Designing Transducers for Compact Active Speakers

AUDIO DESIGN WORKSHOP LIVE

MEET THE EXPERTS - LEARN THEIR SECRETS
Peter Larsen with these companies from 1974

Peter Larsen
LOUDSOFT

LOUDSOFT
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The Design Cycle

- Designing Motors for Small Drivers
- Bass Alignments in Box @ High Power
- Cone Designs and Problems
- Crossover Designs in Practice
- Loudspeaker Measurement Examples
- Challenges in Speaker QC Testing
Designing Transducers for Compact Speakers

BBC LS 3/5A Compact Monitor 1974
Designing Transducers for Compact Speakers

Today's Compact Loudspeakers
Table 1. SUMMARY OF LOUDSPEAKER ALIGNMENTS
adapted from Table 1, Loudspeakers in Vented Boxes

<table>
<thead>
<tr>
<th>No.</th>
<th>Type</th>
<th>Ripple (dB)</th>
<th>$f_r/f_s$</th>
<th>$f_m/f_s$</th>
<th>$C_{AV}/C_{AB}$</th>
<th>$Q_T$</th>
<th>$f_{aux}/f_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>QB3</td>
<td>-</td>
<td>2.68</td>
<td>2.00</td>
<td>10.48</td>
<td>0.180</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>QB3</td>
<td>-</td>
<td>2.28</td>
<td>1.73</td>
<td>7.48</td>
<td>0.209</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>QB3</td>
<td>-</td>
<td>1.77</td>
<td>1.42</td>
<td>4.46</td>
<td>0.259</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>QB3</td>
<td>-</td>
<td>1.45</td>
<td>1.23</td>
<td>2.95</td>
<td>0.303</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>BW4</td>
<td>-</td>
<td>1.000</td>
<td>1.000</td>
<td>1.414</td>
<td>0.383</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>CH4</td>
<td>-</td>
<td>0.852</td>
<td>0.927</td>
<td>1.055</td>
<td>0.415</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>CH4</td>
<td>0.07</td>
<td>0.724</td>
<td>0.829</td>
<td>0.729</td>
<td>0.466</td>
<td>-</td>
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<tr>
<td>8</td>
<td>CH4</td>
<td>0.25</td>
<td>0.704</td>
<td>0.757</td>
<td>0.559</td>
<td>0.518</td>
<td>-</td>
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<tr>
<td>9</td>
<td>CH4</td>
<td>0.51</td>
<td>0.685</td>
<td>0.716</td>
<td>0.485</td>
<td>0.557</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>BW5</td>
<td>-</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>0.447</td>
<td>1.00</td>
</tr>
<tr>
<td>11</td>
<td>CH5</td>
<td>-</td>
<td>0.850</td>
<td>0.912</td>
<td>0.583</td>
<td>0.545</td>
<td>1.22</td>
</tr>
<tr>
<td>12</td>
<td>CH5</td>
<td>0.25</td>
<td>0.698</td>
<td>0.814</td>
<td>0.273</td>
<td>0.810</td>
<td>1.81</td>
</tr>
<tr>
<td>13</td>
<td>CH5</td>
<td>0.5</td>
<td>0.620</td>
<td>0.798</td>
<td>0.227</td>
<td>0.924</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>CH5</td>
<td>1.0</td>
<td>0.554</td>
<td>0.781</td>
<td>0.191</td>
<td>1.102</td>
<td></td>
</tr>
</tbody>
</table>

QB3 ≡ Quasi-Butterworth 3rd order
BW4 ≡ Butterworth 4th order, maximally-flat amplitude response
CH4 ≡ Chebyshev 4th order, equal-ripple amplitude response
BW5 ≡ Butterworth 5th order, maximally-flat amplitude response
CH5 ≡ Chebyshev 5th order, equal-ripple amplitude response

Fig 8. Amplitude Responses of a Vented Box Loudspeaker, with alignments numbered as in Table 1

From Neville Thiele:
“The Loudspeaker Parameters and their Evolution”
Compact speakers require small drivers. These produce less SPL (lower sensitivity).

- *6.5in Woofer in large Box*
- *2in Woofer in 2L Reflex Box*
Initial settings for 6inch example A

1. Cone Area: 136cm²
2. Cone Mass (incl. ½ surround): 11g
3. DCR: 3.0 R (Nominal impedance: 4 ohms)

Initial settings for 3inch example B

1. Cone Area: 31.2cm²
2. Cone Mass (incl. ½ surround): 2.2g
3. DCR: 5.5 R (Nominal impedance: 8 ohms)
Example A:

1. Target $X_{\text{max}} \sim 5\text{mm}$
2. Optimize TS Parameters ($Q_{\text{ts}} < 0.4$)
3. Optimize $\text{BL}(x)$ for Low Distortion
Initial input settings for example A

Acoustic Components

<table>
<thead>
<tr>
<th>Effective Area</th>
<th>Sd</th>
<th>136.000 sq. cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Diameter</td>
<td>D</td>
<td>13.159 cm</td>
</tr>
<tr>
<td>Fixed Mass</td>
<td>Mms-Mvc</td>
<td>11.000 g</td>
</tr>
</tbody>
</table>

Specify Qms | Qms | 3.000 |

Estimate Qms (from VC Former mat.) | Yes | 3.000 |

Voice Coil

<table>
<thead>
<tr>
<th>Wire Type</th>
<th>Round wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Material</td>
<td>Copper</td>
</tr>
<tr>
<td>Former Material</td>
<td>Aluminium</td>
</tr>
</tbody>
</table>

Note: Changing former material will adjust Qms

<table>
<thead>
<tr>
<th>Voice Coil Resistance DCR</th>
<th>Re</th>
<th>3.000 Ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice Coil Inside Diameter</td>
<td>VCID</td>
<td>32.000 mm</td>
</tr>
<tr>
<td>Number of Layers</td>
<td>n</td>
<td>2</td>
</tr>
<tr>
<td>Twin Coil</td>
<td>Yes</td>
<td>2</td>
</tr>
<tr>
<td>Voice Coil Former Thickness</td>
<td>0.0500 mm</td>
<td></td>
</tr>
<tr>
<td>Wire Stretch</td>
<td>0.000 %</td>
<td></td>
</tr>
</tbody>
</table>

Ready
Calculated solutions based on Wire Diameters
(A) Initial Solution: $X_m$ is only 3mm. Move cursor to the right to find solutions having longer Voice Coils ($X_m$ larger).
Now Xm is close to 5mm (OK). However Qts=0.47 is too high.
A larger 90x36x17 Y25 magnet gave $Q_{ts}=0.33$ 😊
But the $BL(x)$ curve is NOT symmetrical or flat.
Extending the pole by 3.68mm produces a nice symmetric BL(x) curve, though not flat. But (IM) distortion will be reduced.
Pole with undercut under and above the air gap gave a flat and symmetric \( BL(x) \) curve.

\( \Phi 8 \) hole caused saturation in the pole. \( \Phi 6 \) was used.
An alternative design using a 4-layer Voice Coil. The air gap OD was auto-adjusted for the larger Voice Coil using a 0.30mm clearance. \(X_m = +/- 6.7 \text{mm}\). Moving Mass Mms up from 16.3 to 29.6g, \(= \text{Woofer} \#2\).
Example B. This small 3inch woofer is designed like before. But this time a Neodymium Magnet + a top Neo magnet was used. The BL(x) curve is good, but sensitivity is low. = Woofer #3
Alternative 3” Ferrite magnet + back magnet solution for low cost. The BL(x) curve is very good. Sensitivity is still low.
Question:

Which parameter influences $Q_{ts}$ most? Mms (Moving mass), Re (DCR) or BL (Force factor)
Qts is defined as the total Q (quality factor) at the resonance Fs.

\[ \frac{1}{Q_{ts}} = \frac{1}{Q_{ms}} + \frac{1}{Q_{es}} \]

\[ Q_{es} < Q_{ms} \quad \text{(typically 0.4 < 5)} \]

\[ Q_{es} = \frac{2\pi \cdot F_s \cdot R_e \cdot M_{ms}}{B L^2} \]

Answer is BL
Next we will study how the designed woofers will behave in cabinets of different sizes and tuning. The effect of high input power will be included.
The 3 example drivers were imported into the FINEBox program:
1. Woofer #1 in 8 Ltr. closed box
2. Woofer #1 in 18 ltr. Bass Reflex, tuned to Fb= 48Hz
3. Woofer #2 in 18 ltr. Bass Reflex, tuned to Fb= 39Hz
4. Woofer #3 in 1 ltr. Bass Reflex, tuned to Fb= 115Hz
#3 has more bass extension, due to more mass and BL.
Bass Reflex Woofer Displacement reaching Xmax of woofer #2. LF rise to be filtered.
Power Compression of Woofer #2 @ 70W IEC input. The Voice Coil has reached 154 deg. C. The magnet temp is 52.4 deg. C
Small woofer #3 @ 34W IEC power. Very high Power Compression, and the Voice Coil is 247 deg. C = Overload! The neodymium magnet is probably demagnetized @ 129 deg. C.
Bass Reflex Port dimensions to avoid air noise due to turbulence for curve No. 2 (Woofer #1)
HEADPHONE DESIGN

Simplified lumped element simulation of Headphone /Earphone with cavities and holes/channels.

(Infinite baffle: No Coupler or Artificial Ear).
Calculated Compression of 6½" Woofer

6.5" Woofer: Normal air gap

- SPL (cold): 108.5 dB
- Power Compression: 3.8 dB (50W)

6.5" Woofer: Tight air gap + Ferrofluid

- SPL (cold): 107.5 dB
- Power Compression: <1.6 dB (50W)

Reduced Compression with Ferrofluid + Tighter Air gap
Cone design used to be a challenge based on trial and error.
Today we can quickly simulate with the help of FEM and gain insight into the mechanical and acoustical behaviour of cones and domes of any size.
Acoustic Finite-Element (FEM) Simulation examples
The driver Geometry can be defined as a simple DXF drawing.
Each segment is given material parameters from a comprehensive database.
FEM simulated 0°/30°/60° deg. frequency responses of 6½” Woofer, compared to actual measurement. The agreement is quite good, especially at high frequencies.
Cone and Dust cap Break-up of 6½” woofer @ 6804 Hz. The outer half of the cone shows the 1st cone mode, and the dust cap has high order break-up.
High order break-up of 6½” woofer @ 13623 Hz. The cone break-up has just reached the Voice Coil former.
Example: 165mm/6.5” Woofer with a response problem 1000-1500 Hz
The FEM analysis reveals a strong edge resonance causing the problem around 1355 Hz.
Solution found by increasing the thickness of a part of the surround.
FEM simulated solution / before

165 Woofer + Modified Surround

Pink curve is before change
FEM simulated 0/30/60 deg. frequency responses of 1” Aluminium Dome Tweeter with break-up @ 25912 Hz.
Crossover design is very simple in theory. In reality many problems makes it difficult and time consuming to design a good cross over circuit without the help of CAD.
Half space/baffle (2Pi) versus Anechoic (4Pi) Loudspeaker response

**FIGURE 4.11:** Half-space versus anechoic response (dotted = half-space, solid = free-standing anechoic).

**FIGURE 4.12:** Spreading loss for 6.5” MTM array.

From “Testing Loudspeakers”

J. D’Apolito
Loudspeaker Measurements and Their Relationships with Listener Preference

Examples from Floyd Tool's article:

Fig. 7. Amplitude response measurements of loudspeakers with fidelity ratings (a) 6.0–6.4.

Fig. 7. Amplitude response measurements of loudspeakers with fidelity ratings (d) 7.5–7.9.

J. Audio Eng. Soc., Vol. 34, No. 5, 1986 May
Example of 2-way cross over circuit with optimized off-axis responses (Controlled power response)
2-way cross over optimized for flat response. But Impedance is too low! (~2R)
2-way cross over circuit now optimized also for impedance Z
2-way cross over further optimized with unit delay for linear phase
Some examples from using modern measuring methods
The swept sine / FFT technique makes it simple to get accurate frequency responses in normal rooms.
The time difference $T$ between the direct and the reflected sound must be large in order to measure low frequencies: $F_{\text{min}} = \frac{1}{T}$ (Hz)

In a small room $T$ can be increased by moving the microphone closer.

This curve measured at 1V/50cm was normalized to 2.83V/1m (=Industry standard)
LF Near field measurements:
Near field measurements will measure all low frequencies. However since these are really pressure responses it is necessary to compensate for the differences due to distance and piston size.

Bass reflex response, complex addition of woofer and port. Auto compensated for area differences.

Total response, combined by far field and near field. Spliced @ 473 Hz.
Harmonic distortion is useful. However, the waterfall provides more information.

The 1-3rd harmonics are high @ 800 Hz.

The waterfall shows a strong reflection @ 800 Hz and a decaying resonance @ 4 kHz.
The curtain shows the reflection @ 800 Hz in detail
Replacing old (DOS) Measuring systems

Old System: DOS

- No Win 7 or 8 (+ 64bit)
- No Amplifier
- No Rub & Buzz

New System: (C++)

- Windows 7 / 8 - 64bit
- THD + 2-9th
- Test: 1sec
- Golden Average
- Best Rub & Buzz
- USB Hardware
- 25W Amplifier
- SPL+Imp direct
Challenges in Speaker QC Testing

A few notes about Speaker End of Line Quality Control in today’s high speed production.
Which parameters should be tested to ensure good speakers and especially micro speakers, in production?
• Use statistics to find The Golden Average (REF)
• Decide response deviations as: Sensitivity and +/- x dB freq. band
Example: Two rejected woofer responses imported into FINE X-over. Red ___ outside frequency tolerance. Blue ___ low sensitivity.
It is vital to find Rub & Buzz especially for micro speakers. This cannot be detected with conventional methods like THD, high harmonics or IM distortion.
How can Rub & Buzz be tested reliably?

Danish F. Leonhard derived in 1993 a new model for auditory perception based on mathematical and physical phenomena that correspond very much to how the human ear perceives sound.

A later detection method based on the Danish research principles uses a completely new protected algorithm to find the annoying sounds, which cannot be detected with conventional methods like THD, high harmonics or IM distortion. Finding fast low level impulses < -80 dB rel. signal is therefore possible.
How Accurate are Speaker Simulations?

Some results from AES 126th
Loudspeaker FEA/BEM Workshop
**Measurement in Vacuum**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>In air</th>
<th>In vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rs</td>
<td>7.13</td>
<td>Ohm</td>
</tr>
<tr>
<td>Lo</td>
<td>0.046</td>
<td>mH</td>
</tr>
<tr>
<td>L2</td>
<td>0.181</td>
<td>mH</td>
</tr>
<tr>
<td>R2</td>
<td>1.64</td>
<td>Ohm</td>
</tr>
<tr>
<td>Cnres</td>
<td>182.02</td>
<td>μF</td>
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<tr>
<td>Lces</td>
<td>5.08</td>
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<tr>
<td>Res</td>
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<td>Ohm</td>
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<td>Fs</td>
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<td>Hz</td>
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<td><strong>Mechanical Parameters</strong></td>
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</tr>
<tr>
<td>Mrms</td>
<td>1.277</td>
<td>g</td>
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<td>M (360)</td>
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<td>cis</td>
<td>0.322</td>
<td>kg/s</td>
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<td>Cms</td>
<td>0.767</td>
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<tr>
<td>kms</td>
<td>1.30</td>
<td>N/mm²</td>
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<tr>
<td>Bl</td>
<td>2.649</td>
<td>N/A</td>
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<tr>
<td>Lambda s</td>
<td>0.096</td>
<td></td>
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</table>

**Conclusion**

The predicted BL is really close to the Klipper Laser measurement.

**TS Parameters**

- Sensitivity: 283V/1.00m
- SPL: 79.72 dB
- VC Resistance DCR: Re: 7.00 Ohms
- Resonance: Fs: 161.00 Hz
- Mechanical Parameters: Qms: 4.00
- Electrical: Qes: 1.27
- Total: Qts: 0.96
- Equivalent air vol.: Vas: 0.25 l
- Compliance: Cms: 0.77 mm/H
- Moving Mass (incl. air): Mms: 1.27 g
- Force Factor: Bl: 2.66 Tm
- Eff. diaphragm area: Sd: 15.33 sq.cm
- Lin. Excursion +/-: Xmin: 0.87 mm

Flux Profile

- Flux Contour with file Bn500.txt
- Offset: 0.00 mm
Dominant Nonlinearities: $B_l(x)$

Measured by using the LSI module:

- Force factor $B_l(x)$
- Voice coil height
- Gap depth

$X_{BL} = 1.3 \text{ mm} \at \at BL_{min} = 82\%$ (10\% intermodulation distortion in SPL, mainly 3rd-order)

FINEMotor BL(x) Calculation:

- $100\%$
- $82\%$
- $50\%$
- VC in
- VC out

$X_m = 1.49$

Predicted by FINEMotor:

$X_{BL} @ 82\% BL_{min} = 1.35 \text{ mm}$. The shape and symmetry of the BL(x) curve is extremely close to that measured by Klippel.

Klippel, Loudspeaker Analysis, Workshop AES 2009, 13
AES 126th Loudspeaker FEA/BEM Workshop

FINECone FEA versus measured response

Sound Pressure Response
Baffle 1 m 1W

Flat SPL response up to 10 kHz
The FINE Circle

www.loudsoft.com