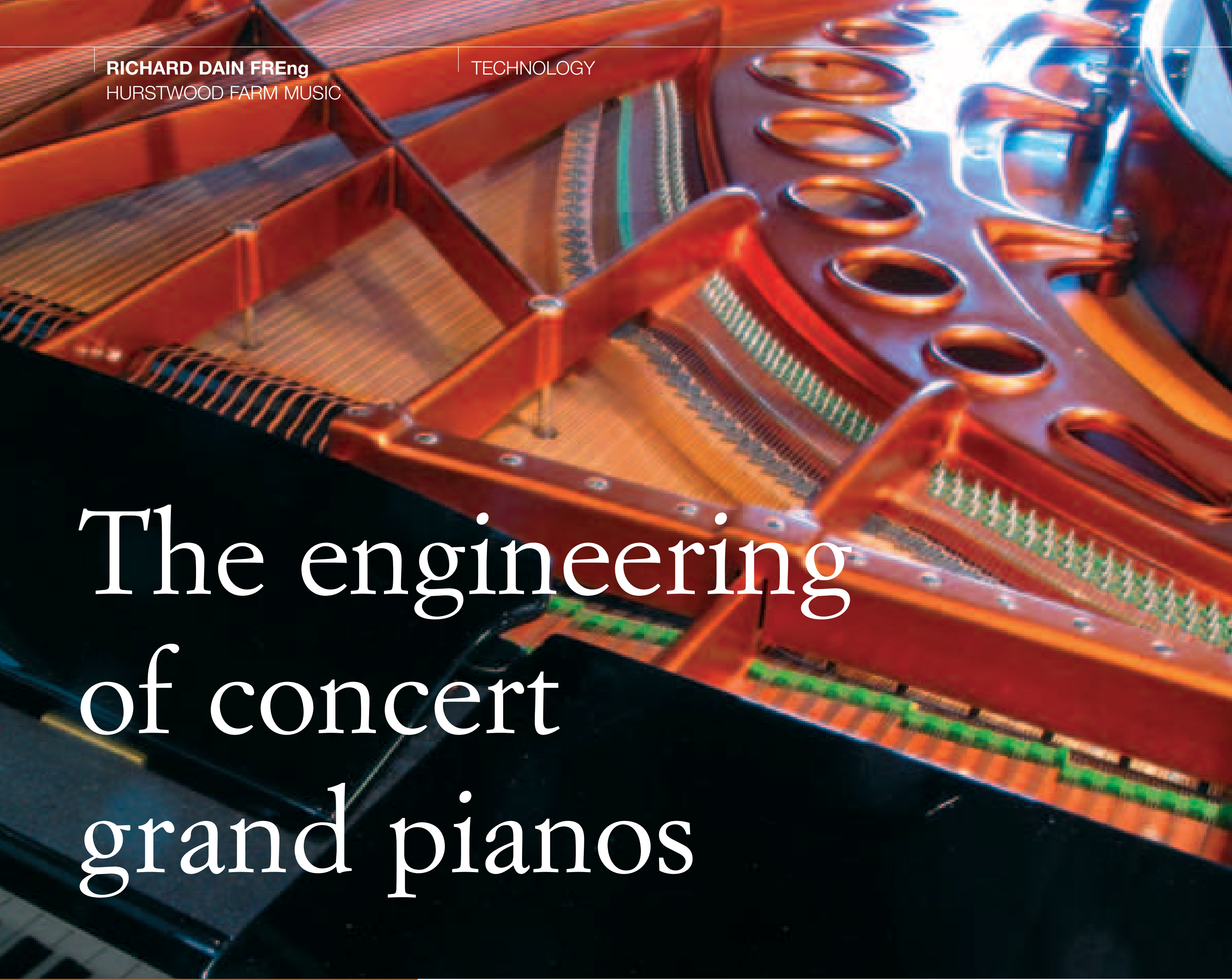
RICHARD DAIN FREng
HURSTWOOD FARM MUSIC



The engineering of concert grand pianos

The basis of grand piano design was explored and established by the 1870s. Since then there have been refinements but no fundamental change. New materials and new analytical tools available to designers to improve piano quality remain largely unused. Richard Dain discusses and displays features of piano sound and piano design to highlight areas where potential for improvement exists. Conservatism and resistance to change in the classical music industry is criticised for failing to offer the public the best in quality and variety of piano sound.

Artists and interpretation of music

A piano consists of a number of primary resonators, the strings, which are driven by hammers travelling at a velocity determined by the pianist. The strings have low surface area and so transmit sound poorly to the air but they are coupled tightly to a secondary resonator, the soundboard. In turn this is coupled to the case, which has its own broadband resonant characteristics and forms a cavity of complex shape in which the whole system sits.

There are only three variables that the pianist's hands can influence to change piano sound. These are:

- the velocity at which the hammer strikes the string, the loudness
- the time when the hammer strikes the string, and
- the point at which the pianist releases the key, allowing the damper to fall and stop the string vibrating. This determines the duration of sound.

The pianist's right foot uses the 'loud' pedal to raise all the dampers, thus sustaining the sound from the vibrating strings and also encouraging sympathetic vibration in other strings. This produces a greater overall volume of sound.

The left foot operates the 'soft' pedal which shifts the keyboard, action, and hammers laterally so that fewer strings are struck and by a softer portion of the hammer surface. The combined effect produces fewer overtones. Additionally, the string that is not struck moves in anti-phase. This lengthens the overall decay time of the sound.

The action of a piano serves to propel a hammer towards the strings by means of an escapement

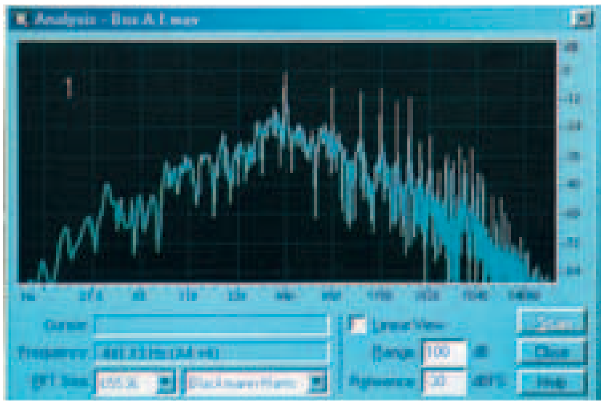


Figure 1

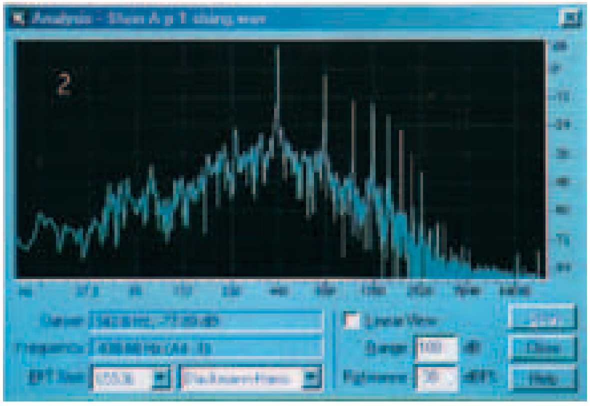


Figure 2

Figures 1 and 2 show harmonic analysis of the sound produced very soon after striking the A=440 string of, respectively, a Bösendorfer and a Steinway concert grand piano. The Bösendorfer has more harmonics in its spectrum.

mechanism. Once the escapement mechanism has operated, the hammer is in free flight, after which nothing the artist can then do with his hands has the slightest influence on the resulting sound. Some of the more demonstrative performers may sway and massage the keys as if they believed it could make a difference.

Although the ear can make only a relatively coarse determination of absolute time and of absolute sound intensity, it is highly sensitive to minute differences in time intervals and successive sound intensity. Consequently, despite the paucity of control factors, great subtlety can be produced in the temporal change of sound produced. It is the ability to manipulate these factors that separates the great pianist from the amateur.

Indeed computers have recently confirmed the findings of makers of piano rolls from an earlier age that different great artists have their own 'fingerprints' in the way they do this. Both factors require an extraordinary degree of sensory and muscle co-ordination when one realises that a grand maestro may accurately control hammer velocity to as many as five hundred levels and timing to within half a millisecond or closer.

The contribution of technology to a great performance

There are three contributors to a great performance: the artist, the tuner/ technician who prepares the piano, and the engineer who designs the instrument.

Tuning

A modern quality piano is not tuned to a mathematically correct temperament. Each instrument has its own natural optimum temperament at which it sounds most interesting and pleasant. Temperament may also need modification to match the hearing of the listener. Older people tend to hear higher notes at a marginally lower frequency than the young. Concert tuners will stretch the intervals by as much as an eighth of a tone per octave in the top registers. The tuner may also deliberately introduce detuning of the unisons to reduce the decay rate of a particular note exhibiting short sound by putting the strings slightly out of phase.

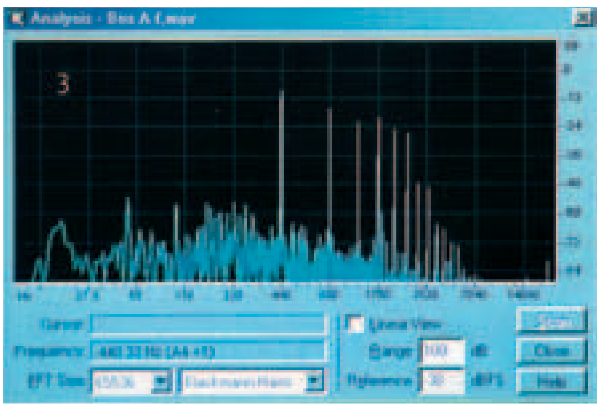


Figure 3

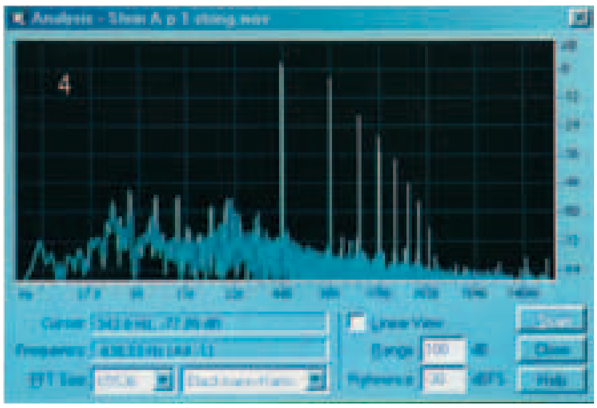


Figure 4

Figures 3 and 4 show analysis of the sound after one second for each piano. The broader harmonic content of the Bösendorfer is maintained; the decay of amplitude of the Steinway is considerably less.

Figure 5

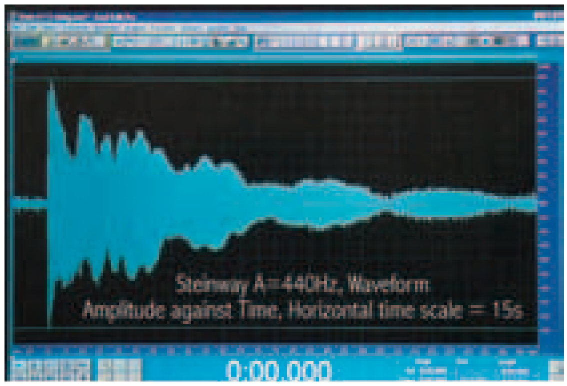


Figure 6

Figures 5 and 6: The waveform displays show the lower rate of decay of the sound from the Steinway. In the case of the Steinway, interference produces large irregularities in amplitude in the initial sound.

The technician

The technician is responsible for:

- adjusting the geometry of the action
- setting static and dynamic weighting of the keys
- minimising unwanted friction
- regulating the escapement mechanism to a predictable and uniform function
- setting the travel (blow distance) of the hammer and the key depression
- adjusting checking of the hammer to avoid bounce
- regulating the repetition system and setting the damper action.

He will also voice the piano to grade the sound level evenly in intensity over the registers, and to adjust the overtone content (warmth or brilliance) of the sound.

A good technician can work wonders with any instrument, but fine results can be achieved only on craftsman-built instruments.

The designer and instrumentation

The contribution of the piano designer is to conceive a piano which is durable, stable, has efficient conversion of mechanical to sound energy, has the right proportion and quality of sound energy assigned to the first strike sound and the singing but decaying after-sound. He must also ensure that the artist hears instantly and authentically what he plays; he must produce a sound of unvarying frequency with the desired overtone content uniformly graded across the registers.

Historically inspired entrepreneurs with ‘a golden ear’ have done this. Modern instrumentation and engineering techniques open a whole new vista of possibilities for refinement and optimisation that has been little used except as a tool for facilitating mass production to a tolerable standard. The application of modern instrument engineering to piano sound analysis could facilitate the summation of many individually barely perceptible gains to produce a significant overall improvement. Yet there is so far no apparent recognition of this opportunity amongst the great piano builders, perhaps because their tradition has not been linked with engineering and they do not comprehend the power of modern technologies.

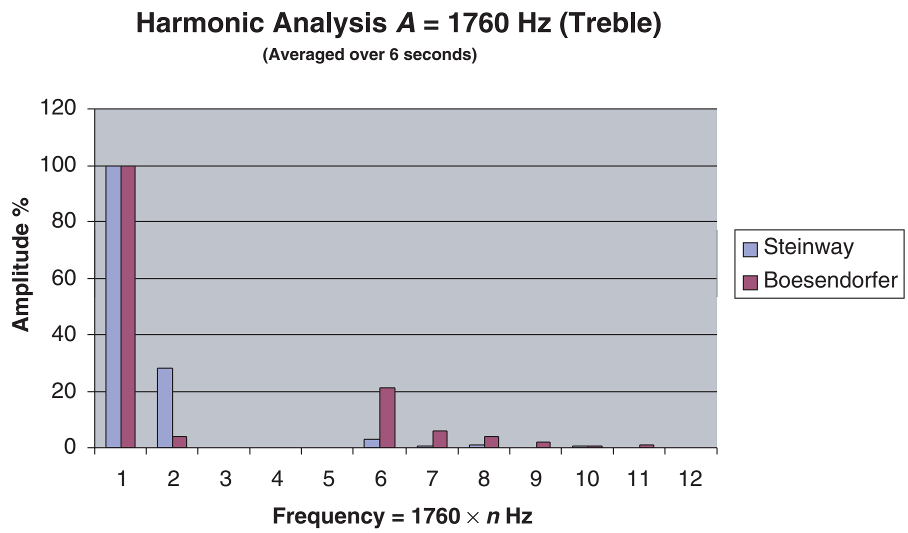


Figure 7: In the upper registers Steinway has a high second harmonic content, perhaps due to the duplex scaling. The Bösendorfer has more harmonics.

The sound board

The piano sound that a listener hears is principally that from the soundboard. The strings emit little direct sound energy. The acoustic emissions of a piano note come in several sequential

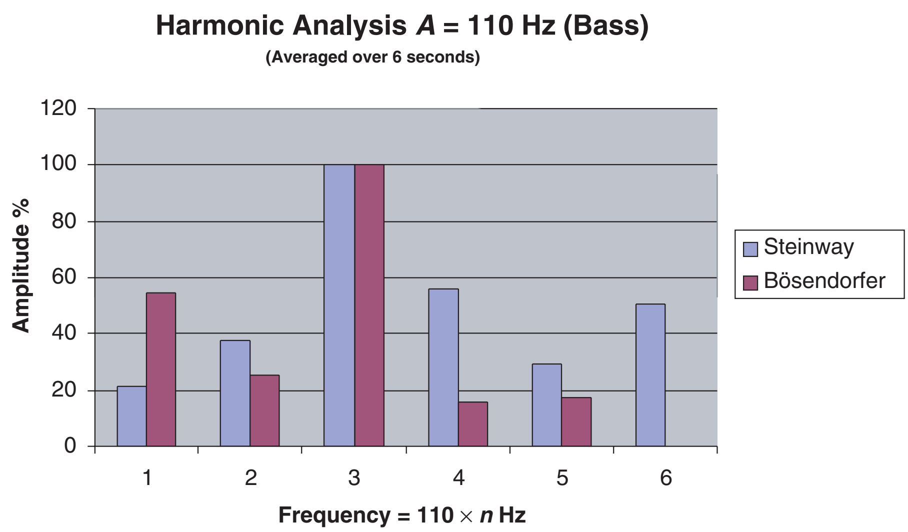


Figure 8: The low register analysis shows the much greater content of the fundamental frequency of the Bösendorfer.

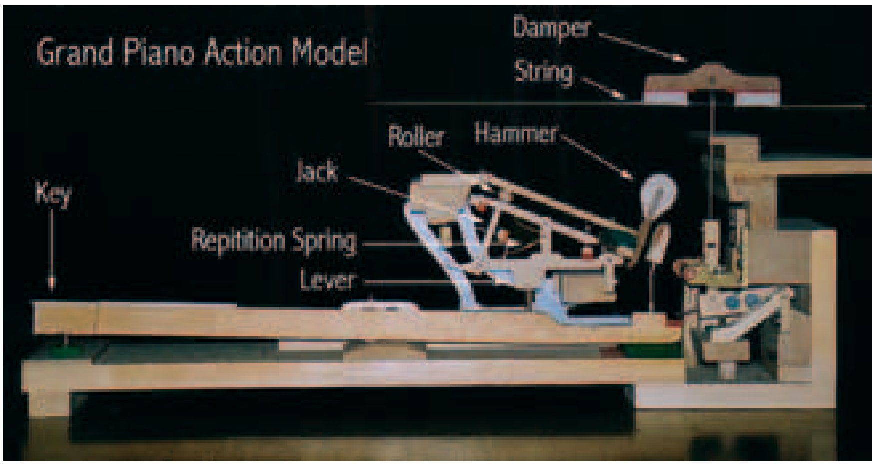
and distinct modes. When a group of two or more strings is first struck the rate of sound transmission to the bridge is high, because the strings vibrate vertically in unison, imparting maximum pulsating forces to the sound board via the bridge. The initial rate of rise of sound intensity depends partly on the hammer hardness, which affects the rate of energy input to the string. The higher the rate, the more immediate and percussive the first sound. Once the sound has peaked, the axis of vibration of the strings begins to rotate: the different strings may also drift into asynchronous vibration. Both of these factors reduce the rate of feed of energy from string to sound board. The piano then produces its long singing tone. At the onset of the singing sound, the sound energy level will have fallen to below 50% of its peak energy level. The amplitude of the sound then decays as energy is dissipated from the string by losses, or as acoustic energy. A fine piano will sing steadily for a long time. It is the job of the designer to minimise losses.

Sound energy loss

Engineers will appreciate that all materials absorb acoustic energy; therefore the more material mass there is, the more the problem of acoustic efficiency. Sound energy will always seek and find an energy sink in an acoustic system. The wise designer will therefore eliminate unnecessary mechanical interfaces away from nodes, or absorbent material such as felt, so far as is practical, because these generate friction by micro-movement of contacting surfaces. He will also seek to constrain acoustic energy within those components that contribute most to desired acoustic emission. It follows that a good sound board should be of high strength, high stiffness material to achieve as low a mass as possible within the bounds of being strong enough to balance the downwards force of the strings passing over the bridge. For this reason conventional soundboards are made of spruce backed by belly bars, which add to stiffness. The author has yet to see an instrument where these bars have been designed to minimise the mass needed to develop the required strength, yet to a rail-track engineer, for example, this is fundamental practice. It is a matter for future evaluation whether materials such as Kevlar or carbon fibre might provide a better engineering solution for soundboards. The designer would need to consider other important factors such as the velocity and absorption of sound in such new materials. Most quality pianos, notably Steinway, have complex contoured soundboard thickness, the contours being chosen by *ad hoc* trial, but no maker is known to the author to have applied finite element stress analysis to optimise soundboard geometry, mass and strength. Financial pressures have driven all but Bösendorfer to adopt artificially cured wood for piano building, despite the detrimental effect this process may have on the material acoustic properties. This may account for some of the perceived variability in modern piano quality compared with instruments from the middle of the last century.

Down-bearing

The down-bearing force of the strings on the bridge was historically determined by the need to keep the strings in contact with the bridge when they are struck from underneath and as they vibrate. Contact across this



interface is enhanced by making the strings zigzag across the bridge (known as side draught) between inclined bridge pins – a device which obviously introduces undesirable friction interfaces. It is well known that excess down-bearing force shortens the duration of sound, although a small amount is probably beneficial. The Stuart piano has re-introduced a device pioneered decades ago that locates the string to the bridge by an agraffe (clip) without the need for side draught across the bridge or for bridge pins. The Stuart piano develops uniquely long duration sound and employs minimal down-bearing.

The case and rim

Rigid location of the soundboard in a piano is vital. In the past, the lead quality builders used deliberately to shrink the soundboards by over-drying them before fitting them to the rim of the case to ensure a tight compression joint. Today this technique seems to have been forgotten. The rigidity, strength and section shape of the rim of the case define how much sound energy is reflected back into the soundboard from its edges and how much passes into the case and structure. In the past, one company used a cast iron rim for a small piano which produced famously powerful sound but was almost too heavy to move! All makers now use massive wood rims. Bösendorfer, while having a conventionally massive lower rim, exceptionally, employs a thin upper case rim that permits torsional rotation of the lower rim and thus vibrating oscillation of the upper case. The upper case then acts as an extension of the sound board and radiates noticeably more sound towards the audience than the artist. In the author's opinion there is potential improvement possible from studying the interaction of soundboard and rim more closely to optimise the projection of sound from the soundboard where it is best controlled.

Extra notes and strings

Several makes of piano, notably Bösendorfer and Stuart, now have extra strings at the bass and/or the treble end; these are not always provided with keys and action components. The extended width and thus extra flexibility and area of the soundboard undoubtedly contribute greatly to the quality and dynamic range of the piano sound, and resonance in these strings also contributes positively to the general sound quality.

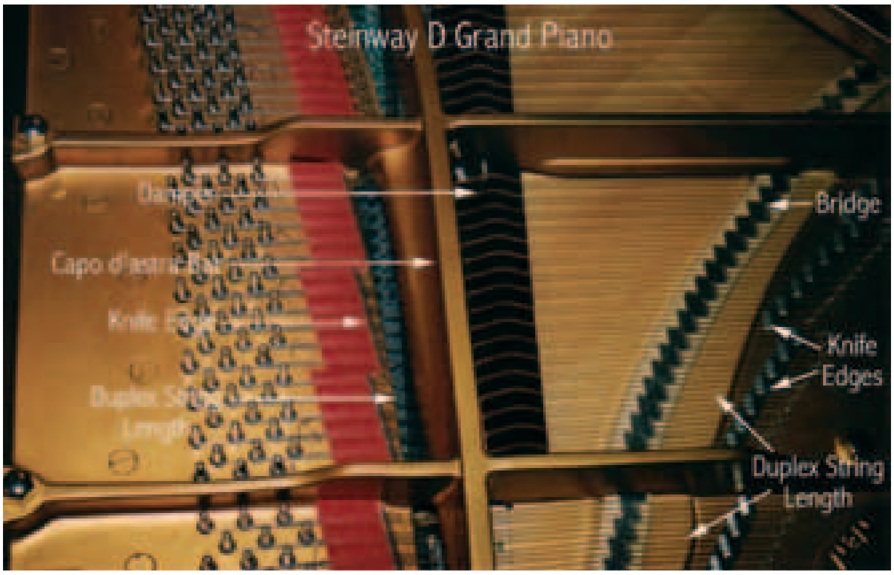
Strings

The strings of a piano are the engine of sound generation. To produce a pure sound a string must be of uniform density and cross-section or it will emit a warble or range of frequencies known as a false note. False notes also arise if the length of the string is even slightly indeterminate. Bridge carving so that the string length is determined precisely by the bridge pin is a highly skilled job, and vital to the purity of acoustic energy from the string. If the bridge pin is not firmly encastered in the material of the bridge then it also may flex and sound purity is lost. The ingenious Stuart bridge agraffe has eliminated the requirement for bridge carving and provides a uniquely definitive termination to the string length. In consequence the Stuart piano is virtually free of false notes.

Each note on a piano may have between one and four strings. Historically, multiple strings in the upper registers were employed in a belief that they increased the sound level; however, they have other effects. As the string is first struck it vibrates in a vertical plane, transmitting maximum energy to the bridge. With time (typically from 0.5 to 3 seconds), small geometric inaccuracy results in the plane of vibration of the string beginning to rotate significantly, so that some or all strings may vibrate out of phase and in a plane that transmits less energy to the bridge. In this mode the quieter singing 'after tone' is generated. The more strings, the more uniform the after sound because the more the rate of energy transmission is statistically smoothed.

The *una corda* pedal typically ensures that the hammer strikes only two strings of a trichord. The 'drone' string vibrates in anti-phase, causing reduction of the energy feed rate to the bridge, thus conserving energy in the string and lengthening the duration of sound while reducing sound intensity. Some Bluthners employ four strings to each upper register note: the fourth is not struck; only two are struck when the una corda is used. Bluthner is famous for its soft singing tone.

At the keyboard end of the string the sounding length is determined by the string passing under a knife-edge on the *capo d'astra* bar or through an agraffe located on the frame. This knife-edge is subject to wear and inaccuracy of manufacture which may be a cause of false notes. The author has experimentally fitted hardened beryllium–copper wire knife edges to one instrument and obtained significant improvement, particularly in reducing sliding friction and aiding the tuner's task.



Duplex scaling

The strings of a piano may have a single sounding length, or they may incorporate duplex scaling at one or both ends of the string. Duplex scaling is an extra length of undamped string that is tuned to one of the harmonics of the sounding length. The effect is two-fold: the extended length changes the string termination point from being partially *encastré* to approaching a pin joint condition. This reduces energy loss rate from the string and thus enhances the duration of sound. It also reduces *inharmonicity* (harmonic frequencies not at the arithmetically predicted frequency) by providing more similar end conditions. The degree of freedom of the termination of the sounding length obviously depends on the tuned frequency of the extension length.

Two modern instruments, Estonia and Fazioli, employ means of accurate tuning of these extension lengths with marked beneficial acoustic results. Steinway and others use duplex scaling with a factory set tuned length.

With duplex scaling, the instrument inevitably possesses many undamped lengths of string which become energised by the vertical motion of the bridge, whether or not the associated note is sounded. A piano with full duplex scaling has thus an enhanced content of dissonant overtones. Together, the duplex lengths contribute a ringing, almost cymbal-like background sound which cuts through the power of a modern orchestra with great effect in a concerto, but may not be ideal for solo performance.

Many artists prefer duplex scaling. Dare one suggest it might in some cases be because accidentally brushed notes are masked giving a greater sense of security? Duplex scaled pianos require more tuning skill and effort to ensure equal tension or, as is so often heard, the piano will not stay in tune throughout a recital. Perhaps judicious use of beryllium–copper knife edges would help with this problem?

Frames

The remaining major feature of a quality piano affecting its sound is the frame. Traditionally made of grey cast iron, the frame has to withstand the tensile forces of the strings that total some twenty tonnes. Cast iron is far from an ideal choice but has survived from the days when it was the only option. Cast iron is highly absorbing of acoustic energy and has a low Young's Modulus. If the frame is too flexible, the piano is difficult to tune because, as one string is corrected for tension, adjacent strings will be altered. Furthermore, if the symmetry of the stringing is broken by a frame-strengthening bar, then the quality of sound from strings on either side of the bar may be noticeably dissimilar.

It is fascinating to examine the frames that one piano maker has been using almost unchanged for many decades. They slavishly retain features introduced long ago for a purpose lost in history. No one recalls why these were originally incorporated and no one dares remove them. One even hears salesmen's elaborate and spurious explanations of why the features are present and what acoustic benefit they impart when to any novice engineer their vestigial origin is obvious.

Historically the metallurgical content of the cast iron used in pianos has been modified to achieve better castability and to reduce sound energy loss: each maker has his own magic ingredients. Some makers now use cast steel frames which obviously have a more favourable Young's modulus to give better stiffness and reduced mass. Carbon fibre frames which might be horrendously expensive would appear to offer mass, strength and stiffness advantages. Without going to that extreme one can envisage titanium as an interesting option, and with the advancement in welding technology, we can look forward to the first fabricated piano frame in due course.

The action

Piano actions, like wind organ actions of the nineteenth century, are traditionally mechanical devices. The roller action pioneered by Erard, a company name still used, has been modified and refined to a high degree of perfection. It is difficult to see how mechanical actions may be significantly improved. Individual actions are now tailored to particular makers' instruments by the lead action manufacturer, Renner. All Renner actions, if well fitted and well regulated, offer superb control. The Steinway/Renner action has wide artist acclaim because it remains reliably playable even if grossly maladjusted. Sadly in many UK venues, maladjustment is commonplace. Bösendorfer has in the past year introduced a new Renner-built action which in the author's opinion is supreme in consistency and touch control.

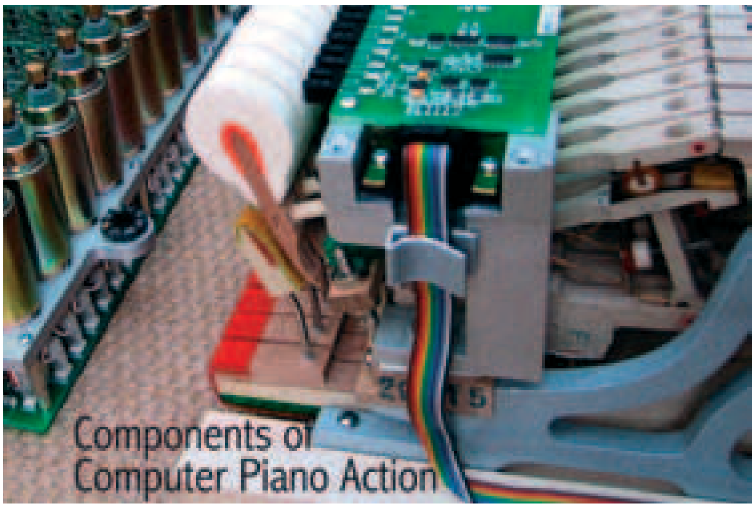
The ease of regulating actions, and how long they stay in regulation, varies enormously. Devices such as the Bösendorfer screw-adjustable Hertz repetition spring that resets the escapement mechanism are no longer used because of justifiable criticism of an earlier device, though it had a radically different type of spring. Bösendorfer repetition springs, as has always been the case on other pianos, can now be adjusted only by bending the spring to regulate its tension. Few technicians have the skill or patience to get the setting correct.

The sternest of critics has never been known to detect the recorded music was reproduced mechanically.

The future of action design?

About 30 years ago a young American, Wayne Stahnke, designed a computer-driven reproducing piano using light sensors to follow the keys and hammers. Some 30 instruments were made by Bösendorfer, but the engineering never progressed beyond prototype form: the pianos proved too expensive to make and maintain. The author has one of only two known to survive in Europe in working order, although little of the original electronic hardware remains, and the control software has been extensively developed. The authenticity of reproduction is so refined that it is almost perfect: editing is comprehensive and traceless. Reproduced classical music performances are regularly downloaded to CD in the author's studio, in the absence of the artist, when industrial and aircraft noise is least. The sternest of critics has never been known to detect the recorded music was reproduced mechanically.

More recently the SE has been applied by S. O'Connell for simulating archive performances by great masters of the past, using data taken from old acoustic recordings. The piano can be heard with artists such as Horowitz, Prokofiev, Moisewich and Art Tatum controlling the keyboard. A small audience at the author's studio recently heard Rachmaninoff play two of his piano concerti 'live', accompanied by a recording of the original orchestra from the 1940s. This system can also be played remotely by an electronic keyboard, or even by satellite link. The challenge to develop it into a self- regulating electronic action adjustable to any artist's preferred touch and response is there to be taken. The Stahnke computer-driven reproducing piano has recently been completely re-engineered in the UK using latest state-of-the-art electronic science and hardware. The pre-production piano, a Bösendorfer Imperial, is now being assessed. The engineer doing this work, R Shepherd, used a Steinway D piano as a test bed. Commercial production is expected by mid-2002.



Components of Computer Piano Action

Pianos in concert

Steinway has had a virtual monopoly of the concert halls of Europe since the Second World War with its very fine Model D, over a century old in concept. Because it is so widely available, artists feel assured by their familiarity with it. Only the grand masters of the profession seem to have the skill, experience and will to challenge conformity and commercial pressures by playing other makes. Steinway can be said to be the 'Jeep' of the quality piano world – rugged, reliable, predictable and versatile. It is a great shame that UK audiences so rarely have the chance to hear other superb makes of concert instrument with their unique qualities.

The massive nine-foot, six-inch Bösendorfer Imperial dates from the early years of the last century and has its origins in pianos designed to withstand the stresses of being played by Liszt. It is considered by many to be the aristocrat of all pianos because of its unsurpassed bass and tenor registers and its rich clarity in its sound. The Imperial has the largest soundboard area of any piano currently in production. Fazioli, the giant ten-foot, two-inch 'Ferrari' of pianos with avant garde design features and a relatively light frame has upper register power unequalled by any other instrument: it responds well in the hands of highly skilled technicians. There is no such Fazioli piano in UK venues! The nine-foot, six-inch Stuart, the latest newcomer from Australia, offers a uniformity of warm powerful sound and purity across the registers unmatched by other makers. It has a singing tone so sustained that it almost challenges the artist's control. There is only one Stuart piano in the UK.

Bösendorfer Imperial fitted with computer recording and reproducing system

May the day soon come when British audiences more vociferously demand greater variety and better piano sound from the far too conservative, entrenched and introspective 'clan' of venue managers, and artists' agents. Until that day, there is limited incentive to advance piano design. ■

Bösendorfer Imperial (left) and computer recording Steinway D pianos in the author's music room. Two demonstration tracks played on these pianos can be downloaded as MP3 files from the Royal Academy of Engineering website, at http://www.raeng.org.uk/news/publications/ingenia/
Each file is around 2 MB in size. The differences between the two pianos will be best appreciated on headphones.

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Richard Dain studied sciences and later engineering at Cambridge, before joining Ruston and Hornsby (Lincoln) as gas turbine and diesel engineer. After working in Switzerland, he joined Davy International, eventually to become Group Director of Research. Aged 40, he formed his own consulting company with Sir Hugh Ford FREng FRS and started Powdrex Ltd, now the world's largest manufacturer of tool steel powder. As Consultant to British Rail, he was responsible for managing the design and manufacture of IC225 trains for the east coast mainline. Pianos are a retirement hobby which he enjoys on his Kent farm where famous international pianists regularly play recitals and where a mechanical nut harvester is under development.
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