ATIAM Master's degree

Synthesis of electric motors sounds based on physical models

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Contents

Abstract

Most widespread sound synthesis methods imply the extraction of sound parameters through analysis, then synthesis according to those parameters, or combination of short sound chunks. They mostly consist in analyzing the sound signal. Physical modeling sound synthesis, on another hand, consists in studying of the physics phenomena behind the production of sound, and reproduction of those phenomena. It therefore requires a specific study of the instrument or body producing the sound, and the application of physical methods and equations, which aim to reproduce the way the sound is physically produced.

The objects we will be interested in here are electrical motors. An electrical motor is naturally quite silent: as opposed to combustion engines, sound is not produced by successive explosions, but by the different vibrating parts of the object. The study of each vibrating part, their coupling and the description of those physical phenomena constitute therefore the basis of the work.

This report presents the work made during an internship in the Audio Engineering team of the Center for Digital Music, in the Queen Mary University of London. The objective of this internship is the study of a sound synthesis based on physical modeling working in real time.

Résumé

Tandis que les techniques de synthèse sonore les plus répandues impliquent l'extraction de paramètres du son existant par analyse, puis la synthèse suivant ces paramètres, par synthèse additive ou soustractive, ou encore par combinaison d'échantillons sonores de différentes longueurs. La synthèse par modélisation physique consiste, quant à elle, à étudier les phénomènes physiques conduisant à la création du son, et la reproduction de ces phénomènes. Elle nécessite donc l'étude spécifique de l'instrument ou corps sonnant et l'application de diverses méthodes physiques, selon la façon dont le son est créé.

Les objets qui nous intéressent ici sont les moteurs électriques. Ceux-ci ont la spécificité d'être, par nature, assez silencieux: contrairement à un moteur à explosion, l'essentiel du son n'est pas créé par une succession d'explosions, mais par les différentes parties vibrantes de l'objet. L'étude de chaque partie vibrante, leur couplage et la description des phénomènes physiques les régissant est donc l'essentiel de nos préoccupations.

Ce rapport présente le travail effectué au cours d'un stage effectué au sein de l'équipe Audio Engineering du Center for Digital Music (C4DM) de l'Université de Queen Mary de Londres. L'objectif de ce stage est l'étude d'un modèle de synthèse sonore sur modèle physique fonctionnant en temps réel.

Introduction

This report is the temporary version of this internship report. It will actually end on the 31st of August, and numerous points need some exploration and adjustments, including in sections 2 and 3. The entirety of the theory and most of the methods already have, however, been developed; that allows us to present this report, which will be completed. The final version, containing all adjustments and discoveries made at that stage, will be given on the 17th August.

Physical synthesis consists in generating the sound by reproducing the phenomena generating it, instead of reproducing the parameters of a recorded sound. Sound sources can be of different kinds: vibrations of plates, strings, membranes, etc. To reproduce them, one needs to know the physical properties and the equations behind the studied object : for the membranes and strings, the wave equation, respectively in one and two dimensions, for a thin plate, Love-Kirchoff equations, and for beams, Euler-Bernoulli equations.

Advantages of that kind of synthesis are multiple; the main one is to be able to create a sound entirely based on the physical properties of the studied object. This allows, for example, to anticipate the sound of a virtual object, for a physical modelization. Insofar, as the model works in real time, it is also possible to conceive the incorporation of such a model into a video game engine, or a total and immediate control of the sound, based on the physical parameters of the object.

Physical synthesis was first conceived in the 1960s, with Kelly and Lochbaum's works on voice synthesis [13], which models the trachea with a succession of accoustic pipes. In 1971, Hiller and Ruiz use finite differences models in order to solve the wave equation [12]. However, the discipline grew most notably in the 1980s, with the works of the CCRMA on guided wavebands [13] and Jean-Marie Adrien's, in the Ircam, with modal synthesis [1] and Modalys.

Motor sounds, as a whole, have been studied in different forms. Among the notable synthesis works, we can cite Andy Farnell's synthesis of combustion engines and electric motors [11], inspired by physics and using additive and substractive synthesis, or various works of granular synthesis, as AudioGaming's plugins. A heavily physics-inspired sound synthesis model has also been studied by Joshua Reiss and Simon Hendry [19], which uses a number of notions initially explored by Andy Farnell, and adding to it a number of parameters and physical controls.

The objective of this internship is to create a synthesis model of electric motors, based as much as possible on the physical phenomena governing them. Another goal is to be able to make that model work in real time. This report will first address the question of operation of electric motors, will explore why and how the sounds of an electric motor is created, before presenting the equations used in order to describe those sounds. Then, it will talk about how to apply those equations, before commenting on the results.

Chapter 1

Operation and decomposition of an electric motor

An electric motor is a machine that converts electric energy into mechanical energy. We will be interested in electric motors powered by a direct current, in short DC motors. It is interesting to note that a dynamo also works on the same principle, but converts mechanical energy into electric energy. Therefore, all methods described here can also apply to a dynamo; we will, however, talk about DC motors to simplify explanations. We will start by quickly explaining how a DC motor works, before lingering on sounds it can produce and how to put those phenomena in equations.

1.1 Operation of the DC motor

Most of the information in this paragraph is from [2]*. All information from other source is explicitly mentioned.*

Electric motors all have an electric current going through a coil; the rotor, fixed on a shaft, has a given number of protrusions and, on each of those protrusions, is rolled up a coil. That current is transmitted by a constant contact between the brushes, thanks to the commutator, a set of conductive plates, one per coil. When it goes through the coils, the current generates a magnetic field. This magnetic field then reacts with the stator, a given number of permanent magnets, usually 2 or 4, fixed on the casing of the motor; this creates an initial rotating movement. When the rotor has rotated enough, the polarization of the magnetic field in which each coil is immersed changes. The commutator has then turned with the motor, and the brushes are not in contact with the same commutator plate anymore, which reverses the polarity of the coils: the magnetic field of the coil, called rotoric field, and the one of the magnets, called statoric, therefore keep their orthogonality, which maintains the rotating movement.

Another kind of motor, called brushless, works by replacing the brushes and commutator by a system of electronic commands. It ensures the conservation of orthogonality of rotoric and statoric fields. However, brushes and commutator are the main source of noise, and we will therefore be interested here mostly in brushed motors, leaving aside brushless motors.

1.2 Decomposition of an electric motor

As any source of sound, those coming from an electric motor can be separated into two kinds: exciters and resonators. The first ones generate the sound, and the second ones will make it resound or, when the sources create a sound outside of the audible range, can make it audible. In the case of the motor, it is essential to understand how the sound is created and what makes it actually heard.

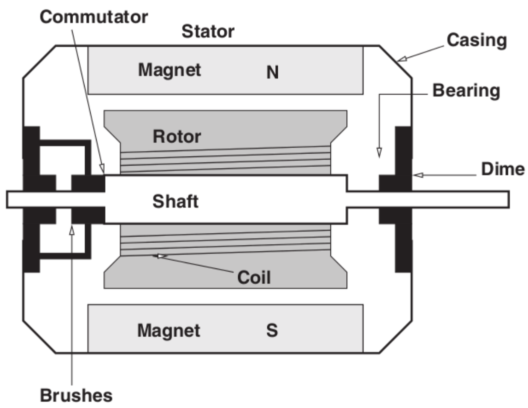


Figure 1.1 – **Lateral section of a DC motor** [11]

Before going on and identifying excitors and resonators, it is important to determine which parts of the motor actually make noise, namely what parts vibrate. The study of each component allows to eliminate from the start the stator as a source or resonator, too thick to vibrate in the audible range, and is therefore considered as rigid. The sources of sound are, by order of importance :

- The periodic contact between the brushes and the commutator. Each contacts results in a slight displacement of one of the non-fixed extremities of the brush,
- The displacement of the stator. The electromagnetic force it is subjected to displaces it slightly. It therefore acts in a similar way as the membrane of a highspeaker at a low frequency,
- If the shaft is not perfectly balanced, a periodic contact between it and the metallic casing,
- Electronical noises.

And the resonant parts are :

- The shaft, periodically excited, either by its contact with the casing, or through the commutator, which is fixed,
- The brushes,
- The casing

1.2.1 Sources

Contact between the brushes and the commutator This contact induces a small displacement of the brush. To a given number N_{rpm} of rotations per minute, and for a given number R of coils on the rotor, which is also equal to the number of plates on the commutator, this equals a frequency of displacements of $\frac{RN_{rpm}}{60}$ Hz

Moreoever, the torque on the moving shaft can be described by the following equation [19] :

$$T = T_s(1 - \frac{\omega}{\omega_f})$$

where T is the torque mentioned, T_s the stall torque, as the torque when the angular frequency ω is zero, and ω_f is the final angular frequency : $\omega_f = \frac{2\pi rpm}{60}$. That torque can be expressed as a function of the moment of inertia J, thanks to the relation $T = J\dot{\omega}$. The equation above then becomes a first order differential equation on ω :

$$\dot{\omega} = \frac{T_s}{J}(1 - \frac{\omega}{\omega_f})$$

The frequency of the motor ramping up and down can therefore be described thanks to the solution of that equation :

$$\omega = \omega_f(1 - e^{-\frac{T_s}{J\omega}t}) \tag{1.1}$$

We can see in the equation above that the ramping of the motor directly depends on the moment of inertia on the shaft, J. On a motor, it is directly related to the load on the motor :

$$J = \iiint d(x, \Delta)\rho dV$$

where $d(x, \Delta)$ is the distance between the central axis of the shaft and the given point, ρ the density and dV an element of volume.

In simpler words, the heavier the load, the more time the motor will take to ramp up to its maximum frequency ω_f. This can be synthesized by just varying the frequency of the pulses.

Electromagnetic resonance The electromagnetic resonances implies a very fast displacement of the stator magnets. The electrostatic forced exerted by one of the magnets on one of the rotor coils can be written as (fig. 1.2) :

$$F_{el} = \frac{B^2}{d_r}, \forall r \in [1, R], \tag{1.2}$$

where F_{el} is the electrostatic force, B the magnetic field generated by the named magnet, R the number of coils, d_r the distance between the magnetic poles, approximated by the center of the magnet and the center of the r^{th} coil. The distance d_r can be written as

$$d_r = r_t\sqrt{1 + cos\theta_r(t)},$$

where $\theta_r(t)$ is the angle at instant t between the r^{th} coil, and r_t the distance between the center of the shaft and the center of the magnetic plate (fig. 1.2),

$$\theta_r(t) = \frac{2\pi}{60}N_{rpm}t + \frac{2r\pi}{R}, \forall r \in [1, R].$$

The overall force is the sum of the R individual forces of the equation (1.2).

Imbalance of the shaft If the shaft is imbalanced, it can bring a periodic contact between itself and the casing. The frequency of this contact heavily depends on the imbalance, but it has to be of a fundamental frequency $60N_{rpm}$, and can be approximated in the same manner as the contact between the brush and the commutator, namely a very short pulse.

Electronic noises This part of the sound is created in an entirely other manner, since it is not due to vibrations. It has been considered in a fashion similar to the methods used by Andy Farnell and Simon Hendry, knowingly substractive synthesis.

1.2.2 Resonators

A large part, and non negligible part of the sound, also comes from the resonators. We can count mostly the brushes, the shaft and the casing.

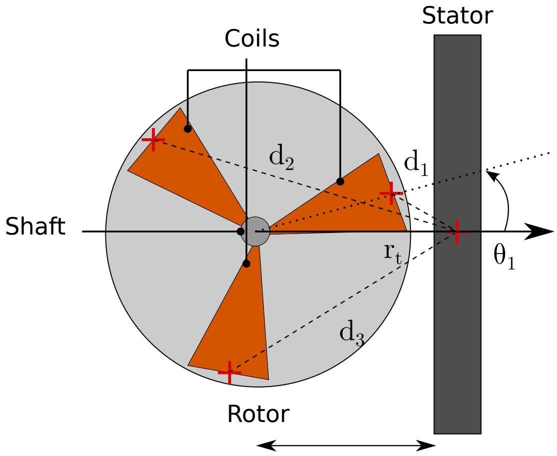


Figure 1.2 – **Front section of a 3-phase electric motor.** *d_1, d_2 and d_3 are the approximations of the distances between the magnet and each of the coils. θ_r is therefore the angle between the r^{th} protrusion of the rotor and the center of the stator..*

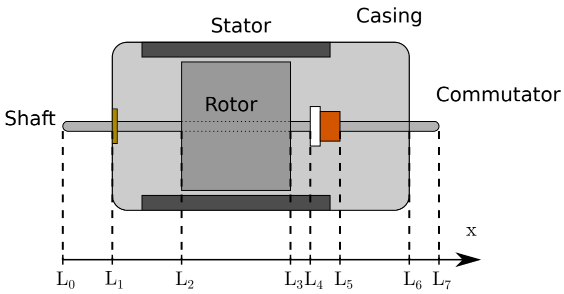


Figure 1.3 – **Lateral section of an electric motor.** *L_1, L_2, ... L_7 are the landmarks on the axis x, alongside the shaft.*

Brushes The brushes are two very thin strips of conductive metal, displaced with each rotation by the contact with the commutator. The movement of the brushes can be described by Euler-Bernoulli's beam theory, simplified by its projection on the main axis. Euler-Bernoulli's equation describes the displacement due to a force, applied normally to the main axis of the beam [24]. Projected on this axis, is can be expressed as:

$$\frac{\partial^2}{\partial x^2}\left(E(x)I(x)\frac{\partial^2 u}{\partial x^2}\right) + \rho(x)\frac{\partial^2 u}{\partial x^2} = f(x,t),$$

where $u(x,y,z,t)$ is the displacement of the beam regarding its position at rest, $I(x)$ its second moment of inertia, $E(x)$ the Young modulus of the said material, $\rho(x)$ its lineic mass, and $f(x,t)$ the force applied to the beam. It's that force that makes the brush vibrate. The motors are mostly made of metals, isotropic materials, and the section of the brushes is constant, therefore E, I and ρ do not depend on x, and the above equation can be simplified :

$$EI\frac{\partial^4 u}{\partial x^4} + \rho\frac{\partial^2 u}{\partial x^2} = f(x,t), \tag{1.3}$$

Boundary conditions described above are, fixed on one extremity, and the force $f(x,t)$ applied to the other one. Without that force, the equation (1.3) could be solved analytically; however, its presence compels the use of a numerical resolution method.

For a beam with a rectangular section, the second moment area can be expressed as :

$$I_b = \frac{bh}{12}(b^2 + h^2), \tag{1.4}$$

where I_b is the second moment area, b the width of the section and h its height.

It is also important to determine the minimal frequency for which the brushes can be considered as flexible, as for which they are effectively considered as vibrating bodies. Considering that each brush is fixed at one of its extremities, we can express the modal frequencies as ([24], sec. 5.2) :

$$f_n = \frac{n^2}{L_b}\frac{EI}{\rho}$$

where f_n is the frequency of the n^{th} mode, L_b the length of the shaft. Through the second moment area I, we find that all dimensions of the shaft are included in that equation. The frequency of the first mode, which will determine if the brush has to be seen as stiff or not, therefore is :

$$f_1 = \frac{1}{L_b}\frac{EI}{\rho}. \tag{1.5}$$

Shaft The shaft can be described as a finite cylinder, of length L_7 a lot longer than the dimensions of its cross section. Euler-Bernoulli's beam equation (1.3) can describe its movement as well. However, the boundary conditions are more complex and numerous than for the brushes (fig. 1.3):

- free in $x = L_0$ and $x = L_7$,
- rigid between $x = L_2$ and $x = L_3$,
- coupled with the casing in $x = L_1$ and $x = L_6$,
- coupled with the movements of the commutator in $x = L_4$ and $x = L_5$.

There are more boundary conditions than previously, which favors some modes of vibration and eliminates others.

The second moment area of a cylindrical section can be written as :

$$I_s = \frac{\pi r^2}{2^9}, \tag{1.6}$$

where I_s is the second moment area and r the radius of the cylinder.

As previously, we can study the dimensions of the shaft for when it has to be seen as stiff. For an indicative value, we can simplify the boundary conditions to their simplest form, considering both points where the shaft is fixed to the casing. The boundary conditions are slightly different from previously, and the modal frequencies are now ([24], sec. 5.2)

$$f_n = \frac{(n+1)^2}{2(L_6 - L_1)^2\sqrt{\frac{EI}{\rho}}},$$

where n is the n^{th} mode. The lowest frequency is then

$$f_n = \frac{1}{2(L_6 - L_1)^2\sqrt{\frac{EI}{\rho}}}. \tag{1.7}$$

Casing The cylindrical shape of the casing poses some issues with its description. As it is, describing the vibrations of a thin cylinder is not as simple as describing those of a beam. To simplify this probem, it has been chosen to use the description of the vibrations of a plate, with a displacement continuity at both ends of the plate. Vibrations of plates can be described with an extension of Euler-Bernoulli's beam theory, Kirchoff-Love's theory. For an isotropic, quasi-static material, for which deformations in the main plan are negligible, the displacements of a plate of width h on the normal axis to it can be written as [6]

$$\frac{16Eh^3}{3(1-\nu^2)}\left(\frac{\partial^4 u}{\partial x^4} + 2\frac{\partial^4 u}{\partial x^2 \partial y^2} + \frac{\partial^4 u}{\partial y^4}\right) + h\rho\frac{\partial^2 u}{\partial t^2} = -f(x,y,t) \tag{1.8}$$

where $u(x,y,t)$ is the displacement previously mentioned, E the Young modulus of the material and ν its Poisson coefficient. Unsurprisingly, this equation is extremely similar to 1.3.

The boundary conditions now are :

- Continuity of displacements at opposed ends, to approximate the plate as a cylinder,
- Coupling with the shaft in $x = L_2$ and $x = L_3$,
- Coupled to the brushes in $x = L_0$.

Chapter 2

Methods

The sound synthesis of the sound of the DC motor can now be obtain by solving the equations described in section 1. We can regroup all the phenomena creating sounds in three large categories :

- Sources, namely the displacement of the brushes (see 1.2.1) and, sometimes, the imbalance of the shaft (see 1.2.1),
- Resonators, that is vibrations of the brushes and of the shaft (eq. 1.3) on one side, and of the casing (eq. 1.8) on the other side,
- Displacements of the stator magnets, as described by the eq. 1.2, which are seen in a different manner.

All those sounds are still mostly governed by the speed of the motor, described with the equation 1.1. They are therefore all harmonic, or pseudo-harmonic, with a fundamental frequency given by this equation.

2.1 Sources

As described previously, sources are essentially displacements. Each displacement is accounted for a pulse, approximated with a Dirac of a short Hann window, of the order of 100 ms.

Those displacements let us define a number of coupling and boundary conditions.

2.2 Resonators

Vibrations of the resonators are obtained by solving each partial differential equation representing them.

Several methods of numerical resolution exist to solve partial differential equations. The simplest ones are, however, the fastest, and were therefore preferred, for a real-time oriented resolution. Therefore, it has been chosen to use a finite differences methods. It adapts Euler's method for the resolution of differential equations to partial differential equations. It offers the multiple advantages of being easy to manipulate and apply. Moreover, it is possible to vectorize it, which is a certain advantage as soon as an interpreted language is used.

2.2.1 Finite differences method for a beam

Euler's method informs us of the approximation of partial derivates of order n on any function $x \longmapsto f(x)$. Specifically :

$$f''(x) \approx \frac{f_{i+2} - 2f_{i+1} + f_i}{\Delta x^2}$$

$$f^{(4)}(x) \approx \frac{f_{i+4} - 4f_{i+3} + 6f_{i+2} - 4f_{i+1} + f_i}{\Delta x^4},$$

where $f_i = f(x_i)$, and $x_i = i\Delta x$.

Let's now approximate any displacement $u(x,t)$ with its discretization : $u(x_i, t_k) = u_i^k$, with $x_i = i\Delta x$ and $t_k = k\Delta t$. According to the equations above, the equation 1.3 becomes

$$EI \frac{u_{i+4}^k - 4u_{i+3}^k + 6u_{i+2}^k - 4u_{i+1}^k + u_i^k}{\Delta x^4} + \rho \frac{u_i^{k+2} - 2u_i^{k+1} + u_i^k}{\Delta x^2} = f_i^k,$$

where $f_i^k = f(x_i, t_k)$, the force given at a point x alongside the axis, at the instant t, also describing the couplings.

This equation allows us to define the movement at instant $t+2\Delta t$, knowing the displacement in t and $t + \Delta t$:

$$u_i^{k+2} = 2u_i^{k+1} - u_i^k - \frac{\Delta t^2}{\Delta x^2} \frac{EI}{\rho} \left(ui + 4^k - 4ui + 3^k + 6u_{i+2}^k - 4u_{i+1}^k + u_i^k \right) + \frac{\Delta t^2}{\rho} f_i^k \tag{2.1}$$

Boundary conditions are defined by fixing the value at those points.

2.2.2 Finite differences method for a plate

Above equations stay valid for a plate. We can now approximate the displacement $u(x,y,t)$ with $u_{i,j}^k$, so that $u(x_i, y_i, t_k) = u_{i,k}^k$. We also have

$$\frac{\partial^4 u}{\partial x^2 \partial y^2} \approx \frac{u_{i+2,j+2}^k - 2u_{i+1,j+2}^k - u_{i,j+2}^k - 2u_{i+2,j+1}^k + 4u_{i+1,j+1}^k - 2u_{i,j+1}^k + u_{i+2,j}^k - 2u_{i+1,j}^k + u_{i,j}^k}{\Delta x^2 \Delta y^2}.$$

Equation 1.8 then becomes

$$u_i^{k+2} = 2u_i^{k+1} - u_i^k - \Delta t^2 \frac{Eh^3}{3\rho(1-\nu^2)} \left(\frac{\partial^4 u}{\partial x^4} + 2 \frac{\partial^4 u}{\partial x^2 \partial y^2} \frac{\partial^4 u}{\partial y^4} \right) + \frac{\Delta t^2}{\rho} f_{i,j}^k, \tag{2.2}$$

where we have to replace the remaining partial derivatives with their discretization. As previously, $f_{i,k}^k$ allows us to integrate the couplings, the boundary conditions are defined by with values of $u_{i,j}^k$, and knowing the displacement at instants t_k and t_{k+1} allows us to know it at instant t_{k+2}.

2.3 Stator magnet

Displacement of the stator magnets gives us directly the appropriate waveform. Using the frequency given by the equation 1.1 in the equation 1.2, we get

$$F_{el} = \frac{B^2}{r_t \sqrt{1 + cos\left(\omega_f (1 - e^{-\frac{T_s}{J\omega} t}) + \frac{2i\pi}{R} \right)}}, \forall r \in [1, R], \tag{2.3}$$

which is straight the equation that needs to be implemented.

Chapter 3

Results

The modelization described in sections 1 and 2 didn't work. Therefore, it has been chosen to use Simon Hendry's model [19], itself almost entirely signal-based, with an implementation of results obtained from the studies shown previously. We can also note that most of Hendry's model is based on Andy Farnell's, thoroughly explained in [11].

3.1 Details of the reimplementation

Hendry's patch is decomposed in subpatches as follows:

- The main one is the central waveform. It represents of the normla force applied to the shaft, and takes the form of a phasor. This signal is then sent to three subpatches.
- One synthesizes the sound of the rotor. It takes as inputs the aforementioned signal, the frequency of the rotor, the amplitude of the signal of the rotor, and the amplitude of the signal of the brush.
- One for the signal of the stator (a rougher version of what is described in eq. 1.2), which takes as an input the main waveform and the amplitude of the signal.
- One generates the sound of the casing. It takes as an input the main waveform, the amplitude of this signal and the resonating frequency of the casing.

The signals generated by the rotor, stator and casing are then summed, and filtered. Those filters were originally integrated by Andy Farnell.

Many of the parameters used in this patch can be calculated thanks to the physics: most of the input frequencies, the speed of the build-up and build-down, the different amplitudes... Our study also allows to improve the functions with the physical parameters. Therefore, all frequencies, the ramp-up speed, etc., have been calculated thanks to equations shown in chapter 1.

3.2 Analysis of the results

3.2.1 Decomposition

All the sections are excited thanks to a similar force. They therefore have very similar time envelopes, but the frequency content is quite different.

3.3 Comparisons

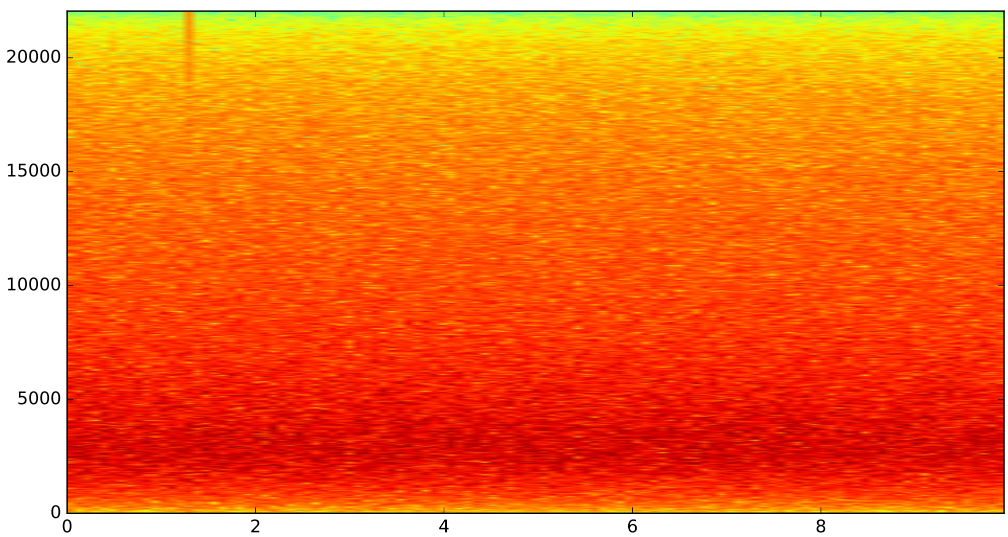
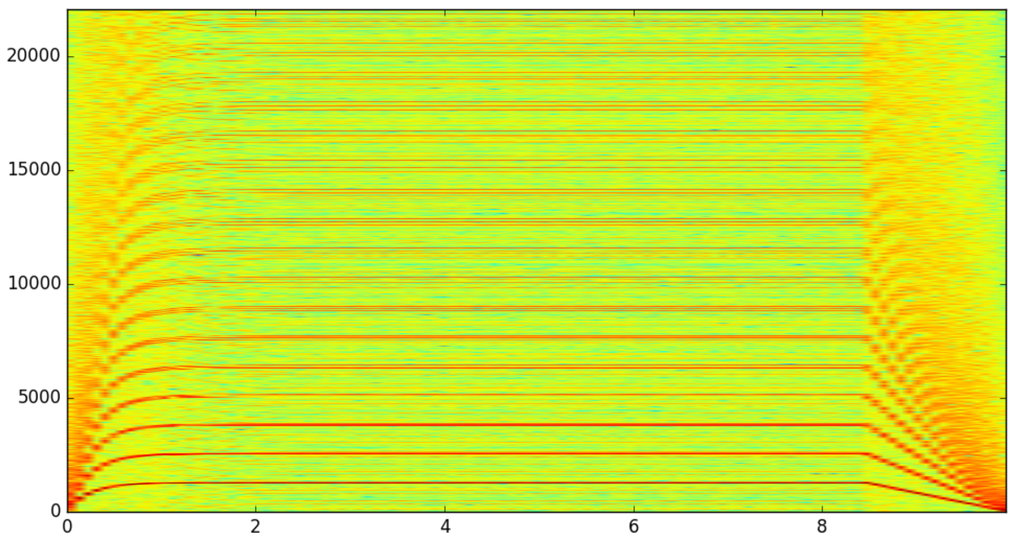
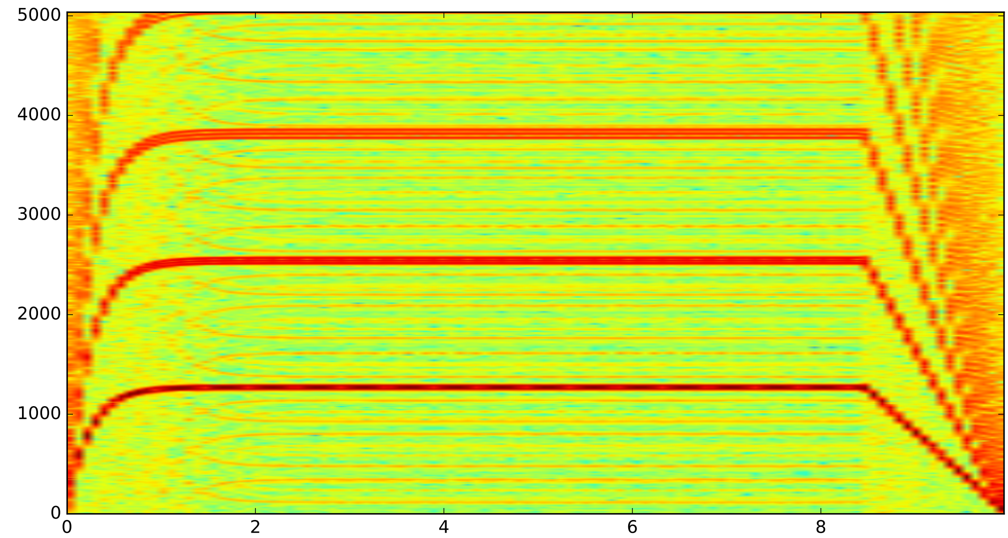


Figure 3.1 – **Spectrogram of the rotor signal.** The rotor shows only some noise. In fact, the resonating frequencies of the brushes are too high to be considered as a hearing frequency, and only noise remains.

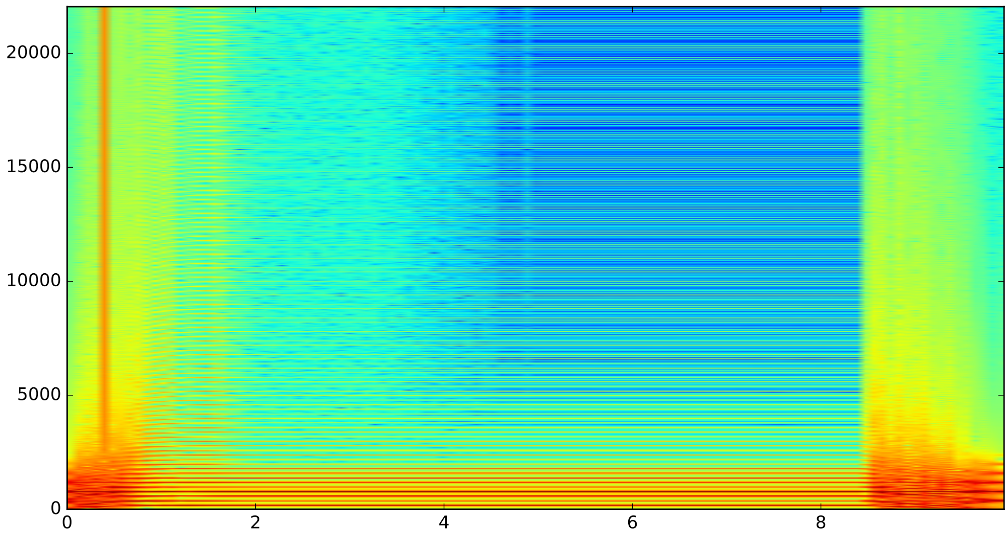


(a) The frequency is evenly distributed from 0 to 20 kHz.

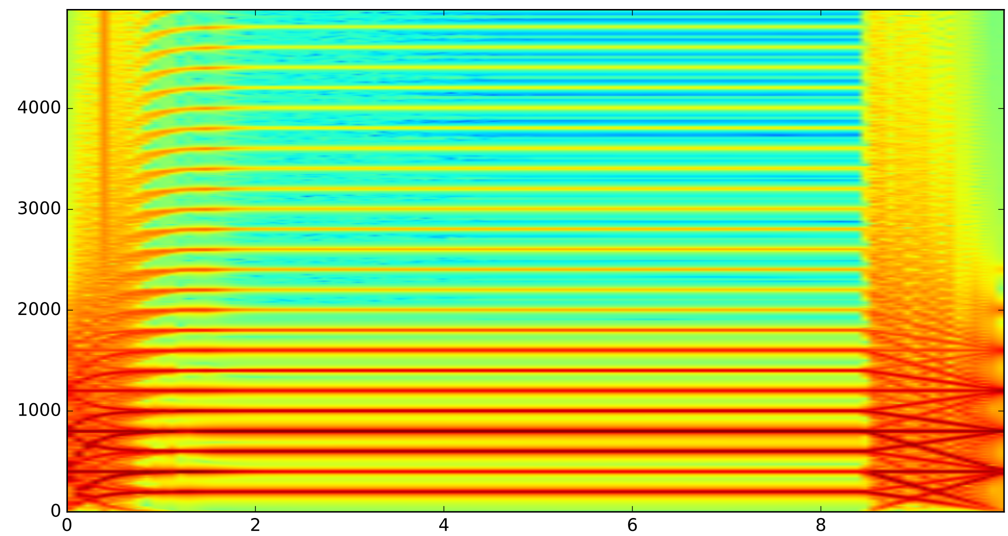


(b) The stator output shows a fundamental frequency around 120 Hz. That fits the main speed of the motor. A strong harmonic appears around 1200 Hz, related to the number of stator plates. The ramp-up and ramp-down of the motor is very distinct.

Figure 3.2 – **Spectrograms of the stator signal**

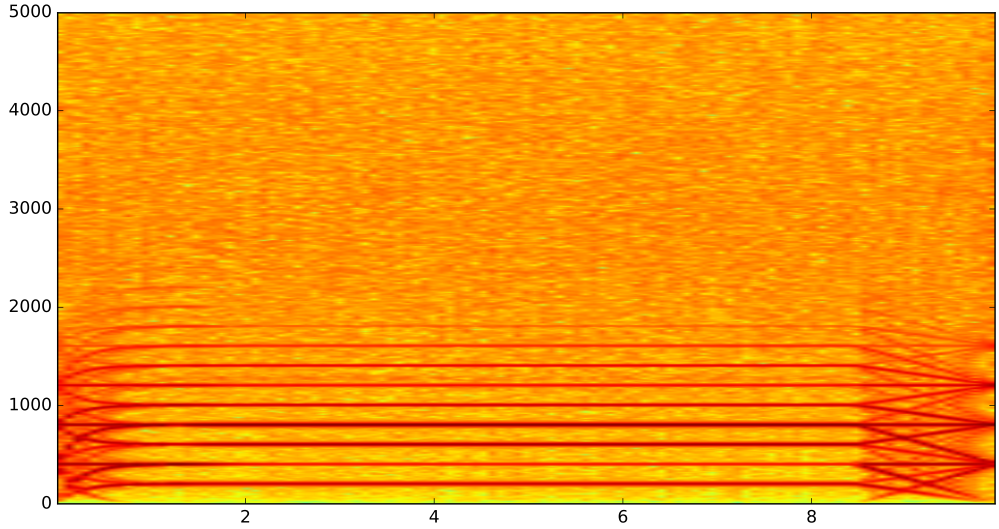


(a) **Spectrogram of the casing signal** The casing signal shows some high energy in lower frequencies, quite little on higher frequencies: most of the sound generated there is in the low frequencies, except during the ramp-up and ramp-down, particularly around 0.5 s.

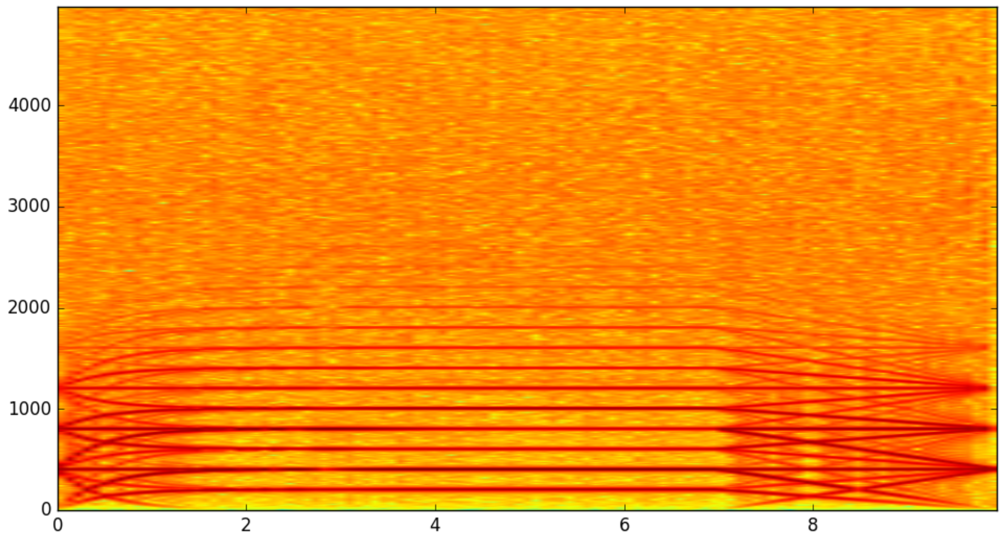


(b) **Spectrogram of the casing signal (0-5kHz)** The motor ramp-up is quite obvious. As expected, we can see a strong fundamental, but a very strong 4th harmonic is also noticeable. The surprising part is what seems to be a parallel signal of higher frequency during the ramp-up and ramp-down. It could be due to some aliasing or beating. Some research about what could cause that result have allowed to its origin, but not to explain it. It is to note that this anomaly doesn't appear on Simon Hendry's model, although it is in theory similar: this is certainly related to the fact that PureData and MaxMSP solve by themselves all abnormalities related to aliasing, pointing moreso to that direction.

Figure 3.3 – **Spectrograms of the casing signal**

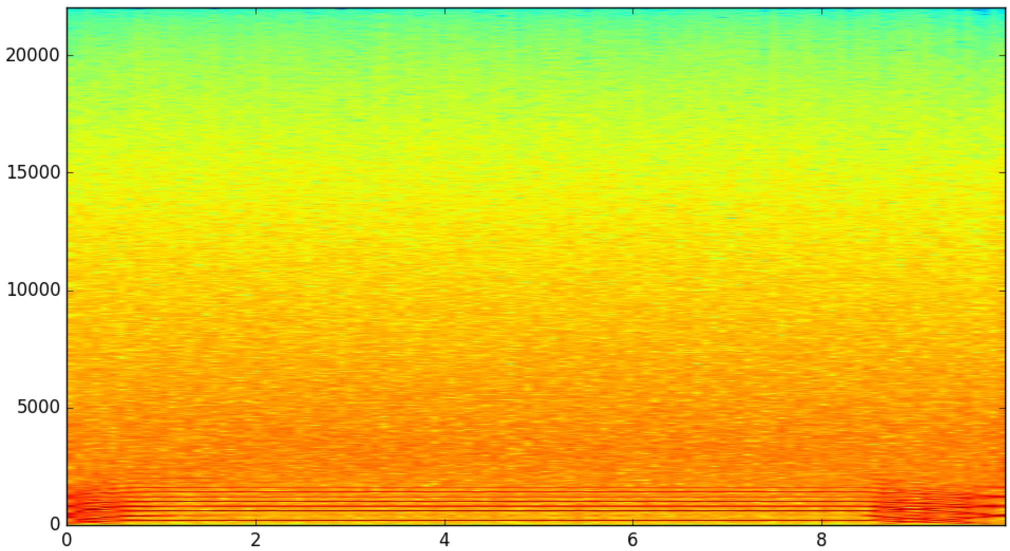


(a) Load of 0.2 kg

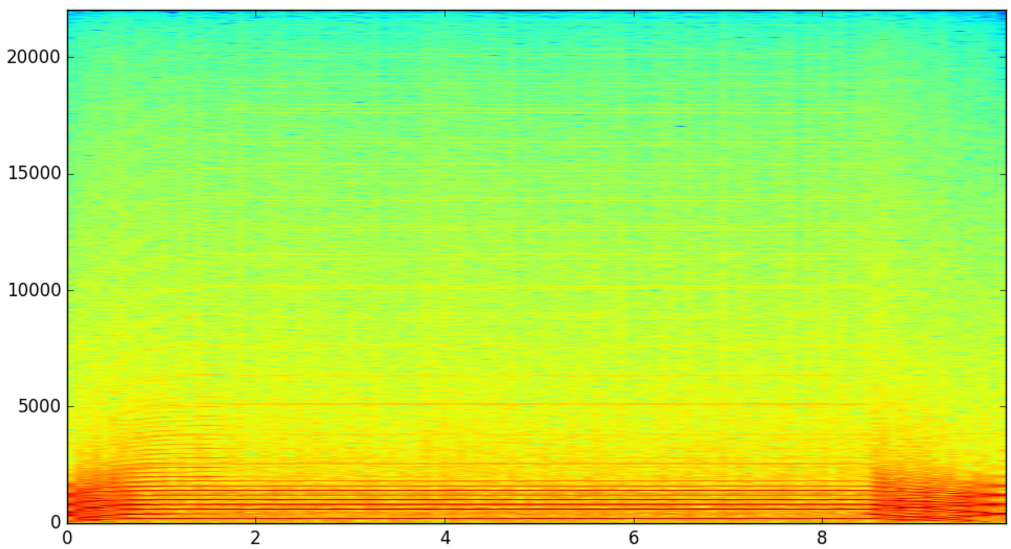


(b) Load of 0.4 kg

Figure 3.4 – **Spectrograms of the full signal for two different loads** The time the motor takes to ramp-up and down is significantly higher for a higher mass. This is in adequation with eq. 1.1, which shows that the time the motor takes to ramp-up is directly related to the moment of inertia, which includes the load. Although the load is the double of the initial load, it doesn't include the weight and load of the axis; therefore, the second ramp-up time is not twice the first one.

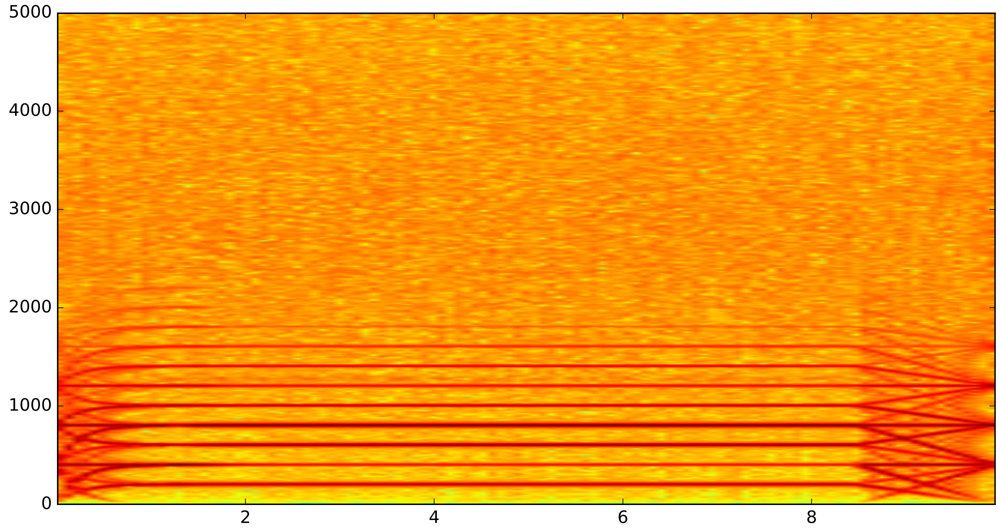


(a) Brushes of $0.5 \times 2 \times 20$ mm

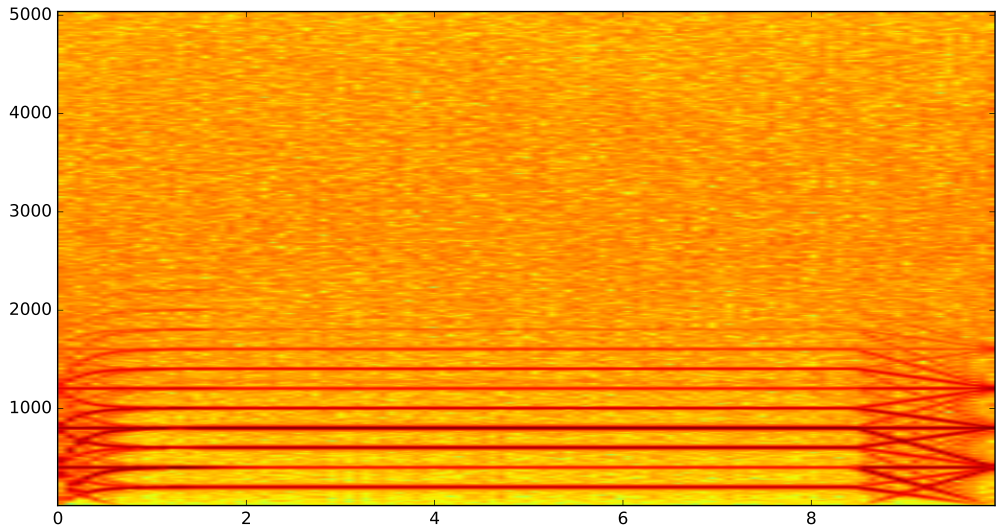


(b) Brushes of $1 \times 4 \times 40$ mm

Figure 3.5 – **Comparison for brushes of two different sizes** For the larger brushes, the white noise is located in lower frequencies : there is far less energy in higher frequencies.

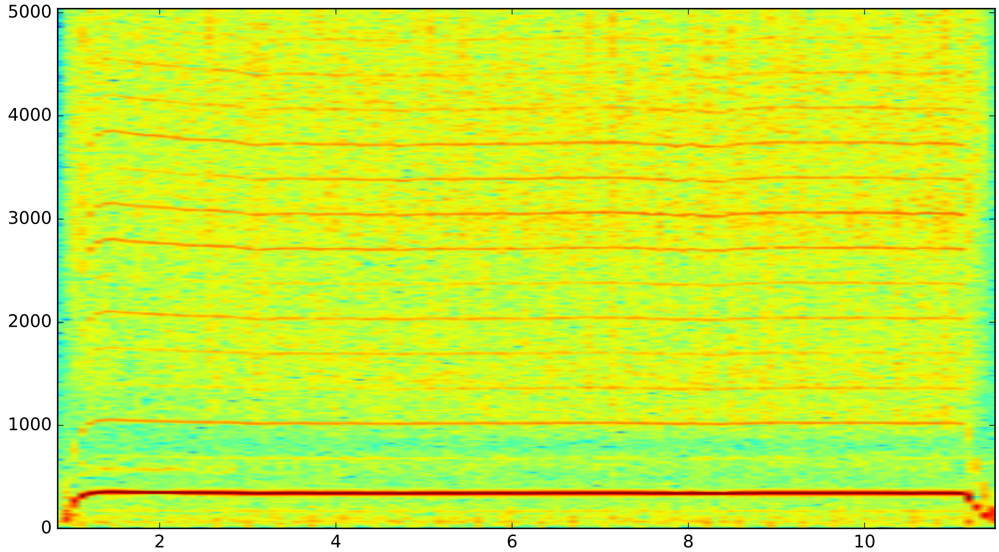


(a) Signal for a stator of radius of 2 cm, length of 2.5 cm and width of 1.5 mm

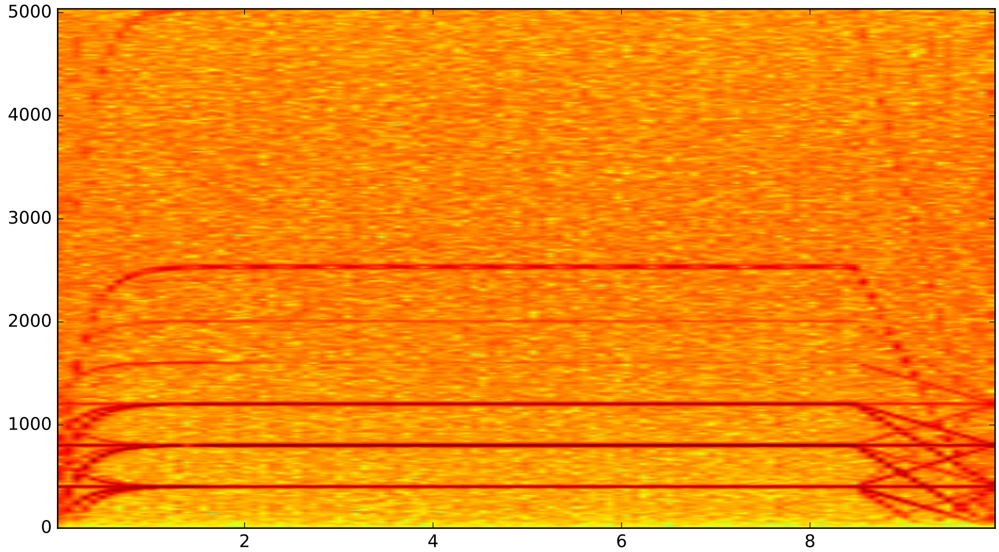


(b) Signal for a stator of radius of 4 cm, length of 5 cm and width of 3 mm

Figure 3.6 – **Comparison for stators of two differents sizes.** Once again, the larger the part, the lower the energy.



(a) **Sample of a recorded motor** This one has been chosen because its dimensions are known.



(b) **Synthesized signal** The physical parameters used there are similar to the ones of the sample above.

Figure 3.7 – **Comparison between a recorded sample and a synthesized sample.** The ramp-up and ramp-downs fit with the sample's, as does the fundamental. The 2nd to 4th harmonics, however are stronger than the ones from the sample, and harmonics after the 6th disappear on the synthesized signal, when they are still present on the sample. Other artifacts, due to the casing signal, also appear.

Conclusion

This internship will have allowed me to address physical synthesis in a new and complete angle. Among the objectives given at the beginning of the internship, several have been fulfilled. First, a physically based model of sound synthesis, has been entirely created. Unfortunately, its application doesn't work in its current state, but the first results seem to indicate that it can. Nevertheless, the results obtained from this study were used to complete the physical aspects of Simon Hendry's model, itself heavily based on Andy Farnell's. The only remaining issues, for example the shape of the casing signal, seem solvable, and highly related to the signal-based aspects of the model. However, the real-time operation of the model has not been completed.

In order to continue that project, and considering what has been and not been successful, several directions can be seen. The main and most interesting one would be to work on making the theoritical model operational. That would allow to have a fully functional physical model. Such a model would fill the gaps left by the current one: mainly coupling, but also the use of the solutions instead of signal-based approximations. It would also allow to find out which parts of the modelization are relevant and which ones might not be, for example. A next step to this would be to improve it in order to make it work in real-time.

During those months spent in the C4DM, I will have had the occasion to be integrated to the *Audio Engineering* team. The extremely diverse and international aspects of the team, of the C4DM more generally speaking, and even of London in its entirety, have allowed me to work with different people from all nationalies and backgrounds, and to bond with a new generation of researchers from all horizons. Those contacts also allowed me to note the advancement of numerous steps of a PHD, and to discover research from a new perspective and in far more depth than any time before, during my previous internships, in the LAM, in the Ircam when it was in public research laboratories, or with AudioGaming in a company.

Bibliography

[1] Jean-Marie Adrien. The missing link: Modal synthesis. In *Representations of musical signals*, pages 269–298. MIT Press, 1991.

[2] H Wayne Beaty and James L Kirtley. *Electric motor handbook*. McGraw-Hill Professional, 1998.

[3] Thomas Bertolini and Thomas Fuchs. *Schwingungen und Geräusche elektrischer Kleinantriebe: Messung, Analyse, Interpretation, Optimierung*. Süddeutscher Verlag onpact, 2011.

[4] JF Bird, RW Hart, and FT McClure. Vibrations of thick-walled hollow cylinders: Exact numerical solutions. *The Journal of the Acoustical Society of America*, 32(11):1404–1412, 1960.

[5] Niels Böttcher and Stefania Serafin. Design and evaluation of physically inspired models of sound effects in computer games. In *Audio Engineering Society Conference: 35th International Conference: Audio for Games*. Audio Engineering Society, 2009.

[6] Antoine Chaigne and Jean Kergomard. Acoustique des instruments de musique. 2008.

[7] DH Chambers. Acoustically driven vibrations in cylindrical structures. Technical report, Lawrence Livermore National Laboratory (LLNL), Livermore, CA, 2013.

[8] Robert C Chanaud. Tools for analyzing sound sources, 2010.

[9] Andrew James Farnell. *Designing sound: procedural audio research based on the book by Andy Farnell*. PhD thesis, Universidade Catolica Portuguesa, 2012.

[10] Andy Farnell. An introduction to procedural audio and its application in computer games. In *Audio mostly conference*, pages 1–31, 2007.

[11] Andy Farnell. *Designing sound*. Mit Press Cambridge, 2010.

[12] Lejaren Hiller and Pierre Ruiz. Synthesizing musical sounds by solving the wave equation for vibrating objects, parts 1 and 2. *Journal of the Audio Engineering Society*, 19(6,7), 1971.

[13] John L Kelly and Carol C Lochbaum. Speech synthesis. 1962.

[14] Javier R Movellan et al. Dc motors. *Machine Perception Laboratory, University of California, San Diego, USA*, 2010.

[15] Sebastiao Lauro Nau and Hugo Gustavo Gomez Mello. Acoustic noise in induction motors: causes and solutions. In *Petroleum and Chemical Industry Conference, 2000. Record of Conference Papers. Industry Applications Society 47th Annual*, pages 253–263. IEEE, 2000.

[16] Sami Oksanen, Julian Parker, and Vesa Välimäki. Physically informed synthesis of jackhammer tool impact sounds. 2013.

[17] Utkarsh Pateriya, Ajay Srivastava, Rajiv Singh, and Birendra Vikram Singh. A review on noise reduction of brushed dc motor. 2015.

[18] P Pfliegel, F Augusztinovicz, and J Granát. Noise analysis and noise reduction of small dc motors. In *Proceedings of the International Seminar on Modal Analysis*, volume 1, pages 119–124. KU Leuven; 1998, 2001.

[19] Joshua Reiss and Simon Hendry. Physical modeling and synthesis of motor noise for replication of a sound effects library. In *Audio Engineering Society Convention 129*. Audio Engineering Society, 2010.

[20] Raul Rojas. Models for dc motors. *Unpublished document.*

[21] Gheorghe Scutaru, Andrei Negoita, and Razvan Mihai Ionescu. Three-phase induction motor design software. In *Automation Quality and Testing Robotics (AQTR), 2010 IEEE International Conference on*, volume 3, pages 1–4. IEEE, 2010.

[22] Julius O Smith. Physical modeling using digital waveguides. *Computer music journal*, 16(4):74–91, 1992.

[23] Gergely Takács et al. Basics of vibration dynamics. In *Model Predictive Vibration Control*, pages 25–64. Springer London, 2012.

[24] Benson H Tongue. *Principles of vibration.* Oxford University Press New York, 2002.