Safety of Industrial Plants

Lecture 13

Ergonomics

Noise

Contents and Goals

- Contents
  - Noise
  - Analysis of the sound environment
  - Sound absorption
  - Sound insulation

- Goals
  - Learn how to assess risks connected to noise

- Professional figures of reference
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Noise

- Noise is an extremely widespread pollutant, the examination of which involves considerable investment; its resolution is quite difficult, despite the technical progress made in recent years.

- Noise is a physical phenomenon due to the propagation of pressure waves, characterized by compression and subsequent rarefaction of air.

- It is, therefore, a periodic phenomenon of which is possible to identify a frequency.

- The sounds that can be perceived by human hearing have variable frequency from a few cycles per second (20 Hz) to about 20,000 Hz (the wavelength - in the field of hearing - varies from 17 mm up to 17 m; the period - in the field of hearing - varies from 50 milliseconds to 50 microseconds)
  - below 20 Hz we speak of infrasounds
  - Over 20.000 Hz we speak of ultrasounds

- Be careful and distinguish sounds from noise. Noises, although similar to sounds, generate discomfort feelings and become harmful when their energy content is excessive in relation to the characteristics of the hearing system

Noise

- Assuming equal to c = 343 m / s the speed of propagation of sound in the air, it can be said that there is a relationship between the wave length, its period and the constant c

$$\lambda = c * T$$

- The product of the air density (r0 = 1.21 kg / m3) and the speed of sound in the air, is called the acoustic impedance of air, Z_0.
- Sound intensity, however, is the energy carried by a sound wave in the unit time and per unit area of the perpendicular plane to the direction of sound propagation
  - in the case of sound sources placed in free space, there is the following relationship between the pressure in a point some meters away from the source, the acoustic impedance and the sound intensity (for the direct field):

$$I = \frac{p_{eff}^2}{Z_0}$$

  - In case of closed but very reflective environments, we can assume the following relation (for the reflected field):

$$I = \frac{p_{eff}^2}{4 \cdot Z_0}$$

Noise

- The sound power in a point at a distance r from a source, and in an isotropic medium, is equal to the product of the intensity I of the sound and the spherical surface having a radius r :

$$W = I * 4 \pi r^2 = 4 \pi r^2 \cdot \frac{p^2_{eff}}{Z_0}$$

- These physical quantities are expressed quantitatively by means of logarithmic levels
  - at least for narrow ranges of intensity, the auditory sensation varies with the logarithm of the magnitudes involved
  - this assumption allows us to contain numeric values in a narrow range

Noise

- The sound pressure level is (in dB):

$$L_p = 10 * \log_{10} (p_{eff}/p_0)^2 = 20 * \log_{10} (p_{eff}/p_0)$$

where $p_0 = 2*10^{-5}$ N/m^2, corresponding to the audibility threshold to 1,000 Hz

- The level of sound intensity is (in dB):

$$L_I = 10 * \log_{10} (I/I_0)$$

where $I_0 = 10^{-12}$ W/m^2

- The sound power level is (in dB):

$$L_W = 10 * \log_{10} (W/W_0)$$

where $W_0 = 10^{-12}$ W

- In the case of a source in free space and in sufficient distance from it, it can be stated that $L_p = L_I$.

Noise

- From the above, we can verify that
  - the increased level of 1 dB is determined by a change in the value of the considered magnitude of 26%
  - correspondingly, the decrease of 1 dB descends from a magnitude reduction of 20%
  - In fact:

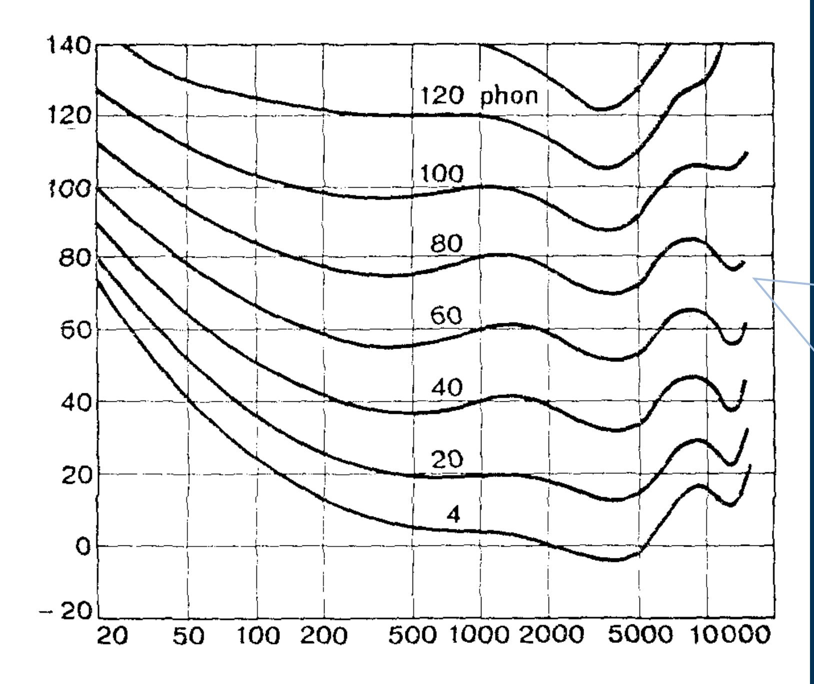
$$I = I_0 \cdot 10^{\frac{L_I}{10}}$$

- In general, we can add that
  - doubling the magnitudes means an increase of the level of 3 dB
  - Halving the magnitudes means a reduction of 3 dB

- One more important aspect is the relationship between the noise level and the corresponding auditory sensation
  - human ear can hear sounds characterized by a frequency in the range Hz20 ÷ 20.000 Hz
  - in particular, the sensitivity increases in the range 500 ÷ 5.000 Hz, resulting poor for low frequencies and moderately high to high frequencies

Noise

dB



Hz

Usually, due to the complexity of the curves, a single isophonic curve is considered. This curve takes into account the behavior of the middle ear. We talk, then, of sensitivity curve of standard ear, so called A curve, which is often used in practical applications

Audiogram of Davidson-Richardson or diagram of standard isophonics

Noise

- The frequency of the sounds equal to 1,000 Hz is taken as the reference of the audiogram, since in correspondence with it, the amplification and attenuation phenomena, which are typical of human ear, vanish
  - below 1,000 Hz there are attenuation phenomena
  - above, up to a value of 5.000 Hz, there are amplification phenomena
  - Beyond the above value, there is attenuation again

- Curve A is constructed taking into account the phenomena of attenuation and amplification producted by the average ear
  - We use a formula in which the sound levels are expressed as a function of the pressure ratio by means of a weight k:

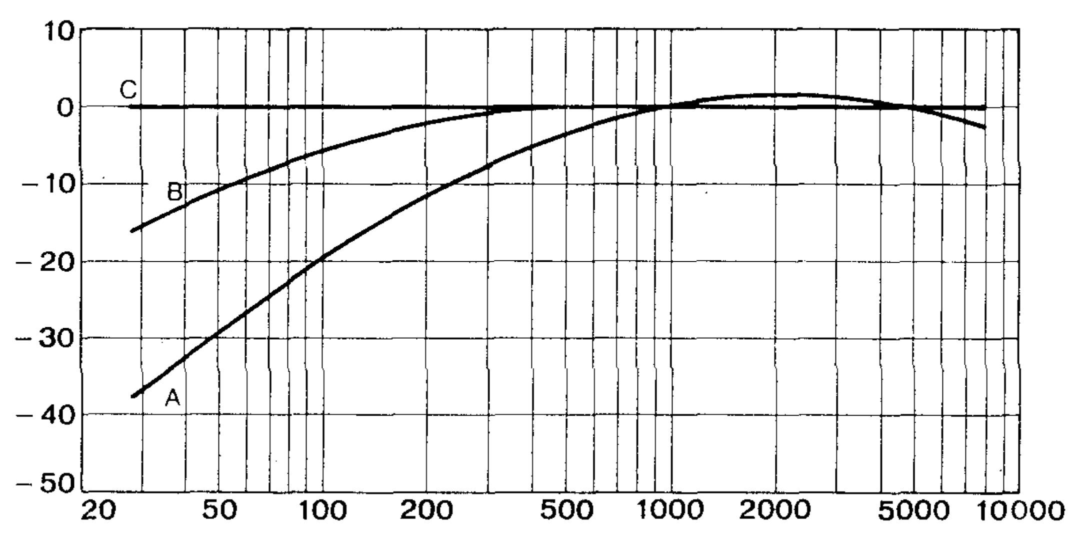
$$L_p = 10 \cdot \log \sum_i k_i^2 \cdot \left(\frac{p_i}{p_0} \right)^2$$

  - The terms pi represent the components of the sound pressure; the weights given to each component are determined by the response curve of the sound level meter in function of frequency

- In addition to the A curve two more curves, B and C are normalized. Whenever, therefore, we report a measurement of sound level in decibels, we have to clearly indicate which curve is referenced by placing the right subscript to the unit of measure (dBA, DBB or dBC).

Noise

dB



Hz

Weighting curves A, B and C

Noise

Type of sound	level (dB_A)
Audibility threshold	0
whispered voice	20
Office	40
normal conversation	60
car, orchestra	80
inside of a car travelling at 120 km / h	100
pneumatic hammer	120
jet plane	140

Examples of sound pressure levels

Noise

- In a workplace, in addition to an analysis of the sound level, an analysis of the sounds frequency has to be performed
  - the materials have a very different behavior with respect to the sounds at different frequencies, significantly changing their absorption, reflection and transmissivity characteristics in function of the frequency
  - in order to simplify the analysis, we can divide into bands the whole range of frequency object of interest, in particular in **octave bands**
    - They are frequency ranges characterized by a precise relationship between the lower and the upper frequencies of each interval
      - the upper frequency fs is twice the lower frequency fi (fs = 2fi)
      - the center frequency fc is defined as the geometric average of the two (fc = $\sqrt{f_s \cdot f_i}$)
  - The result is that is possible to divide the frequency range of interest into **ten intervals**
  - the frequency analysis can be performed by measuring the noise level of the environment, by applying a suitable filter that allows to perceive only the frequency band that affects at the time of measurement

Noise

- Monitoring the progress of sound in the time aiming at a quantitative assessment would be extremely complicated
  - The introduction of a mediated value is helpful. This value represents the equivalent noise level defined as the level that produces energetic effects equivalent to the set of those produced by the real phenomenon and variable in time
- The calculation of the equivalent level of the sound intensity, is conducted from the physical quantity concerned, the intensity I. Considering the sound intensity relating to a time interval ti, it is possible to track the average value of the intensity Im in a time interval T

$$I_m = \frac{\sum_i I_i \cdot t_i}{T} \longrightarrow L_{eq} = 10 \log \frac{I_m}{I_0} = 10 \cdot \log \frac{1}{T} \cdot \sum_i (10^{L_i/10} \cdot t_i)$$

$$\longrightarrow L_{eq} = 10 \log(\frac{1}{T} \cdot \int_0^T \frac{I}{I_0} dt) \qquad \longrightarrow L_{eq} = 10 \log(\frac{1}{T} \cdot \int_0^T \left(\frac{p_m}{p_0}\right)^2 dt)$$

Noise

- The ACGIH considers that, for each increment of 5 dBA of the sound pressure level, the exposure times have to be halved. Noise is measured with reference to the weighting scale A

Noise exposure (ore)	Sound level dB_A
16	80
8	85
4	90
2	95
1	100
1/2	105
1/4	110
1/8	115

Noise

- If the noise exposure of continuous type is not constant, but rather consists of a series of periods characterized by different levels, the following relationship between the noise levels upper 80 dBA indicated with us and the relative exposure times Ti has to be verified:

$$\frac{C_1}{T_1} + \frac{C_2}{T_2} + \ldots\ldots\ldots \frac{C_n}{T_n} < 1$$

- With impulsive or impact noise

number of pulses per second	Peak sound level
100	140
1.000	130
10.000	120

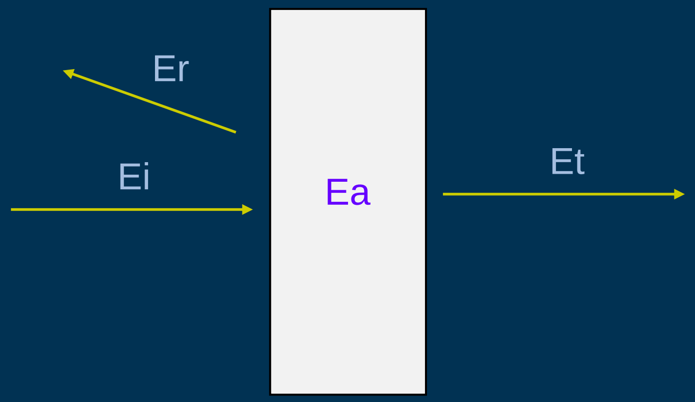
Noise

- Noise effects
  - hypoacusis
    - is produced by the damage caused by the noise of high intensity to Corti cells, which represent the sound transducers from elastic wave to electrical –nervous phenomenon
      - Hypoacusis phenomenon can be temporary
      - if, however, the exposure should be prolonged or repeated significantly over time for the hearing system, the damage may be permanent
      - the Hypoacusis begins between cells sensitive to lower frequencies (around 4000 Hz) in correspondence of which, however, the minority of the sounds or noises manifest: normal conversation, in fact, interesting average higher sound frequencies. This makes Hypoacusis particularly insidious
      - the Hypoacusis is a danger that comes when you have to deal with a source from levels above 80 dBA with exposure which varies over time; even if the level is around 100 dBA, an exposure of a quarter of an hour or half an hour is enough to cause serious damage to the hearing system.
  - masking
    - Masking occurs when in a workplace there are average sound levels high that rise above the sound values of normal conversations and disguise words, anger signals, sirens, etc.
    - the evaluation of this phenomenon can be done by resorting to different criteria. One of the most used is that of the speech interference level (SIL). This calculates the arithmetic average of the sound levels of background noise in octave bands corresponding to 500, 1,000, 2,000 and 4,000 Hz, that is, the characteristic frequency of speech

  - Among extra-auditory effects, we may remember common disorders such as cardiovascular, respiratory, gastrointestinal and nervous disorders which are not often traced to noise although this, very often, constitutes the main cause

Analysis of sound environment

- The measurement of noise levels in an environment may result, at times, complicated by the complexity of the situation. In such cases, therefore, it may be advantageous to use modeling.
- The energy model is the simplest and most useful for the purpose of our considerations. We may consider a sound wave that interacts with a wall; the wave of the elastic type in question carries a quantity of energy, part of which is transmitted through the wall, part is absorbed and, finally, part is reflected.



Interaction of sound energy with a wall

Analysis of sound environment

- The analysis of the energetic quantities involved leads to consider :
  - transmission coefficient

$$\tau = \frac{E_t}{E_i}$$

  - absorption factor

$$\alpha = \frac{E_i - E_r}{E_i} = \frac{E_t + E_a}{E_i}$$

  - Average factor of local absorption

$$\alpha = \frac{\sum_j \alpha_j \cdot S_j}{S_j}$$

  - Absorption

$$A = \sum_j \alpha_j \cdot S_j = \alpha \cdot S$$

The absorption A is a measure of the surface and it is expressed in square meters of an open window: it can be considered that the absorption corresponds to an area completely absorbed (that is why the open window) in a certain environment; the remaining surface of that environment, obviously, can be thought, however, perfectly reflecting

Analysis of sound environment

- The presence of objects in a place induces an increase in the level of general absorption
  - With reference to the different objects, a search in literature has to be performed because of the different behaviour of the individual bodies towards absorption
  - according to Sabine, there are two main types of bodies with regard to the absorbent behavior:
    - highly reflective, typically hard, compact and non-porous bodies
    - low reflective, usually soft and porous objects, characterized by lightness and poor compactness. They are also characterized by widespread porosity with numerous air-filled hollows. When the sound wave affects the material, the air is set in motion according to a continuous compression and rarefaction which gives rise to the next generation of heat, caused by the irreversibility of the phenomenon. Internal frictions and the material deformation make that sound energy convert into thermal energy (heat), resulting in the gradual damping of sound
  - The absorbent behaviour varies with the frequency of sounds taken into account.
- Materials such as glass wool and rock wool, characterized by both phenomena of friction and deformation are the best absorbent.
- Polyurethane foams, however, being characterized by a more rigid structure, convert the sound energy into heat, mainly by friction: they are, in fact, hard and compact materials.
- The best absorbent materials are those open cell
- The calculation of the level of absorption of a place therefore, is difficult because of the complexity due to the objects that may be present and their absorption characteristics

Analysis of sound environment

- The absorption of a room is usually determined experimentally.
- Sabine proposed a relationship between the geometric characteristics of the place, the absorption and the speed rate of descent of the sound level from the time in which the sound sources are switched off, which is expressed by the so-called reverberation time or reverberation (T60), i.e. the time the sound level takes in a room to fall by 60 dB when we turn off the sound source:

$$T_{60} = 0161 \cdot \frac{V}{A}$$

- This report is valid in the case of regularly shaped and not very absorbent environments , i.e. with $\alpha<0,2$.

Analysis of sound environment

- For the reasons expressed above, it is possible to divide into two parts the sound power W placed in an environment:
  - the not reflected, absorbed or transmitted power beyond the considered environment

$$W_a = \alpha \cdot W$$

  - and the power of the reverberated sound field

$$W_r = (1 - \alpha) \cdot W$$

- the sound field within the environment is determined by the superposition of two sound fields :
  - the direct one (that sound sources would develop in the absence of the absorbent structures):

$$I_d = \frac{p_{eff}^2}{\rho_0 \cdot c}$$

  - The one reflected or reverberated :

$$I_r = \frac{p_{eff}^2}{4 \cdot \rho_0 \cdot c}$$

it decreases with the distance from the source, and its value is closely related to the direction of propagation of the sound wave (starting from the equations of the sound intensity of the direct field in the case of point source, we can have the expression of the level of pressure from which we can see that there is a reduction of the pressure level equal to 20 * log r, that is, there is a reduction of 6 dB for each doubling of the distance from the source

The reverberant field tends to be uniform and non-directional.
In case of large distances, it is prevalent compared to the direct one

Analysis of sound environment

- Interventions to control the risk of noise fall into four main types (in logical order):
  - Interventions in the design phase
    - Compartmentalization
    - Proper placement of insiders and outsiders (layout)
    - intermittent exposure
    - Sources directionality
    - an analysis of the problem in the design phase involves considerable cost savings, also in view of the difficulties inherent in the interventions of noise control
  - intervention on the choice of machines, processes and materials; i.e. to opt - when and if it is possible - for less noisy machines, quieter processes and materials that have the noise attenuation characteristics
  - intervention at the source of the noise; it is not easy to apply technical solutions, which require the aid of expert personnel; usually trying to reduce exciter forces and all those phenomena that tend to produce noise; you can think of exploiting the directionalities of the sources in order to reduce the noise level near the places occupied by the operators
  - One more type of applicable intervention to control noise is realized by the confinement of the sound field or with the absorption on appropriate surfaces of its energy content

Sound absorption

- Sound absorption only acts on the reverberant sound field, in fact, it allows to realize a maximum reduction of 10 dB, compared to a very high cost.

- Sound absorption is used primarily as a measure to reduce the irksomeness of noise (hue).

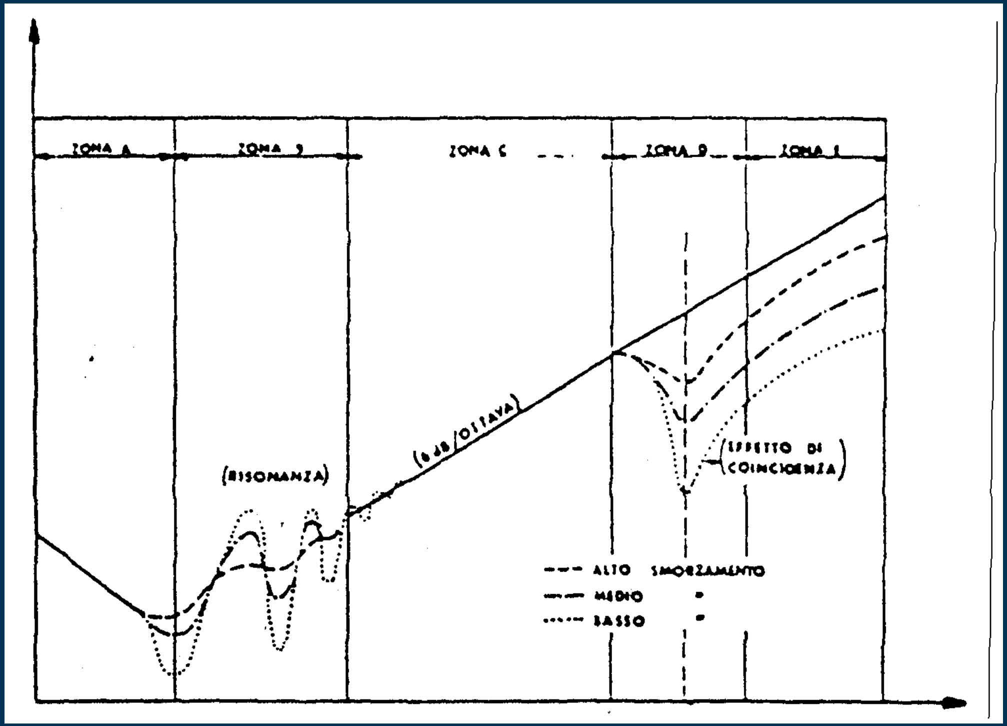
Sound insulation

- Sound insulation is the last intervention to take in a logical order
- It consists in the confinement of the sound energy in a sufficiently low precise volume
- It is realized thanks to materials characterized by particular compactness and rigidity.

Sound insulation

- If we indicate with τ the transmission factor of a wall, we can define soundproofing power of a wall the quantity F:

$$F = 10 \cdot \log\left(\frac{1}{\tau}\right)$$

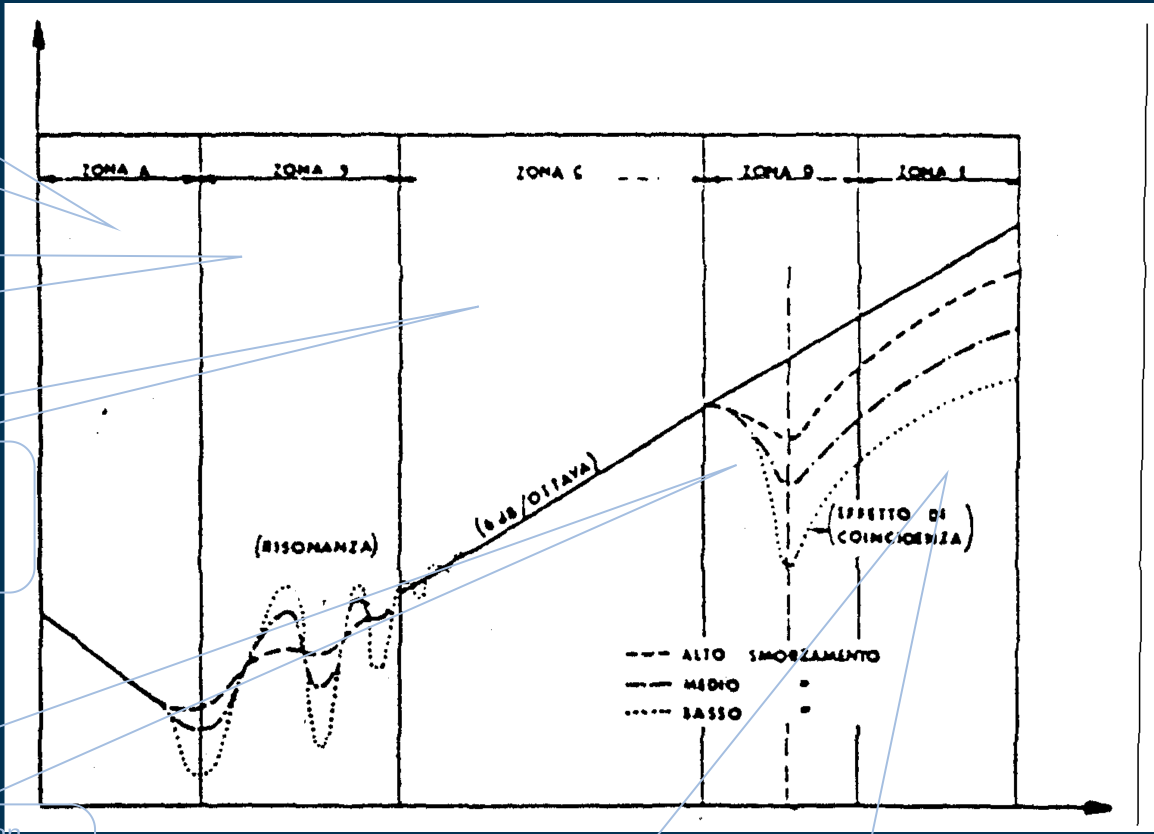


Sound insulation

The area of the stiffness, Zone A: the soundproofing power decreases with the increasing frequency; such behavior is closely related to the type of wall; this decrease in the real walls of sound insulation is somewhat attenuated

The area of the resonance zone B: the wall, that like any other object presents some frequencies of oscillation, presents a not easily discernible behavior

The first area of validity of the laws of mass and frequency, zone C: the soundproofing power becomes a straight line with a slope of about 6 dB; the sound reduction index, increases by 6 dB for each doubling of the frequency or of the mass



The area of coincidence testifies the existence of an important phenomenon, thanks to which the sound energy incident on the wall is transmitted by the wall itself with great efficiency, because the sound insulation power decreases

The second area of validity of the laws of mass and frequency corresponding to the area E of the graph, still shows an upward trend of the sound reduction with frequency

Sound insulation

material	thickness mm	Frequency Hz				
		125	250	500	1.000	2.000
steel	1	23	28	35	41	45
aluminum	0,6	8	14	12,5	17,5	22,5
Glass	4	20	23	27	34	33
lead	3	26	31	27	37,5	44
Wood	6	14	21	21	25,5	26
plasterboards	60	28	32	25	30	40
concrete wall	100	34	39	44	49	54
brick wall	100	38	43	48	53	58
Wooden door	-	13	16	20	23	22
wooden or aluminum window	6	19	20	26	26	28

Soundproofing power (dB) of some materials and joinery

Sound insulation

materials	f (resonance) Hz	f (coincidence) Hz
vetro	28-45-97-114	2.560
muro in mattoni pieni	88-202-239-352	130
lastra di gesso	65-90-233-258	1.000
lastra di acciaio	6-12-20-24	12.200

Resonance and coincidence characteristics of some materials