Non-Linear Behaviour in Sound Production of the Rhodes Piano

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The Rhodes piano is a generic example of a mid-sixties to eighties keyboard, used in such diverse musical genres as Jazz, Funk, Fusion or Pop. Its unique sound is mainly due to its specific mechanical and electromagnetic tone production. The mechanical part of the tone production consists of a small diameter tine made of stiff steel wire and, strongly coupled to the tine, a tonebar made of brass which acts as a resonator. The lower tine is struck by a rubber hammer and vibrates in front of a magnetic pick-up which converts the change in the magnetic flux to an alternating voltage which can be amplified and made audible by an external amplifier. In this work we present a series of measurements taken with a high-speed camera and a piezolectronic transducer that show: a) Opposed to common belief, the tine and tonebar are not alike in pitch or resonance frequency. Their fundamental resonance frequencies are several hundred to more than 1400 cents apart. b) After an extremely short transient the tine vibrates in a perfect sinusoidal motion without appearance of higher harmonics. c) The lower dimensional tine forces the higher dimensional, stronger damped tonebar to vibrate in perfect phase or anti-phase with its lowest *eigenfrequency* pointing to a quasi-synchronisation behaviour. d) The non-linear, *growling* sound is produced due to the position dependant non-linearties in the magnetic field and are best audible in the lower register of the rhodes where the tines have a larger deflection.

1 Indroduction

1.0.1 Brief Historical Overview

The Fender Rhodes electric piano became one of the most popular musical instruments with electromagnetic sound production beneath electronic guitar and bass, the electrostatic Wurlitzer Piano, the Hohner Pianet/Clavinet, the Yamaha CP70/CP80 and not least the Hammond Organ. Their history retrogrades to the inventions of the Telharmonium (1897), the NeoBechstein (1929) and the ViviTone Clavier (1933).

Harold B. Rhodes is acclaimed as the inventor of this instrument. In the 1930's, he began teaching piano on his own nationwide radio program. Doing military service in Europe during World War II he was asked to devise a musical program for soldiers. Rhodes used Air-Force surplus parts to make small piano kits. After the war, Rhodes continued to experiment and refines his work. He was awarded a patent for his asymmetric tuning fork. A system to produce piano like sounds. [2]

Guitar and Amp maker Fender and Rhodes entered into a joint venture. Rhodes was finally able to introduce the first Fender Rhodes electric piano in 1965. Before, pianists had to remain in the background of jazz and rock ensembles. They were not able to compete in volume with drums, bass, horns, and electric guitars. Rhodes's solution was to not only amplify the piano, but to reconsider the sound production itself. The result was a totally unique instrument.

It was trumpeter Miles Davis, always searching for new sounds, who insisted his pianists to play the Rhodes piano instead of the traditional piano. Jazz musicians like Duke Ellington, Bill Evans and Herbie Hancock were using the electric keyboard to bring the piano into the foreground of their arrangements. Soon, very large number of jazz, rock, and pop musicians were hurrying to get the Rhodes sound into their own music. The Rhodes piano was endorsed by almost every significant keyboardist, and became the biggest selling electronic piano of all time. A quarter million units from 1965 to 1984 were produced.

1.0.2 Sound Description

The sound of a Rhodes piano can be described as *glockenspiel* like with an extremely short transient. After the hammer strike the waveform becomes steady after 10-14ms. The lower notes tend to have a growling sound depending on the velocity of keystrokes. The sound can be varied by altering the tines position in the magnet field of the pick up. Velocity sensitivity in this case is to be distinguished by a change in volume to lesser extend than in sound. Playing softly the fundamental comes up, playing harder the more and more growl appears in the sound.

1.0.3 Experiment Description

The following sonic survey is done with a Fender Rhodes MkI. The vibrational behaviour of the asymmetric tuning fork is investigated with high speed camera techniques and a miniature piezo accelerometer and an impulse hammer. Further examinations analyse the influence of the electromagnetic pick-up. A physical Model is build to validate our examinations.

2 Sound Production

Summarized, the sound production consists of the following parts, see Figure 1:

- neopren hammer (14)
- tine (13)
- tonebar (14)
- pickup (20)
- amplifier (not illustrated)

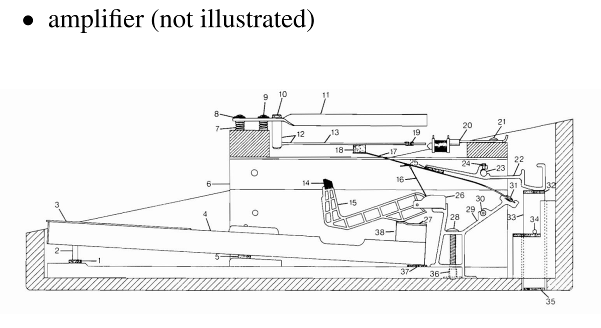

Figure 1: cross section of piano assembly [6]

2.1 Mechanical Part

The key action mechanism is a simplified single action. Each key drives a neopren hammer. It strikes a rod of spring steel of different length determining the fundamental note. The rod is called tine. The tine is shrunk into an aluminium block which is screwed on the tonebar. The latter is a twisted brass bar which acts nearly like a resonator to sustain the vibration caused by the hammer strucked tine. The tine can be described with a differential equation as a beam fixed on one side:

$$\rho \frac{\delta^2 y}{\delta^2} = \frac{\delta^4 y}{\delta x^4} E K^2 \tag{1}$$

Where density ρ multiplied with the second derivation of time equals the fourth derivation of the position, multiplied with the Young's-modulus E and the radius K = r/2. For the tonebar K is defined as:

$$K = \frac{thickness}{3.46} \tag{2}$$

2.2 Electromagnetic Part

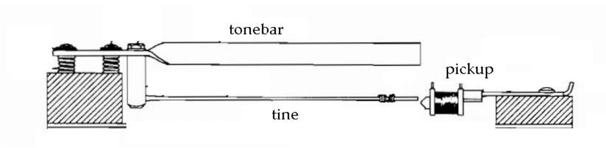

Figure 2: electromechanical sound production unit[6]

An electromagnetic pick-up records the changes in the magnetic flux caused by the struck tine and forwards the induced alternating current to an amplifier. The copper wire winding of each pick up is divided into two sections, connected opposite in phase for hum cancelling. The core consists of a round ferrite magnet. On one end it is wedge shaped pointing to the tine. The sound of a note can be changed by position of the tine to the magnet. The more the tine is aligned towards the middle of the wedge shaped magnet the more upper partials appear in the sound. Vice versa, the more the tine is moved towards the edge the fundamental frequency will be increased. The tine's excitation behaviour in the magnet field can be described as a function like:

$$h(x) = A sin(\frac{2 f \pi t}{x}) + p \tag{3}$$

Where A = amplitude, f = frequency, t = time, p = position of the tine in the magnetic field, where x is the central point position relative to the magnet. Exemplary solved for *f(t)* this means:

$$f(t) = e^{(}\frac{x - 250}{150})^2 - 0.5 \tag{4}$$

An exemplary simple damping function is given as

$$g(t) = e^{-} x / 1000 \tag{5}$$

where t=1...S, where S resembles a sample point. The excitation function multiplied with the damping factor in the magnetic field function is:

$$f(g(x)h(x)) \tag{6}$$

3 Measurements

Through the lack of data in the literature we were forced to do several measurements to clarify the way of sound processing. High-speed camera techniques combined with piezo recordings were applied.

3.1 High-Speed Camera Measurements

At first high-speed camera techniques where applied to look for general vibrational behaviour of tines struck by hammer. To track the vibration of the tine, four points where defined on it and recorded. The camera type is a Vision Research Phantom v711.

Figure 3: high-speed camera measuring configuration

3.1.1 Hammer Strike

First challenge was to find out the duration of contact or possible multiple contacts of the neopren hammer tip on the tine. This was done by partly disassembling the instrument to make room for the camera lens to get significant pictures. A relatively big field of view was chosen.

- 1280x800 pixel
- 7532 fps
- high gain
- low gamma

The determined average time of contact of the hammer on the tine is 6.42ms.

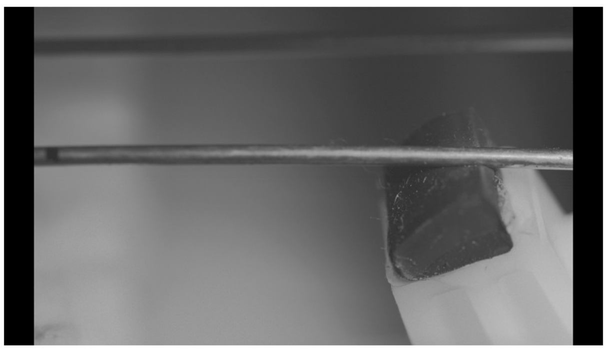

Figure 4: moment in time of hammer collision

3.1.2 Optical Tracking of Tine Movements

To evaluate the movement of the tine lengthwise in y-direction, a tracking point on the tip was defined. The vibration was recorded for 2 Seconds after attack with our high-speed camera set to a resolution 1280x160 pixel and a framerate of 38000 fps. For comparison the movement in z-direction, from the magnet's point of view, is recorded with a framerate of 10000 fps. For this experiment a tonebar-tine-assembly is mounted on a table and struck by a low-mass rubber hammer. The two resulting oscillation

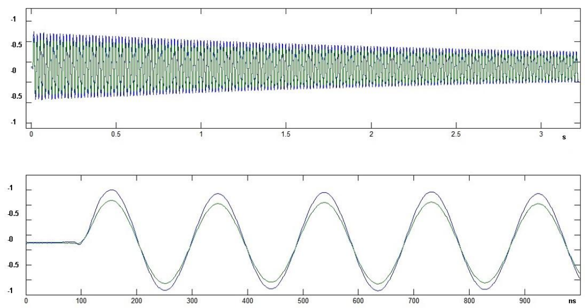

Figure 5: movements in y-(green) and z-(blue) direction

patterns were compared and it was found that they are perfectly the same in pitch and phase. There are no further eigenmodes than the lowest. See Figure 5

3.1.3 Optical Tracking of 4 Points on the Tine

Two points are defined on the tine in a distance of 1 cm near the point of impact. Two further points are defined near the tip of the tine. All tracking point vibrate completely simultaneous.

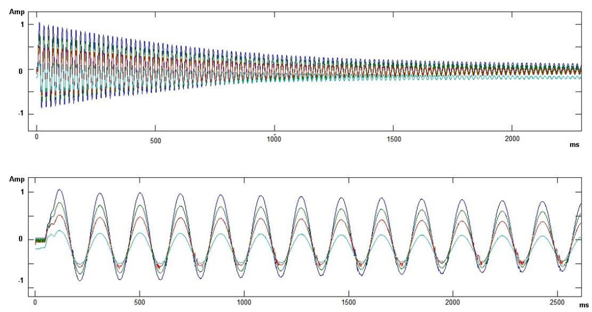

Figure 6: movements of four tracking points

3.2 Piezo Measurements

The vibrational interaction of the two main parts tine and tonebar, the so called asymmetric tuning-fork were recorded. A piezo accelerometer PCB 352C23 is attached to the tonebar and recorded simultaneously and individually together with the RCA-output of the instrument. The former is led to the piezoresistive amplifier Kistler 4603B. Both signals were digitalised by the PC-based oscilloscope Pico-Scope 9000 for further data processing. A Kistler impulse hammer 9722A and the instruments own hammer are used for impulse tests.

3.2.1 Testing the Tone Bar

The tonebar is struck by the impulse hammer. The piezo is changed in placed several times for controlling purposes. The output of both hammer and piezo are recorded simultaneously.

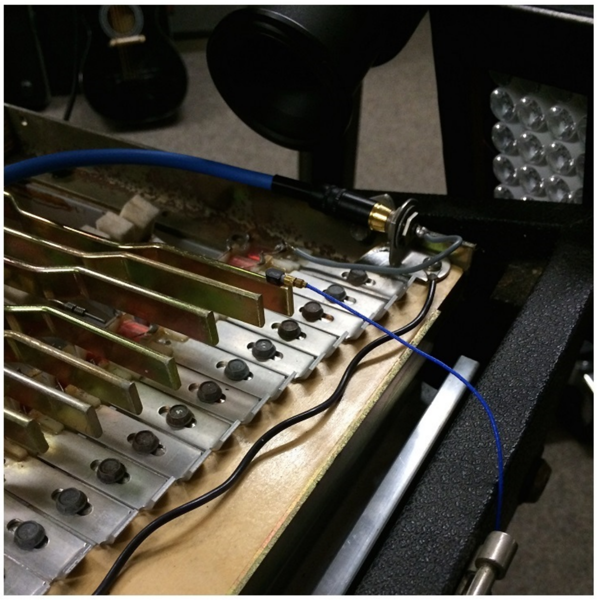

Figure 7: measurement setup for tonebars

The result in Figure 8 shows that the transient consists of an impulse followed by very few periods with an high amount overtones. After ca. 10-14 ms the waveform becomes sinusoidal.

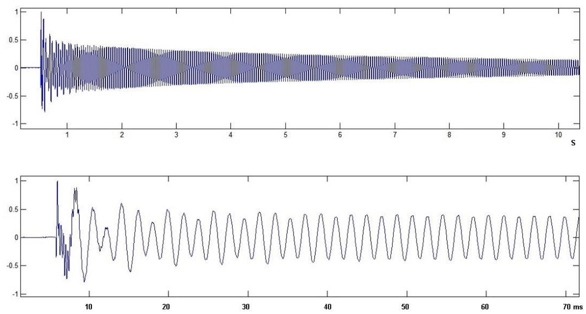

Figure 8: waveform of tonebar measured by accelerometer

3.2.2 Testing for Transfer Function

To test for the transfer function of the sound processing system in- and output signals of the pick up are compared. A piezo is attached on the upper end of the tonebar to record the longitudinal vibration. Additionally the direct out is recorded. The high-speed camera is set up to record the transversal movement of the tine in front of the electromagnetic pick-up. It is set up to reocrd 1280x128 pixels at 44127 fps and an exposure time of 22.302 μs. All recordings are done simultaneously to get the vibrations of all sound influencing parts.

As shown in Figure 9 it is clearly evident that the transversal vibration taken by the camera is a pure sine wave producing no further overtones. The tonebar, recorded by the piezo, is excited by the tine and shows the above, in chapter

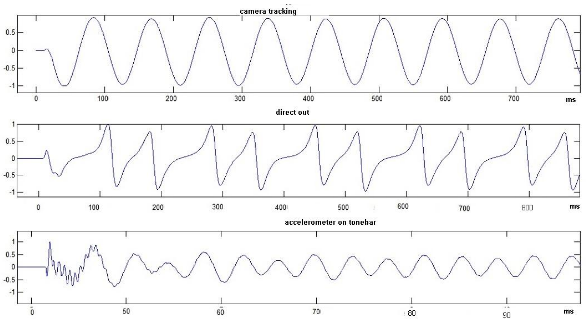

Figure 9: camera tracking compared to direct out and piezo recording

Table 1: tine compared to tonbar vibration and phase

Note	BarNo.	OutputHz	Piezo f0 Hz	PiezoHz	Phase
Eb	12	79	51	79	anti
Bb	19	118	69	118	anti
Bb	19	118	69	118	anti
F	26	176	79	176	in
C	33	263	105	263	in
G	40	393	138	393	in
D	47	588	183	588	anti
A	54	880	140	880	anti
E	61	1316	145	1316	anti
H	68	1969	222	1969	in

3.2.1 mentioned behaviour. The waveform at the end of the signal path is a result of filtering by the electromagnetic pick up and due to the fact that the tine seems to move towards the boundaries of the magnetic field at its largest amplitude. Not least because of this fact the Rhodes piano has such an individual sound.

3.3 Relationships Between Tine and Tone Bar

In Table 1 exemplary shows that the tonebars lowest eigenfrequencies differ a lot to the frequency of the produced note. Tonebar No. 33 has a fundamental f0 of 105Hz, tested with the above mentioned impulse hammer. The frequency at the output, column "DirectOut Hz" is 263Hz in this case. This resembles the frequency of the tine itself. The column "PiezoHz" shows the frequency of the tonebar actuated by the tine. The tonebar vibrates regardlessly its eigenfrequency f0 with the frequency of the tine. The tine forces the tonebar to vibrate with its frequency. This holds true for nearly all tonebars. Moreover, the discrepancy rises with pitch.

Additionally the phase relationship between tine and tonebar is observed. The movement is perfectly either in phase or anti phase, there is no other movement observable .

4 Modeling

A simple MATLAB script is written. Our survey shows the transfer function of the pick up is most important to the sound. Its behaviour can be described as a filter function. The transient is not included up to now. But the results are astonishingly very good. See Figure 10. The excitation is described as

$$D = Asin(2f\pi(\frac{1:sl}{sr})) + rp) \qquad (7)$$

Where A is the amplitude, f = frequency, sl=sample length, sr=sample rate, rp= point of rest position. Additionally a damping is defined by

$$da = exp^{(} - \frac{(1:sl)}{10000}) \qquad (8)$$

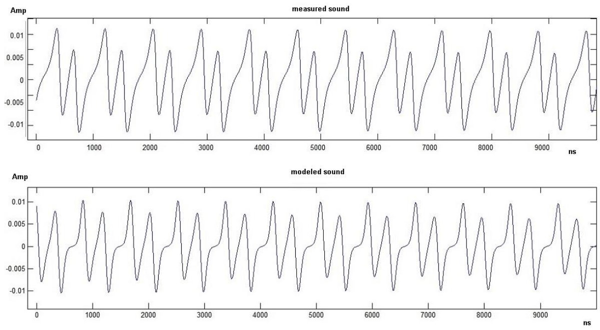

Figure 10: original compared to processed sound

5 Conclusions

The sound processing of the Rhodes has not been studied in detail before. Some exciting findings are achieved. With the use of high-speed camera techniques and piezo accelerometer measuring we observed that the vibration of tine and tonebar builds up very fast after the transient while the latter is one of the shortest found in musical instruments. The electromagnetic part of the assembly, particularly the effects vibration of the tine in the magnet field is not to be underestimated for the characteristic sound of the Rhodes piano.

5.1 Tine-Tonebar Coupling

The tine-tonebar assembly is an example for generator-resonator coupling. The tine seen individually mainly acts like a sine generator forcing the tonebar to vibrate with the tines fundamental frequency. Despite of sometimes extremely different eigenfrequencies the higher, stronger damped dimensional tonebar is forced to vibrate with the same frequency perfectly in or anti phase, a steady sinus, as the lower dimensional, less damped tine. The tonebar is the system with lower eigenvalues and is taken over or enslaved by the tine, the system with higher eigenvalues as shown in Table 1. Further modes or eigenfrequencies than the fundamental of the tine do not appear except for the initial transient. The tonebar is responsible for the timbre of the initial transient. It adds the *glockenspiel* sound to the transient and extends the sustain. Longitudinal waves are detected in the tonebar. They are compressing and expanding the tonebar mostly along its length. Here, transversal deformation can be neglected. Longitudinal waves are 10-15 times faster than transverse waves. Due to its "T" joint geometry the tine-tonebar assembly is a beneficial design to transfer energy from the longitudinal in-plane direction of the tonebar into transverse waves. In construction acoustic the phenomenon of energy transfer in t-beam trusses is well studied [7]. Because of the energy in the high frequency range these waves contribute a lot to the higher overtones of the extremely short initial transient and not least to the sustain behaviour of the Rhodes sound. The eigenfrequencies of the enslaved system, the tonebar in this case, are not present in the sound they only appear in the transient. [1]

This behaviour can be viewed in the framework of Synergetics. Within this formulation the tine-tonebar subsystems lead to a slaving by one subsystem. The tine in this case forces the tonebar to vibrate with its frequency. Due to strong coupling of the two subsystems, the tine-tonebar interaction, a *quasi-synchronisation* is present. While the mathematical definition of synchronisation expects a weak coupling the system is strongly coupled by its solid joints. Here, the system can be compared with the experiment of two pendulums connected through a solid bar. Just in terms of enslaving[1]

5.2 Damping of Higher Modes

Changes in design of the sound processing unit during production period led to a decrease of nonlinear behaviour. The tine as mentioned above is strongly clamped into an aluminium block by shrinking it with the use of liquid nitrogen into the block. Moreover, the tines were improved concerning durability. The newer tines have a thickening at the end which is shrunk into the block. The choice of material and fixture cause higher damping of the tine which is therefore forced to vibrate in its fundamental frequency. For this reason the Rhodes piano can sound dull under certain circumstances. The design obviously neglected the fact that by far most successful instruments like the violin, piano and guitar are highly non-linear systems.

5.3 Perspective

With the above in mind it becomes clear that the sound of the Rhodes piano, listeners and musicians prefer so much is not only produced by the instrument itself, as several classic recordings show us. The bright and clear sound we hear on these recordings are probably produced by the amplifier which is electron tube driven in most cases . Tubes are known to produce harmonic distortion even at clean level settings. Also the initial transient gets more audible in is supposed to become longer in time due to the special behaviour of tubes. So examinations on these definitely musical components are an object for further studies.

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