Engineering Acoustics - Assignment 7

A study on tonal noise and reduction techniques

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Abstract

Your abstract.

1 Introduction

This paper studies the subject of tonal noise towards implementation of an acoustic engineering strategy to reduce noise under Australian regulations in the context of the **Engineering Acoustics** class. Noise can generally be defined as an undesirable acoustic signal in any given situation which the objective is usually to reduce for the observer to comply with safety and health guidelines regarding sound level recommendations. Examples of unhealthy noise can include excessive exposure to loud noises in a factory, or undesirable sound coming from a nearby motorway in a residential area. Many regulations exist for these noises, which will be explored later on in this paper.

Additionally, noise can be characterized by noise features, which describe the nature of the noise. Depending on these features, the guidelines to allowable levels and thus necessity of sound level reduction are variable, and so it is important to take these features into account.

1.1 Noise characteristics

Without going into too much detail, a few noise features are described in this section:

Amplitude-modulated noise

Amplitude modulated noise arises when the level of the noise changes over time. This can be due to various causes. One potential source of amplitude modulated noise could be uneven noise levels caused by activity hours of a factory across the road (a given machine is turned on every other hour for instance). A smaller time scale amplitude modulated can be caused by the beating phenomenon, in which two tonal noise sources (*to be discussed in a later paragraph*) emit tonal noise centered around slightly different pitches, which causes an acoustic beating effect. Such an effect can be seen below in Figure 1.

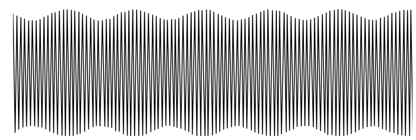

Figure 1: Beating effect observed in binaural beating [1]

Impulse and impact noise

Both impulse and impact noise are forms of discontinuous noise, which are both characterized by a very short duration of noise with no sound generation in between. Common sources are machines which produce regular impacts in factories, or explosions in a quarry. Below (Figure 2) is shown the general shape of an impulsive noise sound wave in the time domain

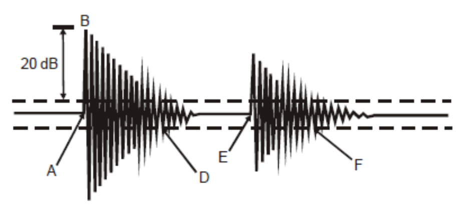

Figure 2: Impulsive noise waveform [2]

However, regulations for impact and impulse noise levels are not well defined globally, so we choose not to study these features for this paper.

tonal noise

Tonal noise can be loosely defined as noise with a given tone or frequency band which is predominant over others in the frequency spectrum, leading to subjective perception by the human ear of a "note" or "color" associated with the dominant frequency or band.

Sources of tonal noise include machines with rotating parts, pipes with resonance frequencies, or other undesirable noise sources with periodic movement within them which can produce undesirable tones. The following figure (Fig. 3) shows the noise spectrum produced by the rotating propeller blades of a rotor.

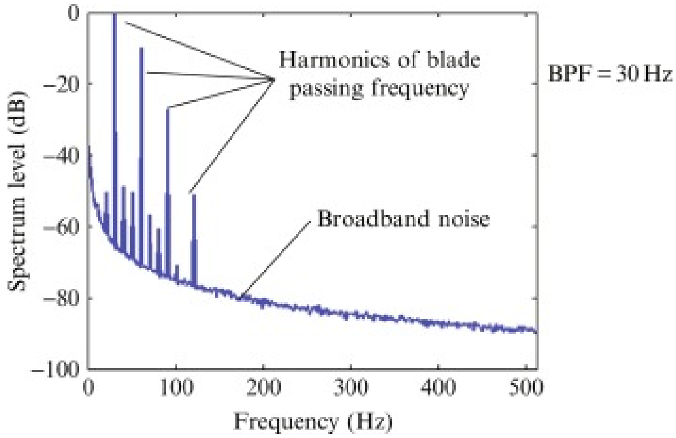

Figure 3: Noise characteristic of the propeller blades of a rotating rotor. [5]

Here, the rotation frequency of the rotor produces a given tone and the subsequent harmonics to this tone can be observed on the spectrum. Tonal noise sources are very common, and the Australian health guidelines to reducing tonal noise are clear, thus the noise that will be studied in this report will be tonal noise.

In a first section, tonal noise will clearly be defined in terms of time domain and frequency domain characteristics. A sample of tonal noise will be generated via matlab in an attempt to mimic the noise produced by a real-life tonal noise source. Regulations regarding tonal noise, specifically in Australia, will be discussed. A final section will address four real-world solutions to reducing the dBA Sound Power Level (SPL) of a tonal noise source, two scenarios considering outside propagation, and two considering inside propagation.

2 What is tonal noise?

As previously discussed, tonal noise will be the noise feature discussed in this paper. Thus, it is important to describe what tonal noise is from a time and frequency domain standpoint. Furthermore, tonal noise sources will be discussed in this section, with a few examples which we will use later on in real life scenarios.

2.1 Time and frequency domain characterization

Firstly, tonal sounds are *steady* sounds, which means that their time-domain representation is an uninterrupted waveform (no silence), as opposed to impulse noise, for instance. Furthermore, specific metrics vary but it is agreed upon that tonal noise, when decomposed into its **1/3 octave band spectrum**, has one band presenting a higher sound pressure level than the others by a given margin. Here are two more specific metrics from South Australia's Environment Protection Agency [3] and Australian Standard 1055 2018

- tonality is defined by [3] as being the case where a given 1/3 octave band in the A-weighted 1/3 octave band spectrum surpasses the sound pressure level of adjacent bands by 5dBA.
- [4] notifies than in NSW, the tonality criterion varies with the center frequency of the band:
  - the measured SPL in dBA for the given 1/3 octave band must be 5dB over the adjactent bands to be considered tonal above 400Hz center frequency
  - 8dB under 400Hz and above 160Hz
  - 15dB under 160Hz.

Though these criteria vary slightly from state to state, the applicable criterion for South Australia is the first one, which is the one we will be using to verify further on that our generated noise can indeed be considered tonal.

2.2 Tonal Noise sources

Section 1.1 mentions that tonal noise is often emitted by machines with rotating parts due to the periodic nature of the movement, which emits a given frequency. However, now that we know how tonal noise is strictly defined in the time domain and frequency domain, we know that a pure tone can also be considered tonal noise. So, a continuing whistle or beep coming from a given machine, car, person can also be considered tonal noise. Here are a few examples of tonal Noise sources.

Tonal noise generated by an engine (moving parts)

Consider a standard 4-stroke cycle piston engine with a constant rate of 3000rpm, with 8 pistons. This can be used to compute the excitation frequency of the overall machinery (this engine can be used to power a machine in a given factory across from a residential area, or could be in a car engine testing room, or in a car on a motorway). Consider f the fundamental frequency of the exciting vibration of the engine:

$$f = n_pistons * \frac{rpm}{120} = 200Hz \tag{1}$$

Thus, this engine is excited at a fundamental frequency of 200Hz, and the accompanying harmonics also come into play when considering the tonality of the signal.

The following figure (Figure 4) taken from [6] shows the SPL spectrum measured for a 4-cylinder engine running at 2200rpm. f_c , f_{en} and f_{ex} are respectively the fundamental two-revolution frequency of the engine, the

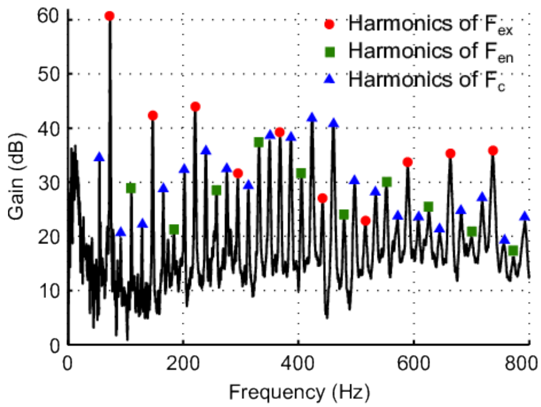

Figure 4: SPL spectrum of an engine [6]

one-revolution frequency, and the explosion frequency of the engine.

Here, looking at the spectrum, we suppose strong tonality in the 63Hz 1/3 octave band.

Tonality caused by resonance

Consider an inside scenario where a water pipe sits in the open (not in an acoustic enclosure and not wrapped). Consider this pipe to be 10m long and open on both sides (one coming from a pump and the other leading to a septic tank, for instance). The pipe diameter is $D = 10cm$ and the speed of sound in water is $c = 1480m/s$. The resonance frequencies of the fluid inside the pipe, likely to be excited in the case of turbulent flow, are given by :

$$f_n = \frac{nc}{2L} \tag{2}$$

Furthermore, the pipe is considered to be a cylinder and will also exhibit mechanical resonance due to the shape of the cylinder, which will also contribute to the overall spectrum of noise produced by the pipe system.

With no other noise sources than the white noise produced by running water in the pipes, the observed spectrum at a small distance from the pipe is likely to be composed mostly of these harmonics, and thus exhibit tonality.

Other sources

These two examples are common, and others can be exhibited. [4] mentions the following examples in which tonal noise can be observed in community or private spaces:

- Low-frequency noise generated by wind farms (blade resonance)
- Electrical transformer exhibiting low-frequency noise due to oscillating electric signal
- Beeping of a construction truck near residential area
- High-frequency motors in a plant room
- Tones produced by pedestrian rail crossing warning alarm

So, tonal noise has many potential sources, many of which can be found in residential and community areas, thus needing guidelines and rules for the allowable level not to be exceeded. The following section focuses on generating tonal noise via matlab.

3 Generating tonal noise

In this section, we generate tonal noise based on the criteria we described before. We will try to mimic the spectrum of the engine shown in Fig4, at least in spirit. We choose to define three fundamental frequencies for one-revolution vibration, half-revolution vibration and explosion vibration in the engine. Say:

- $f_c = 70Hz$
- $f_{en} = 130Hz$
- $f_{ex} = 100Hz$

And to consider the 20 first harmonics for these signals. Furthermore, we implement frequency-dependent amplitude decaying for each harmonic (physically coherent), while adding some randomness to diversify the height of each peak (this would be decided by the engine's geometric and material characteristics in real life).

Furthermore, for additional realism with regards to this artificial signal, we use minoritary pink noise (constant 1/3 octave spectrum to not disturb the tonality of the signal with a SNR signal to noise ratio of about 10 (dependant on harmonic family))

3.1 Code

The matlab code used to produce the signal provided with this hand-in as well as the following visualization is shown below:

```
% generate a white noise with harmonics
close all

flims = [63 11025];
bpo = 3;
opts = {'FrequencyLimits';
    flims;
    'BandsPerOctave';
    bpo};

fs = 22050;
T = 5;
n = fs*T;
t = (0:1/fs:T-1/fs);

Wdb  = 20;

pn = pinknoise(1,n)*1e2;
y = pn;
f0 = 70;
f1 = 100;
f2 = 130;
omega0 = 2*pi*f0;
omega1 = 2*pi*f1;
omega2 = 2*pi*f2;



for k=1:20
    exp1 = exp(-0.5*k*(0.8+(1.2-0.8)*rand()))
    exp2 = exp(-0.5*k*(0.8+(1.2-0.8)*rand()))
    exp3 = exp(-0.5*k*(0.8+(1.2-0.8)*rand()))
    y = y + 0.5e3*sin(k*omega0.*t)*exp1;
    y = y + 2e3*sin(k*omega1.*t)*exp2;
    y = y + 1e2*sin(k*omega2.*t)*exp3;
end


[pxx,f] = pspectrum(y,fs,'FrequencyResolution',25);
```

The generated sound file, *Artificialengine.wav*, is included in this hand-in. 5s of sound were generated using the previous code. it would have been relevant to introduce some artificial rumbling to truly resemble engine noise, but as the following analysis will show, this noise is indeed tonal according to Australian criteria.

The following code was used to generate the figures in the following section:

```
figure;
subplot(1,2,1)
semilogx(f,pow2db(pxx))
grid on
xlabel('Frequency (Hz)')
ylabel('Power Spectrum (dB)')
xlim([5,4000])
title('log scale frequency spectrum of ...
    generated signal')

subplot(1,2,2)
plot(f,pow2db(pxx),'r')
grid on
xlabel('Frequency (Hz)')
ylabel('Power Spectrum (dB)')
xlim([0,4000])
title('linear spectrum of generated signal')

figure;
spectrogram(y,4000,80,1000,fs,'yaxis','power');
ylim([0,4])
title('spectrogram of generated signal')


figure;
subplot(1,2,1)
grid on
poctave(y,fs,opts{:},'Weighting','A')


subplot(1,2,2)
grid on
poctave(y,fs,opts{:})

figure;
plot(t,y)
grid on
ylim([-5000,5000])
title('Generated artificial tonal signal')
xlabel('time (s)')
ylabel('signal amplitude (W)')
```

3.2 Frequency and time domain analysis

The goal of this section is to verify that the generated noise is indeed tonal according to australian guidelines for distinguishing tonal noise. First, the time domain representation of the signal is shown below (Figure 5). Though tonality does not depend much on the reference, as various sound power and pressure levels differ only by an additive constant for same distance from the source, we choose 1W as reference for all calculations of sound power levels:

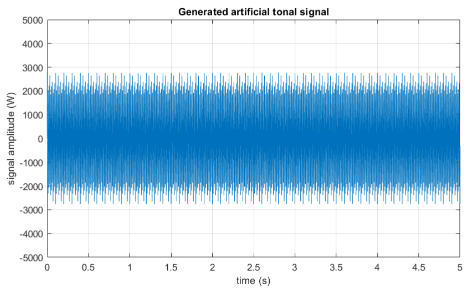

Figure 5: Time domain evolution of generated signal

And the spectral representation can be seen in the following figure (Figure 6). Though it is still apparent the signal is artificial, it somewhat resembles the spectrum shown in Figure 4.

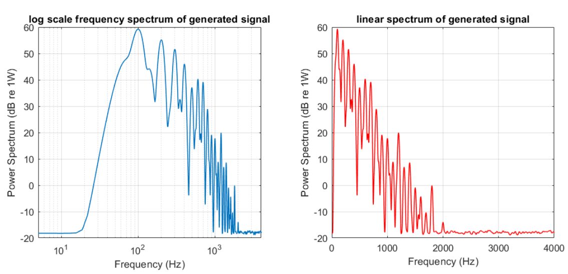

Figure 6: Linear and log-scale spectra of the generated signal

And the following spectrogram (Figure 7) shows the evolution over time of the various frequencies, which, as we have not introduced time-amplitude modulation, do not change with regard to the tonal harmonics:

The most relevant visualization for the task at hand is to compute the 1/3 octave band A-weighted Spectrum to determine whether or not the sound is tonal. The following (Figure 8) shows both spectra for A-weighting and no weighting:

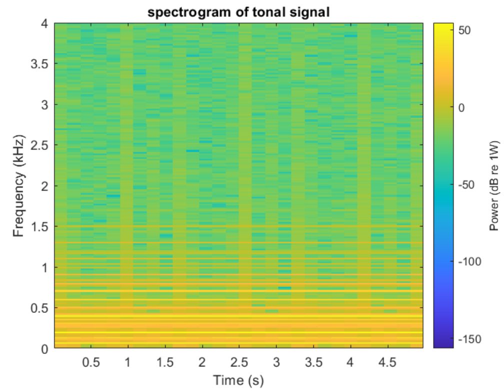

Figure 7: Spectrogram of generated signal

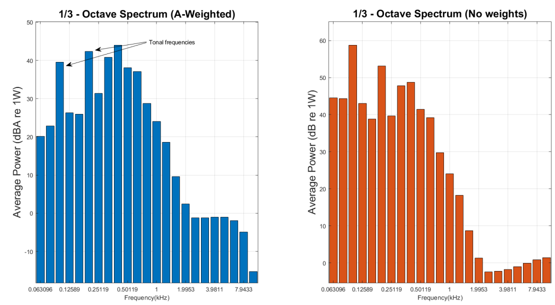

Figure 8: A-weighted spectrum (Left) and non-weighted spectrum (right) for the generated signal

As shown on the previous graph, the A-weighted 1/3 octave band spectrum exhibits two tonal peaks, centered around 100 and 200Hz, which both have a SPL difference of over 5dBA with the adjacent 1/3 bands, which according to regulations in both SA and NSW, qualifies the noise as being tonal.

Having successfully generated a sample of tonal noise, the following section focuses on a more precise overview of tonal noise qualifications and, more generally, community noise criteria and guidelines in Australia, in prevision of the exercise of reducing said noise.

4 Relevant guidelines

5 Reducing a tonal noise source: Problems

5.1 Outside tonal noise propagation

5.2 Inside tonal noise propagation

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References

[1] Beat (acoustics). Beat(acoustics) — Wikipedia, the free encyclopedia, 2010.

[2] Bies, D. A., Hansen, C. H., and Howard, C. Q. *Engineering noise control*. CRC press, 2017.

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[4] Evans, T., and Cooper, J. A comparison of tonal noise regulations in australia. *Proceedings of Acoustics 2015 Hunter Valley* (2015), 15–18.

[5] Glegg, S. A., Devenport, W., and Alexander, N. Broadband rotor noise predictions using a time domain approach. *Journal of Sound and Vibration 335* (2015), 115–124.

[6] Jagla, J., Maillard, J., and Martin, N. Sample-based engine noise synthesis using an enhanced pitch-synchronous overlap-and-add method. *The Journal of the Acoustical Society of America 132* (11 2012), 3098–108.