AES NEW YORK
AUDIO ENGINEERING CONVENTION

Reverse Engineering Memoryless Distortion Effects with Differentiable Waveshapers

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Overview

Distortion modelling:

- Black-, Grey- and White-box modelling
- Wiener-Hammerstein models

Differentiable Digital Signal Processing

Differentiable Waveshapers

- Sumtanh family
- Powtanh family

Objective Evaluation & Listening Test

Distortion Effect Modelling

White-box Models:

- Based on complete knowledge of the system
- Ordinary/partial differential equations to describe behaviour
- Numerical methods to solve them in the continuous or discrete domain

Black-box Models:

- No prior knowledge about the system
- Only input-output measurements
- Includes end-to-end neural network models

Grey-box Models:

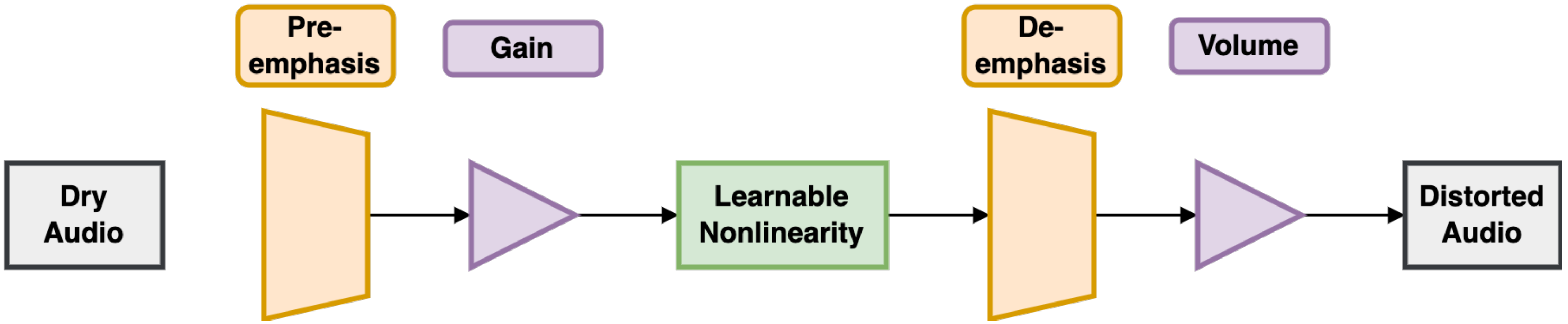
- Partial theoretical structure (Block-oriented model) + Data
- Reduce prior knowledge necessary to model device
- Maintain a degree of interpretability

Wiener-Hammerstein Grey-box Model

Differentiable Digital Signal Processing

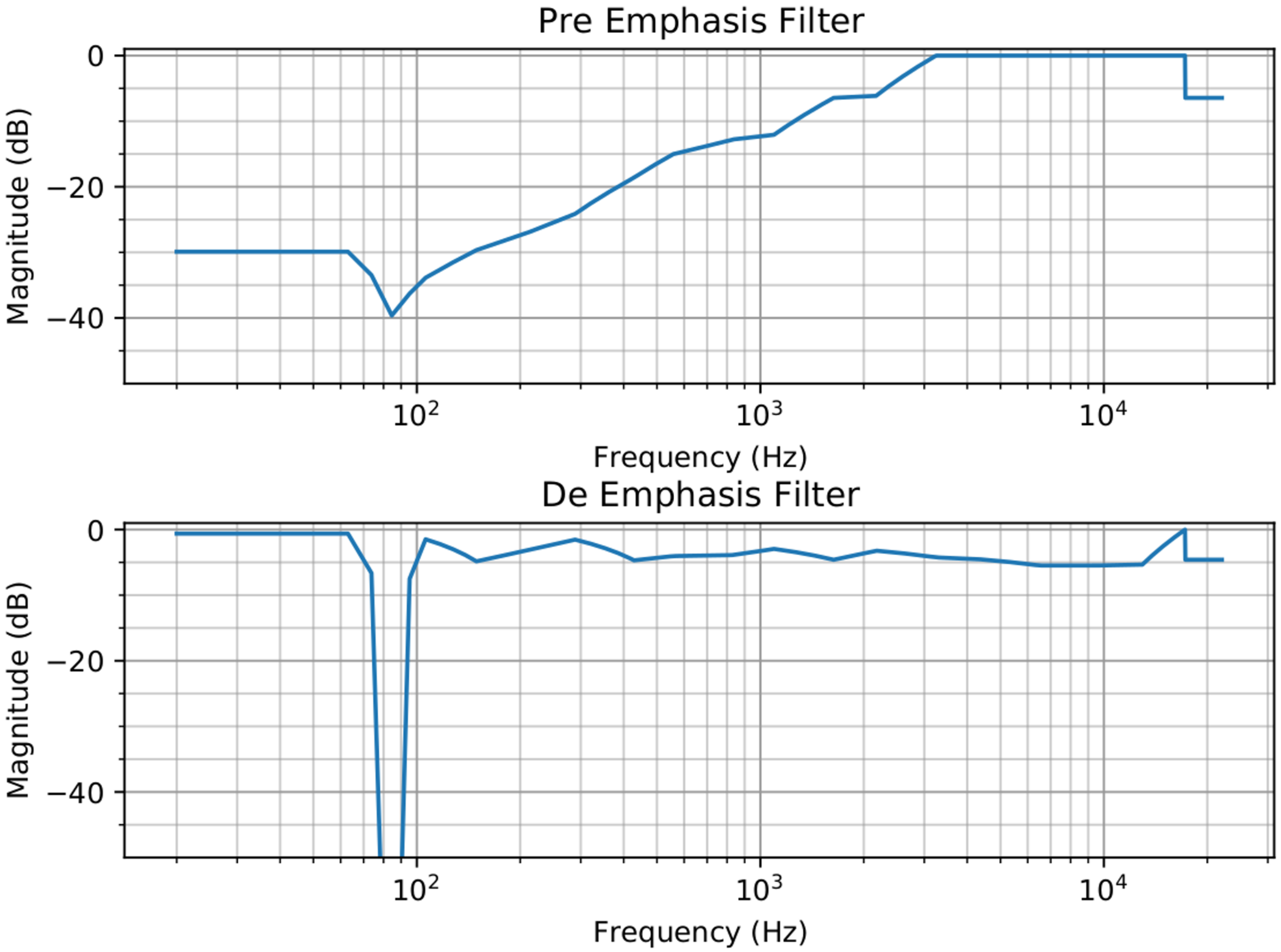
- Common DSP modules implemented in a differentiable framework (e.g., Tensorflow or Pytorch)
- Auto differentiation allows for these modules to be implemented in or controlled by neural networks due to their ability to backpropagate gradients

Proposed Wiener-Hammerstein Model



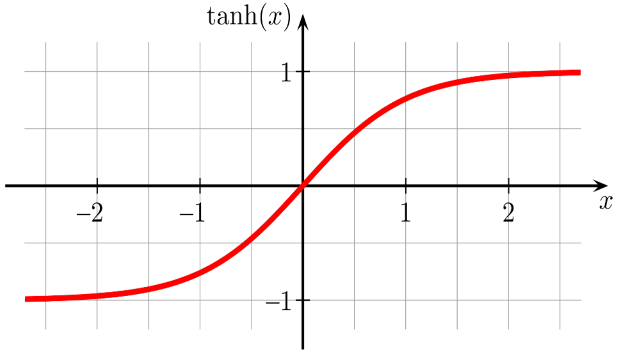
Pre-emphasis and De-emphasis topology

- “Graphic” FIR EQ
- Attenuations specified at semi-octave bands + low and high shelves
- Transfer curve interpolated between these values
- Windowing + spectral sampling method for inversion to time domain

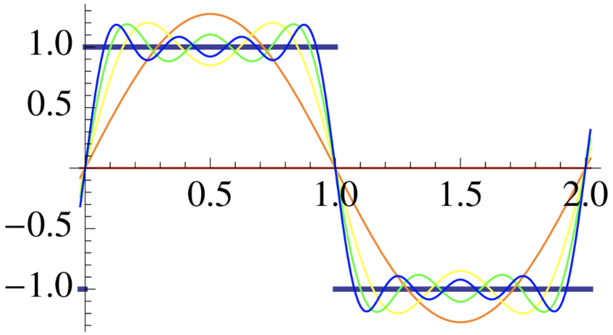


Differentiable Waveshapers

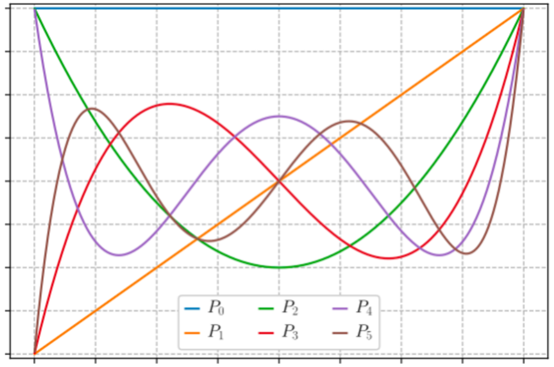
Hyperbolic tangent (tanh) nonlinearity



Fourier Series



Legendre Polynomial Series



Sumtanh nonlinearity

$$f(x) = a_1 \tanh(x) + a_2 \tanh(2x) + \dots$$
$$a_{n-1} \tanh((n-1)x) + a_n \tanh(nx)$$

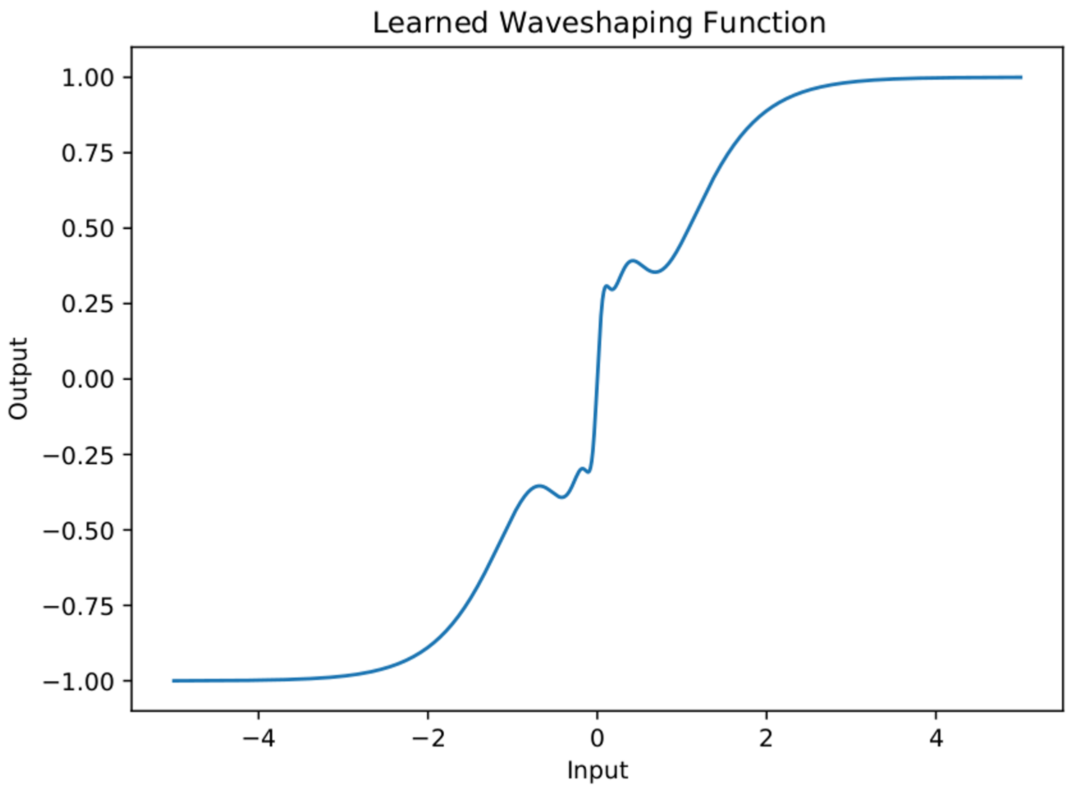
Powtanh nonlinearity

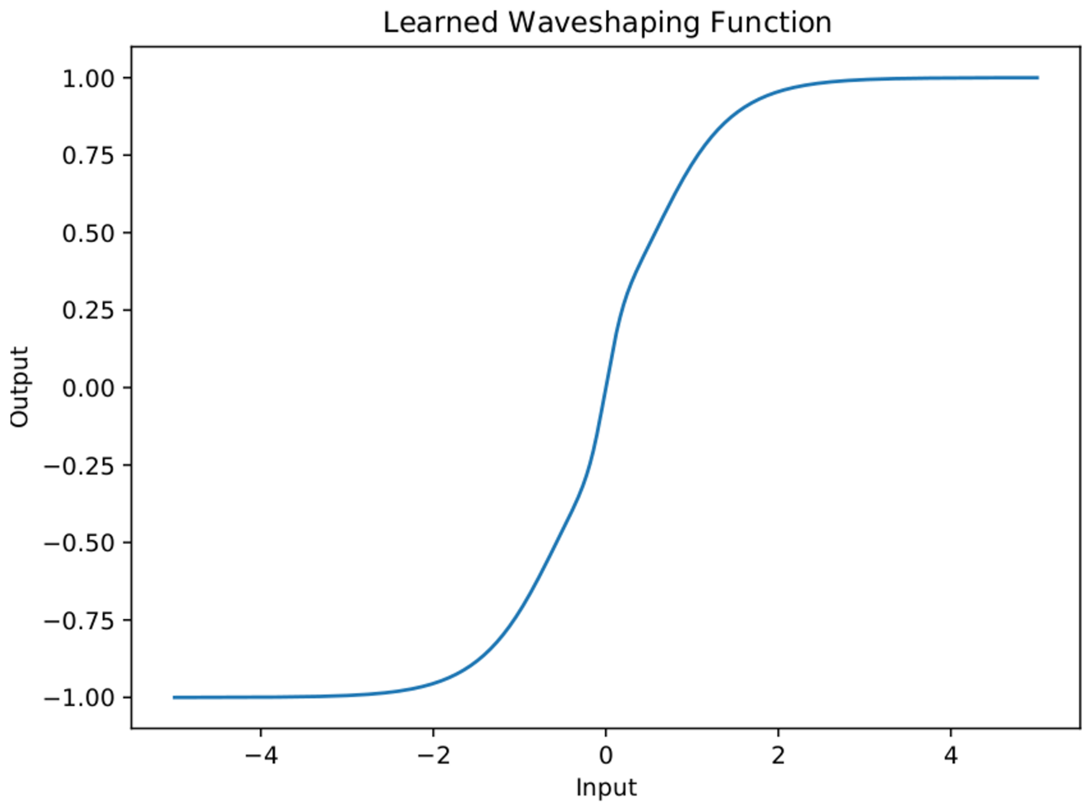
$$f(x) = a_1 \tanh(x) + a_2 \tanh(x^2) + \dots$$
$$a_{n-1} \tanh(x^{n-1}) + a_n \tanh(x^n)$$

Sumtanh family

$$f(x) = a_1 \tanh(x) + a_2 \tanh(2x) + \ldots + a_n \tanh(nx)$$

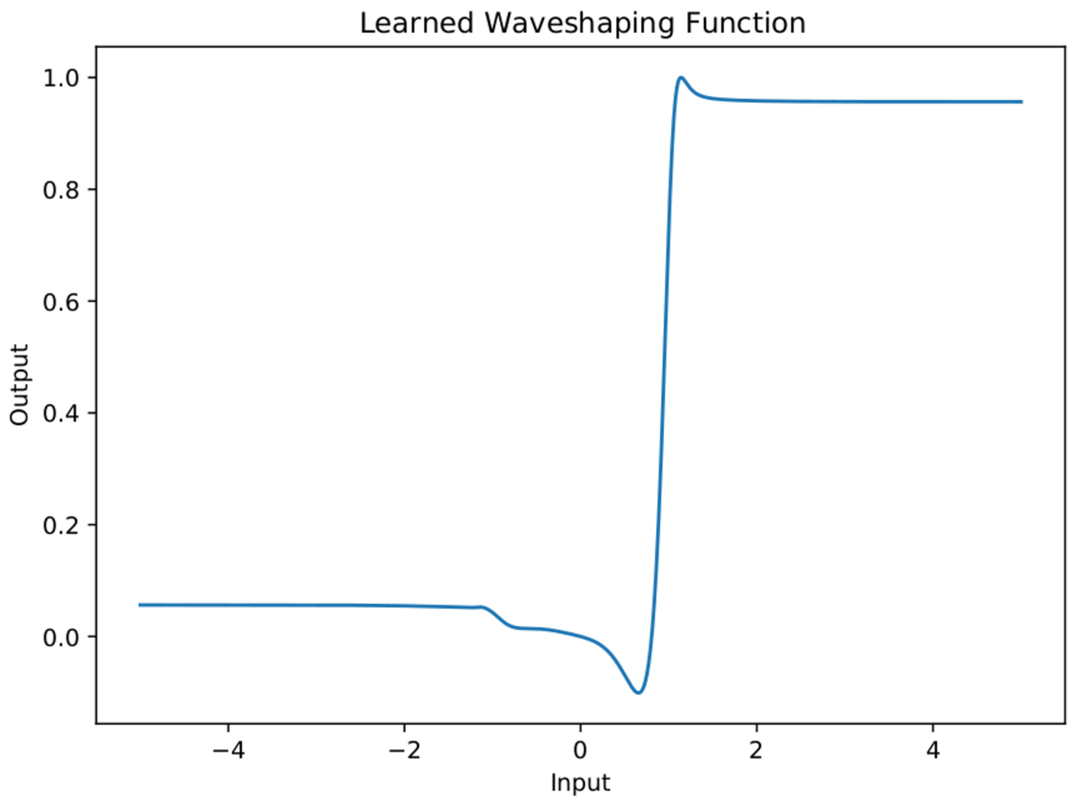
$$a_0 = -\sum_{c=1}^{n} a_c \tanh(c \times b_{DC})$$

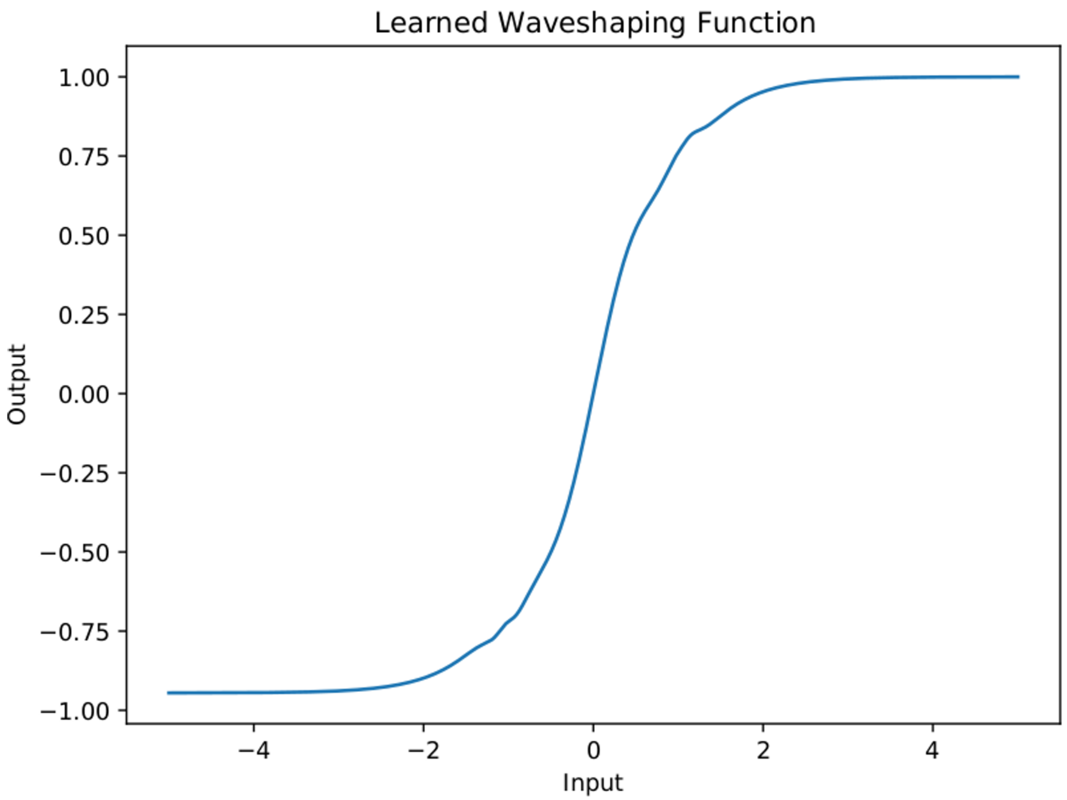




Powtanh family

$$f(x) = a_1 \tanh(x) + a_2 \tanh(x^2) + \ldots + a_n \tanh(x^n)$$





Evaluation - Reverse Engineering Distortion Effects

- Stochastic gradient descent updates the W-H model parameters to fit a dry/wet audio pair

- Parameters include:
    - Attenuations for pre-emphasis and de-emphasis filters
    - Gain
    - All coefficients in the waveshaper
    - Volume

- Loss is calculated by passing a dry audio sample through the estimated W-H model and measuring the multiscale spectrogram loss between the estimated and target audio

Results

Table 3: Mean multiscale spectrogram loss of the waveshapers evaluated across pedals

Waveshaper	*RAT*	*MGS*	*VTB*	*Total*
Powtanh	1.321	**0.559**	**2.117**	**1.332**
Sumtanh	**1.321**	0.573	2.400	1.431
Fourier	1.588	0.603	2.686	1.625
Legendre	1.703	0.640	2.893	1.746
Tanh	1.353	0.597	2.478	1.476

Designer	*Plugin*	*Emulation of*	*Id*
Audified	Multidrive Pedal Pro	ProCo Rat	RAT
Mercuriall	Greed Smasher	Mesa/Boogie Grid Slammer	MGS
Analog Obsession	Zupaa	Vox Tone Bender	VTB

Results

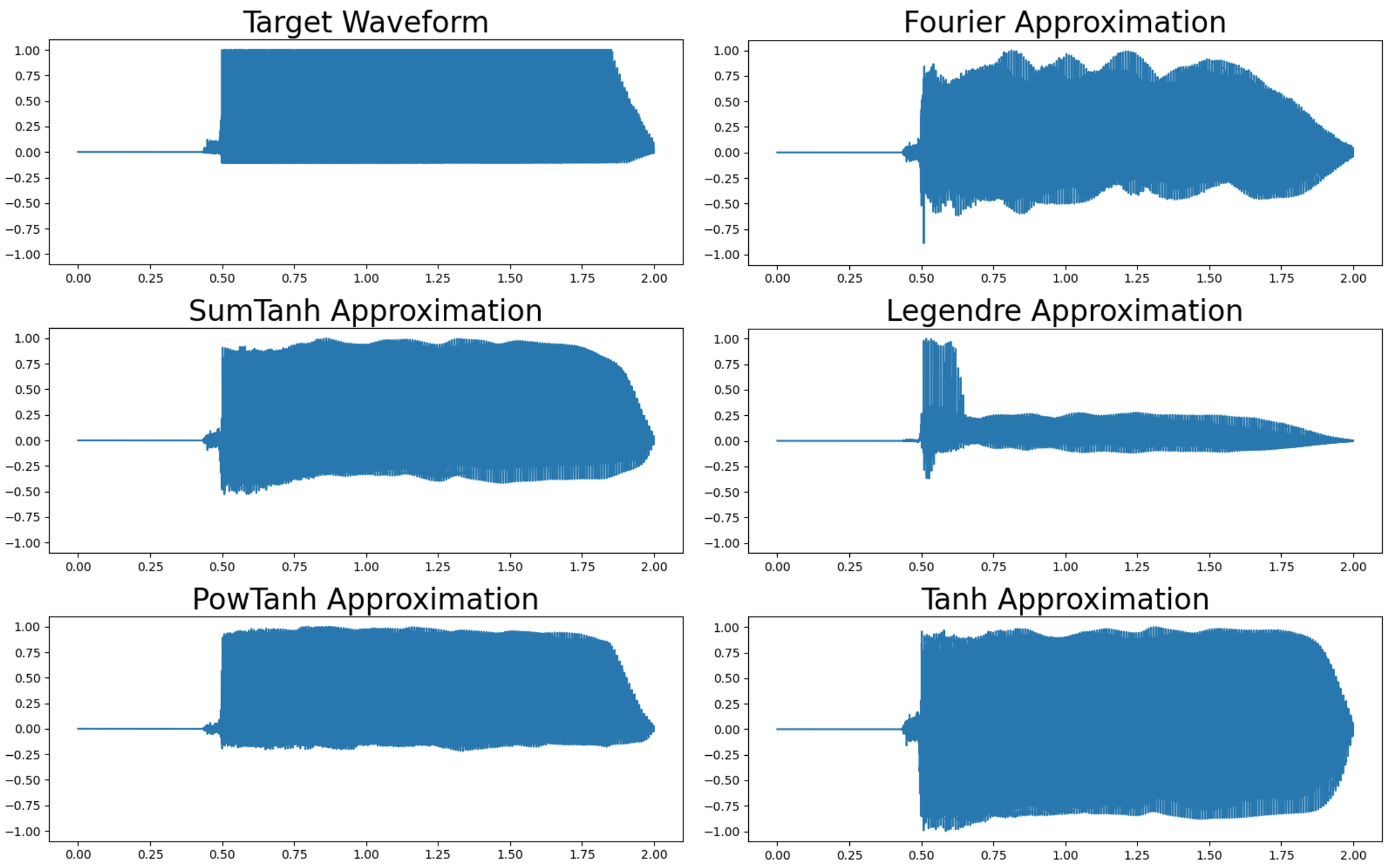
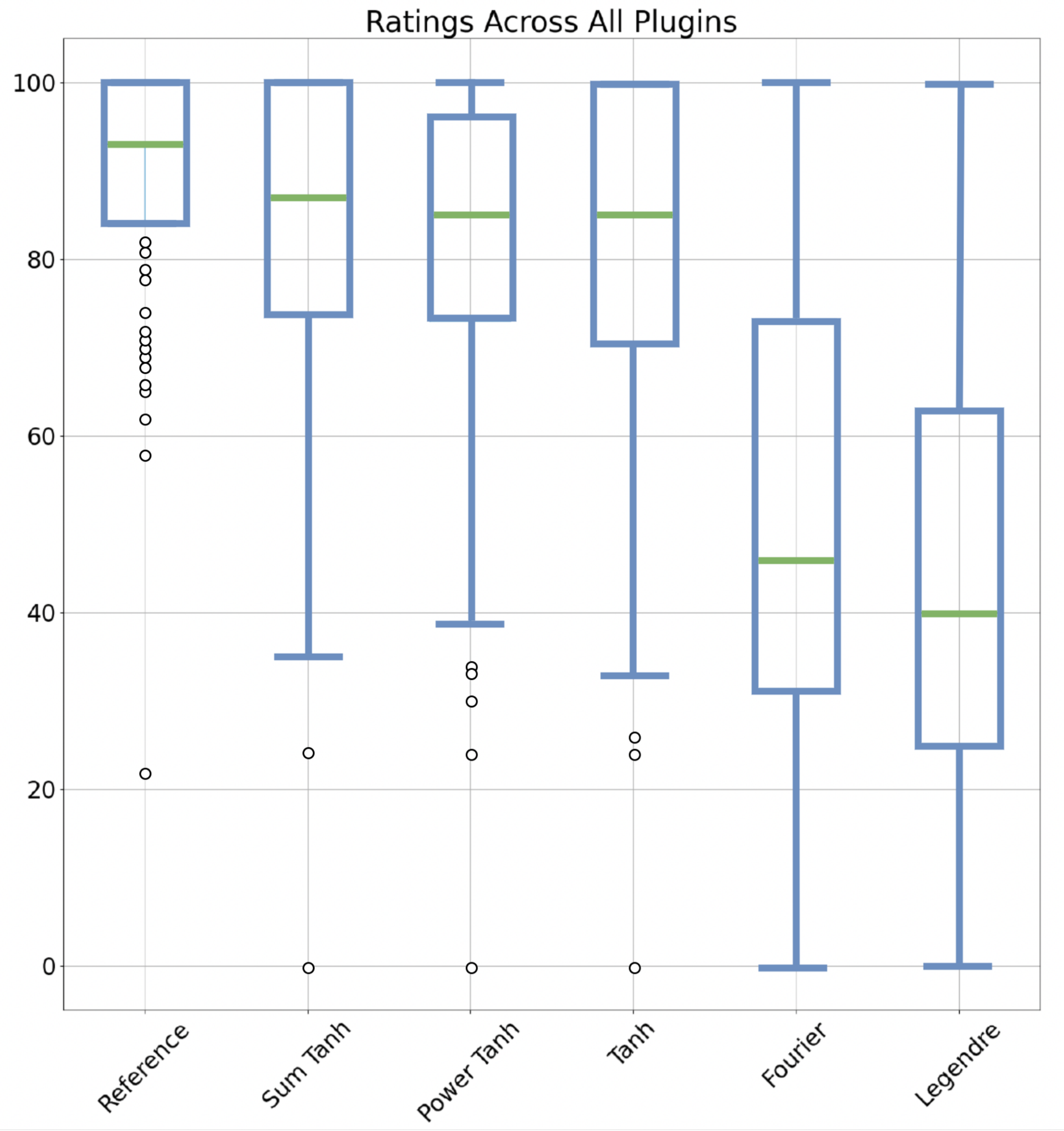


Fig. 2: Example of estimated waveforms for each waveshaping model on a VTB example

Results



Ratings Across All Plugins
100
80
60
40
20
0
Reference
Sum Tanh
Power Tanh
Tanh
Fourier
Legendre

Future Work

- Implement explicit antialiasing
- Model hysteresis for distortion effects with memory
- Implement signal-dependent conditioning for full effect modelling

Thank You

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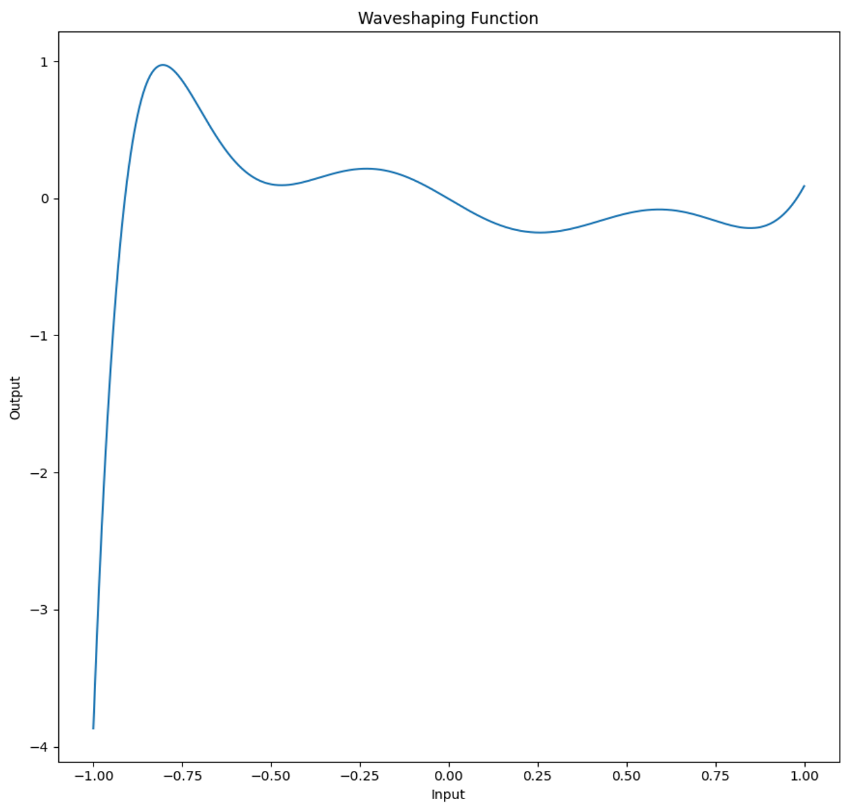
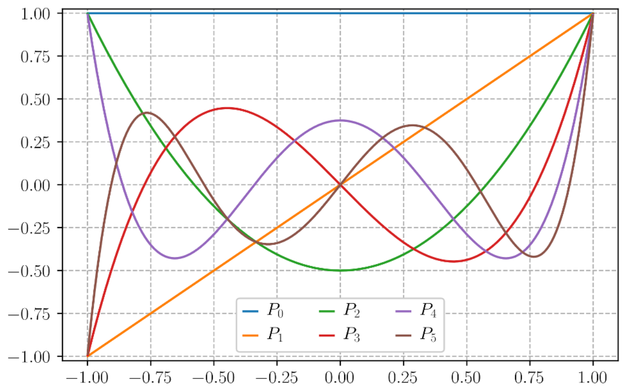
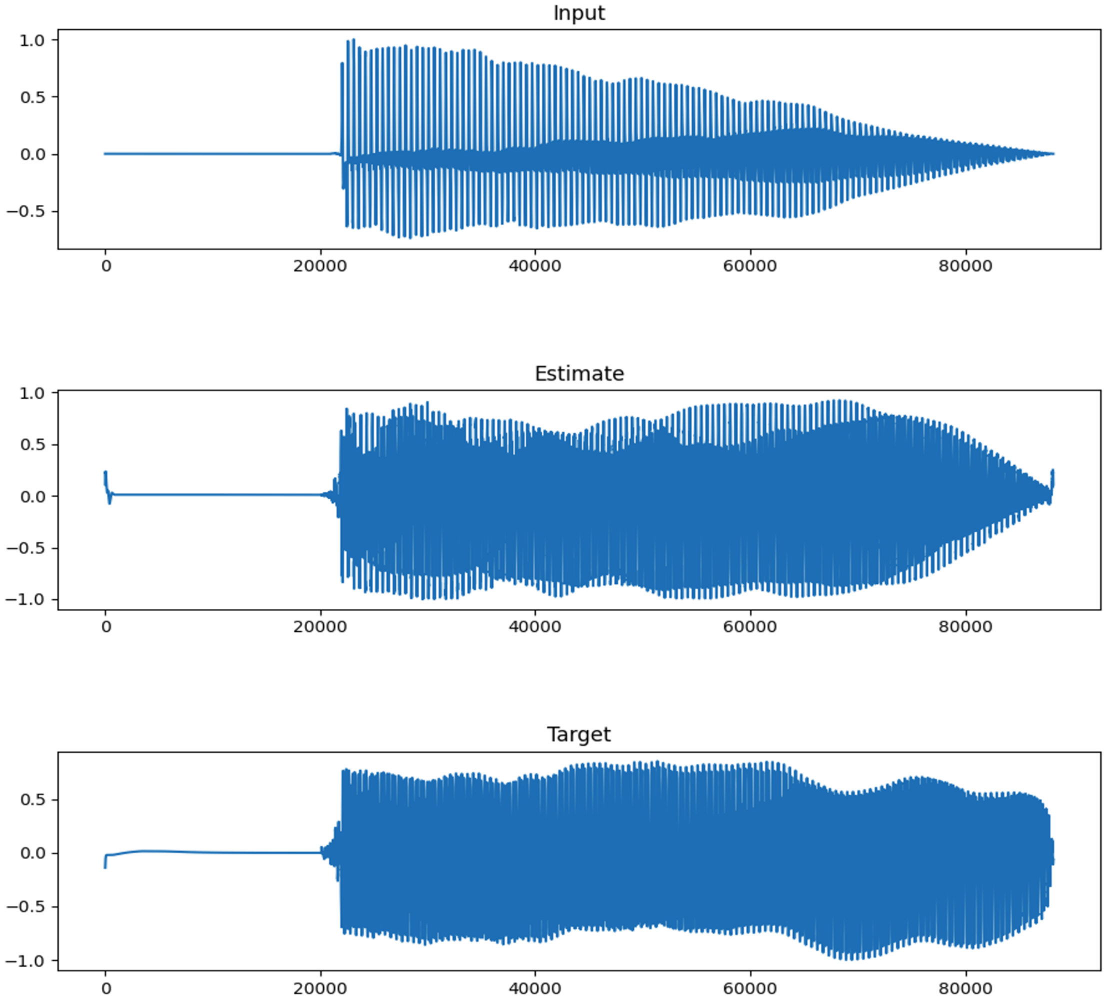
Appendix - Example Legendre Model

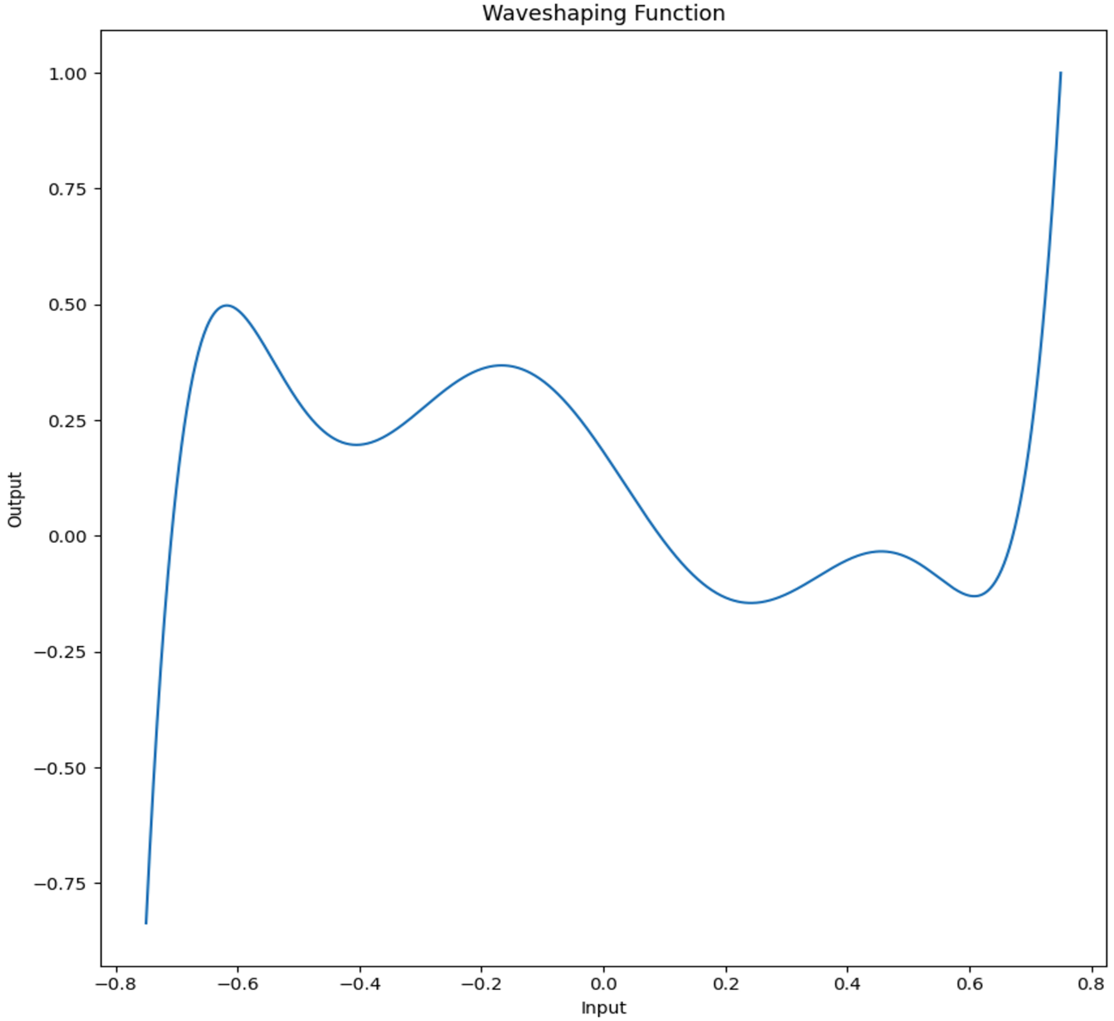
- Complete and orthogonal polynomials (ortho on [-1,1])
- System learns weighted sum of first N polynomials
- Signal normalized to [-0.9,0.9] before waveshaping to avoid overshoot





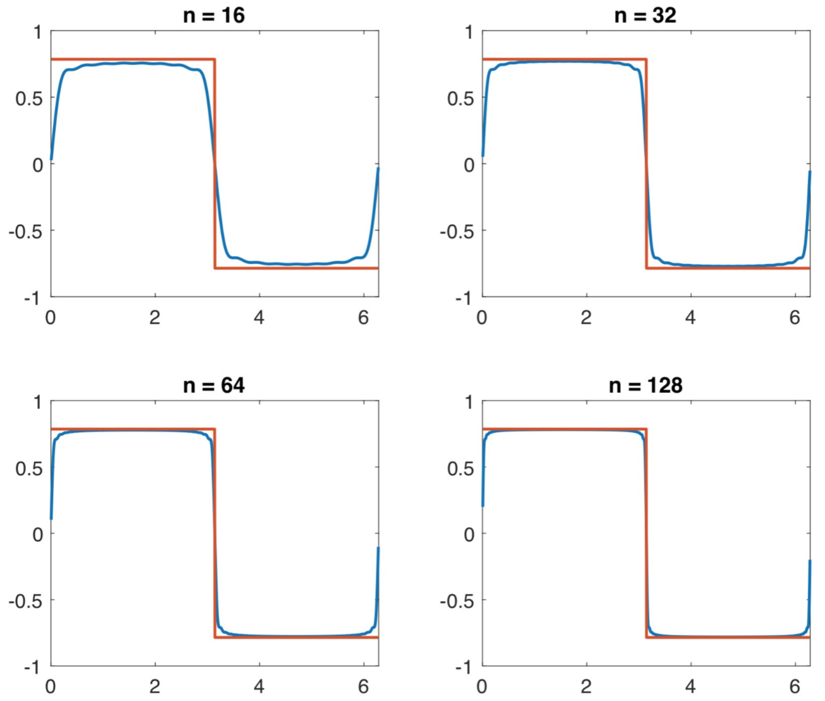
Appendix - Example Legendre Model

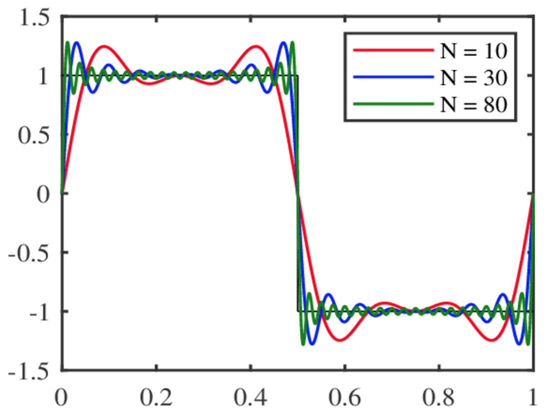




Appendix - Example Fourier Model

- Complete and orthogonal sines and cosines (ortho on [-π,π])
- System learns weighted sum of first N sinusoids
- Signal normalized to [-0.9π,0.9π] before waveshaping to avoid overshoot/zeroing





Appendix - Example Fourier Model