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**Array myths**

- Arrays *must* be curved to shape the lobe...
- FIR filtering to optimise the directivity of arrays is new...
- Arrays can be put anywhere, the software will do the rest...
- You cannot control bass...
WHAT IS AN ARRAY?

A loudspeaker array is a collection of sound sources (or complete enclosures) that is assembled to achieve a coverage pattern that cannot be achieved with a single loudspeaker. The combined array is more powerful and can have a wider or narrower beam than the individual elements.

BEAMFORMING

- Mechanical
  - Minimum interference
  - Beam controlled by shape of array

- Electronical
  - Maximum interference
  - Beam controlled by (digital) signal processing of loudspeaker signals
ARRAY PHYSICS

Beamforming Concepts

- **Mechanical beamforming**
  - Line arrays: Radiation pattern dictated by shape of array.
  - Minimum interference. HF horns are designed to have minimum mutual interference at higher frequencies.
  - Low driver density.
  - No multi-channel signal processing.

- **Electronical beamforming**
  - Radiation pattern determined by (digital) filtering of output channels (i.e., loudspeaker signals)
  - High driver density.
  - Maximum interference: Deliberate, controlled interference for obtaining desired radiation pattern.
ARRAY PHYSICS
Sound Waves

KEYWORDS:

- Sound is a wave phenomenon
  - Frequency $f$
  - Wave length $\lambda$
  - Speed of sound $c$ (=340 m/s)

- Waves interfere

\[
\lambda = \frac{c}{f}
\]

<table>
<thead>
<tr>
<th>$f$ [Hz]</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>5000</th>
<th>10000</th>
<th>20000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$ [m]</td>
<td>17.0</td>
<td>6.8</td>
<td>3.4</td>
<td>1.7</td>
<td>0.68</td>
<td>0.34</td>
<td>0.17</td>
<td>0.068</td>
<td>0.034</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Constructive | Destructive
• A small loudspeaker (monopole) radiates sound in all directions (omni-directional sound wave).
• By combining several loudspeakers in an array, the radiation pattern becomes directional.
• In the target direction the sound waves sum, in other directions they (partially) cancel.
4 monopoles ($f=1\text{kHz}$, spacing=$\lambda/2$)

**Representation:**
- Space-time ($yz-t$)
- Space-frequency ($yz-f$)
- Angle-frequency ($r\theta-f$)

- **Pressure:** $p(y,z,t)$
- **Sound pressure level:** $L_p(y, z)$
- **Polar pattern:** $G(r, \theta)$

10 dB/div
ARRAY PHYSICS

Length and Spacing

BEHAVIOUR OF A PARALLEL-DRIVEN POINT SOURCE ARRAY

Fixed driver spacing, variable array length

Fixed array length, variable driver spacing
$\Delta z = 0.17 \text{ m}$

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Wavelength (m)</th>
</tr>
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<tbody>
<tr>
<td>125 Hz</td>
<td>2.72</td>
</tr>
<tr>
<td>250 Hz</td>
<td>1.36</td>
</tr>
<tr>
<td>500 Hz</td>
<td>0.68</td>
</tr>
<tr>
<td>1 kHz</td>
<td>0.34</td>
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<table>
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<tr>
<th>Loudspeakers (LS)</th>
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<tbody>
<tr>
<td>2</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>16</td>
</tr>
</tbody>
</table>
Effect of array size and wave length:

Beam width $\sim \frac{\lambda}{L}$

Spatial sampling (i.e. driver spacing):

$\Delta z \leq \frac{\lambda}{2}$ (Nyquist criterion)

Note: For directional sources like waveguides this anti-aliasing criterion can be relaxed.
DIRECTIVITY CONTROL
Beamforming technology

AS SHOWN, THERE IS A NEED FOR DIRECTIVITY CONTROL

Objectives:
- Consistent radiation pattern over frequency
- Uniform coverage and frequency response
- Minimize “spill” (e.g., avoid reflective surfaces or reduce outdoor noise pollution)

Methods:
- Mechanical line array optimisation → Minimum interference
- Signal processing → Maximum interference
  - “constant-λ” design, i.e. \( L_{\text{eff}} = C \cdot \lambda \)
  - Beam steering
  - Beam shaping
DIRECTIVITY CONTROL
Beam Steering

Mechanical Aiming versus Electronic Steering

Mechanical aiming

Electronic steering
DIRECTIVITY CONTROL
Beam Steering

Mechanical aiming versus electronic steering

Mechanical aiming

Electronic steering
DIRECTIVITY CONTROL

Beam Steering

- Mechanical aiming
- Electronic steering

Direct + reflected
DIRECTIVITY CONTROL

Some History

Early attempts to control the opening angle ("constant-\(\lambda\)"): 

- Electrical Low-pass filter circuit
- Mid/wide band loudspeaker arrangement
- Barber pole
- Acoustic low-pass filtering
DIRECTIVITY CONTROL

Some History

Electro-Voice LR-4S (1950s)
DIRECTIVITY CONTROL

Some History

UL (1950s)
DIRECTIVITY CONTROL

Some History

“Barber pole” (Philips 1958)
DIRECTIVITY CONTROL
Some History
DIRECTIVITY CONTROL
Advanced techniques

1. **DDC – BEAM STEERING**  
   (Developed and introduced in the early 90-ies by Duran Audio)

2. **DDS – BEAM SHAPING**  
   (Developed and introduced in 1999)
Digital Directivity Control (DDC)

- “Beam Steering”
- Parametric beam control
- Applied in:
  - Intellivox-DC range
$L = 1\lambda$

$\Delta z = 0.17 \text{ m}$

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2 LS

4 LS

8 LS

16 LS
L = \lambda
\Delta z = \lambda / 2

125 Hz (\lambda = 2.72 m)  
250 Hz (\lambda = 1.36 m)  
500 Hz (\lambda = 0.68 m)  
1 kHz (\lambda = 0.34 m)
Frequency independent:

\[ L_{eff}(\lambda) = \text{const} \cdot \lambda \]

Logarithmic positioning:

\[ \Delta z_{\ell} \leq \frac{\lambda_{\text{min}}}{2} \]

Reduction of the number of loudspeakers and signal processing for a given array length
DDC - BEAM STEERING

Beam parameters

DDC beam parameters

WinControl

RS485
A/D

\[ g_1 = \delta(t-t_1) \]

\[ g_2 = \delta(t-t_2) \]

\[ g_3 = \delta(t-t_3) \]

\[ g_N = \delta(t-t_N) \]

IIR

DDC - BEAM STEERING

Block diagram
$z_c = 2.5 \text{ m}$

$z_{ii} = 1.7 \text{ m}$
Opening Angle: 6°
Elevation: -1°
Focus distance: 50 m

Opening Angle: 14°
Elevation: -1°
Focus distance: 50 m

Opening Angle: 6°
Elevation: -5°
Focus distance: 50 m

Opening Angle: 6°
Elevation: -1°
Focus distance: 10 m
Typical use

- Single lobe, horizontal plane
- Single lobe, tilted plane
- Dual lobe, horizontal + tilted plane
• Simple and intuitive parametric control
  • Opening angle
  • Aiming angle
  • Focus distance
• Constant SPL over distance (up to 70m)
• Large direct-to-reverberant ratio
• High speech intelligibility

• Most suitable for flat audience areas
• Mounting height restrictions:
  • Offset between acoustic center and audience plane
    0.3-0.6 m (~1-2 ft.)
BEYOND BEAM STEERING...

What if:
- we could not only steer but also shape the beam?
- we could extend the frequency response?
- we could control bass?
Digital Directivity Synthesis (DDS)
Invert the desired “illumination” of the room to the array.
Boundary conditions:
- Minimum sound power
- Minimum “spill”
- Robustness & Stability
Digital Directivity Synthesis (DDS)

- “Beam Shaping”
- Beam can be adapted to geometry of the room
- Applied in:
  - Intellivox-DS(X) range
Digital Directivity Synthesis (DDS)

Invert the desired “illumination” of the room to the array.

Boundary conditions:
- Minimum sound power
- Minimum “spill”
- Robustness & Stability
DDS - BEAM SHAPING
DDS - BEAM SHAPING

Upload Process

- DDA (User Edition)
- DDA exchange file
- WinControl
- RS485
DDS BEAMFORMING
Block Diagram

A/D → IIR → FIR1 → \( \delta(t-t_1) \) → \( g_1 \)

A/D → IIR → FIR2 → \( \delta(t-t_2) \) → \( g_2 \)

A/D → IIR → FIR3 → \( \delta(t-t_3) \) → \( g_3 \)

A/D → IIR → FIR N → \( \delta(t-t_N) \) → \( g_N \)
SWEDISH PARLIAMENT

- Fan-shaped hall
- Reflective curved back wall
- 2x Intellivox-4c-XL (predecessor of Intellivox-DS430)
• Swedish Parliament
  – Fan-shaped hall
  – Reflective curved back wall
DDS - BEAM SHAPING
Intellivox Application Example

Weights (priority factors)

Desired direct SPL distribution
Realized direct SPL distribution

Far field polar pattern
Flexible array set-up
Tailor-made directivity pattern
  - Requires (basic) 3D geometric model of space → SketchUp® + Plugin
Constant spectral balance for all listening positions
Optimum direct-to-reverberant energy ratio
Both far field and near field control
Directivity pattern can be changed by software, i.e., without re-angling the boxes
Intellivox-DS430

H = 2.5 m
Δz = 0.8 m

H = 4.5 m
Δz = 2.8 m
Intellivox-DS430

H=2.5 m  \Delta z = 0.8 m

H=4.5 m  \Delta z = 2.8 m
<D/R> = -4.6 dB

<D/R> = -7.0 dB

V = 6,400 m³
RT = 3 s
<STI>=0.50

<STI>=0.45

V=6,400 m³
RT=3 s
Conclusions:

- Larger mounting height
  - Larger steering angle & wider dispersion
  - Lower D/R ratio
  - Poorer speech intelligibility and musical clarity

Extremely large steering angles don’t make sense!
CONTROLLING BASS

1. WHAT ARE BEAM-SHAPED DIFFERENTIAL SUBWOOFER ARRAYS?

2. ACOUSTIC MODELLING BY PSM-BEM

3. VALIDATION OF PSM-BEM BY MEASUREMENTS

4. SUMMARY AND CONCLUSIONS
Normal versus cardioid bass arrays

Cardioid bass array

Normal bass array
SUBWOOFER ARRAYS
“Summing”

Directivity:

\[ Q \propto \frac{L}{\lambda} \quad DI = 10 \log(Q) \]

Gain and robustness:

\[ G_{array} = 10 \log \left( \frac{P_{array}^2(f)}{\sum_{l=1}^{L} P_l^2(f)} \right) \]
SUBWOOFER ARRAYS
“Differential”

+ “Superdirectional”, i.e., high Q for small $L/\lambda$
- Less robust than delay-and-sum arrays

1x B-215DIFF

Front

Back

3x B-07

80 Hz
• Combination of delay-and-sum and differential array
• DDS-optimised
  – Requires an accurate model of each box
Point Source Model (PSM)

- Each loudspeaker in the array is represented by a point source with a certain directivity.
- Radiation into free space (free field conditions).
Benefits:
- Computationally efficient
- Only one directivity function for each loudspeaker type

Shortcomings:
- No LF 'coupling' between stacked subwoofers
  - In reality, sensitivity of each box depends on stack size
- No modelling of LF diffraction around array
  - In reality, directivity and F/B ratio of each box depends on stack size
- No accurate ground plane modelling (i.e., half-space) possible with simple mirror image source model

POINT SOURCE MODEL (PSM)
COUPLING EFFECTS
ARRAY SIZE AND LOUDSPEAKER POSITION

Free field

Magnitude (6 dB/div)
COUPLING EFFECTS

Boundary plane

Magnitude (6 dB/div)
Idea:
- Each loudspeaker in the array is modelled as a directional point source
- BEM is applied to calculate directivity functions of loudspeaker facing the actual Acoustic Boundary Conditions (ABC), including half space conditions

Benefits:
- One-time only calculation of directivity library for various ABC
- Library can be easily extended
- Computationally efficient simulation
Procedure:

- Measure normal component of particle velocity in front of cone and ports of subwoofer
- Make finite boundary element model of subwoofer array
- Calculate pressure distribution on boundaries using either full-space or half-space version of Helmholtz Integral Equation (HIE)
- From the measured velocity and the calculated pressure distribution, calculate directivity balloons for active subwoofer
BEM CALCULATION EXAMPLE

Set-up

Free-Field  3U1 full-space  3U1 half-space
Normal particle velocity @80 Hz

Free-Field  3U1 full-space  3U1 half-space
BEM CALCULATION EXAMPLE

SPL @80 Hz

Free-Field  3U1 full-space  3U1 half-space
BEM CALCULATION EXAMPLE

Balloon @80 Hz

Free-Field

3U1 full-space

3U1 half-space
Sensitivity

Front-to-back ratio
VALIDATION PSM-BEM MODEL

\[ R = 7 \text{ m} \]

\[ \Delta \phi = 10^\circ \]

2x B-121
VALIDATION PSM-BEM MODEL

Cardioid
Hyper-cardioid
Dipole

Theoretical

Predicted
(63 Hz octave)
MEASUREMENT RESULTS
Cardiod setting

Mean array parameters:

DI = 4.9 dB

$G_{array} = 1.4$ dB
MEASUREMENT RESULTS
Dipole setting

Mean array parameters:

\[ \text{DI} = 5.3 \text{ dB} \]

\[ G_{\text{array}} = -0.5 \text{ dB} \]
HOW DOES IT WORK IN PRACTICE?

DDS Geo method

Desired direct SPL

Realised direct SPL

Weights

Directivity balloon

DDA Software
HOW DOES IT WORK IN PRACTICE?

DDS Balloon method

Desired radiation pattern

Realised direct SPL

DDA Software

Directivity balloon
Summary & Conclusions

- Hybrid PSM-BEM model handles
  - Full-space
  - Half-space
  - Various array lengths
- Very accurate modelling of beam-shaped differential subwoofer arrays
- Large front-to-back ratio of cardioid subwoofer arrays
- Good Robustness, i.e. array response not sensitive to small deviations in sensitivity of individual drivers