesting sounds.

In recent years, sound processing has been transformed by the use of computers and dedicated digital sound processors. In addition, there has been a shift from analogue to digital electronics, with Gibson introduced the first fully-digital electronics guitar in 2002, and more recently a guitar with computer-controlled tuning screws to tune each string automatically.

Despite such advances, many players take great pride in playing instruments that reproduce the iconic sounds of the 1960s.

X.3.3 Piezo-electric pickups

Although the first electric violins tended to use magnetic pickups actuated by the rocking action of the bridge, guitar-like magnetic pickups sensing the motion of the string directly have never been popular, because they require steel strings, which are less flexible and are more difficult to bow than gut or synthetic strings. The majority of electric violins therefore use piezo (piezo-electric) pickups attached to or encapsulated in the bridge.

A piezoelectric material is an insulator with an asymmetric molecular structure (see, for example, Gauschi 2000). Introducing strain can result in atoms on one side of a thin slab of piezo-electric material acquiring a positive charge, while atoms on the opposite side acquire an equal but negative charge. The charge is proportional to the amount by which the material is strained (i.e. compressed, stretched, bent or sheared). Rather like the magnetism of a magnet, the effect can be increased in strength by initially “electrifying” or “polarising” the piezo-electric material in a very strong electric field.

Changes in surface charge can then be sensed by the voltage $\Delta V = \Delta Q/C$ across metal electrodes attached to the surfaces, where ΔQ is the deformation-induced charge and C is the

capacity between the electrodes – typically 100-1000 pF. The voltages produced by compressing a modern piezoelectric material can be many thousands of volts - generating the spark in a hand-held gas lighter. Their high sensitivity to strain makes them ideal detectors of the small strains set up in the bridge by the force acting on it by bowed or plucked strings.

A particularly useful transducer is the bimorph piezo-strip, in which two long strips of piezoelectric material are glued together with a metallic electrode between them. As the strip is bent, the piezo above the central strip is extended while the other is compressed. This results in equal and opposite charges and voltages across the two outer surfaces. Small amounts of bending cause very large changes in the extension and compression along the length giving a large output.

Although the voltages produced by a piezoelectric transducer can be very large, the pickup can also be very rapidly discharged by the input resistance R of any amplifier placed across it. The CR discharging time-constant is 10^{-3} s for a 1000pF device connected to a $1M\Omega$ input impedance amplifier. This would lead to a very rapid attenuation of audio signals at kHz frequencies and below. To achieve a strong output across the whole audio frequency range, amplifiers with input resistances of at least 10^7 - $10^8 \Omega$ must be used. Fortunately, this is not a problem using modern solid-state electronics.

For bowed string instruments there is a virtue in making use of a low-frequency cut-off. This arises because, at the start of every bowed note, or at any time the bow changes direction, there is a sudden change in direction of the force exerted by the bowed string on the bridge. This step in the dc-force is picked up by any piezo-electric crystal mounted on the bridge, and results in a characteristic and annoying “clunk” in the output sound. Most of the associated sound energy is concentrated below ~ 250 Hz, which will still be strongly radiated by a high quality sound system. However, for a real violin, very little of this sound is heard, because the violin is such a poor radiator of sound below the air resonance at ~ 280 Hz.

.....
Like magnetic pickups on the guitar, piezo-electric pickups are susceptible to mains hum, but this time from electric rather than magnetic fields generated by adjacent mains power supplies. In the absence of any electrical screening, the voltage on the pickup can be as large as a few volts, which appears on both electrodes, in addition to the strain-induced voltage across them. Although an ideal amplifier would only be sensitive to the difference in voltages across its inputs, in practice, amplifiers are also sensitive to their average voltage. To minimise such problems one needs to screen the pickups and connecting leads as well as possible and to use well-designed amplifiers with a high “common-mode” rejection. Most manufacturers of piezoelectric pickups provide helpful information on their web-sites in minimising such problems.
.....

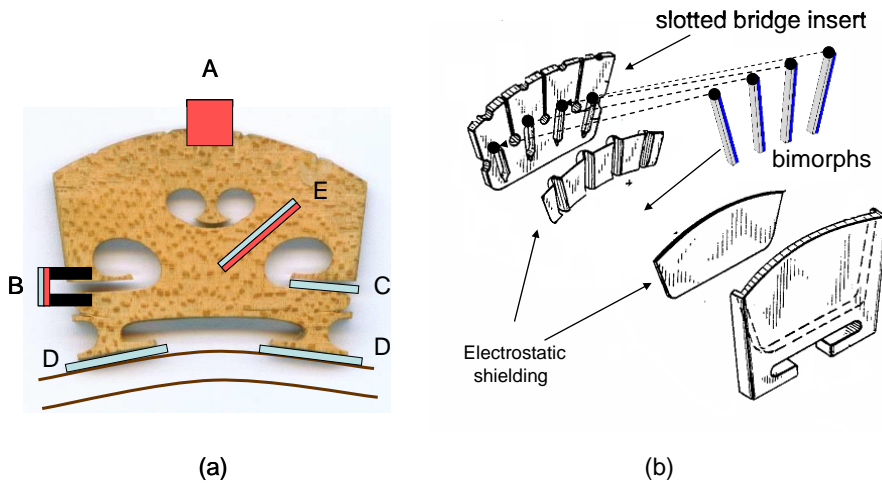


Figure 8. Piezoelectric crystal configurations on (a) a conventional violin bridge and (b) an exploded view of a multi -detector array to record signals from individual strings (after Barberi patent).

Fig. 8a illustrates typical mounting positions for a number of commercially available piezo pickups mounted on a conventional violin bridge. Transducer A measures the velocity or acceleration at the top of the bridge. The transducers B bridging and C wedged into the side-slot respond to the flexing of the top of the bridge relative to the supporting feet, while the embedded piezo bimorph strip E measures such bending directly. The two transducers D clamped between the feet of the bridge and the top plate respond either to the force exerted by the feet on the top plate or to the induced plate bending, depending on their design. Ideally, at low frequencies, all such transducers should give an output proportional to the force of the bowed strings on the bridge. However, the bridge and sometimes the pickups themselves have a resonant peak in their output at $\sim 1.5\text{-}3$ kHz and a sharp decrease in sensitivity at higher frequencies, as illustrated by some representative measurements in Fig.9. Superimposed on the overall trend, there is often additional structure from the resonances of all the strings supported by the bridge

Many electric violins use a somewhat heavier bridge, often with separate piezo pickups under each string. Such pickups can be used as separate inputs to drive a MIDI or more sophisticated computer-controlled sound systems, or can be connected in series to give a single output. A schematic exploded view of the Barberi multi-string transducer (187/89, US 4867027) is illustrated in Fig. 8b. An additional objective of such a pick up is to give an output from each pickup that is insensitive to the vibrations of adjacent strings.

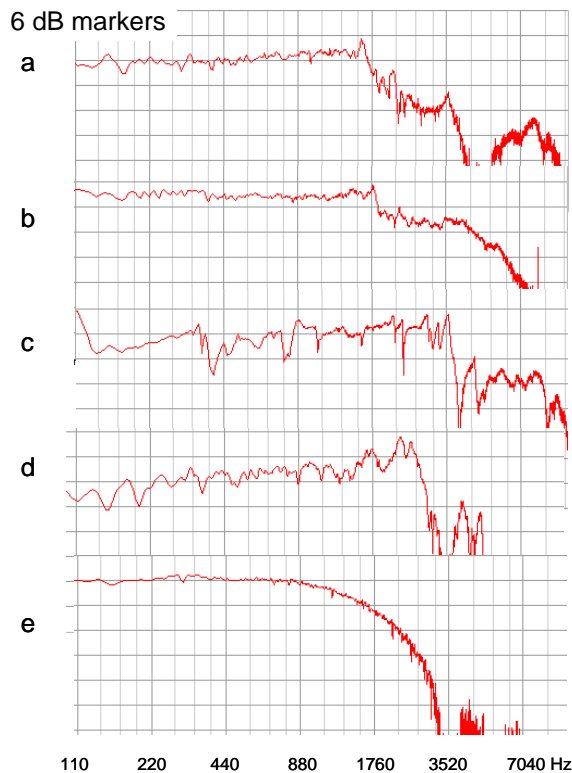


Figure 9. Frequency response of piezo pickups from impact measurements illustrating marked differences between different transducers and mountings. (a) Barcus-Berry side-clip on Vuillaume, (b) Violectra bridge on electric violin, (c) encapsulated piezo in solid bridge on electric violin, (d) Twin-T under-feet Carmen pick-up on electric violin, (e) Shadow -Twin on Vuillaume.

For research, one often requires transducers that only respond to the forces exerted by the bowed string, unaffected by any resonances of the bridge or body of the instrument. It could be argued that this should be the aim of any commercial pickup too, since nowadays it is relatively simple to achieve any desired frequency response by subsequent analogue or digital filtering. Benioff [1938/40, US 2222057] and Matthews [1988/89, US 4860625] pioneered the design of such bridges using piezo crystals to measure the bending of short cantilevers supporting the individual strings. Scherer (1966/69, US 3453920) patented a bridge with orthogonally oriented pairs of pressure sensitive piezo crystals, to record both the vertical and the horizontal forces exerted by the bowed string on the bridge - in much the same way as that used in stereo pickups for LP records. A similar design was used by McIntyre and his colleagues in Cambridge to investigate details of the bowed string waveforms [McIntyre et al 1981]

Like the electric guitar, the use of a solid body and a heavy bridge has a marked effect on the way the strings vibrate after it is plucked or bowed - because of the much reduced transfer of energy from the strings to the body of the instrument. Although considered a virtue for certain guitar styles, this can be a problem for the electric violin or cello, especially for the heavy lower strings, which can continue ringing for several seconds. Moreover, if a relatively light bridge is used, there can be significant coupling between the strings via the bridge. Notes played on higher strings can then excite sympathetic vibrations of the higher partials of the

lower strings. These keep ringing for long after note which excited them has stopped, providing a troublesome drone at the pitch of the lowest open string. The only way to prevent such a problem is to design a bridge that minimises the coupling between adjacent strings or to introduce some additional damping of the lowest resonating string. One way to achieve this is to mount the lowest string across a thick rubber ring, which increases the damping without changing the pitch of the note significantly.

X.2.4 Other types of pickups

Although magnetic and piezoelectric devices are by far the most common transducers in use today, a number of new types of transducer are beginning to appear on the market. These include optical pickups [e.g. Lightwave Systems, California], which use infra-red photo-detectors to sense the vibrations of the string close to the bridge, and magneto-resistive or Hall-effect pickups to replace conventional magnetic pickups. In addition, a number of guitar manufacturers now incorporate piezo pickups in the saddle, which can be used in combination with magnetic pickups to give an even wider range of tonal characteristics.

X.4.1 The electric violin as a research tool

Electric violins with transducers accurately measuring the force of the bowed string on the bridge provide an invaluable tool for investigating the acoustics of real violins. Fig.10 illustrates the different ways in which the acoustic and electric violin convert the bowed-string force at the bridge into radiated sound. In the electric violin, the acoustic filtering of the multi-resonant shell of the violin is replaced by electronic filtering, which can range from the simple analogue tone-controls used in many commercial instruments, a bank of resonant filters, to a powerful, computer-controlled, digital signal processing system. Whereas the acoustic violin radiates sound via the vibrational modes excited on its shell - with a highly directional multi-resonant response, the electric violin uses a loudspeaker (or a pair of headphones) - ideally with a flat-frequency response.

The dotted lines in Fig.10 illustrate how the bowed string input and output sound from a real violin can, in principle, be fed into an electric violin to reproduce the sound of the original instrument. The filter characteristics can then be changed, allowing the player and listener to assess the relative importance of various filter characteristics on the output sound.

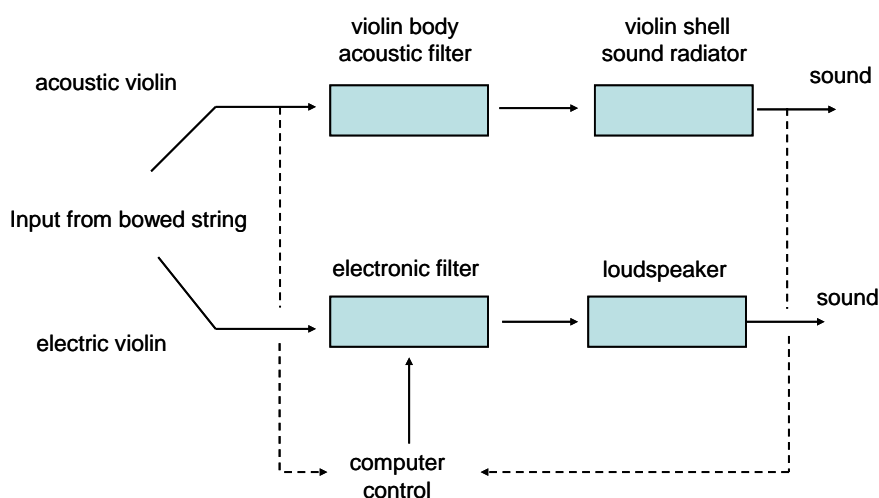


Fig.10 A schematic representation of the signal paths of an acoustic and electronic instrument with dotted lines indicating the use of inputs from a real violin controlling the output of an electric violin.

X.3.1.1 Multiresonant filter characteristics

Mathews and Kohut (1972) at the Bell Laboratories pioneered the use of the electric violin as a research tool. They used a bank of resonant filters with adjustable resonant frequencies and damping, to mimic the multi-resonant response of the violin. To measure the bowed string vibrations they used two horseshoe magnets attached to the face of a relatively heavy bridge, with the four pole-pieces immediately below the four strings. The motion of the strings in the magnetic field induced voltages in the metal-covered strings, which were added together, amplified, passed through the filter bank, and played back to a listening panel through a loudspeaker.

A range of experiments were performed, initially with a bank of 20 resonant frequencies chosen to reproduce 17 prominent peaks on a Stradivarius response curve, plus three additional higher frequencies to cover a frequency range extending to 4500 Hz. The damping of each resonance could be varied to give an essentially flat response across the whole spectrum to a response with peak-to-valley height differences between resonances of order 20-30 dB. Subjective listening tests were made as a function of damping for notes played with and without vibrato. To eliminate the inevitable variability in performance of the player, a tape-recording of a given sequence of notes was used as the input for all subjective assessments using different filter bank arrangements.

Members of the listening panel were mostly violinists or those used to listening to violins. The sound was judged best for a peak-to valley ratio of around 10dB. The flat response gave an even response but slightly harsh sound, and was unresponsive to the use of vibrato and modulations in bow pressure. When the damping was reduced to give a large peak-to-trough ratio ~20dB , the sound became hollow with obvious changes in intensity from note to note. This implies that damping must always be a compromise between being too large, resulting in an unresponsive instrument, or too small, resulting in a hollow-sounding uneven instrument.

The authors then doubled the number of resonances but adjusted the peak-to-valley to remain the same at ~ 12 dB. The resulting sound was judged to be slightly more brilliant, but the difference was small. A second experiment used 24 equally-spaced resonances, a tone apart, with an unchanged peak-to valley ratio. This was judged to be slightly better than the 20 Strad-based resonances and was comparable in quality to the sound of the higher density filter bank. The one exception to the above results was the sound of low notes on the G-string, which for the 24 evenly-spaced resonances sounded more like a viola, while the more widely spaced “Strad resonances” sounded more like a violin. Any preference is clearly a matter of musical taste.

These observations highlighted the importance of the peaks and valleys in the frequency response of real violins, which give rise to complex time-varying waveforms and fluctuating variations in timbre when vibrato is used. Mathews [1969] had already argued that such complexity was important in any subjective assessment of the richness of tone of an instrument. Later researchers [Meyer 1992, Mellody and Wakefield 2000 and Gough 2004] have also used electric violins to demonstrate and assess this hypothesis

Mathews and Kohut also noted solid-bodied electric violins appear to be somewhat easier to play than conventional violins, with an apparent quickness in response and longer decay times – especially on the lower strings. This is almost certainly associated with the reduced loss of energy transfer from the string to the body of a solid-bodied electric instrument

X.3.1.2 Sound perception and acoustical properties

A rather different kind of project, addressing the relationship between the perceived sound of a violin and its acoustical properties, is currently being undertaken by Claudia Fritz in Cambridge, in collaboration with Jim Woodhouse, Brian Moore and Eric Cross - leading experts in acoustics, psychoacoustics and music respectively [Fritz et al 2007]. For the first time, rigorous psycho-acoustic procedures have been used to relate differences in the perception of sounds to differences in the measured acoustical properties of violins. This is the first step towards a rigorous psychoacoustic exploration of why some violins sound better than others.

To accomplish this task, a normal violin with a conventional bridge with force-sensitive pickups under each string was played by a skilled player. This signal was then used as the input to an artificial electric violin corresponding to the lower half of Fig.10.

In an independent set of measurements, the input admittance (induced velocity per unit applied force) of the bowed violin was measured at the point of string support on the bridge. The frequency response of the admittance exhibits all the excited resonances of the body of the instrument and was used as the filter for an electric violin. The measured input from the bowed string could then be “played” through this filter and listened to by members of the assessment panel through high-quality headphones. To give a more realistic impression of the radiated sound of the original instrument, the amplitude of the air resonance at around 280 Hz was increased to reflect its strong radiating properties.

The experiment used the SignalWizard 2 audio signal processor developed by Patrick Gayderecki (2007), which allows the real-time filtering of an input audio signal using any previously measured or computed frequency or impulse response. It is then easy to compare sounds as the filter properties are changed by controlled amounts. This can be done using the real-time input from a violinist playing the actual instrument, though reliable, reproducible, subjective testing requires a previously recorded bowed input signal.

The investigation investigated by how much the centre frequencies and amplitudes of the three acoustically important low frequency resonances of the violin (A0, B1- and B1+) and the four frequency bands identified by Dünwald (1991) as determining the richness, nasality, brilliance and clarity of a violin’s tone (190-650, 650-1300, 1300-4200 and 4200-6400Hz) needed to be changed before such changes became audible. A large number of musicians and non-musicians were tested and their individual responses analysed.

Typically, musicians were slightly better at discriminating small changes than non-musicians, though, not surprisingly, the results varied from note to note, as their partials were affected in different ways by the changes made. In general, it was found that the amplitudes of individual resonances could be changed by ~ 4-8 dB and resonant frequencies by 10-20% before the listener could detect a difference in the sound. Such information is clearly of potential importance to makers, as it implies that positions and amplitudes of resonances can be changed

by quite significant amount before a listener can detect any change in the perceived sound. The authors were also able to show that their results were in excellent agreement with current models for auditory perception.

X.3.1.3 Real-time synthesis of Cremonese instruments

Finally, we briefly mention attempts by Gabi Weinreich and the distinguished American violin maker Joe Curtin [20] and the present author [9] to reproduce in real-time the sounds of great Italian instruments on the electric violin. In both investigations, the SignalWizard processor is again used, but in this application the filter used is derived from radiated sound of the violin recorded from a Stradivari, Guarneri or student violin, when tapped sharply at the bridge rather than using the response at the bridge. The SignalWizard digitises the input signal from the bowed electric violin, essentially producing a sequence of sharp taps at the digitising rate, with heights that follow the input waveform. Each one of these taps then generates a pulse of sound identical to the measured tap-tone response of the original instrument. The sound at any moment is therefore the sum of sounds from all earlier taps. Technically speaking, this process is known as convolution.

In principle, this means that anyone could reproduce the sound of a great Italian instrument on an electric violin, providing the acoustic impulse response of the Stradivari or other chosen instrument had first been measured. However, there are some intrinsic problems. The most important of these arises because the acoustic impulse response is recorded at a particular point in the original performance space. The sound would therefore only be the same if it was listened to with one ear using a specially designed headphone that mimicked the response of the microphone originally used to record the sound. Instead, the sound would generally be replayed by a loudspeaker in yet another performance space. However, this may not be such a serious problem, firstly because the sound quality of a great violin being played by a great player does not change significantly from position to position in the recording studio or concert hall. Furthermore, a great violin still sounds wonderful when one ear is covered in the concert hall or when only one ear is used on a stereo pair of headphones.

Even if the routine reproduction of the sound of really great instruments may be something of a dream, one can certainly change the sound of the electric violin dramatically in all sorts of ways using a computer-controlled signal processor. This must surely be one of the most important opportunities for the future development of the instrument.

For this to happen, the electric violin has to be made even easier to use. Future developments may well include electric violins with light rechargeable batteries driving an integrated, on-board, computer to control the filter characteristics and the sound of an integrated loudspeaker. The instrument would then be truly portable. At the flick of a switch (or voice-command) the player could choose to play a Stradivarius, Guarnerius or two-stringed Chinese violin, use automatic pitch correction to play in tune, play double bass parts on the violin, produce sounds completely different from that of any other known musical instrument, and play with any pre-recorded band, orchestral group or pianist. The possibilities are limitless. It would be fascinating to read the contents of a similar chapter on electric stringed instruments in 50 years time!

References

1. Bacon T (2006) *Electric Guitars: The Illustrated Encyclopedia*. (Thunder Bay Press, Place)
2. Day T (2000) *A Century of Recorded Music* (Yale University Press, New Haven and London)
3. Dünnewald H (1991) Deduction of objective quality parameters on old and new violins, *J. Catgut Soc. Ser.II*, 1, 1-5
4. Errede S (2008), [http://online.physics.uiuc.edu/courses/phys199pom/Labs/Electric Guitar Pickup Measurements.pdf](http://online.physics.uiuc.edu/courses/phys199pom/Labs/Electric%20Guitar%20Pickup%20Measurements.pdf)
5. Evans T and Evans MA (1977) *Guitars: From the Renaissance to Rock* (Paddington Press, New York & London)
6. Fritz C, Cross I, Moore BCJ, Woodhouse J (2007) Perceptual thresholds for detecting modifications applied to the acoustical properties of a violin. *Jnl Acoust Soc* 122, 3640-
7. Gautschi GH (2002) *Piezoelectric Sensorics* (Springer, New York)
8. Gaydecki P (2007) A new multi-channel real-time digital signal processing platform for acoustic signal processing and sensor response emulation, *Jnl of Phys: Conf Ser* 76, 012048
9. Gough CE (2005) Measurement, modelling and synthesis of violin vibrato sounds. *Acta Acustica united with Acustica* 91, 229-240
10. Graesser H, Holliman A (1998) *Electric Violins* (Verlag Erwin Bochinsky, Frankfurt)
11. Heaney BA (2007) *A short illustrated history of Stroh violins, 1899-1949*
<http://www.digitalviolin.com/StrohViolin1.html>
12. Mathews MV (1969) *The Technology of Computer Music* (MIT Press, Cambridge, Mass)
13. Mathews MV, Kohut J (1972) Electronic simulation of violin resonances, *Jnl Acoust Soc Am* 53, 1620- 1626
14. McIntyre ME, Schumacher RT, Woodhouse J (1981) Aperiodicity in Bowed-String Motion, *Acustica* 49, 13-32
15. Mellody M, Wakefield GH (2000) The time-frequency characteristics of violin vibrato: modal distribution analysis and synthesis. *Jnl Acoust Soc Am* 107, 598-611
16. Meyer J (1992) Zur klanglichen wirkung des streicher-vibratos. *Acustica* 76, 283-291
17. Radio News, Vol. 8, No. 10, April 1927
18. Ratcliffe A (2005) *Electric Guitar Handbook* (New Holland Publishers)
19. Smith RR (1987) *The History of Rickenbacker Guitars* (Rickenbacker Int Corp)
20. G. Weinreich and J. Curtin - article in Michigan Daily, 22nd March, 2007
<http://media.www.michigandaily.com/media/storage/paper851/news/2007/03/22/TheBSide/Making.The.Perfect.Violin-2786562.shtml>