Real-time digital simulation of analog audio effects

Brno University of Technology

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Outline

- Introduction and motivation

- Linearized audio effect modeling
- Analog phaser effect example

- Nonlinear audio effect modeling
- Guitar tube preamp

- Sound examples

Introduction and motivation (1)

- Electronic circuit simulators have been available since 1973 – SPICE (Simulation Program with Integrated Circuit Emphasis)
  - **Universal tool** for all kinds of electronic circuits
  - Nodal analysis of the **whole electronic circuit**
  - **Focus on simulation accuracy** (complex electronic device models)
  - Transient analysis (time-domain large-signal solution of nonlinear differential algebraic equations) – numerical algorithms
  - Solution can be used unstable with wrong simulation setup
  - Waveform input in the latest versions
  - **Not suitable for real-time processing of audio signals due to high computational comlexity** especially on common personal computers

Introduction and motivation (2)

- Audio effects and amplifiers (guitar amplifiers)
  - Use **limited** library of electronic components
  - There is limited number of circuit topologies (especially for guitar amplifiers)
  - The circuit schematic can be splitted to several parts according to their function
    - Some parts can be omitted – e.g. power supply circuit
    - Some parts can be linearized – e.g. filters
    - Some parts can be simplified – e.g. oscilators
  - Work in audible region of frequencis (we don't care about high frequency signals)

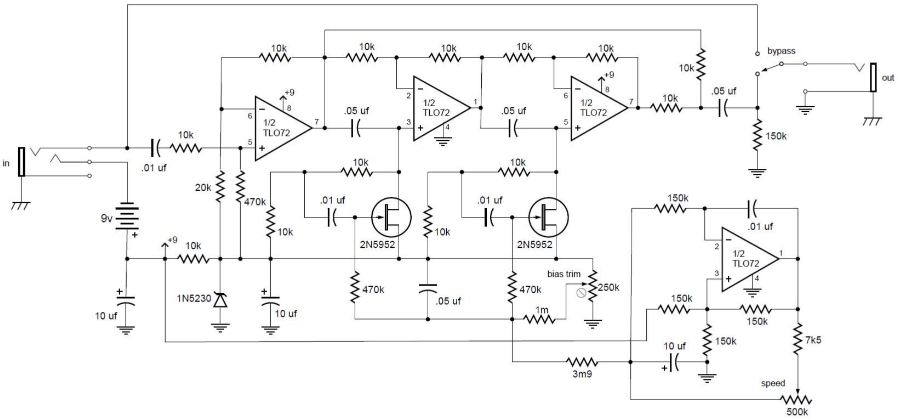
Introduction and motivation (3)

- Algorithms for real-time simulaton of analog audio effects
  - **The goal is to reduce computational complexity as much as possible while the auditory perception remains the same**
  - Can exploit properities from the previous slide
    - Simplified electronic componet models (freq. region 20 Hz – 20 kHz)
    - Division into blocks and simplification of the circuit
  - Linear versus nonlinear blocks
  - Approximations
  - Masking effect
  - Math functions instead of circuits (summation)

Linearized models of analog effects

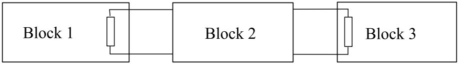
- Quite a lot of analog effects can be linearized
  - Pasive electronic circuits
  - Circuits with operational amplifiers in certain range of output voltages (bellow power supply)
- Linearized models can be desribed by transfer function $H(s)$
- Discretization (e.g. bilinear transform)
- Implementation using digital linear filters

Example – Analog phaser effect

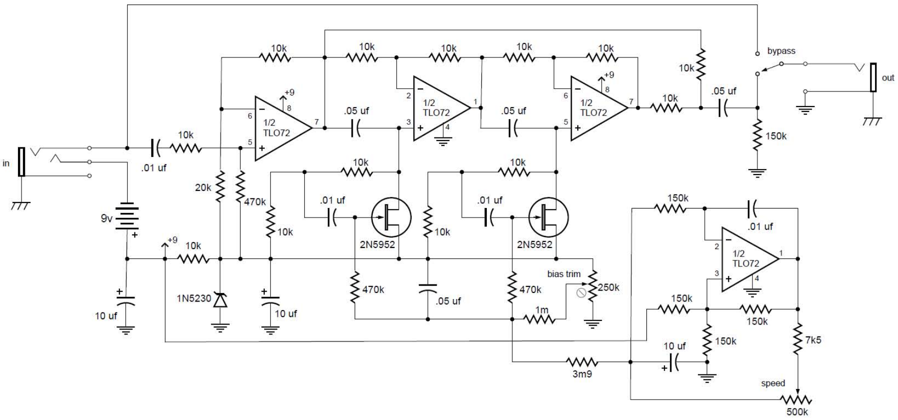


Analog phaser effect – Simulation

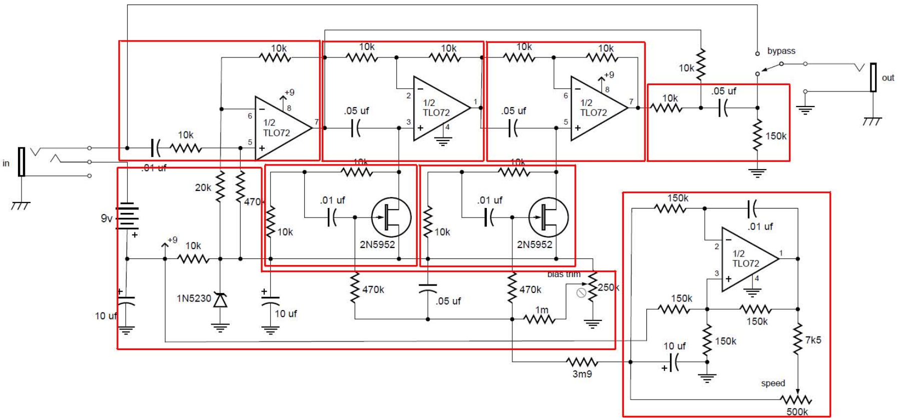
- Simulation using nodal analysis
  - cca 40 circuit nodes $\rightarrow$ 40 circuit equations
  - nonlinear solver
  - at least one matrix inversion in each signal sample
  - high computational complexity
- Simulation optimalized for real-time processing
  - division into smaller and more simple blocks that are solved individually
  - connection of the blocks with respect to mutual interaction – the input and output impedance have to be matched
  - each block must include output impedance from previous block and input impedance from following block



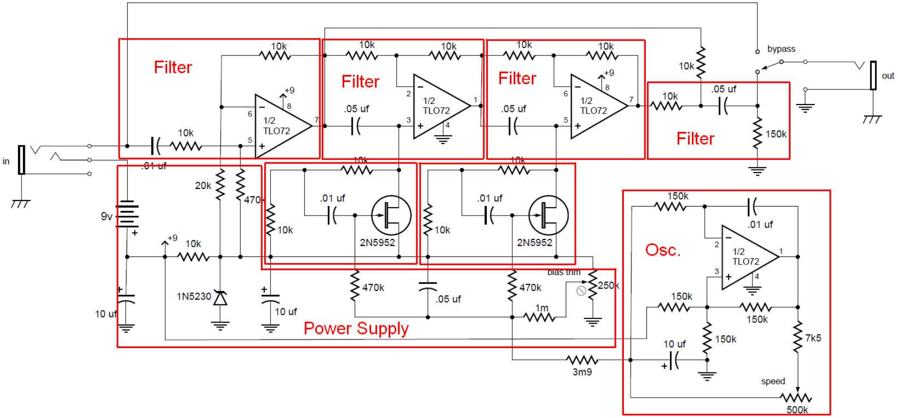
Analog phaser effect – the whole circuit



Analog phaser effect – division into blocks

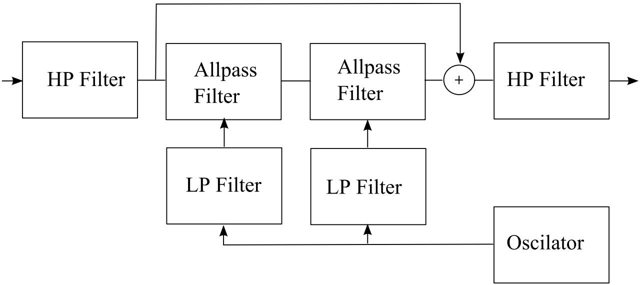


Analog phaser effect – reduction of the model



Analog phaser effect – Real-time implementation

- Four linear time-variable digital filters of first order and one summation in signal path
- Two linear digital filters of first order in parameter path
- Oscilator



Nonlinear models of analog effects

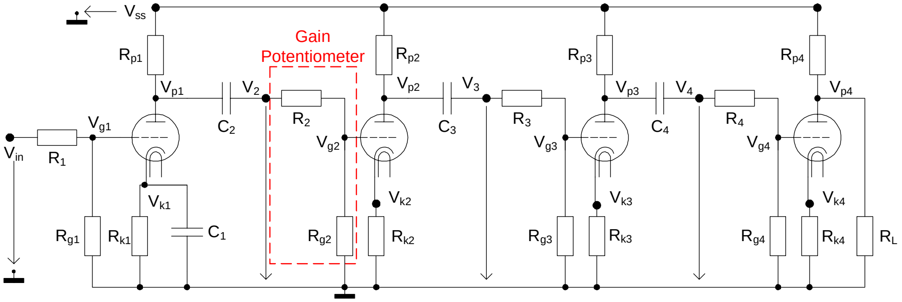
- Some analog audio effecs are highly nonlinear
  - Guitar Distortion and Overdrive effect pedals
  - Guitar amplifiers
  - the goal of the effect is to produce higher harmonics and distort the signal
- Some effects have unwanted nonlinear distortion
  - Dynamic range controllers
  - Circuits with BJT and FET transistors

Techniques for modeling of nonlinear audio effect

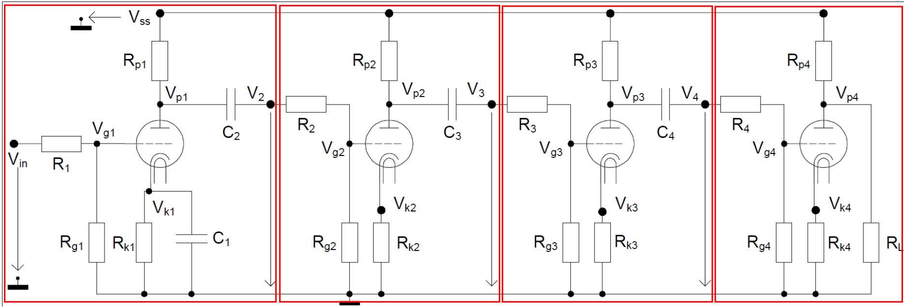
- Static waveshaping
  - static nonlinear mapping from the input variable to the output variable
  - dynamic nonlinear systems are modeled by cascade of linear filters and nonlinear function
- Dynamic modeling
  - Nonlinear wave digital filters
  - Nonlinear state-space models
  - Nonlinear differential equations

  - Require numerical solution of the model and are suitable for simple circuits
    - approximation of the solution
    - division into blocks

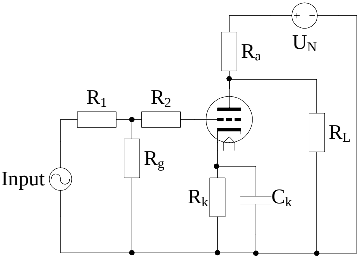
Example – Guitar tube preamp



Guitar tube preamp – division into blocks



Guitar tube preamp – one tube stage

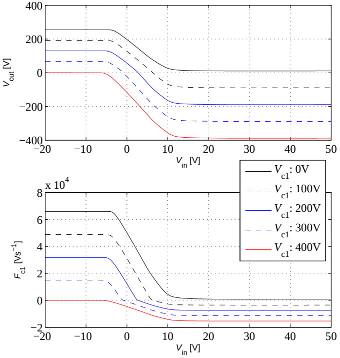


$$
\begin{aligned}
0 &= G_2 \frac{U_{in} G_1 + U_g G_2}{G_1 + G_g + G_2} - U_g G_2 - i_g \\
0 &= U_{c1m} - U_c + \frac{U_k G_k - i_a - i_g}{C_k f_s} \\
0 &= U_N G_a - U_a G_a - U_a G_L - i_a
\end{aligned}
\tag{1}
$$

Precomputation for input variables: U_{in}, U_{c1m}

$$
\begin{aligned}
U_g &= U_{Gapprox}(U_{in}, U_{c1m}) \\
U_k &= U_{Kapprox}(U_{in}, U_{c1m}) \\
U_a &= U_{Aapprox}(U_{in}, U_{c1m})
\end{aligned}
\tag{2}
$$

One tube stage – approximation



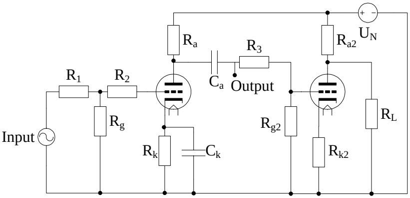
Update of the state variable:

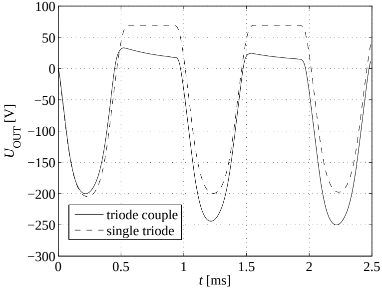
$$\begin{aligned} U_{\mathrm{c1m}} &= U_{\mathrm{c1m}} + \frac{U_{\mathrm{k}} G_{\mathrm{k}} - i_{\mathrm{a}} - i_{\mathrm{g}}}{C_{\mathrm{k}} f_{\mathrm{s}}} \\ &= U_{\mathrm{c1m}} + T_s U_{\mathrm{C1approx}}(U_{\mathrm{in}}, U_{\mathrm{c1m}}) \end{aligned} \tag{3}$$

Final implementation:

$$\begin{aligned} U_{\mathrm{a}} &= U_{\mathrm{Aapprox}}(U_{\mathrm{in}}, U_{\mathrm{c1m}}) \\ U_{\mathrm{c1m}} &+ T_s U_{\mathrm{C1approx}}(U_{\mathrm{in}}, U_{\mathrm{c1m}}) \end{aligned} \tag{4}$$

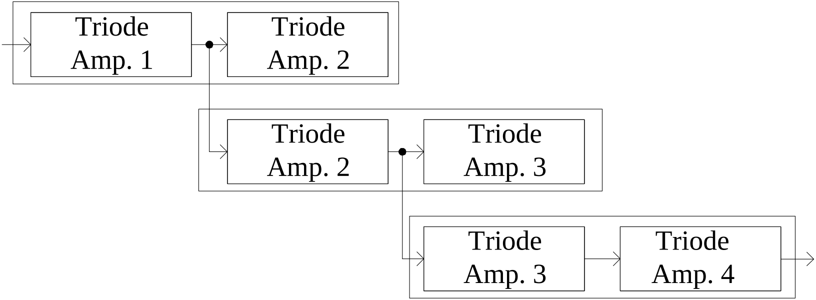
Wrong impedance matching



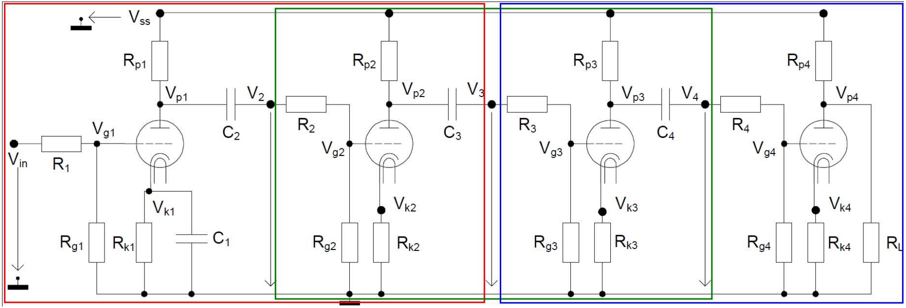


Modified blockwise method

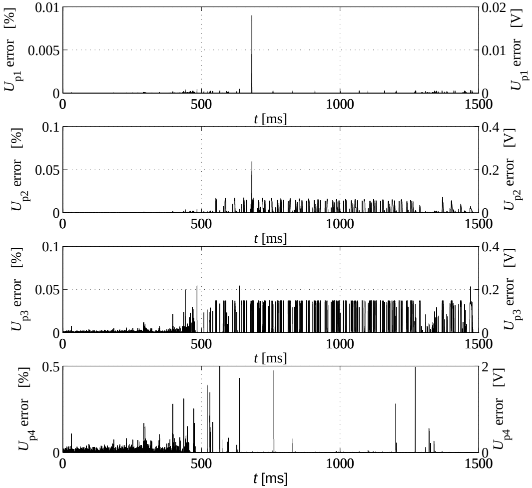
- designed to simulate nonlinear mutual interaction
- computational complexity is higher than with simple division into blocks, but still much lower than simulation of the whole system



Guitar tube preamp – new division into blocks



Guitar tube preamp – error signal between numerical solution and approximation and blockwise method



Was the simulation succesfull?

Thank you for your attention