PROCEEDINGS of ISMA 2019
International Symposium on Music Acoustics

13 - 17 September 2019 in Detmold, Germany

Non-linearities of the mechano-electrical tonegenerator of the Hammond organ *†

Malte Münster(1), Florian Pfeifle(2)

(1)Institute for Systematic Musicology; University of Hamburg, Germany, malte.muenster@uni-hamburg.de 1

(2)Institute for of Systematic Musicology; University of Hamburg, Germany, florian.pfeifle@uni-hamburg.de 2

Abstract

The Hammond Organ with its electro-magnetic generator is still a standard instrument in the western music world. The organ still fulfils musicians' demand for a distinctive sonic identity with intuitive control of some arbitrary parameters. Bequeathed a heritage of some hundreds of thousands of tonewheel organs to the world, most of them still in service since the original manufacturer went out of business. The worldwide organ scene remains a vibrant community. A description of the tone production mechanism is presented based on measurements of a pre-war Model A. The survey includes high-speed camera measurement and tracking of the generator as well as oscilloscope recordings of single pickups. Some properties emerge due to the interaction of the mechanical motion of interaction with the magnetic B-H-field. A FEM model of the geometry shows accordance with the proposed effects. A FDM-model is written and a more complex physical model having a special regard on the geometry and electronic parts of the sound production mechanism.

Keywords: Sound, Music, Acoustics

1 INTRODUCTION

Following the publication of the Wurlitzer and the Rhodes E-Pianos at ISMA 2014, we have a closer look at the unique Hammond Organ with electro-magnetic sound production. It is one of the remaining standard musical instruments in the western world of Jazz-, Rock-, Funk-, Soul-, Gospel-, Reggae-Music and related genres. This can be attributed to its specific mechanical-electromagnetic tone production, key mechanism, wiring, lead dress and amplification/speaker-system. The Hammond Organ still fulfils the musicians' demand for assertiveness and a distinctive sonic identity in some ways, never reached by any other electronic-, sampler-keyboard. Even newer physical-, or PCM-based models struggle with an adequate reproduction. Every decade since the original manufacturer went out of business in 1986, experienced a revival of the original instrument, bequeathed a heritage of some hundreds of thousands of tonewheel organs to the world, most of them are still in service at home, in studios and on stage. Original spare parts and professional service are still available.

In this survey, a description of the outstanding tone production mechanism is presented based on measurements taken on a Hammond Model A built in 1938. The measurements include high-speed camera measurement and tracking of the tonewheel generator. In the case of the Hammond Organ, characteristic sound properties emerge due to the interaction of the mechanical motion of up to 91 small ferromagnetic, toothed wheels interacting with the magnetic H-field of their respective pick-up. Non-linear crosstalk effects like leakage between wheels, changing the complexion of harmonics are descried. The measurements are compared to a FEM model of the respective geometry showing accordance with the proposed effects. A simplified FDM-model is written along with a physical model having a special regard to the geometry and electronic parts of the sound production mechanism.

2 STATE OF RESEARCH

Besides a deeply involved community organised in organ clubs, blogs and forums around the world, few scientific research is done since pre-war era.

*malte.muenster@uni-hamburg.de
†florian.pfeifle@uni-hamburg.de

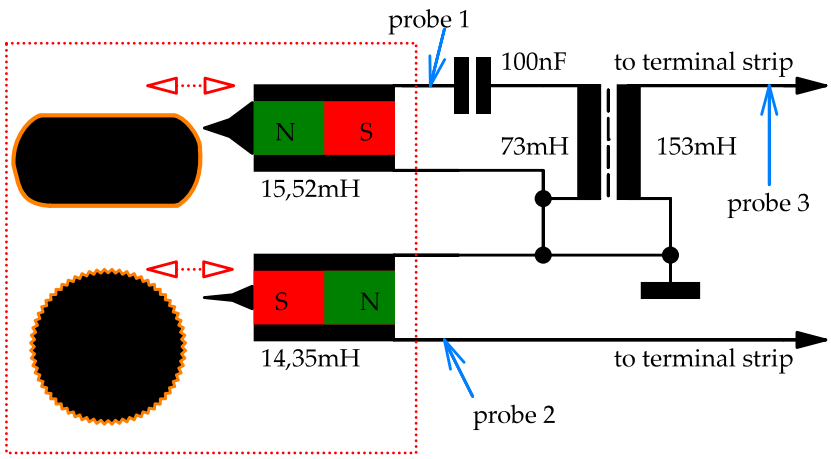

Figure 1. Probe position and some data of a pair of tonewheel 9 of G#0 and 57 of G#4 with pickup and filter attached.

A waveguide filter model of the Hammond organ vibrato/chorus has been build by Werner, Dunkel and Germain. The LC ladder-filter is modeled by using the Wave Digital Filter formalism to introduce their approach to resolving multiple nonadaptable linear elements at the root of a WDF tree. [21]

Werner and Abel describe audio effects emulating the response characteristics of the organ to process audio signals. [22] Savage refined the effects processor. He focused on emulating induced crosstalk between tonewheels. Filtering adds a frequency-dependent tremolo effect to the sound. [19].

Moro, McPherson and Sandler studied the key mechanism. A ninefold lamellar switch toggles the dialed harmonics by pressing a key. The inconsistancy of the switch-mechanism is ultimately responsible for generating the transient by adding a "chiff"-noise to the sound. This can be influenced by key velocity to a certain extend. [17]

A complete model of the tone-production is proposed by Pekonen, Pihlajamäki and Välimäki. An additive computational sythesis of the simplified tone-generator is discussed. A model of the obligatory rotating Leslie-speaker by time-varying specrtal delay filters is also shown. [18]

3 HISTORY OF ELECTRONIC INSTRUMENTS WITH ROTATING DISCS

The most simplest way to produce a low frequency signal is to chop direct current. According to a principle proposed by Karl Ochs, the Rangertone Organ has been introduced by Richard H. Ranger in 1931. 24 rotating electrical choppers with different numbers of teeth matching semitones of two octaves were mounted on a common drive shaft. With additional assemblies running at rotating velocities in a ratio of 1:4:16, enough sounds are provided to build an instrument of six octaves ambit. [16]

The first attempts using profiled iron discs in front of magnet coils for musical purposes were done due to the lack of electron tubes in the late 19th century. A common device was the magneto or ring generator to find in hand-cranked telephones generating a ringing voltage to call the operator. By use of this method, the Dynamophone or Telharmonium has been build by Thaddeus Cahill. In 1906 he played concerts over the telephone network by reason of the lack of loudspeakers. In consideration of the required power, the instruments weight became tremendous around 200t. It consists of 12 multi-tone-generators providing siunsoidal voltage swings. Using an organ-like register table, different harmonics can be mixed by adding the 2nd, 3rd, 4th, 5th, 6th, 8th, 10th, 12th and, or 16th harmonics with the fundamental. Intensities were controlled by damping

resistors for each harmonic. [10] [2]

Charles–Emile Hugoniot experimented with Gramme machines, using rotating toroidal inductors and multiple, adjustable pick-ups per unit. [13] [10]

The tone-generator of the Magneton by Wilhem Lenk and Rudolf Stelzhammer makes use of discs with different profiles to provide a greater range of sound colours. The Instrument has two manuals and one pedal-manual. The compass is five octaves. By using a frequency controlled motor regulator the instrument is able to be transposed. [8]

A synthesis of sounds of 100 harmonics is proposed by Harvey Fletcher. The fundamental can be chosen between $50Hz$ and $100Hz$. The highest harmonic varies therefore between $5kHz$ and $15kHz$. [12]

Electrostatic field charged pick-up rotors are developed by Leslie E.A. Bourn, for the Compton Electrone and Melotrone-Organs. Earlier experiments are done by Wien, Pose und Klein. [10] [6]

A by far larger prevalence is reached by photo-optical methods with rotating discs. The Superpiano and Welte Lichtton-Orgel are the predecessors of a wide range of phonetic instruments and theatre organs. [8] [7]

4 THE HAMMOND ORGAN

Laurens Hammond modernised, miniaturised and stabilised Cahills mechanism in his Organ and made it ready to start mass production in 1935 with big success. [1] The organ uses one profiled disc per note. They are cut to produce a sine wave-form. A lot of different sounds are possible by mixing the fundamental with overtones. The overall tuning is the equal temperament. With higher order harmonics, the overtones differ more and more from the harmonic series. The equal temperament increasingly deviates. For this reason just 8 harmonics are realised, omitting the 7'. Therefore the number of tone-wheels can be reduced. The ambit of 7 octaves is produced by 91 tone-wheels with a diameter of ca. $4cm$ each. [10]

By pressing a key the respective inductive pick-up, lengthways pointing to the edge of the tone-wheels, a switch of nine lamellar contacts is closed nearly simultaneously forming the transient[17]. Two fundamentals and seven harmonics can be mixed by nine drawbars for each manual and three for the bass-manual. A LC-filter is attached in parallel to most pick-ups. Depending on the model, the upper most octave omits these, resulting in a rich, typical squealing sound typical for the instrument. Moreover later models use harmonic foldback: the notes of the highest octave or fifth of the 3'-register and higher harmonics and the 16' sub-fundamental, depending on the model, are taken from the lower octave. [11] [20]

5 STRUCTURE OF HAMMOND ORGAN'S TONE PRODUCTION

As indicated earlier, the tone production of the Hammond organ consists of differently shaped rotating disks influencing the H-field over a magnetic pickup. By their rotation frequency and their specific shape they are able to produce differently pitched tones. According to the user's manual, the wheels have different numbers of teeth, ranging from 2 to 192. By rotating in front of a magnetic pickup they are changing their distance to the magnetic pickup and thereby influencing and changing the magnetic flux amplified by the following preamplifier. In addition to this, every tonewheel has a differently shaped pickup that influences the magnetic field in front of the pickup thereby shaping the strength of the disks influence.

In an idealised version of the instrument the shapes and the positions of the disks are approximately analytical and can be approximated using simple sinusoidal formalism. But as our measurements have shown, the position of the tonewheels in front of the magnetic pickup can vary considerably during several cycles and the distance of the disks perimeter can vary within one period.

Comparable to the pickups of the fender Rhodes, the magnetic pickups are pointy shaped thus influencing the strength of the magnetic field in front of the pickups and thereby minimizing the cross-talk between adjacent rotating disks.

A number of different pickup shapes as well as disk shapes are illustrated in Figure 2 and Figure 1.

Table 1. Number of teeth on number of discs for the measured Hammond organ.

Number of teeth	2	4	8	16	32	64	128	192
Number of discs	12	12	12	12	12	12	12	7
Notes	C0-B0	C1-B1	C2-B2	C3-B3	C4-B4	C5-B5	C6-B6	C7-F#7

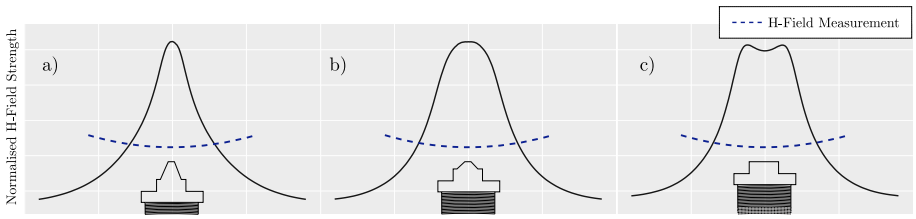

Figure 2. Magnetic field for different pickup shapes.

6 METHODS

To characterise the properties of the different components belonging to the Hammond's tone production, several measurements are performed using a high-speed camera as well as oscilloscope measurements.

6.1 Camera tracking

To qualitatively assess the motion of the tonewheels, a high-speed camera is used to record a set of two tone generation disks, one lower and one higher disks of different pairs of tonewheels. To achieve this, a *Vision Research Phantom V711* high-speed camera is used. The motion of the discs are tracked and the resulting trajectories exported, analysed and evaluated using standard signal processing software. To indicate the period of one disc revolution it is marked with a black marker at one point on its outer circumference.

An image section of a measurement is depicted in Figure 4a).

The voltage produced by the motion of the rotating disc in front of the magnetic pickup are measured with two probes at 3 points in front of the filter circuit and behind it. They are measured using a standard high resolution digital oscilloscope with measurement probes as indicated in Figure 1

6.2 Measurement Results

As is shown in Figure 4a) the tracked motion of the tonewheels are periodic with the basic revolution as well as others motions overshadowing the fundamental rotation. Due to its imperfect fixation and material defects, the measured tonewheels wobble along the x as well as the y-axis. This leads to a pronounced amplitude modulation effect in the resulting voltage as is shown in the next section. As is shown in Figure 3 the voltage induced after the pickup is approximately sine-like and has strong amplitude fluctuation due to the non-linearities in the motion of the tonewheels.

7 Intermediate Summary

The motion of the tonewheels as well as unspecified effects due magnetisation and self-magnetisation of the rotating disk, the pickup rod as well as the copper winding around the metallic core of the pickup,

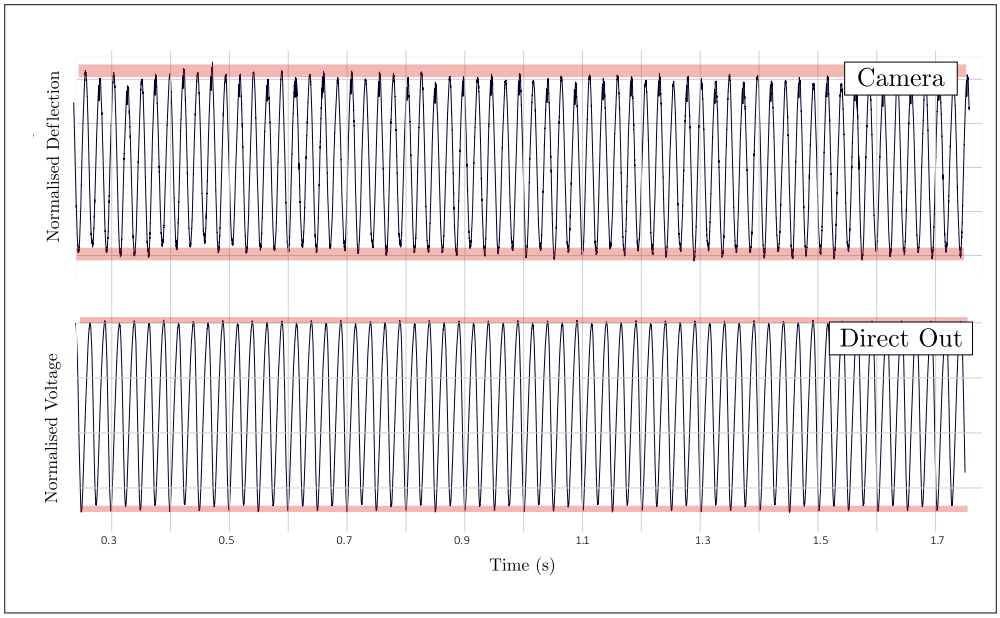

Figure 3. The upper plot shows the camera tracking of the varying distance between pickup and rotating tonewheel. The lower timeseries is the voltage recorded at position "Probe 2" as indicated above. The red bar indicates the amplitude modulation due to nonlinear effects in the motion of the tonewheel.

8 FEM-MODEL OF THE TONEWHEEL

The model is a time-depended 2D simulation of the tone-generator comprising an iron rotor and a magnetic coil forming the stator. The core of the rotating disc with 16 teeth consists of steel with iron powder coating on the edge covering the teeth. The generator rotates with a rotational velocity of $1961.25rpm$ to optain a freuquency of $523Hz$ respective the note C. The original wheel runs at $20000rpm$ to provide a C due to another diameter as measured. The model is solved in the time domain from $t = 0$ s to $t = 1$ s.

The tip of the stator consists of soft iron, which is a non-linear ferromagnetic material which saturates at high magnetic flux density. This material is preferential to provide suitable speed in change of magnetisation.It is implemented as an interpolation function of the B-H curve of the material. The center of the stator is a permanent magnet made of an AlNiCo-alloy, creating a strong magnetic field. The winding is wound around the magnet behind the tip. The copper coil winding is not part of the geometry. The edge of the rotor is covered with iron powder coating.The geometry is represented in Figure 4.

The conducting part of the stator, respectively the pick-up is modeled using Maxwell's formulation of Ampère's. Due to simulating the system under no-load condition (without the tuned bandpass filter) the Lorentz term is omitted in the PDE:

$$\sigma \frac{\partial A}{\partial t} + \nabla \times \left(\frac{1}{\mu} \nabla \times A \right) = 0 \tag{1}$$

For the non-conducting or insulating parts of the generator the magnetic flux conservation equation for the scalar magnetic potential is deployed:

$$-\nabla \left(\mu \nabla V_m - B_r \right) = 0 \tag{2}$$

Rotation is modeled using the ready-made physics interface for rotating machinery in Comsol 5.4. The rotor

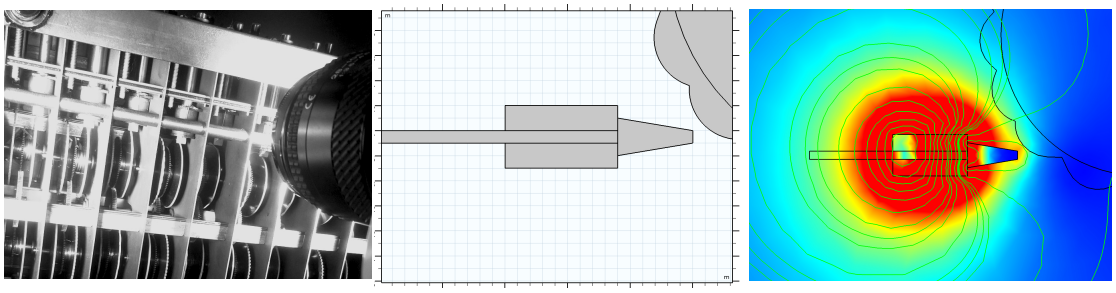

Figure 4. a) A typical setting of a high speed camera recording setup showing the Hammond's tone generator from the bottom. The rotating discs as well as the pickups are visible. b) Geometry of the fem arrangement of pickup and tonewheel. c) Magnetic flux density distribution $|B|$ ($Tesla$), and the field lines of the B field ($Weber$)

and an air-gap are modeled as rotating relative to the coordinate system of the pick-up.

The model solves for magnetic scalar potential V_m in nonconductive regions and for the magnetic vector potential A. The scalar formulation is solved by suitable transformations to the magnetic flux definitions in all domains depending on rotational velocity features, while the vector formulation is solved by Ampére's Law features. The electric scalar potential V and the magnetic vector potential A are given by the equalities: $B = \nabla \times A$ and $E = \nabla V - \frac{\partial A}{\partial t}$.

Rotation is modeled as follows: The center part of the geometry, containing the rotor and part of the air, rotates relative to the coordinate system of the stator.

The output voltage is calculated as the line integral of the E-field of the winding. It is obtained by taking the average z-component of the E-field for each winding crosssection, multiplyed by the axis-length of the stator, and taking the sum over all winding cross sections. Here L is the length of the inductor, $Trns$ the number of windings an A the surface of the winding crossection.[23]

$$V_i = Trns \sum \frac{L}{A} \int E_2 dA$$

The generated voltage in the coil winding is a sinusoidal signal. At a rotation speed of 1961.25rpm the voltage has an amplitude peak of 40mV. The signal is slighly toothe. It us caused by the non-linearities of the unsteady magnetisation/demagnetisation-times and change in magnetic flux in the rotor and stator of the generator, as explained. See Figure2. They can be enforced by more cornered geometries as found in tonewheels of the lowest registers or magnetic disturbance through neighbouring tonewheels in conjunction with bandpass filters designed to reduce noise which is an unavoidable part of the sound.

9 SIMPLIFIED PHYSICAL MODEL

Comparable to the model developed in [55], the tone production of the Hammond organ can be approximated by using a periodic oscillator influencing a magnetic field having a specific distibution depending on the pickup's tip geometry. In this way, it is possible to approximate the tone production of the Hammond organ's tonewheel to a high degree of accuracy. The model developed here is based on the model from the same publication which is inspired by a model derived in [53].

The numerical model presented in present section is based on measured properties presented before, see section 6, qualitative observations on the FEM model and using measured material properties of the Hammond's tonewheel and the pickup.

Using the measurements as a ground-truth for the model leads to several assumptions that simplifies a model of

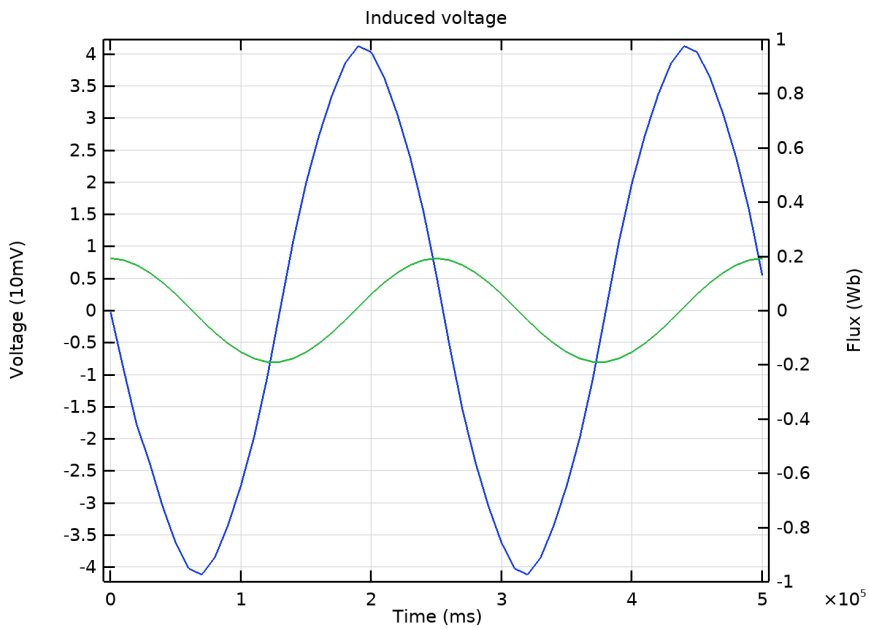

Figure 5. Voltage output swing versus change in magnetic flux in the coil

the tone production. 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 computational as well as modeling complexity.

A model of both pickup systems including all physical parameters would have to take time-varying electromagnetic effects into account using Maxwell's equations for electromagnetism to describe the respective pickup mechanism in complete form. But, 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 as well as the sonic characteristics of the instruments very accurately.

9.1 Tonewheel exciter model

As shown in Figure 1 the tonewheel rotates in front of the electromagnetic pickup. As the FEM simulations, given in figure 4, show, only a small radial part of the disk is influenced by the magnetic field. Therefore, the exciter of the Hammond is modeled as an oscillating mass-point in the normal direction of the magnetic field distribution.

Using Newton's second law, the temporal evolution of a SHO can be written as a second order ordinary differential equation

$$x_{tt} = -\kappa \cdot x \tag{3}$$

with $\kappa = \frac{k}{m}$ the stiffness/springiness of the system, m the mass of the harmonic oscillator, x the deflection and the subscript by t on the left hand side indicating a second derivative in respect to time.

9.1.1 Finite difference approximation

The exciter model of the tonewheel and the magnetic pickup are discretised applying standard finite difference approximations using a symplectic Euler scheme for iteration in time. The discretisation method and the scheme are published in more detail in [48]; [47]. Applying standard FD approximations for the given problem using

the operator notation given in [55] and iterating the scheme in time by using mentioned method leads to the equations

$$\begin{aligned} \delta_t v_{sho} &= -\kappa_{sho} \cdot x_{sho} - \gamma \delta t x_{sho} - F_{int} \\ \delta_t x_{sho} &= v \end{aligned} \tag{4}$$

for the SHO.

9.2 Pickup model

The electromagnetic effects of the organ's pickup system can be reduced from Maxwell's equations for transient electromagnetic effects to a more tractable formulation know as Faraday's law of induction. As shown above, the pickup consists of a magnetized steel tip and a coil wrapped permanent magnet; leaving reciprocal magnetic effects of the induced current in the coil out of our consideration, the voltage induced over the pickup is equivalent to the change of the magnetic flux in the field produced by the magnet

$$\varepsilon = -\frac{\partial \Psi_{\mathbf{B}}}{\partial t} \tag{5}$$

with ε the electromotive force and Ψ_B the magnetic flux due to the change in the magnetic field given by

$$\Psi_{\mathbf{B}} = \int \vec{B} \cdot d\vec{S} \tag{6}$$

with B the magnetic field strength integrated over surface S. Using these equalities, the induced voltage directly depends on the change of magnetic field strength which depends solely on the position of the tonewheel disturbing the field as shown in Figure 2.

The following derivation of the magnetic field distribution uses the unphysical assumption that there exist magnetic monopoles which produce a distributed magnetic field. This assumption proposes an equivalence between the efficient causes of electric fields and magnetic fields and can be used as a mathematical modeling tool, see: [53, pp. 174 ff]. As is shown in [40] this approach yields good approximations of notional magnetic induction fields produced by guitar pickups. Consisting of a plainer geometry, the tip of a guitar pickup bar magnet can be simplified to a circular, magnetically charged disc with a certain cross-section, which reduces the problem to a position-dependent integration of the field over the pickup. Due to the specific pickup geometry of the Hammond organ, a different approach is taken here to calculate the induction field strength above the tip of the magnet.

As depicted in Figure 6 our derivation makes use of several simplifying assumptions facilitating the computation. The disc rotates in an approximate periodic motion in one horizontal plane in front of the pickup. A radial part of the disc oscillates on the trajectory of an ideal circle with the center at its fixation point. Using definition I and II, the calculation of the magnetic induction field depending on the position of the disc tip can be formulated as an integral over the lumped mass point as a centralisation of the part of the disc influencing the magnetic field.

Comparable to an electric point charge we define a magnetic point charge which produces a magnetic field given by

$$\mathbf{B} = B_0 \frac{r_{21}}{|r_{21}|^3} \tag{7}$$

with r_{21} the relative positions of the point charge and a test charge in the surrounding field. Because the magnetic flux changes only due to changes in the z direction we can reduce equation 7 to

$$\mathbf{B}_z = B_0 \frac{\Delta z}{|r_{21}|^3} \tag{8}$$

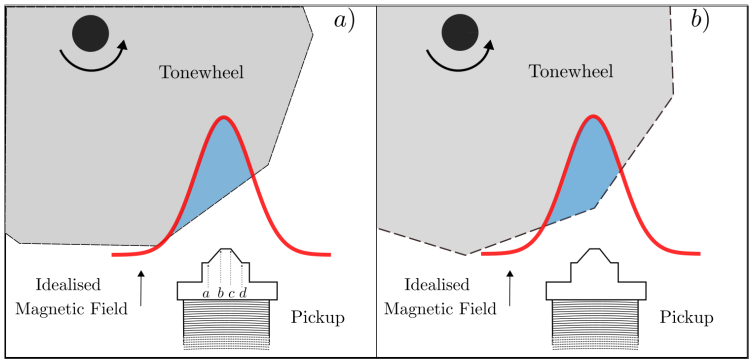

Figure 6. Simplified geometry of the pickup system and the rotating disc. The blue area indicating the influence of the magnetic field on the disc.

The magnetic field for position $(x^{'}, z^{'})$ in front of the of steel tip can thus be written as a three-part integral

$$\begin{aligned} \mathbf{B}_z(x^{'}, z^{'}) = |\mathbf{B}_{disc}| \quad \cdot \quad & \left[\int_a^b \frac{\sigma(z^{'} - z(x))x}{[(x^{'} - x)^2 + (z^{'} - z(x))^2]^{3/2}} dx \right. \\ + \quad & \int_b^c \frac{\sigma(z^{'} - z_k)x}{[(x^{'} - x)^2 + (z^{'} - z_k)^2]^{3/2}} dx \\ + \quad & \left. \int_c^d \frac{\sigma(z^{'} - z(x))x}{[(x^{'} - x)^2 + (z^{'} - z(x))^2]^{3/2}} dx \right] \end{aligned} \tag{9}$$

with σ the constant magnetic charge density.
Integrating this formula for all points on a trajectory given by the position of the Hammond's tonewheel

$$\begin{aligned} z^{'} &= \mathrm{r} - \sqrt{\mathrm{r}^2 - (x^{'})^2} \\ x^{'} &= \hat{\mathrm{x}} \cdot sin(2\pi f_{disc} t) \end{aligned} \tag{10}$$

with f_{disc} the fundamental frequency of the disc, leads to a magnetic potential function characterising the magnitude of relative magnetic field change.
An idealised form of the magnetic field in front of the Hammond's pickup is depicted in Figure 6**a** and 6**b**, it is comparable to the measurements results published in [40].

9.3 Modeling results

Simulation results of a model of one Hammond organ tonewheel-pickup system including measured non-linear motion of the wheel as well as the distribution of the magnetic field distribution are given on the accompanying website which can be found under `www.digitalguitarworkshop.de/ISMA2019.html`.

10 CONCLUSIONS

In this treatise a fundamental consideration of the tone production mechanisms of the Hammond organ was presented. We showed that the characteristic timbre of the instruments is due to the specific setup and geometry of the pickup systems. A simplified modeling approach for the instruments was proposed showing good accordance with the measured sounds. The model is able to run in real-time on a not-so-recent personal computer and can be parametrised for different geometries as well as different pickup designs.

This work serves as a starting point for further research regarding the electro-mechanical and acoustic properties of this family of instruments. Learning about the fundamental mechanism of this and similar instruments can help to elucidate the fact why the sound of this iconic semi-acoustic instruments is still held in such high regards among listeners and musicians.

ACKNOWLEDGEMENTS

Thanks to keyboard artist Michael Petermann for allowing us to work on his Hammond Model A, build in 1938.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

[1] William Bagally:*The Hammond Organ.* In: Wireless World Vol. XLI. , pp.134, Iliffe & Sons Ltd., London(1937).

[2] Ray Stannard Baker:*New music for an old world - Dr.Thaddeus Cahills Dynamophone, an extraordinary electrical invention for producing scientifically perfect music*, In: Mc Clure s Magazine Vol. 27,p.201, The S.S.McClure Co., London(1906).

[3] J. Barrett: *The Hammond Electric Organ.* In: Nature Volume 139, p.1043–1044, London(1937).

[4] William. L. Barrow:*The multitone.*In: Journal of the Acoustical Society of America 10, p.275-279, (1938).

[5] Douglas E. Bush:*The Organ Enzyclopedia.* p.52, pp.122, Routledge, New York(2006).

[6] Leslie E.A. Bourne: US patent: US2579358A. (1951). Retrieved from https://patents.google.com/patent/US2579358

[7] Karl Heinz Dettke:*Kinoorgeln und Kinomusik in Deutschland.* J.P. Metzler, Weimar(1995).

[8] Peter Donhauser:*Elektrische Klangmaschinen.*p.16,51,145,223,pp. 241, Böhlau(2007).

[9] W. Ross Dunkel, Maximilian Rest, Kurt James Werner, Michael Jørgen Olsen, Julius O. Smith III:*The Fender Bassman 5F6-A Family of Preamplifier Circuits - A Wave Digital Filter Case Study.* In: Proceedings of the 19th International Conference on Digital Audio Effects (DAFx-16),Brno (2016).

[10] Werner Meyer-Eppler: *Elektrische Klangerzeugung.*, p. 108-114, Ferd. Duemmlers Verlag, Bonn (1949).

[11] *The Hammond Organ Manual for the Service Engineer.* Ed.: Joe Luca 2016, Hammond Organ Co., Chicago (1978). https://archive.org/details/HSM4952016

[12] Harvey Fletcher:*The pitch, loudness and quality of musical tones. A demonstration lecture introducing the new tone synthesizer.* In: American Journal of Physics 14, p.215-225, (1946).

[13] Charles–Emile Hugoniot: French patent FR22866 (E) 1921-09-05, (1919). Retrieved from https://patents.google.com/patent/DE345923C/

[14] Stevens Irwin:*Dictionary of Hammond-Organ Stops*, Read Books, London(2013).

[15] Earle L. Kent:*A New Electronic Musical Instrument.* In:The Journal of the Acoustical Society of America 11, p.352 (1940). https://doi.org/10.1121/1.1916046

[16] Benjamin F. Miessner:*Electronic Music and Instruments.* In:Proceedings of the institute of Radio Engineers November 1936 Volume 24, New York(1936).

[17] Giulio Moro, Andrew P. McPherson, and Mark B. Sandler: *Dynamic temporal behaviour of the keyboard action on the Hammond organ and its perceptual significance.* In: The Journal of the Acoustical Society of America 142, 2808, (2017).

[18] Jussi Pekonen, Tapani Pihlajamäki, Vesa Vlälimäki: *Computationally efficient Hammond Organ Synthesis.*In: Proceedings of the 14th International Conference on Digital Audio Effects (DAFx-11), Paris(2011).

[19] Evan Savage: *Hammond Organ Effects Synthesis.* MUMT 618, McGill University, Montreal, QC (2018).

[20] Mark Vail: *The Hammond Organ.* Backbeat Books, San Francisco(2002).

[21] Kurt James Werner, W. R. Dunkel, F. G. Germain: *A Computational model of the Hammond Organ Vibrato/Chorus Using Wave Digital Filters.*, in P. Rajmic, F. Rund, J. Schimmel (Eds.), Proceedings of the 19th International Conference on Digital Audio Effects, pp. 271–278, (2016).

[22] Kurt James Werner, Jonathan S. Abel:*Modal Processor Effects Inspired by Hammond Tonewheel Organs.* In: Applied Science 2016, 6(7), 185, (2016).

[23] o.N. ,"AC/DC Module User's Guide", Stockholm 2018, S. 212ff.

[24] Martin Martinez, "Finite element modeling of the magnetic field of guitar pick ups", Regendsburg 2003.

[25] T.Furukawa, H. Tanaka, "Dynamic Electromagnetic Analysis of Guitar Pickup Aided by COMSOL Multiphysics", Tokyo 2012.

[26] A. Kovetz, "The Principles of Electromagnetic Theory", Cambridge University Press, 1990.

[27] Jianming Jin, "The Finite Element Method in Electromagnetics", 2nd ed., Wiley-IEEE Press, May 2002.

[28] R.K. Wangsness, "Electromagnetic Fields, 2nd ed.", John Wiley, 1986.

[29] D.K. Cheng, "Field and Wave Electromagnetics, 2nd ed.", Addison-Wesley, 1991.

[30] . O.C. Zienkiewicz, C. Emson, and P. Bettess, "A Novel Boundary Infinite Element," International Journal for Numerical Methods in Engineering, vol. 19, no. 3, pp. 393–404, 1983.

[31] Fanny Littmark, "Permanent Magnet", Stockholm 2013

[32] o.N., "Das elektroakustische Klavier", VDI-Verlag, Berlin 1936.

[33] Peter Donhauser, "Elektrische Klangmaschinen: die Pionierzeit in Deutschland und Österreich", Böhlau Verlag, Wien 2007.

[34] Werner Meyer-Eppler, "Elektrische Klangerzeugung: elektronische Musik und synthesische Sprache", Bonn, 1949

[35] Oskar Vierling,"Das elektroakustische Klavier", Berlin 1936

[36] Oskar Vierling, "Elektrisches Musikinstrument Electric musical instrument", DE1932V0030615, 1937.

[37] Benjamin F. Miessner, "Method and apparatus for the production of music", US Patent 1,929,027, 1931.

[38] A. R. Duchossoir , "Gibson Electrics - The Classic Years", Milwaukee 2006.

[39] David K. Cheng. *Field and wave electromagnetics*. The Addison-Wesley series in electrical engineering. Addison-Wesley, Reading, Mass, 1989.

[40] Nicholas G. Horton and Thomas R. Moore. Modeling the magnetic pickup of an electric guitar. *American Journal of Physics*, 77(2):144, 2009.

[41] Jian-Ming Jin. *The finite element method in electromagnetics*. John Wiley & Sons Inc, Hoboken. New Jersey, third edition edition, 2014.

[42] Attay Kovetz. *The principles of electromagnetic theory*. Cambridge University Press, Cambridge [England] ; New York, 1990.

[43] Karl Küpfmuller, Wolfgang Mathis, and Albrecht Reibiger. *Theoretische Elektrotechnik*. Springer-Lehrbuch. Springer Berlin Heidelberg, Berlin, Heidelberg, 2013.

[44] Martin Martinez Villar. *Finite element modelling of the magnetic field of guitar pickups with ANSYS*. Master, University of Applied Sciences, Regensburg, July 2003.

[45] Malte Muenster and Florian Pfeifle. Non-Linear Behaviour in Sound Production of the Rhodes Piano. In *Proceedings of the International Symposium of Musical Acoustics (ISMA) 2014*, pages 247–252, Le Mans, France., 2014.

[46] Malte Muenster, Florian Pfeifle, Till Weinrich, and Martin Keil. Nonlinearities and self-organization in the sound production of the Rhodes piano. *The Journal of the Acoustical Society of America*, 136(4):2164–2164, 2014.

[47] Florian Pfeifle. Multisymplectic Pseudo-Spectral Finite Difference Methods for Physical Models of Musical Instruments. In Rolf Bader, editor, *Sound - Perception - Performance*, volume 1 of *Current Research in Systematic Musicology*, pages 351–365. Springer International Publishing, 2013.

[48] Florian Pfeifle and Rolf Bader. Real-Time Finite-Difference Method Physical Modeling of Musical Instruments Using Field-Programmable Gate Array Hardware. *J. Audio Eng. Soc*, 63(12):1001–1016, 2016.

[49] Roald K. Wangsness. *Electromagnetic fields*. Wiley, New York, 2nd ed edition, 1986.

[50] O. C. Zienkiewicz, C. Emson, and P. Bettess. A novel boundary infinite element. *International Journal for Numerical Methods in Engineering*, 19(3):393–404, March 1983.

[51] Stefan D. Bilbao. *Numerical sound synthesis: finite difference schemes and simulation in musical acoustics*. Wiley, Chichester, 2009.

[52] Charles Jordan. *Calculus of finite differences*. Chelsea Publ. Co, New York, 1 edition, 1950.

[53] John D. Jackson *Classical Electrodynamics* John Wiley & sons, Inc., 3rd edition, 1998

[54] John C. Strikwerda. *Finite Difference Schemes and Partial Differential Equations, Second Edition*. Society for Industrial and Applied Mathematics, Philadelphia, USA, 2nd ed edition, 2004.

[55] Florian Pfeifle and Malte Münster, Tone Production of the Wurlitzer and Rhodes E-Pianos. In Albrecht Schneider, editor, *Studies in Musical Acoustics and Psychoacoustics*, volume 4 of *Current Research in Systematic Musicology*, pages 75–107. Springer International Publishing, 2017.