
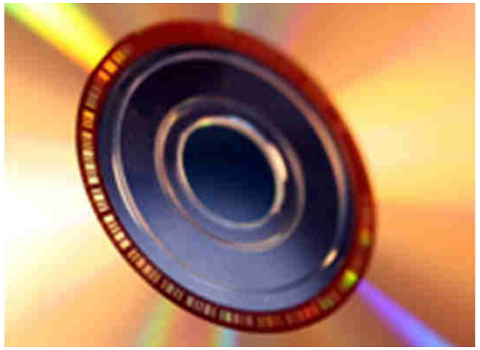
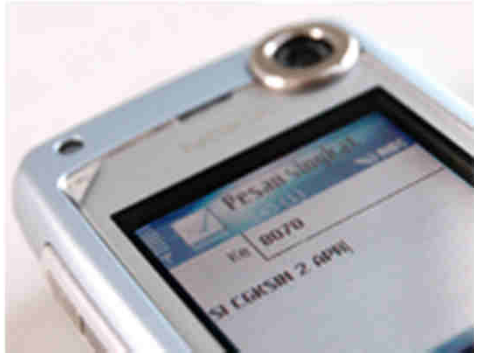

BASICS OF ROOM ACOUSTICS

Study aid to learn Communication acoustics, VIHIAM 000

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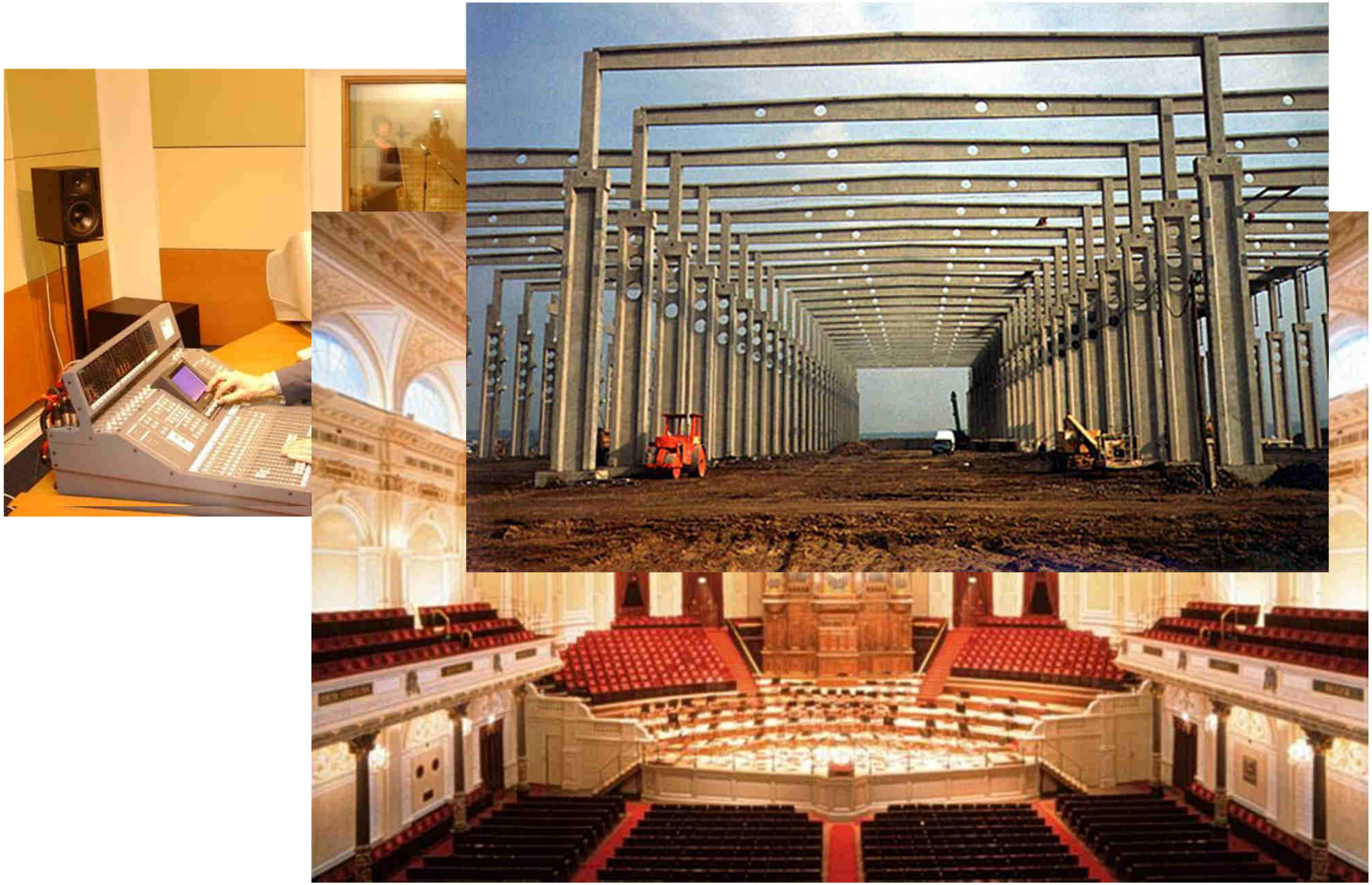
Main issues

- Notion of small and large rooms (as compared to wavelength)
- From reflections to reverberation
- The notion and characteristics of reverberation
- Direct and diffuse sound field
- Notion and characteristics of sound absorption
- Characteristics and parameters of sound absorbers
- Relationship of sound absorption and reverberation
- Reverberation time
- Typical RTs, measurement and design

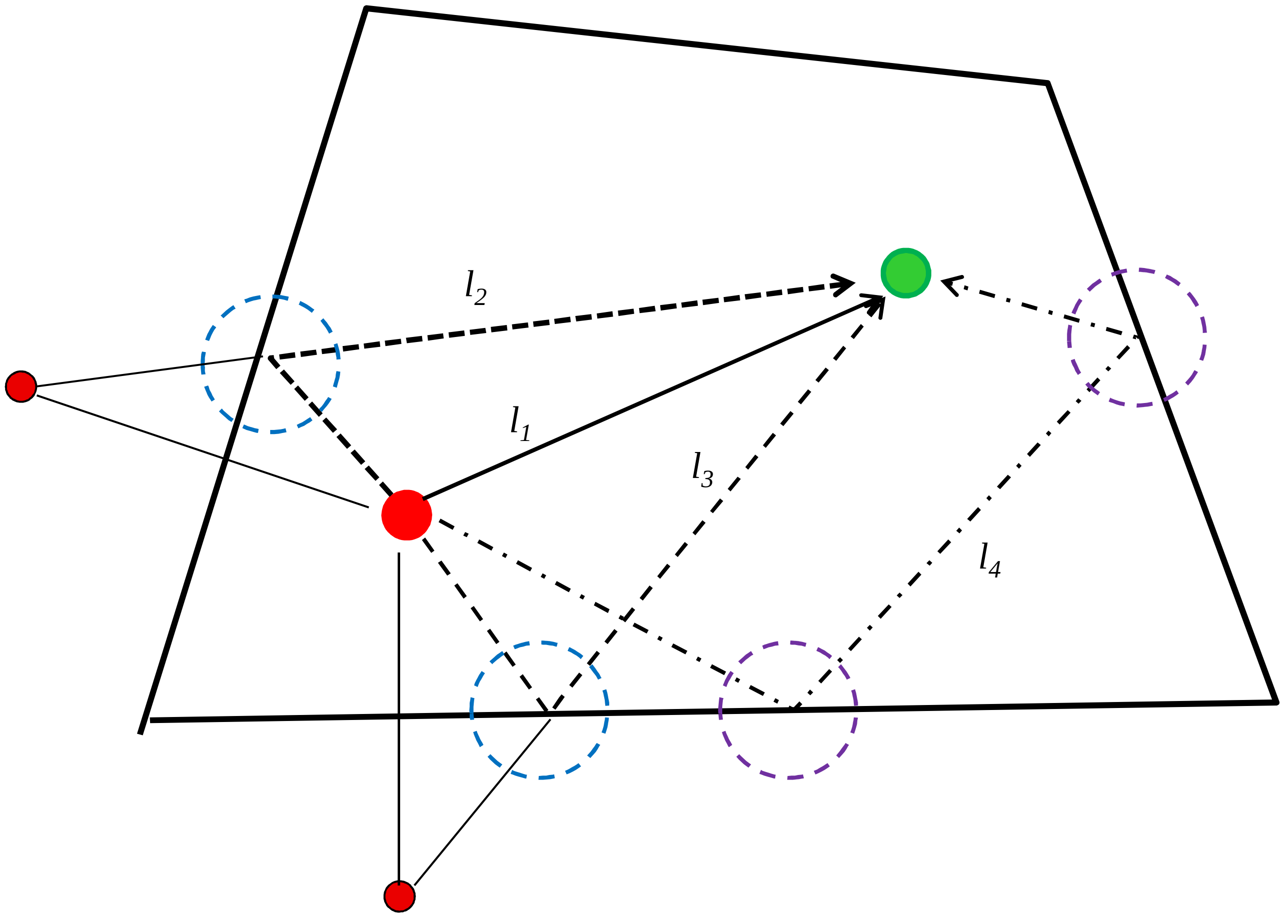
What is small, what is large?



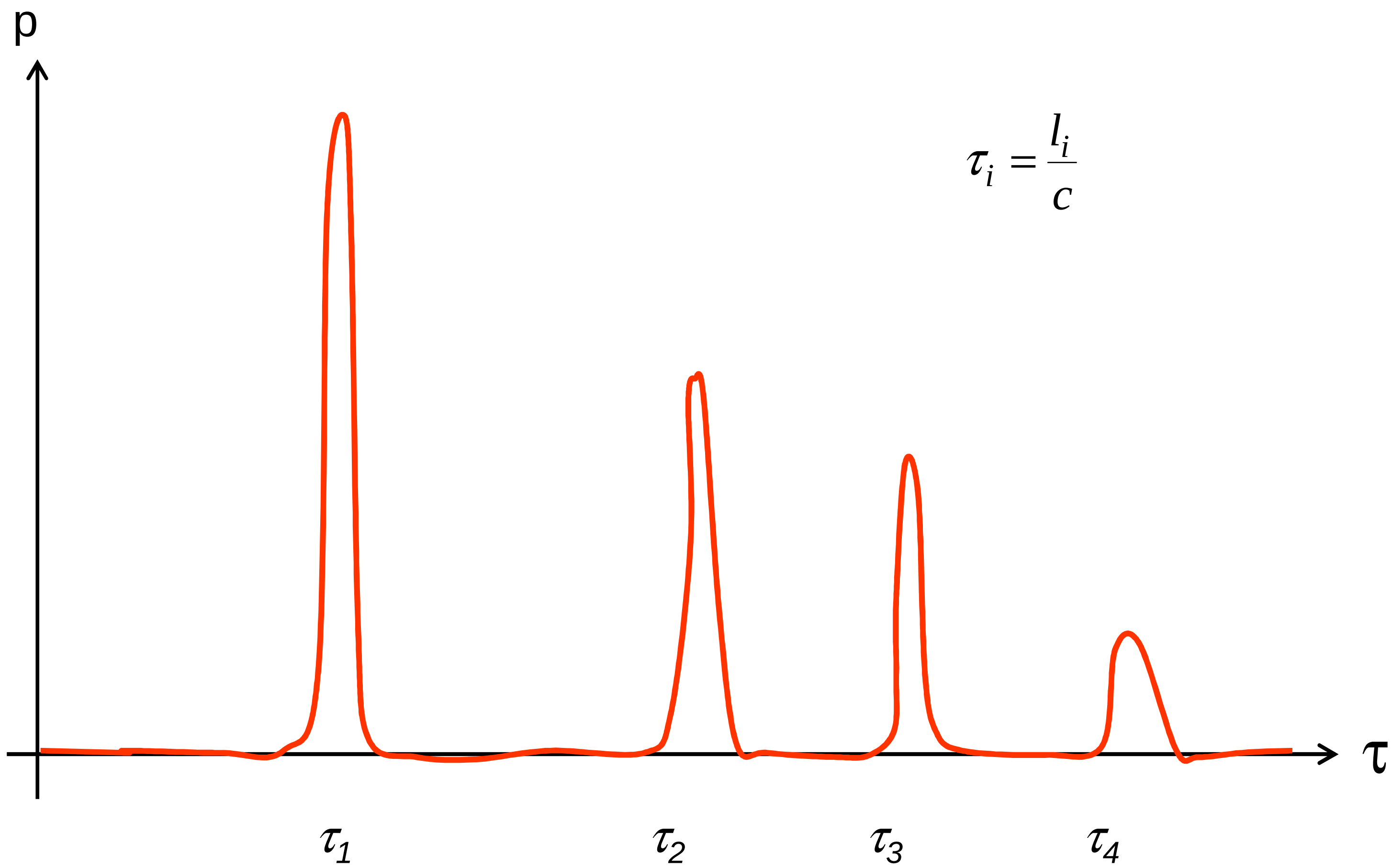
Various models in room acoustics

- Low frequency: wave acoustics
  - dimensions comparable to wavelength
- Medium to high frequency: geometrical acoustics
- High frequency: statistical acoustics
  - dimensions much larger than the wavelength

Reflections

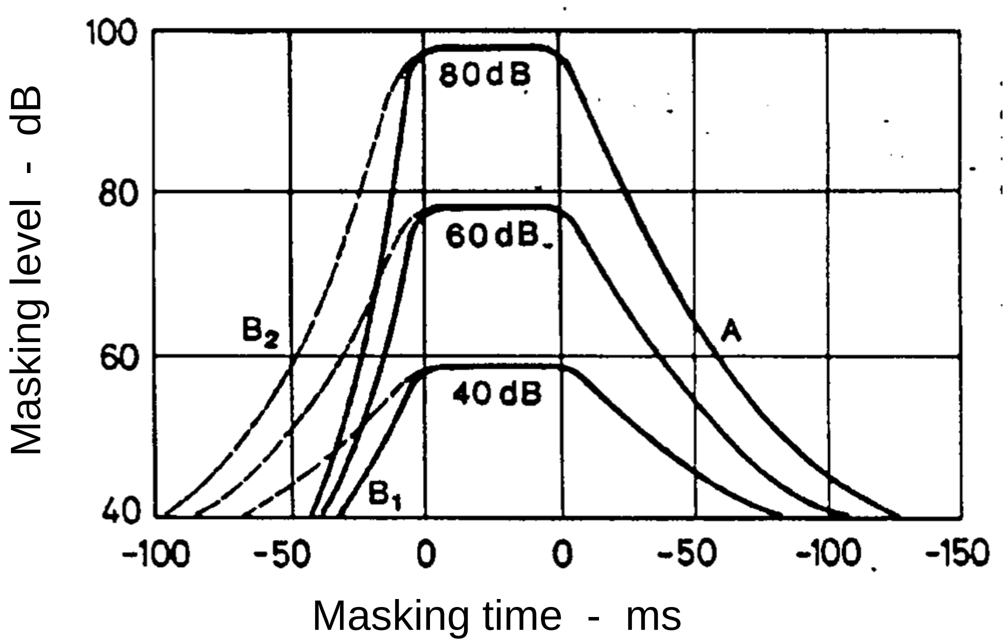


An important descriptor: the impulse response



What is the effect of reflections?

- Early reflections (< 50 ms, not too many)
  - one cannot distinguish between direct and reflected sound
    > Haas-effect
  - increased loudness
  - advantageous, no amplification is needed



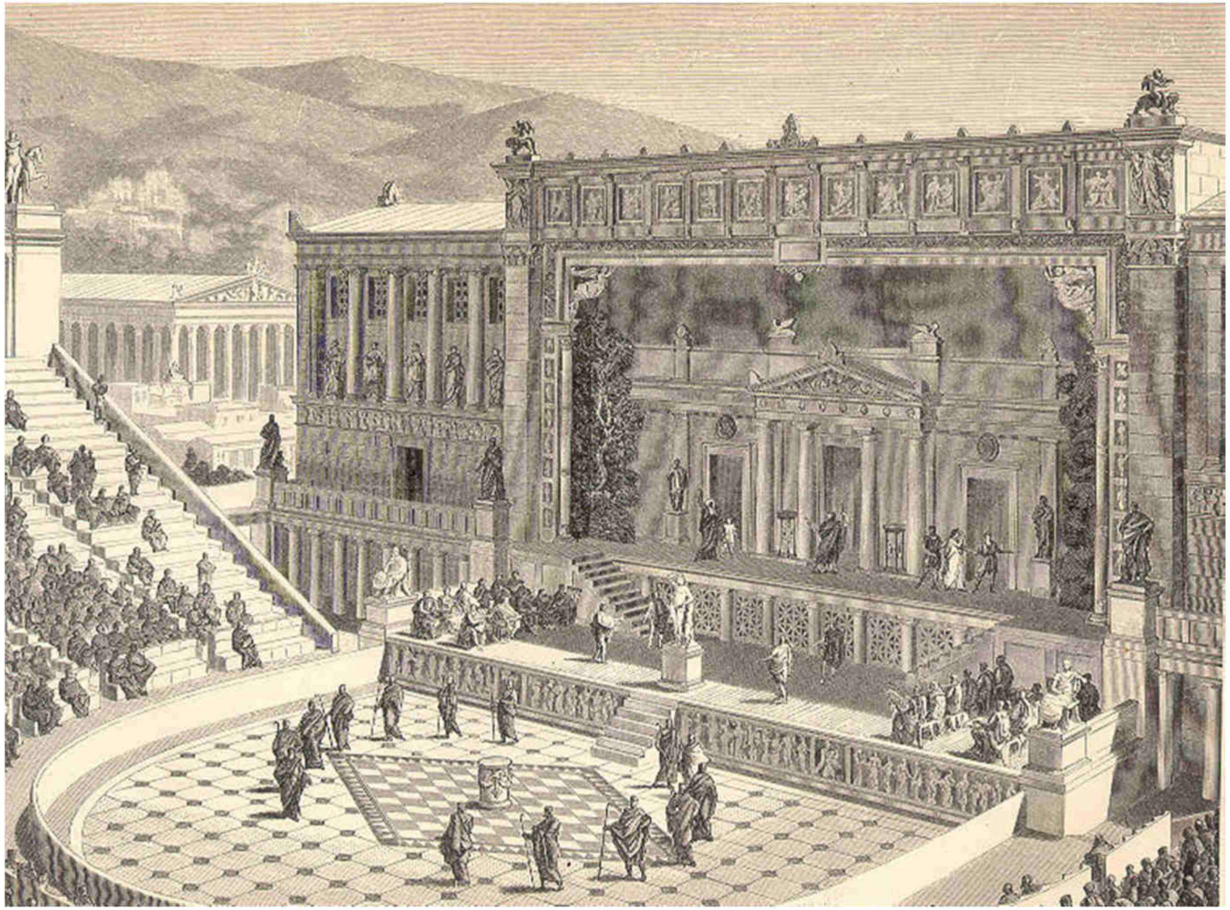
What is the effect of reflections?

- Medium reflections
  - still cannot be heard separately
  - generates spaciousness
  - make music performances more enjoyable
  - different pieces require different acoustic environment

- Late reflections
  - plenty of them, of more or less continuous (but not uniform!) distribution
  - deteriorates or even hinders speech intelligibility

The role of reflections in the ancient theatres

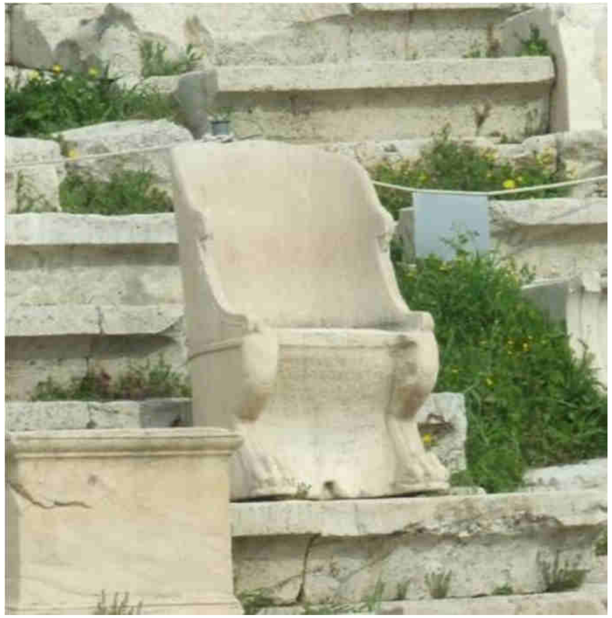
As imagined in the 19th century:



(Pierers Konversationslexikon, Stuttgart, 1891)

The role of reflections in the ancient theatres

And the reality: Ruins of the Dyonysos theatre at the foothill of Acropolis in Athens



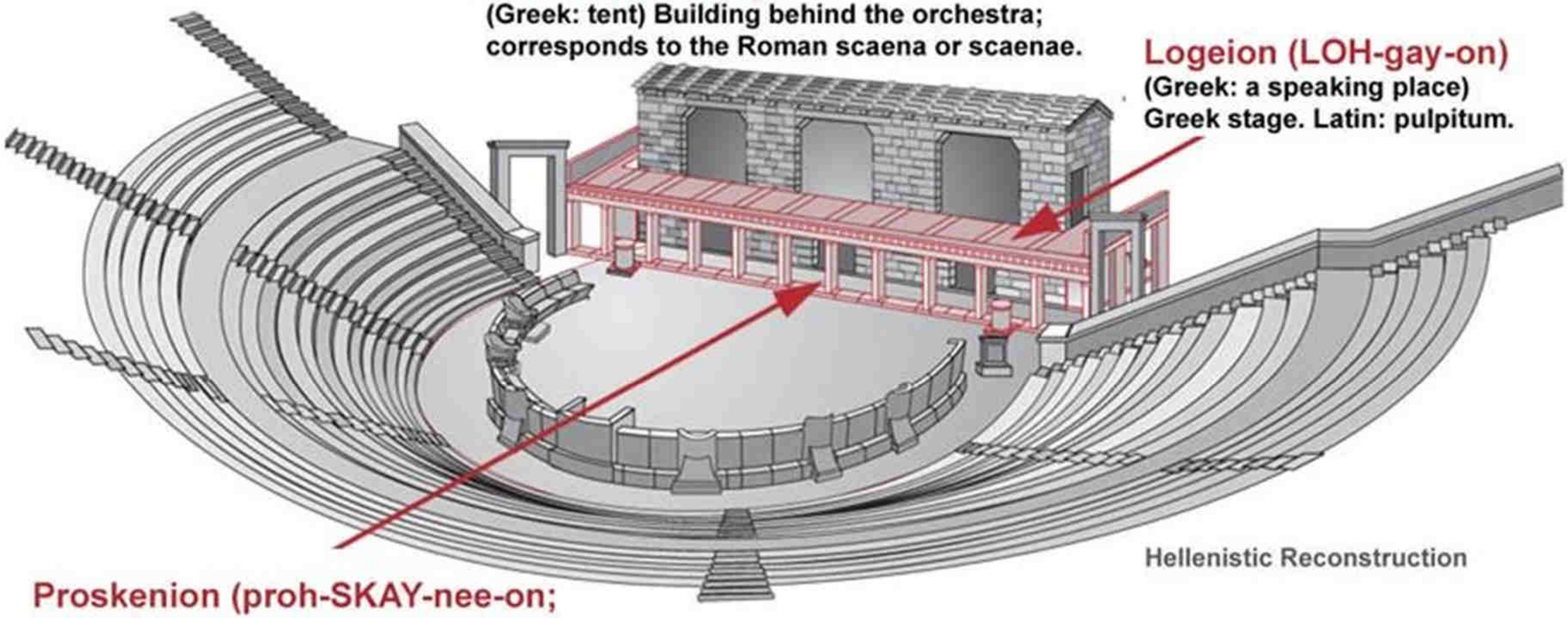
The throne of the priest of Dionysos Eleutherios (the god of wine). 4th century B.C.

Marmor thrones, dedicated to nobilities

Elements of the ancient greek theatres

Skene (SKAY-nay)
(Greek: tent) Building behind the orchestra; corresponds to the Roman scaena or scaenae.

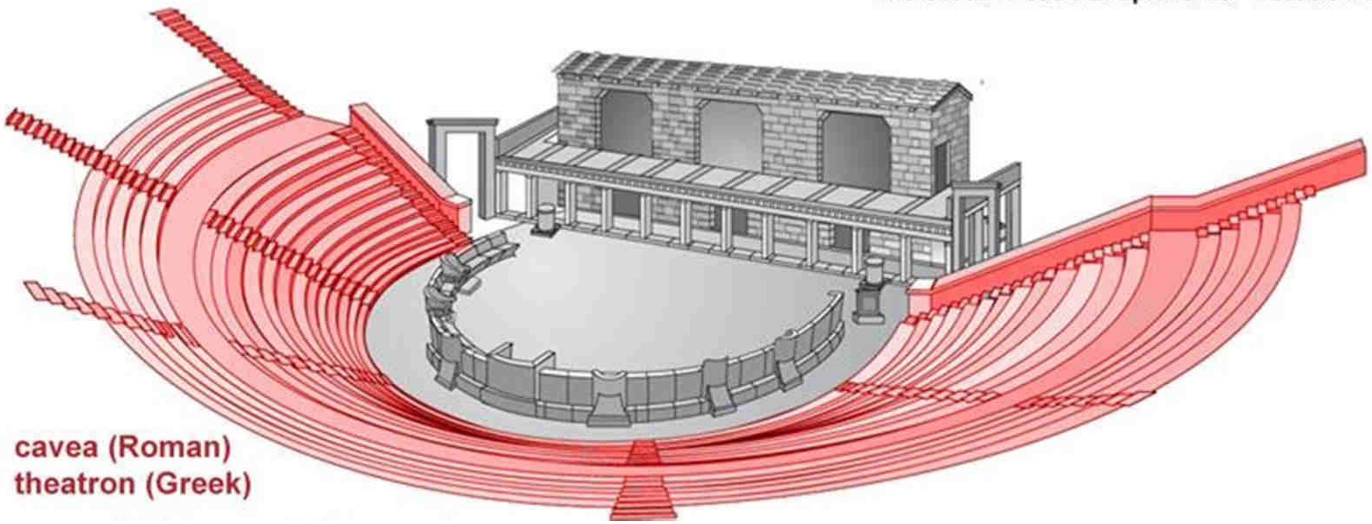
Logeion (LOH-gay-on)
(Greek: a speaking place) Greek stage. Latin: pulpitum.



Proskenion (proh-SKAY-nee-on; proh-SKEE-nee-on)
(Greek; Latin: proscaenium) Also called the okribas. Front wall of the stage; an acting area which projected in front of the skene (proskenion literally means "something set up before the skene"); in Classical Greek theatre, the ground-level portion immediately in front of the skene was used as an acting area; in Hellenistic period, the proskenion was a raised platform in front of the skene; the skene eventually included two levels, a lower level with a roof (the Hellenistic logeion or stage) and the second story skene with openings for entrances (thyromata).

Amphytheatre [sound refraction and absorption]

The Greek Theatre at Epidaurus - Theatron View



Amphytheatre

- Orchestra (place of the dancers): floor reflection!

Theatre at Priene, Turkey - Orchestra Detail

Theatre at Delphi, Greece - Orchestra Detail

Theatre at Epidaurus, Greece - Orchestra Detail

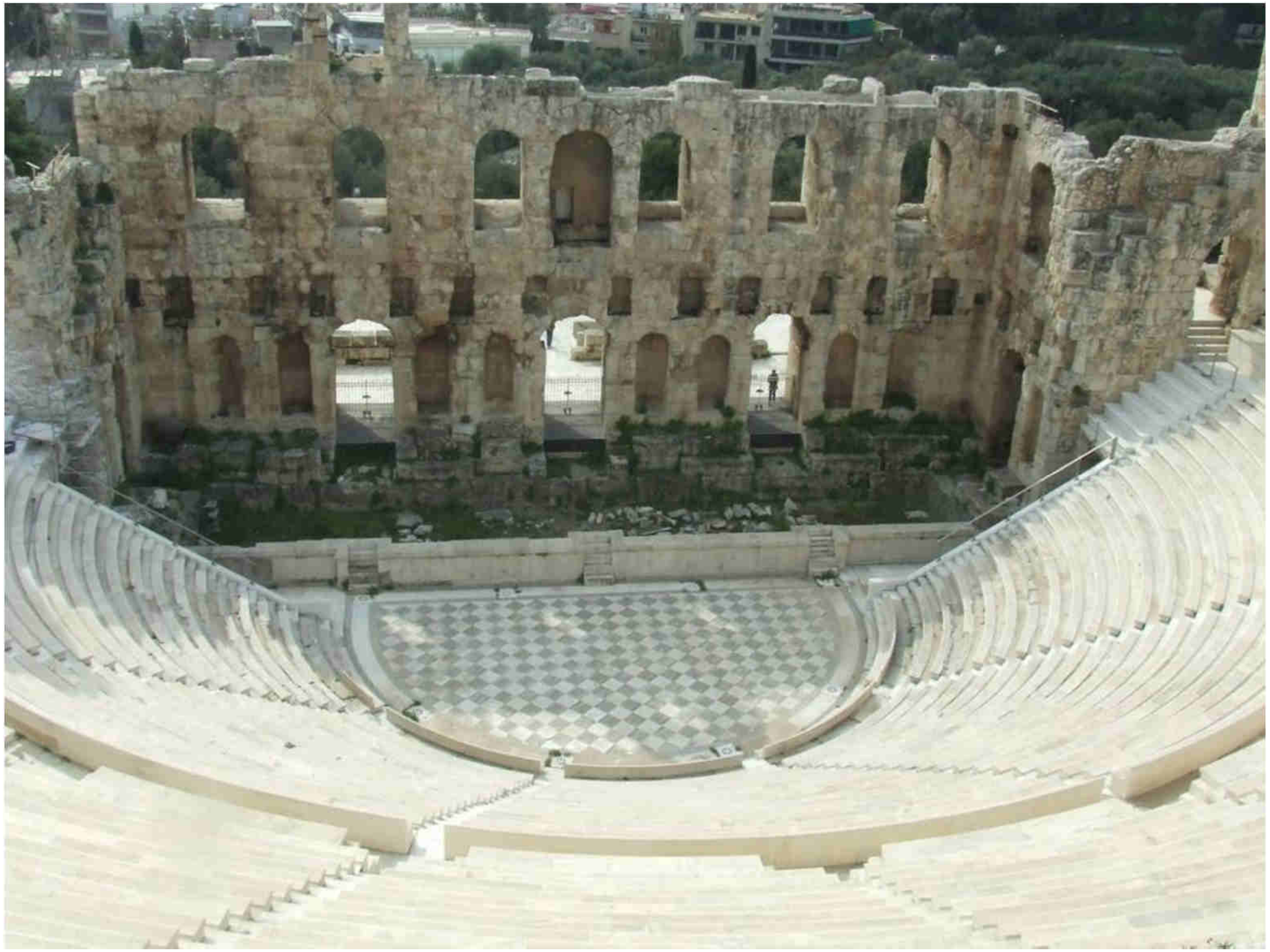
Theatre of Dionysus, Athens, Greece - Orchestra Detail

Masque

- masque: a sound amplifying, impedance matching element

There is nothing new under the sun: the ancient Roman theatre

Thde odeion of Herodes Atticus in Athens

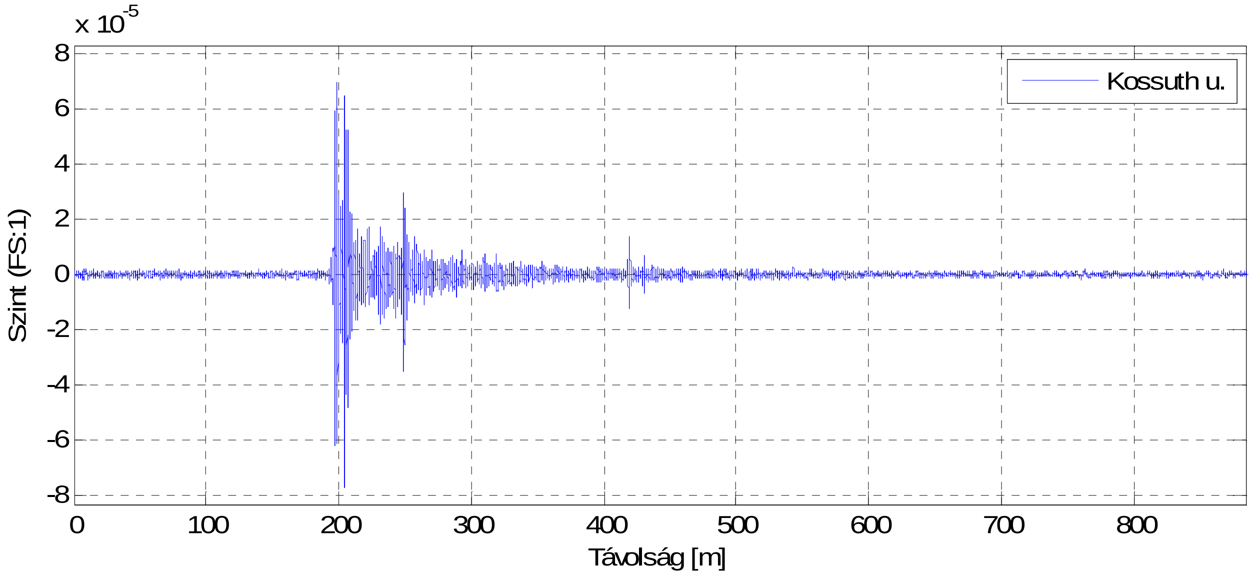


What is the essence of room acoustics?

- The main difference: reflections
- How to discribe the reflections?
  - Impulse response: response to an ideal Dirac-impulse
  - Reverberation time: quantitative descriptor of energy decay

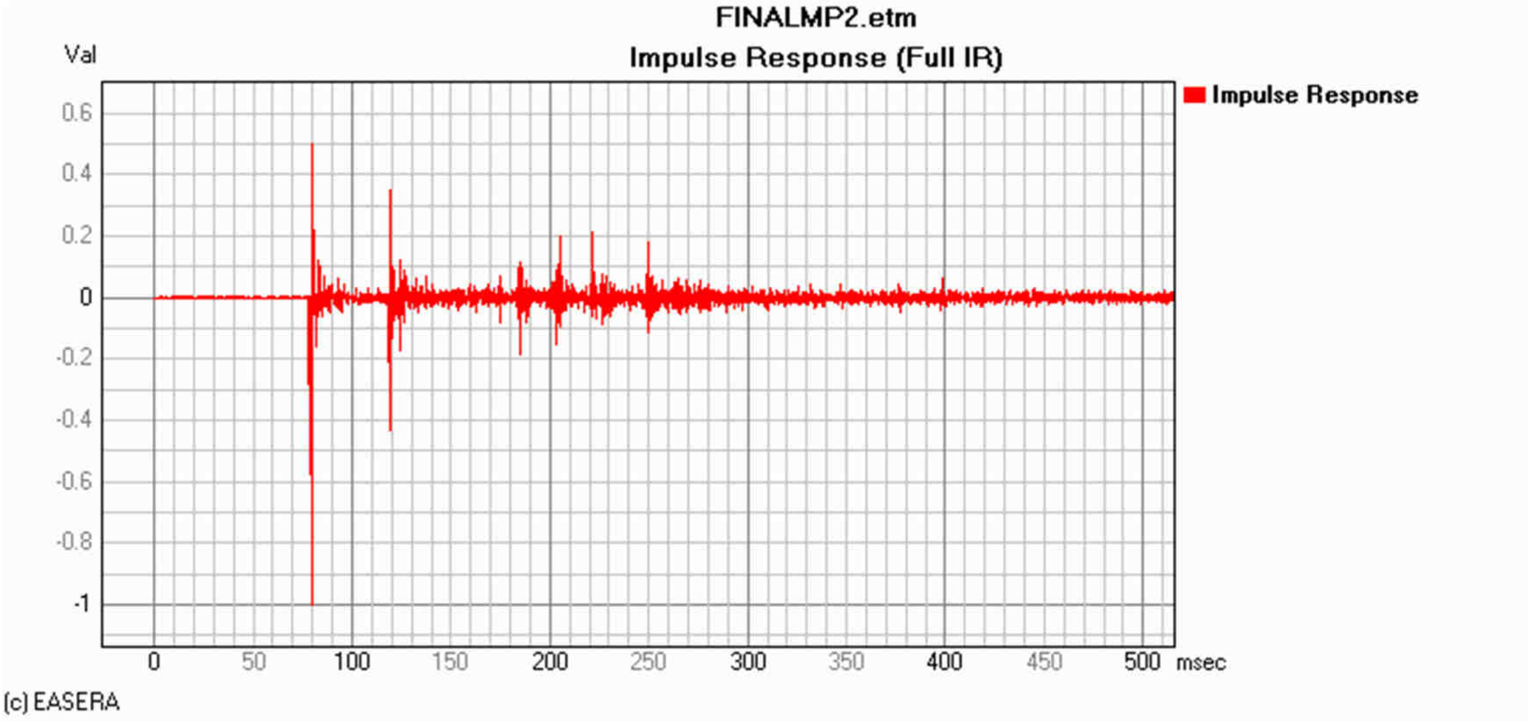
Impulse response measurements

- (in earlier times) by a handgun
- by spark source
- by continuous random noise
- by swept sine

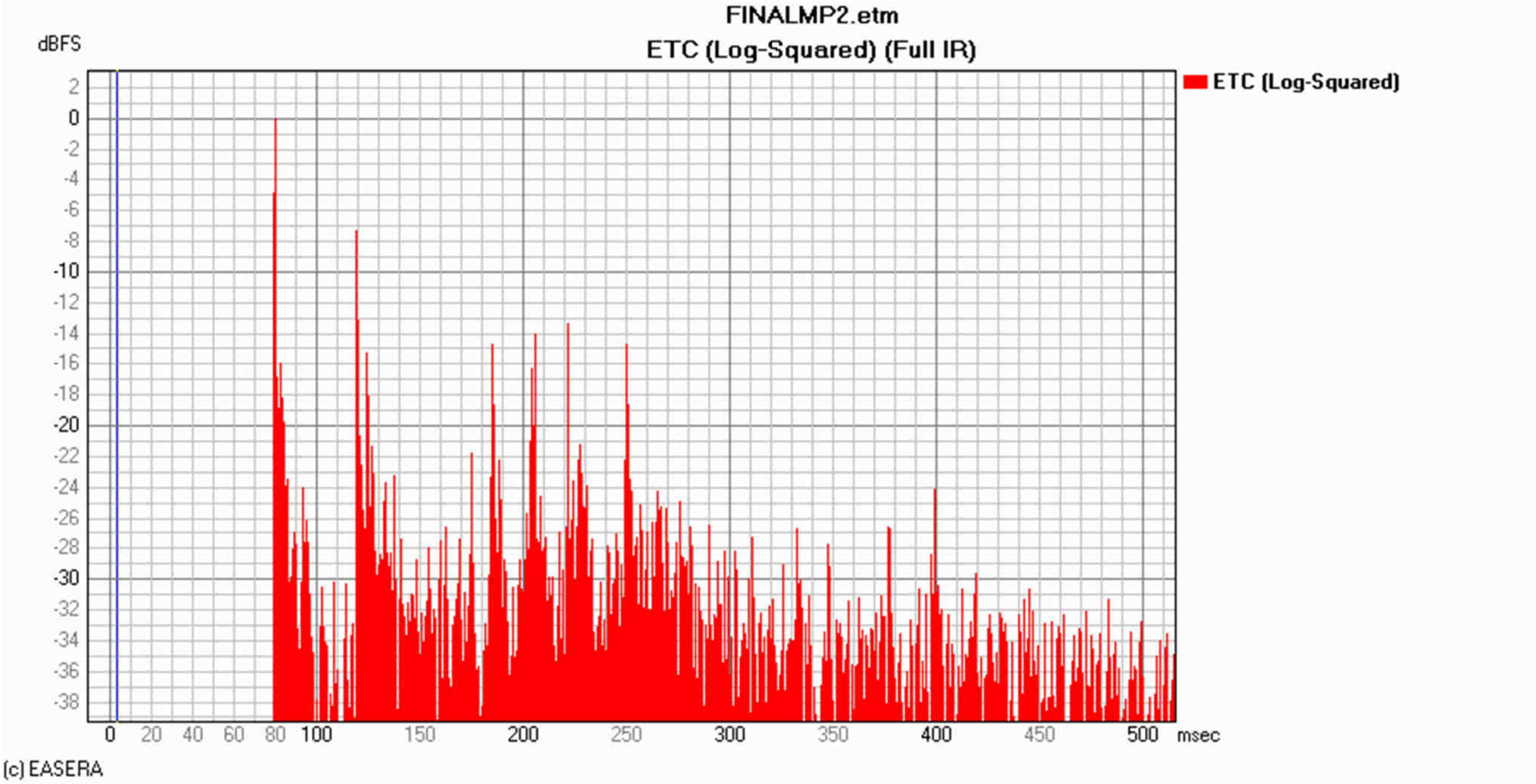


Impulse response / 3

Measured impulse response



Echogram


FINALMP2.etm
ETC (Log-Squared) (Full IR)
dBFS
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
-36
-38
0
20
40
60
80
100
150
200
250
300
350
400
450
500
msec
ETC (Log-Squared)
(c) EASERA

Transition from direct to reverberant field

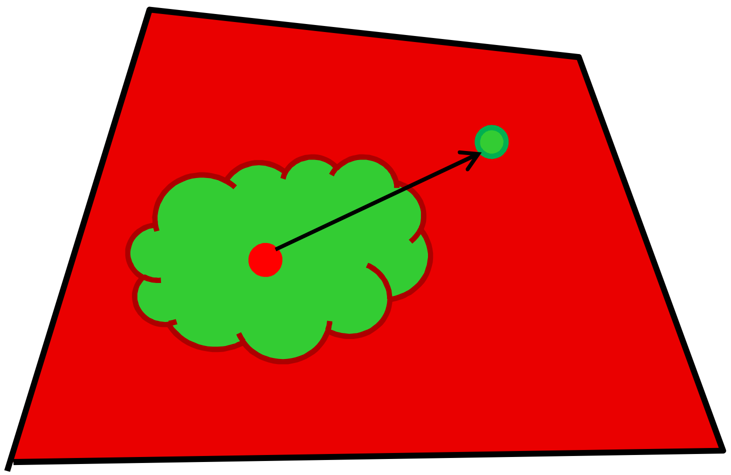
- Direct sound field
  - 6 dB / double distance rule

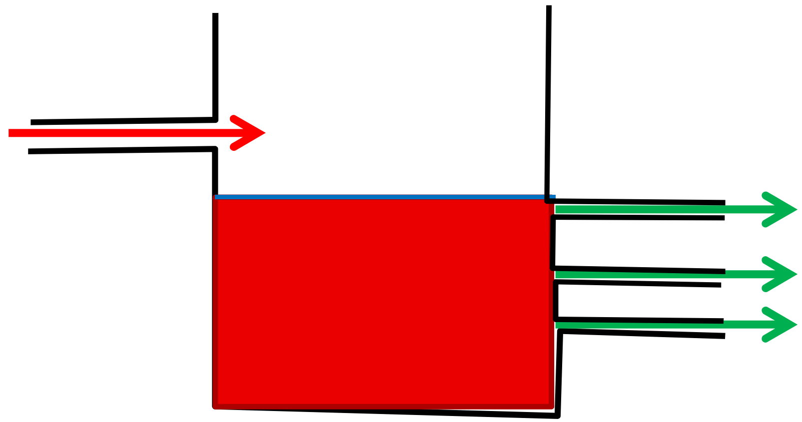
- Reverberant sound field
  - In principle spatially independent

- Influencing parameters
  - Room size
  - (Room shape, to some extent)
  - amount of sound absorption in the room

Energy considerations

- The source fills up the system with energy, the absorption of the walls sinks
- After sufficient time energy balance is reached





What is sound absorption?

- Conversion of energy:
  - from **acoustic** (movement of air particles due to wave phenomena)
  - to **mechanic** (movement of solid structures)

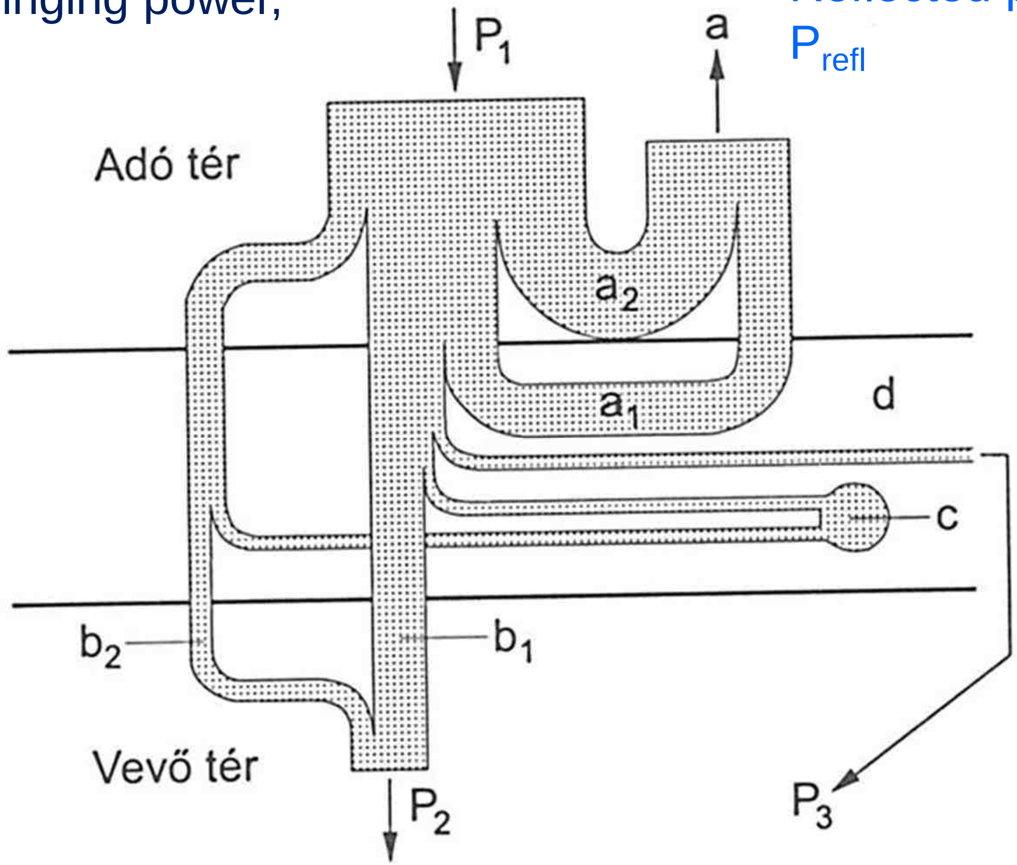
  and
  - to **heat** (increased temperature of air particles and solid structures, due to friction)

- Description: **sound absorption coefficient**

Energy balance at a reflection

Impinging power, P_{in}

Reflected power, P_{refl}



Absorbed power, P_{abs}

Transmitted power, P_{trans}

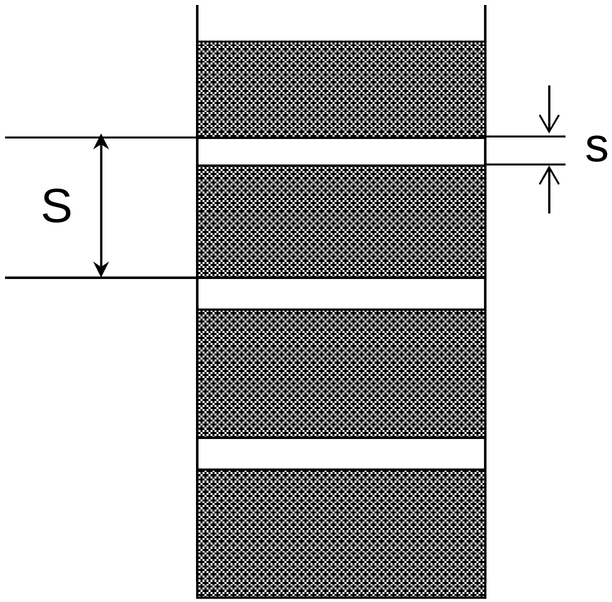
$$P_{in} = P_{refl} + P_{abs} + P_{trans}$$

$$1 = \rho + \alpha + \tau$$

Sound absorbing mechanisms / 1

1. The simplest model:

   Rayleigh's porosity model



$$r = \frac{4}{\left(\sqrt{\frac{S}{s}} + \sqrt{\frac{s}{S}}\right)^2}$$

Sound absorbing mechanisms / 2

2. The structural frame (skeleton) is also set into motion:
   - extra energy deduction
3. Flow resistence
   - friction dissipation

Descriptors

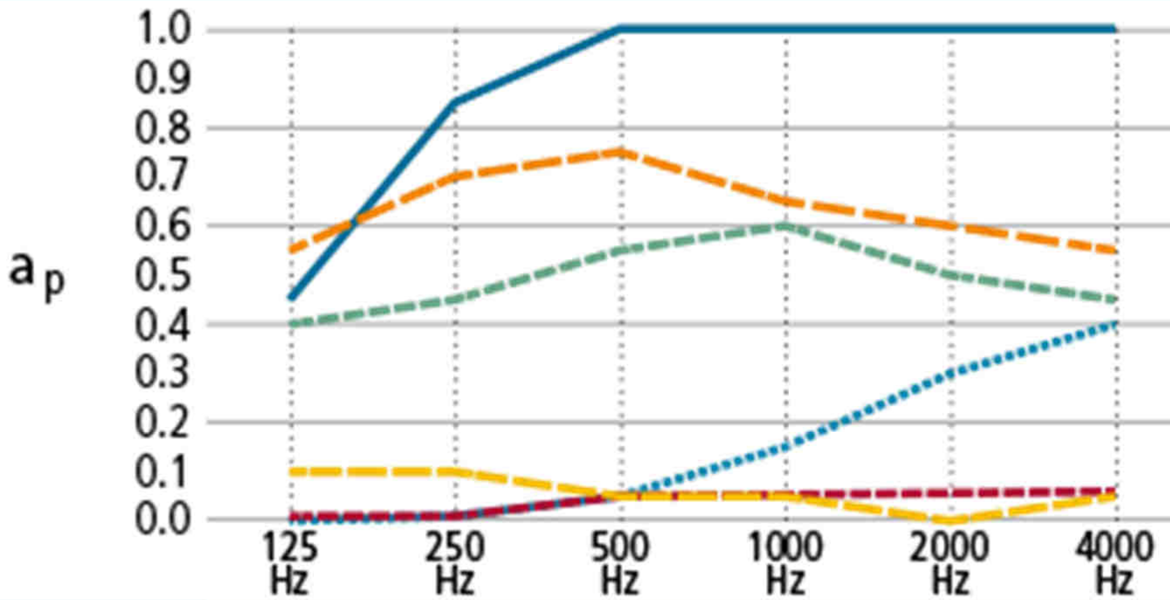
- Makro level descriptors
  - Sound absorption coefficient, α
  - Weighted sound absorption coefficient, α_w
- Influencing factors
  - Porosity
  - Flow resistence
  - Tortuosity

Typical sound absorbers

- Glasswool
  - made of super slender wool added with phenolic resin binder by pressing, heating and solidifying. Can be covered with Pwc cloth or aluinium foil.
- Rock wool
  - made of volcanic rock, typically basalt and/or dolomite (nowadays also from recycled materials made from slag…)
- Plastic foam

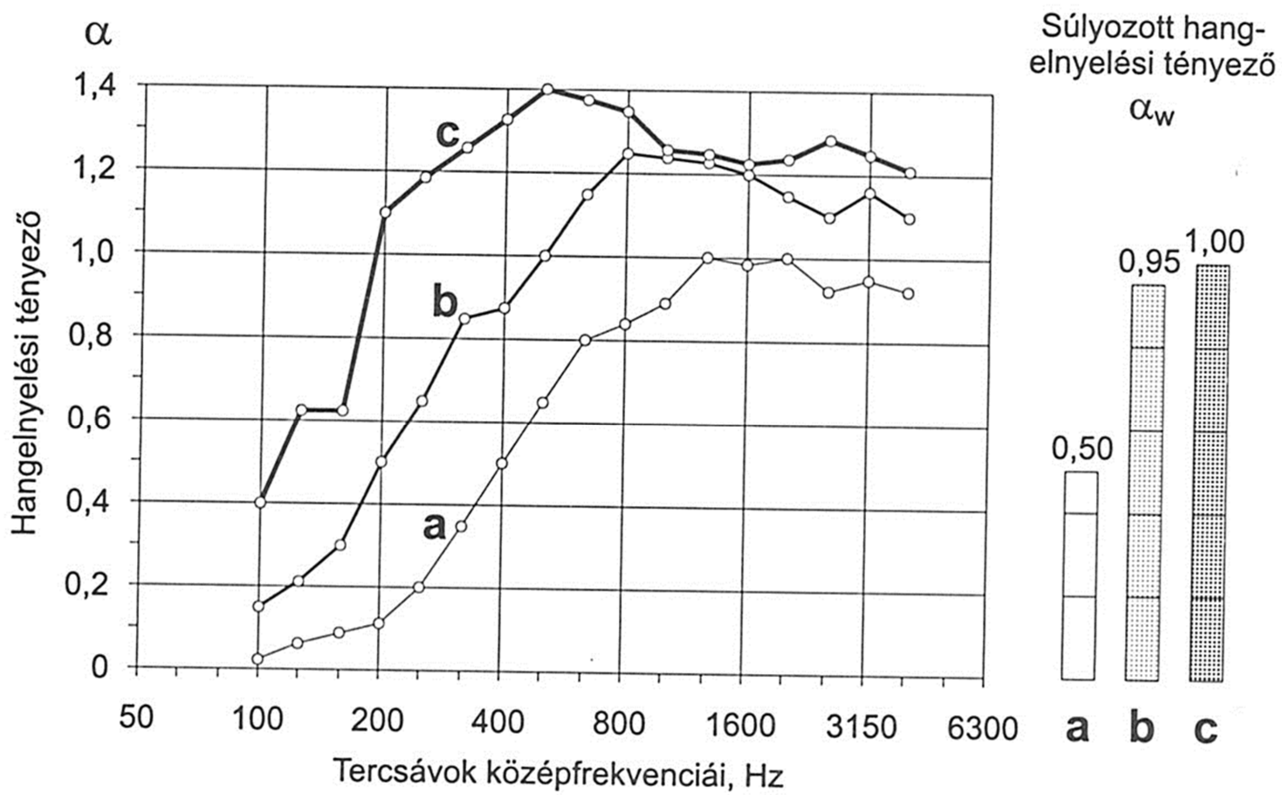
Some typical sound absorption curves

Sound Absorption Coefficients



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Rockfon Sonar	0.45	0.85	1.00	1.00	1.00	1.00
Perforated Gypsum	0.55	0.70	0.75	0.65	0.60	0.55
Wetfelt Tile	0.40	0.45	0.55	0.60	0.50	0.45
Carpet	0.01	0.02	0.05	0.15	0.30	0.40
Stone/Linoleum	0.02	0.02	0.05	0.05	0.05	0.07
Unperforated Gypsum	0.10	0.10	0.05	0.05	0.00	0.05

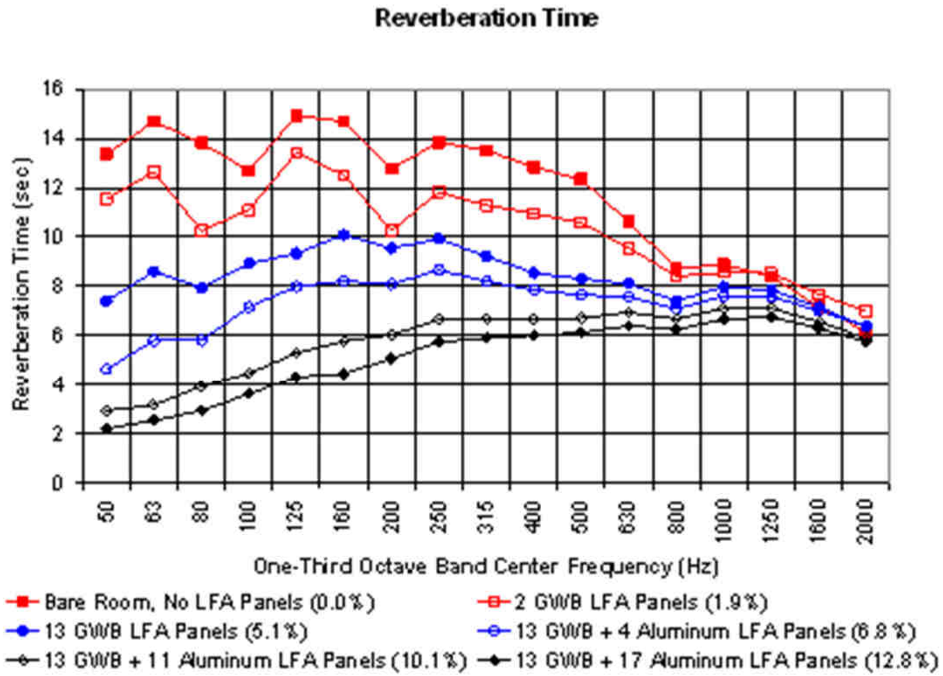
The effect of flow resistence and thickness



Cloth covered glasswool plate of various thickness and flow resistance, measured in a reverberation room

Measurement of sound absorption / 1

- Reverberation chamber method



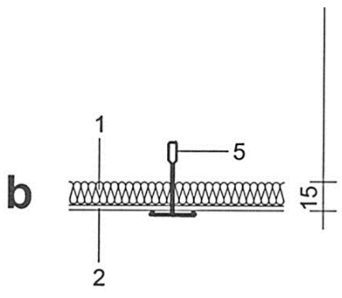
Measurement of sound absorption / 2

Impedance tube method

Sound absorption tables

Nature of surface	Sound Absorption Coefficients at Frequency(Hz)					
	125	250	500	1000	2000	4000
Acoustic tile, rigid mount	0.2	0.4	0.7	0.8	0.6	0.4
Acoustic tile, suspended	0.5	0.7	0.6	0.7	0.7	0.5
Acoustical plaster	0.1	0.2	0.5	0.6	0.7	0.7
Ordinary plaster, on lath	0.2	0.15	0.1	0.05	0.04	0.05
Gypsum wallboard, 1/2" on studs	0.3	0.1	0.05	0.04	0.07	0.1
Plywood sheet, 1/4" on studs	0.6	0.3	0.1	0.1	0.1	0.1
Concrete block, unpainted	0.4	0.4	0.3	0.3	0.4	0.3
Concrete block, painted	0.1	0.05	0.06	0.07	0.1	0.1
Concrete, poured	0.01	0.01	0.02	0.02	0.02	0.03
Brick	0.03	0.03	0.03	0.04	0.05	0.07
Vinyl tile on concrete	0.02	0.03	0.03	0.03	0.03	0.02
Heavy carpet on concrete	0.02	0.06	0.15	0.4	0.6	0.6
Heavy carpet on felt backing	0.1	0.3	0.4	0.5	0.6	0.7
Platform floor, wooden	0.4	0.3	0.2	0.2	0.15	0.1
Ordinary window glass	0.3	0.2	0.2	0.1	0.07	0.04
Heavy plate glass	0.2	0.06	0.04	0.03	0.02	0.02
Draperies, medium velour	0.07	0.3	0.5	0.7	0.7	0.6
Upholstered seating, unoccupied	0.2	0.4	0.6	0.7	0.6	0.6
Upholstered seating, occupied	0.4	0.6	0.8	0.9	0.9	0.9
Wood seating, unoccupied	0.02	0.03	0.03	0.06	0.06	0.05
Wooden pews, occupied	0.4	0.4	0.7	0.7	0.8	0.7

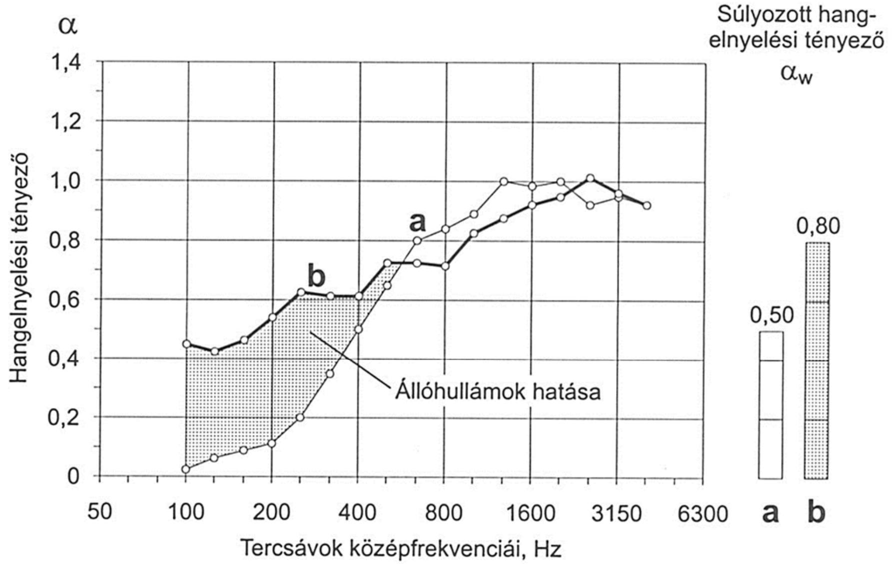
Effect of air gap behind the absorber



1 üveggyapot lemez:
$\rho = 100$ kg/m^3, R = 0,6 kPa s/m
2 üvegszálszövet
3 üres légtér
4 födém alsó síkja
5 függesztő szerkezet

6.17) Ezzel függ össze, hogy súlyozott hang-elnyelési tényezője is nagyobb.

4 4



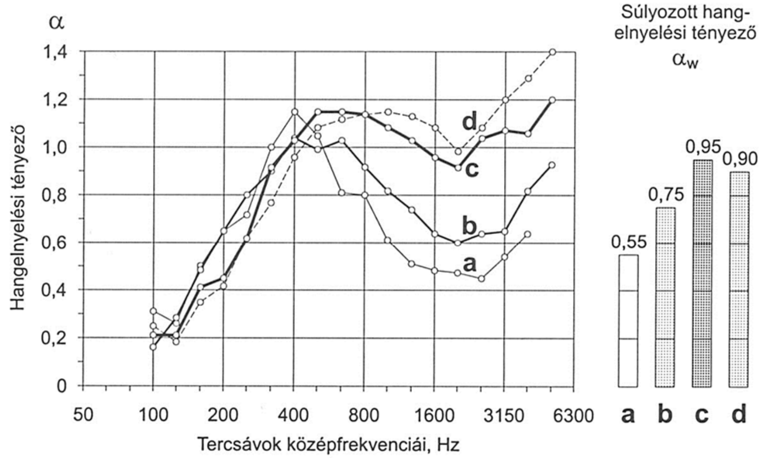
6.11. ábra
Üvegszálszövettel kasírozott üveggyapot lemezek hangelnyelési jellemzői [92]
a Merev felületen **b** Álmennyezetként

Effect of perforation

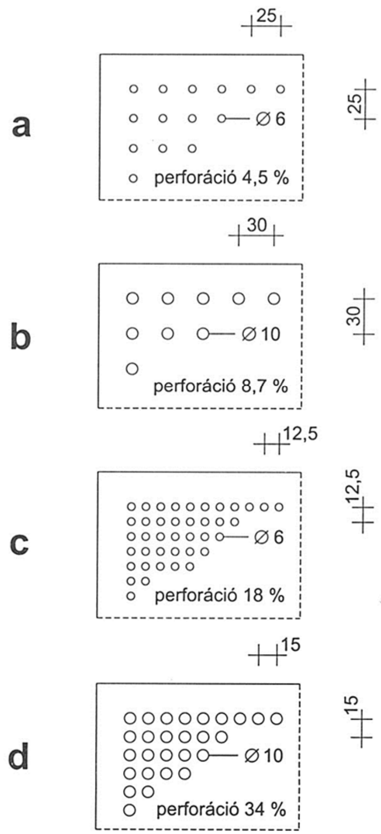
6.3.2. A perforáció mértékének hatása

A 6.24. ábrával a perforáció mértékének[6.27)] a hangelnyelési tényezőre gyakorolt hatását szemléltetjük, zengő szobában végzett méréseink [89] alapján. A ∅ 6 és 10 mm lyukakkal különböző mértékben perforált 3 mm vastag kemény farostlemez alatt minden változat esetében 50 mm vastag, üvegszálszövettel kasírozott üveggyapot lemezt helyeztünk el a zengő szoba merev padlóján.

6.27) A lyukak összes felületének %-os arány a burkolat felületéhez viszonyítva.



6.24. ábra
A perforáció mértékének hatása a 3 mm vastag kemény farostlemezzel takart, 50 mm vastag üveggyapot lemez hangelnyelési jellemzőire [89]



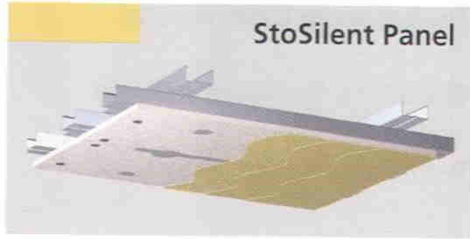
A perforált kemény farostlemezek alatt lévő üveggyapot lemez jellemzőit lásd a 6.23. ábrán

A 6.24. ábra hangelnyelési görbéinek legfontosabb tanulságai a következők:

- A 400 Hz-nél kisebb középfrekvenciájú tercsávokban minden változat hangelnyelési tényezője a frekvenciával folytonosan növekszik. A ∅ 6 és 10 mm átmérőjű lyukakra nézve egyaránt fennáll a (6.18) egyenlőtlenség.

Practical example: (sound absorbing) suspended ceiling

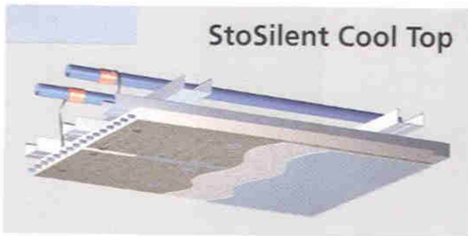
Fugenloses Akustikplattensystem mit feiner Schlussbeschichtung



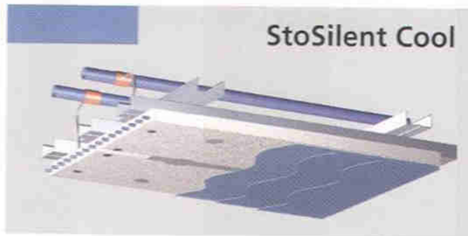
Fugenloses Akustikplattensystem mit rauer Schlussbeschichtung

Fugenloses nichtbrennbares Akustikplatten-system mit feiner Schlussbeschichtung

Fugenloses nichtbrennbares Akustikplatten-system mit rauer Schlussbeschichtung

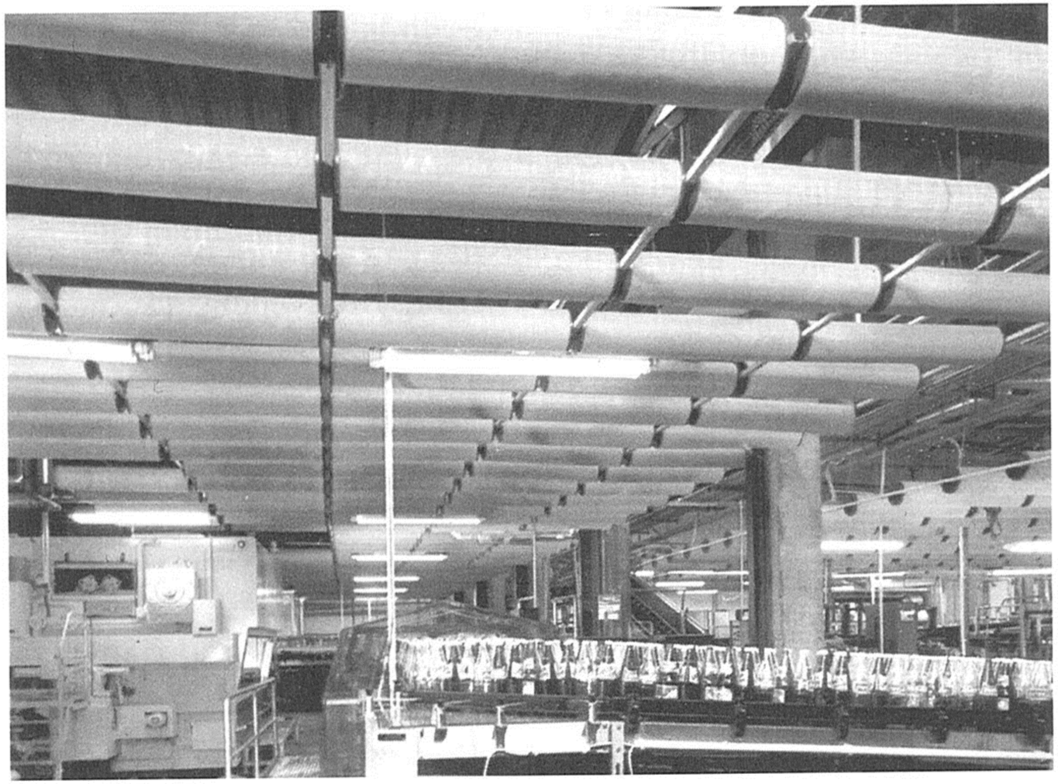


Fugenloses Akustikplattensystem mit Kühl- und Heizfunktion, feine Oberfläche



Fugenloses Akustikplattensystem mit Kühl- und Heizfunktion, raue Oberfläche

Spatial elements

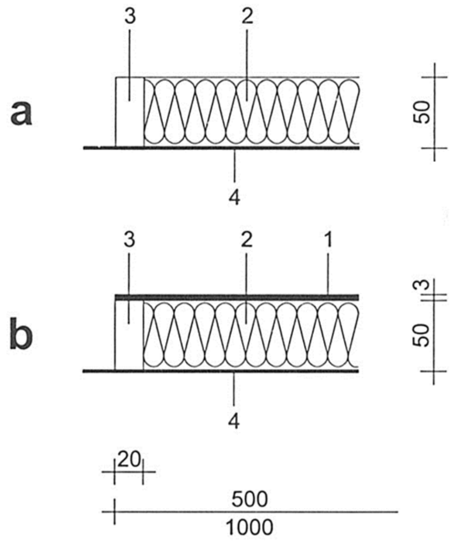


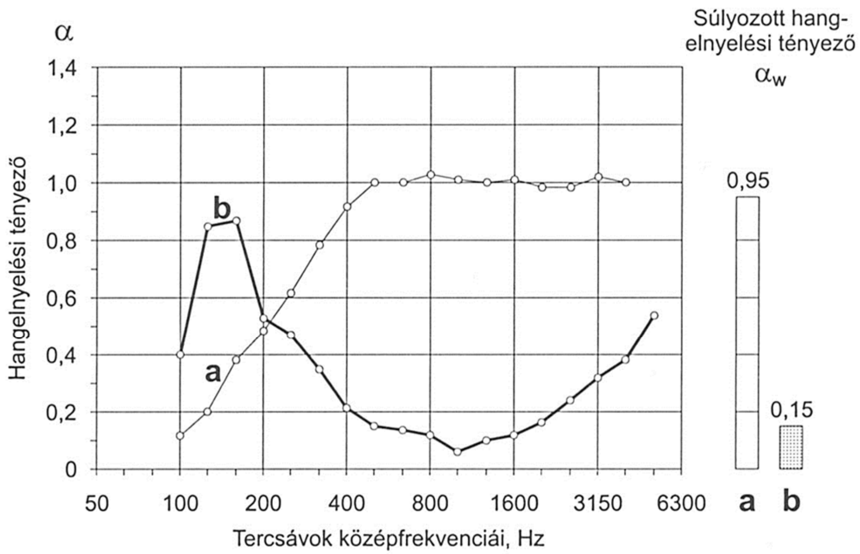
6.20. ábra
Vízszintesen elhelyezett finompórusú műanyaghab elemek fényképe [99]

Membrane resonator

jellemzőit hasonlítjuk össze.

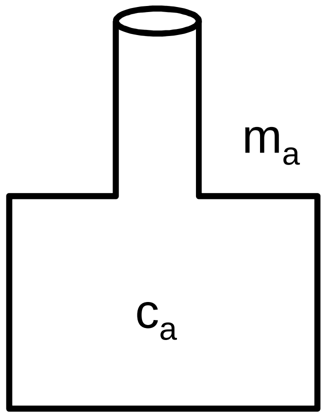
6.27. ábra
Nehéz (**a**) és könnyű (**b**) PVC fólia alkalmazásával kialakított hajlékony lemezrezonátorok metszetei és hangelnyelési görbéi [6]



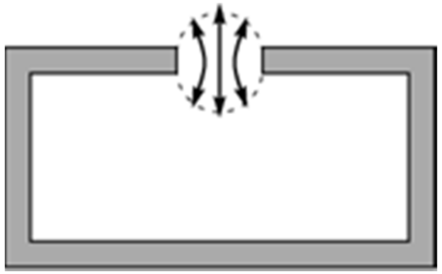


6.28. ábra
Egy hajlékony lemezrezonátor és a benne elhelyezett üveggyapot lemez hangelnyelési jellemzőinek összehasonlítása [89]

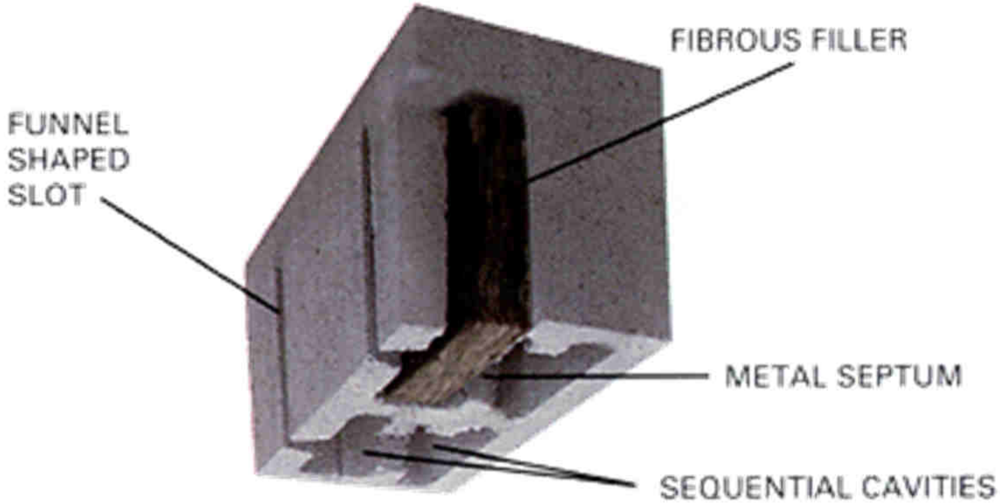
Helmholtz-resonator



$$\omega_0 = \sqrt{\frac{1}{m_a c_a}}$$



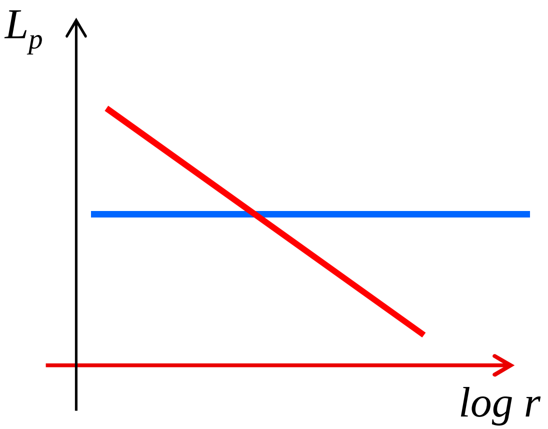
H-resonators in practice

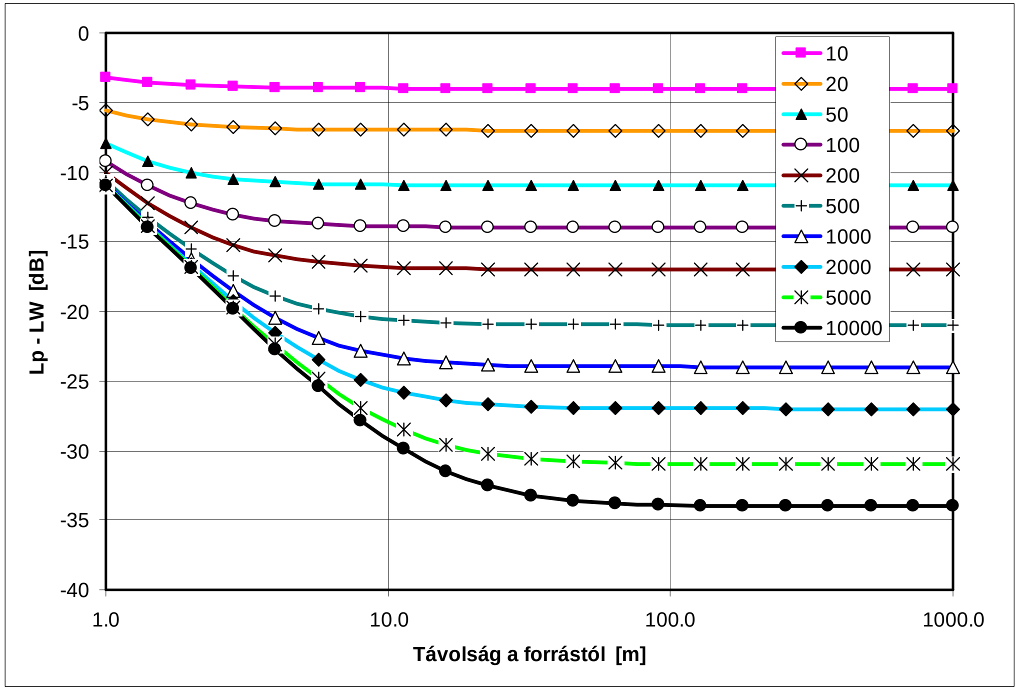


Regions of the sound field

- Direct field and reverberant (or diffuse) field

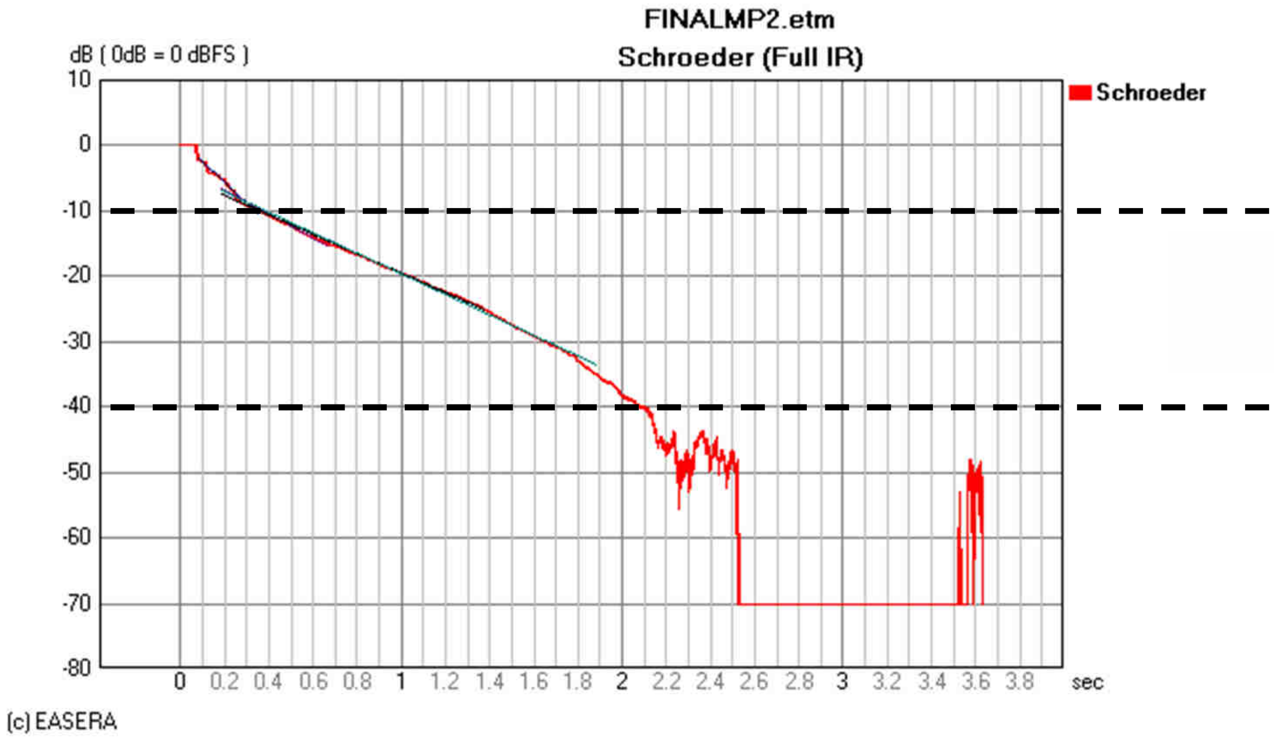
$$L_p = L_W + 10\log\left(\frac{1}{4r^2\pi} + \frac{4}{R}\right)$$





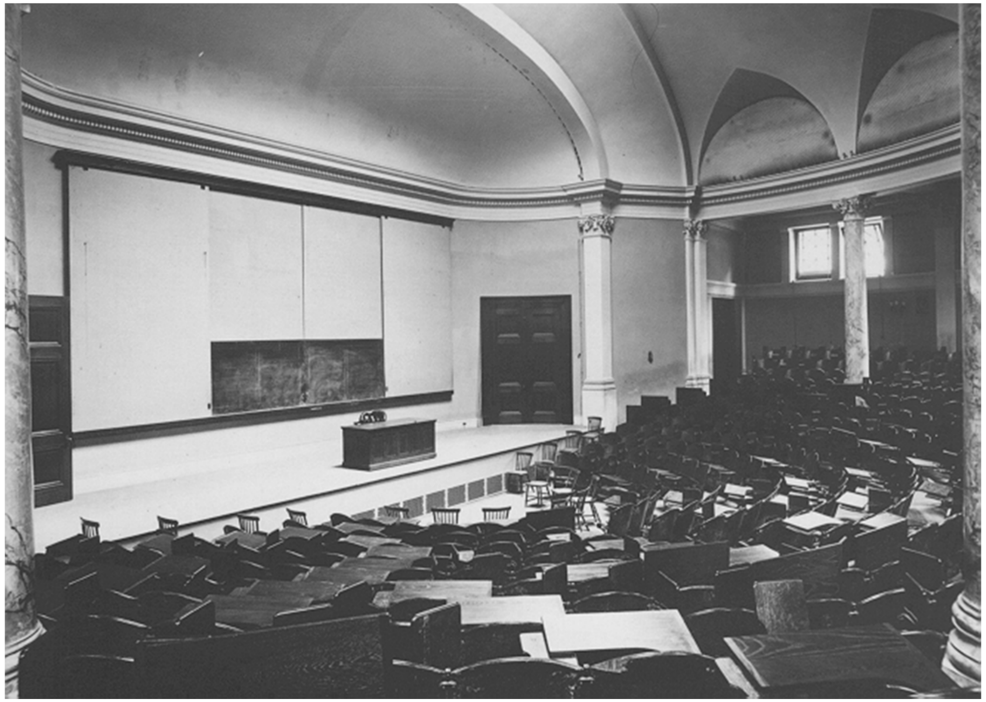
Back to the description of the reverberant sound field

Notion of the reverberation time, T: time period, in which the energy content of the sound field reduces to one millionth. Expressed in SPL this corresponds to 60 dB decrease.



$$T_{30} = \frac{T_{60}}{2}$$

The founder of modern room acoustics



Auditorium Fogg

W. C. Sabine (1868-1919)

Reverberation time

$$T_{60} = 0.16\frac{V}{R} \cong 0.16\frac{V}{A\overline{\alpha}} = 0.16\frac{V}{A_1\alpha_1 + A_2\alpha_2 + \ldots + A_n\alpha_n}$$

$$\overline{\alpha} = \frac{A_1\alpha_1 + A_2\alpha_2 + \ldots + A_n\alpha_n}{A_1 + A_2 + \ldots + A_n} = \frac{\sum_{i=1}^{n} A_i\alpha_i}{\sum_{i=1}^{n} A_i}$$

$$\overline{\alpha}$$

$$R = \frac{A\overline{\alpha}}{1-\overline{\alpha}} \cong A\overline{\alpha}$$

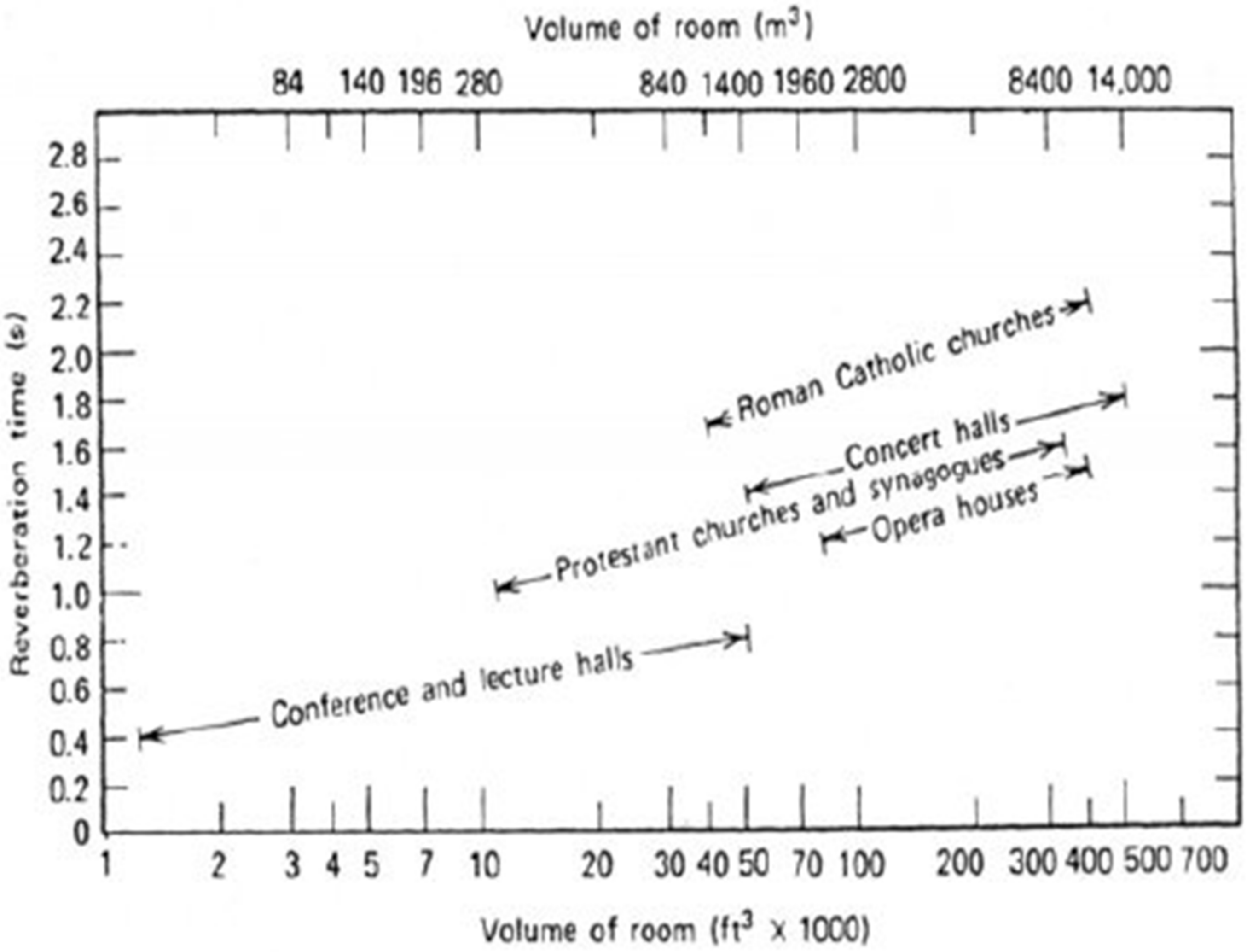
- Influencing parameters:
  - directly proportional to the volume V of the room,
  - inversely proportional to the average sound absorption $\overline{\alpha}$ and the total surface of surrounding walls A

Room constants, typical values

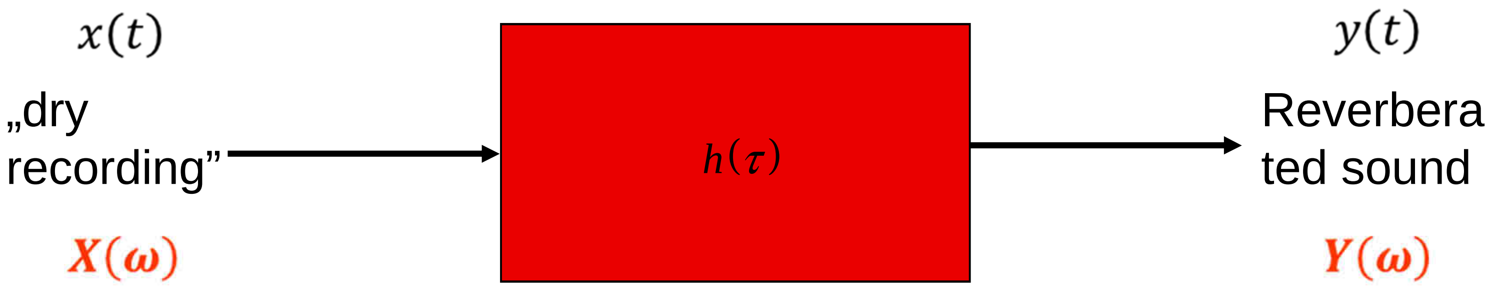
$$R = \frac{A\bar{\alpha}}{1-\bar{\alpha}} \cong A\bar{\alpha}$$

Volume	α=0,35	α=0,3	α=0,2	α=0,15	α=0,07
[m3]	**Auditorium**	**Cinema**	**Thatre, opera**	**Concert hall**	**Church**
100	150	—	—	—	—
200	230	—	—	—	—
400	350	280	—	—	—
700	400	350	170	—	—
1 000	650	500	250	190	—
2 000	1150	900	450	350	160
4 000	1650	1400	700	550	240
7 000	2300	1900	900	710	320
10 000	2900	2400	1200	950	430
20 000	—	3800	1900	1430	640
30 000	—	—	2500	1900	860
40 000	—	—	—	2400	1000

Optimal reverberation time vs volume



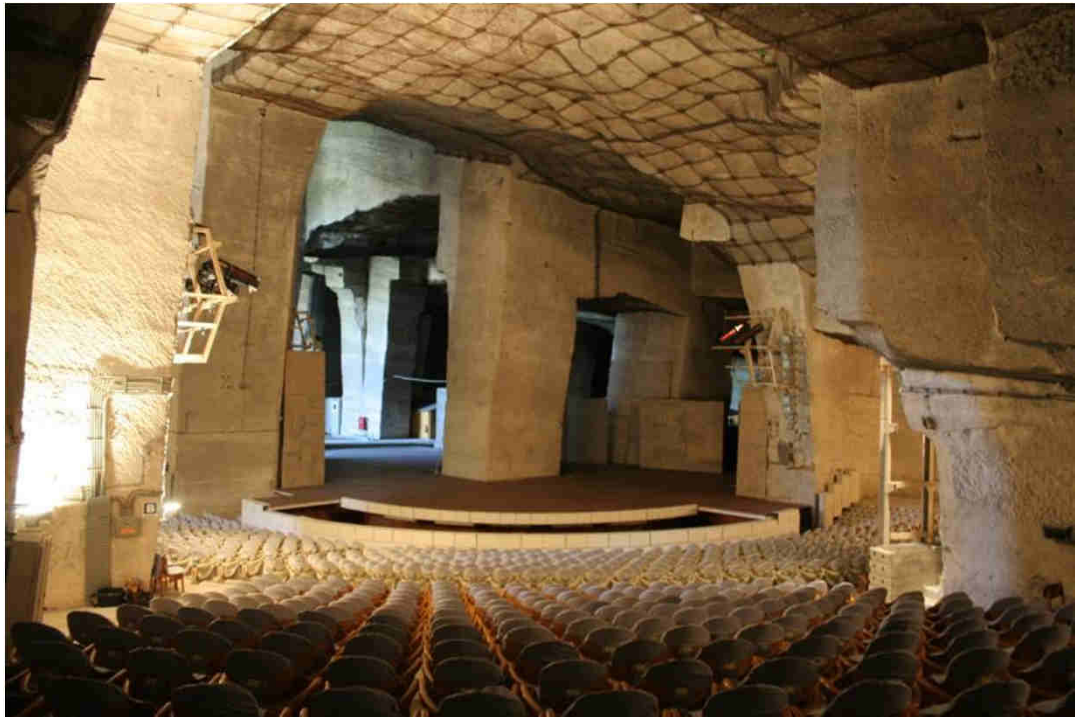
Reverb (auralization)



$$y(t) = \int_{-\infty}^{t} x(\tau)h(t-\tau)d\tau$$

$$Y(\omega) = X(\omega)H(\omega)$$

Reverberation of text



Quarry in West Hungary, Fertőrákos

Room acoustical modelling

Fig. 1. Schlieren photograph showing reflections of ultrasound wave fronts in a sectional model of the Gewandhaussaal in Leipzig. (Teddington – from Engl, [2]).

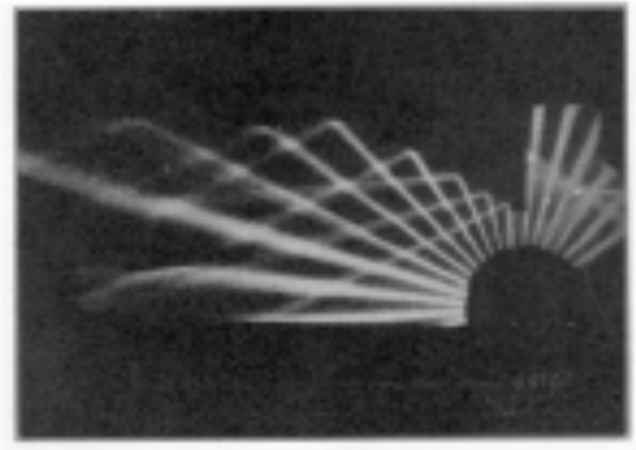
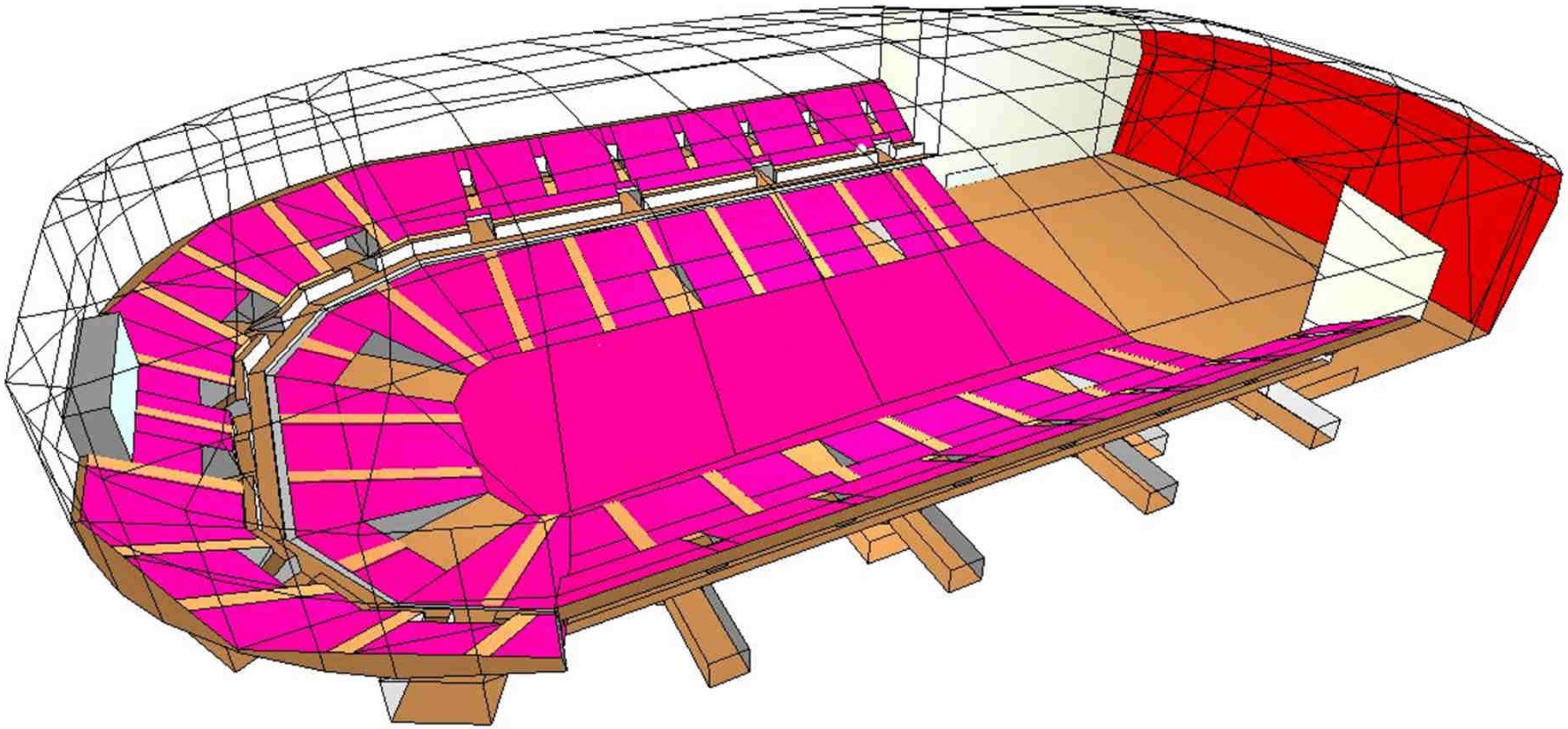


Fig. 2. Light beam investigation of reflections in a sectional model of Okuma Memorial Auditorium. (Satow, 1929 – from Knudsen [4]).

Fig. 5. View from a 1:10 scale model of the Major Hall for the Sydney Opera House (not the final design, but the last Utzon design around 1966). ([11] fig. 4.10).

Computer aided acoustical modelling



Computer aided acoustical modelling