Sound Generation in a Piano: Multichannel Measurements

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Abstract

The sound production in a grand piano, despite the many investigations done, is still subject to nowadays investigations. We investigate the way the vibrations of the strings propagate through the piano body by means of transfer and correlation functions, and the cepstrum. Different types of vibrations, produced by a grand piano, are recorded simultaneously with a multichannel measurement. The data aquisition used 1) poleshoes placed over the piano strings, 2) piezo-crystals located at the piano bridge and on the resonance board and 3) a single capacitor microphone positioned over the instrument. To follow the spread of excitations, 31 simultaneous measurements were carried out at various locations.

The grand piano is known since 300 years, but there is still interesting research left due to the complex physics involved. Several recent publications were concerned with piano physics [1, 2, 3, 4]. The present multichannel investigation wholistically record the vibrations of individual parts of the piano (strings, sound bridge and resonance board) simultaneously in order to reconstruct the sound propagation in the instrument. The measurements were carried out on a grandpiano “Steinway & Sons, New York Hamburg (1899)“ As representative for the lower tones with two coupled strings, we focused on G2 (≈ 98Hz). Alltogether 31 signals were recorded over 2 seconds at a sample rate of 48 kHz. Different data aquisition techniques were used:

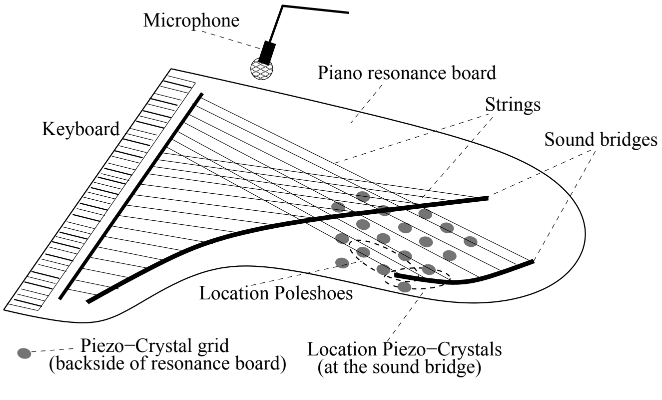

Figure 1: Locations of the sensors: poleshoes, the piezo-crystals at the sound bridge and on the backside of the resonance board and the microphone.

4 poleshoes, 1 microphone, 2 piezoelectric sensors at the sound bridge and 24 located on the backside of the resonance board (see Fig. 1). Two transversal directions of the string vibrations were measured with othogonally oriented poleshoes (electromagnetic induction) using an individual electric circuit. The alternating induction current yields the vibration time signal [1, 2, 4]. Here, we measure different string locations simultaneously using separate electric circuits. While the emitted piano sound wave was recorded with a Brüel & Kjær capacitor microphone, the vibrations at the sound bridge and in the resonance board were detected with piezoelectrical accelerometers: the bottom side of the soundboard was covered with a grid of 24 individual piezoelectrical sensors; two sensors were located at the piano bridge (Fig. 1). An example for the poleshoe time signal and the associated frequency spectrum is displayed in Fig. 2.

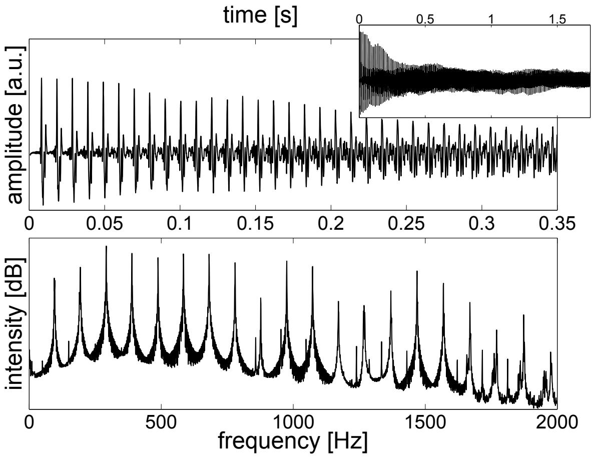

Figure 2: Time (top) and frequency (bottom) signal from a poleshoe measurement. The inserted plot show the time signal in the full range.

If a sound wave propagates through a piano the characteristic of the wave changes due to the material properties. One approach to characterize the acoustical transmission through the material is the transfer function $t(\nu)$. It is determined by two recordings of the *same* sound wave at different piano locations $x_1(t)$ and $x_2(t)$. $t(\nu)$ is given in Fourier representation by

$$t(\nu) = \frac{|\mathfrak{F}(x_2(t))|}{|\mathfrak{F}(x_1(t))|}\ , \qquad (1)$$

where $\mathfrak{F}$ denotes the Fourier transform. Real and imaginary part give the damping and the phase transmission of a sound wave transferred through material. The result is shown in Fig. 3 for a sound wave parallel t_p and orthogonal t_o to the texture of the wood in the piano resonance board. The major properties between t_p and t_o are:

- higher noise level in the second measurement (after the transmission through the instrument)
- bad transfer in the range 200Hz - 350Hz and a value around 2400Hz independent from the direction
- bad transfer around 680Hz and 1070Hz orthogonal to the wood texture
- additional intensity for 98 Hz (orthogonal)

A second characterization uses the correlation function $\xi(\tau)$ of two quantities x and y, defined by

$$\xi(\tau) = \int_{-\infty}^{\infty} x(t) y(t+\tau) \mathrm{d}t \qquad (2)$$

$\xi \in [-1, 1]$; where -1 means perfect anti-correlation, 0 represents no correlation at all and 1 means perfect correlation. In this sense, the correlation characterizes (similar to the transfer function) the change of shape of a wave over a time interval τ, or distance Δx, respectively. The correlation between every signal yields a 'correlation map', which is different for each piano tone (Fig. 3). Due to the commutativity of the correlation, the 'map' is mirrored around the diagonal, which represents the auto-correlation with value 1. All the other correlation values range between 0 and 1. Channel 1 to 4 represent the poleshoes, 5 & 6 are the piezo-crystals at the piano bridge, 7 to 30 are the piezo-crystals on the backside of the resonance board and the last channel is the microphone. Generally the correlation between the piezo-crystals at the bridge (channel 5 & 6) and the correlation between some parts of the resonance board is very good. Two channels have a below-average correlation (11 & 30), which indicates a non–perfect functionality of the piezo. The other correlations are within a certain range (0,3 to 0,6). These values furthermore correspond to a time delay, which can be used to determine the sound wave velocity in the resonance board. Further studies connect these correlations to the structure of the sound board.

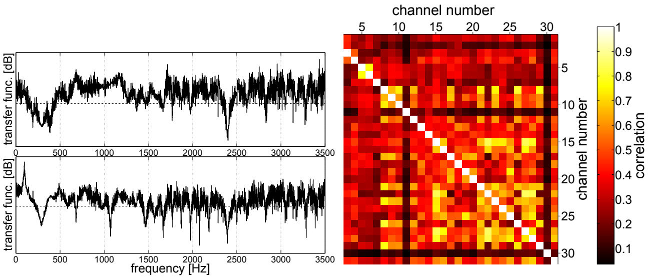

Figure 3: *Left*: Transfer functions along (top) and orthogonal (bottom) to the texture of the resonance board. *Right*: 'Correlation map': Signal correlation between all signals. The white diagonal represents the auto-correlation, which is defined as 1.

The difference of the longitudinal and transversal vibration allows the calculation of the velocity within the string ($v_{\text{string}} = 4520\frac{\text{m}}{\text{s}}$), which turns out to be in the range of copper ($v_{\text{copper}} = 3810\frac{\text{m}}{\text{s}}$) and iron ($v_{\text{iron}} = 5120\frac{\text{m}}{\text{s}}$); of course this makes perfect sense due to the copper wrapping of the iron core. Fig. 4 shows the speed of sound velocity dependent on the distance from the excitation (the bridge). Over a certain range of distances (0,1 m to 0,3 m) the velocity distribution is very broad (dashed line). With increasing distance this distribution begins to decrease, which is depicted with the dot-dashed line. The bigger the propagation distance in the resonance board, the more ribbs have to be transfered. The fast velocities of the distribution happens to be along the texture of the wood. But after a certain distance the ribbs, placed on the backside of the resonance board, slow down these propagation. Thus after 0,5m the propagation velocity is equal in each direction (about 350 m/s).

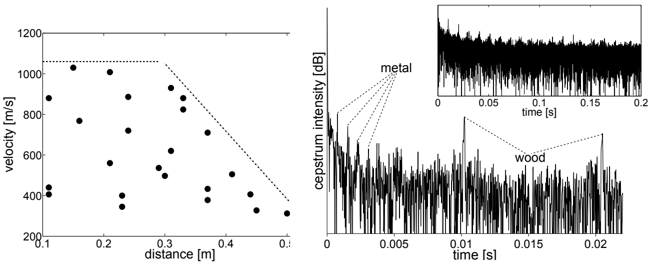

Figure 4: *Left*: Velocity distribution dependent on the propagation distance in the resonance board. Indicated by the dashed line is a broad range of velocities within small distance. The more ribbs on the backside of the resonance board came across the sound wave, the distribution thins out to relatively slow velocities (dotted-dashed line). *Right*: Cepstrum from the signal gathered at the sound bridge in longitudinal direction (inserted graph show a broader range).

We validate this measurement by the calculation of the *cepstrum* $C(t)$:

$$C(t) = \left|\mathfrak{F}\left(\log|\mathfrak{F}(x)|^2\right)\right|^2. \qquad (3)$$

$C(t)$ finds signal echos within the *same* signal. These echos correspond to a time delay and with the dimensions of the resonance body it is possible to determine the velocity. A piezo-crystal, positioned at the sound bridge, would not only measure the echos from the resonance board, but also the string echos (shown in Fig. 4). This yields to the velocity in the string ($v_{\text{string}} = 4545\frac{\text{m}}{\text{s}}$) and in the resonance board ($v_{\text{board}} = 390\frac{\text{m}}{\text{s}}$).

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