PAM’s story

Parametric Acoustic Modelling

A Structured Approach to Loudspeaker Design and Guided Media Acoustics

Presentation by Graeme Huon

IP, Patent applications apply

Parametric Acoustic Modelling – integrated design

The year 2000 Australian Centenary celebrations needed a portable loudspeaker capable of reproducing a cathedral Organ in any venue for Mahler's Eighth Symphony

Parametric Acoustic Modelling (PAM) was used to design a compact loudspeaker with response from 16 Hz – 70Hz ±1dB at 125dB SPL and with less than 2%THD/IMD

What is PAM?

Melbourne Exhibition buildings (Sans Organ)

Evolution of the Loudspeaker Part 1 - Waves, always waves!

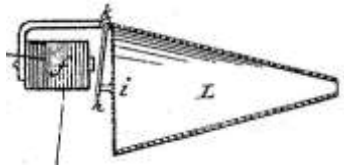
Shofar (Gericho)
~7000 BCE

iPhone (New York)
2016 CE

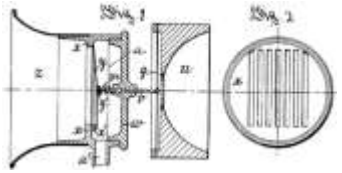
Evolution of the Loudspeaker Part 2 – The motor

Reis (1851)
magnetostriction

Meucci (1856)
Moving iron

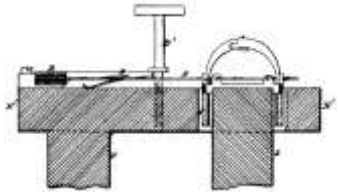


Bell (1876)
Rocking armature

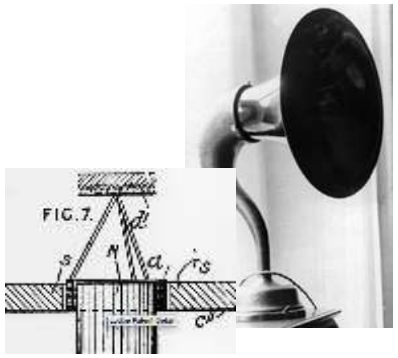


Short-Parsons (1898)
Compressed air
Auxetophone
http://www.youtube.com/user/ReneRondeau

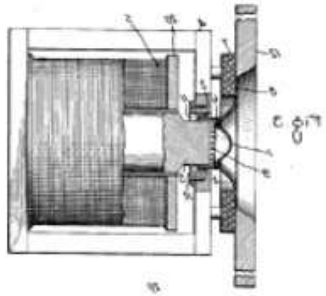
Moving coil designs



Ernst Siemens (1874)



Lodge (1898)



Rice–Kellogg (1924)

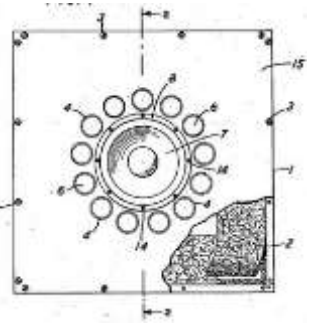
Adding a cabinet

Egyptian frame drum
1500 BCE

Atwater Kent
1926 CE

Open back cabinet

African skin drum
300 BCE



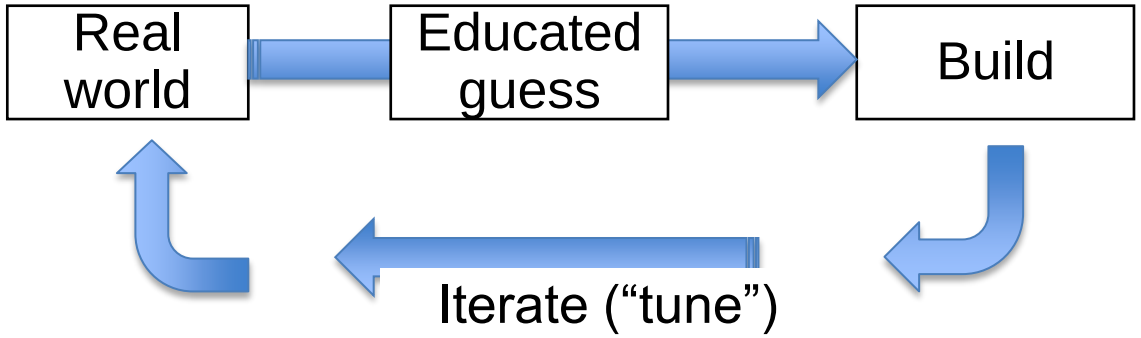
Bass reflex
Thuras (1932)

Vented box

Membranophone
~3000 BCE

Acoustic Research
1956 CE

Sealed box



Evolutionary design

House “rules of thumb”

Bigger magnets, voice-coils make better speakers
Bigger are more costly and heavier, give bad bass
Light cones are louder, Light cones distort
Good bass needs big boxes, big boxes cost money, big boxes sound “flappy”

The quest for the best loudspeaker materials (ongoing):

(Alnico, aluminium, bamboo, bananas, carbon fibre, copper, diamond, ferrite, flax, glass, glass fibre, kevlar, magnesium, mylar, neodymium, Nubian ear wax, paper, polypropylene, Stradivarius varnish, titanium etc)

Core belief:
There must be a magic enclosure design – if only we could find it!

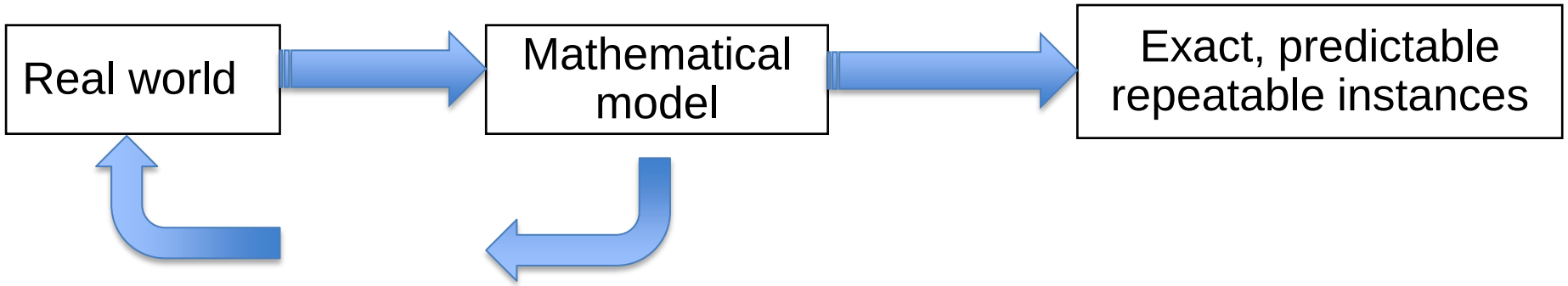
Evolution Part 3 - Lumped theory (1958, Neville Thiele)

Radiated sound comes from the movement (velocity) of the cone

- Cone moves air
- Moving air creates (radiates) waves
- Therefore need to determine cone movement with frequency

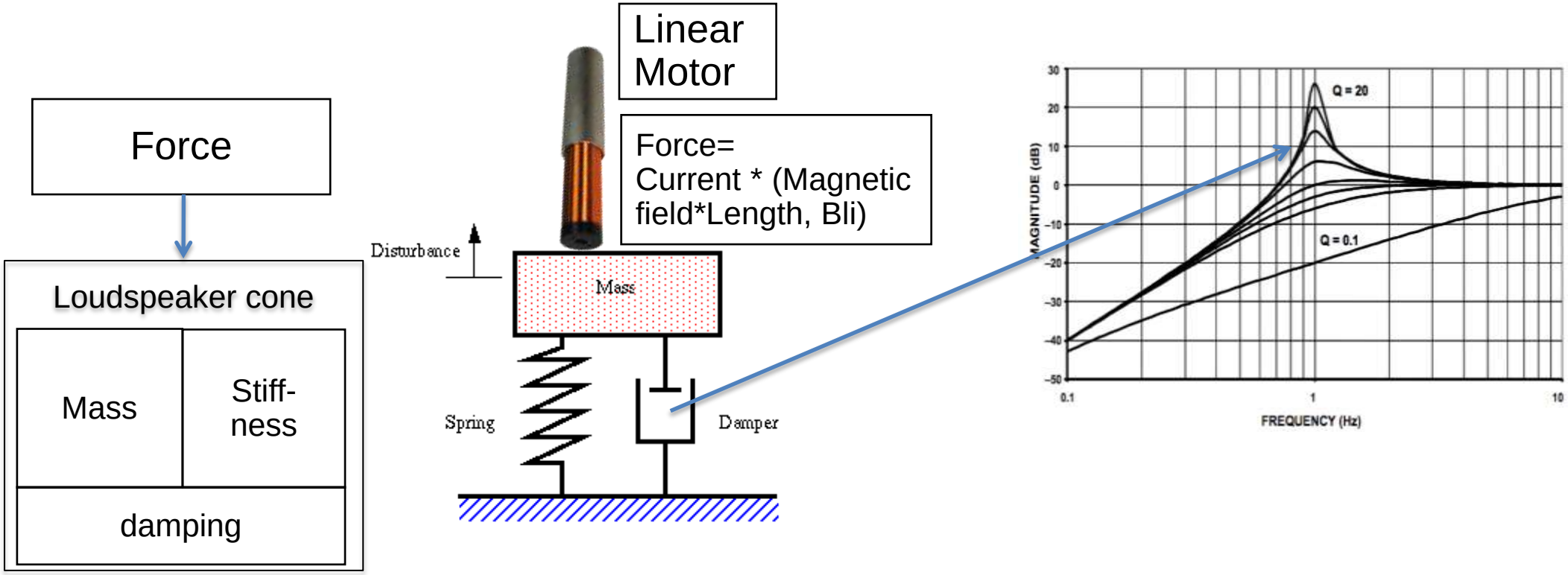
Neville saw this mathematically - as a second order electromechanical filter

$$T(s) = \frac{s^2}{s^2 + k_1 s + k_2}$$



Thiele-Small parameters (2)

The bare loudspeaker is a 2nd order system (low frequencies)



Parameters are *lumped* (mass, stiffness, damping)

Add a (sealed) enclosure to the back of the loudspeaker

1. Front and back waves separated (useful!)
2. Overall Stiffness, mass (and damping) change, BUT

Still the same second order system!

- Same mathematical form - just change the co-efficients
- Thiele-Small parameters!

A vented box is a new (4th order) equation

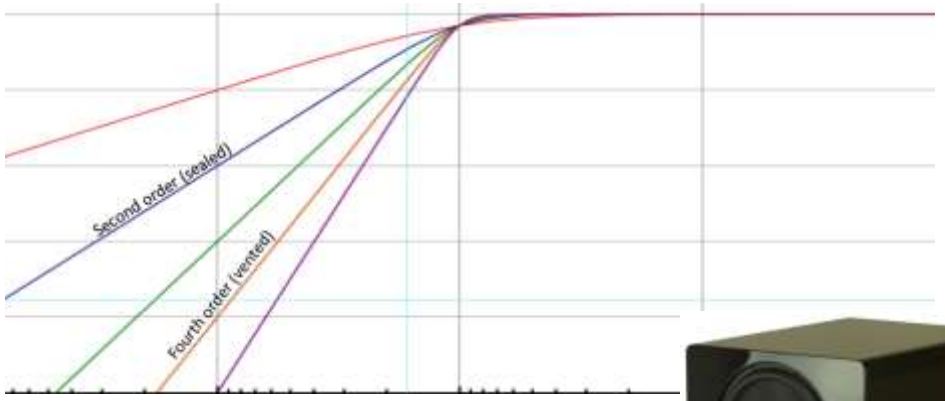
$$F(s) = \frac{s^4}{s^4 + k_1 s^3 + k_2 s^2 + k_3 s + k_4} = \frac{s^4}{(s^2 + As + B)(s^2 + Cs + D)}$$

Two interacting resonant parameter sets

- Fv (A/l), Fs, Fb, Qs, Qb, Cmb (Qv assumed)
- E.g. Butterworth

Cone travel changed

- Good for distortion reduction at cut-off
- Bad for distortion below cut-off

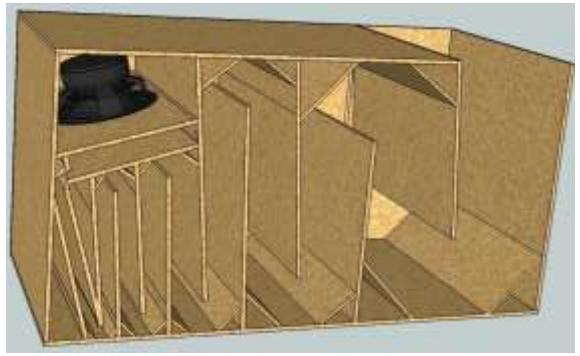


Interlude - the quest for the magic box design

There is no magic box design!

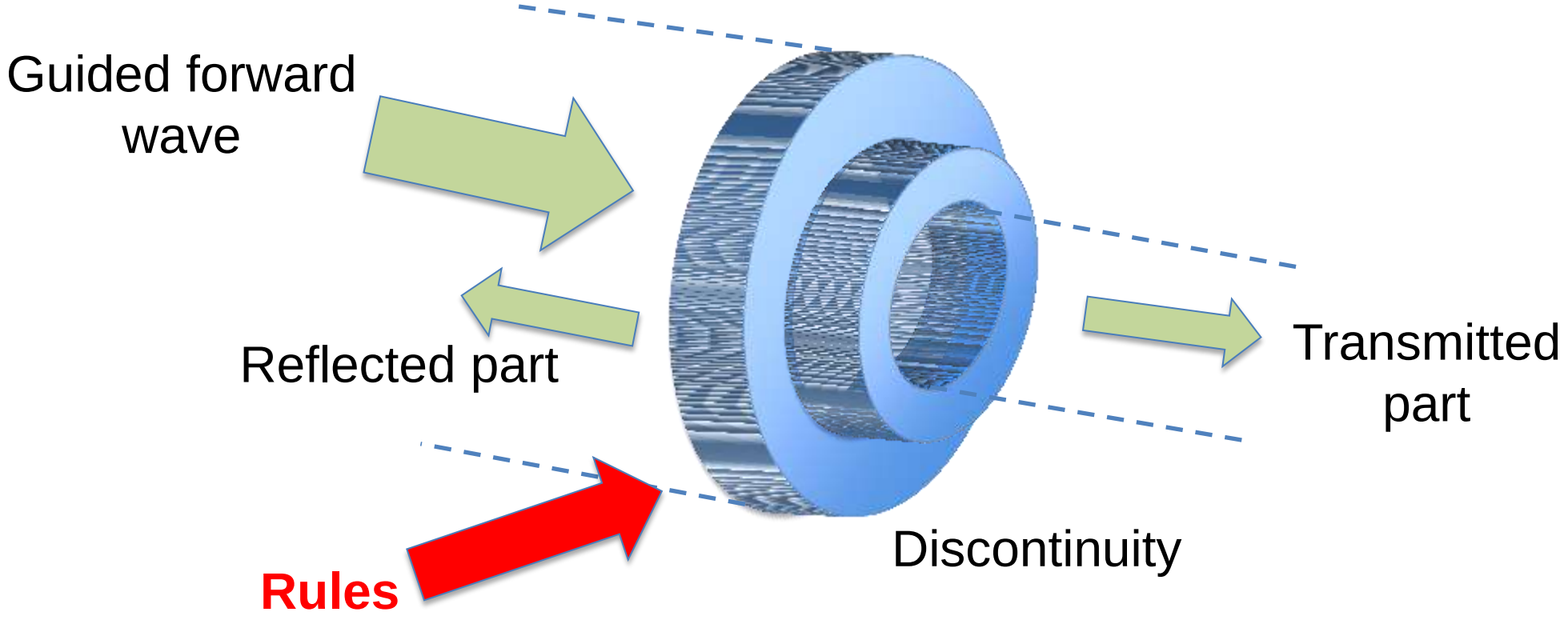
- There is a known trade-off between efficiency, cut-off frequency and box volume
- You can do worse, but not better!

Ref. Jeffrey Harrison “ An integral limitation upon loudspeaker frequency response and enclosure volume” JAES Vol 44 No. 12 December 1996 Pp 1097 – 1103.



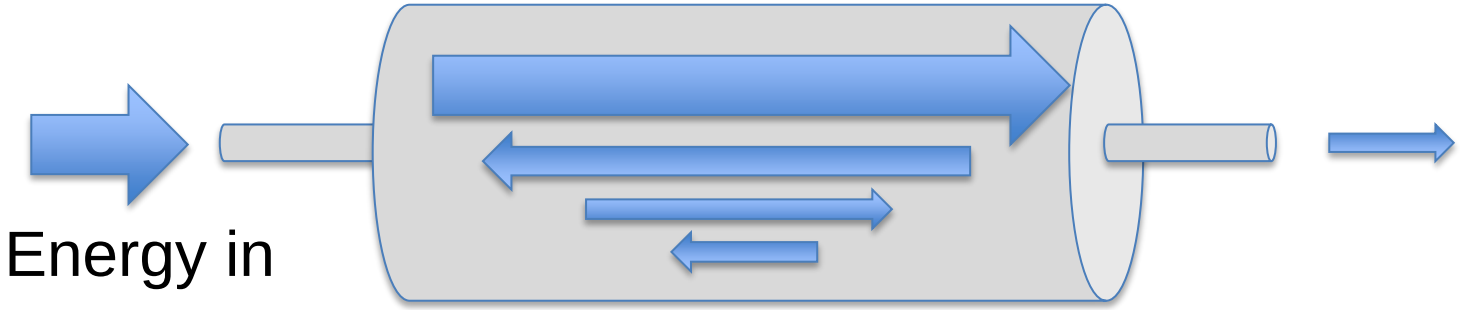
Evolution Part 4 – Distributed theory

Parametric Acoustic Modelling (Huon-Cambrell 1995)



Ref. Huon, Cambrell – "A new low frequency enclosure configuration" Preprint 4038 AES 5th Australian Regional Conference
US patent 6,223,853 – Huon et al. "Loudspeaker incorporating acoustic waveguide and method of construction".

Multiple Reflections



Frequency domain:

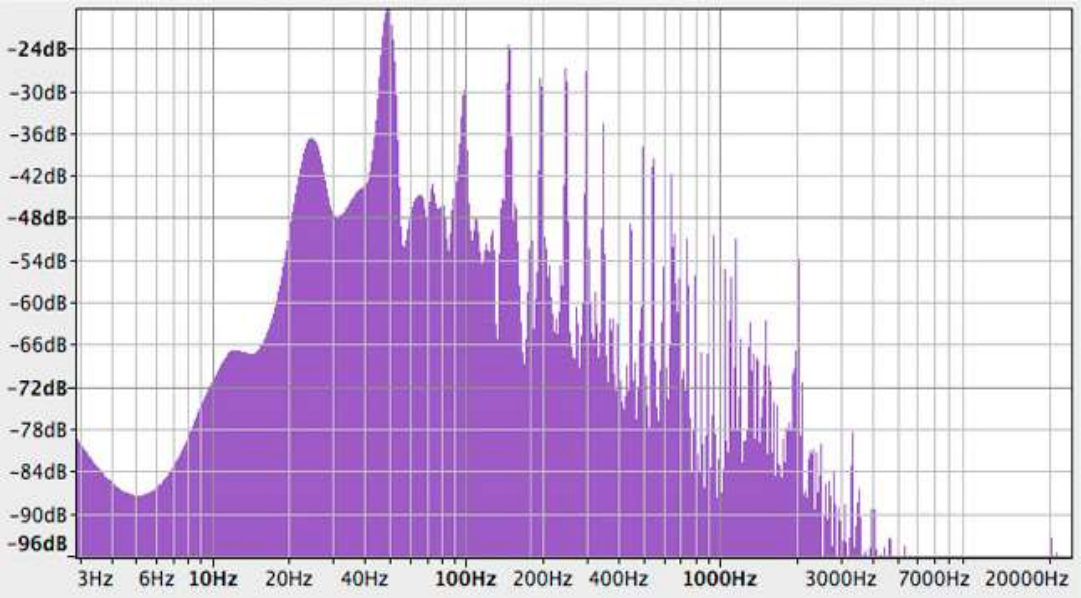
F(0), F(1), F(2) +F(3).....= f, 2f, 3f, 4f, ...

Plucked string analogy

Piano single G note = 60 overtones plus

All sections interact

More complex than strings



Ref: Audacity forum

Parametric Acoustic Modelling “rules”

Energy splits according to energy balance (impedance)

- Amplitude and phase

Can have multiple transmissions, reflections, attenuation

- Infinite series
- Complex

Can have path splits, combines

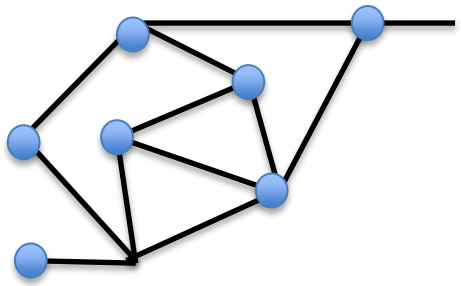
- Very complex

Forced to use distributed analysis techniques

- Distance (time), impedance, loss
- Compare with Thiele-Small lumped parameters

Making PAM easier

1. Recognise guided acoustics as a mesh
   - Transmission line paths and nodes
   - Can use network solvers (E.g. SPICE)



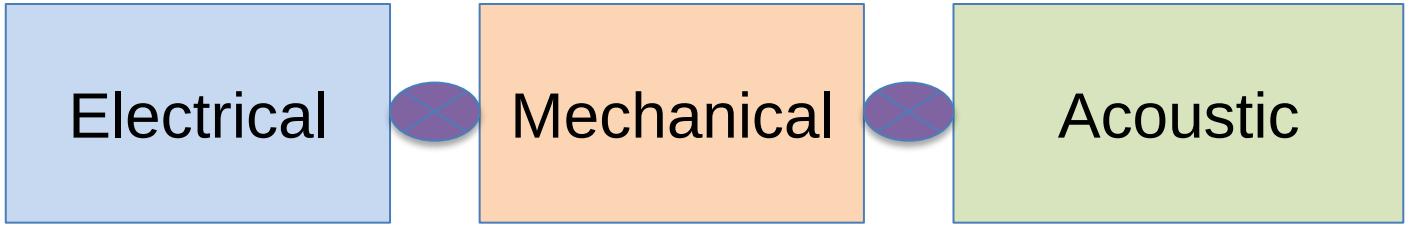
2. Can extend to other domains:

Acoustic to mechanical - needs “force over an area”

- Cone velocity

Mechanical to electrical - needs a “motor”

- Current



*SPICE – UC Berkeley: Simulation Program with Integrated Circuit Emphasis

Making PAM easier (2)

Other domain rules

Electrical domain – Voltage and current (electrical impedance = V/I)

Mechanical domain - Force and velocity (mechanical impedance = Force/Velocity

Acoustic domain – Pressure and velocity (acoustic impedance = Pressure/velocity

Domain transforms

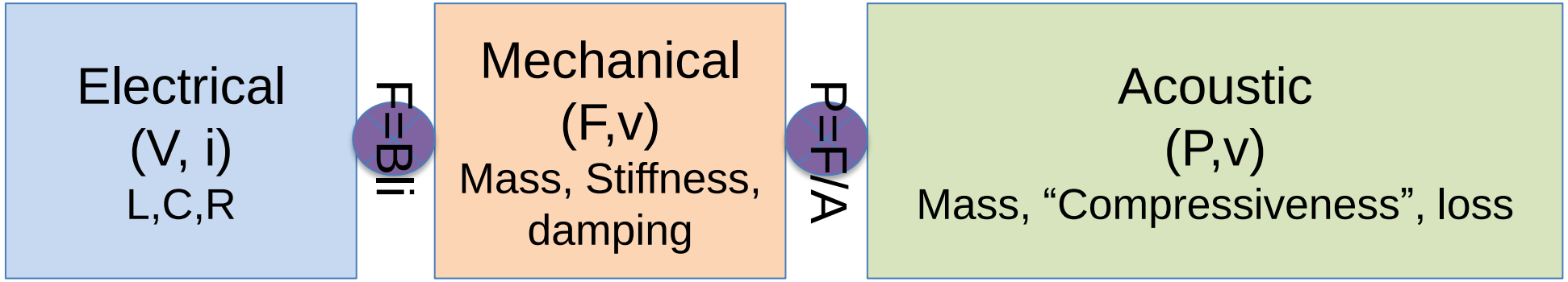
Match the “Flow” (or through) and “Potential” (or across) variables by scaling

PAM domain linking

4. Combine the domains

Unified “Force-Response” based model

Scale and match node “potentials”



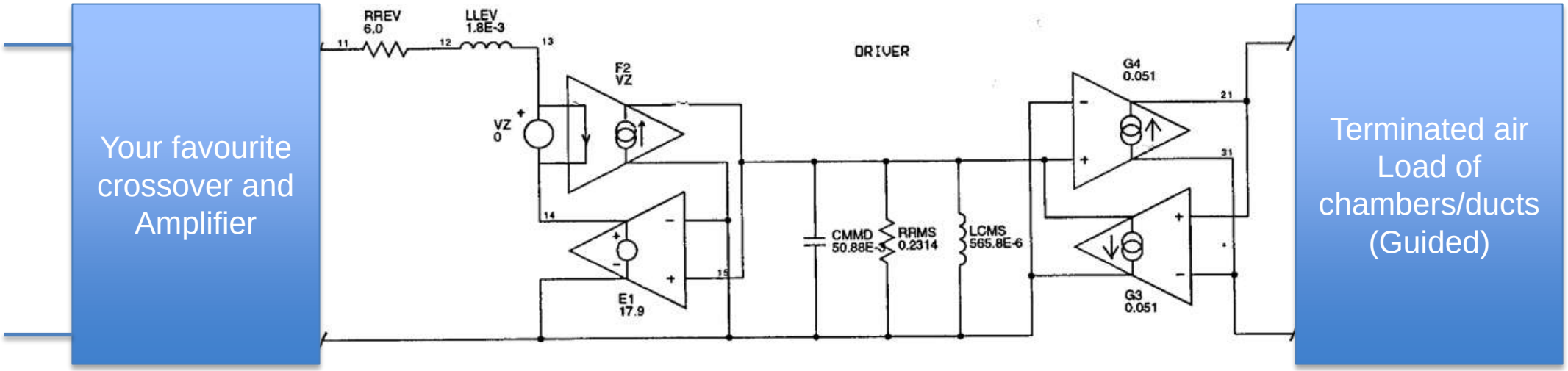
Electrical-mechanical: F=Bli,

Mechanical – acoustic P=F/A

Full end-to-end response!

Reciprocal – Downstream changes reflect upstream

Example: Loudspeaker motor

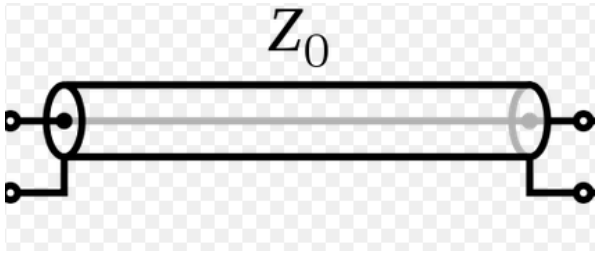


"Natural" parameters are convenient (mass, stiffness, damping)

Eg. F=ma, mass=force/(rate of change of velocity)

Can convert to/from Thiele/Small from/to Natural parameters

Acoustic domain - transmission line waveguides



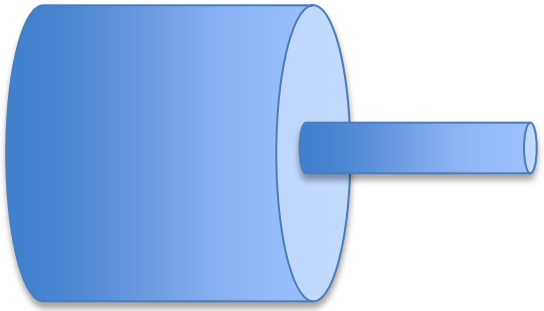
$Z_0=\rho_o c_o/A$ Length=$c_o t$

Boxes are now Impedance-time devices that trap volume
Energy divides at each impedance change

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

7. Express gas volumes as Areas (impedance) x length (time)

Rear chamber = 250mm dia pipe
l=700mm long
Zo=8420 (Ohm)
t=2.04msec
Volume =34.4 litre



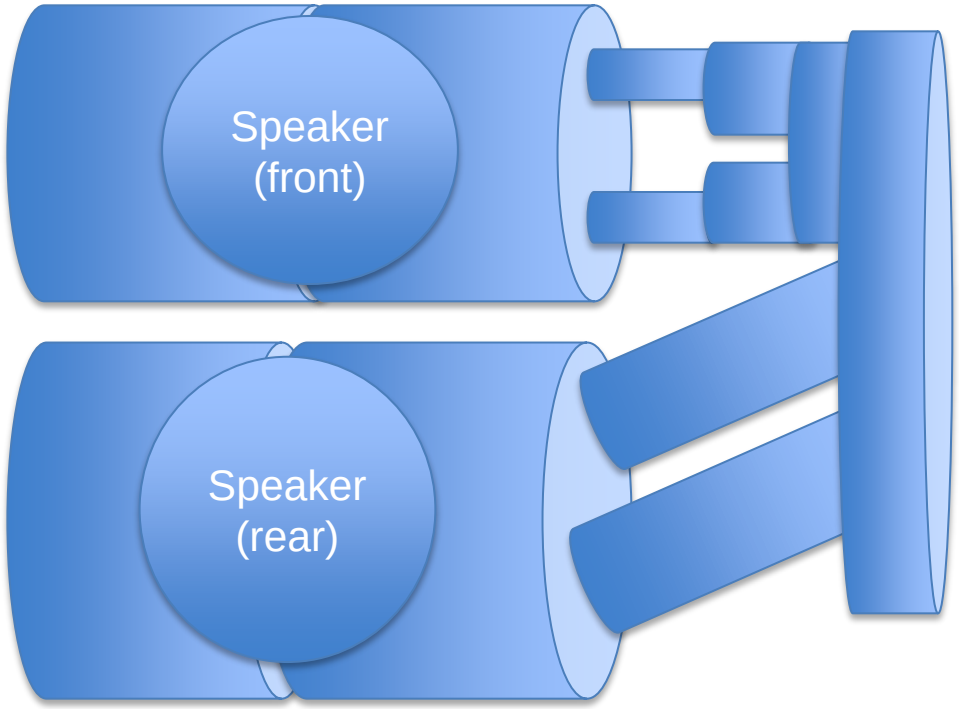
Vent = 100mm dia pipe, l=300mm
Zo=52,600(Ohm), t=874usec
Volume =2.36 litre

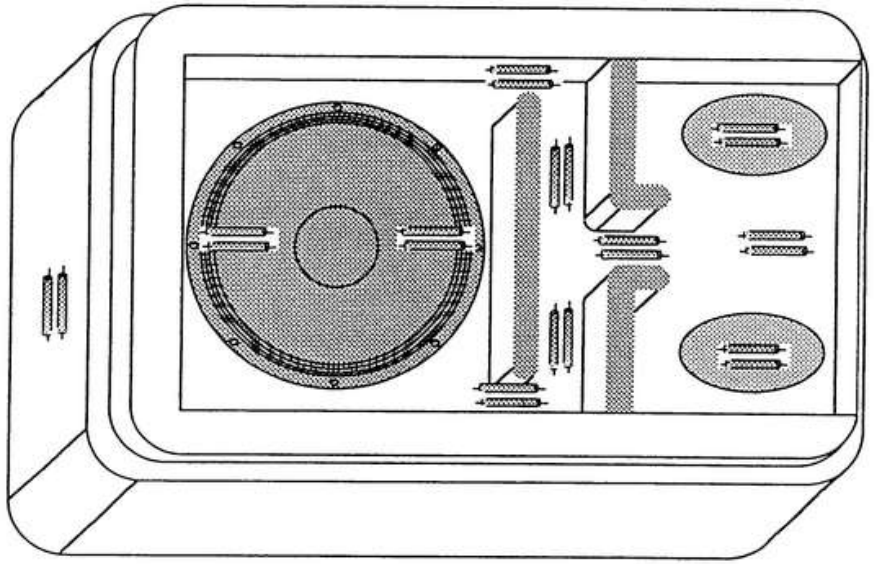
Transmission line acoustic waveguides - 2

Example TLB320 (Profunder) (Refer US Pat. 6223853)

Loudspeaker front Tx labrynth filter:

- First (front) chamber has “no-flow” stub and outlet port(s)
- Front and rear chambers both terminate into the room





Putting it all together (example)

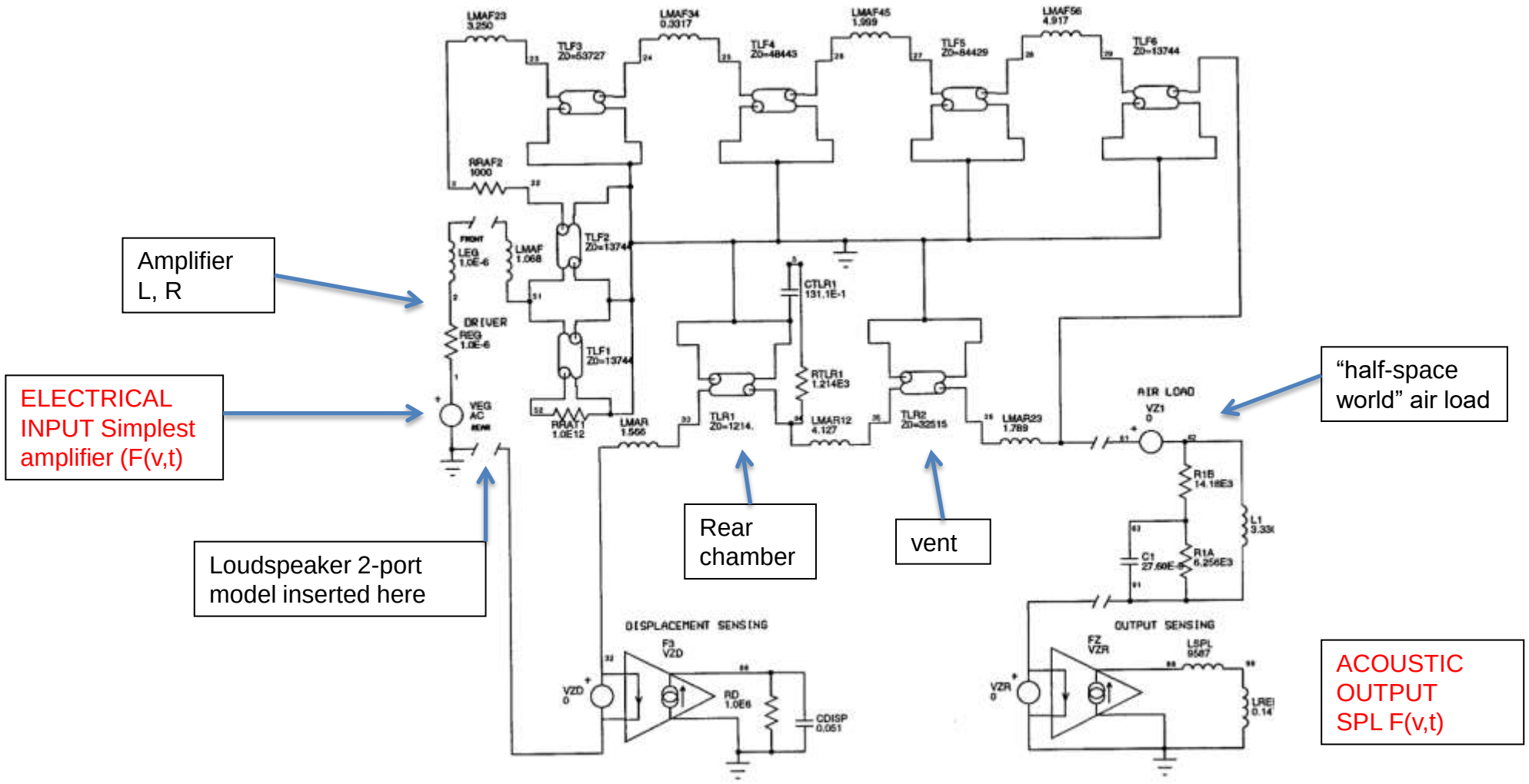
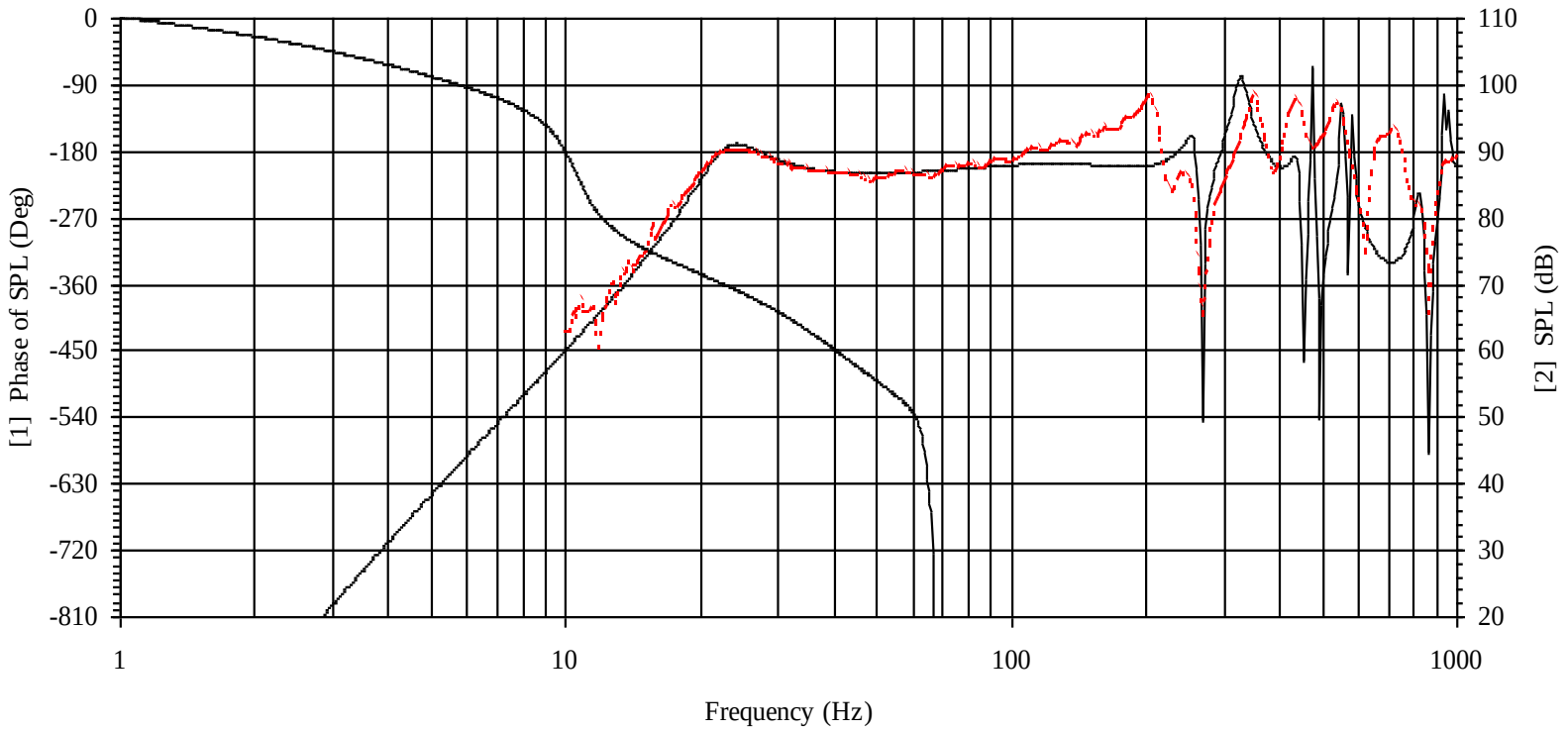


Figure 9: Equivalent circuit of new enclosure design example as analysed with SPICE.

Theory versus practice – Does it work?

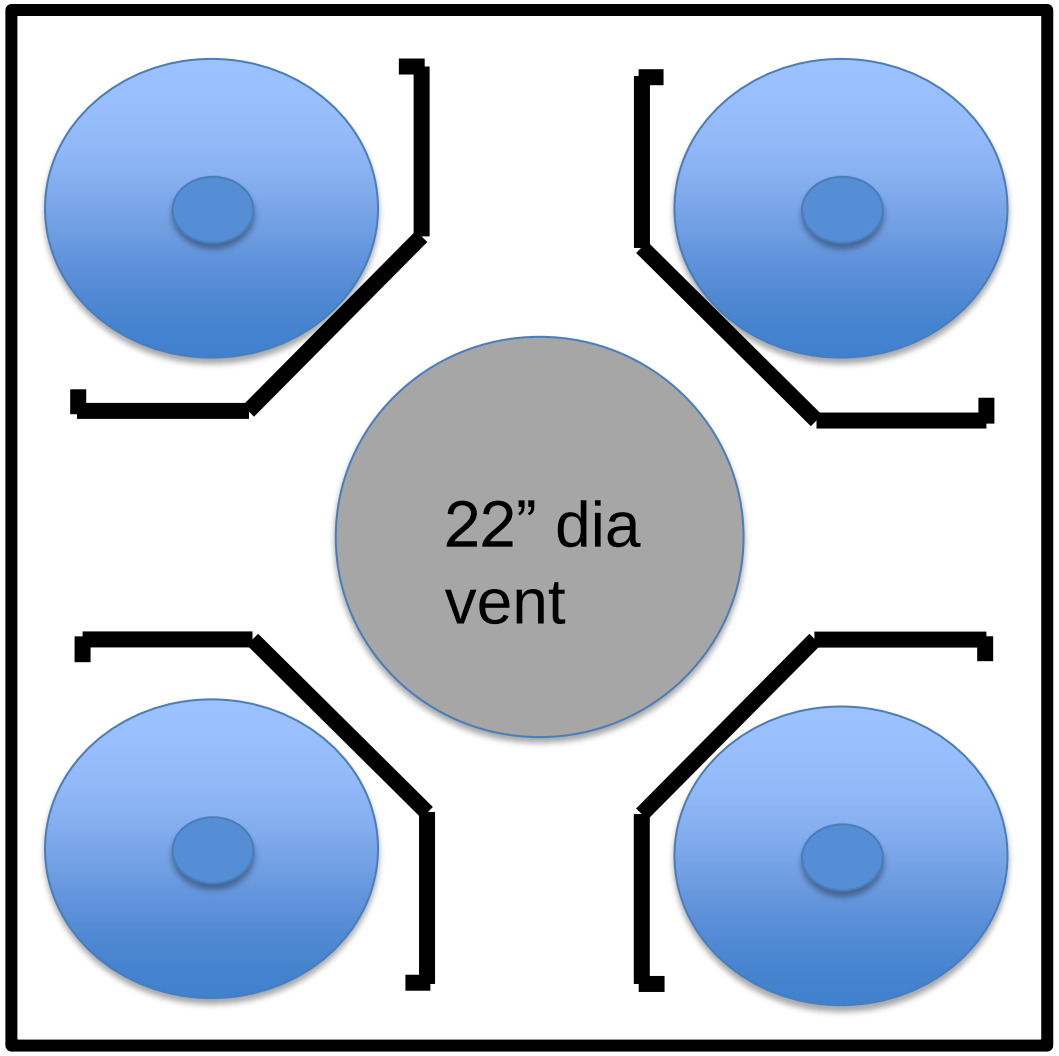


More importantly, response tailoring has been done losslessly with reactances

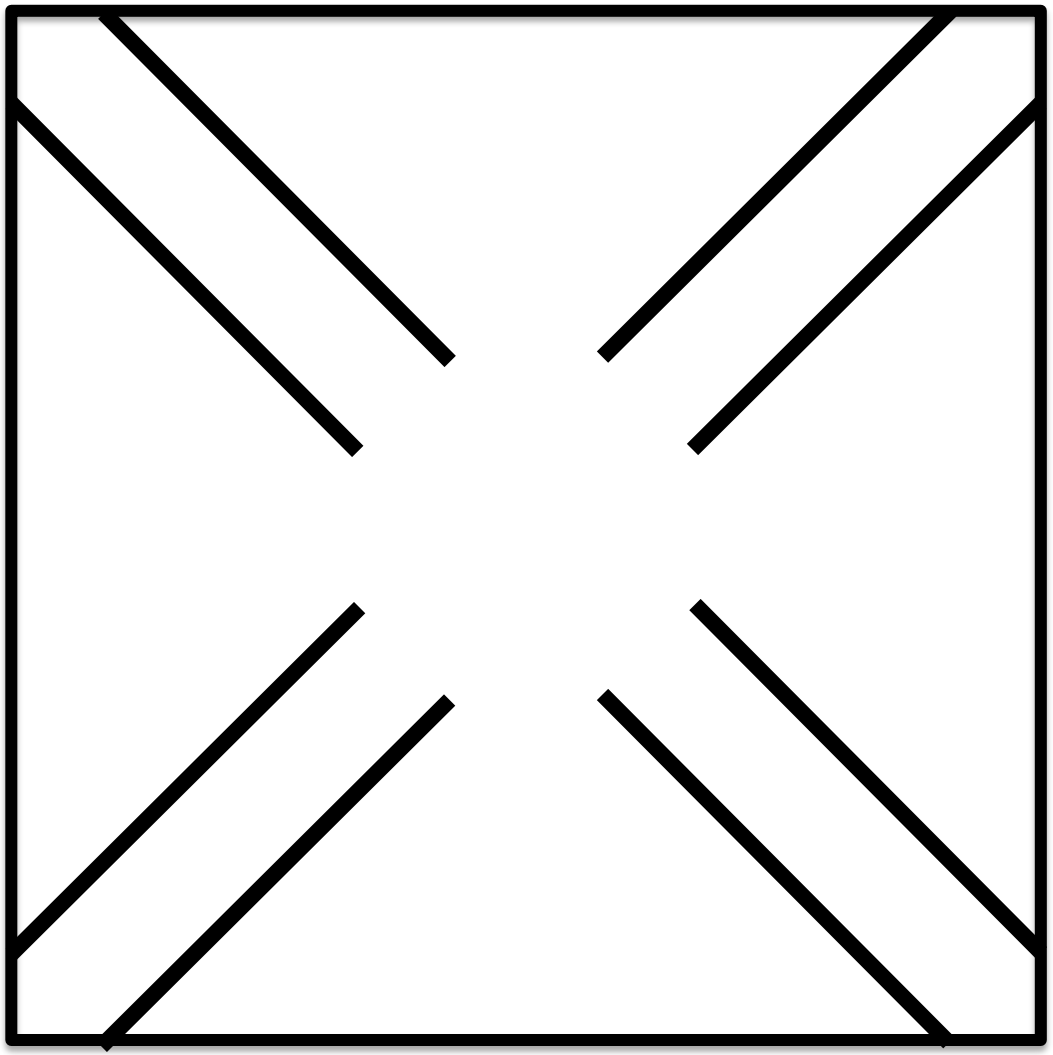
- More accurately tailored
- Highest possible efficiency

Example taken from US patent 6,223,853 – Huon et al

Profunder 616 design



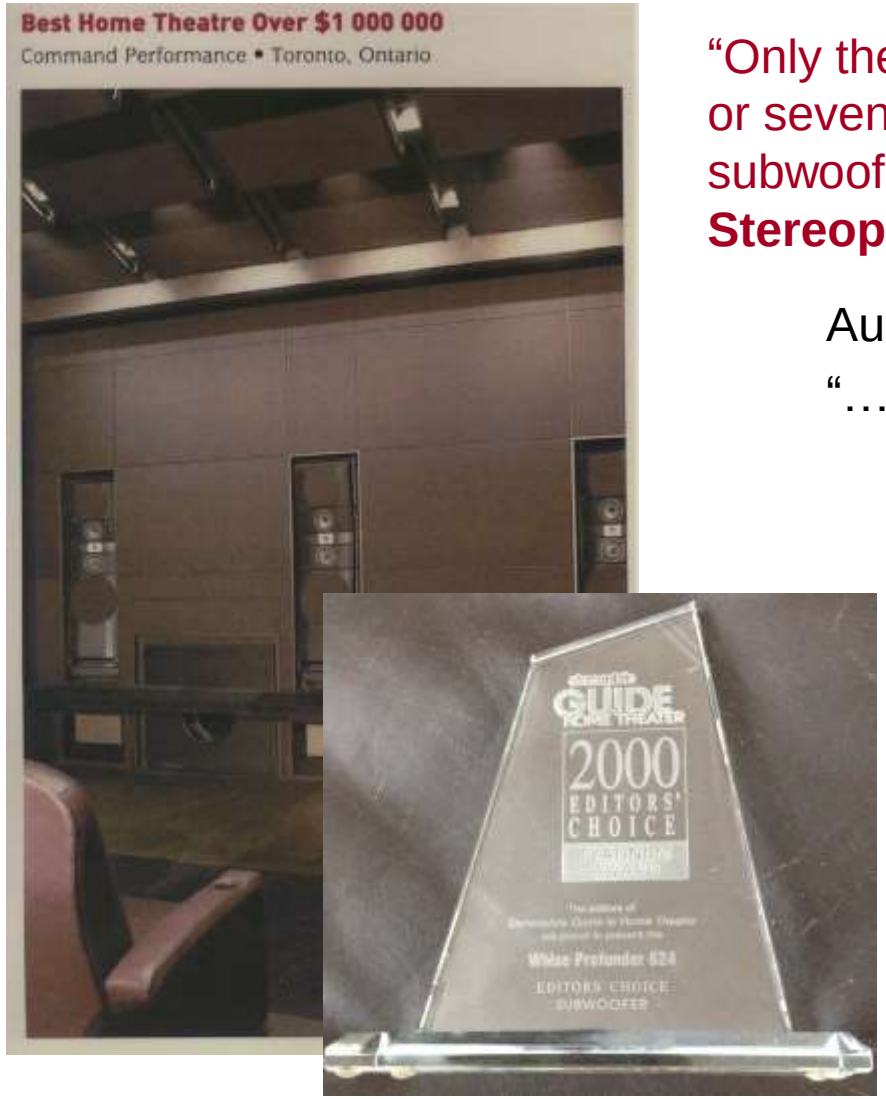
Front – 15” woofers x 4 (cover removed)



Rear internal - stub equalisers x 4

IP restrictions, Patents and applications apply

Proof of the PAM pudding –Whise Profunder, Techtonic (USA)



"Only the fact that we haven't tried, say a stack of four Velodyne HGS 18's or seven Paradigm Servo -15s keeps the Whise from bumping every other subwoofer out of class AAA and throwing our subwoofer ratings into chaos!"
Stereophile Guide to Home Theater April 2000, Page 55

Audio USA, September 1999

"…the loudest, cleanest bass I have heard...besting all other subwoofers I have tested" DB Keele Jr

"The impact and quality of the (Whise) bass is unsurpassed in my experience by any other system small enough to move."

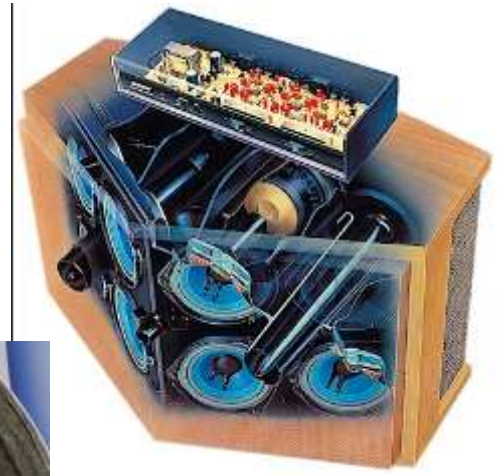
"The performance is simply mind blowing. I know of no other word that describes it. The detail is outstanding. There is no mistaking the step upward in increased detail, lower distortion and dramatically greater dynamic range"

Thomas J Norton Stereophile Guide to Home Theater, July-August 1999

Exploiting Parametric Acoustic Modelling

Basic PAM enables:

- Amplifier parameter inclusion (eg. response, driving point impedance distortion (overdrive/clipping-recovery, failure modes))
- Crossover and filter parameters (digital, analogue, passive)
- Passive crossover – loudspeaker interactions
- Protection devices (e.g. Guardian)
- Full time alignment and propagation adjustment
- Simple/complex enclosures/vents, ”interesting” box designs
- “Interesting” loudspeaker drivers

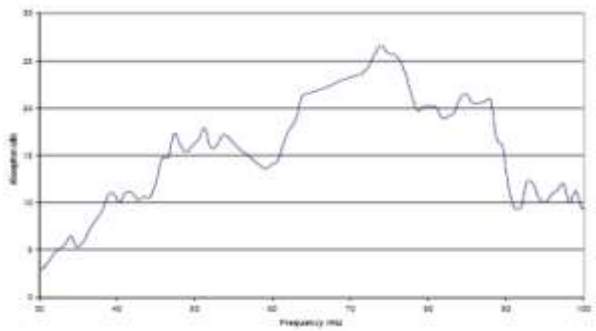


Electrical ⊗ Mechanical ⊗ Acoustic

Exploiting Parametric Acoustic Modelling (2)

Bass “trapping”

- Passive
- Variable damping active
- Active (point cancellation)



MSR Inc. Dimension4 SpringTrap™

“Alternate Cascade” Acoustic designs

- Acoustic “current drive” (High to low P/V)
- Acoustic “voltage drive” (Low to high P/V)
- E.g. Room couplers/cancellers, car couplers

Parametric Acoustic Modelling - beyond the basic loudspeaker box

Multiple paths and multiple drivers catered for

- Basic loudspeaker/aperture summing and directivity

Cascaded elements allow stepped approximations

- Generic acoustic filter design (front and rear)
- Acoustic stubs, filters
- Mufflers

Mechano-acoustic part handles passive structures

- Structure-born noise and vibration
- ¼, ½ wave diffusers/diffractors
- Leaky, lossy acoustic structures

Non-linear media

- (Step-incremented acoustic impedance, loss modelling)

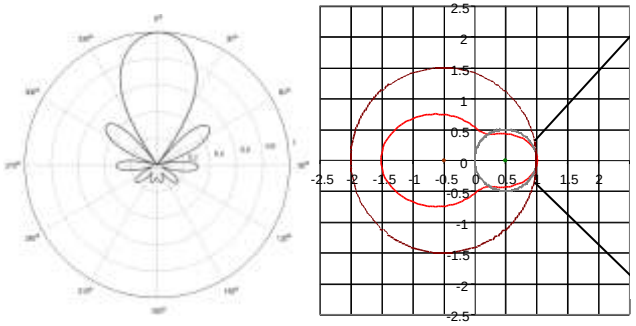
Parametric Acoustic Modelling extensions

Cascaded elements allow stepped approximations to (e.g.) horns

- Generic acoustic filter and horn design (front and rear)
- Aperture directivity
- Leaky acoustic structures
- Non-linear media (e.g. Stepped acoustic impedance, loss)

Amplitude-phase line of flight (“Ray Tracing”) extensions (tools)

- Allow unguided combining of PAM sources
- Multiple sources, multiple drivers
- Array analysis and simulation
- Listening room loads and room propagation
- Controlled directivity studies



Some further PAM “discoveries”

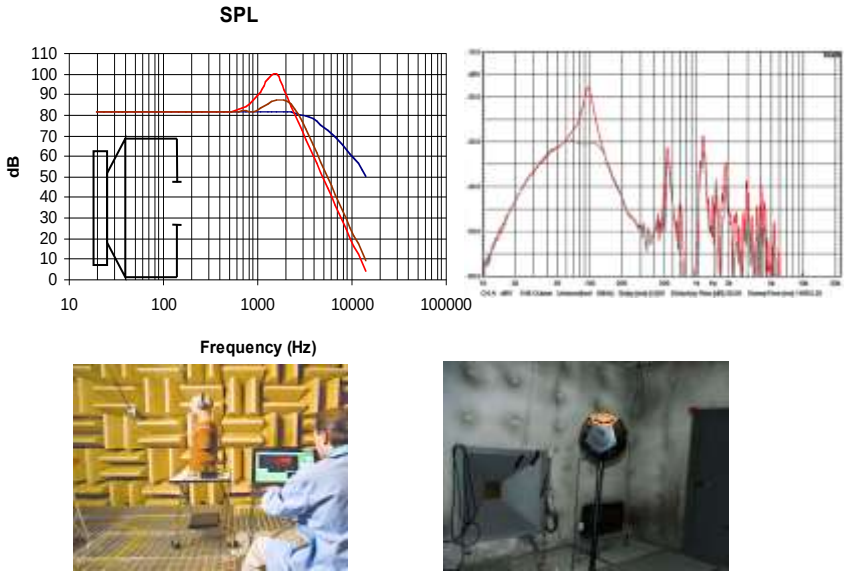
Aperture peaked designs and distortion gain
- Includes band-pass (double-resonant) boxes

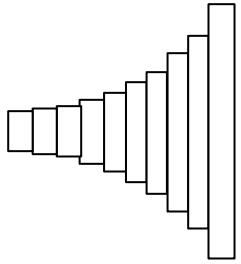
New acoustic damping approaches
- Reactive and lossy materials can be modelled
- Variable density and variable geometry absorbers
  - Eg. Anechoic chambers

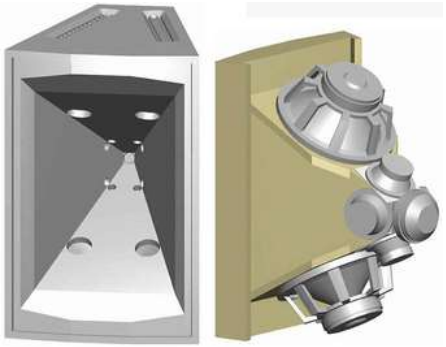
Distributed Multi-driver horns (multiple entry)
- E.g. Renkus-Heinz and Servodrive (Tom Danley)

Reactive (non-dissipative) equalisation, stubs
- E.g. Vent tube equalisers (Profunder 319, 616)

Flares, Horns etc. modelled as cascaded structures







A word about the driver

Excellent!

PAM designs (eg. Profunder 320) provide reasonable cone loading - Driver design not as critical, BUT

Driver must be very low distortion

- Profunder 624 (ITU 775 Post production specification) - 24 – 100 Hz (-3dB) – 121dB spl.
- Inaudible
- Less than 2% THD/IMD (1.6% measured)

Ref. Mike Barabasz “Practical challenges of manufacturing loudspeakers to critical design parameters” AES 5th Regional Convention April 1995 Preprint 4039

LORANTZ
Melbourne Australia

Parametric Acoustic Modelling

Waves for loudspeakers and beyond