Comparison of Different Nonlinear Identification Methods: a Guitar Tube Amplifier Practical Case

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Communication Outline

1. Application
2. Nonlinear methods
   - Hammerstein Kernels Identification by Sine Sweep (HKISS)
   - Recurrent Neural-Network (RNN)
   - Polynomial Nonlinear State Space (PNLSS)
   - Volterra kernels estimation
3. Methods of comparison
4. Summary

Section 1

Application

Practical case: a tube amplifier emulation

Figure: Goal: replace hardware effects by software emulations

Amplifier with Vacuum tube triodes:

The sound of *old* tube amplifiers is perceived by most musicians as warmer and more dynamic but their nonlinear behaviors make them hard to model.

Emulation advantages:

- Wide variety of sounds and timbres.
- Weight and overcrowding.
- Cheaper.
- More robust.

Section 2

Nonlinear methods

Proposed methods for nonlinear modeling

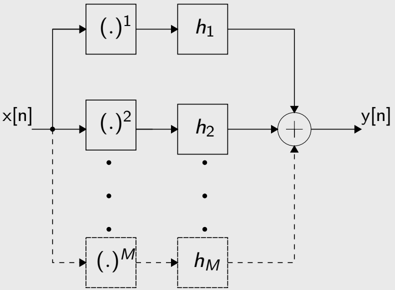
Comparison of the following methods:

- Hammerstein Kernels Identification by Sine Sweep (HKISS).
- Recurrent Neural-Networks (RNN).
- Polynomial NonLinear State Space model (PNLSS).
- Volterra kernels estimation.

Feel free to contact me at **T.Schmitz@uliege.be** to propose or add an other method.

Parallel Hammerstein Models (PHM)

Model:



$$y[n] = \sum_{m=1}^{M} h_m[n] \circledast x^m[n] \qquad (1)$$

Main issue: the *PHM* **does not work** to model the tested tube amplifiers if the amplitude of the input signal is different from the one chosen during the measurement phase.

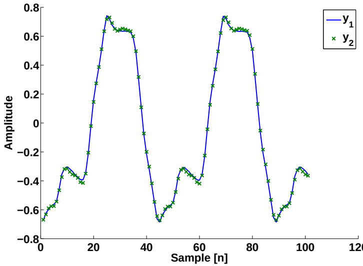


Figure: $y1$=output of the amplifier, y_2= output of the emulator. When the input signal is $sin(2\pi.1000.t)$

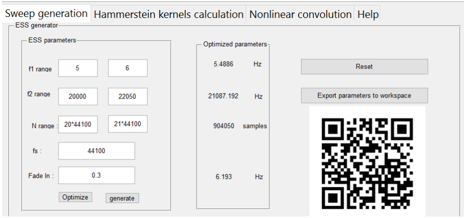


Figure: HKISS Toolbox is proposed in [2]

HKISS method:

Identification of the Hammerstein kernels methodology:

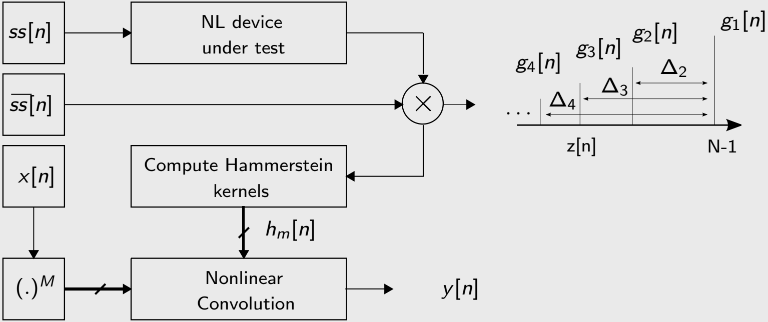


Figure: $ss[n]$: exponential sine sweep, $\overline{ss}[n]$: inverse sine sweep, $x[n]$ input signal, $h_m[n]$: m^{th} Hammerstein kernel, $z[n]$: deconvolution of the sine sweep passing through the nonlinear device under test, $g_m[n]$: harmonic kernels, $y[n]$: emulated signal

References:

The details of the method can be found in [1] and the Toolbox [2] can be downloaded **here**. A comparison of identification methods (Exponential Sine Sweep and Least Square method) can be found in [3]

Long Short Term Memory (LSTM) Neural-Network: a cell

Model:

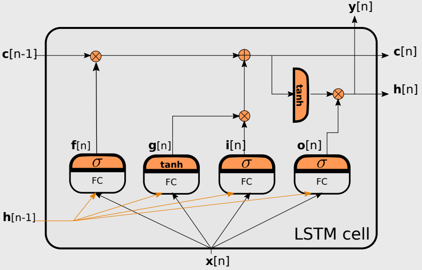


Figure: presents a LSTM Cell, where c is the long term state, h is the short term state, y is the output of the cell, x is the input of the cell, f, g, i, o are the forget,candidate,input,output gate respectively, *FC* is a *fully connected layer*, σ is the sigmoid function and tanh is the hyperbolic tangent function

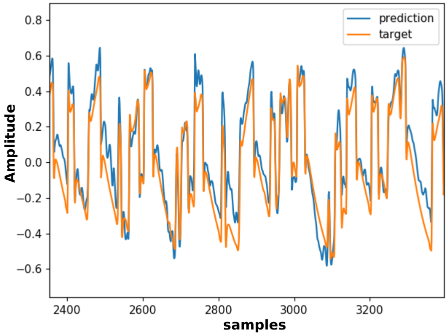


Figure: The result of the emulation : in orange the *target* (output of the amplifier), in blue the prediction (output of the Neural-Network).

Long Short Term Memory Neural-Network: a layer

Identification of the weight and bias of the Network methodology:

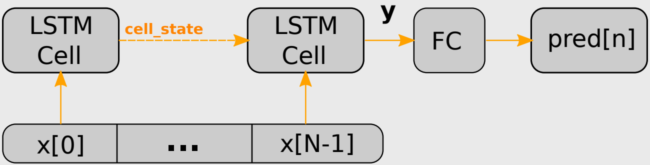


Figure: Based on the last N values of the input signal x, a prediction *pred* is computed. A cost function $C = E\{|target - pred|^2\}$ is minimized using the back propagation through time algorithm [4]

Conclusions:

The method has been developed in [5] and has been improved to reach the real-time (40ms latency) constraint in [6] with less than 2% of Root Mean Square Error (RMSE) between the target and the predicted signals.

Polynomial Nonlinear State Space:

Model:

$$
\begin{aligned}
x(t+1) &= A\,x(t) + B\,u(t) + E\,\zeta(x(t),u(t)) \\
y(t) &= \underbrace{C\,x(t) + D\,u(t)}_{\text{linear state-space model}} + \underbrace{F\,\eta(x(t),u(t))}_{\text{polynomials in } x \text{ and } u}
\end{aligned}
$$

Where:

- $u \in \mathbf{R}^{n_u}$ the inputs of the system.
- $y \in \mathbf{R}^{n_y}$ the outputs of the system.
- $x \in \mathbf{R}^{n_a}$ the state memory of the system.
- ζ et η contain all the distinct monomial combinations of x and u up to a chosen degree p.

Identification of A,B,C,D,E,F parameters methodology:

The Best Linear Approximation is computed, then a parametric linear model is estimate from it. Finally the full nonlinear model is computed by using a nonlinear search routine. Method and Toolbox can be found in [7].

Volterra kernels estimation

Volterra Series

$$y(t) = \sum_{m=1}^{\infty} \int_{-\infty}^{+\infty} \cdots \int_{-\infty}^{+\infty} v_m(\tau_1, \ldots, \tau_m) \times \prod_{i=1}^{m} x(t - \tau_i) \; d\tau_1 \ldots \tau_m \quad (2)$$

In practice, Volterra kernels v_m have to be truncated in time (t) and order (m)

Identification of the v_m kernels

- Maximum Likelihood estimation of the parameters.
- Regularized nonparametric estimation [8].
- Pre-estimation of the diagonal elements with HKISS method [1]?
- Estimation of the first three kernels based on Wiener filter estimation by perfect sequences and multiple-variance sequences. [9, 10]

Section 3

Methods of comparison

Comparison methodology:

Goals:

The aim of this study is to be able to emulate a tube amplifier with a high level of distortion.

To be compared:

- Accuracy.
- Learning time.
- Computational cost during the emulation phase.
- Robustness.

Performances Indexes (PI):

The output signal of the amplifier y_{test} has to be compared with an estimate signal $\hat{y}_{test}$ when the input x_{test} (a guitar scale at different amplitudes) is provided.

$$PI_1 = \frac{\sum_{t=0}^{T} \left[\hat{y}_{test}[t] - y_{test}[t]\right]^2}{\sum_{t=0}^{T} \left[y_{test}[t]\right]^2} \quad (3)$$

- Listening test ?
- Others ?

Section 4

Summary

Guitar tube amplifier in real-time

Results:

- **LSTM** method:
  - Tube amplifier ENGL, emulation with less than 2% of RMSE
  - Sampling rate: 44100Hz
  - Latency: 400 samples
  - Compare audio sound **here**
- **PNLSS** method: to do
- **Volterra kernels** method: to do

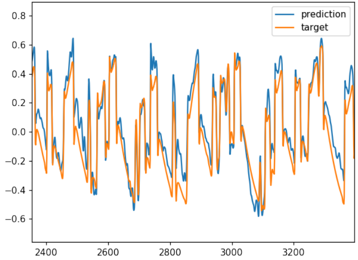


Figure: Sound from amplifier (target) Vs emulator (prediction) (LSTM)

Figure: Goal: replace hardware effects by software emulations

Useful informations for this project:

GitHub repository for this project **here**

Thank you for your attention!

Bibliography I

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