Design Project
ECE4445 – Audio Engineering

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In this design project, various simulations were performed. The simulations are:

1. Loudspeaker mounted on infinite baffle.
2. Loudspeaker mounted inside a closed box.
3. Loudspeaker with matching network mounted inside a closed box.
4. Loudspeaker with matching network and 2nd order crossover network mounted inside a closed box.
5. Loudspeaker with matching network and 3rd order crossover network mounted inside a closed box.
6. Loudspeaker mounted inside a vented box.

All the simulations were performed using PSPICE. The SPICE circuits and netlists are attached at the end of the report.
Zoff := READPRN(“off.txt”)  Zon := READPRN(“on.txt”)  

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<td>13.896</td>
<td>6.16</td>
<td>13.357</td>
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\[ R_E := 5.33 \quad \text{DC resistance} \quad V_T := 1.56 \quad \text{Test box volume} \]

\[ N := 300 \quad \text{Number of data points minus 1} \]

\[ Z(x, y) := \frac{x\cdot y}{x + y} \quad \text{Parallel combinaton} \]

From the Zoff array:

\[ f_S := 30.482 \]

\[ R_{ES} := 43.614 - R_E \quad R_{ES} = 38.284 \]

\[ R_1 := \sqrt{R_E (R_E + R_{ES})} \]

\[ R_1 = 15.247 \]

\[ f_1 := 18.36 \quad f_2 := 50.582 \quad \sqrt{f_1\cdot f_2} = 30.474 \]

\[ Q_{MS} := \frac{f_S}{f_2 - f_1} \sqrt{\frac{R_E + R_{ES}}{R_E}} \quad Q_{MS} = 2.706 \]

\[ Q_{ES} := \frac{R_E}{R_{ES}} Q_{MS} \quad Q_{ES} = 0.377 \]

\[ Q_{TS} := \frac{R_E}{R_E + R_{ES}} Q_{MS} \quad Q_{TS} = 0.331 \]
\[ n_e := \frac{2}{\pi} \cdot \text{arg} \left( \text{Zoff}_{250,1} \cdot \cos \left( \text{Zoff}_{250,2} \cdot \frac{\pi}{180} \right) - R_E + j \cdot \text{Zoff}_{250,1} \cdot \sin \left( \text{Zoff}_{250,2} \cdot \frac{\pi}{180} \right) \right) \quad n_e = 0.65 \]

\[ L_e := \sqrt{ \left( \text{Zoff}_{250,1} \cdot \cos \left( \text{Zoff}_{250,2} \cdot \frac{\pi}{180} \right) - R_E \right)^2 + \left( \text{Zoff}_{250,1} \cdot \sin \left( \text{Zoff}_{250,2} \cdot \frac{\pi}{180} \right) \right)^2 } \quad L_e = 0.03 \]

\[ n := 0 \ldots N \quad f_n := 10 \cdot \left( \frac{20000}{10} \right) \quad \text{Frequency range variable for calculating } Zvc(f) \]

\[ L_E := 13 \cdot 10^{-3} \quad \text{"Tweaked" value of parallel lossless inductor in Allen Robinson's model} \]

\[ Zvc(f) := R_E + Z_p \left[ j \cdot 2 \cdot \pi \cdot f \cdot L_e \cdot \left( j \cdot 2 \cdot \pi \cdot f \right)^n_e \right] + R_{ES} \cdot \frac{1}{Q_{MS}} \left( \frac{j \cdot f}{f_s} \right) + \left( \frac{f}{f_s} \right)^2 + \left( \frac{j \cdot f}{f_s} \right)^2 \]

From the Zon array:

\[ f_{CT} := 75.889 \quad R_{ECT} := 34.353 - R_E \quad R_{ECT} = 29.023 \quad R_1 := \sqrt{R_E (R_E + R_{ECT})} \]

\[ R_1 = 13.531 \quad f_{1T} := 55.988 \quad f_{2T} := 95.33 \quad \sqrt{f_{1T} \cdot f_{2T}} = 73.057 \]

\[ Q_{MCT} := \frac{f_{CT}}{f_{2T} - f_{1T}} \cdot \sqrt{\frac{R_E + R_{ECT}}{R_E}} \quad Q_{MCT} = 4.897 \]

\[ Q_{ECT} := \frac{R_E}{R_{ECT}} \cdot Q_{MCT} \quad Q_{ECT} = 0.899 \quad Q_{TCT} := \frac{R_E}{R_E + R_{ECT}} \cdot Q_{MCT} \quad Q_{TCT} = 0.76 \]

\[ V_{AS} := V_T \left( \frac{f_{CT}}{f_s} \cdot \frac{Q_{ECT}}{Q_{ES}} - 1 \right) \quad V_{AS} = 7.711 \]
Infinite Baffle:

In this section, parameters are calculated to construct the electrical circuits which simulate the speaker mounted on an infinite baffle. From these electrical circuits, it is possible to obtain the input impedance, the sound pressure level produced by the loudspeaker, and the diaphragm peak displacement. The equations used for the calculations are shown below. Also, the graphics show the parameters measured from the SPICE simulation.

\[ Q_{MS} = 2.706 \quad Q_{ES} = 0.377 \quad Q_{TS} = 0.331 \]
\[ \rho_o := 1.18 \quad c := 345 \quad a := 0.12 \quad V_{AS} := 0.218 \quad \text{--> in m}^3 \]
\[ f_s = 30.482 \quad V_{AS} = 0.218 \quad S_D := \pi a^2 \quad S_D = 0.045 \]

\[ C_{MS} := \frac{V_{AS}}{\rho_o c^2 S_D^2} \quad C_{MS} = 7.584 \times 10^{-4} \]
\[ M_{MS} := \frac{1}{(2\pi f_s)^2 C_{MS}} \quad M_{MS} = 0.036 \]
\[ R_{MS} := \frac{M_{MS}}{Q_{MS} \sqrt{C_{MS}}} \quad R_{MS} = 2.544 \]
\[ B_l := \sqrt{\frac{R_E M_{MS}}{Q_{ES} C_{MS}}} \quad B_l = 9.869 \]
\[ M_{MD} := M_{MS} - 2 \cdot \frac{8 \rho_o}{3 \pi^2} S_D^2 \quad M_{MD} = 0.025 \]
\[ M_{A1} := \frac{8 \rho_o}{3 \pi^2} \quad M_{A1} = 2.657 \]
\[ R_{A2} := \frac{\rho_o c}{\pi a^2} \quad R_{A2} = 8.999 \times 10^3 \]
\[ R_{A1} := \frac{128 \rho_o c}{9 \pi^3 a^2} - R_{A2} \quad R_{A1} = 3.969 \times 10^3 \]
\[ C_{A1} := \frac{5.94 a^3}{\rho_o c^2} \quad C_{A1} = 7.308 \times 10^{-8} \]
SpcIBZin := READPRN("SpiceIBZin.txt")

Electrical Input Impedance

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<tr>
<th>Frequency [Hz]</th>
<th>Impedance [Ohms]</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
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<tr>
<td>10^4</td>
<td>1</td>
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<td>10^5</td>
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SpcIBSPL := READPRN("SpiceIBSPL.txt")

On-Axis SPL

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>SPL [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>63.33</td>
</tr>
<tr>
<td>100</td>
<td>76.67</td>
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<tr>
<td>10^3</td>
<td>90</td>
</tr>
<tr>
<td>10^4</td>
<td>76.67</td>
</tr>
<tr>
<td>10^5</td>
<td>63.33</td>
</tr>
</tbody>
</table>
SpcIBXpp := READPRN("SpiceIBXpp.txt")

![Graph showing the relationship between Peak to Peak Diaphragm Displacement and Frequency.](image)
Closed Box:

In this section, parameters are calculated to build the circuits that model the loudspeaker mounted inside a closed box. The first three graphs show the results of the SPICE measurements. A matching network was designed with the purpose of making the input impedance behave like if it was only the voice coil resistor \( R_E \), the graph shown under "Matching Network Design" shows the electrical input impedance before and after adding the matching network. Also, 2nd and 3rd order crossover networks were designed with the purpose of only allowing low frequencies to reach the woofer. The measured sound pressure levels without crossover network, with a 2nd order network, and with a 3rd order network, are shown in the graph under "Crossover Network Design".

\[
\alpha := \left( \frac{Q_{ECT}}{Q_{ES}} \right)^2 - 1 \quad \alpha = 4.698
\]
\[
V_{AB} := \frac{V_{AS}}{\alpha} \quad V_{AB} = 0.046
\]
\[
C_{AB} := \frac{V_{AB}}{\rho_o c^2} \quad C_{AB} = 3.304 \times 10^{-7}
\]
\[
R_{AB} := \left( \sqrt{1 + \alpha} \cdot \frac{Q_{MS}}{Q_{MCT}} \right) \frac{R_{MS}}{S_D^2} \quad R_{AB} = 1.64 \times 10^3
\]
\[
M_{MC} := \left( \frac{B^2 Q_{ECT}}{\pi \cdot a^2 \cdot c \cdot R_E} \right)^2 \cdot \frac{V_{AS}}{\rho_o (1 + \alpha)} \quad M_{MC} = 0.036
\]
\[
R_{MS} := \frac{1}{Q_{MS}} \cdot \frac{M_{MC}}{\sqrt{C_{MS}}} \quad R_{MS} = 2.544
\]
\[
M_{AB} := \frac{M_{MC} - M_{MD}}{\pi \cdot a^2} - M_{A1} \quad M_{AB} = 2.657
\]
\[
R_{AL} := \frac{1}{2 \pi (1) \cdot C_{AB}} \quad R_{AL} = 4.818 \times 10^6
\]

\text{SpcCBZin} := \text{READPRN("SpiceCBZin.txt")}

\text{SpcCBSPL} := \text{READPRN("SpiceCBSPL.txt")}

\text{SpcCBXpp} := \text{READPRN("SpiceCBXpp.txt")}
Matching Network Design:

\[
f_c := f_S \sqrt{1 + \alpha} \quad f_c = 72.764 \quad f_{1\text{mn}} := 2000 \quad f_{2\text{mn}} = 20 \cdot 10^3 \quad L_e = 0.03 \quad n_e = 0.65
\]

\[
R_E = 5.33 \quad Q_{\text{MCT}} = 4.897 \quad Q_{\text{ECT}} = 0.899 \quad Q_{\text{EC}} := Q_{\text{ES}} \sqrt{1 + \alpha}
\]

\[
R_{1\text{mn}} := R_E \quad C_{1\text{mn}} := \frac{L_e}{\left(1-n_e\right)^2 \cdot f_{1\text{mn}} \cdot f_{2\text{mn}}}
\]

\[
C_{2\text{mn}} := \frac{L_e}{\left(2\pi\right)^2 \cdot R_E \cdot f_{1\text{mn}} \cdot f_{2\text{mn}} \cdot \left(2+n_e\right) \cdot \left(1+n_e\right)}
\]

\[
R_{3\text{mn}} := R_E \left(1 + \frac{Q_{\text{ECT}}}{Q_{\text{MCT}}}\right)
\]

\[
L_{1\text{mn}} := \frac{R_E \cdot Q_{\text{ECT}}}{2\pi f_c}
\]

\[
C_{3\text{mn}} := \frac{1}{2\pi f_c \cdot R_E \cdot Q_{\text{ECT}}}
\]

\[
R_{1\text{mn}} = 5.33 \quad C_{1\text{mn}} = 2.054 \times 10^{-5} \quad C_{2\text{mn}} = 1.293 \times 10^{-5} \quad R_{2\text{mn}} = 2.484
\]

\[
R_{3\text{mn}} = 6.309 \quad L_{1\text{mn}} = 0.01 \quad C_{3\text{mn}} = 4.563 \times 10^{-4}
\]

SpcCBwMNZin := READPRN("SpiceCBwMNZin.txt")

Electrical Input Impedance

![Impedance vs Frequency Graph](image)
Crossover Network Design:

. 2nd Order Network:

Assuming \( Q_w = 0.5 \), \( f_w = 800 \), \( R_E = 5.33 \)

\[
\begin{align*}
L_w &= \frac{R_E}{2\pi f_w Q_w} \\
C_w &= \frac{Q_w}{2\pi f_w R_E} \\
L_w &= 2.121 \times 10^{-3} \\
C_w &= 1.866 \times 10^{-5}
\end{align*}
\]

. 3rd Order Network:

\( f_c = 72.764 \), \( f_w = 800 \)

\[
\begin{align*}
L_2 &= \frac{R_E}{4\pi f_w} \\
L_1 &= 3L_2 \\
C_3 &= \frac{2}{3\pi f_w R_E} \\
L_1 &= 1.591 \times 10^{-3} \\
L_2 &= 5.302 \times 10^{-4} \\
C_3 &= 4.977 \times 10^{-5}
\end{align*}
\]

\[
\text{SpcCBw2COSPL := READPRN("SpiceCBwMN2COSPL.txt")}
\]

\[
\text{SpcCBw3COSPL := READPRN("SpiceCBwMN3COSPL.txt")}
\]
Vented Box:

In this section, parameters are calculated to build the circuits that will simulate the behavior of the loudspeaker mounted inside a vented box. The electrical input impedance was measured, along with the sound pressure level and the peak displacement. The graph labeled "On-Axis SPL" shows the sound pressure levels produced by the diaphragm and the air in the vent, along with the total SPL. The plot labeled "Peak-to-Peak Displacement" shows the displacement of the diaphragm as well as the displacement of the air in the port.

\[ d_w := 0.305 \quad \rightarrow \quad 12 \text{ in} = \text{woofer frame diameter} \]

\[ a_w := 0.12 \quad \rightarrow \quad 12 \text{ cm} = \text{piston radius} \]

\[ a_p := 0.04 \quad \rightarrow \quad 4 \text{ cm} = \text{port radius} \]

woofer-port spacing assumed to be 1.6 times the woofer frame radius, then:

\[ d_1 := 0.8d_w \quad d_1 = 0.244 \]

\[ S_w := \pi a_w^2 \quad S_w = 0.045 \]

\[ B := 0.65 \quad \rightarrow \quad \text{Assumed Value (p.114)} \]

\[ M_{AB} := \frac{B \rho_o}{\pi \cdot a_w} \quad M_{AB} = 2.035 \quad \text{Old Mab was 2.657} \]

\[ C_{AB} = 3.304 \times 10^{-7} \]

\[ Q_{1S} = 0.331 \quad Q_L := 7 \]

With assumed \( Q_L=7 \) and Alignment Chart on p.138:

\[ h := 1.1998 \quad f_B := h \cdot f_S \quad f_B = 36.572 \]

\[ R_{AL} := \frac{Q_L}{2\pi f_B \cdot C_{AB}} \quad R_{AL} = 9.221 \times 10^4 \]

\[ M_{AIP} := \frac{8\rho_o}{2 \cdot 3\pi \cdot a_p} \quad M_{AIP} = 7.971 \]

\[ M_{AP} := \frac{1}{(2\pi f_B)^2 \cdot C_{AB}} - M_{AIP} \quad M_{AP} = 49.355 \]
\[ R_{A2P} := \frac{\rho_o c}{\pi a_p^2} \quad R_{A2P} = 8.099 \times 10^4 \]

\[ R_{A1P} := \frac{128\rho_o c}{9\pi^3 a_p^2} - R_{A2P} \quad R_{A1P} = 3.572 \times 10^4 \]

\[ C_{A1P} := \frac{5.94a_p^3}{\rho_o c^2} \quad C_{A1P} = 2.707 \times 10^{-9} \]

\[ k_p := \frac{3\pi a_p}{16d_1} \quad k_p = 0.097 \]

\[ S_p := \pi a_p^2 \quad S_p = 5.027 \times 10^{-3} \]

\[ M_{A1W} := \frac{8\rho_o}{3\pi^2 a_w} \quad M_{A1W} = 2.657 \]

\[ R_{A2W} := \frac{\rho_o c}{\pi a_w^2} \quad R_{A2W} = 8.999 \times 10^3 \]

\[ R_{A1W} := \frac{128\rho_o c}{9\pi^3 a_w^2} - R_{A2W} \quad R_{A1W} = 3.969 \times 10^3 \]

\[ C_{A1W} := \frac{5.94a_w^3}{\rho_o c^2} \quad C_{A1W} = 7.308 \times 10^{-8} \]

\[ k_w := \frac{3\pi a_w}{16d_1} \quad k_w = 0.29 \]

SpcVBZin := READPRN("SpiceVBZin.txt")

SpcVBSPLv := READPRN("SpiceVBSPLv.txt")

SpcVBSPLw := READPRN("SpiceVBSPLw.txt")

SpcVBSP := READPRN("SpiceVBSP.txt")

SpcVBXppD := READPRN("SpiceVBXppD.txt")

SpcVBXppP := READPRN("SpiceVBXppP.txt")
Summary and Conclusions

This report shows the result of simulating the behavior of a loudspeaker under different operating conditions. In the case of the closed box simulation, a matching network was placed in parallel with the voice coil. The purpose of this network is to cause the voice coil impedance to behave as if it were purely resistive, i.e. to cancel the peak at the resonant frequency as well as the high frequency rise due to the voice coil inductance. Furthermore, 2\textsuperscript{nd} and 3\textsuperscript{rd} order crossover networks were placed at the input of the voice coil circuit, i.e. before the matching network. The purpose of these networks is to allow only low frequencies to reach the woofer. The plots of the sound pressure level when using the crossover networks show how the slope of the magnitude Bode plot changes from -20 dB per decade (without C/O network) to -40 dB per decade (with 2\textsuperscript{nd} order network) and -60 dB per decade (with a 3\textsuperscript{rd} order crossover network).

In the case of the vented box, it is important to notice that the sound pressure level that we hear is the result of adding the SPL produced by the diaphragm and the SPL produced by the air in the port. In the plot showing the SPL of the vented box system, it is easy to notice that at some frequencies, the SPL produced by the air in the vent is considerably larger than the SPL produced by the diaphragm.
Appendix
SPICE Circuits and Netlists
Infinite Baffle Circuits

Electrical

Mechanical

Acoustical
Closed Box Circuits

Electrical

Mechanical

Acoustical
Electrical With Matching Network

Electrical With Matching Network and 2nd Order Crossover Network
Electrical With Matching Network and 3rd Order Crossover Network
Vented Box Circuits

Electrical

Mechanical
Acoustical
*-------------------------------------------------*
* Infinite Baffle *
*-------------------------------------------------*
*INFINITE BAFFLE NETLIST *
*DISPLAY VM(1)/IM(VD1) FOR INPUT IMPEDANCE *
*DISPLAY 20*LOG10(VM(13)) FOR ON-AXIS PRESSURE *
*DISPLAY VM(14) FOR DIAPHRAGM DISPLACEMENT *

**ELECTRICAL CIRCUIT**
VEG 1 0 AC 1V
RE 1 2 5.33
*L O S S Y V O I C E - C O I L I N D U C TANCE *
GZE 2 3 LAPLACE \{V(2, 3)\} = \{1/(0.03*PWR(S, 0.65))\}
HBLUD 3 4 VD2 9.869
VD1 4 0 AC 0V

**MECHANICAL CIRCUIT**
LMMD 5 6 0.025
RMS 6 7 2.544
CMS 7 8 7.584E-4
HBLIC 5 0 VD1 9.869
ESDPD 8 9 10 0 0.045
VD2 9 0 AC 0V

**ACOUSTICAL CIRCUIT**
LMA1 10 12 5.314
RA1 10 11 7.938E3
RA2 11 12 17.998E3
CA1 10 11 3.654E-8
VD3 12 0 AC 0V
FSDUD 0 10 VD2 0.045

**ON-AXIS PRESSURE SOURCE**
EPD 13 0 LAPLACE \{I(VD3)\} = \{9390*S\}
**DI APH R A G M DI SP L A C E M EN T SOURCE**
EXD 14 0 LAPLACE \{I(VD3)\} = \{1/S\}

.AC DEC 77 10 100K
.PROBE
.END

*-------------------------------------------------*
* CLOSED-BOX *
*-------------------------------------------------*
*DISPLAY VM(1)/IM(VD1) FOR INPUT IMPEDANCE *
*DISPLAY 20*LOG10(VM(13)) FOR ON-AXIS PRESSURE *
*DISPLAY VM(14) FOR DIAPHRAGM DISPLACEMENT *

**ELECTRICAL CIRCUIT**
VEG 1 0 AC 1V
RE 1 2 5.33
*L O S S Y V O I C E - C O I L I N D U C TANCE *
GZE 2 3 LAPLACE \{V(2, 3)\} = \{1/(0.03*PWR(S, 0.65))\}
HBLUD 3 4 VD2 9.869
VD1 4 0 AC 0V

**MECHANICAL CIRCUIT**
HBLI 5 0 VD1 9.869
LMMD 5 6 0.025
RMS 6 7 2.544
CMS 7 8 7.584E-4

Page 1
*ACOUSTICAL CIRCUIT

FSDUD 13 10 VD2 0.045
LMA1 10 12 2.657
RA1 10 11 3.969E3
RA2 11 12 9E3
CA1 10 11 7.308E-8
VD3 12 0 AC 0
LMAB 13 14 2.657
RAB 14 15 1.64E3
CAB 15 0 3.304E-7
RAL 15 0 4.818E6

*ON-AXIS PRESSURE DISPLAYS IN PROBE WITH 20*LOG10(VM(16))
EXP 16 0 LAPLACE {i(VD3)} = {59E3*S}

*DIAPHRAGM DISPLACEMENT DISPLAYS IN PROBE WITH VM(17)
EXD 17 0 LAPLACE {i(VD2)}={1/S}

.AC DEC 50 10 10K
.PROBE
.END

*--------------------------------------------------
*CLOSED-BOX WITH MATCHING NETWORK
*--------------------------------------------------

*DI SPLOY VM(1)/IM(VD1) FOR INPUT IMPEDANCE
*DI SPLOY 20*LOG10(16) FOR ON-AXIS PRESSURE
*DI SPLOY VM(17) FOR DIAPHRAGM DISPLACEMENT

*ELECTRICAL CIRCUIT
VEG 1 0 AC 1V
RE 1 2 5.33

*LOSSY VOICE-COIL INDUCTANCE
GZE 2 3 LAPLACE {V(2, 3)}={1/(0.03*PWR(S, 0.65))}
HBLUD 3 4 VD2 9.869
VD1 4 0 AC 0

*Matching Network
RR1 1 18 5.33
CC1 18 0 2.054E-5
RR2 18 19 2.484
CC2 19 0 1.293E-5
RR3 1 20 6.309
LL1 20 21 0.01
CC3 21 0 4.563E-4

*MECHANICAL CIRCUIT
HBLI 5 0 VD1 9.869
LMMD 5 6 0.025
RMS 6 7 2.544
CMS 7 8 7.584E-4
ESDPD 8 9 10 13 0.045
VD2 9 0 AC 0

*ACOUSTICAL CIRCUIT
FSDUD 13 10 VD2 0.045
LMA1 10 12 2.657
RA1 10 11 3.969E3
RA2 11 12 9E3
CA1 10 11 7.308E-8
All Nets.txt

VD3 12 0 AC 0
LMAB 13 14 2.657
RAB 14 15 1.64E3
CAB 15 0 3.304E-7
RAL 15 0 4.818E6

*ON-AXIS PRESSURE DISPLAYS IN PROBE WITH 20*LOG10(VM(16))
EXP 16 0 LAPLACE {I(VD3)} = {59E3*S}
*DI APHGRAM DI SPLACEMENT DI SPLAYS I N PROBE WITH VM(17)
EXD 17 0 LAPLACE {I(VD2)}={1/S}
AC DEC 50 10 10K
PROBE
END

*-----------------------------------------------------------
*CLOSED-BOX WITH MATCHING NETWORK AND 2ND ORDER C/O NETWORK
*-----------------------------------------------------------
*DISPLAY VM(1)/IM(VD1) FOR INPUT IMPEDANCE
*DISPLAY 20*LOG10(16) FOR ON-AXIS PRESSURE
*DISPLAY VM(17) FOR DIAPHRAGM DISPLACEMENT

*ELECTRICAL CIRCUIT
VEG 1 0 AC 1V

*--------------------------
*2nd Order C/O Network
LLw 1 2 2.121E-3
CCw 2 0 1.866E-5

*---------------------------
*Matching Network
RR1 2 3 5.33
CC1 3 0 2.054E-5
RR2 3 4 2.484
CC2 4 0 1.293E-5
RR3 2 18 6.309
LL1 18 19 0.01
CC3 19 0 4.563E-4

*----------------------------
RE 2 20 5.33
*LOSSY VOICE-COIL INDUCTANCE
GZE 20 21 LAPLACE {V(20,21)}={1/(0.03*PWR(S,0.65))}
HBLUD 21 22 VD2 9.869
VD1 22 0 AC 0

*--------------------------
*MECHANICAL CIRCUIT
HBLI 5 0 VD1 9.869
LMMD 5 6 0.025
RMS 6 7 2.544
CMS 7 8 7.584E-4
ESDPD 8 9 10 13 0.045
VD2 9 0 AC 0

*ACOUSTICAL CIRCUIT
FSDUD 13 10 VD2 0.045
LMA1 10 12 2.657
RA1 10 11 3.969E3
RA2 11 12 9E3
CA1 10 11 7.308E-8
VD3 12 0 AC 0
LMAB 13 14 2.657
RAB 14 15 1.64E3
CAB 15 0 3.304E-7
**Electronic Circuit**

VEG 1 0 AC 1V

---

**3rd Order C/O Network**

LLco1 1 2 1.591E-3
CCco 2 0 4.977E-5
LLco2 2 3 5.302E-4

---

**Matching Network**

RR1 3 4 5.33
CC1 4 0 2.054E-5
RR2 4 18 2.484
CC2 18 0 1.293E-5
RR3 3 19 6.309
LL1 19 20 0.01
CC3 20 0 4.563E-4

---

**Lossy Voice-Coil Inductance**

GZE 21 22 LAPLACE \{V(21,22)\}={1/(0.03*PWR(S,0.65))}

HBLUD 22 23 VD2 9.869
VD1 23 0 AC 0

---

**Mechanical Circuit**

HBLI 5 0 VD1 9.869
LMMD 5 6 0.025
RMS 6 7 2.544
CM5 7 8 7.584E-4
ESDPD 8 9 10 13 0.045
VD2 9 0 AC 0

---

**Acoustical Circuit**

FSDUD 13 10 VD2 0.045
LMA1 10 12 2.657
RA1 10 11 3.969E3
RA2 11 12 9E3
CA1 10 11 7.308E-8
VD3 12 0 AC 0
LMAB 13 14 2.657
RAB 14 15 1.64E3
CAB 15 0 3.304E-7
RAL 15 0 4.818E6
*ON-AXIS PRESSURE DISPLAYS IN PROBE WITH 20*LOG10VM(16)
EXP 16 0 LAPLACE {I(VD3)} = {59E3*S}
*DIAPHRAGM DISPLACEMENT DISPLAYS IN PROBE WITH VM(17)
EXD 17 0 LAPLACE {I(VD2)}={1/S}
.AC DEC 50 10 10K
.PROBE
.END

*------------------------------------------------------
*VENTED BOX
*------------------------------------------------------
*DI SPLAY VM(1)/IM(VD1) FOR INPUT IMPEDANCE
*DI SPLAY VM(21) FOR DIAPHRAGM DISPLACEMENT
*DI SPLAY VM(22) FOR PORT DISPLACEMENT
*DI SPLAY 20*LOG10VM(23) FOR ON-AXIS PRESSURE
*DI SPLAY 20*LOG10VM(24) FOR DIAPHRAGM PRESSURE
*DI SPLAY 20*LOG10VM(25) FOR PORT PRESSURE

*ELECTRICAL CIRCUIT
VEG 1 0 AC 1V
REW 1 2 5.33
*LOSSY VOICE-COIL INDUCTANCE
GRA 2 3 LAPLACE {V(2, 3)}={(1/(0.03*PWR(S, 0.65)))
HBLUW 3 4 V2W 9.869
V1W 4 0 AC 0V

*Mechanical Ckt
HBLIW 5 0 V1W 9.869
LMMDW 5 6 0.025
RMSW 6 7 2.544
CMSW 7 8 7.584E-4
ESDPW 8 9 17 10 0.045
V2W 9 0 AC 0V

*Acoustical Ckt
FSDUW 10 17 V2W 0.045
LMABW 10 11 2.035
CABW 11 12 3.304E-7
V3W 0 12 AC 0
RALW 11 0 9.221E4
LMAP 11 13 49.355
FKP 15 13 V6W 0.097
LMA1P 13 15 7.971
RA1P 13 14 3.572E4
CA1P 13 14 2.707E-9
RA2P 14 16 8.099E4
V4W 15 16 AC 0V
V5W 16 0 AC 0V
FKWUP 19 17 V4W 0.29
LMA1W 17 19 2.657
RA1W 17 18 3.969E3
CA1W 17 18 7.308E-8
RA2W 18 20 9E3
V6W 19 20 AC 0V
V7W 20 0 AC 0V

*DI APHRAGM DI SPALCMENT SOURCE
EXD 21 0 LAPLACE {I(V2W)}={1/S}
*PORT DISPLACEMENT SOURCE
EXP 22 0 LAPLACE {I(V5W)}={1/(5.027E-3*S)}
*ON-AXIS PRESSURE SOURCE
EPSUM 23 0 LAPLACE {I(V3W)}={9390*S}
*DIAPHRAGM PRESSURE SOURCE
EPD 24 0 LAPLACE {I(V7W)}={9390*S}
*VENT PRESSURE SOURCE
EPV 25 0 LAPLACE {I(V5W)}={9390*S}
.AC DEC 100 10 10K
.PROBE
.END