

# Stationary and non-stationary sinusoidal model synthesis with phase vocoder and FFT<sup>-1</sup>

Clément Cazorla, Vincent Chrun, Bastien Fundaro, Clément Maliet  
ENSEEIHT - 3EN TSI 2016-2017

March 7, 2017

## Abstract

The present document is to serve as both a technical report and a documentation for the code produced during the long project. As such the first part will explain the theoretical framework and the state-of-the-art of the field. The second part will give some insight about the code structure and the conventions that were adopted and last but not least, the third part will serve as an actual documentation and details every class, methods and attributes.



# Contents

<b>I</b>	<b>Introduction</b>	<b>4</b>
1	The company	4
2	Objective	4
3	Context of the project	5
4	Work environment and project management	5
4.1	Work environment . . . . .	5
4.2	Project management (Gantt chart) . . . . .	6
<b>II</b>	<b>Method Overview</b>	<b>7</b>
5	Additive Synthesis (Time Domain)	7
6	Method Overview	7
<b>III</b>	<b>The additive synthesis in frequency domain</b>	<b>8</b>
7	Stationary Case	8
7.1	Phase Coherence . . . . .	8
8	Quasi-Stationary Case	9
8.1	Theory . . . . .	9
8.2	phase vocoder . . . . .	9
9	Non-Stationary Case	9
9.1	Theory . . . . .	9
9.2	phase vocoder . . . . .	9
<b>IV</b>	<b>Result</b>	<b>10</b>
10	Sationary Case	10
11	Non-Stationary Case	10
<b>V</b>	<b>Code structure and conventions</b>	<b>11</b>

<b>12 Conventions</b>	<b>11</b>
12.1 Naming conventions . . . . .	11
12.2 Spectrum and sinusoids parameters classes . . . . .	12
12.2.1 Spectrum . . . . .	12
12.2.2 Parameters . . . . .	13
12.2.3 NonStationaryParameters . . . . .	13
<b>13 Code structure</b>	<b>14</b>
13.1 General structure . . . . .	14
13.2 Class structure . . . . .	14
<b>VI Documentation</b>	<b>15</b>
<b>14 Core module</b>	<b>15</b>
14.1 Synthesizer . . . . .	15
14.2 StationarySynthesizer . . . . .	16
14.3 NonStationarySynthesizer . . . . .	16
<b>15 Spectrum generation module</b>	<b>17</b>
15.1 SpectrumGenerator . . . . .	17
15.2 StationarySpectrumGenerator . . . . .	17
15.3 NonStationarySpectrumGenerator . . . . .	18
15.4 LobeGenerator . . . . .	18
15.4.1 StationnaryLobeGenerator . . . . .	18
15.4.2 NonStationaryLobeGenerator . . . . .	19
<b>16 Phase Vocoder module</b>	<b>19</b>
16.1 PhaseVocoder . . . . .	19
16.2 StationaryPhaseVocoder . . . . .	20
16.3 NonStationaryPhaseVocoder . . . . .	20
<b>A Phase advance and propagation along the signal</b>	<b>22</b>
A.1 On the first attempt at Phase Vocoder use . . . . .	22
A.1.1 "Pure" synthesis . . . . .	22
A.1.2 "Parametered" synthesis . . . . .	23
A.2 Theoretical phases advance . . . . .	24

# Part I

## Introduction

### 1 The company

For this project we work with Audiogaming. Audiogaming is a start-up company which creates audio plug-in for movies and video games. They are base in Toulouse and Paris.

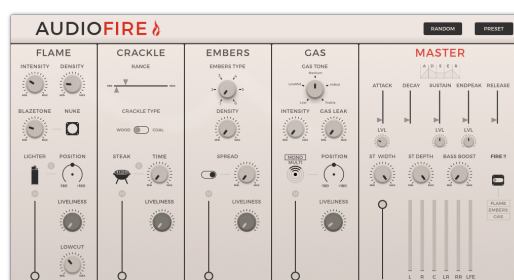


Figure 1: Audiofire: audio plug-in that recreates fire sound

### 2 Objective

The objective of the project is to use inverse Fourier transform to synthesize a sound. There are two parts in this process: the Analysis and the Synthesis.

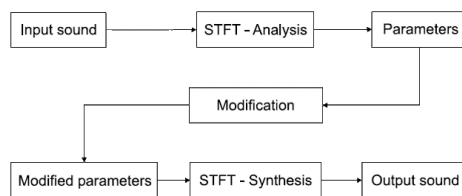


Figure 2: General approach for modifying a sound in the spectral domain

Our objectives were to focus on the synthesis. We supposed that the analysis part is done and that we know all the parameters. The work is divided into two parts : the stationary synthesis and the non-stationary synthesis.

### 3 Context of the project

We had 6 weeks to do this work. As a beginning, we had the work of the previous group which worked on this project in 2015. They had done an analysis estimator of sinus parameters and sinus generation with those parameters (only stationary) in Python and some research on the Non-stationary synthesis with the LUT of lobes in Matlab. We imposed to ourself an Object Oriented Programming tree structure in Python, in that way the code will be easier to use by the client and the next group which will work on this project. This structure will be described in details in this report.

### 4 Work environment and project management

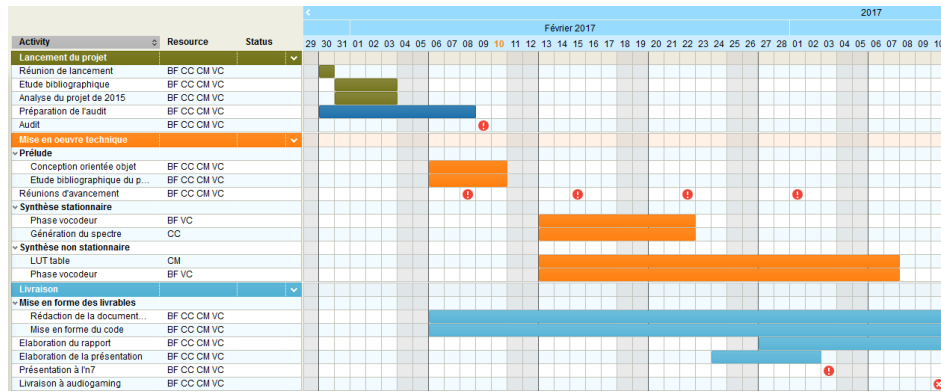
#### 4.1 Work environment

We used PyCharm to program in Python, Slack to communicate with our supervisor (ask questions, send some quick results, plan a meeting...). An other important tool was GitHub, we used it to share our codes and to work all at the same time in the same project.



Figure 3: *PyCharm* as Python IDE , *Slack* to communicate, *GitHub* to stock the codes and have a versionning, *Freedcamp* to plan the project events

## 4.2 Project management (Gantt chart)



## Part II

# Method Overview

5 Additive Synthesis (Time Domain)

6 Method Overview

## Part III

# The additive synthesis in frequency domain

## 7 Stationary Case

### 7.1 Phase Coherence

The phase becomes a problem when we are synthesizing a signal, even a simple sinusoid, because for each frame we create a "different" sinusoid with the same parameters. That is not what we want, we want to create a single sinusoid :

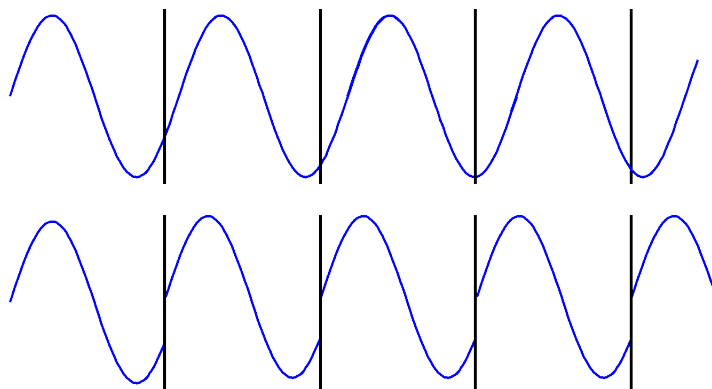


Figure 4: Coherent phase (above) vs. Incoherent phase (below) between frames

When we listen to a signal which phase is incoherent between frames (vertical jump) it will sound as "pops". This is something very unpleasant to listen to. We need to do something to make sure there is no discontinuity. Thus, correcting the phase is absolutely necessary.

In the stationary case, it is something easy to do. Knowing the exact frequency and for each frame, we advance the phase of  $2\pi\tilde{f}R_a$ . To see details of the theoretical phase advance for the stationary case, please refer to the appendix (A.2).



## 8 Quasi-Stationary Case

### 8.1 Theory

### 8.2 phase vocoder

## 9 Non-Stationary Case

### 9.1 Theory

### 9.2 phase vocoder

## Part IV

# Result

10 Stationary Case

11 Non-Stationary Case

## Part V

# Code structure and conventions

## 12 Conventions

In this section we remind the reader of a few coding convention necessary to ensure a seamless work flow and a bug free program as much as possible. Files should contains an entire module (as described in 13.1) not just a single class to limit the number of files and ease the bug tracking. Imports in files should be kept to a minimum and left in namespaces (do not use the **from** module **import** \* syntax). It is preferable to import a whole module if more than three elements from the module are needed in the file, otherwise consider the **from** module **import** element1 , element2 syntax to avoid unnecessary memory flooding. If conflicts exists, notwithstanding the number of elements needed, the whole modules are to be loaded with a namespace. Namespaces may be abbreviated to the programmer's convenience however some abbreviation are to be universally respected :

- (i) `numpy` should always be imported as `np`
- (ii) `matplotlib.pyplot` should always be imported as `plt`

Finally math functions should always come from the `numpy` module and not python's `math` module to guarantee a universal behaviour across the program.

### 12.1 Naming conventions

Naming conventions are freely adapted from Python recommended conventions defined in PEP8 [1], as such :

- (i) *Class* should be named in **CapitalizedWord**
- (ii) *Methods* and *functions* should be named in **lower\_case\_with\_underscores**
- (iii) *Attributes* and *variables* should be names in **lower\_case\_with\_underscores**
- (iv) *Instantiation* following the fact that everything is an object in python should be named as *variables*.

Moreover during class declaration, the following principles should be adopted :

- (i) Non-public methods and attributes should use one leading underscore.
- (ii) Elements that conflicts with python reserved name should use one trailing underscore rather that simplification or a misspelling.
- (iii) Accessors or mutators using one leading underscore should be interpreted as properties of their associated attribute. As such it should be guaranteed that they induce a low computational cost.

- (iv) Non-public elements that should not be inherited or may cause conflicts during inheritance should use two leading underscore and make use of Python name-mangling.

To seamlessly manipulate both *stationary* and *non stationary* models, class that are inherited in two versions are preceded with either **Stationary** are **NonStationary** respectively.

## 12.2 Spectrum and sinusoids parameters classes

Because many spectra, main lobes and sinusoidal model parameters have to be traded between modules we created two classes, respectively **Spectrum** and **Parameters**. They mainly serve as containers, holding the data and returning them in a point wise fashion. This way we can prevent conflicts and errors that would come from a non-uniform data sharing protocol and as well ensure that every operation performed on either spectra or parameters are made following the same principles and algorithms.

### 12.2.1 Spectrum

Spectrum
<pre> _amplitude : np.array _phase : np.array _nfft : int ----- __init__(self, amplitude, phase) __add__(self, other) __iadd__(self, other) __mul__(self, other) __imul__(self, other) from_complex_spectrum(cls, complex_spectrum) @classmethod void_spectrum(cls) @classmethod set_spectrum(self, amplitude, phase,               start_bin=None, stop_bin=None) set_complex_spectrum(self, complex_spectrum,                      start_bin=None, stop_bin=None) get_amplitude(self, k) get_phase(self, k) get_nfft(self) </pre>

The Spectrum class stores a spectrum in amplitude and phase, however it may be created or changed from a complex **np.array** respectively with the class method **from\_complex\_spectrum** and the method **set\_complex\_spectrum**. Those two methods may take optional parameters **start\_bin** and **stop\_bin** if one need to update only a part of the spectrum, for example a single lobe. The class checks that the given data are consistent upon instantiation. The **+** operation as well as the **+** = operation have been defined between two **Spectrum** objects and between a **Spectrum** object and an array of complex numbers.

The  $\times$  operation as well as the  $\times =$  operation have been defined between a **Spectrum** object and an array of complex numbers. Addition and multiplication attempts between other data type will result in a **NotImplementedError** exception.

### 12.2.2 Parameters

Parameters
<pre> _amplitudes : np.array _frequencies : np.array _phases : np.array _number_sinuses : int ----- __init__(self, amplitudes, frequencies, phases) get_amplitude(self, k) get_frequency(self, k) get_phase(self, k) get_number_sinuses(self) </pre>

The Parameters class is more of a structure than a class and only contains the stationary sinusoidal model parameters and their respective accessors. It also stores the number of sinuses and checks that the given data are consistent upon instantiation.

In the stationary sinusoidal model the signal  $s(t)$  is defined as follow<sup>1</sup> :

$$s(n) = \sum_{i=1}^{N_{sinus}} \alpha_i \sin(2\pi \tilde{f}_i n + \phi_i)$$

with  $\tilde{f}_i = \frac{f_i}{f_s}$  the normalised frequency.

We then store the parameters as follows :

**\_amplitudes** stores the  $\alpha_i$

**\_frequencies** stores the  $\tilde{f}_i$

**\_phases** stores the  $\phi_i$

### 12.2.3 NonStationaryParameters

NonStationaryParameters(Parameters)
<pre> _acrs : np.array _fcrs : np.array ----- __init__(self, amplitudes, frequencies, phases, acrs, fcrs) get_acr(self, k) get_fcr(self, k) </pre>

The stationary sinusoidal model can be extended to the first order development

to better model fast amplitude and frequency change over time. The signal  $s(t)$  can then be expressed as a sum of linearly varying chirps<sup>1</sup> :

$$s(n) = \sum_{i=1}^{N_{sinus}} (\alpha_i + \mu_i \cdot nT_s) \sin(2\pi \tilde{f}_i n + \frac{\psi_i}{2}(nT_s)^2 + \phi_i)$$

Where we define the **Amplitude Change Rate**  $\mu$  and the **Frequency Change Rate**  $\psi$ .

Thus we inherit the **Parameters** class to add the two additional parameters as follow :

`_acrs` stores the  $\mu_i$

`_fcrs` stores the  $\psi_i$

## 13 Code structure

### 13.1 General structure

### 13.2 Class structure

---

<sup>1</sup>Please look up section 9 page 9 for more details

## Part VI

# Documentation

## 14 Core module

### 14.1 Synthesizer

Synthesizer
<pre>_window_size : float _window_type : float _nfft : float _analysis_hop : float _synthesis_hop : float _current_parameters : Parameters _past_parameters : Parameters _fs : float _past_spectrum : Spectrum _current_spectrum : Spectrum __init__(self, window_size, window_type, zero_padding_factor, analysis_hop, synthesis_hop, current_parameters, fs=None) __del__(cls) reset_synthesizer (self, window_size, window_type, zero_padding_factor, analysis_hop, synthesis_hop, current_parameters, fs) get_next_frame(self) set_next_frame(self, next_parameters) _set_window_size(self, window_size) _set_window_type(self, window_type) _set_analysis_hop(self, analysis_hop) _set_synthesis_hop(self, synthesis_hop) _set_current_parameters(self, current_parameters) _get_current_spectrum(self) _set_current_spectrum(self, new_spectrum)</pre>

## 14.2 StationarySynthesizer

StationarySynthesizer
<pre>_window_size : float _window_type : float _nfft : float _analysis_hop : float _synthesis_hop : float _current_parameters : Parameters _past_parameters : Parameters _fs : float _past_spectrum : Spectrum _current_spectrum : Spectrum _spectrum_generator : StationarySpectrumGenerator ----- __init__(self, window_size, window_type, zero_padding_factor, analysis_hop, synthesis_hop, current_parameters, fs=None) get_next_frame(self) inverse_fft(self, current_spectrum)</pre>

## 14.3 NonStationarySynthesizer

NonStationarySynthesizer
<pre>_window_size : float _window_type : float _nfft : float _analysis_hop : float _synthesis_hop : float _current_parameters : NonStationaryParameters _past_parameters : NonStationaryParameters _fs : float _past_spectrum : Spectrum _current_spectrum : Spectrum _spectrum_generator : StationarySpectrumGenerator ----- __init__(self, window_size, window_type, zero_padding_factor, analysis_hop, synthesis_hop, current_parameters, fs=None) get_next_frame(self) inverse_fft(self, current_spectrum)</pre>



## 15 Spectrum generation module

### 15.1 SpectrumGenerator

SpectrumGenerator
<pre><code>_parameters : Parameters _nfft : np.float _spectrum : Spectrum _window_size : np.float _analysis_hop : np.float ----- __init__(self, window_size, parameters, nfft, analysis_hop) _add_lobe(self, k, lobe) _set_window_size(self, window_size) _set_window_type(self, window_type) _get_parameters(self, new_parameters) _get_spectrum(self)</code></pre>

The aim of this class is to generate a synthetic spectrum from known parameters (amplitudes, phases, frequencies). This class is divided into two subclasses that generate stationary and non-stationary spectrums.

### 15.2 StationarySpectrumGenerator

StationarySpectrumGenerator (SpectrumGenerator)
<pre><code>_parameters : Parameters _nfft : np.float _spectrum : Spectrum _window_size : np.float _analysis_hop : np.float _lobe_generator : StationaryLobeGenerator ----- __init__(self, window_size, parameters, nfft, analysis_hop) _add_lobe(self, k, lobe)</code></pre>

## 15.3 NonStationarySpectrumGenerator

NonStationarySpectrumGenerator (SpectrumGenerator)
<pre><code>_parameters : Parameters _nfft : np.float _spectrum : Spectrum _window_size : np.float _analysis_hop : np.float _lobe_generator : NonStationaryLobeGenerator _regular_lut : np.array __init__(self, window_size, parameters, nfft, analysis_hop) _add_lobe(self, k)</code></pre>

This class has not been made yet, but the goal is the same as for the StationarySpectrumGenerator.

## 15.4 LobeGenerator

LobeGenerator
<pre><code>_window_type : np.float _window_size : np.float _nfft : np.float _window : np.array _lobe : Spectrum __init__(self, window_type, window_size, nfft) _set_window_size(self, window_size) _set_window_type(self, window_type) _gen_lobe(self) _get_lobe</code></pre>

This class generates a 11 points main lobe.

### 15.4.1 StationnaryLobeGenerator

StationaryLobeGenerator(LobeGenerator)
<pre><code>_window_type : np.float _window_size : np.float _nfft : np.float _window : np.array _lobe : Spectrum _gen_lobe : Spectrum __init__(self, window_type, window_size, nfft) _gen_lobe(self)</code></pre>

### 15.4.2 NonStationaryLobeGenerator

NonStationaryLobeGenerator(LobeGenerator)
<pre> _abcisse : np.array _ordonnee : np.array _interpolated_lobe : np.array _regular_grid : np.array _domain : np.array _number_acr : np.float _number_fcr : np.float _number_points : np.float _LUT : np.array _gen_lobe : Spectrum ----- __init__(self, regular_grid, acr_domain, fcr_domain, number_acr, number_fcr, window_type, window_size, nfft, fs=None, method_a=None, method_p=None, method_f=None) _gen_uniform_lut(self) _gen_non_uniform_lut(self) _genlobes_legacy(self, i, j, acr, fcr, t, n) _gen_lobe(self) _get_lobe(self) _interpolate_lobe(self, acr, fcr, method_a=None, method_p=None, method_f = None)) </pre>

The aim is to generate a LUT with a uniform or a non-uniform grid, and to generate a lobe for a given ACR/FCR couple by interpolating with existing lobes of the LUT. The user must chose the kind of interpolation he or she wants to use for magnitude, phase and frequency. Besides, he can choose the size of the LUT to build by giving the number of ACRs and FCRs.

## 16 Phase Vocoder module

### 16.1 PhaseVocoder

PhaseVocoder
<pre> _analysis_hop : int _synthesis_hop : int _omega : np.array _past_analysis_spectrum : Spectrum _past_synthesis_spectrum : Spectrum _current_analysis_spectrum : Spectrum _current_synthesis_spectrum : Spectrum ----- __init__(self, analysis_hop, synthesis_hop, current_synthesis_spectrum) _get_region(self, k) _get_pv_spectrum(self, k) </pre>

**This module is not used !**

The PhaseVocoder file gathers both the Stationary Phase Vocoder and the Non-Stationary Phase.

## 16.2 StationaryPhaseVocoder

StationaryPhaseVocoder
------------------------

get_pv_spectrum(self)
-----------------------

The Phase Vocoder algorithm is located here. It will correct the phase at each frequency bin  $k$  (remember that this module is not used at the end). To do so it proceed in 5 steps :

- Get the phase difference,
- Remove the expected phase difference,
- Map the phase shift to  $[-\pi; \pi]$  range,
- Get the true frequency,
- And finally get the final phase.

For the details, please refer to paper [2] where the algorithm is well detailed.

## 16.3 NonStationaryPhaseVocoder

NonStationaryPhaseVocoder
---------------------------

get_pv_spectrum(self)
-----------------------

**This module is not complete !** The detailed algorithm called Scaled-Phase Locking is also described in the paper [2]. The idea is to correct the phase on the peaks bin and then apply this correction on each bin of the region containing the peak. To do so, a peak trajectory detection is needed to know between two frames if the peak is the same one on the other frame, because it could have changed his frequency bins due to the non-stationary case. We also need to get the region (bins near the peak bin). And then we apply on this peak the phase vocoder and the corrected phase shift is applied on all bins of the region corresponding to this peak. A Matlab implementation can be found in [3].

## Conclusion

## A Phase advance and propagation along the signal

### A.1 On the first attempt at Phase Vocoder use

In the stationary case, the Phase Vocoder is expressed in 3 equations as follow :

$$\Delta\Phi_k^u = \angle X(t_a^u, \Omega_k) - \angle X(t_a^{u-1}, \Omega_k) - R_a\Omega_k \quad (1)$$

$$\hat{\omega}_k(t_a^u) = \Omega_k + \frac{\Delta_p\Phi_k^u}{R_a} \quad (2)$$

$$\angle Y(t_s^u, \Omega_k) = \angle Y(t_s^{u-1}, \Omega_k) + R_s\hat{\omega}_k(t_a^u) \quad (3)$$

What (1) means is that we look for the true phase shift (the analysis phase shift) during the frame  $u$  and  $u-1$  which is  $\angle X(t_a^u, \Omega_k) - \angle X(t_a^{u-1}, \Omega_k)$  and we compute the error in phase shift, that is to say the difference between the *true* phase shift and the *expected* phase shift.

In (2) we use the error in phase shift to compute the deviation in frequency  $\frac{\Delta_p\Phi_k^u}{R_a}$  from the expected frequency  $\Omega_k$  and thus compute the *true* frequency at which the bin was excited between  $t_a^{u-1}$  and  $t_a^u$ .

Finally (3) assume the correct synthesis phase shift will be  $R_s\hat{\omega}_k(t_a^u)$  that is the true frequency times the synthesis hop.

The issue with such an approach in our case is that we dropped the analysis. We want to use the Phase Vocoder to *create* phase shifts in our spectra, but the Phase Vocoder is in fact nothing but a fancy way to copy existing phase shifts while taking into account a different hop during analysis and synthesis. I will try and break down the issues I have into two cases.

#### A.1.1 "Pure" synthesis

We wish to synthesize a stationary or a sum of stationary sinusoid from scratch. For simplicity's sake and without loss of generality we will take the one sinusoid case. That is to say that we want, without prior knowledge to generate  $s(n)$  such as :

$$s(n) = \alpha \cos(2\pi\tilde{f}n + \phi) \quad (4)$$

knowing only  $\alpha$ ,  $\tilde{f}$  and  $\phi$ .

We will also, to ease the process, assume that we know the application<sup>1</sup>  $f_{w,\tilde{f}}(\phi) : \phi \mapsto \tilde{\phi}$  which takes into account the effect of windowing on the phase of the frame spectrum's phase<sup>2</sup>.

---

<sup>1</sup>And this this is a very strong hypothesis in the sense that it will never be true, but this is not the core issue at stake here.

<sup>2</sup>For more details on the theory, please read part II page 7

The first step is then to generate a synthetic spectrum with the desired parameters. To do this we only generate a main lobe derived from the Fourier transform of the normalized window  $w$  supposedly<sup>3</sup> used during analysis, and place it at the right position on the spectrum. This involves to interpolate the relevant bins value if by any chance the wanted frequency  $\tilde{f}$  is not exactly on a bin, that is to say if  $\tilde{f} \notin \{\frac{2k\pi}{N}\}_{k=0\dots N-1}$ . We then multiply the generated lobe by  $\frac{A}{2}$  and set the lobe phase to  $\tilde{\phi} + 2\pi\tilde{f}R_a$ <sup>4</sup>. We then wished to use the phase vocoder to advance the phase (compute the needed phase shift). To get the temporal frame, we theoretically only have to compute the inverse Fourier transform of the generated spectrum.

In order to use the Phase Vocoder we assumed the generated spectrum to be equivalent to the analysis spectrum  $X(t_a^u)$  and the antecedently phase corrected spectrum to be equivalent to the past synthesis spectrum  $Y(t_a^{u-1})$ .

At the first iteration :

- $X(t_a^{u-1})$  is void because by hypothesis, nothing happened before.
- $X(t_a^u)$  is the freshly generated spectrum
- $Y(t_a^{u-1})$  is also void for the same reasons

Equation 1 gives, for  $k \in 1\dots N-1$  s.t  $X(t_a^u, \Omega_k)$  is a bin of the lobe a phase shift error of  $\tilde{\phi}$ .

Then after 2 and 3 we obtain :

$$\begin{aligned}\angle Y(t_s^u, \Omega_k) &= \angle Y(t_s^{u-1}, \Omega_k) + R_s \hat{\omega}_k(t_a^u) \\ &= \angle Y(t_s^{u-1}, \Omega_k) + \frac{R_s}{R_a} \tilde{\phi} + R_s \Omega_k\end{aligned}$$

If  $R_s = R_a$  we have a perfect reconstruction of the time synthesized overlap-add test signal. However, in that case, the Phase Vocoder is perfectly irrelevant to the synthesis, indeed, since we have no *actual* analysis phase, we only need to modify  $R_a$  to change the length of the final signal.

At the following iteration, we have to update the phase of the generated spectrum to  $\tilde{\phi} + 2 \times 2\pi\tilde{f}R_a$  instead of  $\tilde{\phi} + 2\pi\tilde{f}R_a$  (as computed in (7)), recursively, we can define the phase of the lobe the  $i$ th generated spectrum as :

$$\begin{cases} \tilde{\phi}_i = \tilde{\phi}_{i-1} + 2\pi\tilde{f}R_a \\ \tilde{\phi}_0 = \tilde{\phi} \end{cases} \quad (5)$$

### A.1.2 "Parametered" synthesis

In this case, we will not synthesize a truly stationary signal but we assume that the signal is quasi-stationary, which is to say that given a small enough analysis

<sup>3</sup>Because no actual analysis happened

<sup>4</sup>This is because we wish to generate frame spaced by  $R_a$  so we have to compensate the *expected* phase shift by hand. In fact, in the purely stationary case, the expected phase shift is the theoretical phase shift.

window, it can be considered stationary within that frame.

$$s(n) \cdot \mathbb{1}_{[t_a^{u-1}, t_a^u]} \simeq \alpha \cos(2\pi \tilde{f}n + \phi) \quad (6)$$

Note that the initial phase  $\phi$  is constant from one frame to the other *by definition*, indeed, a change of phase is equivalent to a sweep in frequency. Also this is more of a constrain of stability on frequency than it is on amplitude because of the nature of the overlap-add process.

We can assume that under the right conditions the method developed in subsection A.1.1 above still holds, if we update the parameters  $\tilde{f}$  and  $\alpha$  in the spectrum generation.

## A.2 Theoretical phases advance

For stationary signals expressed as in (4) the phase advance from one frame to the other is elementary to compute :

$$\begin{aligned} \Delta\Phi_f^{t_a} &= \Phi_f^{t_a+H_a} - \Phi_f^{t_a} \\ &= 2\pi f(t_a + H_a) + \phi - 2\pi f t_a - \phi \\ &= 2\pi f H_a = 2\pi \tilde{f} R_a \end{aligned} \quad (7)$$

Where  $H_a$  is the hop-size in seconds that is  $H_a = \frac{R_a}{f_s}$ .  
For non stationary signal expressed as :

$$s(n) = (\alpha + \mu \cdot t_a) \sin(2\pi f t_a + \frac{\psi}{2} t_a^2 + \phi) \quad (8)$$

The phase advance is computed in the same way :

$$\begin{aligned} \Delta\Phi_f^{t_a} &= \Phi_f^{t_a+H_a} - \Phi_f^{t_a} \\ &= 2\pi f(t_a + H_a) + \frac{\psi}{2}(t_a + H_a)^2 + \phi - (2\pi f t_a + \frac{\psi}{2} t_a^2 + \phi) \\ &= 2\pi f H_a + \frac{\psi}{2}(t_a^2 + 2t_a H_a + H_a^2) - \frac{\psi}{2} t_a^2 \\ &= 2\pi f H_a + \frac{\psi}{2}(2t_a H_a + H_a^2) \\ &= 2\pi(f + \frac{\psi}{2\pi} t_a) H_a + \frac{\psi}{2} H_a^2 \end{aligned} \quad (9)$$



## References

- [1] G. Van Rossum, B. Warsaw, and N. Coghlan, “Style guide for python code,” Aug. 2013.
- [2] T. Karrer, E. Lee, and J. O. Borchers, “Phavorit: A phase vocoder for real-time interactive time-stretching.” in *ICMC*, 2006.
- [3] J. Grünwald, “Theory, implementation and evaluation of the digital phase vocoder in the context of audio effects,” *Institute for Electr. Music and Ac, Graz Univ. of Dramatic Arts, Graz*, 2010.