Subtractive Synthesis Modelling of the Irish Uilleann Pipes

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T. Ó Póil, J. Timoney, T. Lysaght, V. Lazzarini, R. Voigt

NATIONAL UNIVERSITY OF IRELAND
MAYNOOTH

ISSTA
IRISH SOUND SCIENCE AND TECHNOLOGY ASSOCIATION

Introduction

- Subtractive Synthesis of Acoustic Instruments
  - Prior to sampling, FM, Phase Distortion & Physical Modelling
  - Painstaking iteration through parameter changes
- Howard Massey – ‘A Synthesist’s Guide to Acoustic Instruments’
  - Comprehensive, useful
  - Popular & orchestral instrument recreations
  - Still relevant – Has not been rewritten yet

Introduction

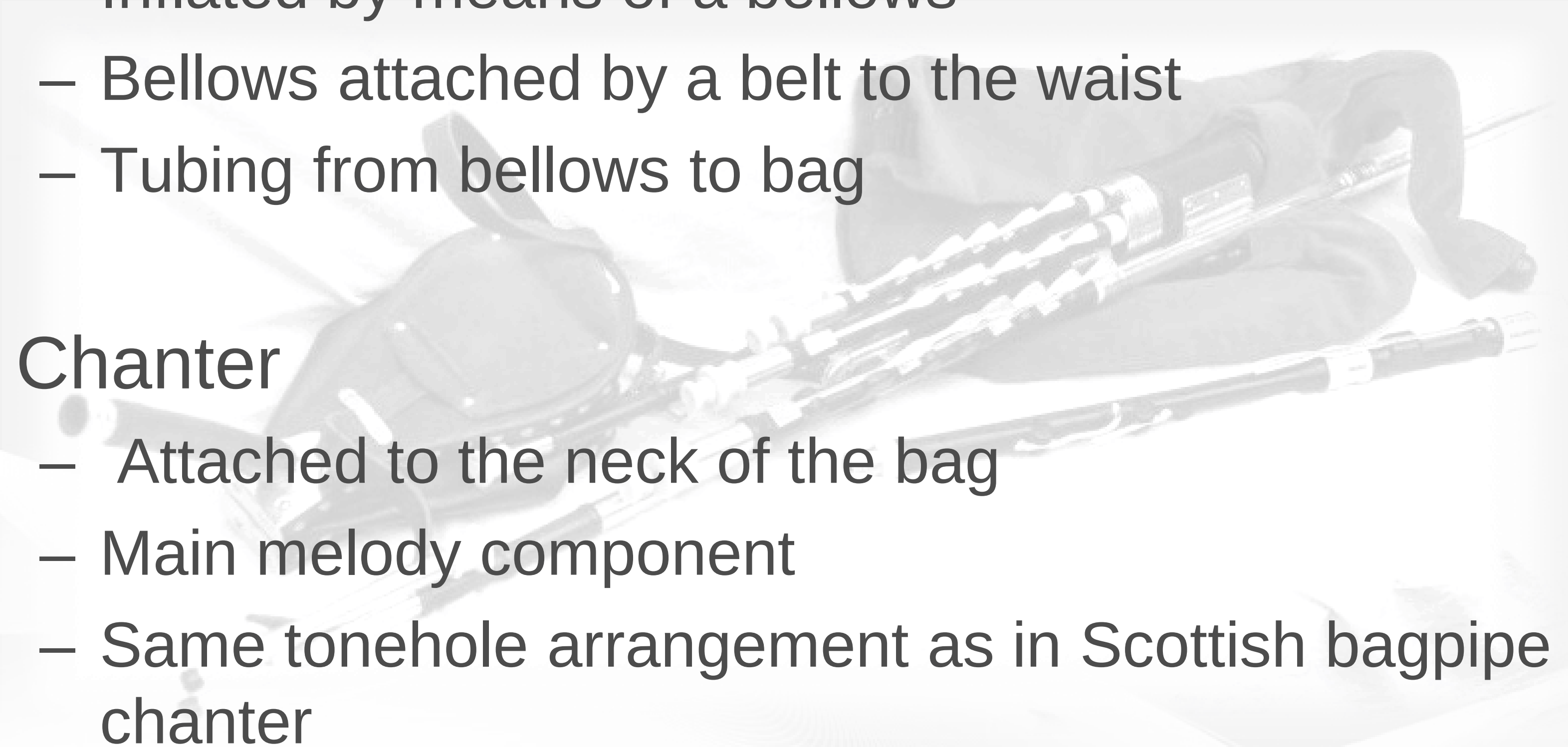
- Aims
  - Provide useful parameters to a synthesist
  - Add to previous work

- Contents
  - Description of Uilleann Pipes
  - Issues encountered in recording
  - Introduction to Subtractive Synthesis
  - Analysis Procedures/Techniques
  - Histogram plots of useful parameters

The Irish Uilleann Pipes

- Parts
  - Bag / Reservoir
  - Chanter
  - Drones
  - Regulators

The Irish Uilleann Pipes



- Bag
  - Inflated by means of a bellows
  - Bellows attached by a belt to the waist
  - Tubing from bellows to bag
- Chanter
  - Attached to the neck of the bag
  - Main melody component
  - Same tonehole arrangement as in Scottish bagpipe chanter

The Irish Uilleann Pipes

- Drones
  - Supply a continuous drone accompaniment
  - 3 Drones – Tenor, Baritone and Bass
  - Tongued Reed
  - Tuned by means of a slide
  - Can be switched off

- Regulators
  - Somewhat like keyed chanters
  - Played with the wrist
  - No note is played until a key is pressed
  - Lie side-by-side across the player’s knee
  - Chords

The Irish Uilleann Pipes

- Played sitting down
  - Bellows Operated by elbow of one arm
  - Bag under elbow of the other
  - Pressure adjusted by squeezing/releasing ‘bag arm’

- Chanter played resting on the knee
  - Can play staccato and legato notes
  - Can be modulated by raising chanter off knee
  - Vibrato by waving fingers over toneholes and raising from knee

Recording of the Uilleann Pipes

- Procedure
  - Recorded on a standard concert set of pipes
  - Chanter tuned to D Major
  - Recorded using Logic Pro and a Shure SM58 positioned approx. 15cm in front of chanter

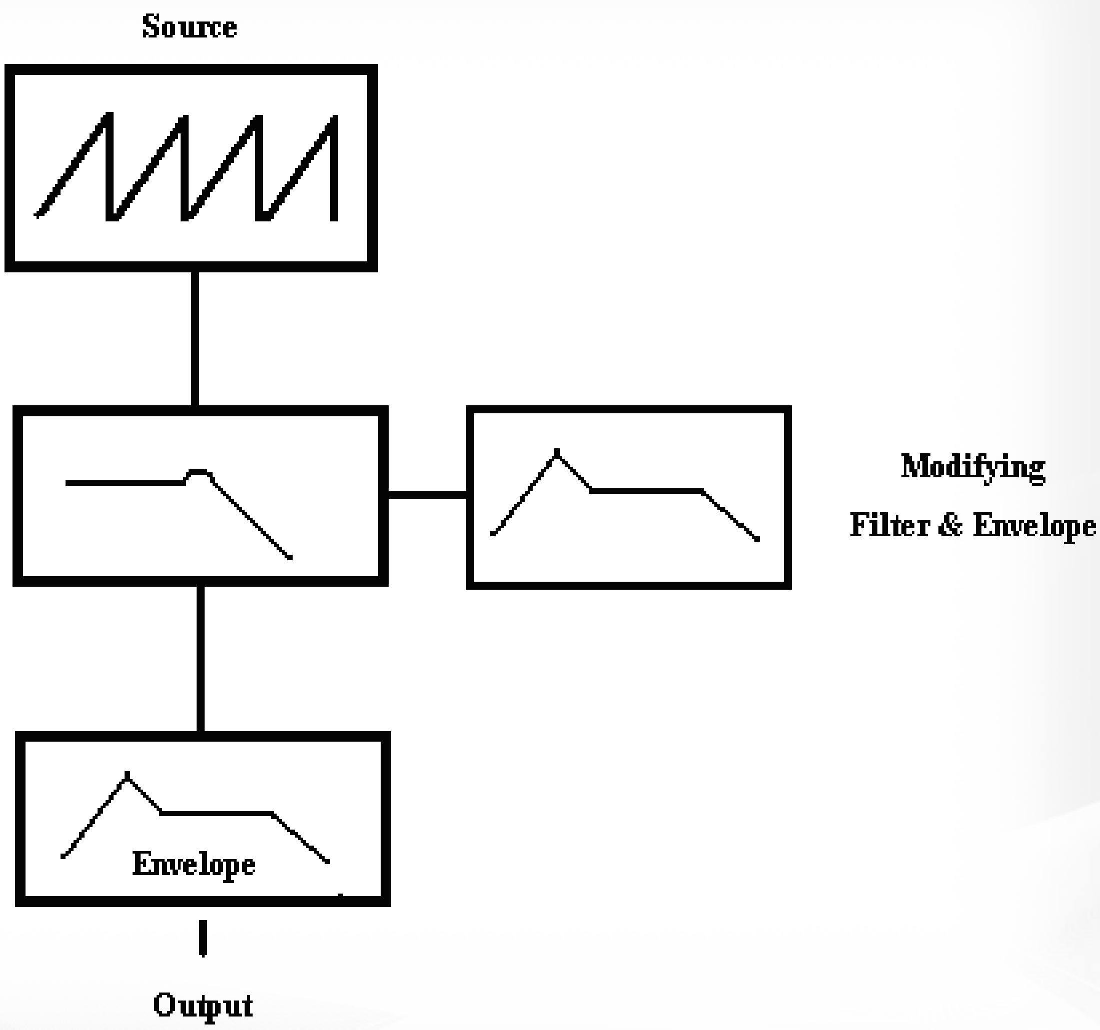
- Issues that arose
  - Playing notes in isolation is unusual in performance
    - Achieved by ‘cutting’ (playing grace note before desired note)

  - Leather valve flaps on bellows prevent air-return, but cause some noise when recording in close proximity
    - Noise gate used in recording -> Impacts analysis

Recording of the Uilleann Pipes

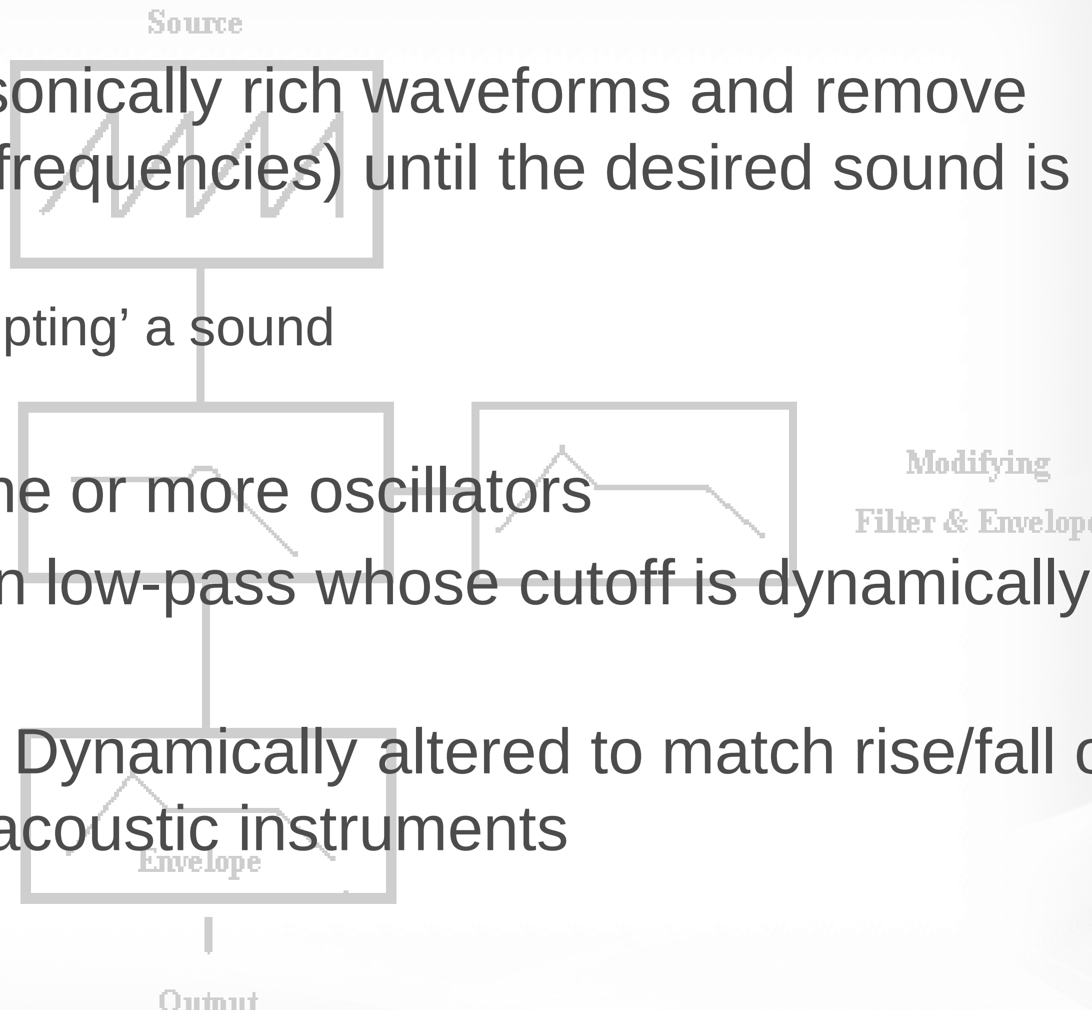
- Issues that arose
  - Microphone must be repositioned for each note to match the tonehole locations
  - Recording session produced only 1.5 octaves of good-quality notes
    - Further recording limited by logistics
    - Additional notes from sample CDs used to supplement the data

Subtractive Synthesis



Subtractive Synthesis

- Overview
  - Start with sonically rich waveforms and remove elements (frequencies) until the desired sound is achieved.
    - As if 'sculpting' a sound
  - Source: One or more oscillators
  - Filter: Often low-pass whose cutoff is dynamically varied
  - Amplitude: Dynamically altered to match rise/fall of volume in acoustic instruments



Subtractive Synthesis - Oscillators

- Three main waveforms: Sawtooth, Square, Triangle
  - Easily reproduced using electronic components in early analogue synths
  - Sawtooth is richest in terms of frequency content, while Triangle has a purer sound; closer to that of a Sine wave
- Noise oscillators are also often available
  - Generates ‘white noise’ which can be used to add random/breathy quality to sound

Subtractive Synthesis - Filters

- Remove undesired frequencies and allow boosting of certain frequencies if required

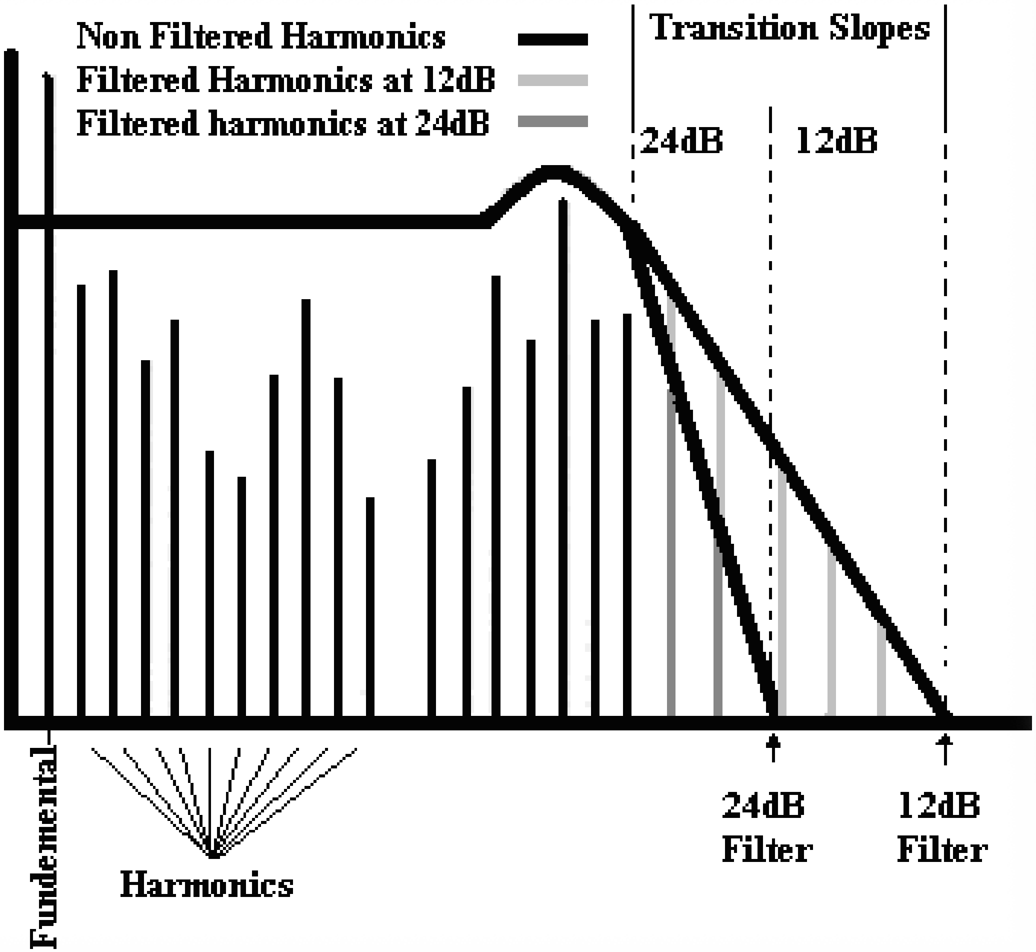
- Two typical parameters:
  - Cutoff frequency
    - The point at which the output is 3dB below unfiltered components
  - Resonance
    - A peak in frequency response around the cutoff

Subtractive Synthesis - Filters

- Lowpass is most common
  - Attenuates high frequency components above cutoff and preserves components below the cutoff
  - Fundamental component is retained
  - Dynamic timbre of acoustic instruments is closer to a moving lowpass filter than to a highpass filter
    - Highpass tends to sound more 'synthetic'

- Slope illustrates the level to which components are attenuated
  - Two common types: 12dB/Octave, 24dB/Octave
  - Bump around cutoff -> Resonance peak

Subtractive Synthesis - Filters



Subtractive Synthesis - Envelopes

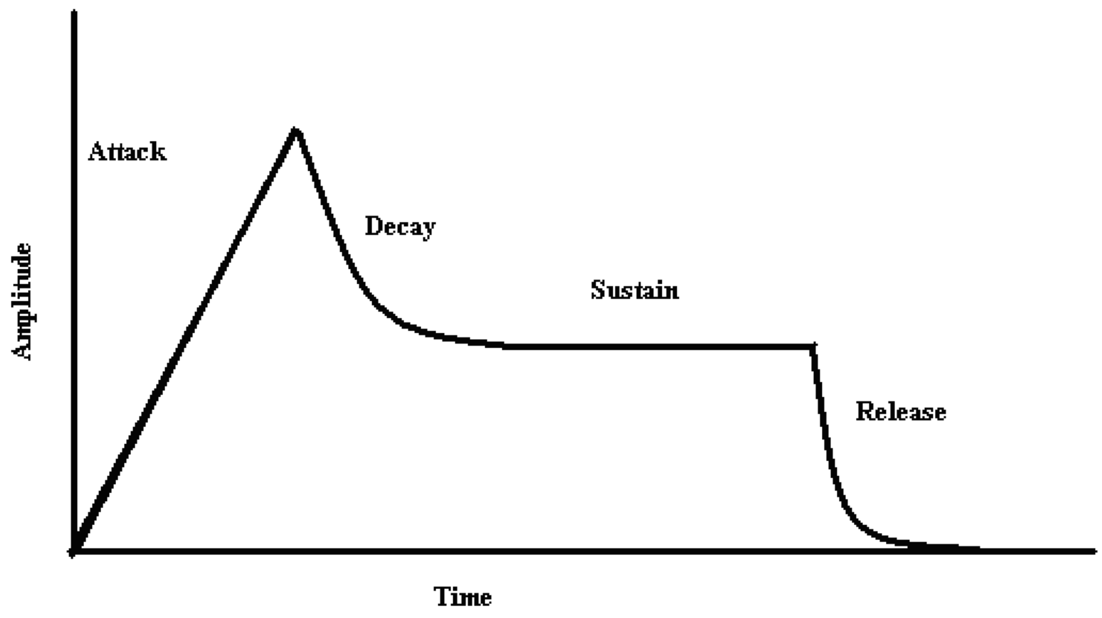
- Two main ways of adding dynamic interest:
  - Change waveform volume over time
  - Move filter cutoff over time
- Volume: Amplifier Envelope
  - Begins and ends at zero
  - Envelope Max. = Max. synth output level
- Filter: Cutoff Envelope
  - Begins at user cutoff value, increases to specified max., returns to user cutoff

Subtractive Synthesis - Envelopes

- ADSR – Most common type of Envelope
  - Attack:
    - Time taken for envelope to move from initial zero level to the maximum level.
  - Decay
    - How long it takes for the envelope level to drop from maximum to Sustain level.
  - Sustain
    - The relatively stable portion of the envelope before Release
  - Release
    - How quickly the level drops to zero from the Sustain level

Subtractive Synthesis - Envelopes

- ADSR



Parameter Extraction

- Procedures for extracting useful parameters from analysis

Parameter Extraction – Oscillators

- Determine the best combination of oscillators to use to match the basic timbre of the Uilleann Pipes sound prior to filtering.
- Assume that the same oscillators operate for the entire duration of a note.
  - Allows us to analyse any portion of the sound sample to establish the most suitable waveforms, frequencies and amplitude values.
  - Select a frame of waveform data from the Sustain portion of the sound sample
- 'Undo' the spectral shaping of the frequency components from this frame that would be the result of the filter.
  - A high-order IIR filter that can be inverted and applied to the waveform form is used.
  - This should result in the primary excitation signal of the sound.

Parameter Extraction – Oscillators

- Analyse the excitation signal and determine the best combination of oscillator waveforms to use in recreating it synthetically.

- Use two oscillators and compare their spectrum to that of the excitation signal.

  – Find the best match amongst the available waveforms. This will determine the waveform for the first oscillator.
    - Remove that waveform's spectrum from the excitation spectrum.

  – The greatest remaining peak in the excitation spectrum is used to determine the most suitable waveform for the second oscillator.
    - Remove that waveform's spectrum from the excitation spectrum.

Parameter Extraction – Oscillators

- A reasonable match is achieved but a strong frequency component is missing in the synthesized note
  - This issue could be rectified with a third oscillator, if available.
- A tuneable notch/comb filter is used to remove all harmonic components from the remaining spectrum.
  - A noise oscillator can then be used to emulate noise of a similar character.

Parameter Extraction – Filters

- Split the whole signal into multiple frames of approx. 100msec duration with 50msec overlap
- A low-order (4-pole) LPC spectral model is applied to each frame, normalized to align with the spectrum of the frame at DC
- Location of LPC spectrum peak -> Resonance peak of actual spectrum
  - Strength of the peak is retrieved from magnitude of pole associated with that peak
- 3dB below the 0dB point is assumed to be the filter cutoff
  - Due to earlier definition of Filter Cutoff
- Cutoff values from each frame are stored for later use in the filter envelope

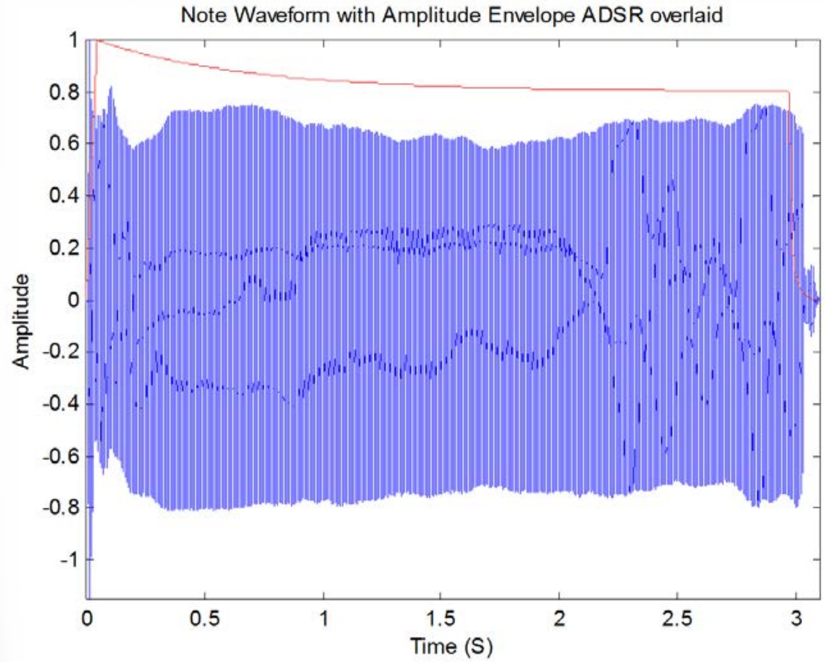
Parameter Extraction – Envelopes

- Three time parameters and constant attack slope
- Parameters for both signal and filter cutoff envelopes are calculated using an automatic algorithm and equations:
  - Attack: $c(k) = k/A, k = 0,\ldots,A-1 \quad (1)$
  - Decay: $c(k) = \gamma_D c(k-1) + (1-\gamma_D)S, k = A,\ldots,A+D-1 (2a)$
  - Sustain: $c(k) = \gamma_D^{k-A}(1-S) + S, k = A,\ldots,A+D-1 \quad (2b)$
  - Release: $c(k) = \gamma_R C(k-1), \quad k = A,\ldots,A+D+R-1 \quad (2c)$

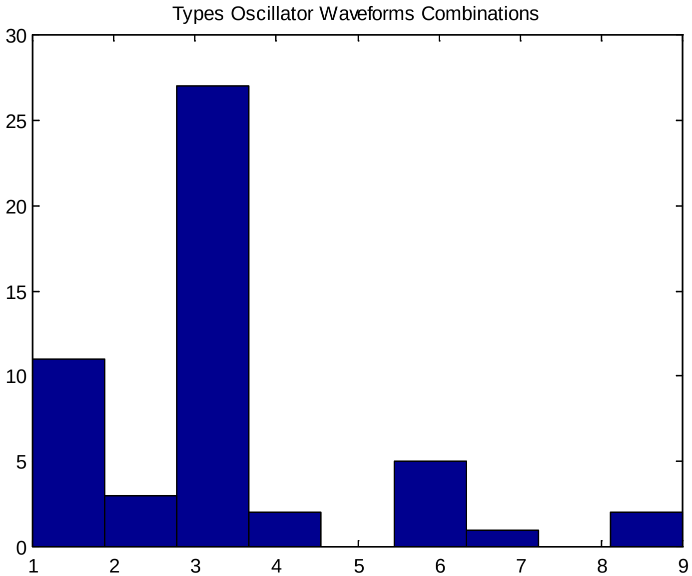
Parameter Extraction – Envelopes

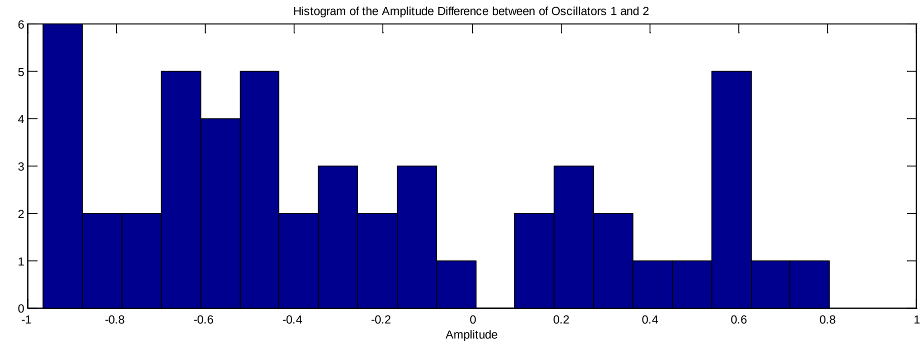
- Envelope is filtered for smoothing, then differentiated.
  - Significant peaks near the changepoints (between ADSR sections) give values for A and R
  - D is obtained using: DS = L-A-R where L is the total length of the envelope.
- The sustain level is estimated as the median value of the decay portion of the envelope.

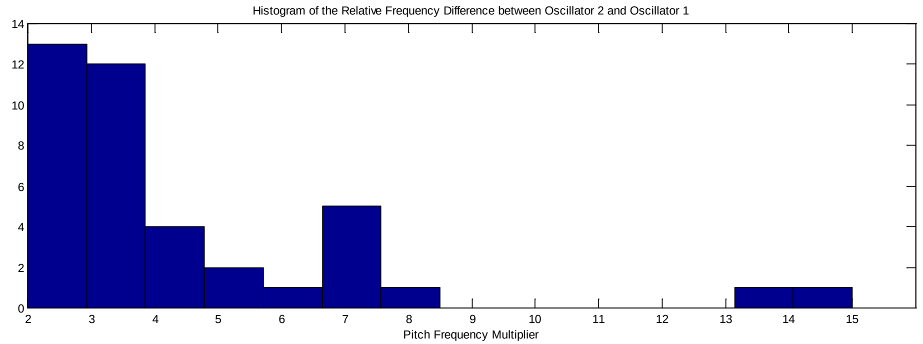
- Same algorithm used for filter envelope, but cutoff values are normalized before processing.
  - Max. value of cutoff trajectory is used to define the envelope amount.



Results – Oscillators (Main)



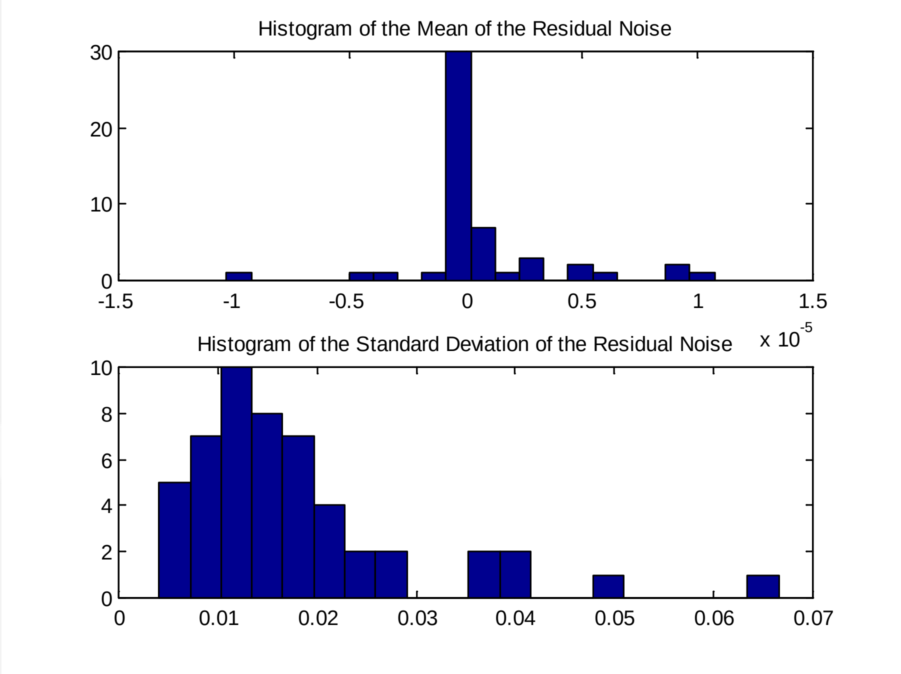




- Waveform Combinations
- (Type 1 / Type 2)
- Sawtooth/Triangle combination is most prevalent

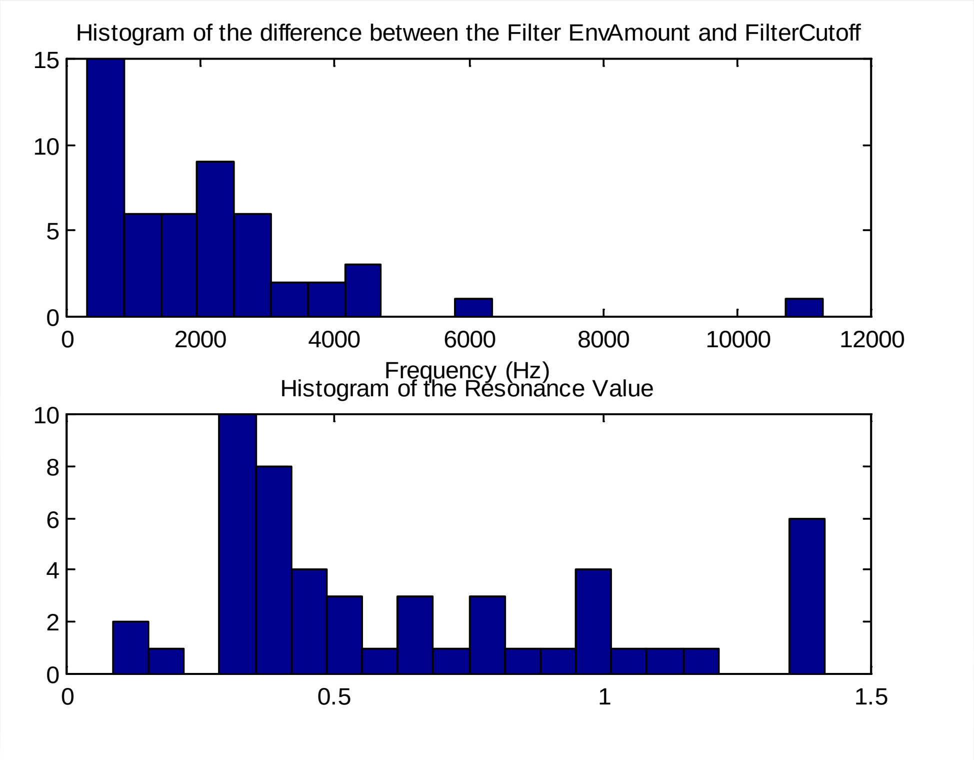
- Relative amplitude difference
  - Osc. 2 typically 1.4 - 1.95 times greater amplitude than Osc. 1
- Relative frequency difference
  - 2-3 times Osc. 1

Results – Oscillators (Noise)



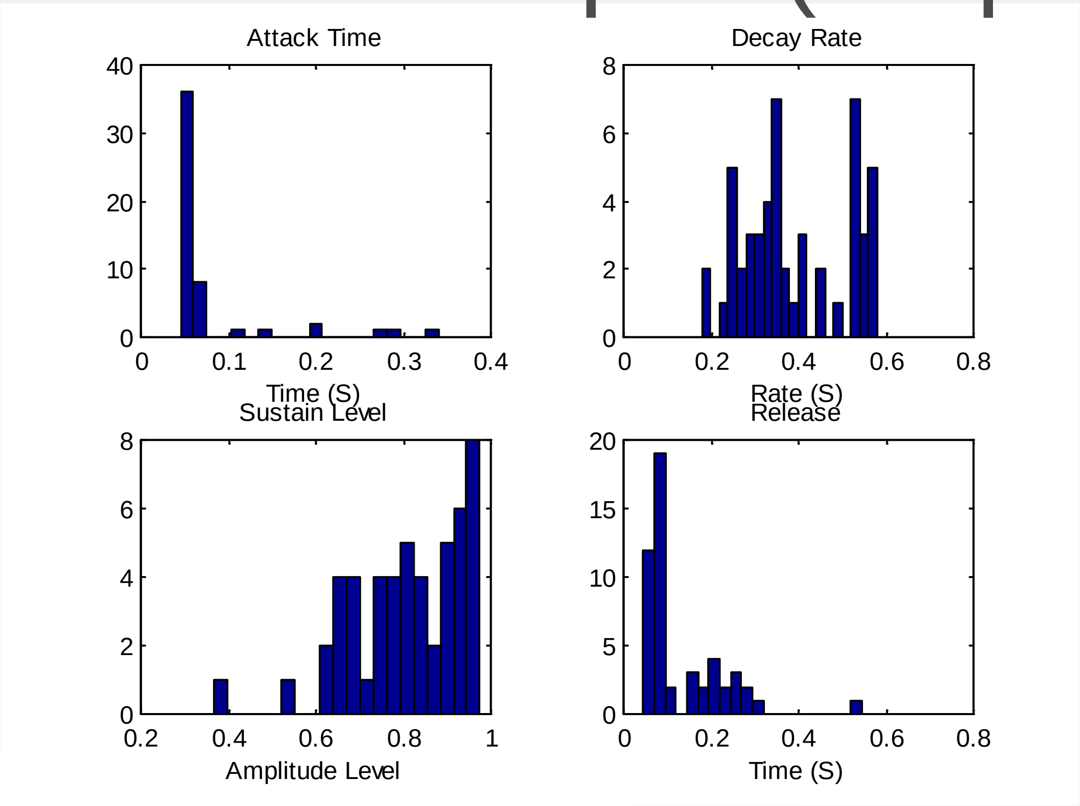
- Residual Noise Mean
  - Centered around 0
- Residual Noise Standard Deviation
  - Clustered around 0.005 – 0.028
- Minimal contribution to sound
  - Conclusion tempered by corruption of analysis by noise gate in recording

Results - Filters



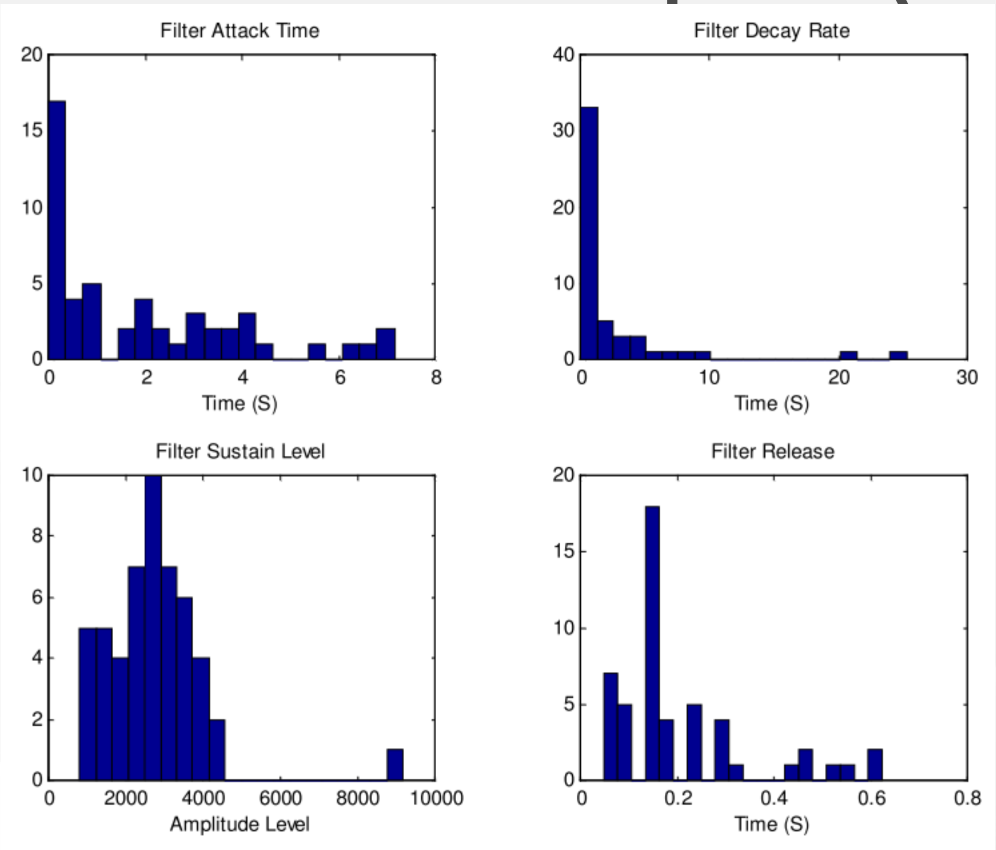
- Frequency difference between filter envelope amount and filter cutoff
  - Between 500Hz and 4500Hz
  - Most frequent difference between 500Hz and 1000Hz
- Resonance Value
  - Peak of 0.25 on most occasions

Results – Envelopes (Amplitude)



- Attack: < 0.1s, typically ~0.05s
- Release: 0.12s or less
- Sustain: 0.65 – 0.95
- Decay Rate: 0.35 – 0.55
  - $decay\ rate = 10^{-2/decay\ time}$
  - Time: 4.3 – 7.7s

Results – Envelopes (Filter)



- Attack: 0.25s
- Release: 0.15s
- Decay: <1s
- Sustain: 2000Hz - 4000Hz
  - Most frequent values around 3000Hz

Conclusion

- Analysis
  - Parameters presented in histograms should be useful for synthesists interested in recreating Uilleann Pipe sounds subtractively.
- Future work – Three issues
  - Finding improved ways of recording the Uilleann Pipes so that individual notes are more accurately determined.
  - A comprehensive assessment of the signal processing algorithms and synthesis model could be done to improve their performance.
  - A re-application of the aforementioned techniques could be applied to other traditional Irish instruments that have not yet been the subject of such analysis.