Electroacoustic Simulation for Neophytes

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1. Introduction

2. Components
   - Electrical
   - Mechanical
   - Acoustical
   - Interconnections

3. Simulation with SPICE

4. Applications
   - Loudspeakers
   - Horns
   - Headphones (next time)

5. Conclusion
Introduction

1. Lumped vs. Distributed Parameters

2. Linear vs. Non-linear models

3. Reasoning by Analogy
   - EFP (Voltage-Force-Pressure)
   - IFP (Current-Pressure-Force)
Resistance

- **Electrical:**
  \[ r_E = \frac{e}{i} \quad (1) \]

- **Mechanical:**
  \[ r_M = \frac{f_M}{v} \quad (2) \]

- **Acoustical:**
  \[ r_A = \frac{p}{U} \quad (3) \]
Capacitance/Compliance

- **Electrical:**
  \[ i = C_E \frac{de}{dt} \]  \hspace{1cm} (4)
  \[ C_E = \frac{q}{e} \]  \hspace{1cm} (5)

- **Mechanical:**
  \[ C_M = \frac{x}{f_M} \]  \hspace{1cm} (6)

- **Acoustical:**
  \[ C_A = \frac{V}{\rho c^2} \]  \hspace{1cm} (7)
Inertance / Inductance

- **Electrical:**

\[ e = L_E \frac{di}{dt} \]  \hspace{1cm} (8)

- **Mechanical (mass):**

\[ f_M = m \frac{dv}{dt} \]  \hspace{1cm} (9)

- **Acoustical (inertance):**

\[ p = M \frac{dU}{dt} \]  \hspace{1cm} (10)

\[ M = \frac{m}{S^2} \]  \hspace{1cm} (11)
Summary of Domains and units:

*Electrical*:

- Resistance: ohms
- Capacitance: farads
- Inductance: henries

*Mechanical*:

- Resistance: Mech. ohms
- Compliance: m/n
- Mass: kg

*Acoustical*:

- Resistance: rayls
- Compliance: $m^5$-n
- Mass: kg-$m^4$
Summary of Components:

<table>
<thead>
<tr>
<th>Electrical</th>
<th>Mechanical</th>
<th>Acoustical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistor</td>
<td>Friction</td>
<td>Ac. Resistance</td>
</tr>
<tr>
<td>Capacitor</td>
<td>Spring</td>
<td>Volume</td>
</tr>
<tr>
<td>Inductor</td>
<td>Mass</td>
<td>Tube</td>
</tr>
</tbody>
</table>
Domain interconnection: Electromagnetic-mechanical

- Back emf:

\[ e = Blu \quad (12) \]

- Force generated:

\[ f = Bli \quad (13) \]

Solution: Controlled Sources (CCVS, CCCS)
Domain interconnection: Mechanical-acoustical

- Force over area:

\[ f = pS \] (14)

- Mechanical velocity:

\[ v = \frac{U}{S} \] (15)

\[ Z_M = \frac{f}{v} = \frac{pS}{U} = \frac{p}{U}S^2 \] (16)

Solution: Controlled Sources (VCVS, CCCS)
Simulation with circuit simulators

- Use circuit simulators (like SPICE)
- Public domain software (i.e., free)
- *linear circuits* only
- Can perform transient, AC analyses
Strategy

- Describe each domain with R,L,Cs
- Interconnect with controlled sources
- Insert "meters" at interesting points
- Label with node numbers
- Perform transient, AC analyses
What is SPICE?

- Simulation Program with Integrated Circuits Emphasis

- Open Source code from Berkeley

- Available with various enhancements: PSPICE, LTSPICE

- Syntax dates back to the punched card era (really)
SPICE description

- Title Card Description of circuit

- Comment Card a line beginning with the symbol *

- Element Cards circuit is described with element cards: element name and the node numbers

- Control Cards Specify options to the program and the analyses to be performed. All control cards begin with the character "."

- the .END card
Analysis methods

- Frequency response (incl. Bode Plots)
- Transient Response
- DC analysis (not useful)
- Noise analysis (not useful)
## SPICE syntax - elements

<table>
<thead>
<tr>
<th>Category</th>
<th>Syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance</td>
<td>$R_x \text{ node node value}$</td>
</tr>
<tr>
<td>Capacitor/Compliance</td>
<td>$C_x \text{ node node value}$</td>
</tr>
<tr>
<td>Inductance/Inertance</td>
<td>$L_x \text{ node node value}$</td>
</tr>
<tr>
<td>Voltage/Pressure</td>
<td>$V_x \text{ node+ node- value}$</td>
</tr>
<tr>
<td>Current/Velocity</td>
<td>$I_x \text{ node+ node- value}$</td>
</tr>
</tbody>
</table>
### SPICE syntax - controlled sources

<table>
<thead>
<tr>
<th>Type</th>
<th>Syntax</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCVS</td>
<td>( V_{CVS} )</td>
<td>( E_x ) ( \text{node}^+ ) ( \text{node}^- ) ( \text{control}^+ ) ( \text{control}^- ) ( \text{gain} )</td>
</tr>
<tr>
<td>VCCS</td>
<td>( V_{CCS} )</td>
<td>( G_x ) ( \text{node}^+ ) ( \text{node}^- ) ( \text{control}^+ ) ( \text{control}^- ) ( \text{gain} )</td>
</tr>
<tr>
<td>CCCS</td>
<td>( C_{CCS} )</td>
<td>( F_x ) ( \text{node}^+ ) ( \text{node}^- ) ( y ) ( \text{gain} )</td>
</tr>
<tr>
<td>CCVS</td>
<td>( C_{CCVS} )</td>
<td>( H_x ) ( \text{node}^+ ) ( \text{node}^- ) ( y ) ( \text{gain} )</td>
</tr>
</tbody>
</table>
Electroacoustic variables

| e | V |
| i | I |
| f | V |
| v | I |
| p | V |
| U | I |
Analysis strategy:

- All volumes become acoustic compliances (C) with one terminal grounded
- Connect compliances with pipes (L) and resistors (R)
- Leaks are resistors (R) to ground
- Outside enclosure is *radiated* to radiation impedance
Acoustic components:

- Cavities: \( Z_A = \frac{V}{\rho c^2} \)

- Pipes: \( Z_A = \frac{V}{\rho c^2} \)

- Resistances: depends...

- Radiation impedance: (approx. from Beranek)

\[
Z_{AL} = \frac{\rho_0 \omega^2 \pi a^4}{2c_0} + j \frac{8\rho_0 c_0^2 a}{3}
\]  

\( (17) \)
Electrodynamic loudspeaker: US Patent 1,812,389

Parts:
- cone 12
- former 36
- voice coil 22
- magnetic annulus 23
- spider 40
- chassis 36
- centering ring 39
Modeling the loudspeaker

\[ V_S \quad Blv \quad R_E \ L_E \quad L_m \ C_m \ R_m \quad Z_{AF} \]

Force factor = \( Bli \)
Back emf = \( Blv \)
Diaphragm area = \( S_D \)
Boxes with ports

- Box volume = compliance
- Box edges (leaks) = resistance
- Back of diaphragm air = mass
- Port = mass
- Port couples with the driver
Ported box

\[ \begin{align*}
\text{port} & \quad R_{AL} \quad M_{AP} \quad M_{AB} \quad C_{AB} \quad \text{driver} \\
\text{radiation} \quad \text{load} & \quad \text{load} 
\end{align*} \]
Ported box parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance</td>
<td>$R_E$</td>
<td>6.5$\Omega$</td>
</tr>
<tr>
<td>Inductance</td>
<td>$L_E$</td>
<td>1 mH</td>
</tr>
<tr>
<td>Damping</td>
<td>$R_{MD}$</td>
<td>3.72</td>
</tr>
<tr>
<td>Suspension compliance</td>
<td>$C_{MD}$</td>
<td>2.14e-4</td>
</tr>
<tr>
<td>Diaphragm mass</td>
<td>$M_{MD}$</td>
<td>0.064</td>
</tr>
<tr>
<td>12” Driver area</td>
<td>$S_D$</td>
<td>4.5e-2</td>
</tr>
<tr>
<td>38mm port</td>
<td>$S_P$</td>
<td></td>
</tr>
<tr>
<td>Box compliance</td>
<td>$C_{AB}$</td>
<td>V$_{AB}$/\rho c^2</td>
</tr>
<tr>
<td>Air load on diaphragm</td>
<td>$M_{AB}$</td>
<td>2.03</td>
</tr>
<tr>
<td>Box leaks</td>
<td>$R_{AB}$</td>
<td>6.91e-4</td>
</tr>
<tr>
<td>Driver port coupling</td>
<td>$k_{DP}$</td>
<td>3$\pi a/16d$</td>
</tr>
<tr>
<td>Port driver coupling</td>
<td>$k_{PD}$</td>
<td>0.124</td>
</tr>
</tbody>
</table>
SPICE input - Electro-mechanical

Vented box (from Leach)
Veg 1 0 AC 1V DC 0V
Rew 1 2 6.5
Lew 2 3 1M
HBLUW 3 4 V2W 16.5
V1W 4 0 AC 0V DC 0V
*
HBLIW 5 0 V1W 16.5
LMmdw 5 6 0.064
Rmsw 6 7 3.72
Cmsw 7 8 2.14e-4
ESDPW 8 9 17 10 4.5E-2
V2W 9 0 AC 0V DC 0V
SPICE input - Acoustical

FSDUW 10 17 V2W 4.5e-2
Lmabw 10 11 2.03
Cabw 11 12 4.03e-7
V3W 12 0 AC 0V DC 0V
Ralw 11 0 6.91E4
Lmap 11 13 30.9
*
FKPUW 15 13 V6W 0.124
Lma1p 13 15 8.37
Ra1p 13 14 3.94e4
cia1p 13 14 2.34e-9
Ra2p 14 16 8.93e4
V4W 15 16 AC 0V DC 0V
V5W 16 0 AC 0V DC 0V
*
FKPUP 19 17 V4W 0.393
Lma1w 17 19 2.66
Ra1w 17 18 3.97e3
cia1w 17 18 7.31e-8
Ra2w 18 20 9e3
V6W 19 20 AC 0V DC 0V
V7W 20 0 AC 0V DC 0V
SPICE input - control

.AC DEC 20 10 10K
.print ac I(V7W)
.END
How to use the results...

\[ |p(r)| = \frac{\rho_0 f}{r} |U_B| \]  \hspace{1cm} (18)

\[ \text{SPL} = 20 \log_{10} \frac{p}{p_{\text{ref}}} \]  \hspace{1cm} (19)

Where: \( p_{\text{ref}} = 10^{-5} \text{ Pa} \), \( \rho_0 = 1.18 \)

|\( U \)|? Insert Ammeters at important branches...

Let \( r = 1 \).
Simulation

Loudspeaker simulations
Compression driver

(from U.S. Patent 1,707,545)
<table>
<thead>
<tr>
<th>Compression driver parts</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>magnet</td>
<td>11</td>
</tr>
<tr>
<td>voice coil</td>
<td>14</td>
</tr>
<tr>
<td>diaphragm</td>
<td>17</td>
</tr>
<tr>
<td>phasing plug</td>
<td>23</td>
</tr>
<tr>
<td>back cavity</td>
<td>27</td>
</tr>
<tr>
<td>resistor</td>
<td>28</td>
</tr>
</tbody>
</table>
Phasing plug

(from U.S. Patent 5,117,462)
Modeling the compression driver

What is $Z_{AB}$? What is $Z_{AF}$? What are the electrical and mechanical parameters?
Compression driver model

- $Z_{AB} = \text{back cavity compliance}$

- $Z_{AF} = \text{front cavity, phasing plug, load}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance</td>
<td>$R_E$</td>
<td>7.5Ω</td>
</tr>
<tr>
<td>Inductance</td>
<td>$L_E$</td>
<td>0.35 mH</td>
</tr>
<tr>
<td>Force factor</td>
<td>$B_l$</td>
<td>19 N-m</td>
</tr>
<tr>
<td>Resonance</td>
<td>$f_s$</td>
<td>560 Hz</td>
</tr>
<tr>
<td>Damping</td>
<td>$R_{MD}$</td>
<td>unknown</td>
</tr>
<tr>
<td>Suspension compliance</td>
<td>$C_{MD}$</td>
<td>unknown</td>
</tr>
<tr>
<td>Diaphragm mass</td>
<td>$M_{MD}$</td>
<td>0.0032 gm</td>
</tr>
<tr>
<td>Driver area</td>
<td>$S_D$</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Mechanical damping and compliance are not given.
Nonlinear model
Additional calculations:

- $F_S = \frac{1}{2\pi \sqrt{C_{MD}M_{MD}}}$ so $C_{MD} = 2.52e - 5$

- $R_{MD}$ is still unknown

- $C_{AB} = 7.04e - 6V_{AB}$, what is $V_{AB}$??
  Let $V_{AB} = 1.2e - 4$, then $C_{AB} = 8.4480e - 10$

- $C_{AF} = 7.04e - 6V_{AF}$, what is $V_{AF}$??
  Let $V_{AF} = 2.9368e - 04$, then $C_{AF} = 2.0675e - 09$

- $M_{MP} = \rho V_P / 3 = 1.2131e - 05$
SPICE input - Electro-mechanical

JBL 2446H
Veg 1 0 AC 1V DC 0V
Re 1 2 7.5
Le 2 3 0.35m
HBLU 3 4 V2 19
V1 4 0 AC 0V DC 0V
*
HBLI 5 0 V1 19
LMms 5 6 3.2m
Rms 6 7 1e-6
Cms 7 8 2.52e-5
ESDP 8 9 20 10 0.008
V2 9 0 AC 0V DC 0V
SPICE input - Acoustical

FSDU 10 20 V2 0.008
* back cavity
CAB 10 11 8.4480e-10
Rab 10 11 1e12
V3 11 0 AC 0V DC 0V
* front cavity
CAF 20 30 2.0675e-09
* phase plug
LAP 20 23 2.0675e-06
RAP 23 24 126
V5 24 21 AC 0V DC 0V
* 2 inch air load
la1 21 30 6.2515
ca1 21 22 5.6758e-09
ra1 21 22 2.1844e+04
ra2 22 30 4.9532e+04
V4 30 0 AC 0V DC 0V
Simulation

Horn simulation

Velocity into load

40
SPICE simulation deficiencies

- Lumped circuits only (not distributed)
- Linear circuits only (or hack solutions)
- Can’t study wave phenomena
Where to read more...

- Beranek, *Acoustics*
  An oldie but goodie. Available from ASA (in pb).

- Olson, *Dynamic Analogies*
  Another oldie but real goodie (on the web)

- Leach, *Introduction to Electroacoustics and Audio Amplifier Design*
  a Modern master
Next talk... How to use SPICE to simulate various headphones and earphones

July 24th?