IMPROVING THE UPRIGHT PIANO

Martin Keane

Acoustics Research Centre,
University of Auckland, New Zealand

This paper was awarded the **2006 Presidents' Prize** for the best technical paper presented at the Australasian Acoustical Society's Conference, Christchurch, New Zealand. A version was published in the proceedings of that conference, edited by Terrence McMinn.

This paper reports a study of piano vibrations, undertaken to find whether improvements may be achieved by altering the piano case materials. Modal analysis and sound level measurements showed that, because of the manner in which sound is radiated by the piano, the tone does not change significantly when typical materials are used in the case. A method was developed for analysing the spectra of recorded notes; it showed differences in vibrations between upright and grand pianos. A finite element model of a piano suggested that changing one component (the keybed) of the upright would reduce the key vibration level, and make the upright feel more like a grand. These changes were made to one of a pair of pianos, which were subjectively compared by a group of pianists; the results showed that the upright piano had been improved.

INTRODUCTION

This paper gives a (mostly) non-technical overview of the vibrations and radiated sounds of grand and upright pianos. The overall aim was to investigate whether new materials for the case could be found which would bring about an improvement in the subjective evaluation of the piano.

The most important acoustic component of the piano is the soundboard, and many researchers focus solely on this component. The case (and the other components) can affect the vibration of the soundboard, but the degree to which this is important was not known when this project began.

Figure 1 shows the soundboard, frame, action and other important components of a typical upright piano.

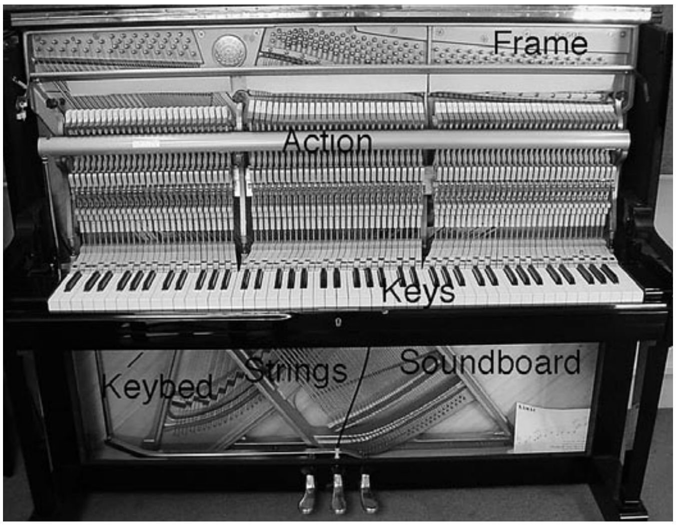

Figure 1. The interior and major components of an upright piano. The keybed, which will be of importance in this paper, is the structure beneath the keys.

At the commencement of the research it was hypothesised that there are three ways in which the case could affect the radiated sound. We will discuss these first. Later a more successful method of influencing the piano performance was discovered, this will be described in the second half of the paper.

The first way in which the case can have an effect is by changing the edge conditions of the soundboard, and thus altering the distribution of modes (the vibrational modes of the soundboard determine its response to the input from the strings). The second is by reflecting the sound radiated by the soundboard (as with the lid of a grand piano) and the third is by direct radiation from the case itself. Each of these methods was investigated in turn.

THE SOUNDBOARD AND CASE

The soundboard is the major sound radiating component in the piano. It is driven by vibration from the strings which is passed through the bridges. The modern soundboard is normally made from Sitka spruce, and is between 6.5 – 9.5 mm thick (Conklin 1990). Ribs are added to the back of the soundboard perpendicular to the grain direction, as shown in Figure 2, in such a way that the stiffness is approximately equal in both directions. Although the soundboard in the grand piano is larger than the upright, the function and basic characteristics of each are the same.

Figure 2. The soundboard of a typical upright piano. Ribs are indicated. The grain direction is perpendicular to the ribs.

> The case provides the rigid structure on which all the other components are mounted, as well as edges for the soundboard which attempt to approximate clamped supports. The case is designed, from a vibrational point of view, to prevent the loss of mechanical vibrations from the soundboard. The soundboard is the most efficient radiator, so it is desirable to keep vibrational energy there rather than letting it pass into other components. This is accomplished if the mechanical impedance of the case is much higher than that of the soundboard. High impedances are given by dense, stiff materials such as solid woods, so traditional cases were/are typically made of maple, beech, mahogany or walnut However, modern upright piano cases are often made from medium density fibreboard, as it is cheap and easy to work with, being homogeneous.

The mechanical impedance of the strings is fixed by the string parameters, and is much lower than that of the soundboard. The impedance load imposed by radiation is fixed by the room acoustics. The impedance of the soundboard varies with frequency and is approximately 1000 kg/s, and is essentially fixed by the desire to have notes with slow decay, as lowering the impedance would result in more rapid decay. Therefore the only option left to the piano designer are to limit soundboard damping, which is achieved by using spruce, and to increase the case impedance. Current designs achieve very high case impedance (of the order of 500,000 kg/s) compared to the soundboard, so only incremental further improvements are possible, at the expense of large increases in case mass or material expense.

In a grand piano, the lid is also important, as it is tilted to reflect sound out to the side, to where the audience would be during a performance. This sound field directivity is more pronounced at high frequencies. The major factors affecting this directionality are the angle of the lid and the surface finish used (Fletcher and Rossing, 1991).

RADIATION EXPERIMENTS

Modal analysis

Modal analyses were made of an upright and a grand piano. These were intended to find the soundboard modes and admittance, and to investigate the interaction between the soundboard and the case. Although much previous work has been carried out regarding piano vibrations, this experiment was the first in which the combined motion of the case and soundboard was investigated in both the upright and the grand.

It was found that the upright soundboard deformation always exceeded the case deformation by at least 10 dB, and more typically by 20-30 dB. In the grand, the difference between the soundboard and the case was larger, i.e. the vibrational separation between the soundboard and the case was greater. Some of the soundboard modes were aided by the deformation of case panels. The lowest six soundboard modes are shown in Figure 3. Thus for those modes, in both the upright and grand piano, the frequencies were reduced and the amplitudes increased, but these effects were small, less than 5%. The grand and upright soundboards had impedances of the same order, but it was found that the upright soundboard had the (1,1) mode (at 73 Hz) at unusually high impedance, causing a lack of radiated sound power in the upright bass range. The (1,1) modes of four other uprights were tested and all were found to be at a similarly low amplitude. This may be one of the reasons uprights are considered to sound inferior to grands. The impedance function was found to be smoother throughout in the grand (which is desirable for even playing), this may be due to the irregular shape of the grand soundboard.

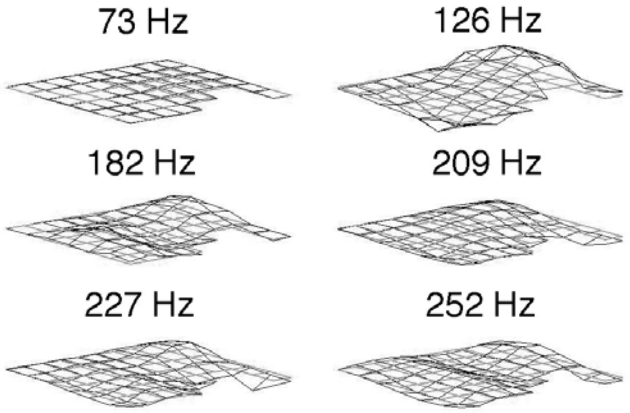

Figure 3. The lowest six vibrational modes of an upright piano soundboard. Note the low amplitude of the (1,1) mode at 73 Hz.

Finite Element Model

Following the modal analysis, a finite element (FE) model of the upright piano was built in ANSYS. This study was intended to assess the errors introduced through the simplifying assumptions that are often used in piano modelling, such as ignoring the case, or assuming an isotropic soundboard.

It was found that including the case in the analysis increased the accuracy of the results, at the expense of greatly increased computation time. Excluding the case from the model gave correct mode shapes, but incorrect frequencies. Using the soundboard with simple supports predicted mode frequencies too low by 5% and clamped supports predicted frequencies too high by 10%. The effect of the soundboard ribs is to make the soundboard approximately isotropic at low frequencies, and modelling the soundboard simply as an isotropic plate can give reasonable results below 250 Hz, and greatly reduces computation time. In both the modal analysis and the FE model, it was clear that as the frequency increased, the simplifying assumptions became less applicable.

Reflection and radiation

The possibility of influencing the radiation or reflection of sound by changing the materials of the case was considered next. Individual case panels were excited to the levels measured during the modal analysis and sound radiation was measured with a sound level meter, and found to be at least 20 dB lower than the radiation from the soundboard. This confirmed that radiation from panels other than the soundboard can be ignored. Also, because the case impedance is so much higher than the impedance of the soundboard and of air, changes to the case materials have very little effect on the reflected sound, since more than 90% of the incident sound is reflected with a normal lid.

Conclusion of radiation experiments

These studies confirmed that, because the case impedance is higher than that of the soundboard and of the radiation load, changes to the case material do not affect the radiation from the piano to a subjectively important degree. However, it was found that another possibility existed: the feedback of vibrations to the pianist through the hands, an important transmission path that does not involve radiated sound or the soundboard, which is affected by the materials of the keybed.

VIBRATION TRANSMISSION EXPERIMENTS

Introduction

When playing, the pianist receives aural and tactile feedback. The measured vibration level of the keys is above the tactile threshold (Askenfelt and Jansson 1992), yet pianists do not seem, in general, to be consciously aware of this feedback path. To date, vibration feedback in pianos has not received extensive study. However, it was found by Galembo (2001) that subjective assessment of a piano was affected more by vibration and touch/feel than by sound.

Tonal and broadband components

It is well known that piano tones consist of a broadband and a tonal component (also known as the BC and TC). The tonal component comes from the strings, and consists of the harmonically related overtone series for that note. The broadband component is by contrast of wide spectrum, with some individual modes at low frequencies but decreasing at a constant rate of 20 dB per octave at higher frequencies, and extending up to around 5 kHz. The spectral differences between these two components allow them to be separated.

Feedback paths are different for the tonal and broadband components. The tonal component originates in the strings, and is transmitted through the bridge and soundboard, then the case and keybed to the keys and to the pianist. The broadband component is composed of vibrations from many parts, but for the pianist the most important is the vibration of the keybed when struck by the falling key. This vibration is transmitted directly back into the keys and to the pianist. Therefore the broadband key vibrations are almost completely determined by the keybed.

The keybed

The keybed is the part of the piano on which the keys rest. There are marked differences in keybed construction between upright pianos and grands, leading to differences in transmission of vibrations and radiation of sound. In uprights, the keybed is a solid plate, 45 mm thick and made from plywood. In grands, by contrast, the keybed is a part of the case and about 60 mm thick. Above this there is another, movable frame, called the keyframe, on which the keys rest. The purpose of the movable frame is to accommodate the una corda pedal.

Analysis of piano tones

A new method was developed for splitting recorded piano notes into tonal and broadband components. This method has several advantages over those previously proposed. It is worth going into greater detail to describe the problem and the algorithm used here.

Previous research

The most important previous work concerning the relationship between the components of piano tones is that of Galembo (2003), who investigated the quality of tones in the extreme treble range. Building on the work of Smurzynski (1983) and Revvo (1988), who both removed the tonal component by damping the strings with felt, Galembo used comb filters to remove the harmonics (of which, for extremely high notes, there are typically only two or three) from recorded tones. This method is superior to mechanically damping the strings in that it allows the recovery of the tonal component. However, this method is problematic, as the filter will remove any broadband signal that is within the filter stopbands. Ideally some of the energy in the stopbands should be retained in the broadband signal.

The primary finding of the Galembo study was that “The judged note quality in listening tests increases when the broadband component is less intense, of narrow spectrum, and decays rapidly, while the tonal component is more intense and decays slowly” (Galembo, 2003).

The separation algorithm

A paper describing the technique used to reconstruct the broadband and tonal signals in detail has been accepted for publication in Applied Acoustics, here we will give a précis of the method. The purpose was to create an approximate broadband spectrum from the available data, and then use the inverse Fourier transform to return to the time domain (in the actual program, a series of windowed spectra were used, i.e. a spectrogram). The majority of the broadband spectrum was simply taken from the spectrum of the original signal, however near each harmonic it was the tonal spectrum which dominated. Consequently, in a small frequency range around each harmonic the broadband spectrum was inferred, based on the assumption that it varied linearly over such a small range. A linear interpolation was made across each harmonic peak in the spectrum. Figure 4 illustrates the process for two harmonics of a sample note. Across each harmonic, the broadband spectrum was inferred by interpolating between points on either side of the peak. The shaded area represents the harmonic content that is removed.

Taking the inverse FFT of this approximate spectrum reconstructed the broadband signal (the complex spectral data was used to allow return to the time domain). By subtracting it from the original signal the tonal signal was also recovered. Due to the nature of piano notes, this algorithm was limited to notes between approximately F2 (87 Hz) and C7 (2100 Hz).

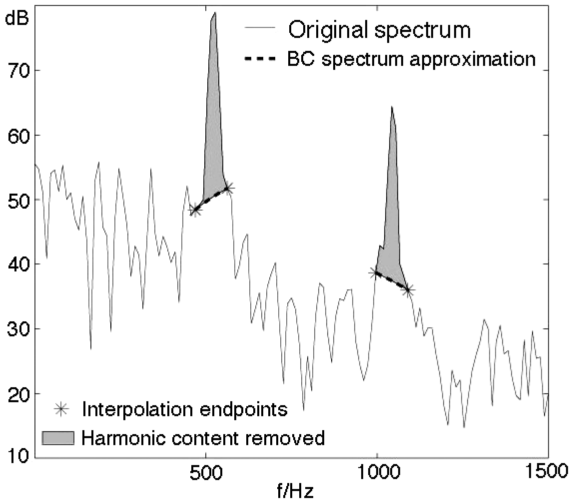

Figure 4. Example removal of spectral peaks. Asterisks mark the endpoints for the interpolation, and the dashed line shows the interpolated spectrum. The shaded area represents the harmonic content which is removed. The decibel scale has an arbitrary reference.

This algorithm was written in Matlab and all parts were automated, including the detection of harmonics and the choice of endpoints, however these tasks could equally have been done by hand. Analysis of a typical note took around 10 seconds on a 3 GHz P4 PC. Also of note was that the algorithm worked equally well whether the input was sound or vibration recorded by an accelerometer.

The broadband to tonal ratio

Recordings were made of radiated sounds and key vibrations (measured with an accelerometer) of four upright and four grand pianos, and analysed with the separation algorithm. The broadband to tonal ratio, which was first used by the authors previously mentioned, Smurzynski (1983), Revvo (1988) and Galembo (2003), was useful when analysing the separated components. The broadband to tonal ratios are twice as large in the measured uprights as in the grands. These differences were not seen in the radiated sound. Hence we concluded that reducing the strength of the broadband acceleration in the upright pianos may lead to an improvement in subjective quality. It was likely that the keybed could be used to moderate the key vibrations as it provides the structure underneath the keys, and so any key vibrations must pass through it.

FE model of the keybed

The ANSYS FE model was again used to investigate the influence of keybed materials on transmitted vibrations in the upright piano. A number of materials were considered, both hypothetical and real. It was shown that, due to the geometry of the piano, broadband vibrations are strongly affected by the impedance of the keybed, while tonal vibrations are not. Thus it was suggested that a material with relatively high impedance would be a suitable replacement material for the keybed. For example, the model predicted that a keybed made from high density fibreboard would reduce the broadband acceleration level by as much as 10 dB, without significantly altering tonal vibrations. Of the readily available materials, this was found to be the most suitable for the subjective experiment detailed below.

Making a new keybed

A replacement keybed was manufactured from high density fibreboard and fitted in the upright piano. The impedance of the new keybed was measured by modal analysis to be on average 10 dB higher than the original (plywood) keybed, yet it had the same speed of sound and thus the modes remained at the same frequencies. Modal analysis and measurements of sound and vibration with the new keybed installed show that the transmitted vibrations were reduced by the modifications: the broadband acceleration level was reduced by an average of 3.2 dB for notes between C3 and C6 (the most heavily used part of the keyboard). This was much less than ANSYS had predicted, however it was greater than the just noticeable difference for tactile vibrations, of 2 dB (Gescheider et. al. 1990). In addition, radiated sound levels were unchanged by the keybed replacement.

The most probable reason for the discrepancy between the ANSYS prediction and the behaviour of the actual keybed is that ANSYS overpredicted the vibration levels in the original keybed. As the impedance of the original keybed was lower, vibrational energy was more easily passed from it to the other parts of the case, which were also of lower impedance. This transmission path was not accurately accounted for in the model. With the higher impedance replacement keybed, this interaction was reduced and so this source of error was less significant.

Subjective assessment of the new keybed

Following these modifications, a subjective experiment was carried out in which two groups of experienced pianists (12 in each) compared two pianos, one of which had the replacement keybed installed, but which were otherwise identical. Both pianos were professionally tuned after the modified keybed was installed. The subjects in the control group, which compared the two pianos before modifications were made, showed no clear preference for either piano. In the experimental group, 10 out of 12 subjects preferred the modified piano and 2 preferred the unmodified piano. This result was significant at the 90% confidence level, thus a clearly sensible improvement was made by using the high density fibreboard keybed. The subjects indicated in their responses that significant differences were found between the timbres of the pianos in the high frequency range, an unexplained result as the tone was not measured to have been significantly modified. In addition, none of the factors such as age or years of playing experience were found to be predictors of preference.

Overall, the subjective results showed that the modifications proposed gave an improved instrument for the pianist, by reducing the acceleration level of the keys.

CONCLUSIONS

The vibration of upright and grand pianos was studied as part of an investigation into the possibility of improving pianos by altering the case. Modal analysis showed that because of the difference in impedance between the case and the soundboard, the tone cannot be altered by changing the case. A new and more accurate method for splitting tones and vibrations into broadband and tonal components was developed. By this method it was found that the magnitude of the broadband vibration component of the keys was twice as large in the four measured upright pianos as in the four grands. Thus, by replacing the keybed with a higher impedance material, it is possible to reduce the broadband vibrations and improve the subjective feel of the upright piano. A high density fibreboard keybed was substituted into one of a pair of pianos, and measurements confirmed that key vibrations were reduced. Comparison of the pianos by groups of 12 experienced pianists confirmed that this resulted in an improved instrument for players.

ACKNOWLEDGEMENTS

This study was carried out at the Centre for Advanced Composite Materials and the Acoustics Research Centre at the University of Auckland, with financial support from the Foundation for Research Science and Technology.

REFERENCES

Askenfelt, A., Jansson, E. 1992, *On vibration sensation and finger touch in stringed instrument playing.* Music Perception, 9(3):311–350

Conklin, H. 1990, *Piano design factors – their influence on tone and acoustical performance.* In *The Acoustics of the Piano*, Royal Swedish Academy of Music, Stockholm

Fletcher, N., Rossing, T. 1991, *The Physics of Musical Instruments.* Springer–Verlag, New York

Galembo, A. 2001, *Perception of musical instrument by performer and listener (with application to the piano). In Proceedings of the International Workshop on Human Supervision and Control in Engineering and Music,* International Federation of Automatic Control, Kassel

Galembo, A. 2003, *Quality of treble piano tones.* In *Proceedings of the Stockholm Musical Acoustics Conference*, Royal Institute of Technology, Stockholm

Gescheider, G., Bolanowski, S., Verillo, R., Arpajian, D., Ryan T. 1990, *Vibrotactile intensity discrimination measured by three methods.* Journal of the Acoustical Society of America, 87(1):330–338

Revvo, A. 1988, *Criteria for objective quality evaluation of piano sounds*. In *Novelties of musical instrument industry*, Scientific Research and Design Technological Institute of Musical Industry, Moscow

Smurzynski, J. 1983, *Objective and subjective measurements on treble piano sounds,* Czechoslovakian Scientific and Technological Society, Hradec Kràlové