Nonlinear Modeling of a Guitar Loudspeaker Cabinet

David Yeh, Balazs Bank, and Matti Karjalainen

1) CCRMA / Stanford University
2) University of Verona
3) Helsinki University of Technology
   Dept. of Signal Processing and Acoustics

http://www.acoustics.tkk.fi

Digital Audio Effects That Emulate Analog Equipment Are Popular

• “Modeling” amplifiers – Line 6, Yamaha, Roland, Korg, Digidesign, etc.
• CAPS open source LADSPA suite
  – http://quitte.de/dsp/caps.html
• Emulate guitar amplifier in software
• For portability and flexibility
Loudspeaker Modeling Work

- Linear response is primary contributor
  - Convolutional impulse response libraries
e.g., [http://noisevault.com/nv/](http://noisevault.com/nv/)
  - CAPS Audio Suite, [http://quitte.de/dsp/caps.html](http://quitte.de/dsp/caps.html)
  - Virtual Air Guitar (Karjalainen et al. JAES 2006)

- Nonlinear studies and simulations
  - Fränken et al. (IEEE 2001): nonlinear WDF
  - Klippel (AES 2001, etc): nonlinear state space
  - Quaegebeur and Chaigné (JAES 2008): nonlinear state space

Guitar Loudspeakers and Cabinets

- Electro-dynamic driver, closed- or open-back box
  - Classical driver models with relatively soft cone and stiff suspension have complicated behavior

  - Linearity only at low power levels
  - High directivity at high frequencies
  - Limited bandwidth, e.g. 100 – 6000Hz

Figure 1: Open-back cabinet and electrodynamic drive

Figure 2: Equivalent circuit of a loudspeaker driver.
Nonlinearities in Loudspeakers

- Many types of nonlinearities, especially:
  - Nonlinear compliance ($C_m$), stiffer for large excursion
  - Inhomogeneous magnetic field ($B_l$)
  - Variation of voice coil inductance ($L_e$)
  - Nonlinearity of cone stiffness in guitar loudspeakers

Measurement Setups (1)

- Sound pressure response (anechoic chamber)
  - Near field, far field in azimuth and elevation angles
- Cone vibration (laser vibrometer)
- Voltage/current relationship

Engl 12 inch cabinet with Celestion G12 Vintage 30 driver
Measurement Setups (2)

- Linear response measured by logarithmic sweep
  - FuzzMeasure (Macintosh)
- Nonlinearity measured at single frequencies by linearly growing sine-wave ramps
  - Harmonic distortion analyzed from sine responses

Example of fundamental (1) and harmonics level (dB) growth for sine-wave ramp

Linear Response

Free-field pressure

Velocity

Electrical impedance
Nonlinear Measurements, 70 Hz

- Velocity measurements indicate higher distortion with increasing radius.

Nonlinear Measurements, 200 Hz

- Distortion falls rapidly with frequency.
- Distortion further away from driving point of cone is higher.
Complicated Nonlinear Behavior at 1kHz

- Plotted are harmonics of 500Hz
- Loudspeaker was excited with 1kHz

Pressure signal shown.
Pitch halving effect at 1 s.
Linear modeling (1)

- Common pole modeling with parallel second-order filters
- Logarithmic frequency resolution as a result of estimating the poles by warped IIR filter design

![Diagram of linear modeling](image)

Linear modeling (2)

- Common pole modeling results:

![Plot of linear modeling results](image)
Nonlinear modeling

- Distortion modeling only at low frequencies where it is most significant
- Distortion at low frequencies depends on cone displacement

\[ e^{H_1(z)} x^{F(x)} x_d^{H_2(z)} e_d \rightarrow P \]

Nonlinearity modeling \hspace{2cm} Radiation modeling

Nonlinear modeling (1)

Second-order IIR filter \hspace{2cm} Second-order FIR filter
Nonlinear modeling (2)

\[ e^{-H(z)x} F(x) x_d^{-H(z)} e_d \rightarrow P \]

Nonlinearity modeling
Radiation modeling

5th order polynomial

Nonlinear modeling (3)

- Perfect fit only at a single frequency:
- Polynomial coefficient fit for 70Hz
Nonlinear modeling (4)

- Qualitatively correct behavior at higher frequencies (140 Hz displayed)

Nonlinear modeling sound examples

<table>
<thead>
<tr>
<th>Linear response</th>
<th>Nonlinear model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine wave (82 Hz)</td>
<td>![Sound icon]</td>
</tr>
<tr>
<td>Power chord (E)</td>
<td>![Sound icon]</td>
</tr>
</tbody>
</table>
Summary

• Measured linear and nonlinear behavior of a Celestion G12 guitar loudspeaker.
• Proposed linear model based upon parallel filter bank design.
• Proposed simple/efficient model with static nonlinearity.
• Most salient effects are linear. Nonlinear effects are subtle.
• Nonlinear behavior is complicated and requires further investigation.

Thank you for your attention!

Acknowledgements: Jyri Pakarinen, Miikka Tikander