Modeling the Large Signal Behavior of Micro-speakers

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133rd AES Convention 2012
Abstract

The mechanical and acoustical losses considered in the lumped parameter modeling of electro-dynamical transducers may become a dominant source of nonlinear distortion in micro-speakers, tweeters, headphones and some horn compression drivers where the total quality factor $Q_{ts}$ is not dominated by the electrical damping realized by a high force factor $B_l$ and a low voice resistance $R_e$. This paper presents a nonlinear model describing the generation of the distortion and a new dynamic measurement technique for identifying the nonlinear resistance $R_{ms(v)}$ as a function of voice coil velocity $v$. The theory and the identification technique are verified by comparing distortion and other nonlinear symptoms measured on micro-speakers as used in cellular phones with the corresponding behavior predicted by the nonlinear model.
Scope of the Paper

- Which are the dominant nonlinearities?
- How to verify the new modeling?
- How to measure those nonlinearities?
- What kinds of nonlinear symptoms (distortion, compression) are generated?
- How good is the prediction of those symptoms using the measured nonlinear parameters?
- What are the consequences for passive transducer design?
- How important are the nonlinearities for digital systems providing mechanical protection of microspeakers?
Generation of Signal Distortion

Input Signal → \( H(s) - 1 \) → Measured Signal

- Linear distortion
- Nonlinear distortion
- "Rub&Buzz" and other irregular distortion

Input Signal → Regular Nonlinearities → Noise

Defects → Nonlinear distortion
Transducer Nonlinearities

Regular Nonlinearities
- generate deterministic distortion which are predictable
- are related with the design (geometry and material)
- are compromised by size, weight and cost

Nonlinear Behavior

Destruction

Large signal performance

Small signal performance

- Maximal Output
- Distortion
- Power Handling
- Stability
- Compression

- Bandwidth
- Sensitivity
- Flatness of Response
- Impulse Accuracy
Nonlinear Transducer Modeling

Single Input

Air compression

Electric-mechanical Transducer

Mechano-acoustical Transducer

Port nonlinearity

Dominant nonlinearities

Bl(x)
Kms(x)
Le(x)
Le(i)
Rms(v)

Cone vibration

Doppler effect

Wave steepening

Multiple Outputs

Radiation

Sound Propagation

Room Acoustics

Room Interference

p(r1)

p(r2)
sound field

p(r3)

Sound Propagation

Radiation

Radiation

Sound Propagation

Room Interference

Room Interference

Multiple Outputs

Linear

Nonlinear

Linear

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Force Factor $B_l(x)$

$F = B_l(x)i$

Electro-dynamical driving force

$U = B_l(x)v$

Back EMF

$B_l(x)$ determined by
- Magnetic field distribution
- Height and overhang of the coil
- Optimal voice coil position
Stiffness $K_{ms}(x)$ of Suspension

$$F = K_{ms}(x)x$$

- restoring force
- displacement

Kms(x) determined by
- suspension geometry
- impregnation
- adjustment of spider and surround

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Voice Coil Inductance $L_e(x)$

$U_{ind} = \frac{d\varphi(x,i)}{dt} = \frac{d(L(x)i)}{dt}$

Differentiated Magnetic flux

Reluctance force

$L_e(x)$ determined by

- geometry of coil, gap, magnet
- optimal size and position of short cut ring

\[ R_{rel} = -\frac{i^2(t)}{2} \frac{dL(x)}{dx} \]
Nonlinear Mechanical Resistance $R_{ms}(v)$

$R_{ms}(v)$ depends on velocity $v$ of the coil due to air flow and turbulences at vents and porous material (spider, diaphragm).
Nonlinear Lumped Parameter Modeling

\[
K_{ms}(x)x + \left( R_{ms}(v) + \frac{B_l(x)^2}{R_e} \right)v + M_{ms} \frac{dv}{dt} = \frac{B_l(x)}{R_e} \left( u(t) - \frac{d(L_e(i,x)i)}{dt} \right) + i^2 \frac{dL_e(x)}{dx}
\]
Ranking List of Transducer Nonlinearities

1. Force Factor $B_l(x)$
2. Compliance $C_{ms}(x)$ → tweeter
3. Inductance $L_e(x)$
4. Flux Modulation of $L_e(i)$
5. Mechanical Resistance $R_{ms}(v)$ → microspeaker
6. Nonlinear Sound Propagation $c(p)$
7. Doppler Distortion $\tau(x)$
8. Flux Modulation of $B_l(i)$
9. Nonlinear Cone Vibration
10. Port Nonlinearity $R_A(v)$
11. many others ...

→ microspeaker
→ tweeter
→ woofer
→ horns
Nonlinear Mechanical Resistance $R_{ms}(v)$

\[ K_{ms}(x)x + \left( \frac{Bl(x)^2}{R_e} + R_{ms}(v) \right)v + M_{ms} \frac{dv}{dt} = \frac{Bl(x)}{R_e} \left( u(t) - \frac{dL_e(i,x,i)}{dt} \right) + \frac{i^2}{2} \frac{dL_e(x)}{dx} \]

Nonlinear Damping

**Source of distortion:**
Multiplication of velocity with a function of velocity

This nonlinearity is important for:
- microspeakers
- air compression drivers
- microphones
- headphones
- transducers with dominant mechanical damping

\[ \frac{Bl(x)^2}{R_e} < R_{ms}(v) \]

This nonlinearity is not relevant for:
- woofers
- subwoofers
- midrange drivers (tweeters)
- transducers with dominant electrical damping

\[ \frac{Bl(x)^2}{R_e} > R_{ms}(v) \]
Block-oriented Model
of loudspeaker with $R_{ms}(v)$ under current drive

$$v = L^{-1} \left[ \frac{s}{K_{mx} + R_{mx}(0)s + M_{mx} s^2} \right] \ast \left( Bi (R_{mx}(v) - R_{mx}(0)v) \right)$$

nonlinear operation
Generalized Signal Flow Model
describing a separated loudspeaker nonlinearity

\[
\begin{align*}
\text{Voltage} & \quad \text{post-shaping} \\
\text{distortion added to the input} & \quad \text{distortion} \\
\text{distortion} & \quad \text{pre-filter} \quad H_2(f) \\
\text{multiplier} & \quad \text{Static Nonlinearity} \\
\text{1st state variable} & \quad \text{pre-filter} \quad H_{1,1}(f) \\
\text{2nd state variable} & \quad \text{post-shaping} \\
\text{sound pressure} & \quad \text{feed-back loop} \\
\end{align*}
\]
### The Particularities of Each Nonlinearity

<table>
<thead>
<tr>
<th>NONLINEARITY</th>
<th>INTERPRETATION</th>
<th>PRE-FILTER $H_{1,1}(f)$ (output)</th>
<th>PRE-FILTER $H_{1,2}(f)$ (output)</th>
<th>POST-FILTER $H_2(f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness $K_{ms}(x)$ of the suspension</td>
<td>restoring force</td>
<td>Low-pass (displacement $x$)</td>
<td>Low-pass (displacement $x$)</td>
<td>1</td>
</tr>
<tr>
<td>Force factor $B_l(x)$</td>
<td>electro-dynamical force</td>
<td>Band-stop (current $i$)</td>
<td>Low-pass (displacement $x$)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>nonlinear damping</td>
<td>Band-pass (velocity $v$)</td>
<td>Low-pass (displacement $x$)</td>
<td>1</td>
</tr>
<tr>
<td>Inductance $L_e(x)$</td>
<td>self-induced voltage</td>
<td>Band-stop (current $i$)</td>
<td>Low-pass (displacement $x$)</td>
<td>differentiator</td>
</tr>
<tr>
<td></td>
<td>reluctance force</td>
<td>Band-stop (current $i$)</td>
<td>Low-pass (displacement $x$)</td>
<td>1</td>
</tr>
<tr>
<td>Inductance $L_e(i)$</td>
<td>varying permeability</td>
<td>Band-stop (current $i$)</td>
<td>Band-stop (current $i$)</td>
<td>differentiator</td>
</tr>
<tr>
<td>Mechanical resistance $R_{ms}(v)$</td>
<td>nonlinear damping</td>
<td>Band-pass (velocity $v$)</td>
<td>Band-pass (velocity $v$)</td>
<td>1</td>
</tr>
<tr>
<td>Young’s modulus $E(\varepsilon)$ of the material</td>
<td>cone vibration</td>
<td>Band-pass (strain $\varepsilon$)</td>
<td>Band-pass (strain $\varepsilon$)</td>
<td>1</td>
</tr>
<tr>
<td>Speed of sound $c(p)$</td>
<td>nonlinear sound propagation (wave steepening)</td>
<td>High-pass (sound pressure $p$)</td>
<td>High-pass (sound pressure $p$)</td>
<td>differentiator</td>
</tr>
<tr>
<td>Time delay $\tau(x)$</td>
<td>nonlinear sound radiation (Doppler effect)</td>
<td>High-pass (sound pressure $p$)</td>
<td>Low-pass (displacement $x$)</td>
<td>differentiator</td>
</tr>
</tbody>
</table>
Interaction Between Nonlinearities
coupling via fundamental component

Feedback to the nonlinearities
Using the Loudspeaker as Sensor

to identify Motor and Suspension Nonlinearities

Stimulus
Noise,
Audio signals
(music, noise)

Multi-tone complex

Linear Parameters
• T/S parameters at x=0
• Box parameters fb,Qb
• Impedance at x=0

Nonlinear Parameters
• nonlinearities Bl(x), Kms(x), Cms(x), Rms(v), L(x), L(i)
• Voice coil offset
• Suspension asymmetry
• Maximal peak displacement (Xmax)

Thermal Parameters
• Thermal resistances Rtv, Rtm
• Thermal capacity Ctv, Ctm
• Air convection cooling

State Variables
• peak displacement during measurement
• voice coil temperature
• electrical input power,

Nonlinear System Identification

Digital processing

Power amplifier

Voltage & current

Speaker

Stimulus

Noise,
Audio signals
(music, noise)

Multi-tone complex

Linear Parameters

Nonlinear Parameters

Thermal Parameters
Nonlinear Parameter Identification

Microspeaker

**DISTORTION caused by**

<table>
<thead>
<tr>
<th></th>
<th>AIR</th>
<th>VACUUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{ms}(x)$</td>
<td>28%</td>
<td>36%</td>
</tr>
<tr>
<td>$B_l(x)$</td>
<td>20%</td>
<td>17%</td>
</tr>
<tr>
<td>$L_e(x)$</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>$R_{rms}(v)$</td>
<td>45%</td>
<td>6%</td>
</tr>
</tbody>
</table>
Agreement
Measured and predicted peak and bottom displacement

- Linear model
- Nonlinear model
- Measured

GENERATION OF A DC COMPONENT
COMPRESSION OF THE FUNDAMENTAL COMPONENT
Analysis of Peak and Bottom Displacement

\[ L(x) \]

nonlinear model

\[ B_l(x) \] and \[ K_{ms}(x) \] generate dc-component

\[ R_{ms}(v) \] causes compression of the fundamental at resonance component caus
DC Displacement of the Voice Coil measured by a single tone

rest position

BI maximum

softer side of the suspension
Analysis of THD

Total Harmonic Distortion

Bl(x) and Kms(x) is dominant source of THD below resonance

Rms(v) and Kms(x) is dominant source of THD at resonance
Analysis of Intermodulation

2nd-order component

Bl(x) is the dominant source of 2nd-order IMD

constant frequency $f_1 = 700$ Hz

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Analysis of Intermodulation

3rd-order component

- $B(x)$ distortions are independent of frequency.
- $K_{ms}(x)$ distortions are falling with displacement.
- Doppler distortions are negligible.
- $R_{ms}(v)$ distortions are falling with 6dB per octave.
- Inductance distortions are negligible.

Constant frequency $f_2 = 700$ Hz.
Nonlinear Symptoms of $R_{ms}(v)$

- **Harmonics** in SPL (maximal at resonance $f_s$)
  - 3rd-order component is larger than 2nd-order distortion
  - decreases by 18dB per octave to lower and higher frequencies
- **Intermodulation** decreasing by 6dB/octave
- **Compression** of the fundamental at resonance
- no Xdc component
Loudspeaker Nonlinearities – Causes, Parameters, Symptoms


- Get a free poster for your workshop at our booth
Summary

• variation of the (mechanical) resistance $R_{\text{rms}}(v)$ versus velocity is a dominant nonlinearity in micro-speakers
• caused by turbulences in air leaks (disappears in vacuum)
• contributes significantly to harmonic distortion at resonance (high impact on sound quality)
• dominant compression of the amplitude at resonance (important for mechanical protection systems)
Many Thanks!
Monday 10:15 -12:15

Product Design Session PD11

“Rub & Buzz and Other Irregular Loudspeaker Distortion”

- Root Cause Analysis
- Defect Classification and Process Control
- Measurement in R&D and Manufacturing
- Perceptive Assessment using Auralization Techniques
- Audibility and Impact on Sound Quality