Tone Production of the Wurlitzer and Rhodes E-Pianos

Florian Pfeifle, Malte Münster

Insititut für Systematische Musikwissenschaft, Universität Hamburg, Deutschland, Email: florian.pfeifle@uni-hamburg.de

Introduction

In this work, two idiomatic examples of electromechanical instruments are presented. Wurlitzer EP200 and Rhodes Mark-I/II pianos, which are still highly valued among musicians, music producers and listeners regarding their specific genre, which primarily is Jazz, Funk and Soul music and related styles. Even modern popular R'n'B-styles or even Country-Pop are hardly to imagine without these pianos. Sounds available in modern keyboards and synthesizers are often based on analog instruments either completely acoustic, electro-mechanic or analog-electronic, pointing to a preferred sound aesthetic. Moreover it is quiet common to generate these sounds by sequencer plug-in software to run on digital audio workstations. Thus, a faithful reproduction of those originally analog sounds could improve the musical experience. [1]

Sound Production of the Rhodes Piano

The mechanical part consists of a rod made of spring steel shrunk into an aluminium block on one side, thus creating a quasi cantilever beam. The dimensions of the rod and the position of a small tuning spring, adding mass, determines its fundamental frequency f0. The rod is excited by a neoprene hammer tip. The key action mechanism is a simplified single action and every tine is damped by an individual felt damper. The fixation of the rod is tightly connected to a, sometimes $\pi/2$ twisted, brass bar which acts as the second prong of the patented "tuning fork" system (see Fig.1).

When played softly, the sound of a Rhodes piano can be described as glockenspiel-like, with an extremely short transient showing higher partials. Non-harmonic partials are created by the brass bar and are more prominent in the upper register of the instrument. This playing characteristics adds to the Rhodes piano's expressivity as a music instrument.

The electromagnetic pickup consists of a wound permanent magnet comparable to a pickup of an electric guitar.[2] The geometry of the magnet shapes the specific distribution of the magnetic field . The motion of the tine changes the magnetic flux which produces a change in the electromotive force resulting in an alternating voltage which is to be amplified, see Fig.2. The sound can be altered by changing the position of the tine in respect to the magnet. The more a tine is aligned towards the center of the wedge shaped magnet the more symmetrical the resulting waveform is. When aligned perfectly centered, the produced sound behind the pickup is twice the fundamental of the tine. The more the tine is shifted towards the edge the more asymmetric the resulting sound is, leading to a higher amount of harmonic partials, see Fig.3.

Figure 1: Tines with tuning spring in front of pickup

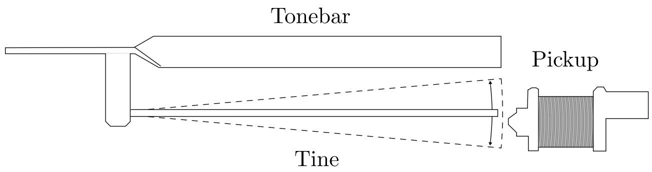

Figure 2: Rhodes pickup system

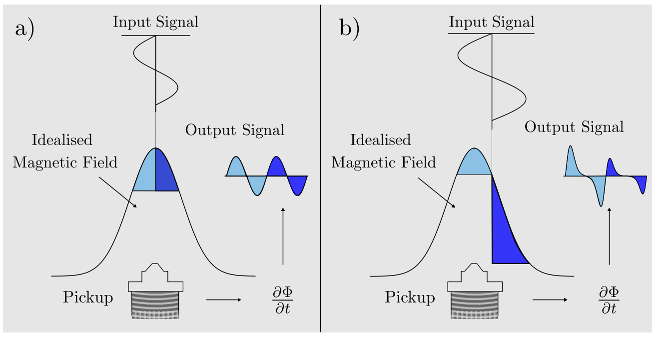

Figure 3: (a)A low amplitude input of a sinusoidal vibration of the magnetic flux weighted by the magnet fields distribution. (b) A slightly displaced mid-point for the input motion resulting in a different weighting function of the magnetic field.

Sound Production of the Wurlitzer

A steel plate impacted by a hammer vibrates as an electrode of a capacitor leads to a time-varying change in capacitance, see Fig.4.The plate, called reed, is made of hardened light spring steel, fixed at one end. The dimensions of the reed and the amount of solder on the tip of the reed both factors determine f0. A high voltage is applied to a fixed plate and the reed acts as the low

Figure 4: The reed is inducing a change of capacity in the electric field provided by the loaded plate

potential electrode of the capacitor. The reeds vibrate freely, providing a surface area large enough to produce a measurable change in capacitance. The air gaps between plate and reed act as dielectric material, see fig 5. Analogous to a capacitor microphone, the capacity varies inversely proportional to the distance between the electrodes. The key action mechanism is a miniaturized grand piano action. Higher velocity results in a richer harmonic sound than playing softly.

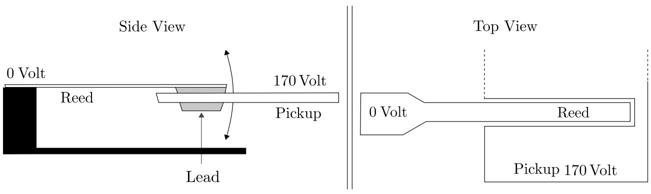

Figure 5: Schematic view of the Wurlitzers' capacitive pickup

Mesurements on Tone Generators

A high-speed camera ***Vision Research Phantom V711*** is used to record visibly moving parts. In case of the Rhodes, the motion of a freely vibrating tine and a hammer impacted tine vibration. In case of the Wurlitzer, the motion of a hammer impacted reed vibration is tracked. For tracking ***MaxTRAQ 2D*** is used. The traced trajectories are analysed with scripts coded in ***Julia*** language, using wavelet methods as well as Fourier transform analysis. Audio signals are measured near the generators, avoiding any coloring of the subsequent amplifier circuitry.

The presented measurements of the mechanic part and the electronic part of the tone generators of both instruments leads to the conclusion that the primary mechanical exciters are secondarily for the sound production of both instrument and their specific timbres are influenced primarily by the specific pickup system. See Fig.6 and 7.

A crucial part of the instruments sound characteristic and timbre must be attributed to the coupled electro/mechanical systems. All measurements show that the two different generators are performing nearly sinusoidal motions. The resulting sounds measured directly

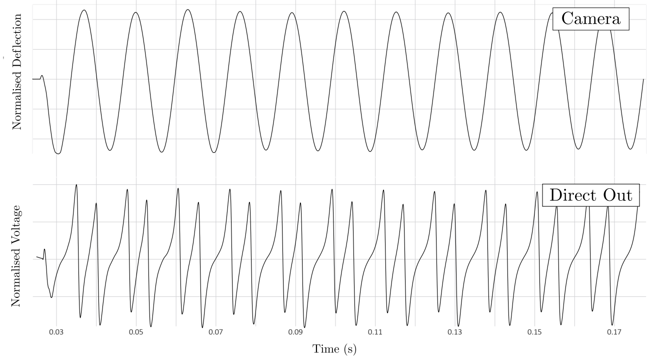

Figure 6: The upper graph shows the tracked signal from a high-speed camera recording of the tine's tip. The lower graph shows the voltage measured behind the pickup at the direct-out jack of the Rhodes Stages piano.

behind the pickups show a more complex behaviour. In the case of the Wurlitzer, the specific pickup geometry leads to a highly complex decay characteristic showing interesting effects like non-exponential decay characteristics and beating of higher partials.

Finite Element Models of Sound Production Assemblies

To assess the influence and the specific distribution of the magnetic and electro- static fields in the vicinity of the pickups[4], FEM models of the sound production units of both electric pianos are developed and simulated using COMSOL.

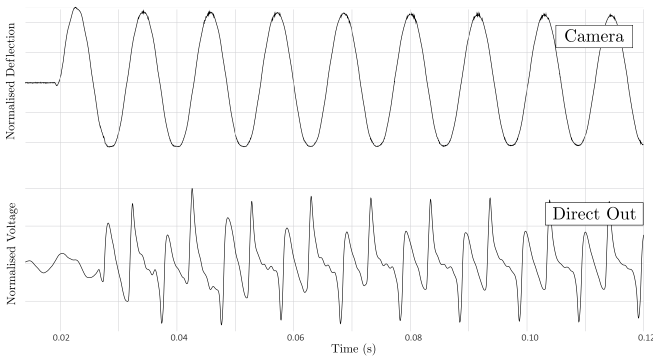

Figure 7: The upper graph shows the tracked signal from the high-speed camera recording again exhibiting approximately sinusoidal motion. The lower graph shows the voltage measured behind the pickup over a resistor ahead of the preamplification circuitry

Magnetic Field of the Rhodes Pickup

The FEM-model of the Rhodes' pickup system includes the magnetic field surrounding the iron conic section as well as the attached magnet. It is simplified by omitting the copper coil windings and thus leaving electrodynamic effects out of the consideration. The static magnetic field distribution is computed using a scalar magnetic potential. [5][3]

The tine is positioned in close proximity to the steel tip of the pickup. The flattened sides of the frustum focuses the magnet field in the center showing an approximate bell curve characteristic. The sound is shaped by the distance between the tine and the magnet, caused by the strength of magnetic flux at the respective position. The model shows the disturbance of the magnetic field. As the deflection of the tine gets larger, the change of magnetic flux gets more and more asymmetrical . An idealised model of the pickup system is depicted in Fig.8 showing a distribution of the static H-field forces surrounding the tip of the magnet.

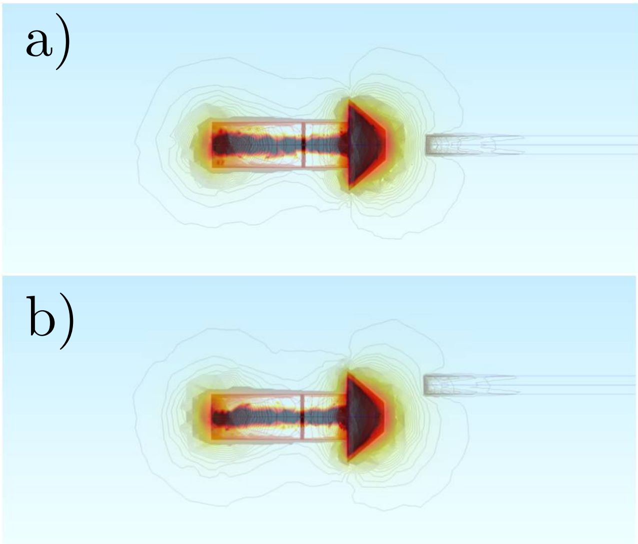

Figure 8: FEM simulation of the Rhodes' tine and pickup system showing the resulting force lines due to the magnetic field. a) Symmetric positioning b) Asymmetric positioning

Electrodynamic Interaction of the Wurlitzer Piano

The capacitive FEM model is developed to solve the dynamic influence of the vibrating reed on the capacitance of the system. This is achieved by solving Poisson's equation for several static positions on the trajectory of the reed's motion. The stationary electrode of the modeled pickup is charged whereas the reed is kept at zero potential, see Fig.10. Changing distances over time between the vibrating reed and the plate results in a changing capacitance. A varying current produces a varying voltage across an external resistor which is decoupled and amplified to produce an usable output signal as is shown in Fig.9. At the capacitance minima of the curve, the excitation of the reed is maximum and at the peaks where capacitance is maximum the reed is near its rest position. Because of the non-symmetric design of the reed, the capacity change differs at each excursion depending on moving direction.

Finite Difference Models

The numerical models presented in this section are based on the measured properties, qualitative observations of FEM models and conjectures regarding material properties of vibrating parts. Taking the measurement results

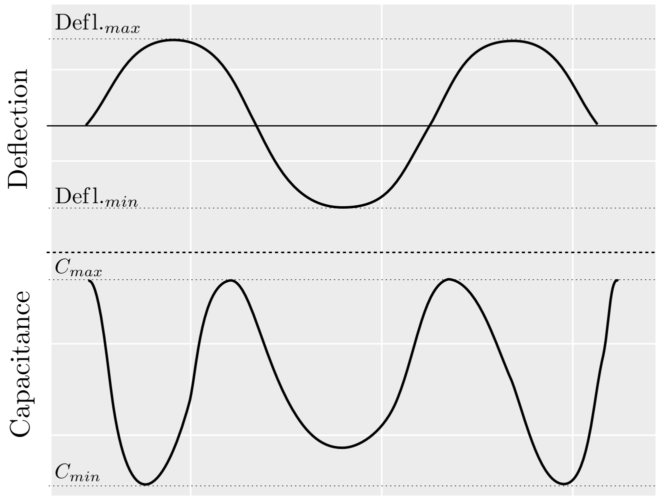

Figure 9: The capacity change differs at each excursion depending on moving direction

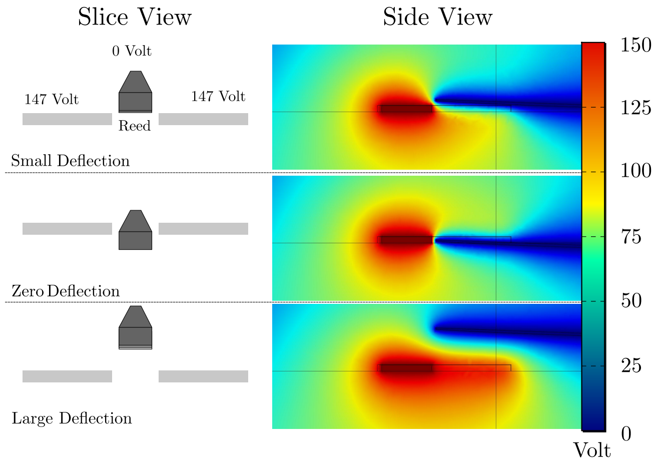

Figure 10: Distribution of the electric field for three exemplary reed deflections. On the left hand side one slice of geometry on the right hand side the results from the FEM model.

as a basis for the models, leads to assumptions that simplify the model description of the physical system considerably. Regardless of the introduced simplifications both models are able to capture the vibratory motion and the acoustic properties of both instruments to a high degree while minimizing modeling complexity.[10][6][11] Due to the small changes in the magnetic as well as electric fields, the proposed simplifications lead to models that are able to approximate the vibratory and the sonic characteristics of the instruments. Both have a hammer-impacted resonator exiting a spatial transfer function modeled after the characteristic pickup system.

The exciter of the Rhodes is modeled as a hammer impacted simple harmonic oscillator (SHO) representing the quasi-sinusoidal motion of the tip [7]. A hammer impact with elastic material properties of the hammer tip can be simulated by using a hysteretic hammer model. The impacted SHO is extended with a model for hammer impacts developed by *Hunt* and *Crossly* [8], that has shown suitable results for models of hammer impacts with moderate impact velocities and plain geometries. For simplification, further definitions of the Rhodes tone generator are chosen: (a)The tine vibrates in an approximate sinusoidal motion in one horizontal plane in front of the pickup. (b)The tip of the tine vibrates on the trajectory of an ideal circle with the centre at its fixation point.

The reed of the Wurlitzer is modeled as a cantilever beam including large deflection effects, modeled by the inclusion of shearing effects in the beam. $Traill$ and $Nash$ [9] showed that the shear beam is a better approximation for the vibrations of the fundamental frequency then the Euler-Bernoulli beam and less complex than the similar accurate Timoshenko beam model.

Torsional motion of the plate were not measured and thus are either not present compared to the transversal deflection of the fundamental mode or are very small. In addition to that, the measurements show that the influence of higher modes are comparably small. The mode of vibration could be approximated by the reeds first natural frequency. As shown in $Traill$ and $Nash$ [9] the inclusion of shear effects to the Euler-Bernoulli beam raises the accuracy of the fundamental frequency as well as the accuracy of higher partials. The following assumptions for Wurlitzers capacitive tone generator are made: (a)The time dependent charging/discharging curve of the capacitor is linear in the considered range. (b)The time dependent charging/discharging curve of the capacitor is linear in the considered range.

Modeling Results

The simulation results are depicted in Fig.11. An aural comparison of the simulated and measured sounds shows that both simulations are close to their real counterparts. The full sounds and additional material can be found on the accompanying web-site. `http://www.systematicmusicology.de/` A more in-depth study is presented by the authors in [1].

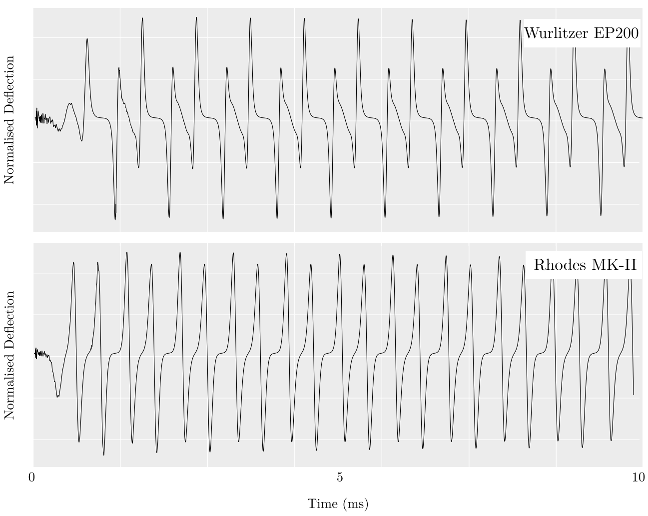

Figure 11: The first few milliseconds of two simulated keyboard sounds.

Conclusions and Perspectives

Fundamental considerations of the tone production mechanisms of the Wurlitzer EP200 series and the Rhodes Mark-I/II electric pianos were presented.The characteristic timbre of both instruments is due to the specific setup and geometry of the respective pickup systems. A simplified modeling approach for both instruments was proposed showing good accordance with the measured sounds. Both models are able to run in realtime on a common computer and can be parametrised for different geometries as well as different pickup designs. It is hoped-for that this work serves as a starting point for further research regarding the acoustic properties of these or other electro-mechanical instruments. Learning about the fundamental mechanisms of those instruments could help to elucidate the fact why the sound of semi-acoustic instruments are still held in such high regards among listeners and musicians.

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