Comparison of measurements on a simplified piano model with a condenser microphone and a piezoelectric polymer sensor.

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Abstract

We investigate the sound emitted from the resonance board of a multichord, as a paradigma for piano vibrations. We use two different measurement techniques: (1) thin film sensors made from polyvinylidene fluoride (PVDF), mounted between the multichord bridge and the resonance board, and (2) condensor microphones for airborne sound. The usability of the piezoelectric polymer as calibrated acoustical sensor was tested and characterized with respect to different parameters, such as the input pressure, the force amplitude, the long term stability and the frequency response. The parameters were varied in order evaluate the effectivity and the durability of the electro-mechanical transducer. In addition, we placed ribs on the rear side of the resonance board in order to investigate how their number affects the sound radiation. Depending on the rib distance, significant high-frequency reductions of the response spectrum are observed with the peaks from the allowed vibration modes in between.

Due to their flexibility, light weight, and good resistance to heat piezoelectric polymers cover a wide range of application in vibrational measurements and pulse detection, a prominent example being polyvinylidene fluoride (PVDF) [1, 3, 5], which has become one of the working horses for minimal-invasive sensor technology today. In addition, the low cost compared to other fluoropolymers predestine PVDF for sensor applications in general. The main advantage in using piezopolymers for body vibrational measurements is, apart from the quasi non-invasive recording, an acoustical impedance which is compatible with many materials; prominent examples are wood and most of the synthetics. Hence, the sound wave can propagate almost undisturbed by the sensor because reflexions at the transition are minimal. The functionality of the piezopolymer is as follows: An external force changes the polymer dipole density and therefore the internal polarization; i.e. a variation of external mechanical stress generates corresponding compensation charges at the sample surfaces of the transducer which yield a measurable signal, which can be calibrated such that an external force can be accurately determined. We focus on the audible range, i.e. on low frequencies below 20kHz.

Calibration and Characterization of the Piezoelectric Polymer

d_{33} is a tensor describing the piezoelectric coefficient [4], which characterizes the surface charges generated in dependence on a normal force; it is proportional to the sensor efficiency. We calibrate and characterize the d_{33} coefficient of the investigated sensors with respect to key characteristics, such as the initial pressure, excitation force amplitude, the long term stability and the frequency response function. The d_{33} long term stability (cf. 2) was modeled with an exponential function + offset:

$$d_{33}(t) = d_0 \cdot e^{(-t/\tau)} + d_{33,eq}, \quad (1)$$

where d_0, τ and $d_{33,eq}$ represent respectively the initial d_{33} value, the half-value period and the converged d_{33} value in which the sensor reached its equilibrium state (about 96% compared with the initial value). For the investigated sensors 1 and 2 we find $d_{33,eq_1} = 13.2$pC/N and $d_{33,eq_2} = 15.5$pC/N. Along with the d_{33} measurements humidity and room temperature were controlled simultaneously (cf. 2, bottom). No correlation with the long term behavior was found.

The frequency response function (also cf. 2) show a high pass filter effect due to the capacitance of the sensor, which can be approximated via:

$$\mathrm{T} = \frac{f/f_c}{\sqrt{1+(f/f_c)^2}} \quad (2)$$

where f_c represents the cutoff frequency (3dB below the maximum), which is in our case $f_c = 305$Hz. A deconvolution of the signal with this capacitor effect shows the resulting frequency response, cf. 2, big frame. It is linear over the whole frequency range from 100Hz to 17000Hz.

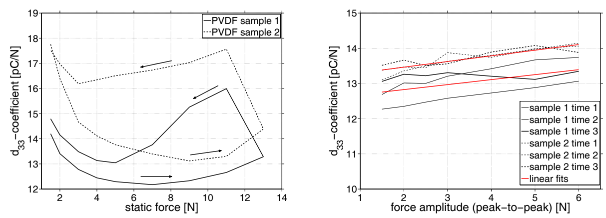

Figure 1: *Left*: Hysteresis of the d_{33} coefficient over the static force F_{stat}. The amplitude of the external force is held at 2N $\pm$0.1N (peak-to-peak). Increasing and decreasing of F_{stat} is indicated by the arrows.
Right: The d_{33}-coefficient plotted against the dynamic force amplitude with a constant static force of 6N $\pm$0.1N. Three independent measurements (recorded in the range of several days) for each investigated sample (black) with a linear fit of d_{33} over this amplitude range, which is indicated by the straight (red) line (slope for both is $m \sim (0.15 \pm 0.016)$pC/N^2).

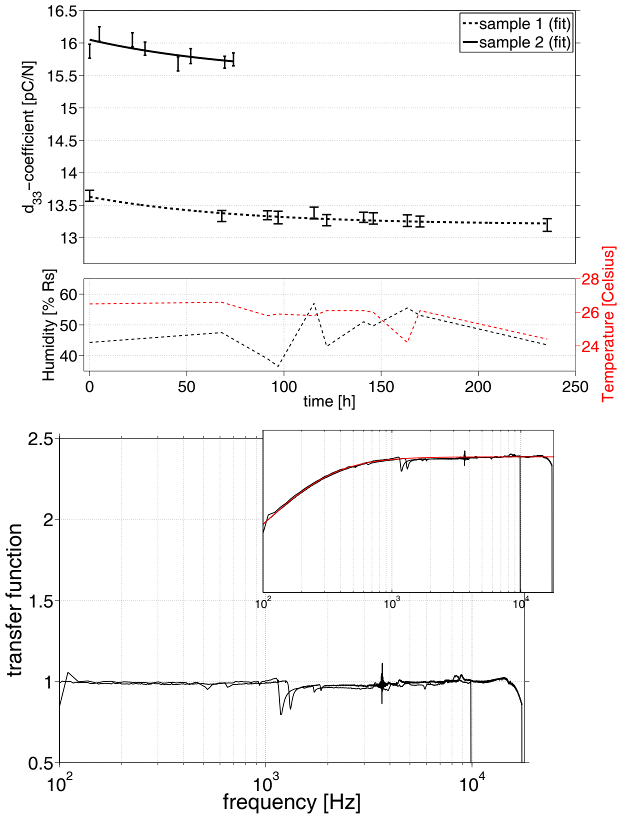

Figure 2: *Top*: A broader time range (up to 235 hours) for the d_{33} long term behavior in the upper plot. Both curves were fitted with an exponential function with offset (description see text). The lower frame show the evolution for the humidity (black) and the temperature (red) in the course of the sample 2 measurement; no correlation were found.
Bottom: PVDF transfer function of a sweep from 100Hz to 17000Hz. The inset show a high pass effect, which can be modeled with the red graph; the deconvoluted flat frequency response of the PVDF in the bigger graph.

Multichord Measurements

In the following we give an example how to apply the sensors developed. The physical question concerned the generation of sound in musical instruments. We wanted to know in how far the transmission of a single excitement through a wooden construction is reflected in the radiated sound. We consider this measurement as a generic setup for vibrational measurements; it is described completely in [2]. Body vibrations were measured by the self-prepared PVDF sensor mounted between parts of the build-up. Simultaneously the airborne sound was measured by a condenser microphone. The spectra of both sensors (normalized to power) and the difference spectrum between microphone and PVDF sensor are shown in Figure 3. The most interesting acoustical features appear in both signals at about 4000Hz, 8000Hz, and 12000Hz (indicated by arrows), however the peaks are much more pronounced in the piezopolymer signal. This indicates damping and redistribution of energy in the process of radiation. The measurement setup is constructed in such a way that broad frequency ranges of the body vibrations

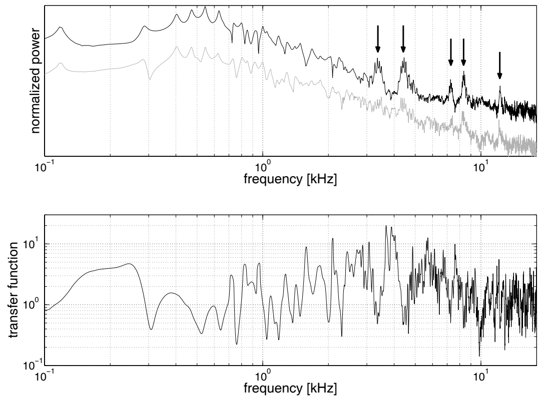

Figure 3: *Top*: Direct spectral comparison of a body sensor signal measured by the piezopolymer (depicted in the upper black curve) and a condenser microphone (lower gray curve). A single, pulse-like excitation of a wooden construction was recorded and Fourier-transformed. The PVDF curve is enhanced by a factor of 100 to have a better comparability between both lines. Both spectra are normalized to power and depicted in double logarithmic scale.
Bottom: Difference spectrum between microphone and PVDF sensor signal (microphone/PVDF) also in double logarithmic scale, i.e. we can precisely capture the difference between internal vibration and radiated sound.

are damped (cf. Fig. 3 all the regions bigger than one in the difference spectrum). Only some special modes can be clearly seen in the piezopolymer signal due to the fact that they are allowed (4000Hz, 8000Hz, and 12000Hz) in this configuration. The airborne sound radiation is not restricted to any modes and the allowed frequency bands from the body vibration spectrum are difficult to identify and would probably be overseen with only the microphone measurements. To get the full picture of generation and radiation of sound waves in certain constructions it is ideal to combine both data acquisition techniques simultaneously.

References

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