POLITECNICO DI MILANO

Room Acoustics

Sound absorption_2

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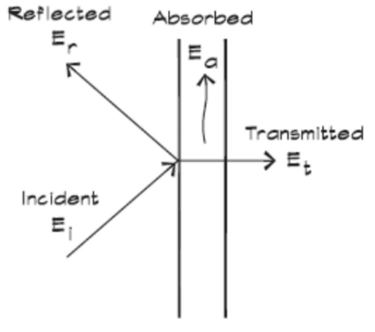
Absorbtive materials tend to fall into three categories:

- **porous materials**
- **panel absorbers**
- **resonant absorbers**

Interaction of Sound Waves with a Surface



Reflection and Transmission Coefficients

When sound waves interact with real materials the energy contained in the incident wave is reflected, transmitted through the material, and absorbed within the material. The surfaces treated in this model are generally planar, although some curvature is tolerated as long as the radius of curvature is large when compared to a wavelength. The energy balance I

$$E_i = E_r + E_t + E_a$$

Since this analysis involves only the interaction at the boundary of the material, the difference between absorption, where energy is converted to heat, and transmission, where energy passes through the material, is not relevant. Both mechanisms are absorptive from the standpoint of the incident side because the energy is not reflected. Because we are only interested in the incident side of the boundary, we can combine the transmitted and absorbed energies.

$$1 = \frac{E_r}{E_i} + \frac{E_{t+a}}{E_i}$$

We can express each energy ratio as a coefficient of reflection or transmission. The fraction of the incident energy that is absorbed (or transmitted) at the surface boundary is the coefficient

$$\alpha_\theta = \frac{E_{t+a}}{E_i}$$

and the reflection coefficient is

$$\alpha_r = \frac{E_r}{E_i}$$

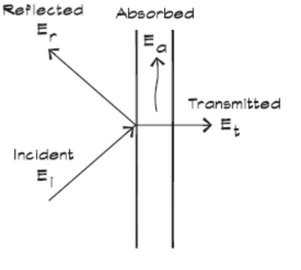
Substituting these coefficients

$$1 = \alpha_\theta + \alpha_r$$

and the apparent absorption coefficient is

$$\alpha_\theta = 1 - \alpha_r$$

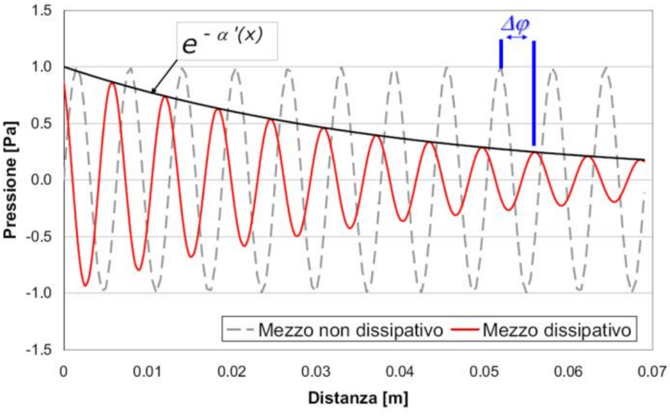
Interaction of Sound Waves with a Surface



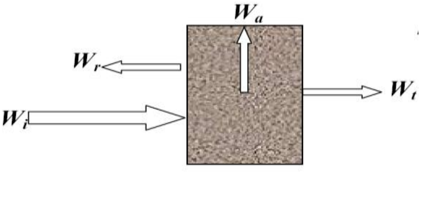
The reflected energy is

$$E_r = (1 - \alpha_\theta)E_i$$

Dissipative material



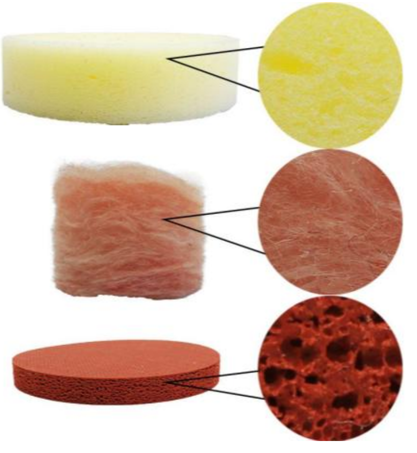
Acoustics Absorption



$\alpha = W_a / W_i$ Acoustics Absorption Coefficient of porous materials

Porous materials

- fiberglass
- Mineral fiber products
- Fiberboard
- pressed wood shavings
- Cotton
- Felt
- Neoprene foam
- Carpet
- Sintered metal
- ***Spaced porous materials***



Material	Mount	Frequency, Hz 125	250	500	1k	2k	4k
Walls							
Glass, 1/4", heavy plate		0.18	0.06	0.04	0.05	0.02	0.02
Glass, 3/32", ordinary window		0.55	0.25	0.18	0.12	0.07	0.04
Gypsum board, 1/2", on 2×4 studs		0.29	0.10	0.05	0.04	0.07	0.09
Plaster, 7/8", gypsum or lime, on brick		0.013	0.015	0.02	0.03	0.04	0.05
Plaster, on concrete block		0.12	0.09	0.07	0.05	0.05	0.04
Plaster, 7/8", on lath		0.14	0.10	0.06	0.04	0.04	0.05
Plaster, 7/8", lath on studs		0.30	0.15	0.10	0.05	0.04	0.05
Plywood, 1/4", 3" air space, 1" batt,		0.60	0.30	0.10	0.09	0.09	0.09
Soundblox, type B, painted		0.74	0.37	0.45	0.35	0.36	0.34
Wood panel, 3/8", 3-4" air space		0.30	0.25	0.20	0.17	0.15	0.10
Concrete block, unpainted		0.36	0.44	0.51	0.29	0.39	0.25
Concrete block, painted		0.10	0.05	0.06	0.07	0.09	0.08
Concrete poured, unpainted		0.01	0.01	0.02	0.02	0.02	0.03
Brick, unglazed, unpainted		0.03	0.03	0.03	0.04	0.05	0.07
Wood paneling, 1/4", with airspace behind		0.42	0.21	0.10	0.08	0.06	0.06
Wood, 1", paneling with airspace behind		0.19	0.14	0.09	0.06	0.06	0.05
Shredded-wood fiberboard, 2", on concrete	A	0.15	0.26	0.62	0.94	0.64	0.92
Carpet, heavy, on 5/8-in perforated mineral fiberboard		0.37	0.41	0.63	0.85	0.96	0.92
Brick, unglazed, painted	A	0.01	0.01	0.02	0.02	0.02	0.03
Light velour, 10 oz per sq yd, hung straight, in contact with wall		0.03	0.04	0.11	0.17	0.24	0.35
Medium velour, 14 oz per sq yd, draped to half area		0.07	0.31	0.49	0.75	0.70	0.60
Heavy velour, 18 oz per sq yd, draped to half area		0.14	0.35	0.55	0.72	0.70	0.65

continued

Material	Mount	Frequency, Hz 125	250	500	1k	2k	4k
Floors							
Floors, concrete or terrazzo	A	0.01	0.01	0.015	0.02	0.02	0.02
Floors, linoleum, vinyl on concrete	A	0.02	0.03	0.03	0.03	0.03	0.02
Floors, linoleum, vinyl on subfloor		0.02	0.04	0.05	0.05	0.10	0.05
Floors, wooden		0.15	0.11	0.10	0.07	0.06	0.07
Floors, wooden platform w/airspace		0.40	0.30	0.20	0.17	0.15	0.10
Carpet, heavy on concrete	A	0.02	0.06	0.14	0.57	0.60	0.65
Carpet, on 40 oz (1.35 kg/sq m) pad	A	0.08	0.24	0.57	0.69	0.71	0.73
Indoor-outdoor carpet	A	0.01	0.05	0.10	0.20	0.45	0.65
Wood parquet in asphalt on concrete	A	0.04	0.04	0.07	0.06	0.06	0.07
Ceilings							
Acoustical coating K-13,							
1"	A	0.08	0.29	0.75	0.98	0.93	0.96
1.5"	A	0.16	0.50	0.95	1.06	1.00	0.97
2"	A	0.29	0.67	1.04	1.06	1.00	0.97
Acoustical coating K-13 "fc" 1"	A	0.12	0.38	0.88	1.16	1.15	1.12
Glass-fiber roof fabric, 12 oz/yd		0.65	0.71	0.82	0.86	0.76	0.62
Glass-fiber roof fabric, 37.5 oz/yd		0.38	0.23	0.17	0.15	0.09	0.06
Acoustical Tile							
Standard mineral fiber, 5/8"	E400	0.68	0.76	0.60	0.65	0.82	0.76
Standard mineral fiber, 3/4"	E400	0.72	0.84	0.70	0.79	0.76	0.81
Standard mineral fiber, 1"	E400	0.76	0.84	0.72	0.89	0.85	0.81
Energy mineral fiber, 5/8"	E400	0.70	0.75	0.58	0.63	0.78	0.73
Energy mineral fiber, 3/4"	E400	0.68	0.81	0.68	0.78	0.85	0.80
Energy mineral fiber, 1"	E400	0.74	0.85	0.68	0.86	0.90	0.79
Film faced fiberglass, 1"	E400	0.56	0.63	0.69	0.83	0.71	0.55
Film faced fiberglass, 2"	E400	0.52	0.82	0.88	0.91	0.75	0.55
Film faced fiberglass, 3"	E400	0.64	0.88	1.02	0.91	0.84	0.62

continued

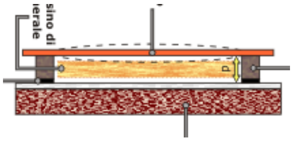
Material	Mount	Frequency, Hz 125	250	500	1k	2k	4k
Glass Cloth Acoustical Ceiling Panels							
Fiberglass tile, 3/4"	E400	0.74	0.89	0.67	0.89	0.95	1.07
Fiberglass tile, 1"	E400	0.77	0.74	0.75	0.95	1.01	1.02
Fiberglass tile, 1 1/2"	E400	0.78	0.93	0.88	1.01	1.02	1.00
Seats and Audience							
Audience in upholstered seats		0.39	0.57	0.80	0.94	0.92	0.87
Unoccupied well-upholstered seats		0.19	0.37	0.56	0.67	0.61	0.59
Unoccupied leather covered seats		0.19	0.57	0.56	0.67	0.61	0.59
Wooden pews, occupied		0.57	0.44	0.67	0.70	0.80	0.72
Leather-covered upholstered seats, unoccupied		0.44	0.54	0.60	0.62	0.58	0.50
Congregation, seated in wooden pews		0.57	0.61	0.75	0.86	0.91	0.86
Chair, metal or wood seat, unoccupied		0.15	0.19	0.22	0.39	0.38	0.30
Students, informally dressed, seated in tablet-arm chairs		0.30	0.41	0.49	0.84	0.87	0.84
Duct Liners							
1/2"		0.11	0.51	0.48	0.70	0.88	0.98
1"		0.16	0.54	0.67	0.85	0.97	1.01
1 1/2"		0.22	0.73	0.81	0.97	1.03	1.04
2"		0.33	0.90	0.96	1.07	1.07	1.09
Aeroflex Type 150, 1"	F	0.13	0.51	0.46	0.65	0.74	0.95
Aeroflex Type 150, 2"	F	0.25	0.73	0.94	1.03	1.02	1.09
Aeroflex Type 200, 1/2"	F	0.10	0.44	0.29	0.39	0.63	0.81
Aeroflex Type 200, 1"	F	0.15	0.59	0.53	0.78	0.85	1.00
Aeroflex Type 200, 2"	F	0.28	0.81	1.04	1.10	1.06	1.09
Aeroflex Type 300, 1/2"	F	0.09	0.43	0.31	0.43	0.66	0.98
Aeroflex Type 300, 1"	F	0.14	0.56	0.63	0.82	0.99	1.04
Aeroflex Type 150, 1"	A	0.06	0.24	0.47	0.71	0.85	0.97
Aeroflex Type 150, 2"	A	0.20	0.51	0.88	1.02	0.99	1.04
Aeroflex Type 300, 1"	A	0.08	0.28	0.65	0.89	1.01	1.04

continued

Material	Mount	Frequency, Hz 125	250	500	1k	2k	4k
Building Insulation - Fiberglass							
3.5" (R-11) (insulation exposed to sound)	A	0.34	0.85	1.09	0.97	0.97	1.12
6" (R-19) (insulation exposed to sound)	A	0.64	1.14	1.09	0.99	1.00	1.21
3.5" (R11) (FRK facing exposed to sound)	A	0.56	1.11	1.16	0.61	0.40	0.21
6" (R-19) (FRK facing exposed to sound)	A	0.94	1.33	1.02	0.71	0.56	0.39
Fiberglass Board (FB)							
FB, 3lb/ft^3, 1" thick	A	0.03	0.22	0.69	0.91	0.96	0.99
FB, 3 lb/ft^3, 2" thick	A	0.22	0.82	1.21	1.10	1.02	1.05
FB, 3 lb/ft^3, 3" thick	A	0.53	1.19	1.21	1.08	1.01	1.04
FB, 3 lb/ft^3, 4" thick	A	0.84	1.24	1.24	1.08	1.00	0.97
FB, 3 lb/ft^3, 1" thick	E400	0.65	0.94	0.76	0.98	1.00	1.14
FB, 3 lb/ft^3, 2" thick	E400	0.66	0.95	1.06	1.11	1.09	1.18
FB, 3 lb/ft^3, 3" thick	E400	0.66	0.93	1.13	1.10	1.11	1.14
FB, 3 lb/ft^3, 4" thick	E400	0.65	1.01	1.20	1.14	1.10	1.16
FB, 6 lb/ft^3, 1" thick	A	0.08	0.25	0.74	0.95	0.97	1.00
FB, 6 lb/ft^3, 2" thick	A	0.19	0.74	1.17	1.11	1.01	1.01
FB, 6 lb/ft^3, 3" thick	A	0.54	1.12	1.23	1.07	1.01	1.05
FB, 6 lb/ft^3, 4" thick	A	0.75	1.19	1.17	1.05	0.97	0.98
FB, 6 lb/ft^3, 1" thick	E400	0.68	0.91	0.78	0.97	1.05	1.18
FB, 6 lb/ft^3, 2" thick	E400	0.62	0.95	0.98	1.07	1.09	1.22
FB, 6 lb/ft^3, 3" thick	E400	0.66	0.92	1.11	1.12	1.10	1.19
FB, 6 lb/ft^3, 4" thick	E400	0.59	0.91	1.15	1.11	1.11	1.19
FB, FRK faced, 1" thick	A	0.12	0.74	0.72	0.68	0.53	0.24
FB, FRK faced, 2" thick	A	0.51	0.65	0.86	0.71	0.49	0.26
FB, FRK faced, 3" thick	A	0.84	0.88	0.86	0.71	0.52	0.25
FB, FRK faced, 4" thick	A	0.88	0.90	0.84	0.71	0.49	0.23
FB, FRK faced, 1" thick	E400	0.48	0.60	0.80	0.82	0.52	0.35
FB, FRK faced, 2" thick	E400	0.50	0.61	0.99	0.83	0.51	0.35
FB, FRK faced, 3" thick	E400	0.59	0.64	1.09	0.81	0.50	0.33
FB, FRK faced, 4" thick	E400	0.61	0.69	1.08	0.81	0.48	0.34
Miscellaneous							
Musician (per person), with instrument		4.0	8.5	11.5	14.0	15.0	12.0
Air, Sabins per 1000 cubic feet @ 50% RH					0.9	2.3	7.2

Panel absorbers

nonporous lightweight sheets, solid or peforated, that have an air cavity behind them, which can be filled with an absorbtive material such as fiberglass



Resonant absorbers

Lightweight partitions vibrating at their air-mass-air resonance

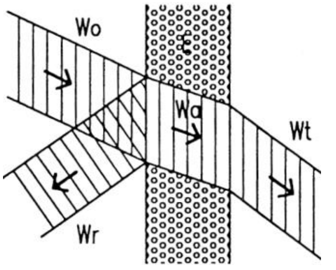
Helmholtz resonators or other similar enclosures, which absorb sound in the frequency range around their resonant frequency- They can also may be filled with absorbent porous materials.

In general, porous absorbers are too complicated for their precise impedances to be predicted from first principles.

It is customary to determine the **resistive component of the impededence R.**

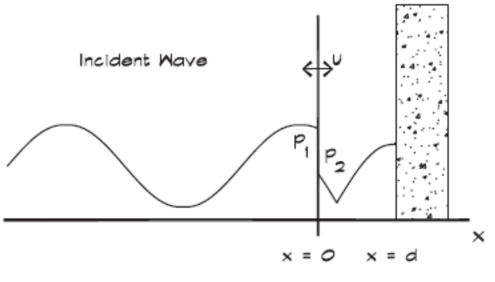
R represents the difficulty of the air flux to go through the material under a pressure gradient

$$R_s = \frac{\Delta P}{U}$$ [Pa*s/m]



Spaced porous absorbers

Spaced thin porous absorbers



The porous absorber does not move but air flows through it, creating a standing wave in the cavity behind.

If a thin porous absorber is positioned such that it has an airspace behind it, the composite impedance at the surface of the material and thus the absorption coefficient, is influenced by the backing.

The **flow resistance** is the difference in pressure across the material divided by the velocity rough the material.

$$r_f = \frac{p_1 - p_2}{u}$$

where $\mathbf{p}_1$ is the pressure on the left side of the sheet and $\mathbf{p}_2$ is the pressure just to the right of the sheet. In this analysis it is assumed that the resistance is the same for steady and alternating flow. The velocity on either side of the sheet is the same due to conservation of mass. The equation above can be written in terms of the impedance at the surface of the absorber (at x = 0) on either side of the sheet.

$$r_f = z_1 - z_2 \qquad\qquad z_1 = r_f + z_2$$

To calculate the impedance of the air cavity for a normally incident sound wave we write the equations for a rightward moving wave and the reflected leftward moving wave assuming perfect reflection from the wall.

$$\begin{aligned} p_2(x) &= A\left[e^{-j\,k(x-d)} + e^{j\,k(x-d)}\right] \\ &= 2\,A\cos\left[k\,(x-d)\right] \end{aligned}$$

The velocity in the cavity is

$$\begin{aligned} u_2(x) &= \frac{A}{\rho_0 c_0}\left[e^{-j\,k\,(x-d)} - e^{j\,k\,(x-d)}\right] \\ &= -\frac{2\,j\,A}{\rho_0 c_0}\sin\left[k\,(x-d)\right] \end{aligned}$$

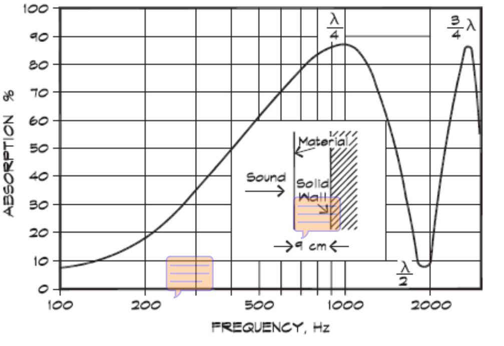
$$z_2 = \left(\frac{p_2}{u_2}\right)_{x=0} = -j\,\rho_0 c_0 \cot(k\,d)$$

The ratio of the pressure to the velocity at the sheet surface (x = 0) is the impedance of the cavity

$$z_n = r_f - j\,\rho_0 c_0 \cot(k\,d)$$

the absorption coefficient for normal incidence

$$\alpha_n = 4\left\{\left[\sqrt{\frac{r_f}{\rho_0 c_0}} + \sqrt{\frac{\rho_0 c_0}{r_f}}\right]^2 + \frac{\rho_0 c_0}{r_f}\cot^2\left(\frac{2\pi f d}{c_0}\right)\right\}^{-1}$$

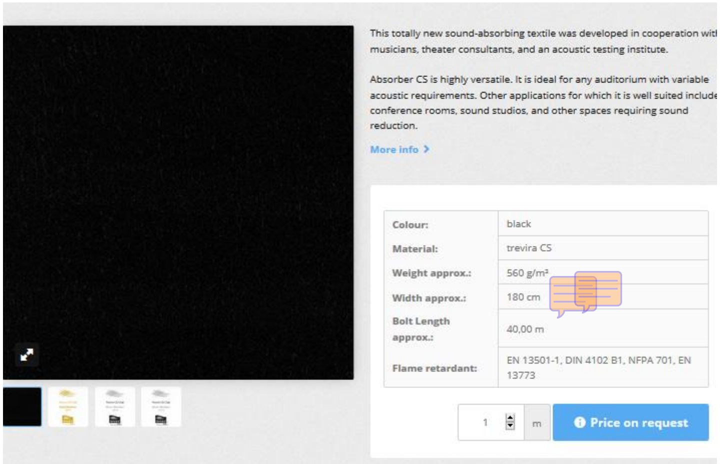


Absorption of freely suspended, thin porous material arranged parallel to a plane hard surface.

Flow resistance $\mathbf{r_f}$ $2\rho_0 c_0$

Spaced porous absorbers

Acoustic Curtain ABSORBER CS



Acoustic Curtain ABSORBER CS

This totally new sound-absorbing textile was developed in cooperation with musicians, theater consultants, and an acoustic testing institute.

Absorber CS is highly versatile. It is ideal for any auditorium with variable acoustic requirements. Other applications for which it is well suited include conference rooms, sound studios, and other spaces requiring sound reduction.

Its exceptionally high density and weight of approx. 560 g/m² earned ABSORBER CS a class C acoustic absorption rating, which distinguishes this fabric as highly sound absorbent.

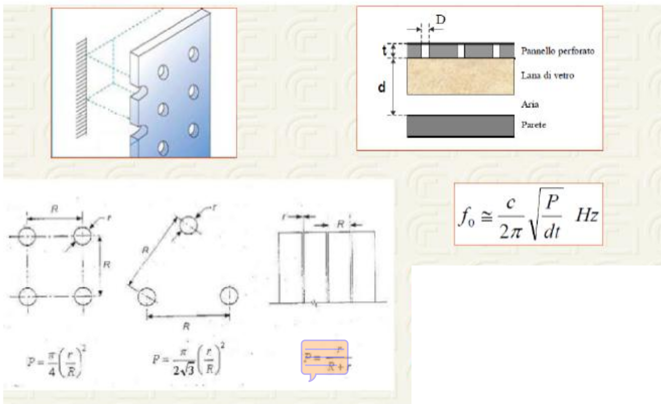
Acoustic absorption values per certificate
according to DIN EN ISO 354: aw = 0.65-0.90.
Acoustic absorption class: A-C.

Flow resistance according to DIN EN 29053:
Rs = approx. 1,300 Pa s/m

- Acoustic certificate available.
- Inherently flame retardant.
- Piece length approx. 40 - 50 rm (43.7 - 54.6 yds).
- Minimum quantity for custom dyed colours approx. 200 rm / 218.7 yds.

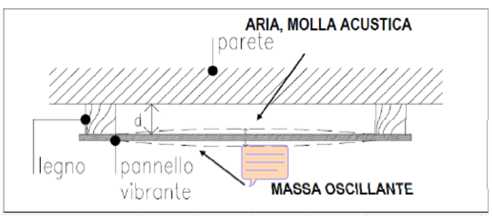
Custom curtains and draperies manufacured in our workshops.

Panel absorbers

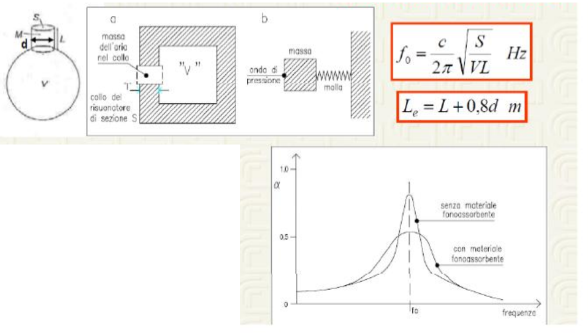


$$f_0 \cong \frac{c}{2\pi}\sqrt{\frac{P}{dt}}\ Hz$$

$$P=\frac{\pi}{4}\left(\frac{r}{R}\right)^2 \qquad P=\frac{\pi}{2\sqrt{3}}\left(\frac{r}{R}\right)^2$$



$$f_0 = \frac{600}{\sqrt{(M'd)}}\quad \text{Hz}$$



Type of seats	Frequency (Hz) 125	250	500	1000	2000	4000	6000
Audience seated on wooden chairs, two persons per m²	0.24	0.40	0.78	0.98	0.96	0.87	0.80
Audience seated on wooden chairs, one person per m²	0.16	0.24	0.56	0.69	0.81	0.78	0.75
Audience seated on moderately upholstered chairs, 0.85 m × 0.63 m	0.72	0.82	0.91	0.93	0.94	0.87	0.77
Audience seated on moderately upholstered chairs, 0.90 m × 0.55 m	0.55	0.86	0.83	0.87	0.90	0.87	0.80
Moderately upholstered chairs, unoccupied, 0.90 m × 0.55 m	0.44	0.56	0.67	0.74	0.83	0.87	0.80

Table 6.2 Equivalent absorption area of persons, in m² (after Kath and Kuhl[3])

Kind of person	Frequency (Hz) 125	250	500	1000	2000	4000
Male standing in heavy coat	0.17	0.41	0.91	1.30	1.43	1.47
Male standing without coat	0.12	0.24	0.59	0.98	1.13	1.12
Musician seated, with instrument	0.60	0.95	1.06	1.08	1.08	1.08

Table 6.4 Absorption coefficients of unoccupied and occupied seating areas in concert halls (after Beranek and Hidaka[6])

Type of seats		Frequency (Hz) 125	250	500	1000	2000	4000
Heavily upholstered	Unoccupied (seven halls)	0.70	0.76	0.81	0.84	0.84	0.81
	Occupied (seven halls)	0.72	0.80	0.86	0.89	0.90	0.90
Medium upholstered	Unoccupied (eight halls)	0.54	0.62	0.68	0.70	0.68	0.66
	Occupied (eight halls)	0.62	0.72	0.80	0.83	0.84	0.85
Lightly upholstered	Unoccupied (four halls)	0.36	0.47	0.57	0.62	0.62	0.60
	Occupied (six halls)	0.51	0.64	0.75	0.80	0.82	0.83

First group: 7.5 cm upholstery on front side of seat back, 10 cm on top of seat bottom, arm rest upholstered. Second group: 2.5 cm upholstery on front side of seat back, 2.5 cm on top of seat bottom, solid arm rests. Third group: 1.5 cm upholstery on front side of seat back, 2.5 cm on top of seat bottom, solid arm rests.