AN EVALUATION OF PIANO SOUND AND VIBRATION LEADING TO IMPROVEMENTS THROUGH MODIFICATION OF THE MATERIAL PROPERTIES OF THE STRUCTURE

Martin Keane

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering, The University of Auckland, 2006.

ABSTRACT

A study of vibrations and sound radiation in upright and grand pianos has been made to determine whether the piano may be improved by altering the materials of the component parts which are traditionally fabricated in timber.

Modal analysis and sound level measurements of an upright piano has shown that the radiation from the case is at least 20 dB lower than the radiation from the soundboard, and therefore the case is not a significant determinant of piano tone.

A method was developed for separating piano sound and vibrations into broadband and tonal components and used to compare the performance of upright and grand pianos. Using this method it was found that the broadband vibration level was twice as high in the uprights as in the grands.

A finite element model of an upright piano was developed and used to demonstrate that replacing the keybed with a higher impedance material than conventionally used would reduce the key vibration level, and hence bring the uprights closer in performance to grand pianos, and improve the 'feel' of the instrument for the player. The keybed of one of a pair of identical pianos was replaced with high density fibreboard, and subsequent objective measurements showed that the broadband component of key vibrations was reduced by 3.2 dB while the radiated sound was unchanged. A controlled subjective comparison between the modified and unmodified pianos undertaken by experienced players showed that a statistically significant number preferred the modified piano, and that the upright piano had been improved.

Acknowledgements

The research presented in this thesis was carried out at the Acoustics Research Centre and the Department of Mechanical Engineering at the University of Auckland. The work was undertaken as part of a Technology for Industry Fellowship funded by the Foundation for Research Science and Technology (FRST) and Fletcher Wood Panels. The support, financial and otherwise, provided by FRST and Fletcher Wood Panels is gratefully acknowledged.

I would like to thank my supervisors, George Dodd and Debes Bhattacharyya, as well as my mentors from FWP, Paris Alexiou and Dean Smart.

I would also like to gratefully acknowledge the following people:

Keith Jones and Chris Huggins of Uniservices. The staff of the Acoustics Research Centre: Gian Schmid, Murray Hollis, and Cliff Wright; the School of Music: James Tibbles, Eric Hollis and Peter Kerr; and the Department of Mechanical Engineering: Ivan Bailey, Rex Halliwell, Jos Guerts, Barry Fullerton and especially Roger Halkyard. David Jenkin and Yuji Nakamura of Jenkin Piano Tuners. Jane Walkinton and Stephanie Callaghan of FWP, and Callum McKenzie of Dynea NZ. Martin Upsdell of AgResearch. My colleagues in both Acoustics and Engineering: Thomas Scelo, Miro Duhovic, Hyuck Chung, Fady Talab, Daniel Wadsworth, Arif Zaher, Ming (Michelle) Li, David Lee and Michael Buntain.

Thanks to my proofreaders: Jim and Sheryll Keane, Maria Vendetti, Sophie Meehan, Aimee James, Sam Marsh, Gareth Kayes, Carl Schnackenberg and Olivia Kember.

Thanks also to the pianists who participated in the subjective experiment.

Contents

List of Figures

List of Tables

List of Symbols

The following notation is used in this thesis:

Symbol	Description	Units
A	Admittance	s/kg
B	Flexural stiffness	Nm^2
E	Young's modulus	Pa
F	Force	N
G	Shear modulus	Pa
$H(s)$	Hilbert transform of $s(\tau)$	
I	Sound field intensity	W/m^2
L	String length	m
P	Probability	
R	Sound reduction index	
RT	Reverberation time	s
S	Area, cross sectional area of string	m^2
T	Contact time between hammer and string	s
V	Volume	m^3
W	Radiated sound power	W
X	Average soundboard displacement	m
$X(\omega)$	Fourier transform of $x(t)$	
Z	Characteristic impedance	kg/m^{2}s
a	Plate length	m
b	Plate width	m
c	Speed of sound	m/s
c_b	Bending wavespeed	m/s
d	String diameter	m
f	Frequency	Hz
h	Plate thickness	m
i	$\sqrt{-1}$	
m	Number of half-wavelengths in plate a direction	
m'	Mass per unit length	kg/m
m''	Mass per unit planar area	kg/m^2
n	Mode numbers: 1, 2, 3...	
p_0	Atmospheric pressure	Pa
v	Velocity of vibration	m/s
$x(t)$	Signal in time domain	
ζ	Damping, expressed as a fraction of critical damping	
λ	Wavelength	m
ν	Poisson's ratio	
ρ	Density	kg/m^3
σ	Radiation efficiency	
τ	String tension	N
ω	Angular frequency	rad/s

To avoid confusion, throughout this thesis admittance refers to the ratio of velocity to input force, while impedance refers to material characteristic impedance, given for solids by $Z = \sqrt{E\rho}$.

Pitch notation

The scientific or American system of pitch notation is used. In this system notes are named starting from the bass (left hand) end of the keyboard: A_0, $\mathrm{B}\flat_0$, B_0, $\mathrm{C}_1\ldots$ Thus the note commonly known as 'middle C', or c^i in Helmholtz notation, is C_4, and the note 'concert A', with pitch 440 Hz, is A_4.

Coordinate system

The origin is taken as the point at the leftmost end of the keyboard from the perspective of the pianist, at the A_0 key. The x axis is directed along the keyboard, while the y axis is directed vertically up, normal to the keyboard. The z axis is normal to the upright soundboard, pointing forward from the perspective of the pianist. The same system is used for both upright and grand pianos, thus in the grand it is the y axis that is normal to the soundboard.

Abbreviations

The following abbreviations are used in this thesis:

BAC	Broadband acceleration component
BC	Broadband component
BPC	Broadband pressure component
C	Clamped support (no displacement or rotation)
CFD	Computational fluid dynamics
DAT	Digital Audio Tape
DL	Difference limen
F	Free support
FE	Finite element
HDF	High density fibreboard
MDF	Medium density fibreboard
MIDI	Musical Instrument Digital Interface
QS	Question score
RMS	Root mean square
S	Simple support (no displacement)
TAC	Tonal acceleration component
TC	Tonal component
TPC	Tonal pressure component

Glossary

action - the mechanical assembly that includes the piano keys, hammers and dampers.

admittance - a measure of the velocity with which a structure will vibrate when excited by a given input force.

ANSYS - a commercial software package for analysing problems via finite element methods.

antiresonance - a frequency between two modes of vibration where their contributions interfere destructively, giving a low response amplitude.

boundary conditions - in a finite element or modal analysis problem, the boundary conditions are the restraints imposed at the edge of a structure. Common types include simple (no displacement) and clamped (no displacement or rotation).

cancellation - see interference.

circle of fifths - a geometric representation of the relationships between musical keys. Keys that are adjacent on the circle of fifths differ from each other by only one sharp or flat.

coherence - a measure of the dependance of the input and output of a system. Coherence is 1 for perfect measurement of a linear system, and is lowered by nonlinearities and measurement noise.

compass - the entire range of notes available on a given piano.

critical frequency - the frequency at which the speed of a bending wave in a structure is equal to the speed of an incident wave in air. At this frequency, radiation from the structure is relatively large in magnitude.

damper - the component in the piano action which returns to the string after the key is released, quickly stopping the string vibration.

damping - a measure of the rate at which a free vibration will decay, for a given oscillating system. Where damping is low, vibrations will decay slowly.

degrees of freedom - the set of independent displacements that describe the motion (linear or rotational) of a system.

difference limen - in human perception, the smallest difference in a stimulus that is detectable. Also known as the just noticeable difference.

dissonance - in music, notes that do not sound well together are dissonant. Dissonance is the opposite of consonance.

eigenmode - see mode of vibration.

filter - a process or system that allows some regions of the frequency spectrum to pass unattenuated, while reducing the amplitude of others. Common filters include lowpass (attenuates high frequencies), highpass (attenuates low frequencies) and comb (a series of notches, removing harmonically related frequencies).

finite element method - method used for analysing the vibration of structures, by dividing the structure into many smaller parts known as elements. The elements and the relationships between them are described by a large number of equations, which are solved simultaneously.

fortissimo - a direction for playing musical instruments meaning 'very loudly'.

Fourier transform - a transform that decomposes a signal or function into its frequency components (its spectrum). This is known as going from the time domain to the frequency domain. The inverse Fourier transform reverses the operation. The forward (continuous) transform is given by $X(\omega) = \int_{-\infty}^{\infty} x(t)e^{(-i\omega t)}dt$, and the reverse transform by $x(t) = \int_{-\infty}^{\infty} X(\omega)e^{(i\omega t)}d\omega$. Equivalent versions are used for discrete data.

fundamental - the lowest frequency in a harmonic series, the pitch of a note.

hammer - the component in the piano action which strikes the string. The head of the hammer is covered in felt.

harmonics - the frequency components of a complex tone. Harmonics are integer multiples of the fundamental for a periodic signal.

Hilbert transform - a transform that returns the complex envelope of a signal. It is given by $H(s) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{s(\tau)}{t-\tau}d\tau$.

homogeneous - a material that has the same properties at every point, such as a metal.

hysteresis - in an integration of partial differential equations with respect to time, hysteretic terms are those that involve the state of a system at a previous timestep.

impedance - the characteristic impedance of a material describes the degree to which structures made of that material will resist vibration. For solids, the impedance is given by $Z = \sqrt{E\rho}$.

impedance hammer - a hammer used in modal analysis. The tip contains a force transducer to measure the force input during each blow.

interference - the addition of two or more waves, which results in patterns of vibration. Destructive interference refers to the addition of a positive and negative wave to give an output of zero at a point.

isotropic - isotropic materials exhibit the same properties in every direction, such as metals

key - the chord which is established as the final resolving point for a musical piece.

Matlab - a commercial software package designed for numerical computation, particularly suited to working with matrices.

modal analysis - the decomposition of the vibration of a structure into individual modes.

mode of vibration - the natural shapes and associated frequencies with which a structure will vibrate under free vibration.

modulus - a measure of the stiffness of a material. It is the ratio of the rate of change of stress with strain.

node - in a mode shape, nodes are the points at which displacement is zero.

note - a single playing of a sound of definite pitch, for example the sound made by striking the C4 key once.

orthotropic - orthotropic materials have properties that differ in orthogonal directions, such as wood.

overtones - see harmonics.

partials - see harmonics.

pianissimo - a direction for playing musical instruments meaning 'very quietly'.

pitch - the fundamental frequency of a sound.

Poisson's ratio - a measure of the tendency of a material to contract or expand in the directions normal to an applied load.

polyphonic - music that is polyphonic contains two or more independent notes played at the same time.

regulation - the process of softening the hammers of a piano, which tend to harden with use. Regulation is intended to maintain the timbre of the instrument.

spectral centroid - the frequency which divides the spectrum in two, with equal energy above and below it. A high centroid is strongly perceptually correlated with 'sharp' or 'bright' tone [Grey, 1977].

spectrogram - a graphical representation of the Fourier transform of a signal, divided into short time windows. A three dimensional plot of energy content with respect to time and frequency.

spectrum - a plot of the energy content of a signal with respect to frequency. It may be obtained via the Fourier transform.

staccato - to play notes in a manner such that silence takes up the latter part of the time allocated to the note.

supports - see boundary conditions.

synthesis - the creation of musical notes by electronic or computational methods, as opposed to physical vibrations.

temperament - methods of slightly altering the tuning the musical notes to allow an instrument to be played in more than one key.

timbre - the perceived sound quality of a musical note.

transfer function - a measure of the relationship between the input and output of a system, such as the measured velocities of two connected components.

una corda - a pedal on the grand piano that shifts the entire action to the right, so that hammers that normally strike three strings only strike two, modifying the timbre of the note.

voicing - see regulation.

window - a function that is zero outside of a given interval. The window is stepped along the length of a signal, while other operations are performed such as the Fourier transform. Within the interval the window may take many shapes which are typically designed to reduce signal leakage. Commonly used windows include the rectangular (all uniformly equal to one), triangular (increases linearly from 0 to 1 then decreases to 0) and Hamming (raised cosine).