MIT Student
21M.380

FP2: Research and Modeling

1   Introduction and Description

This document introduces a model for the Mitsuba M2096 motor, chosen for the final project sound design. The motor only is about 2-5 horsepower. It is a brushless DC motor, meaning it is controlled through a motor controller that takes a high voltage DC input and produces AC sinusoidal waveforms to drive the three phases of the motor. As it is driven with AC waveforms, there is no need for brushes or other mechanical commutators. This removes one element of mechanical sound present, though there are still several other sources of vibration and sound generation.

The aim of the project is to produce a PD patch that can mimic the sound of a Mitsuba motor spin up to speed, hold at speed, and spin down to a stop. The motor sounds generated should be reasonably accurate representations of the mechanical noises present in a motor as it moves; essentially all of the sound comes from the mechanical nature of the motor rather than its specific electrical properties.
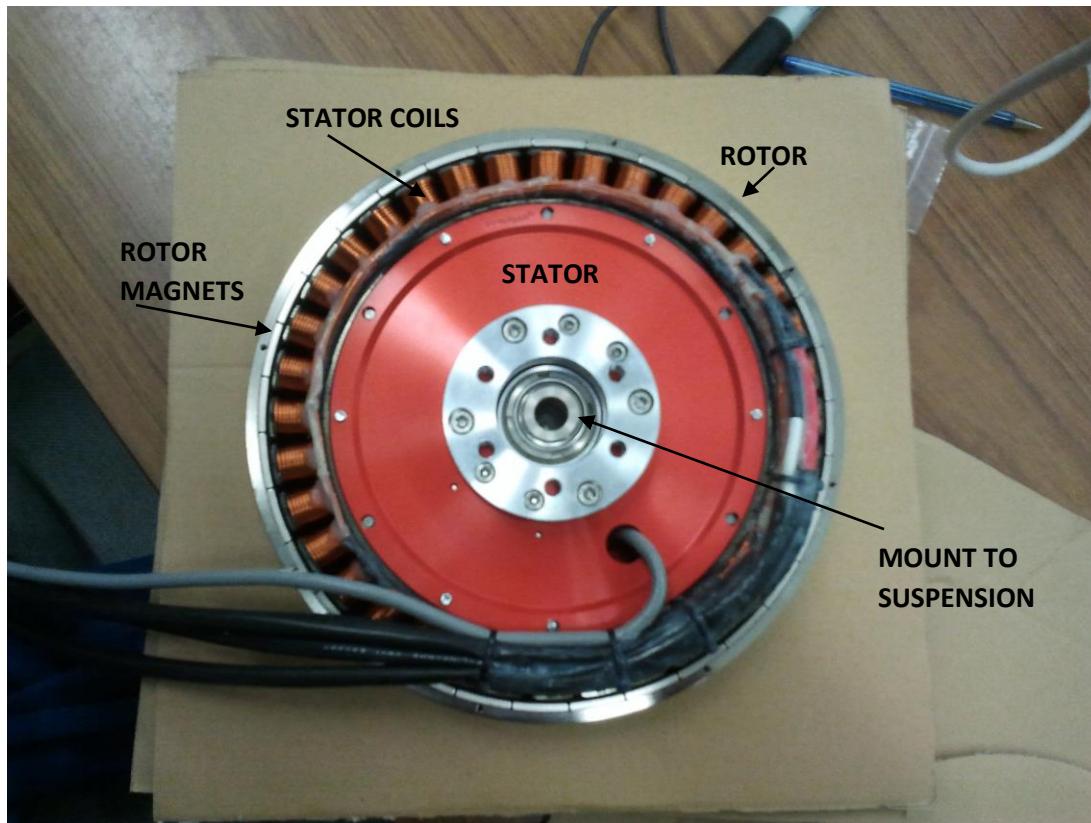
1.1   Motor Design

1.1.1   Mechanical Design

A motor consists of two main parts: the rotor (the part that spins) and the stator (the part that is stationary). The rotor can either be outside the stator or inside the stator. The former is called an out-runner, while the latter is called an in-runner. The Mitsuba is an out-runner as well as a hub motor, meaning the entire stator plus rotor is mounted directly on the wheel hub of the car. The rotor is connected to the wheel, causing it to spin, while the stator is mounted to the suspension (stationary with respect to the rotor, though the suspension does bounce up and down as the car drives). Since the rotor is an out-runner, it consists of an outer shell surrounding the inner stator. Therefore, unlike many types of motors, the rotor isn't a large coil wound cylinder, but rather a hollow shell. Therefore, some of the eccentricity or heavy lopsided sounds produced by a large metal piece rotating quickly in a common DC machine is not present in the Mitsuba sound. However, no motor is perfectly aligned, so there will still be vibration in the housing due to the inevitable eccentricity in the spin. In addition, there are friction and grinding sounds between bearings, housings, the motor shaft, and other mechanical parts.

1.1.2   Electrical Design

The stator has coils on it, which when energized by the motor controller produce a varying magnetic field. The rotor has an equal number of 'matching' magnets on it. The rotor magnets are dragged around by the stator, as they try to align with the varying magnetic field. Unlike the motor that is detailed in *Designing Sound*, the Mitsuba is driven by AC waveforms, removing the need for commutators or brushes. In a DC motor, clicks can be heard when the brushes make contact with the commutator. These clicks aren't present in the Mitsuba sound. Similarly, there shouldn't be any spark sounds, as these are due to the electrical breakdown of the air under high voltage when the connection between the brushes

and commutators is broken. Additionally, the Mitsuba has 36 poles, or 18 pole pairs. The more poles, the smoother the pushing and pulling forces on the rotor magnets are, causing the spin to sound smoother as well. However, the motor still has very distinct pulse sounds as it spins, allowing you to hear each revolution of the rotor. The motor torque is a function of its current, while its speed is a function of voltage. If the motor is current controlled, it will spin up to whatever speed corresponds to the commanded current. If the motor is voltage controlled, the motor controller will only use enough current to reach the desired speed. If the motor is unloaded (it doesn't have the weight of the car acting on it), it can reach much higher speeds, so the sound profile is different depending on the loading.

2   Speed

2.1   Model

The speed curve of the motor affects the sound significantly. Higher speeds will produce timbres with higher frequencies present. Vibration related sounds can also increase at higher speeds. The pulses of the motor completing a revolution will also be spaced closer together along the time axis. Lighter and smaller motors can get up to speed faster than bigger or heavier motors due to the inertia of the rotor. Additionally, heavily loaded motors will take longer to spin up to speed. As the speed goes up, the available torque decreases, leading to a leveling off in rotational speed as the motor spins up. When the power is removed from the motor, the spin down is essentially immediate. The overall time to spin down (when power is removed) is much quicker than the ramp up and also linear in nature since only
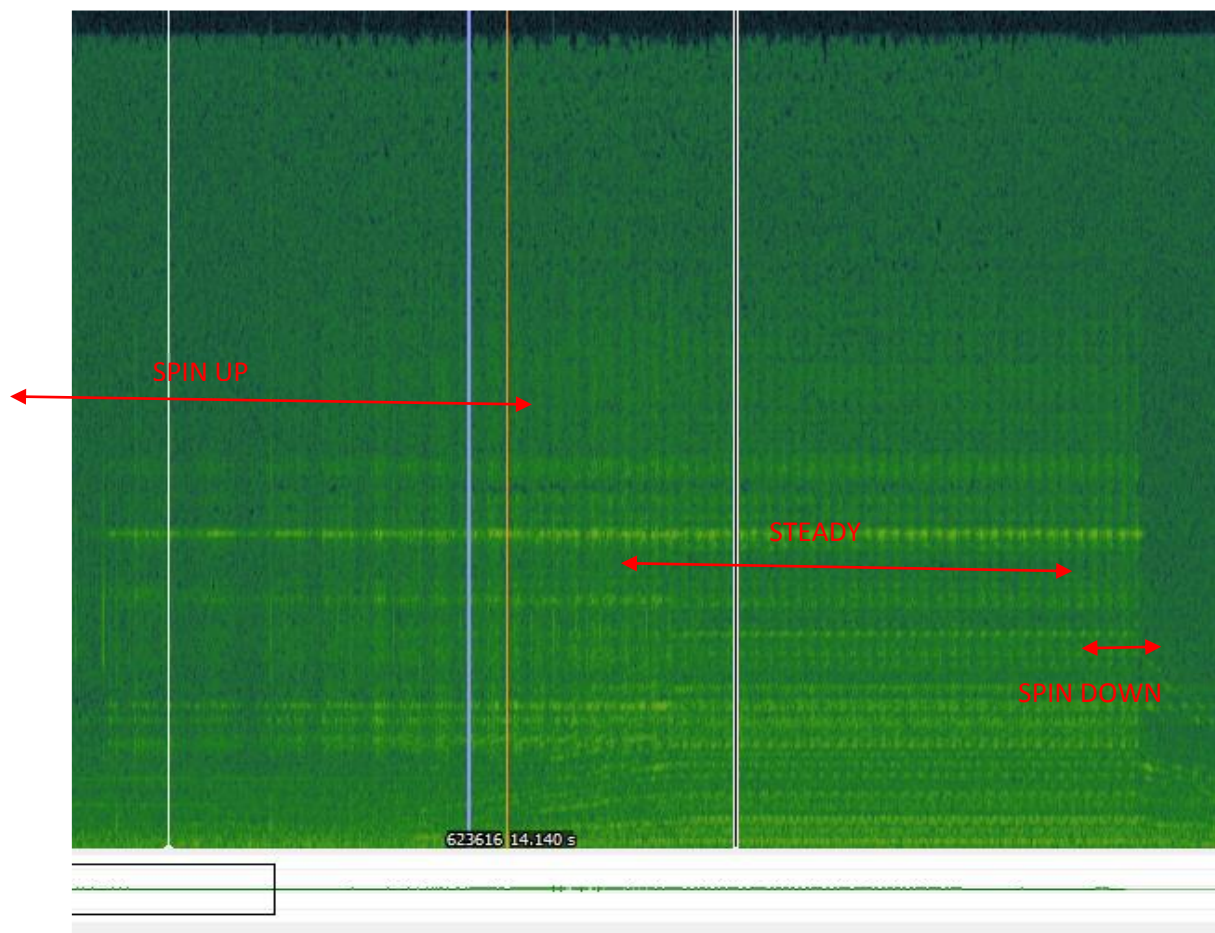
the friction and load, which are constants, are present. However, when driving the car, the driver can decelerate slowly, causing a more gradual slow down. A heavily loaded motor can also stop much more quickly as it is being acted on by much more substantial friction forces, and needs higher torque compared to the unloaded motor to reach the same speed.
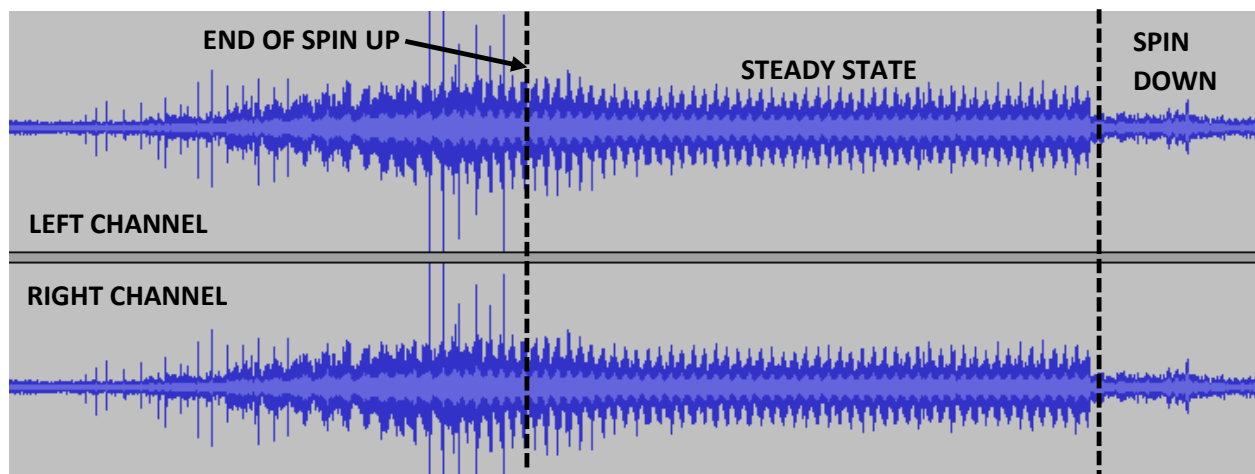
There are three main stages of the motor sound:

- Spinning up
- Steady state
- Spinning down

The motor controller starts off in a control mode called 'Trapezoidal,' which uses a trapezoidal approximation of a sine wave to drive the motor. Once the motor reaches high enough speeds (about 8 mph when the car is driving), the motor controller switches over to a sinusoidal drive. The sinusoidal drive is much smoother than the trapezoidal approximation, causing there to be a slight decrease in overall volume at the transition. This effect is much more prominent when the motor is loaded; otherwise the main sound effect seen is that the fast whine or whir of the motor dominates over the slower mechanical clinks and grinds as the motor starts spinning faster. For this PD implementation, the amplitude drop at the transition will be considered negligible, and only the dominance of the pitched sounds over mechanical grinding will be considered.

The spectrogram below shows the three states. The pulses during the steady state are much more regular than those during the spin up, meaning that the mechanical sounds are much more periodic as the motor more quickly goes through a revolution.

Spectrogram of Mitsuba motor, depicting Spin Up, Stead State, and Spin Down.

Stereo waveform plot from Audacity taken from same sound sample as in the spectrogram above.

These pulses can be clearly seen in the above waveform (in the time domain), which shows periodic spikes in the motor sound. Additionally, you can see the three stages clearly here: the slow ramp up of the signal volume during spin up, the amplitude (volume) pulsating during the steady state, and the relatively quick cut-off of the volume when the current is set to zero.

Using Sonic Visualiser, the time between the pulses during steady state in this particularly case is measured at ~ .005 sec. The frequency of the pulses is then 200 Hz (not the pitch). The frequency of the pulses for the implemented design should therefore be around the 100 – 300 Hz range, to account for slower or faster steady state speeds.
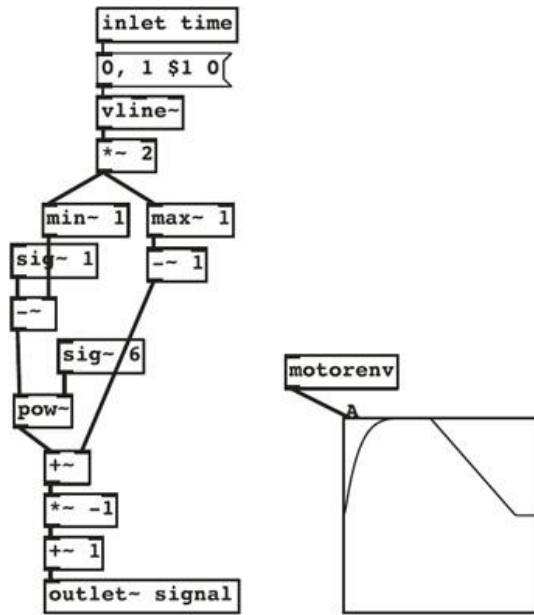
2.2   Method

We can therefore design several different speed-sound profiles to match the different stages. The overall design will consist of an envelope generator that modulates the correct parameters (such as volume or frequency) as the speed is increased or decreased. Because everything is synchronous (all parts and EM fields are moving together), the majority of the sounds present in the sound design can be shaped with the same envelope.

Following *Designing Sound*, this can be done by using a single phasor to drive the envelope model. The pulse frequency of the overall sound of the motor will also need to be sped up or slowed down as the motor speed changes, and can be created using a raised cosine waveform.
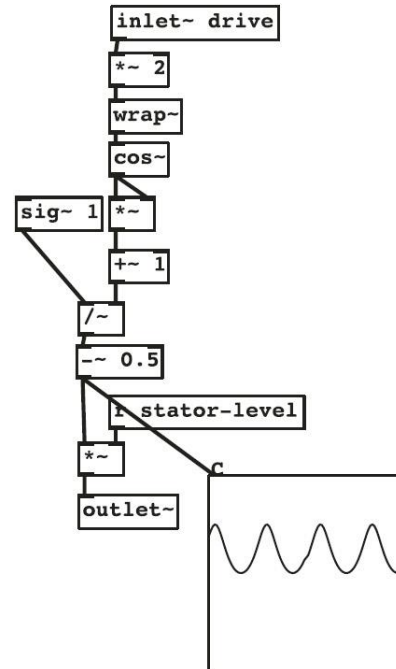
We need to make an envelope similar to the one shown in Figure 44.2 from *Designing Sound*, shown here for convenience. Here, the attack and decay portions are created using the left and right paths shown. The attack portion is shaped as a signal raised to power 6, to create a highly curved attack profile. The decay is simply a linear branch, to reflect the fact that when the current is removed the system is responded to the linear parameters of friction and load. For this motor, I would like to make the decay much quicker than the ramp up, so the linear section's slope will increase in magnitude. In addition, there should be a sustain portion to reflect the motor operating in steady state.

The pulse like vibrations can be created in a similar way to the stator sound from *Designing Sound*. Here, pulse-like vibrations are obtained using a cosine rasied according to $y = 1/(x^2 + 1)$, producing a harder and thinner sound than a cosine of the same frequency. Narrower pulse widths give the motor a smaller and faster feel, so the pulse width can be changed based on the loaded to give the sound a lighter or heavier feel.

inlet time
0, 1 $1 0
vline~
*~ 2
min~ 1   max~ 1
sig~ 1   -~ 1
-~
sig~ 6
pow~
+~
*~ -1
+~ 1
outlet~ signal

motorenv

(a) Subpatch   (b) Graph

Fig 44.2 Speed Control Envelope from
Designing Sound

inlet~ drive
*~ 2
wrap~
cos~
sig~ 1   *~
+~ 1
/~
-~ 0.5
r stator-level
*~
outlet~

Fig 44.4 Stator with pulse-like vibrations from
Designing Sound

3   Vibration

The motor housings vibrate as it spins. Additionally, certain speeds can excite the housings near resonance, so that there is a greater vibration.

Because the motor is connected directly to the wheel, there is not a long axle or shaft for the motor to spin on. This reduces some of the vibration that would be present in large common industrial-type DC motor.

3.1   Model

3.1.1   Vibration Present During Spin Up

There are clicks, at a frequency around 2000 Hz, that are very prominent during the spin up stage before the whir of the motor becomes dominant. These start off at a slower frequency in time than the pulses of the motor during steady state. The clicks are due to the rotating parts, but are distinct from the general 'grind' of the housing spinning. After a bit, the more pitched sounds of the motor come in. The grinding during startup is much more granular and not as smooth.
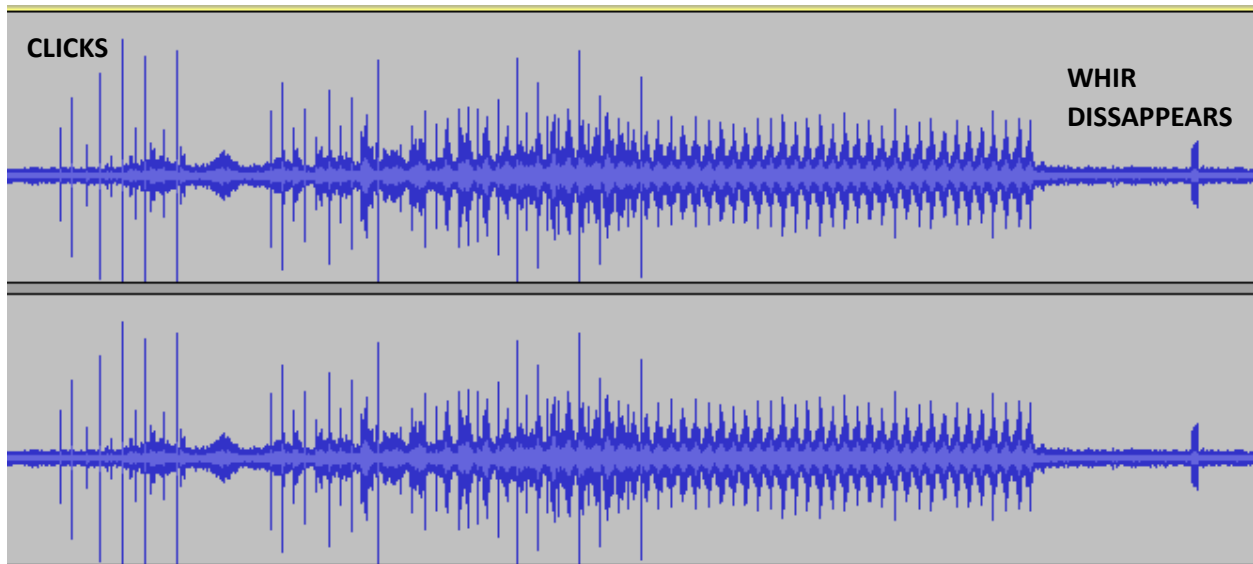
3.1.2   Vibration Present During Steady State

Most of the tonal sounds are around the 600 Hz. However, there are several harmonics of this frequency present, including a high-pitched 6000 Hz tone. It pulses in volume at the same frequency as described in the speed section. Around 3000 Hz, there's a mechanical moving sound, almost like shaking the seeds in a rain maker, in addition to the 6000 Hz high pitched whir. However, much of the other mechanical is very spread out, as an inharmonic noise signal.
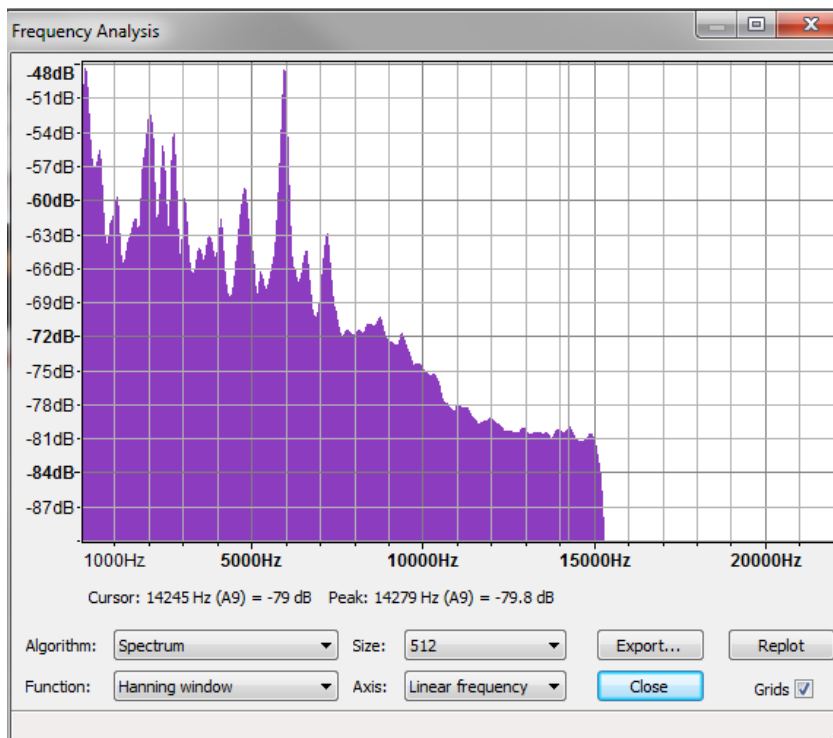
3.1.3   Vibration Present During Spin Down

As soon as the motor starts spinning down, the whirring sounds (both the 600 Hz and the 6000 Hz) quickly drops. Also, the amplitude pulsing stops as well, and the sound simply droops in pitch as it gets quieter. The mechanical sounds all but disappear instantly, just leaving the drooping tones.

This is a picture of the motor waveform after high-passing at 5000 Hz. There are still some high frequency components in the clicks during the spin up phase that can be seen as spikes right at the beginning of the signal. The dominant sound is the 6000 Hz whir, which can be seen to have a periodic variation in volume during steady state operation.
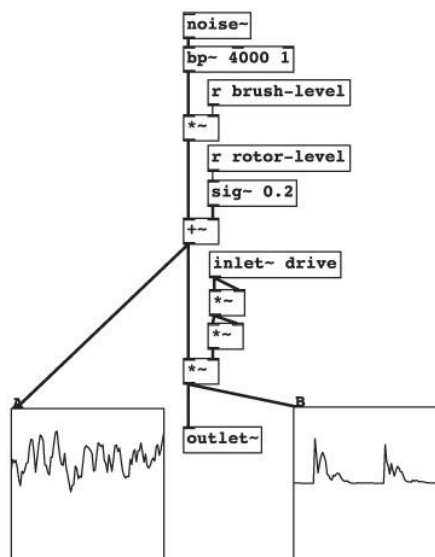

The spectrum of the sound file was taken using Audacity. High peaks can be seen at frequencies of 160 Hz, 600 Hz, 2050 Hz, and 6000 Hz. The 600 Hz sound corresponds to the whine of the motor as it spins, while the 2050 range is resultant from the mechanical clicks and grinding heard in the motor. The 6000 Hz sound corresponds to one of the dominant harmonics of the motor, which comes across as a high pitched whine.

In addition, the attached appendix gives explicit formulas for mechanical noise generation frequencies. Though these are for an induction motor, much of the noise types will be the same (bearings, housings etc.), and so can be applied to the mechanical vibration noises between 2000 – 4000 Hz to add more varied and complex harmonics. See equations (12) – (20).

3.2   Method

The motor has a very complex overlay of sounds, from the more pitched whir of the motor, to the more widespread spectrum of noise. There are several resonances and periodic features due to the cyclical nature of a rotating machine.

The clicks present during spin up can be implemented in a similar manner to how *Designing Sound* implement the commutator clicks. However, these will die out as the motor reaches steady state, and also do not have the same number / cycle relationship as the commuter clicks. The clicks can be formed with a bandpassed noise generator, to add somewhat of a harmonic tone but still keep an overall feel of mechanical noise. Similarly, the mechanical grinding present around 2000 – 3000 Hz can either be multiplied into this as the rotor signal is in Fig 44.3 from *Designing Sound*, or formed from a separate bandpass filter. Since much of the mechanical sound is at discrete pitches, I may want to generate the rotor mechanical sounds from a phasor rather than a noise source.

Fig 44.3 Rotor from *Designing Sound*, showing generation of clicks and mechanical noise

4   Overall Outline

The user will be able to control the speed of the motor, and the respective lengths of time of the spin up, steady state, and spin down regions. I would like the user to be able to control the motor with current and speed sliders, as that is how the actual motor can be controlled using its software. These would correspond to increasing the speed and mechanical vibrations of the motor. If possible, I would like to add loaded vs. unloaded sound profiles.

Signal Generation Outline:

1. Speed
    a. Amplitude of waveform increases as the motor speeds up (amplitude envelope)
    b. Pulse-like vibrations follow speed (raised cosine)
    c. Pitched sounds of motor droop during spin down (frequency envelope)
2. Vibrations
    a. Clicks at the beginning (band-passed noise)
    b. Mechanical grinding (2000 – 4000 Hz starts during ramp up, continues for steady state, drops out very quickly during spin down) (shaped noise or phasor)
    c. Pitched sounds from 600 Hz – 6000 Hz (more pitched can be created from phasor or harmonic overtones of oscillators)

5   Appendix Equations

The mixed product of stator and rotor winding space harmonic create forces at frequencies

$$f_r = f_1 \cdot \left[\frac{n.Z_r}{p} \cdot (1-s) + 2 \right]$$

$$f_r = f_1 \cdot \left[\frac{n.Z_r}{p} \cdot (1-s) \right] \tag{12}$$

Where

- f_1... Supply frequency [Hz]
- n.... value n=0, ±1, ±2,... [-]
- p... number of pole pairs [-]
- N_{rs}...Number of rotor slots [-]
- s... slip

The mixed product of stator winding and rotor eccentricity space harmonics create forces with frequencies

$$f_r = f_1 \cdot \left[\frac{n.N_{rs}}{p} \cdot (1-s) + 2 \right]$$

$$f_r = f_1 \cdot \left[\frac{n.N_{rs}}{p} \cdot (1-s) \right]$$

$$f_r = f_1 \cdot \left[\frac{n.N_{rs}}{p} \cdot (1-s) + \frac{1-s}{p} \right]$$

$$f_r = f_1 \cdot \left[\frac{n.N_{rs}}{p} \cdot (1-s) + 2 + \frac{1-s}{p} \right] \tag{13}$$

The mixed product of stator winding and rotor saturation harmonics create forces at frequencies

$$f_r = f_1 \cdot \left[\frac{n \cdot N_{rs}}{p} \cdot (1 - s) + 4\right] \tag{14}$$

$$f_r = f_1 \cdot \left[\frac{n \cdot N_{rs}}{p} \cdot (1 - s) + 2\right] \tag{15}$$

3.2. Rotor eccentricity

The air gap width depends only on position (no on time) in the static eccentricity. We conclude that the magnetic field in the air gap is rotating synchronous speed. That is given by the mains frequency and with the number of pole pair's induction machine. Modulation of magnetic field in one period is function, which is represented by a variable air gap, i.e. a function of its conductivity. Static eccentricity is defined as the rotor axis offset from the axis of the stator. The air gap has a variable character. There is stronger interaction of stator and rotor magnetic field at the point where the gap is smaller. Influence of the static eccentricity manifests as the emergence of side frequency bands, which are shifted from the mains frequency f_1 of the synchronous frequency f. For static eccentricity is the angular frequency $\Omega_\varepsilon = 0$.

Static eccentricity is straight-line. The frequency for static eccentricity is twice power frequency

$$f_{stat} = 2 \cdot f_1 \tag{16}$$

The relative eccentricity ε is defined as

$$\varepsilon = \frac{e}{g} = \frac{e}{R - r} \tag{17}$$

Where

- R... Inner stator core radius
- r... Outer rotor radius
- e... Rotor eccentricity
- g... Ideal uniform air-gap for e=0

Dynamic eccentricity occurs when the rotor failure or its affiliates. Ratios are complicated by the fact that the width of air gap is not just a function of position, but is also a function of time. The variable air gap is changing at the rotation of the rotor. There is emergence of side bands that appears in the frequency range of vibrations of electric machine.

Angular frequency for dynamic eccentricity

$$\Omega_\varepsilon = \Omega \cdot (1 - s) = \frac{\omega}{p} \cdot (1 - s) = 2 \cdot \pi \cdot \frac{f}{p} \cdot (1 - s) \tag{18}$$
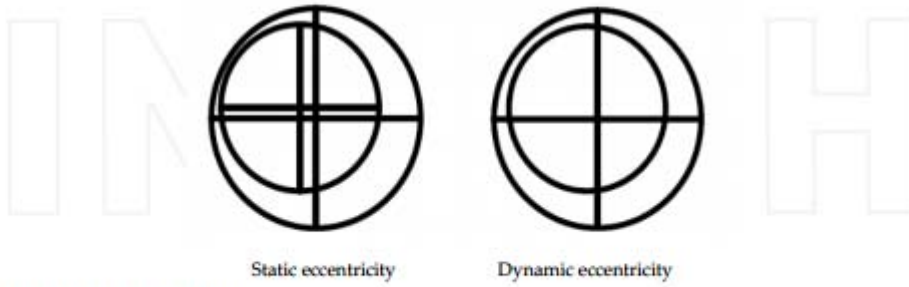
The frequency generated by the dynamic eccentricity

$$f_{DYN} = f_1 \pm (1 - s) \cdot f_{SO} \tag{19}$$

For frequency generated by eccentricity is true also relationship

$$f_{exc}\left[(n_{rt}.R \pm n_d).\frac{1-s}{p}.n_{\omega s}\right].f \qquad (20)$$

Where

- R...Number of grooves engine
- s... Chute
- p... Number of pole pairs

<div align="center">Static eccentricity   Dynamic eccentricity</div>

Figure 2. Rotor eccentricity

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21M.380 Music and Technology: Sound Design
Spring 2016

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