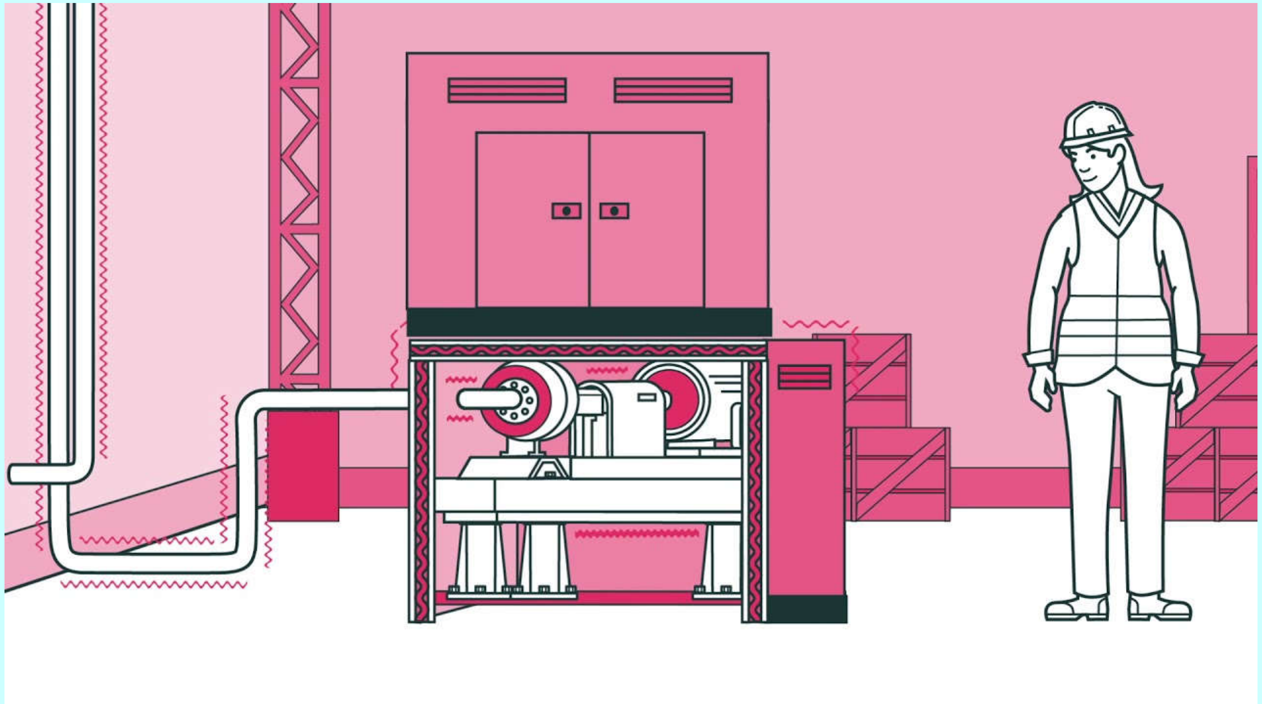
MEBS7014 Advanced HVAC applications

http://ibse.hk/MEBS7014/



Noise and Vibration Control I

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Contents

- Basic principles
- Noise & vibration from HVAC
- Noise control in HVAC
- Vibration control

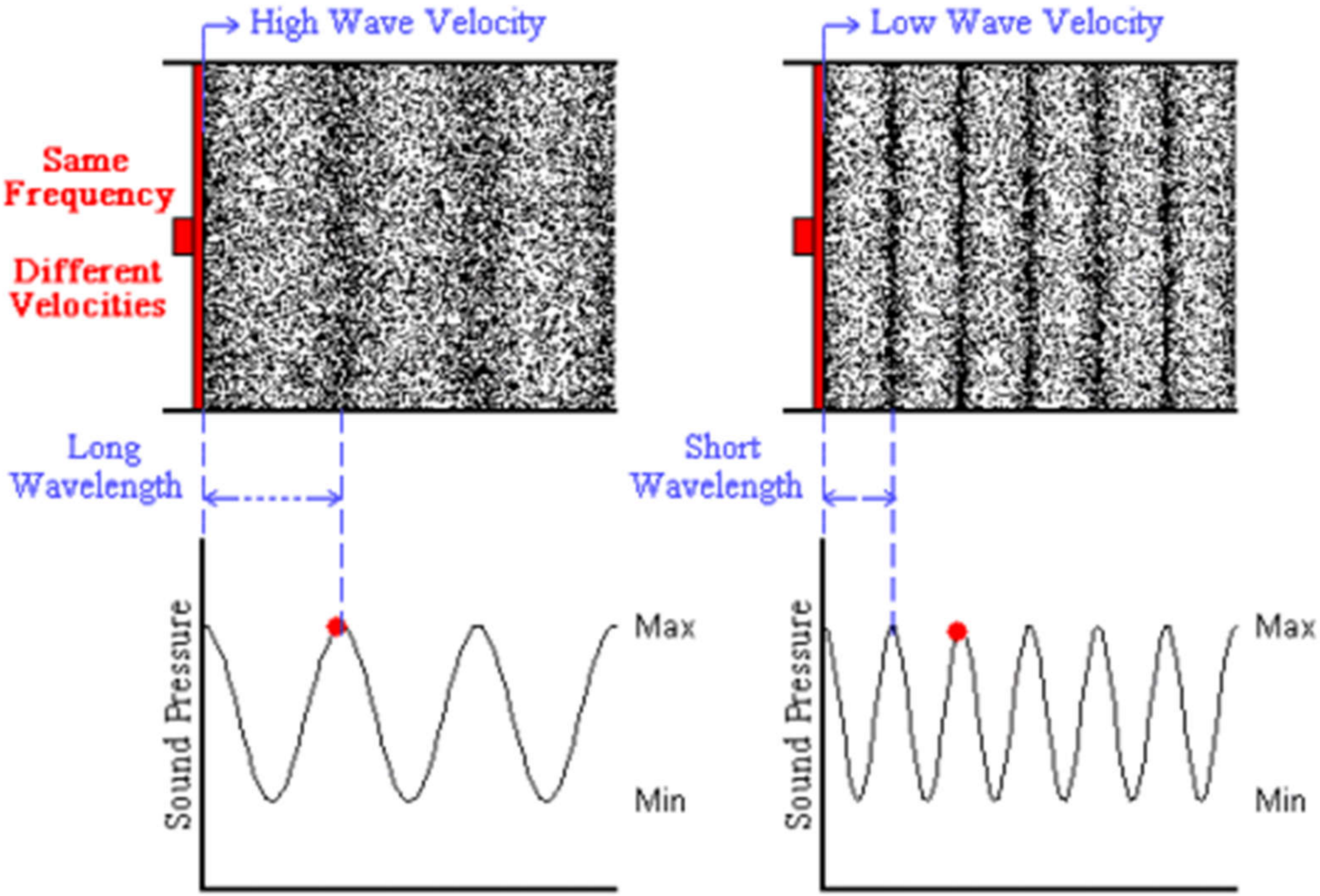
Basic principles

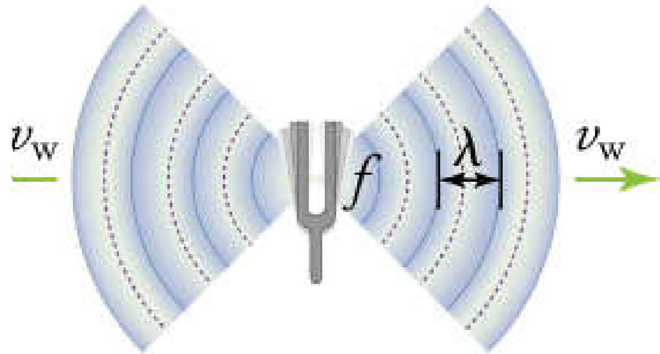
- Sound is produced by very small but rapid pressure fluctuations in the air
- Noise is often defined as ‘unwanted’ sound
- Sound pressure is the instantaneous change in atmospheric pressure caused by the sound wave (sinusoidal), measured in pascals (Pa), (where 1 Pa = 1 $N.m^{-2}$)
- Sound frequency is the number of cycles of pressure variations per second, measured in hertz (Hz)

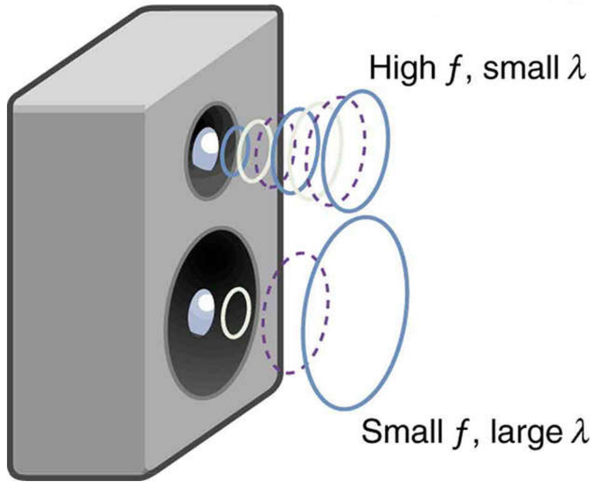
Sound frequency, wavelength and velocity

$$c = \lambda f$$

where c is the velocity (~ 345 m·s^{-1}), λ is the wavelength (m) and f is the frequency (Hz)

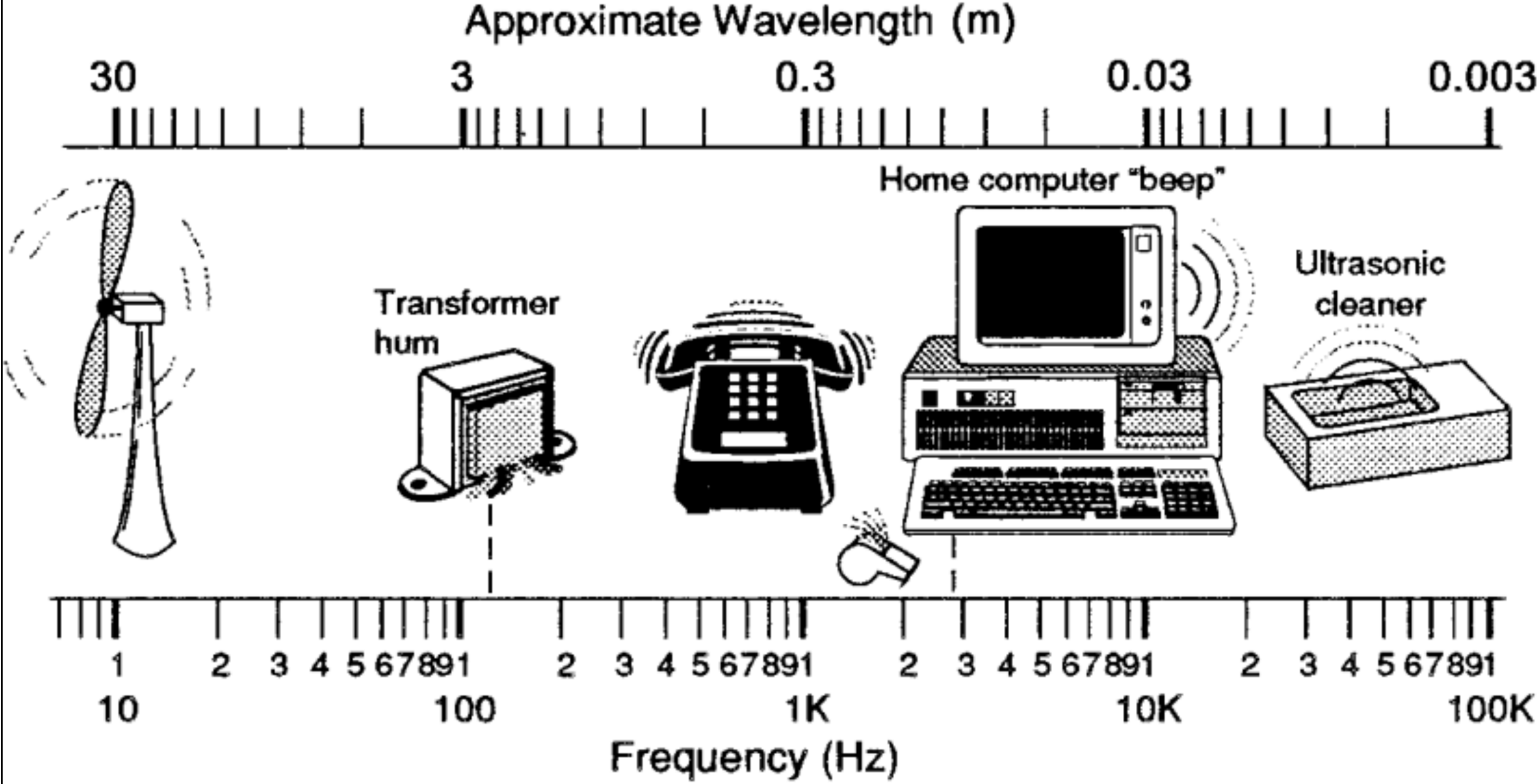






(Image source: https://blog.soton.ac.uk/soundwaves/wave-basics/wavelength-frequency-relation/)

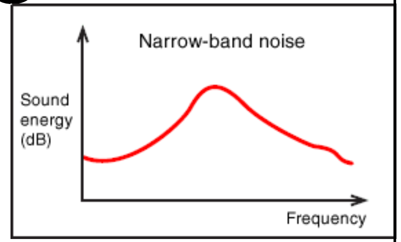
Everyday sound sources -- their frequencies and wavelengths



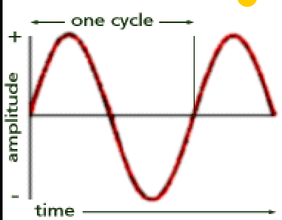
(Source: Schaffer M. E., 2011. *A Practical Guide to Noise and Vibration Control for HVAC Systems*, 2nd Edition (SI))

Basic principles

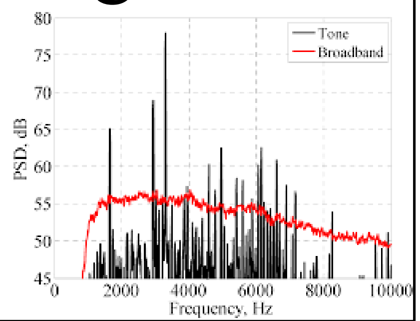
- Broad band noise is the sound containing a mixture of a wide range of frequencies
  - Measured using octave or ⅓-octave bands



- Pure tone component is a sound or a signal with a sinusoidal waveform



  - Such tonal components are usually more annoying and therefore noise containing tones is often assessed more severely than the corresponding broad band noise without tones
  - Reflected in the shape of noise spectrum



Basic principles

- Sound power, in watts (W), is sound energy radiated by the sources and spread out as it travels into the surrounding environment
- Sound intensity (in $W.m^{-2}$) is a measure of the rate of flow of sound energy at a point
- Decibel scale is a logarithmic scale used for comparing ratios of powers, or quantities related to powers
  - Compare sound power on a decibel scale (dB)
    - N dB = $10 \times \log_{10} (W_1 / W_2)$

Sound power level, sound intensity level and sound pressure level

Sound power level (SWL or PWL):

$$L_W = 10 \log (W / W_0) \text{ in dB re. } W_0 = 10^{-12} \text{ W}$$

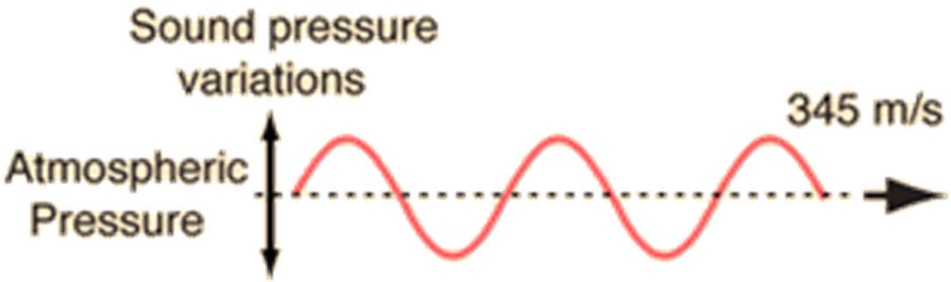
Sound intensity level (SIL):

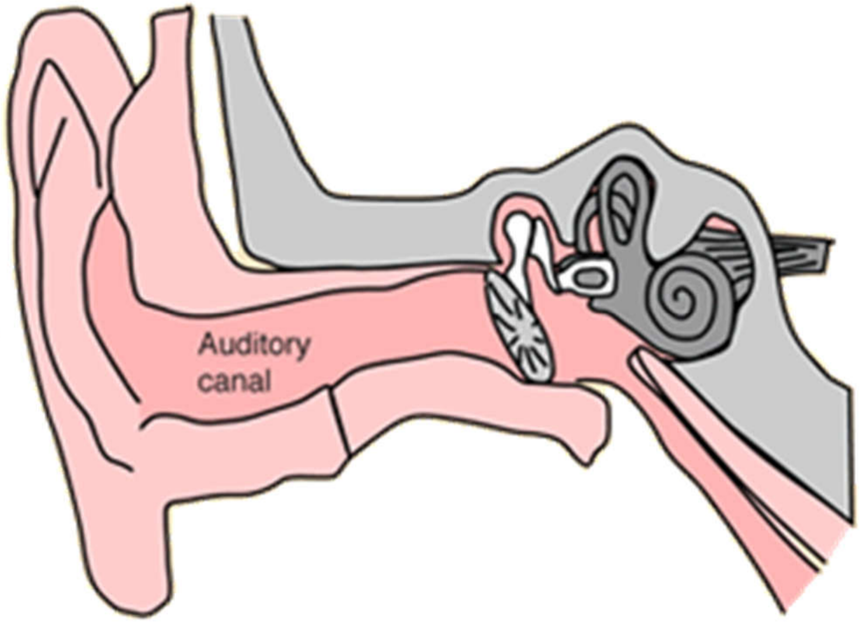
$$L_I = 10 \log (I / I_0) \text{ in dB re. } I_0 = 10^{-12} \text{ W/m}^2$$

Sound pressure level (SPL):

$$L_P = 10 \log (P / P_0)^2 = 20 \log (P / P_0) \text{ in dB re. } P_0 = 2 \times 10^{-5} \text{ Pa}$$

Sensitivity of human ear

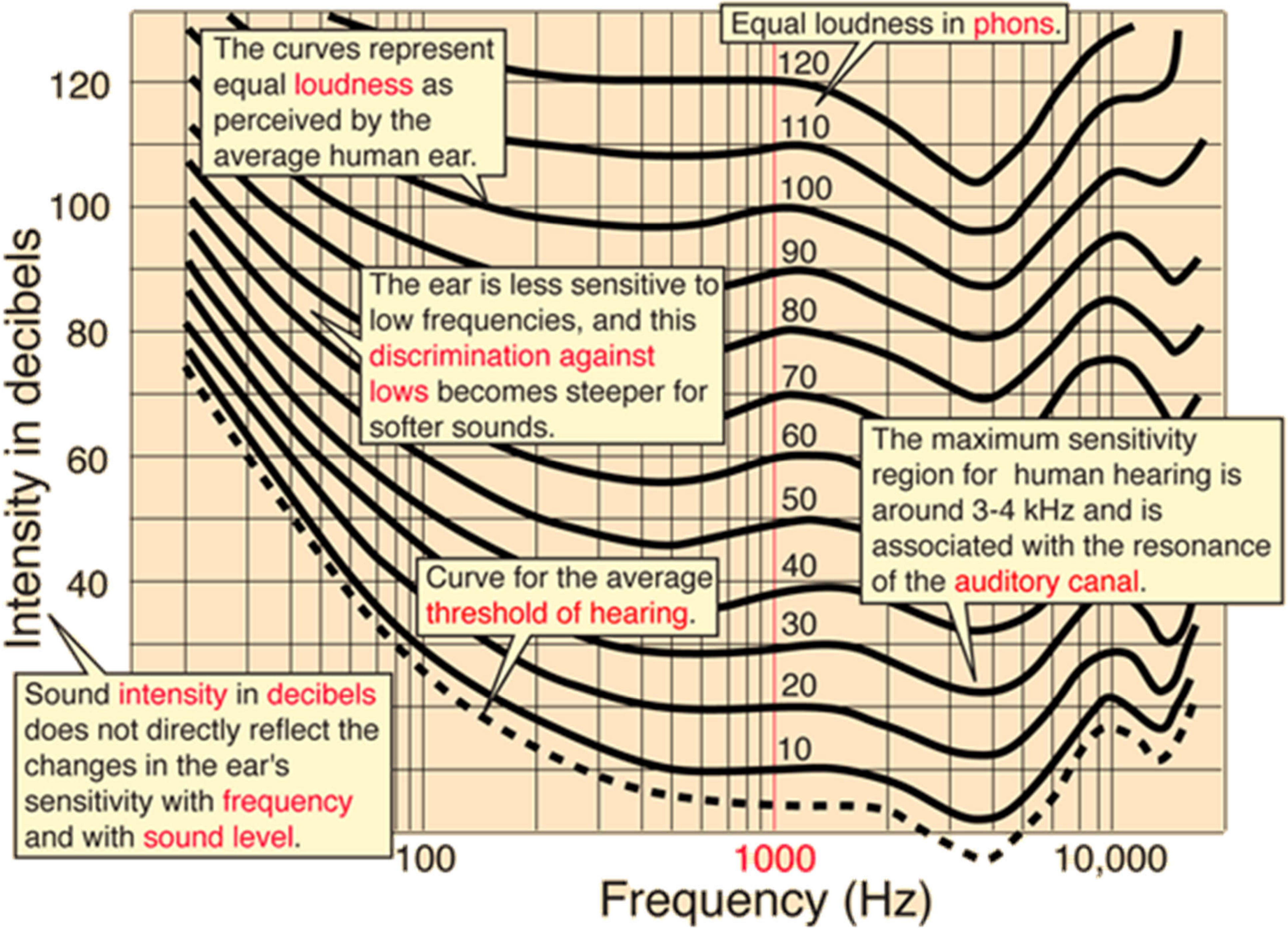




Sound loudness is a subjective term describing the strength of the ear's perception of a sound

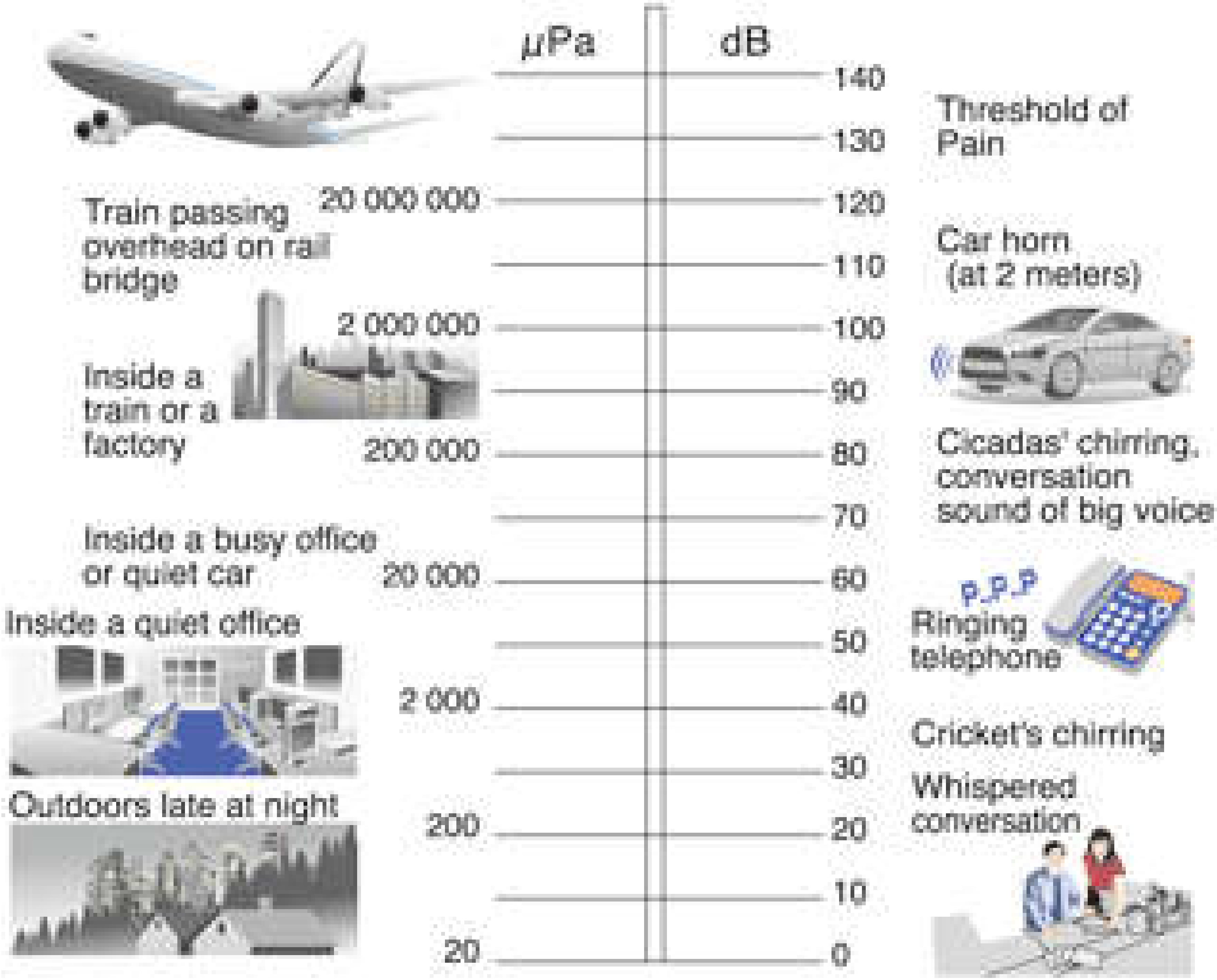
(Image source: http://hyperphysics.phy-astr.gsu.edu/hbase/Sound/earsens.html)

Equal loudness curves of sound (as perceived by the average human ear)



(Source: http://hyperphysics.phy-astr.gsu.edu/hbase/Sound/eqloud.html)

Sound pressure (μPa) and sound pressure level (dB)

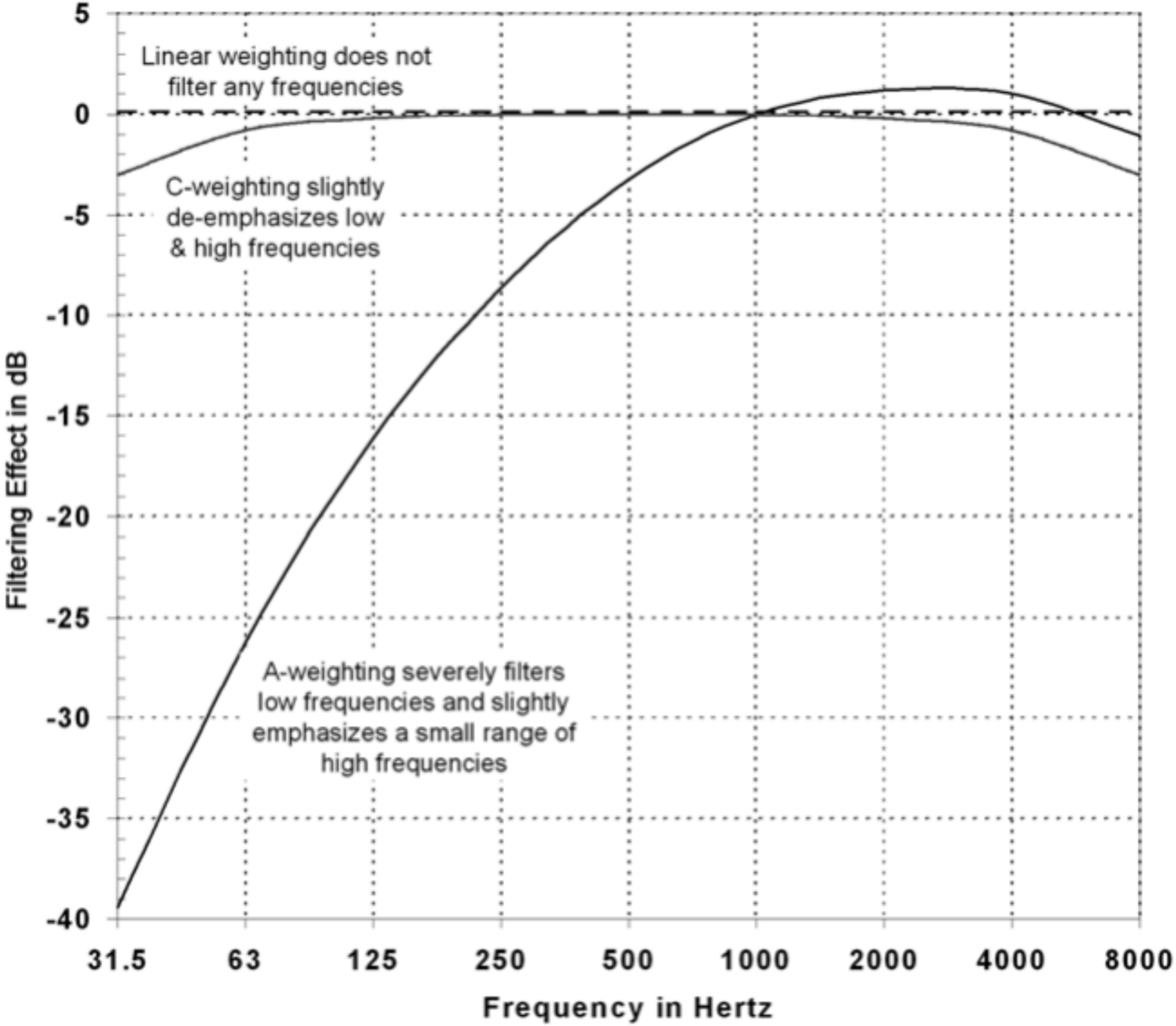


(Source: https://svmeas.rion.co.jp/support/st_sound_en.aspx)

Basic principles

- Acoustical rating systems and criteria
  - A-weighted (dBA) and C-weighted (dBC) sound level
  - Loudness level (sones)
  - Room criterion (RC) and RC Mark II
  - Noise criterion (NC), balanced noise criterion (NCB), noise rating (NR)
- Acceptable HVAC system noise (indoor sound)
  - It is not too loud
  - Does not fluctuate significantly over short time periods
  - It does not have audible tones
  - Spectrally balanced (i.e., not too much rumble, roar, or hiss)
  - It is not too quiet

Frequency weighting curves: linear, A-weighting and C-weighting filters

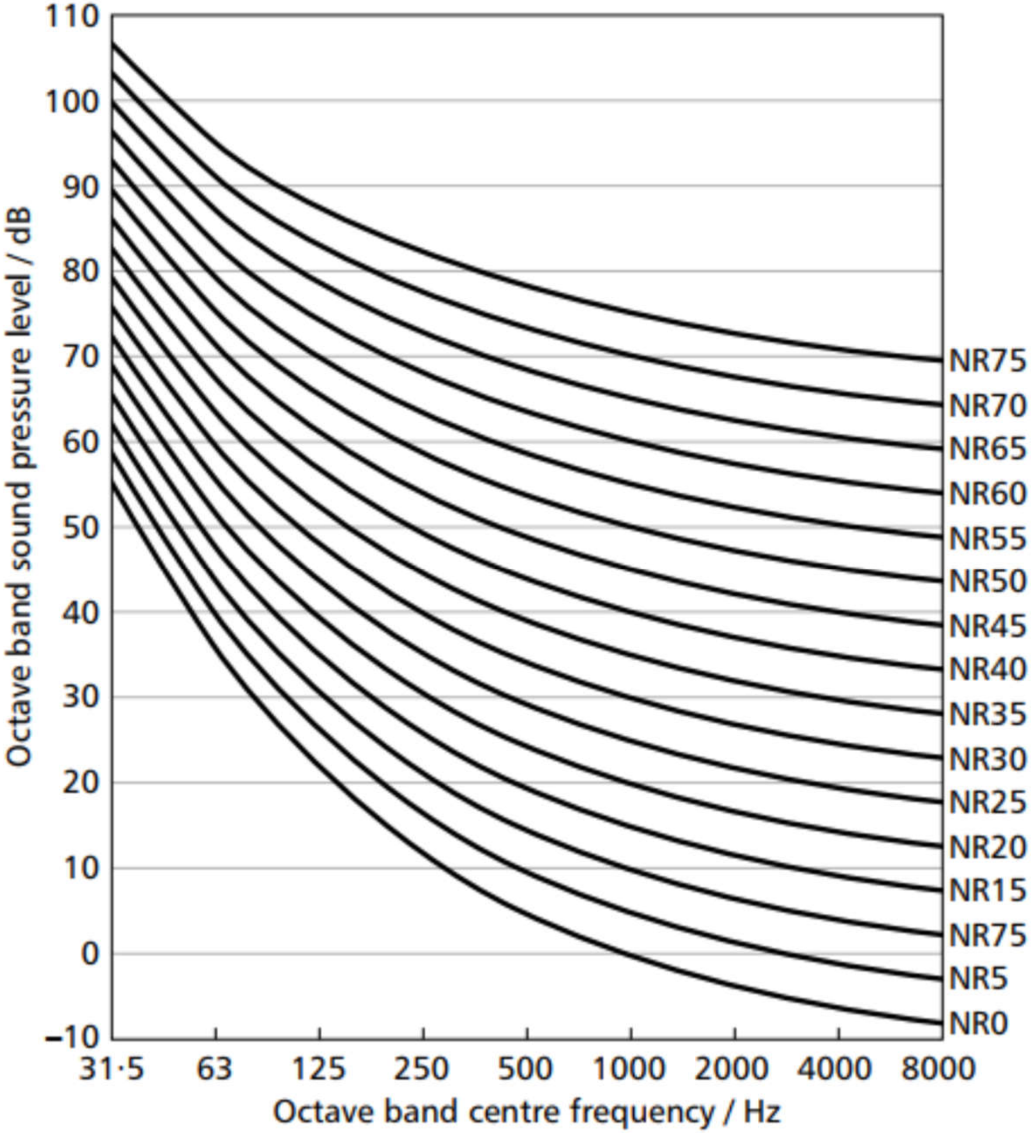


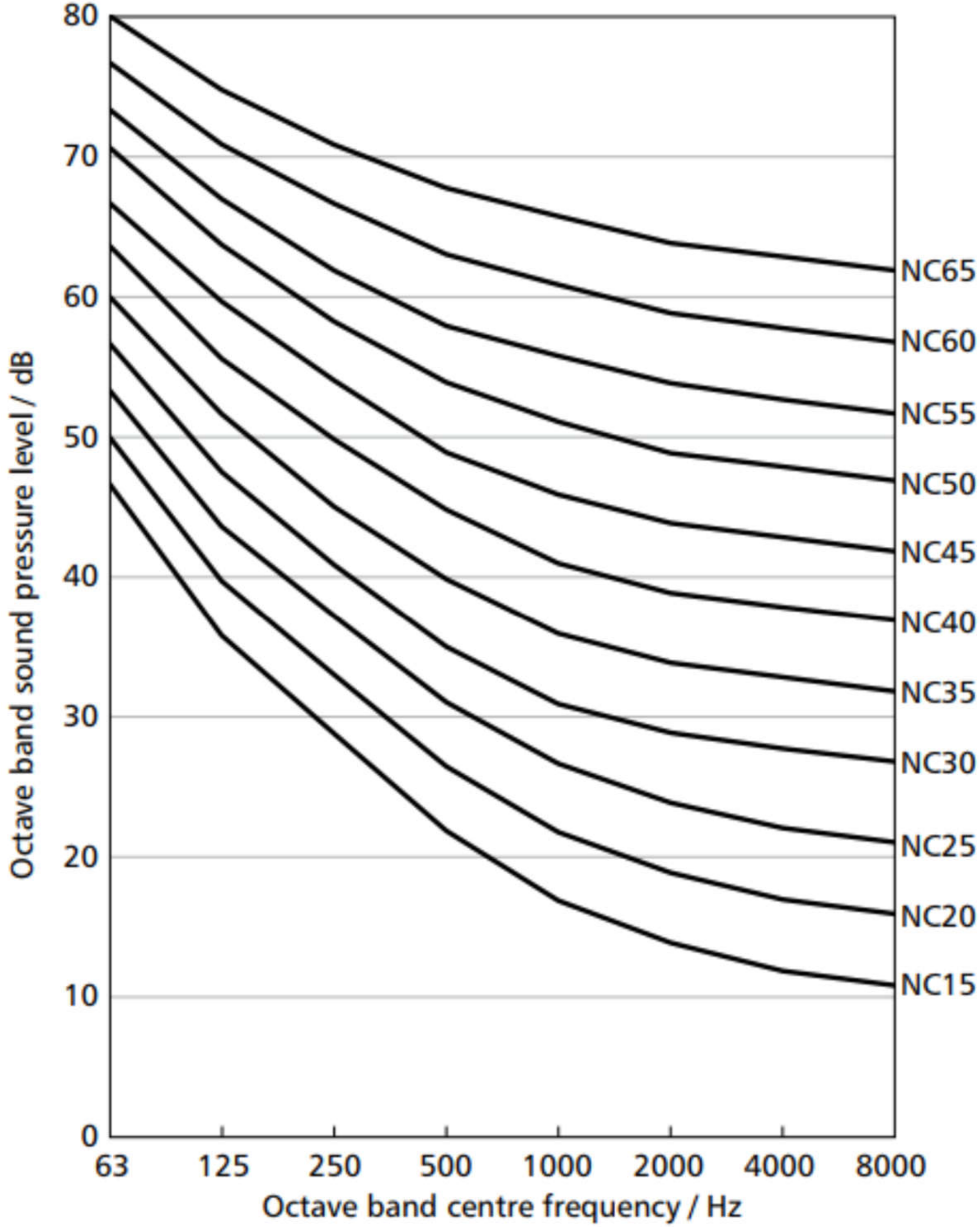
(Source: Schaffer M. E., 2011. *A Practical Guide to Noise and Vibration Control for HVAC Systems*, 2nd Edition (SI))

Basic principles

- Purposes of noise criteria
  - Set performance standards for a space or building
  - Provide guidance for the detailed acoustic design of a space or building
  - Act as benchmarks in the investigation of noise problems or complaints
- Choosing noise criteria parameters
  - Overall noise levels (e.g. dBA, dBC, NC, NR)
  - Noise quality (e.g. spectral characteristics)
  - Time variation (e.g. L_{eq}, L_{90}), speech interference

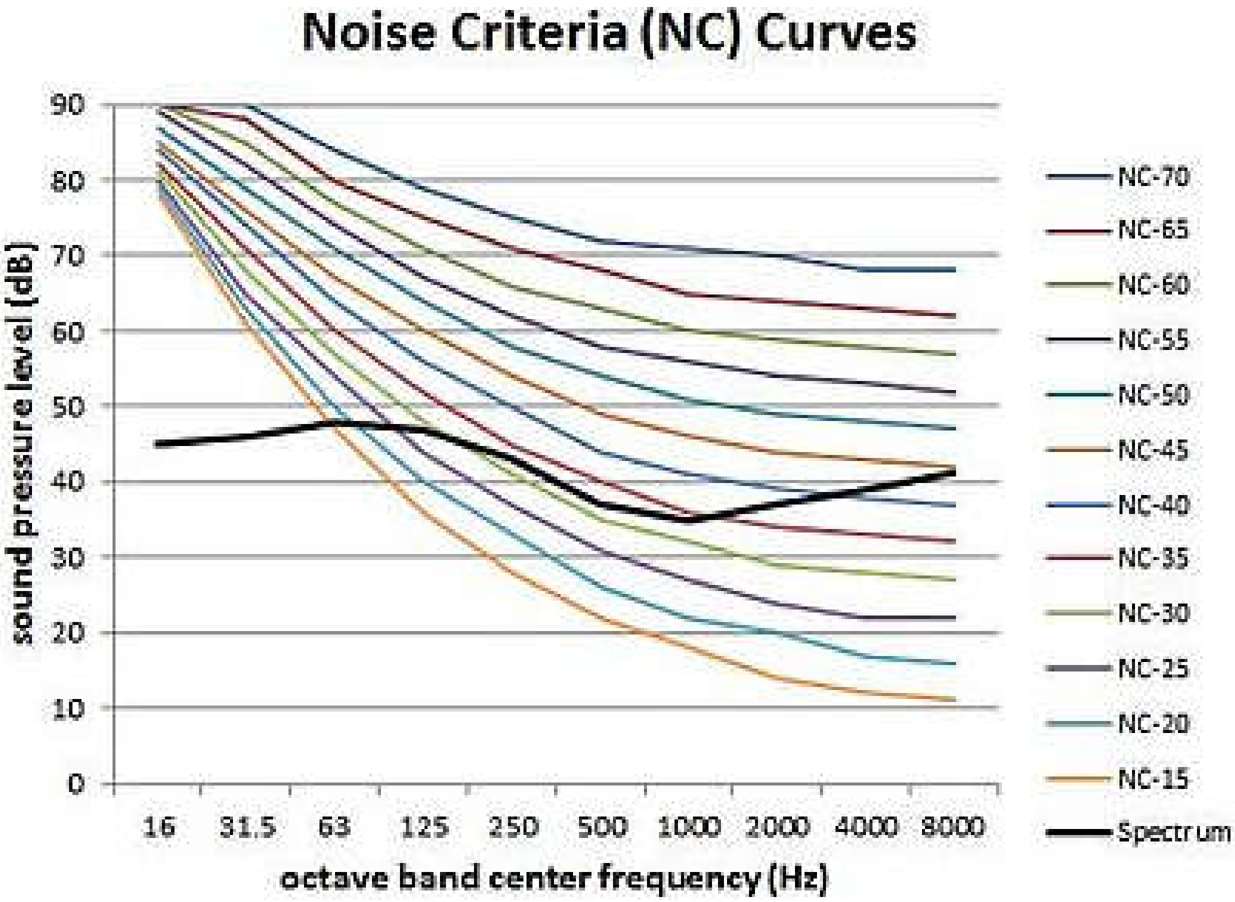
NR (noise rating) curves and NC (noise criteria) curves





(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

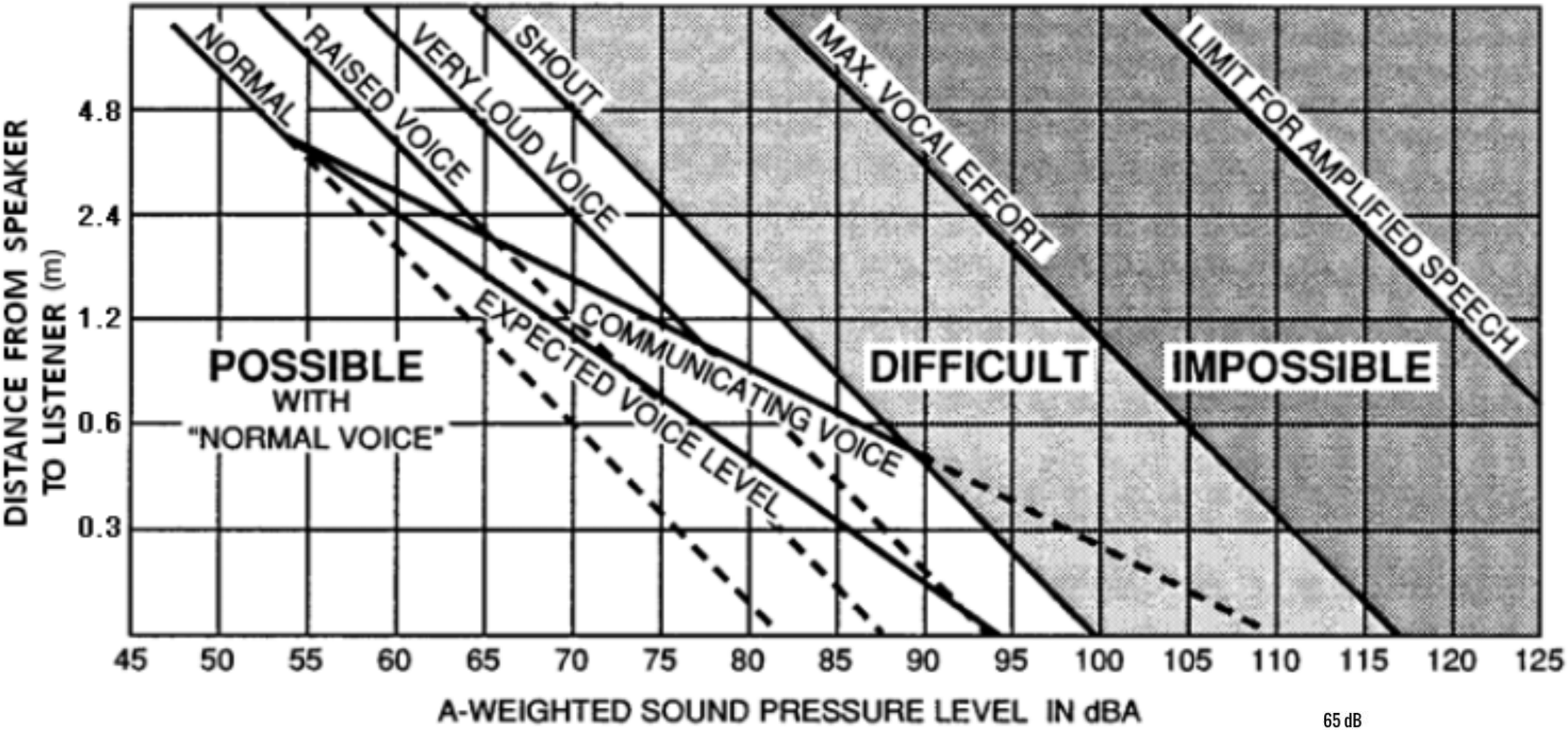
Noise criterion (NC) curves and recommended NC level & dBA

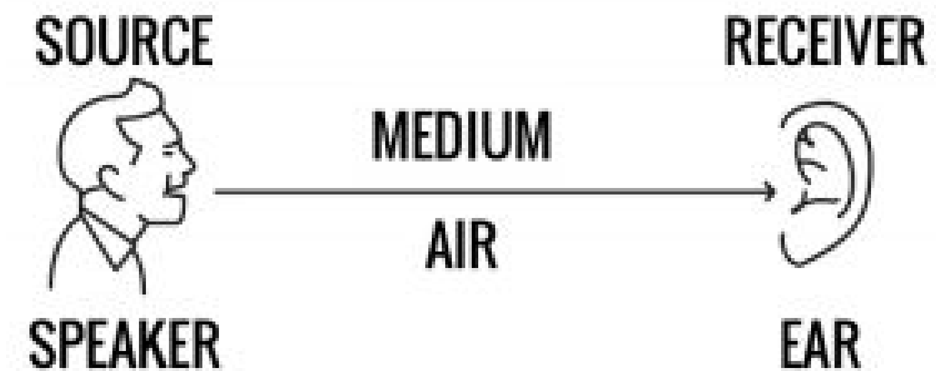


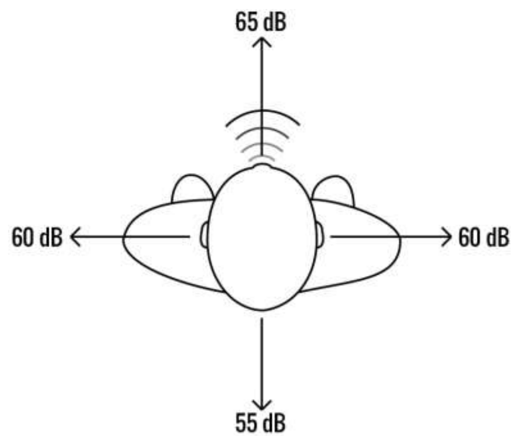
Type of Room - Space Type	Recommended NC Level	Equivalent Sound Level
	NC Curve	dBA
Apartments	25-35	35-45
Assembly Halls	25-30	35-40
Churches	30-35	40-45
Courtrooms	30-40	40-50
Factories	40-65	50-75
Private Residences	25-35	35-45
Restaurants	40-45	50-55
TV Broadcast studies	15-25	25-35
Recording Studios	15-20	25-30
Concert and recital halls	15-20	25-30
Sport Stadiums	45-55	55-65
Sound broadcasting	15-20	25-30
Movie motion picture theaters	30-35	40-45
Libraries	35-40	40-50
Hotels/Motels		
- Individual rooms or suites	25-35	35-45
- Meeting or banquet rooms	25-35	35-45
- Halls, corridors, lobbies	35-40	50-55
Offices		
- Conference rooms	25-30	35-40
- Open-plan areas	35-40	45-50
- Business machines/computers	40-45	50-55
Hospitals and Clinics		
- Private rooms	25-30	35-40
- Operating rooms	25-30	35-40
- Public areas	35-40	45-50
Schools		
- Lecture and classrooms	25-30	35-40
- Open-plan classrooms	35-40	45-50

(Source: https://en.wikipedia.org/wiki/Noise_curve)

Quality of speech communication in background noise

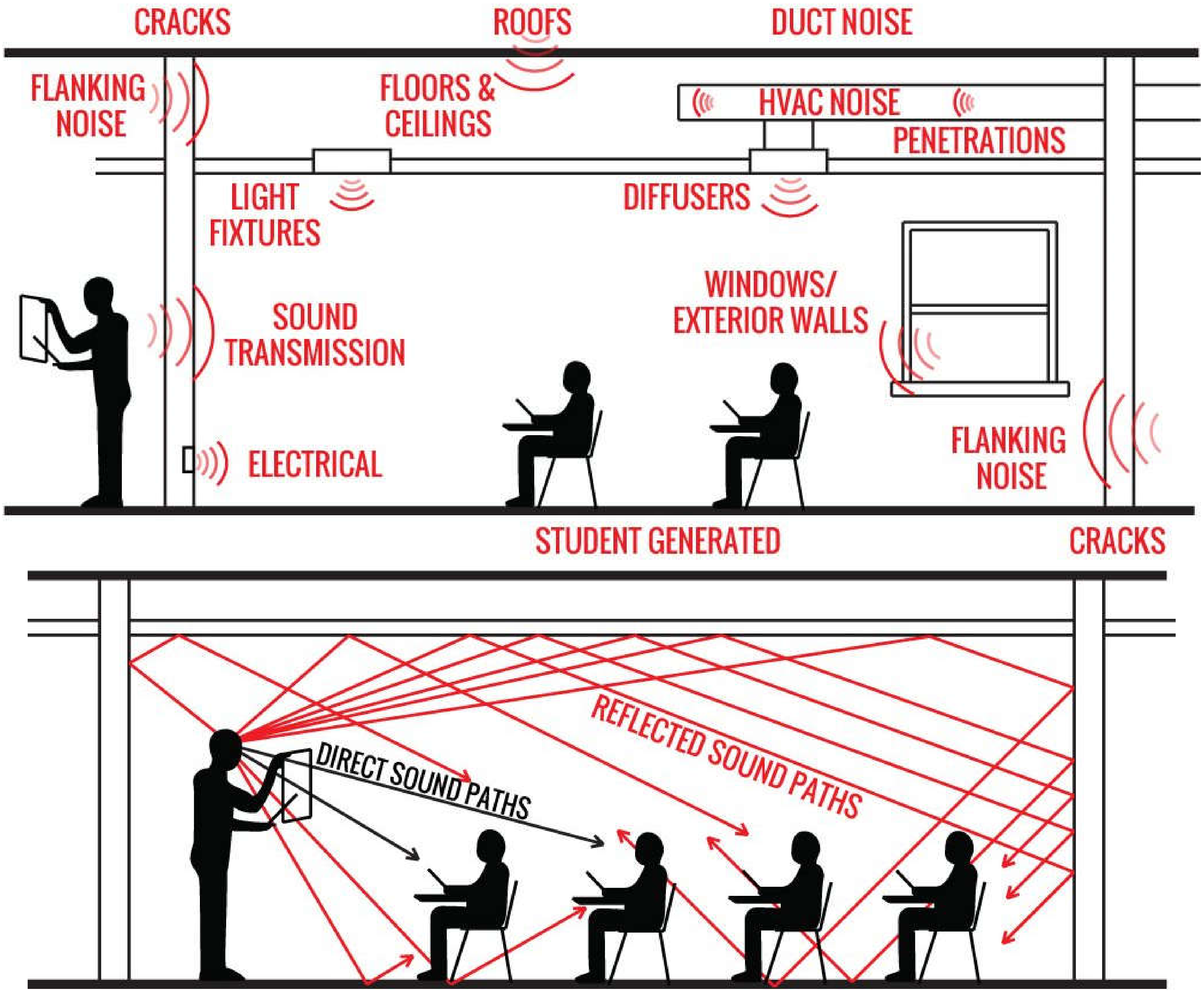






(Source: Schaffer M. E., 2011. *A Practical Guide to Noise and Vibration Control for HVAC Systems*, 2nd Edition (SI))

Noise sources and transmission in a classroom

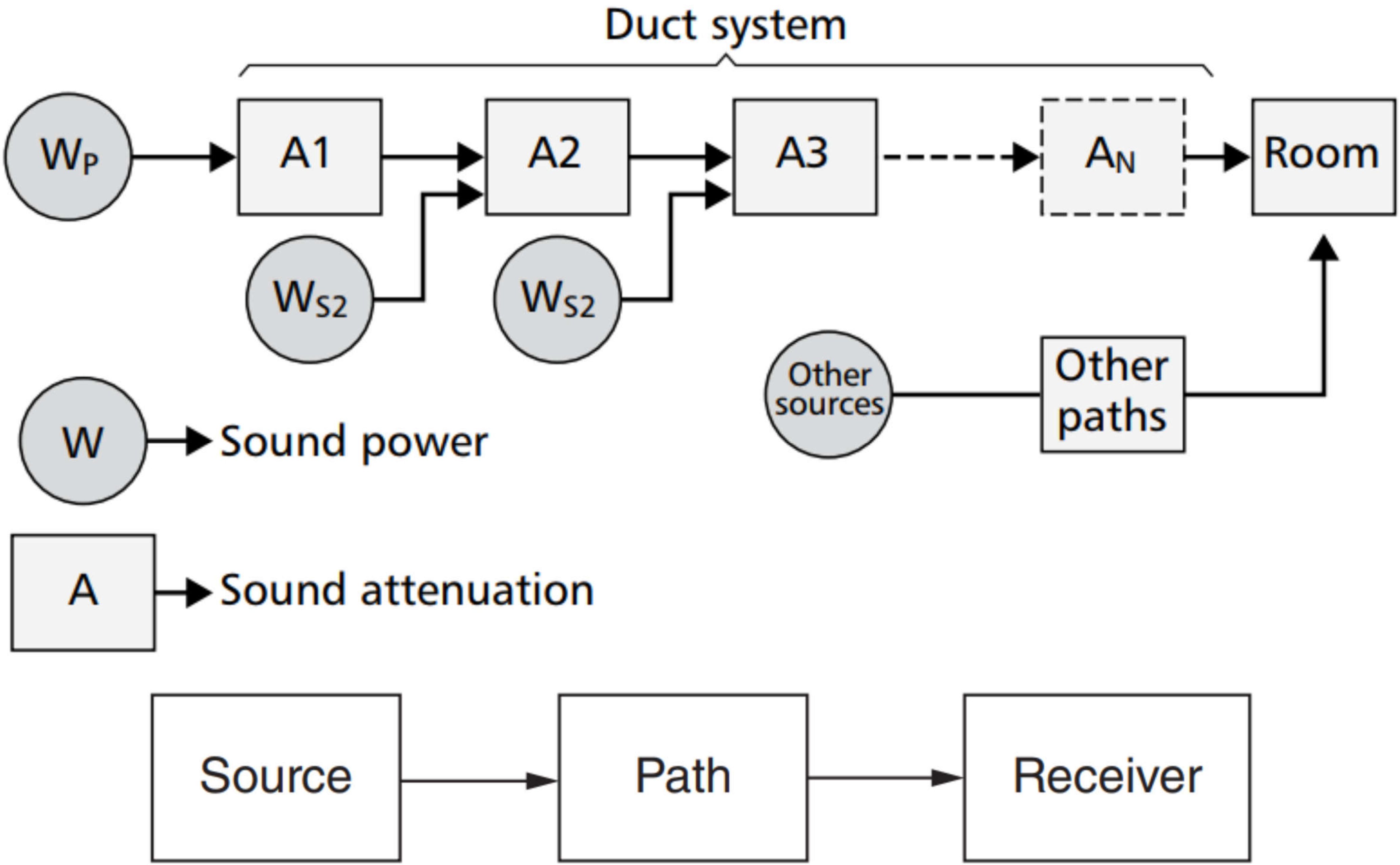


(Image source: http://www.technature.ca/acoustics-101/noise-sources/)

Noise & vibration from HVAC

- Noise & vibration from HVAC can cause annoyance and disturbance to the occupants inside the building and to those outside
- Noise levels can be predicted so that system designs can be modified as necessary to achieve noise targets/limits
- Mechanisms of noise generation, noise sources and transmission paths, e.g.
    - Tracking the flow of sound energy from the fan in plant room through air duct & other components

The flow of sound energy in an HVAC system



(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

Noise & vibration from HVAC

- Common noise problems in HVAC systems
  - Sound transmission of the exhaust vent
  - The effect of holes & gaps on noise
  - Problems with exhaust facilities
  - Problems in the design of the air supply system
  - Noise problem of air supply equipment
  - Noise problem caused by the air-conditioned machine room close to the conference room
  - Noise problem of cooling tower
- Noise source, path & receiver (e.g. occupants)

Common HVAC noise sources

Fans (to move the air)
- Axial
- Centrifugal
- Propeller

Pumps (to circulate liquids)
- Centrifugal
- Reciprocating

Compressors (to convert gas to liquid)
- Piston
- Rotary
- Scroll
- Centrifugal
- Screw

Diffusers and ductwork (to distribute air)
- Turbulent aerodynamic noise
- "Break-out" noise

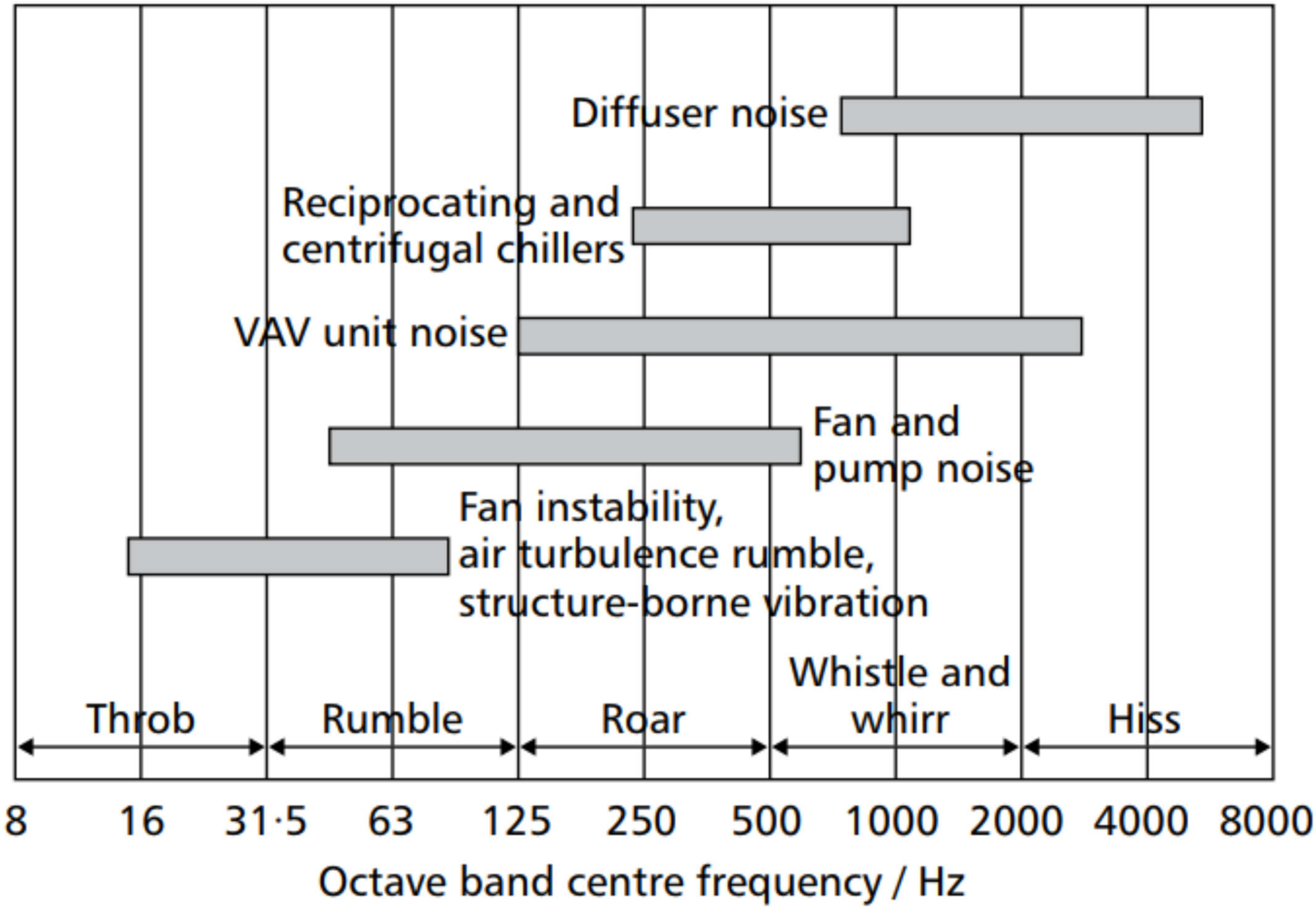
Terminal units
- Fan coil unit
- VAV box

Others
- Waste and rain piping
- Transformers/generators
- Dimmer racks
- Lights & ballasts
- Elevator equipment

Noise & vibration from HVAC

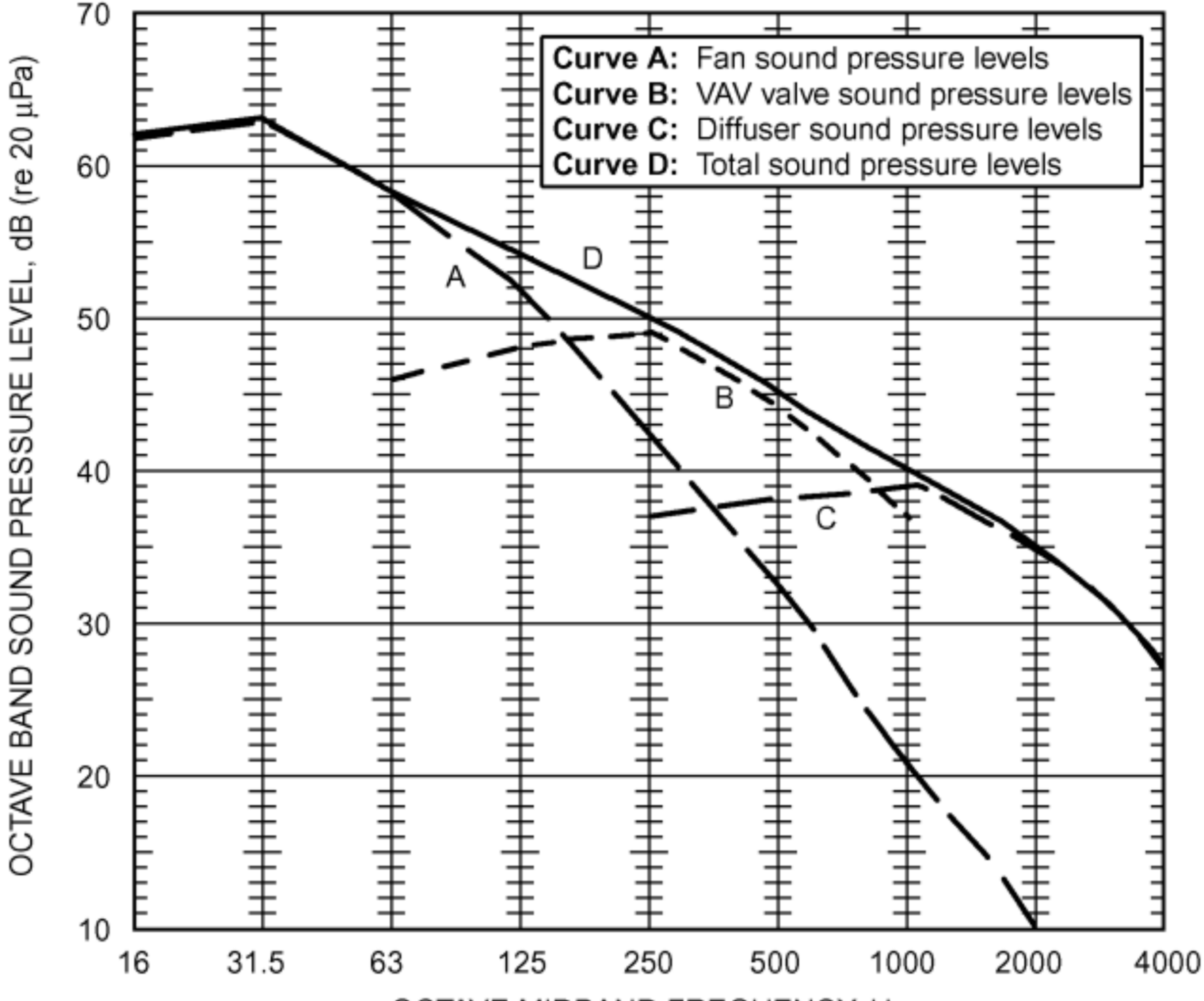
- Typical HVAC noise sources
  - Rotating machines, e.g. a motor, pump or fan
  - Vibrating surfaces & moving air streams
  - Interaction of fluid flow with solid objects, e.g. louvres in a duct termination
- Different types of mechanical equipment produce noise over different frequency ranges
  - Central plant (fans & pumps): up to about 500 Hz
  - VAV units: 125-3000 Hz; Chillers: 250-1000 Hz
  - Higher frequencies: due to diffuser noise

Frequencies at which different types of mechanical equipment generally control sound spectra



(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

HVAC sound spectrum components for occupied spaces

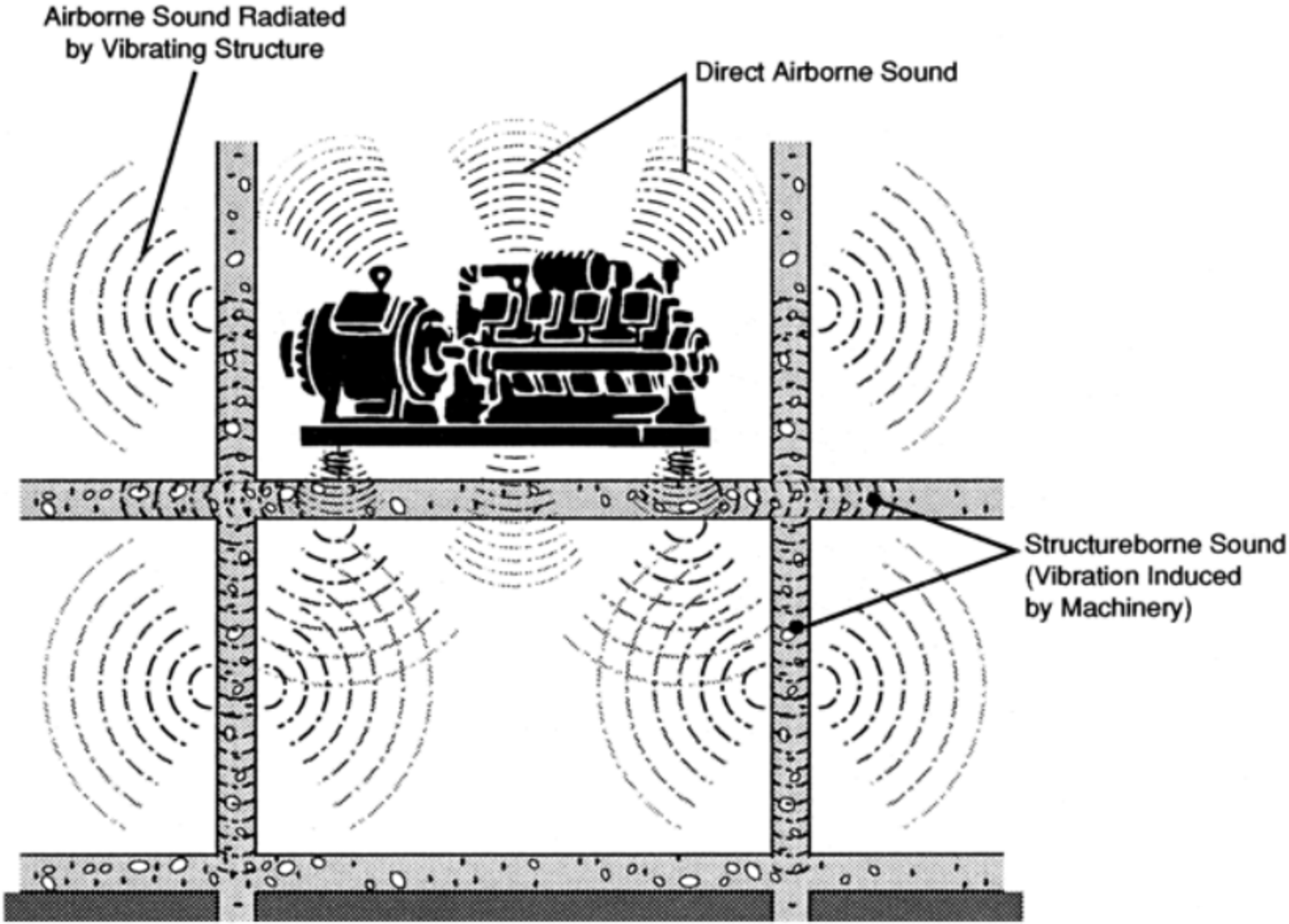


(Source: ASHRAE, 2019. *ASHRAE HVAC Applications Handbook 2020*, SI edition, Chp. 49 Sound and Vibration Control)

Noise & vibration from HVAC

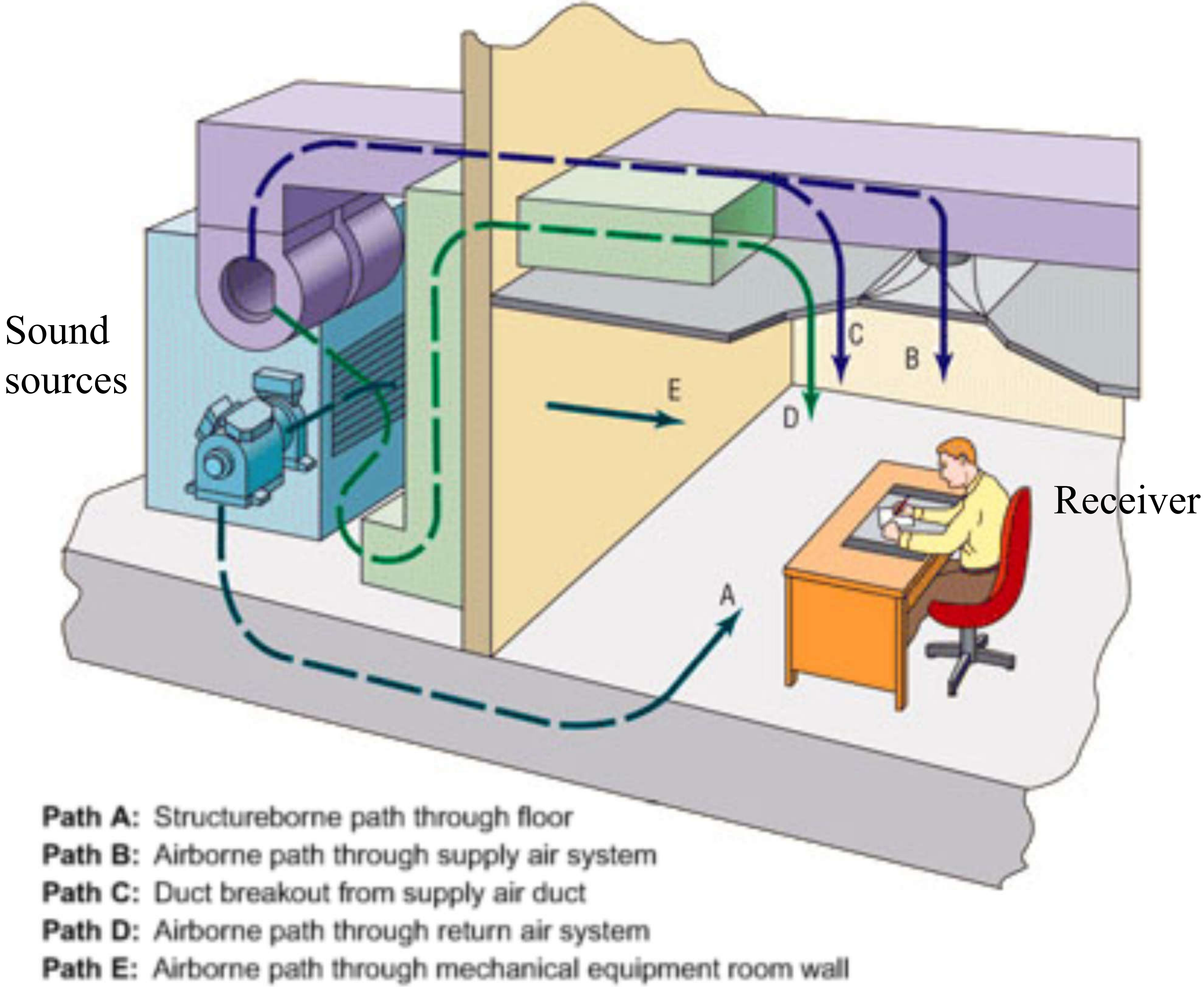
- Types of sound transmission
  - Airborne sound: sources which produce sound by directly setting the air around them into vibration
  - Impact sound: sources which produce sound by impulsive mechanical excitation of part of a building (e.g. by footsteps, electric light switches, slamming doors)
  - Structure-borne sound: is often used to refer to sound that travels for long distances via the structure, especially in connection with vibrating machinery linked directly to the structure

Airborne and structure-borne sound transmission from equipment



(Source: Schaffer M. E., 2011. *A Practical Guide to Noise and Vibration Control for HVAC Systems*, 2nd Edition (SI))

Typical paths of noise and vibration propagation in HVAC systems

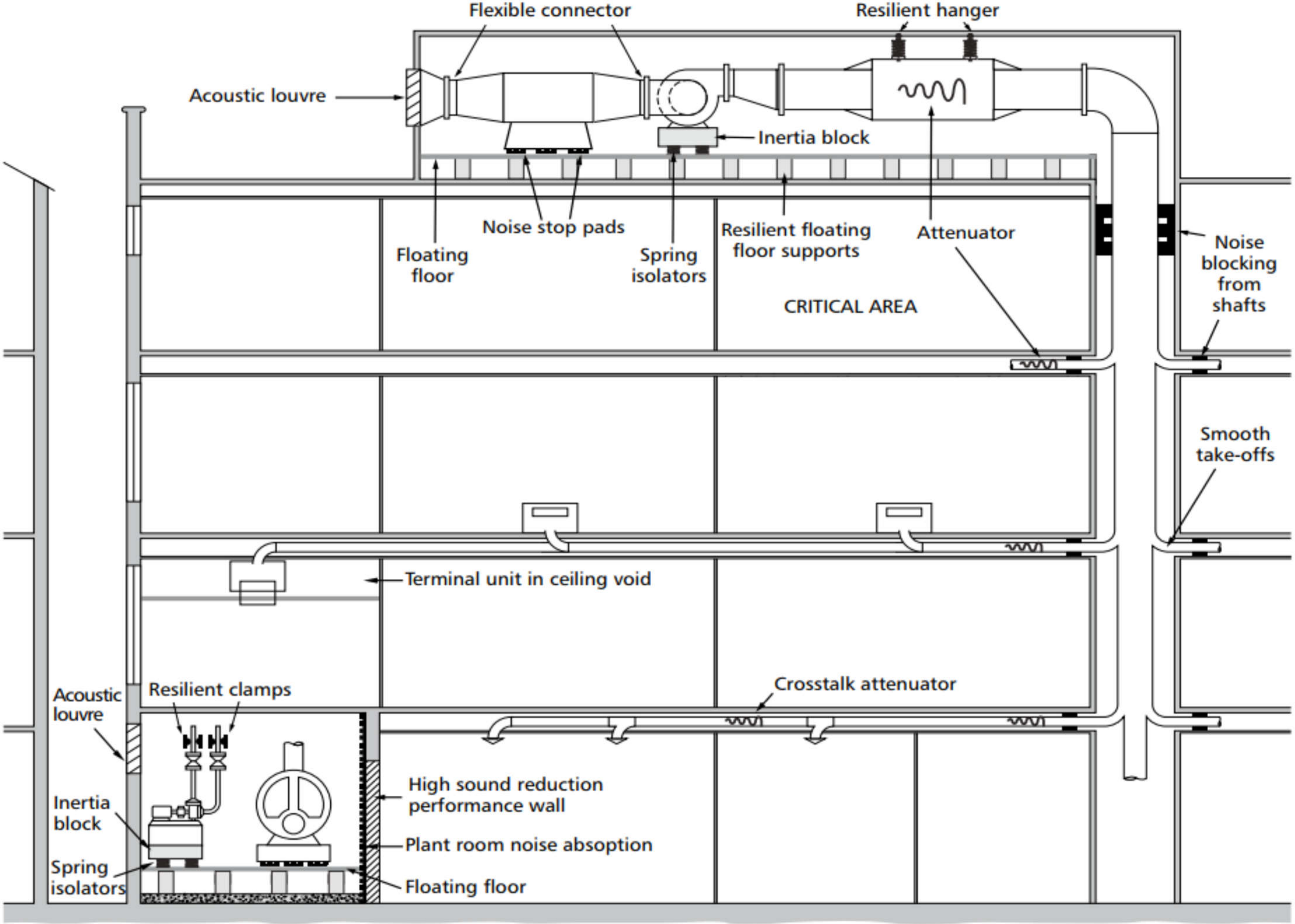


(Source: ASHRAE, 2019. *ASHRAE HVAC Applications Handbook 2020*, SI edition, Chp. 49 Sound and Vibration Control)

Noise & vibration from HVAC

- Typical HVAC noise transmission paths
  - Noise radiates to atmosphere from air inlet/outlet
  - Vibration from the fan transmits to the structure
  - Noise from the plant breaks out of the plant room
  - Noise of supply duct breaks out to adjacent spaces
  - Incorrect duct or pipe anchoring may put vibration into the structure
  - Duct borne noise emitted from the room units
  - Vibration from ground level plant gets into the structure
  - Noise from plant transmits through walls or windows to adjacent spaces

Noise from HVAC plant and possible means of attenuation



(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

Noise control in HVAC

- Sound insulation: the act of impeding the transmission of sound from one area to another or from a source to a receiver, e.g. by the use of heavy materials (concrete or gypsum board)
- Sound absorption: the phenomenon whereby some or all of the sound energy incident on a surface is either converted into heat or passes through the absorber
- Sound attenuation: combined effect of sound scattering and absorption

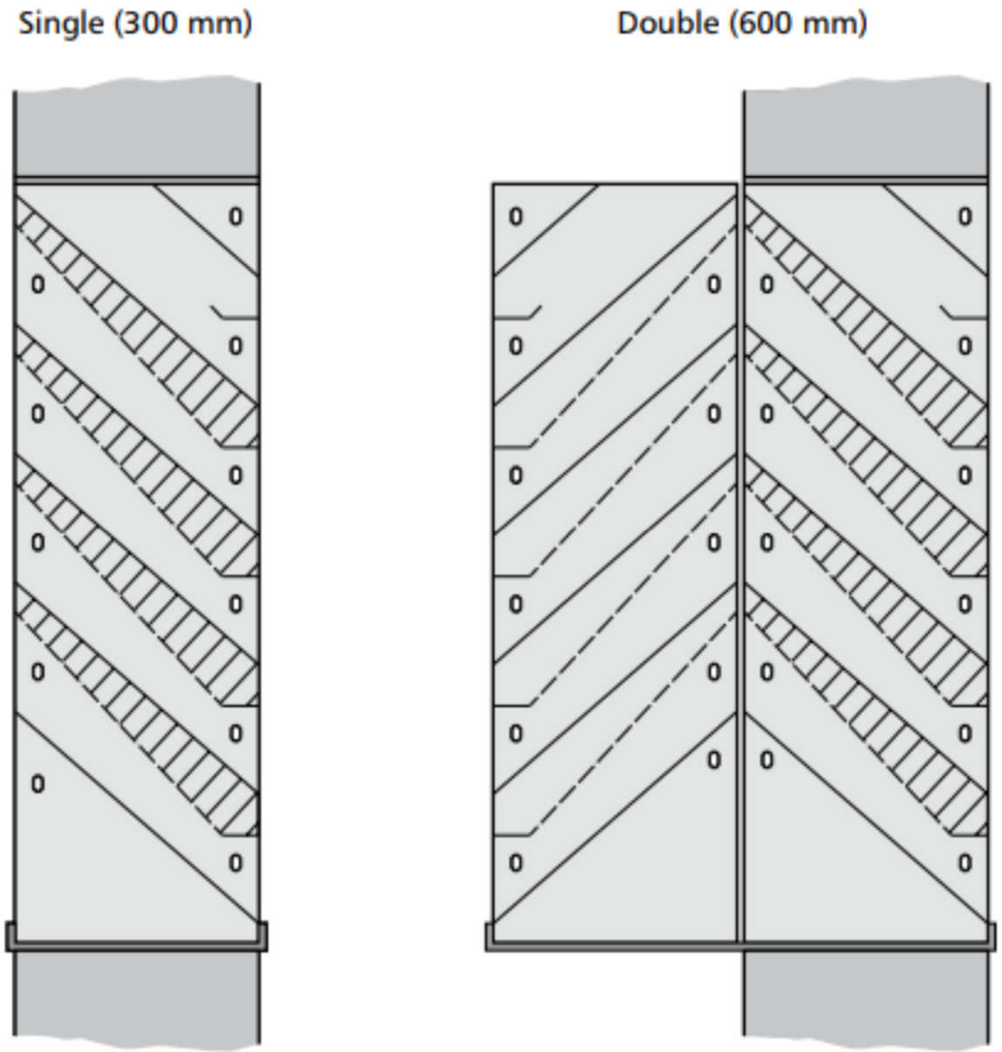
Noise control in HVAC

- Insertion Loss (IL): (in dB), the decrease in sound pressure level or sound intensity level measured at a receiver when the silencer or a sound-attenuating element is inserted into the path between the source and the receiver
- Dynamic Insertion Loss (DIL): the insertion loss at a given air flow direction and velocity
- Noise Reduction Coefficient (NRC): a measure of the acoustical absorption performance of a material

Noise control in HVAC

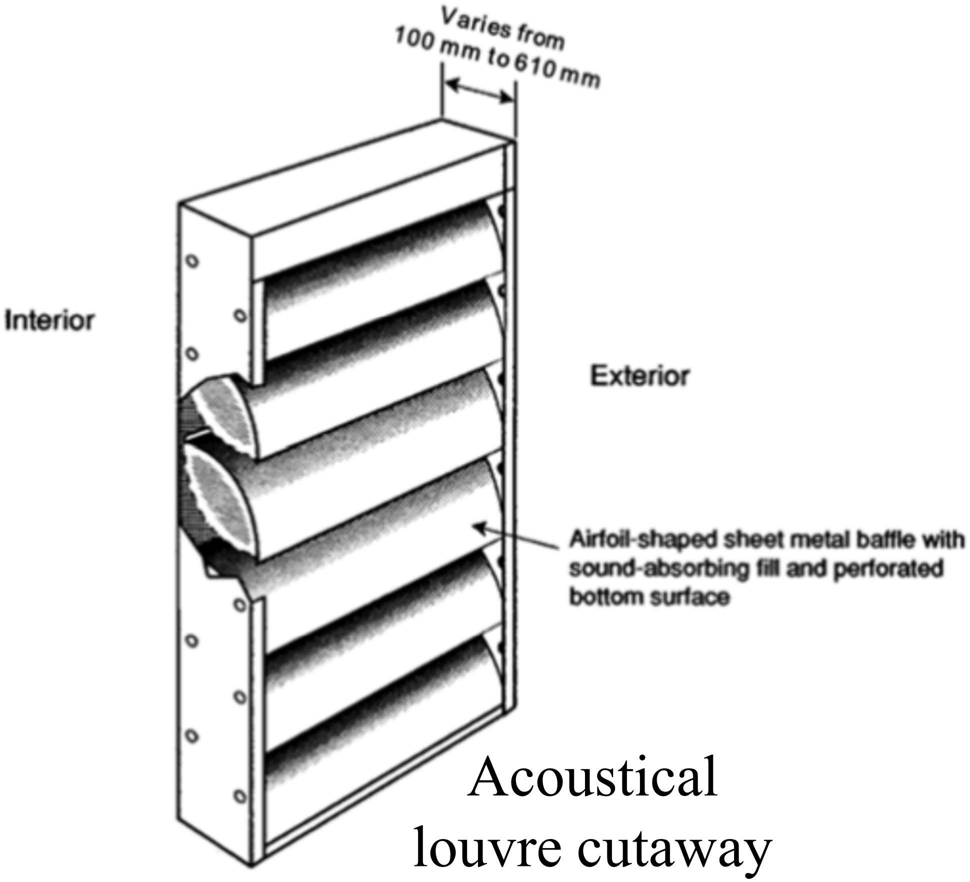
- Sound Transmission Class (STC): A rating system designed to give an estimate of the sound insulation properties of floors, walls, ceilings, windows, doors, etc.
- Transmission Loss (TL): (in dB), a reduction of sound levels as a result of passage through an obstruction such as a wall, partition, or ductwork

Acoustic louvres concept: single and double

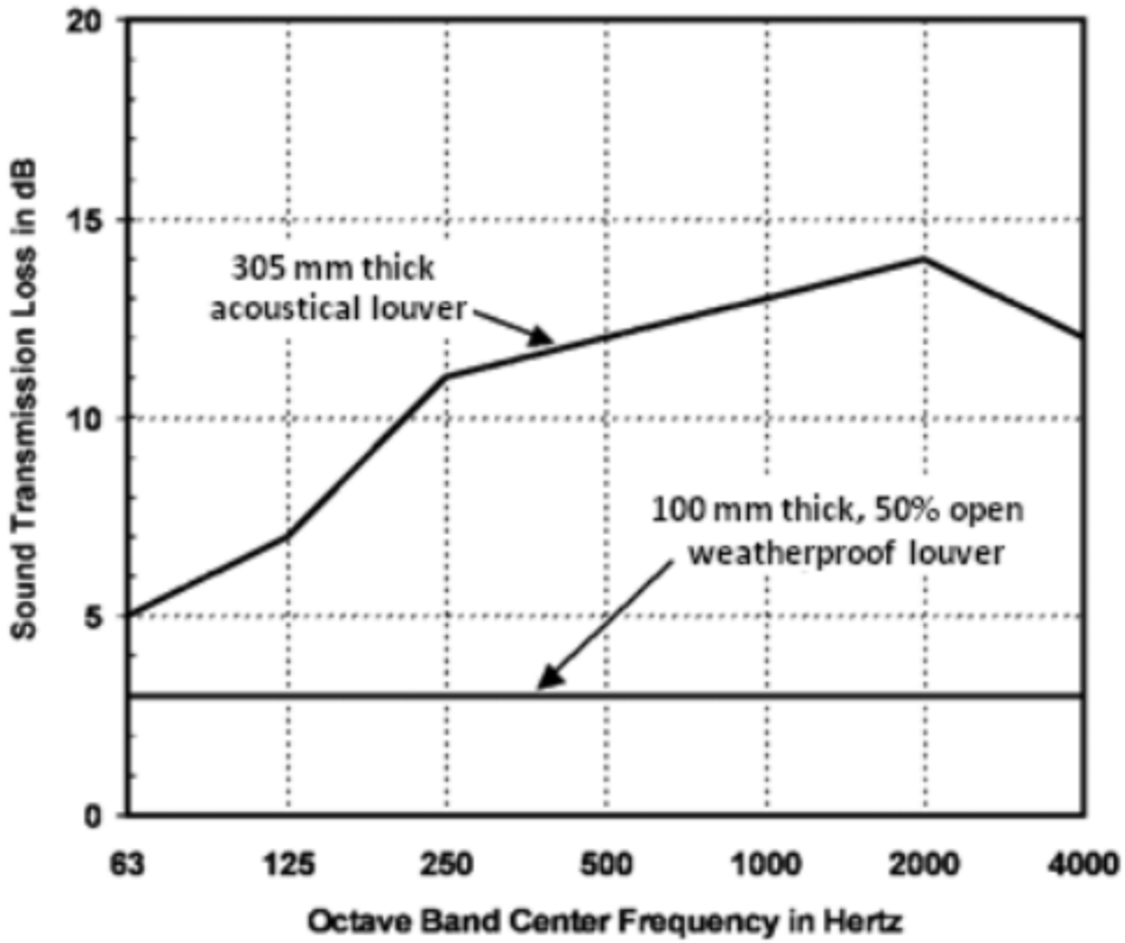


(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

Sound transmission loss of acoustical and weatherproof louvres



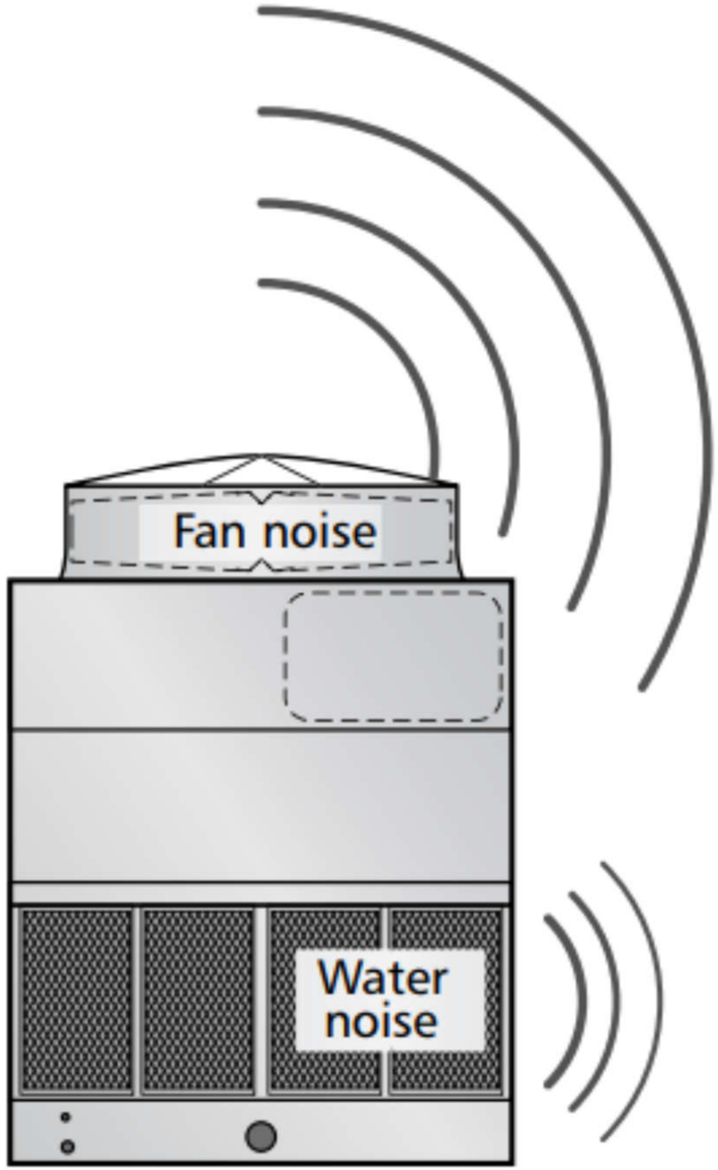
Acoustical louvre cutaway

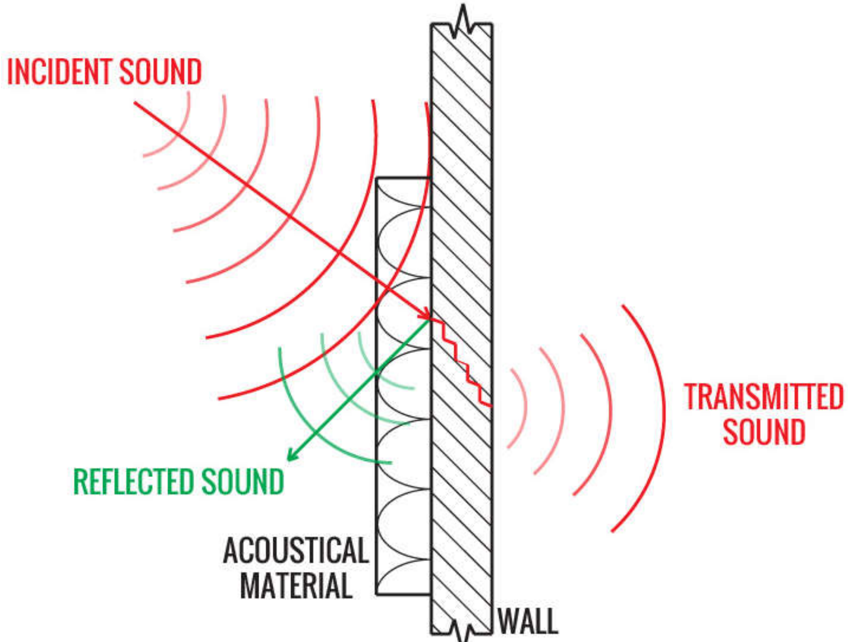


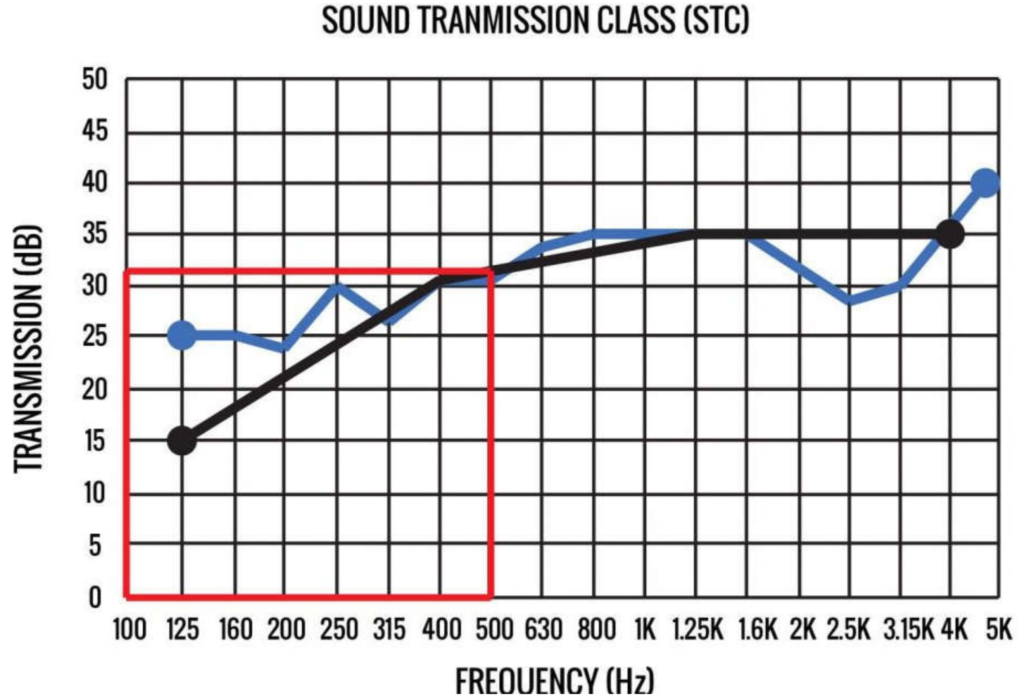
Sound barrier and enclosure

(Source: Schaffer M. E., 2011. *A Practical Guide to Noise and Vibration Control for HVAC Systems*, 2nd Edition (SI))

Sound generated from a cooling tower and transmission at enclosure





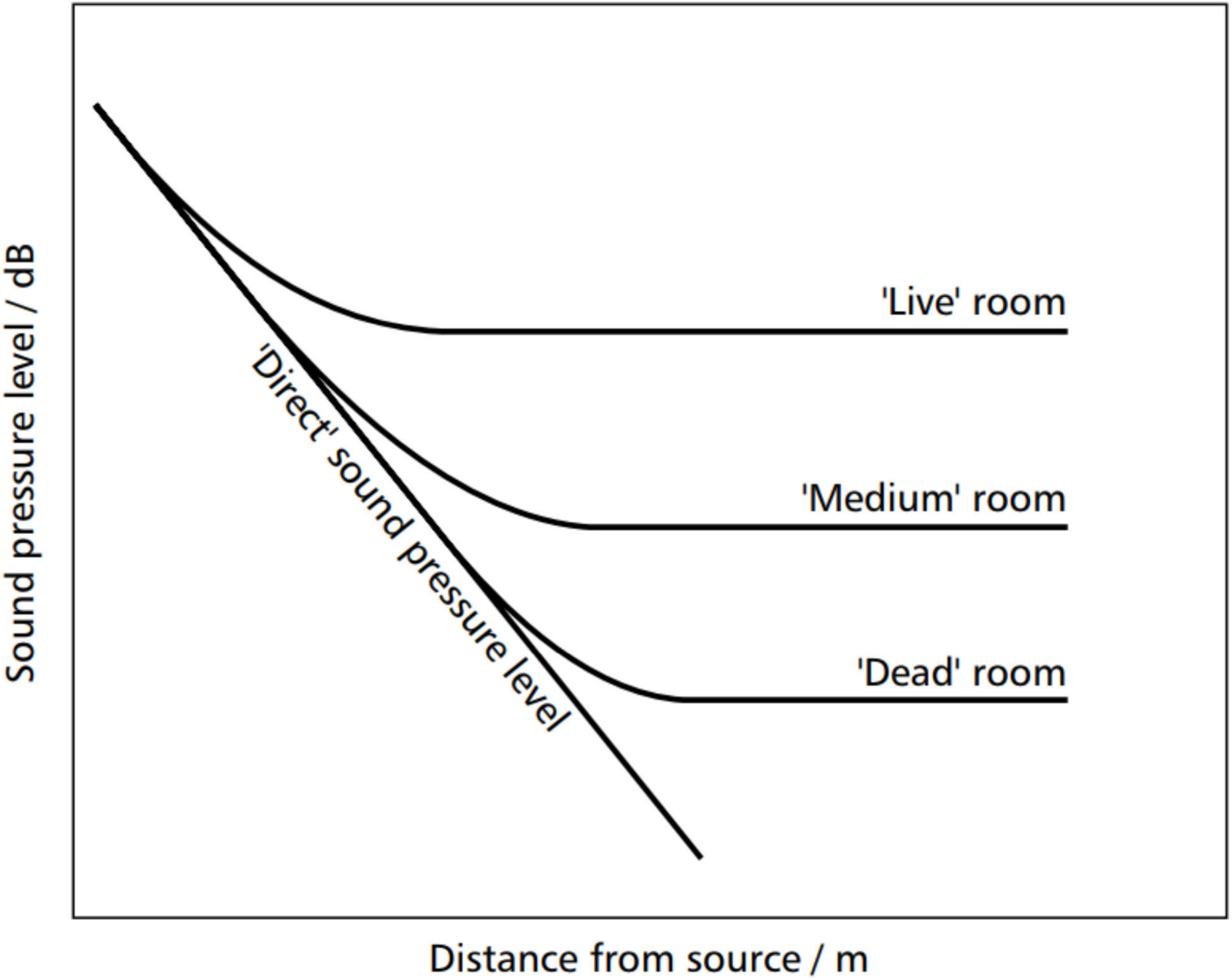


(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

Noise control in HVAC

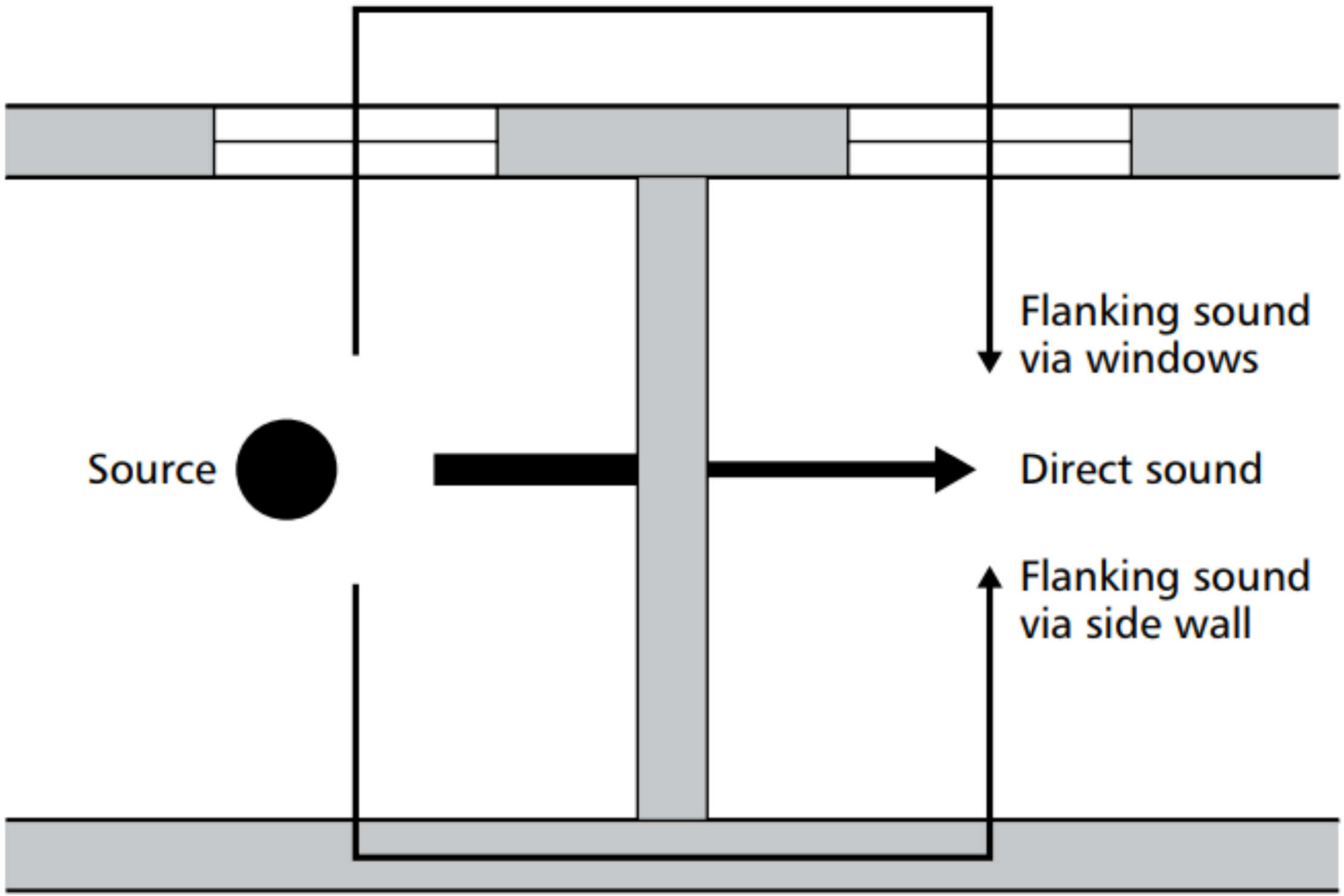
- Transmission of noise
  - From a room to the outside and to other rooms
  - Transmission of external noise to the inside
- Behaviour of sound in rooms
  - Direct sound: that which comes directly from the source to the listener
  - Reverberant sound: that which has been reflected before it reaches the listener
  - Cross-talk: When two adjacent rooms are sharing the same ductwork, sound travels within ducts and decrease the sound insulation dramatically

Variation in sound pressure level with distance from source



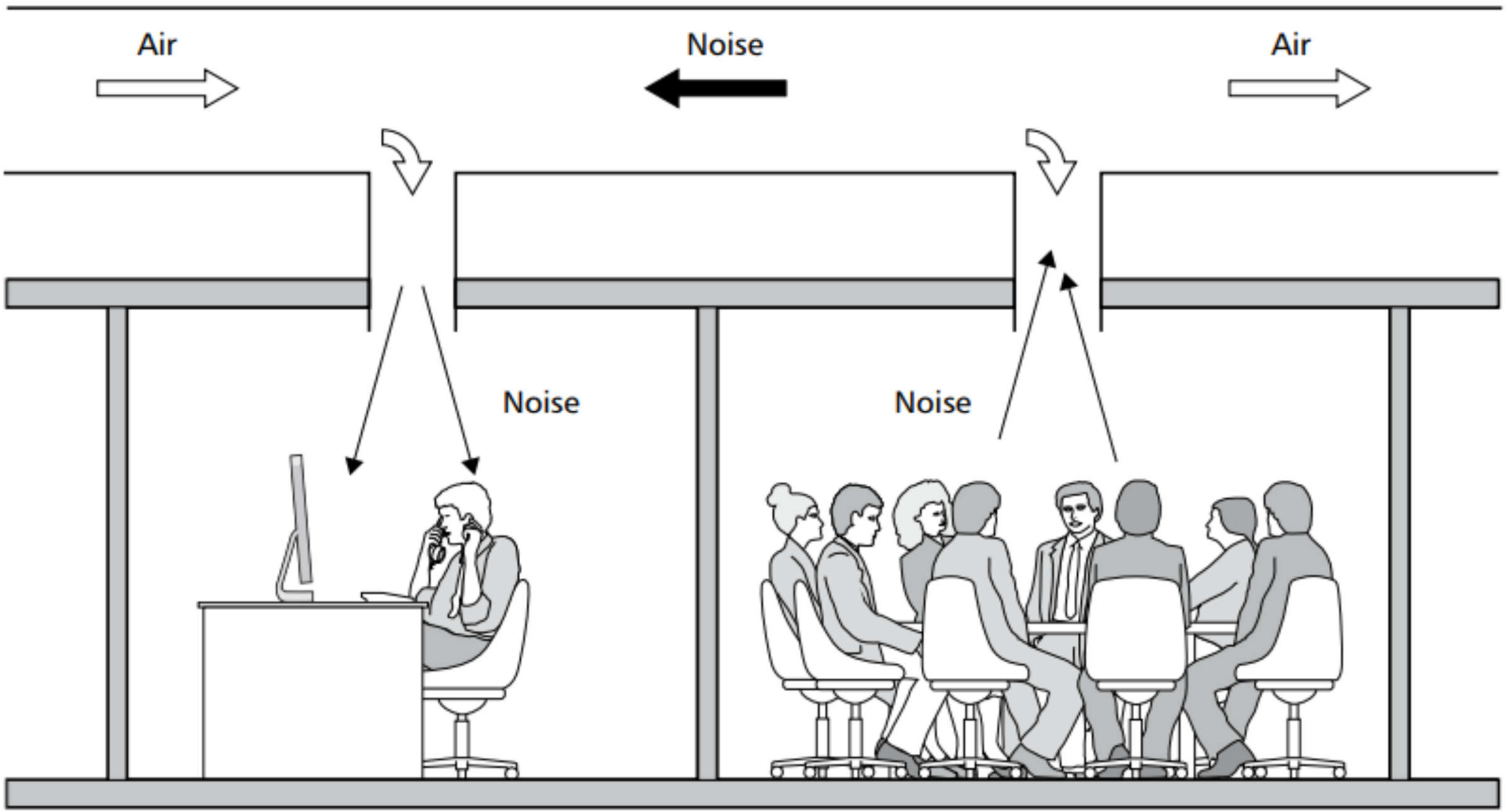
(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

Sound transmission paths between rooms



(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

Crosstalk between rooms

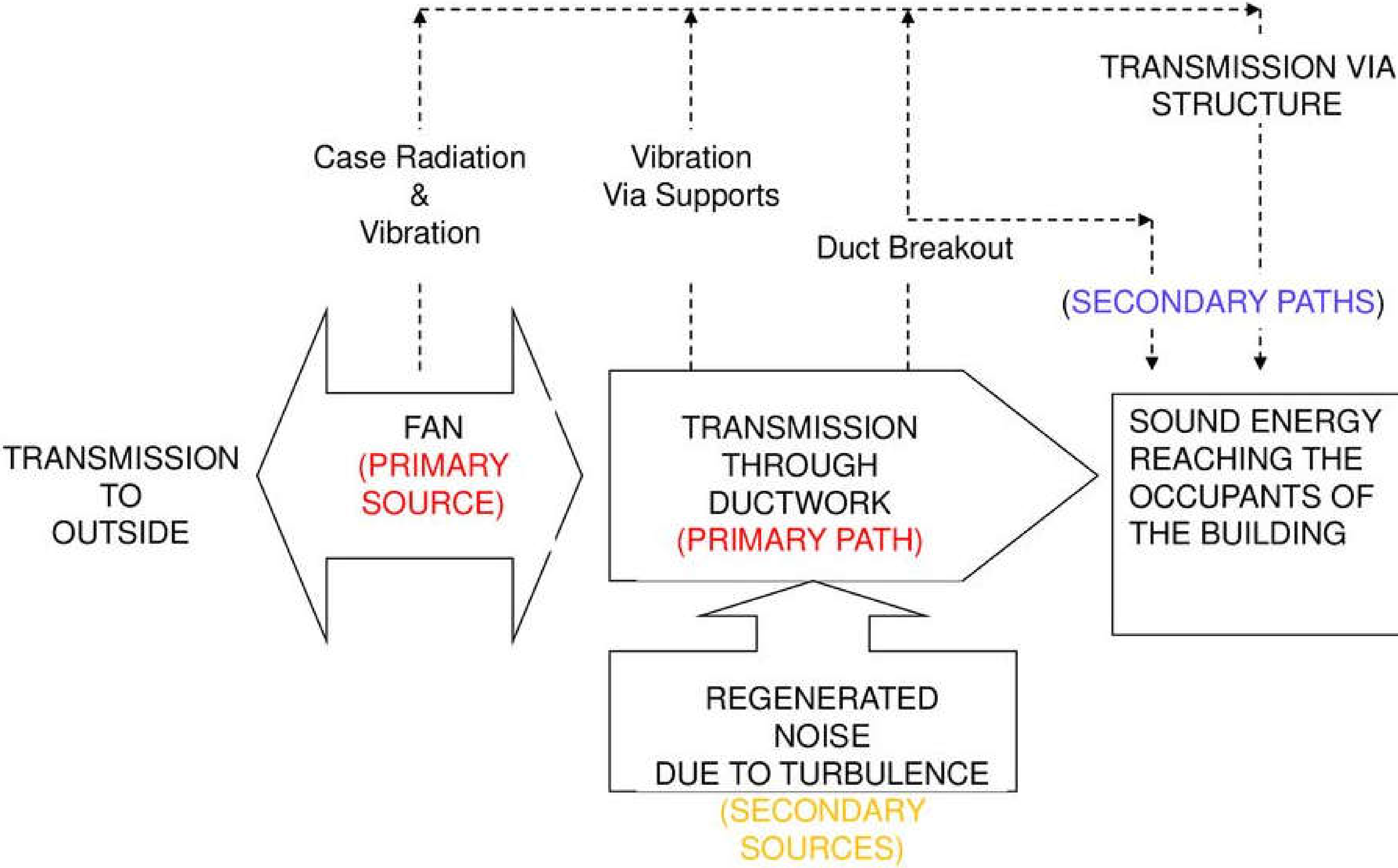


(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

Noise control in HVAC

- Noise prediction of sound pressure levels
  - Room effect: in the worst affected receiving room (with reverberant or 'live' acoustic conditions)
  - System noise: produced at the duct air entry/exit points (with attenuation requirements)
  - Breakout/break-in noise: produced at any point along the duct system
  - Noise propagation to outside: as measured at a receptor point (e.g. roof mounted or external plant, air inlet or extract in an external wall, louvred openings or ventilation grilles)

HVAC noise sources and transmission paths



(Source: https://slideplayer.com/slide/14449393/)

Noise control in HVAC

- Dealing with secondary sources & paths
  - These can be minimised by:-
    - Minimising turbulence and reducing velocities
    - Enclosing the fan
    - Cladding ductwork
    - Flexible couplers between fan and ductwork
    - Anti-vibration mounts for the fan
    - Anti-vibration hangers for the ductwork
  - This leaves primary source and path as our main concern – and can be split into the atmospheric side and the room side

Noise control in HVAC

- Five main types of HVAC noise:
  - 1. Duct borne noise: caused by the flow of air and directly dependent on the velocity of air
  - 2. Radiated equipment noise: caused by vibration of equipment and inherent sound pressure of the equipment
  - 3. Break-in noise: radiated noise entering the ductwork and propagates down the duct system
  - 4. Break-out noise: transmit through the duct wall
  - 5. Terminal end noise: caused by the air flows at the terminal devices e.g. diffuser or register

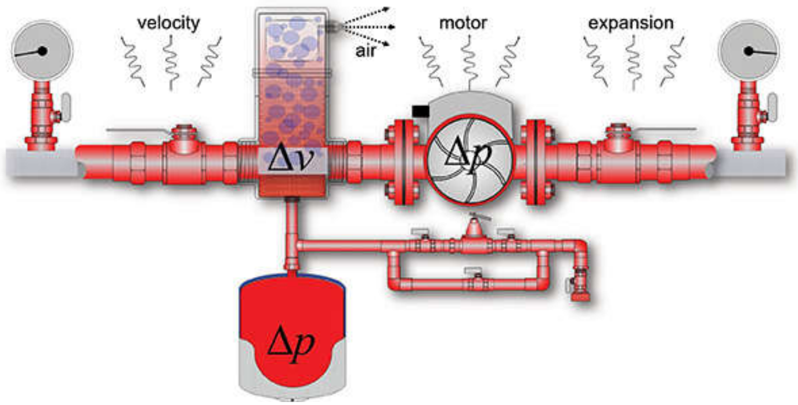
General advice for controlling noise in HVAC systems

- Choose a quiet fan, which is sized to operate at an efficient point on its characteristic.
- Design for good airflow; aim to minimise turbulence and pressure loss, both of which produce noise.
- Include all sources in predictions, e.g. breakout, in addition to duct borne noise.
- Do not forget that building services systems might affect the sound insulation between neighbouring areas.
- Seal all wall penetration with flexible material. This reduces both noise and vibration.
- Choose the location and selection of external plant and air grilles to avoid noise disturbance to nearby properties.

(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

General advice for controlling vibration in HVAC systems

- Choose a good location for the plant, remote from sensitive areas. This also helps with noise control.
- Ensure that vibration isolation is properly installed with no bridging material across the flexible mountings.
- Ensure that vibration isolators are loaded to give equal deflections and installed to maintain vertical alignment of their springs and other components.
- Remember that misaligned isolators are a source of many problems.
- Check support bolts for integrity and free movement.
- Do not neglect vibration from pipes and ducts; use flexible attachments to the structure.



(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

Vibration control

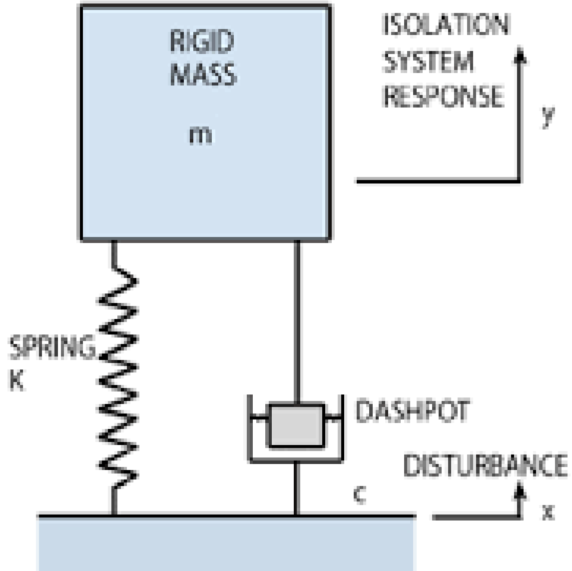
- Vibration problems & control
  - Out-of-balance forces & structure borne vibration
    - Excessive vibration threatens the stability and service life of structures, may interfere with proper functioning of plant and equipment, will shorten (or, in extreme cases, destroy) plant working life, and will also interfere with human comfort
  - The best form of vibration control is avoidance
    - Achieved by careful design and location of plant rooms, and selection and location of low vibration equipment within them, such that vibration is not manifested at levels beyond the vibration isolation criterion

Vibration control

- HVAC vibration control
  - Architectural/structural solutions: floating floor systems, building isolation bearings, seismic restraints, ordnance resistance
  - Mechanical solutions: spring inertia bases, pads, elastomeric mounts, helical spring mounts, helical spring/elastomeric hangers, pipe/duct flexible connectors, and (very rarely) pneumatic springs
    - Such as isolation of reciprocating and circulating plant via mount and hanger systems and flexible connectors (incorporating hydraulic & mechanical damping)

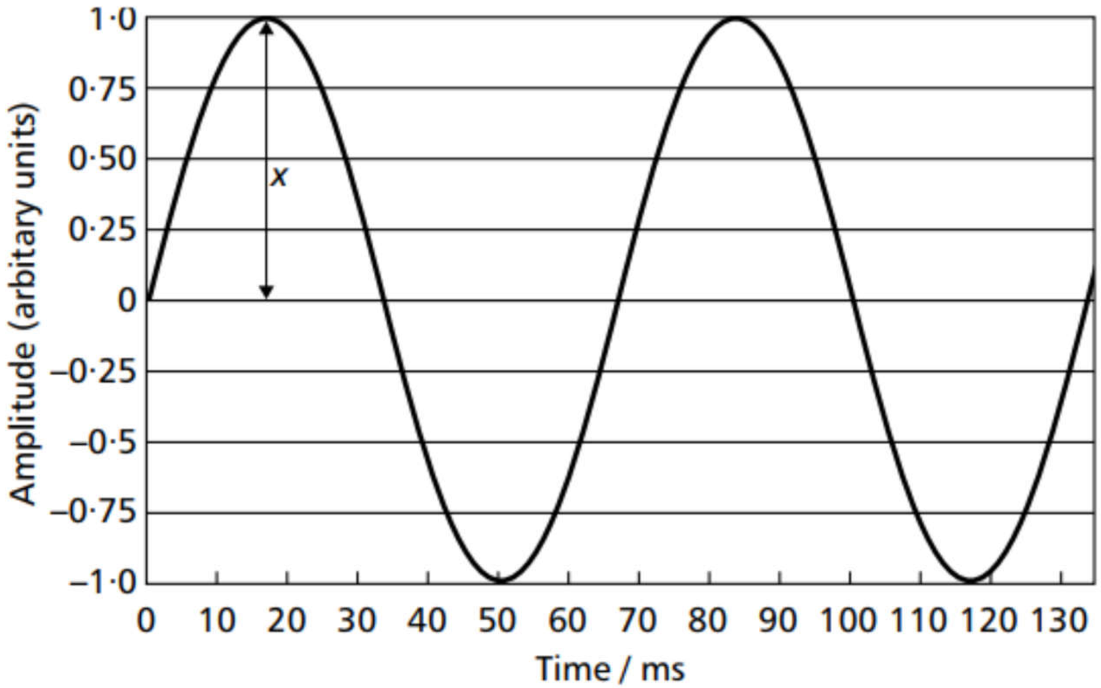
Vibration control

- Vibratory force in four physical quantities:
  - Displacement, x (mm)
  - Velocity, v ($mm \cdot s^{-1}$)
  - Acceleration, a ($mm \cdot s^{-2}$)
  - Frequency, f (Hz)



- Other important parameters:
  - Natural frequency, static deflection, spring rate, disturbing frequency, damping, vibration isolation efficiency

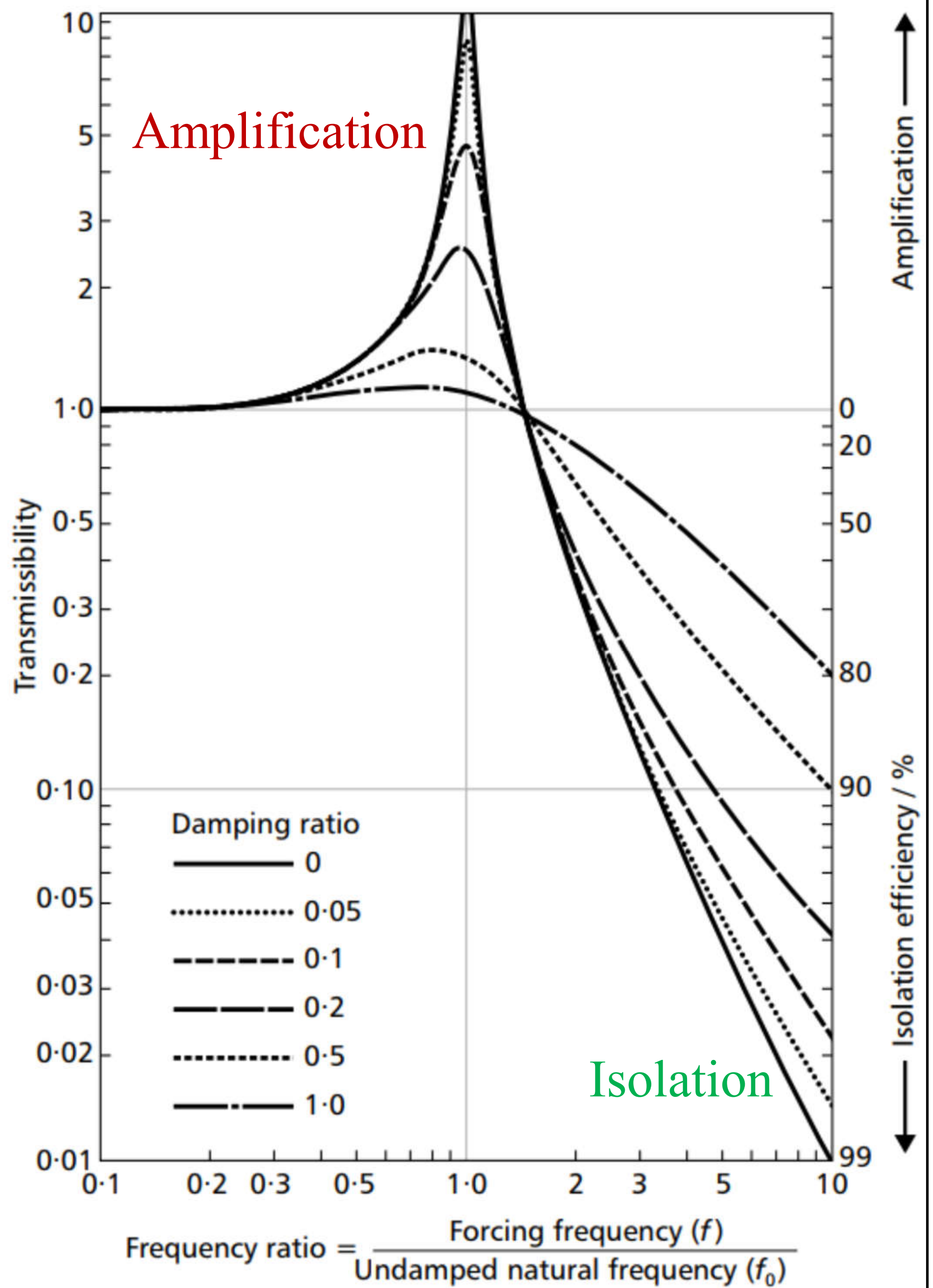
Vibration quantities and transmissibility



(a) Vibration quantities

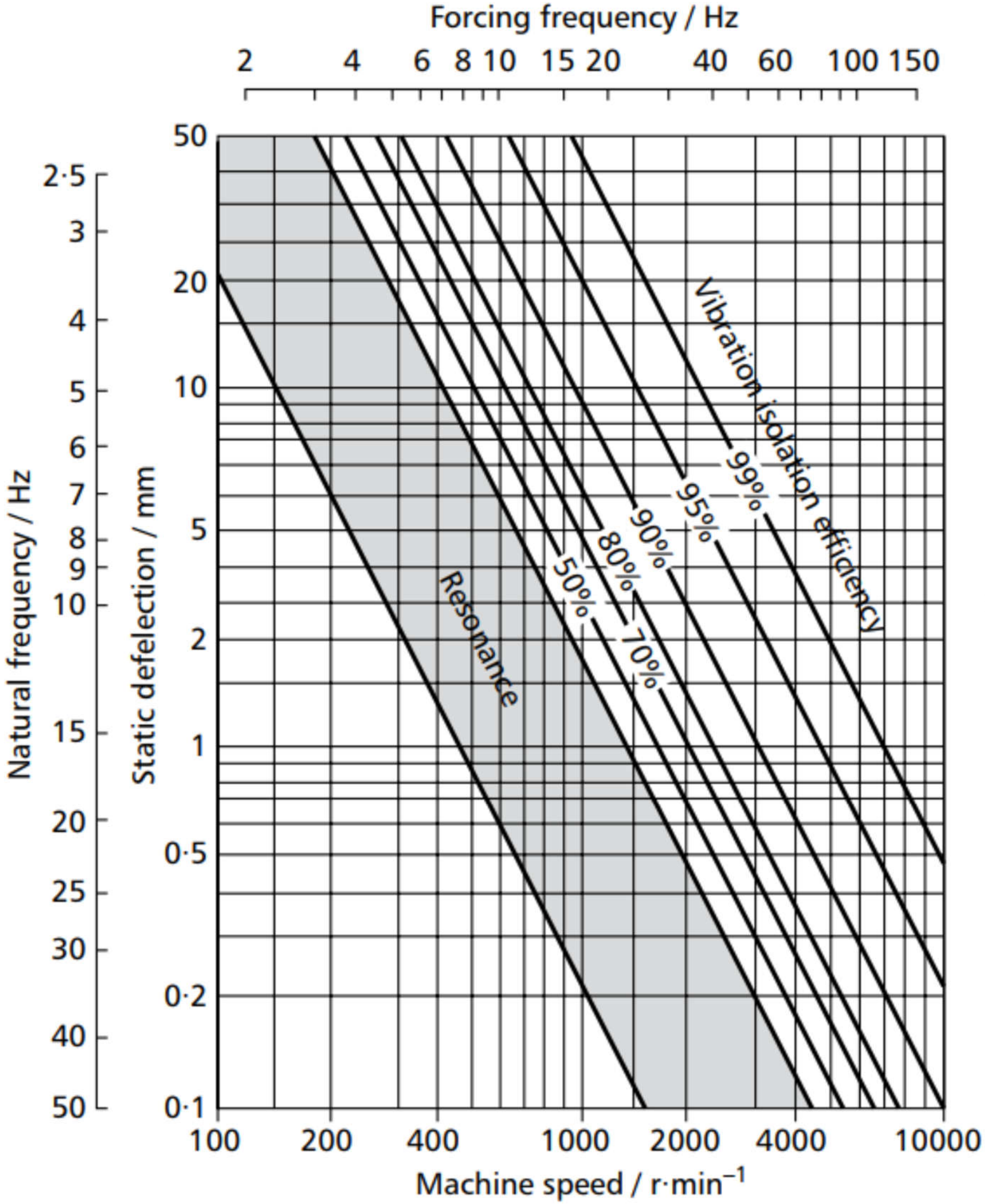
(b) Relation between vibration quantities

Quantity	Angular relationship	Maximum value at frequency 14.8 Hz
Displacement, x	$x = X \sin(2\pi f t)$	$X = 1$ mm
Velocity, v	$v = V \cos(2\pi f t)$	$V = 2\pi f X = 93$ mm·s^{-1}
Acceleration, a	$a = -A \sin(2\pi f t)$	$A = 2\pi f V$ $= 8648$ mm·s^{-2}



(c) Vibration transmissibility

(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)



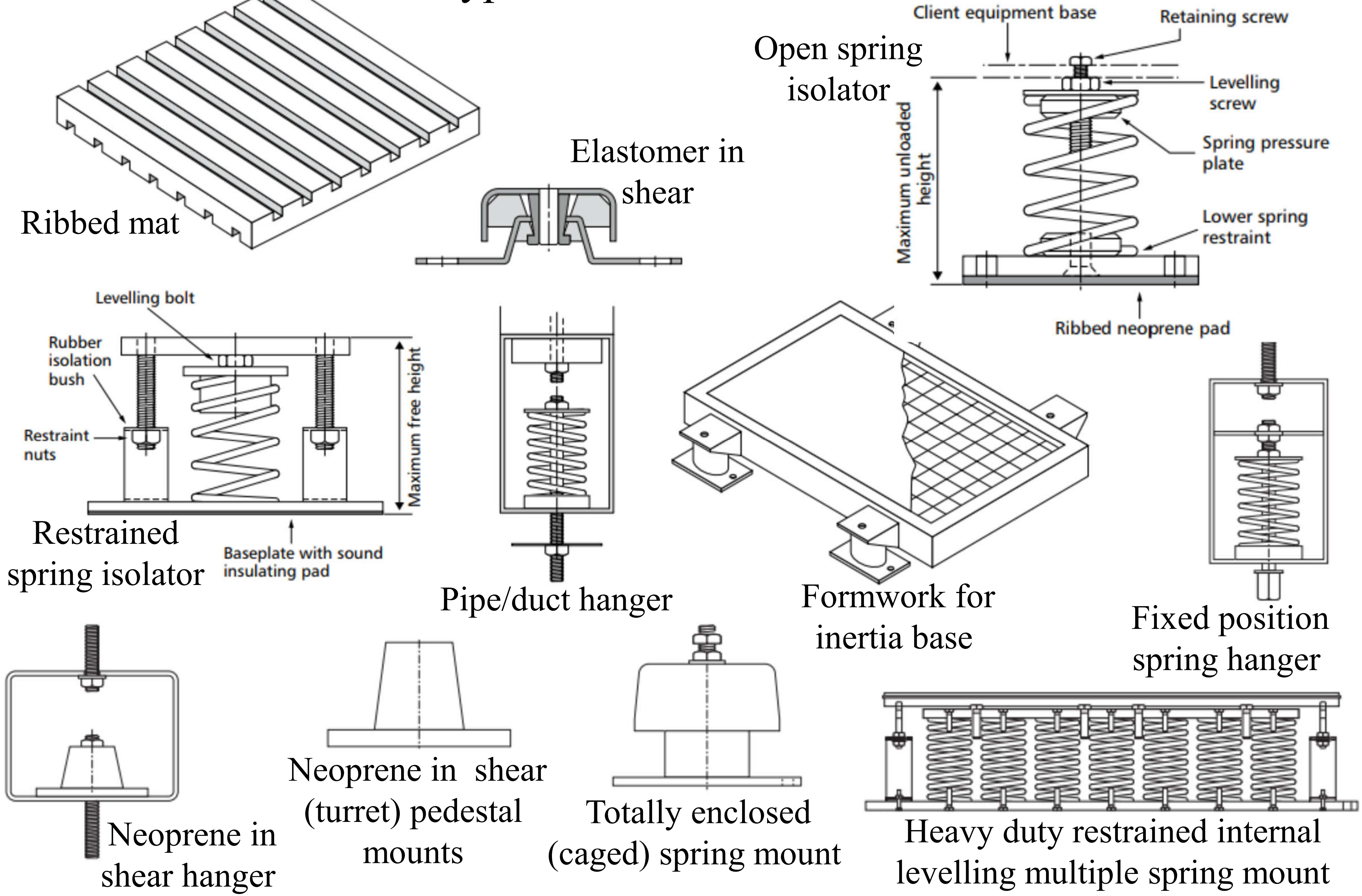
Relationship between frequency, static deflection and vibration isolation efficiency

(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

Vibration control

- Vibration isolation criteria
  - Vibration control for personal comfort conditions
    - An upper acceleration level at a specific frequency or vibration dose value, such as for special isolation where unusual room conditions apply (e.g. studios)
  - Vibration at source & the associated structure
    - Floor span, absorbed power levels and coupling
  - Vibration rating for machinery
    - Machine fragility levels (maximum acceleration levels that can be withstood at a range of input frequencies without resulting in machine malfunction)

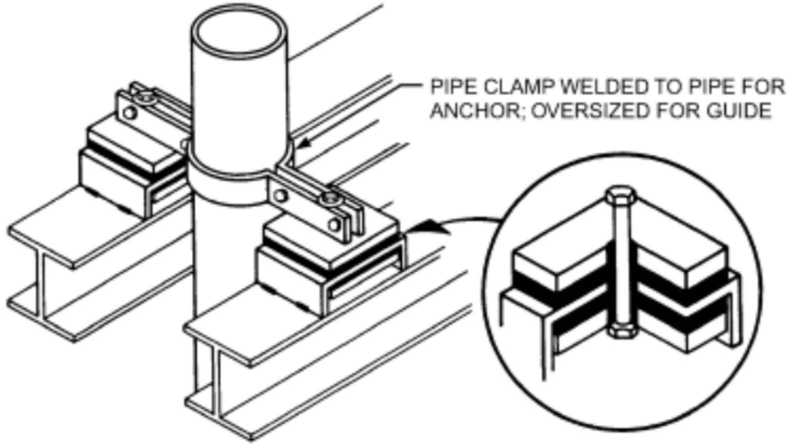
Typical vibration isolators



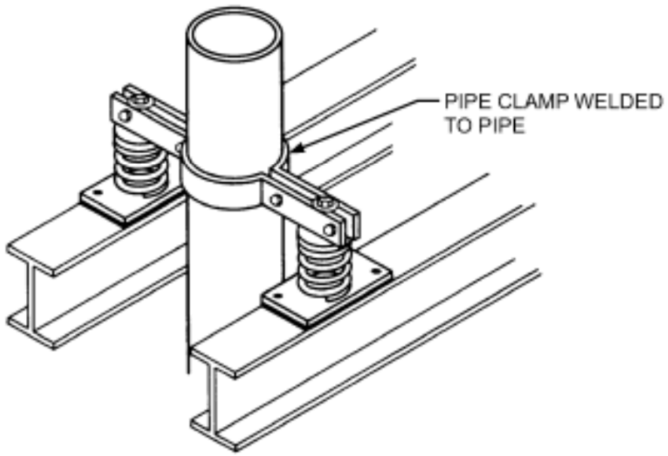
(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

Isolating vibration and noise in piping systems

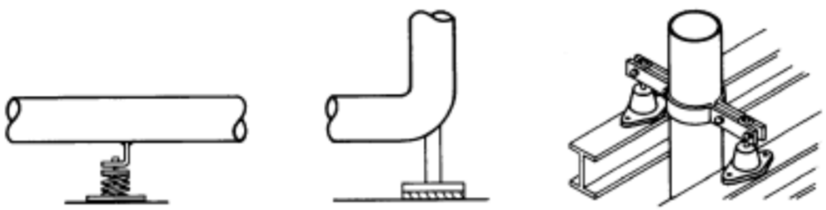
Resilient anchors and guides for pipes



RESILIENTLY ISOLATED PIPE ANCHORS AND GUIDES

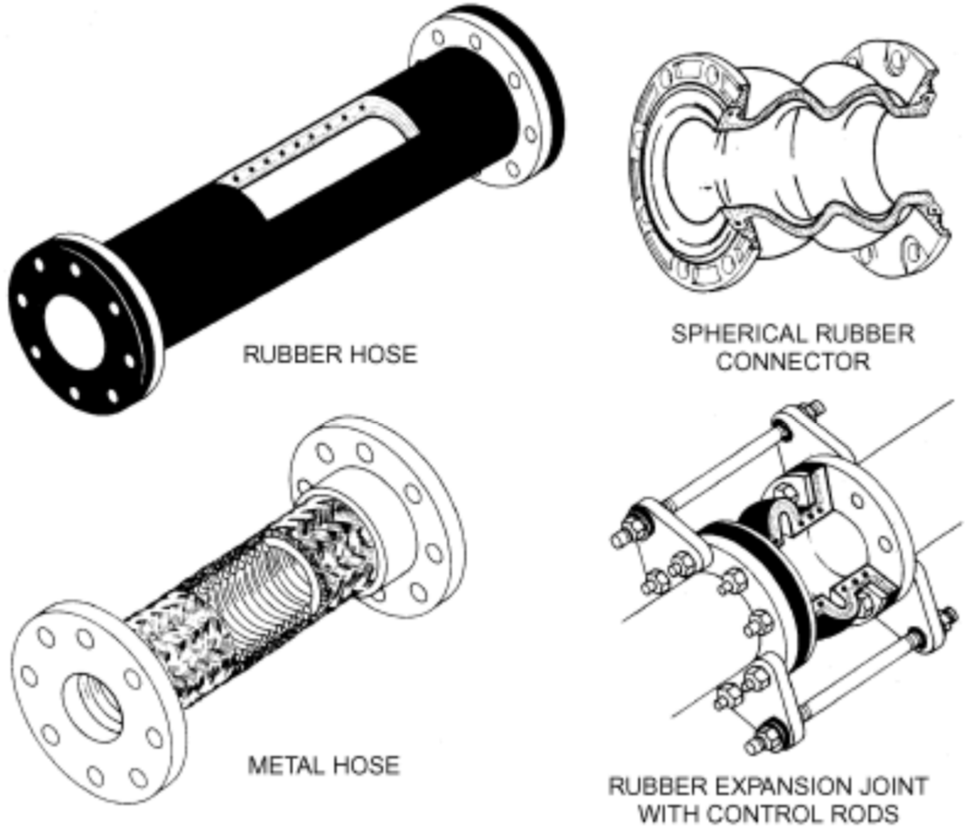


SPRING-ISOLATED RISER SYSTEM

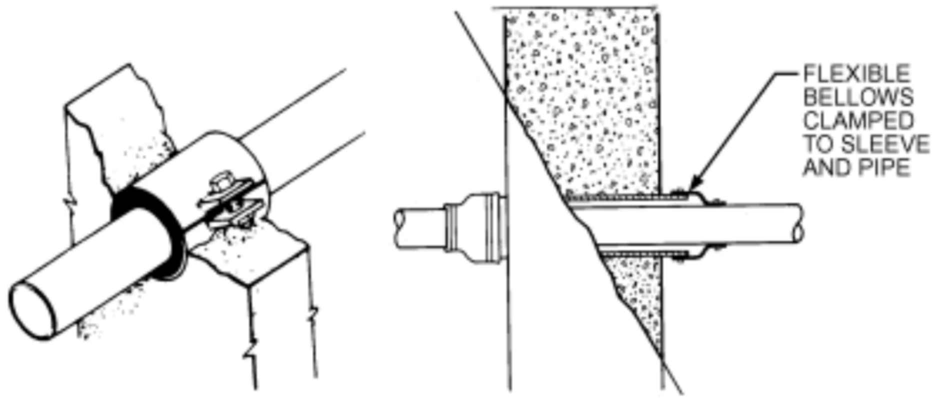


CONVENTIONAL ISOLATORS AS PIPE SUPPORTS FOR
LINES WITH EXPANSION JOINTS

Flexible pipe connectors



Acoustical pipe penetration seals

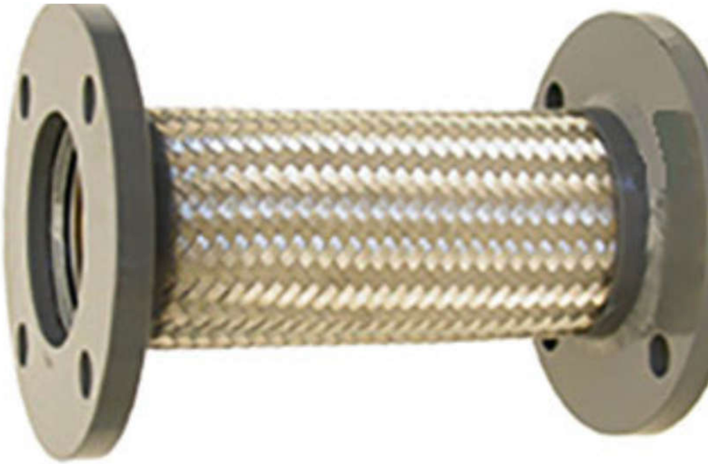


(Source: ASHRAE, 2019. *ASHRAE HVAC Applications Handbook 2020*, SI edition, Chp. 49 Sound and Vibration Control)

Vibration control

- Factors affecting noise and vibration in piping systems: characteristics of the connected equipment; the number, type and location of pipe supports; the pipe material, pressure and pipe geometry
- It is important to consider the entire pipe assembly as a system, with changes in any one component affecting the noise and vibration characteristics of the entire pipe run

Different types of connectors for piping systems



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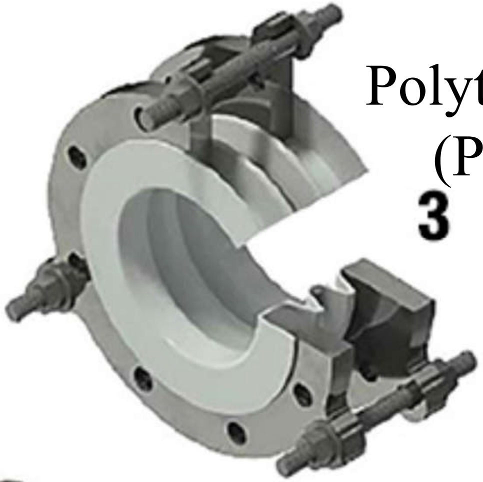
Hose-and-braid connectors (stainless steel or bronze)



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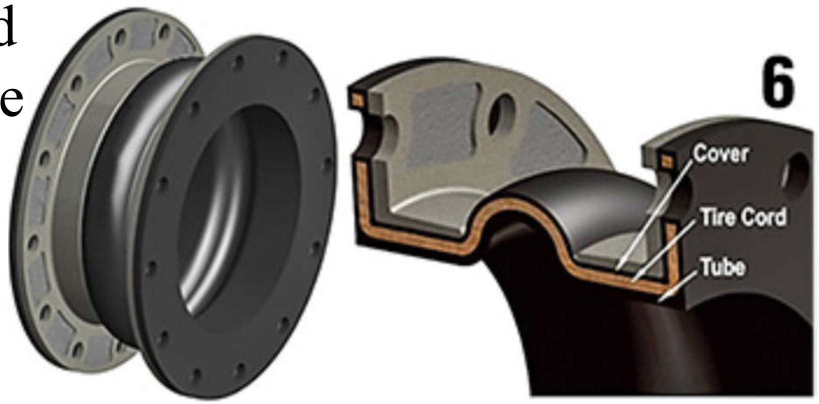
Polytetrafluoroethylene (PTFE) couplings

4

5

Elastomeric couplings with neoprene and ethylene propylene diene monomer (EPDM)



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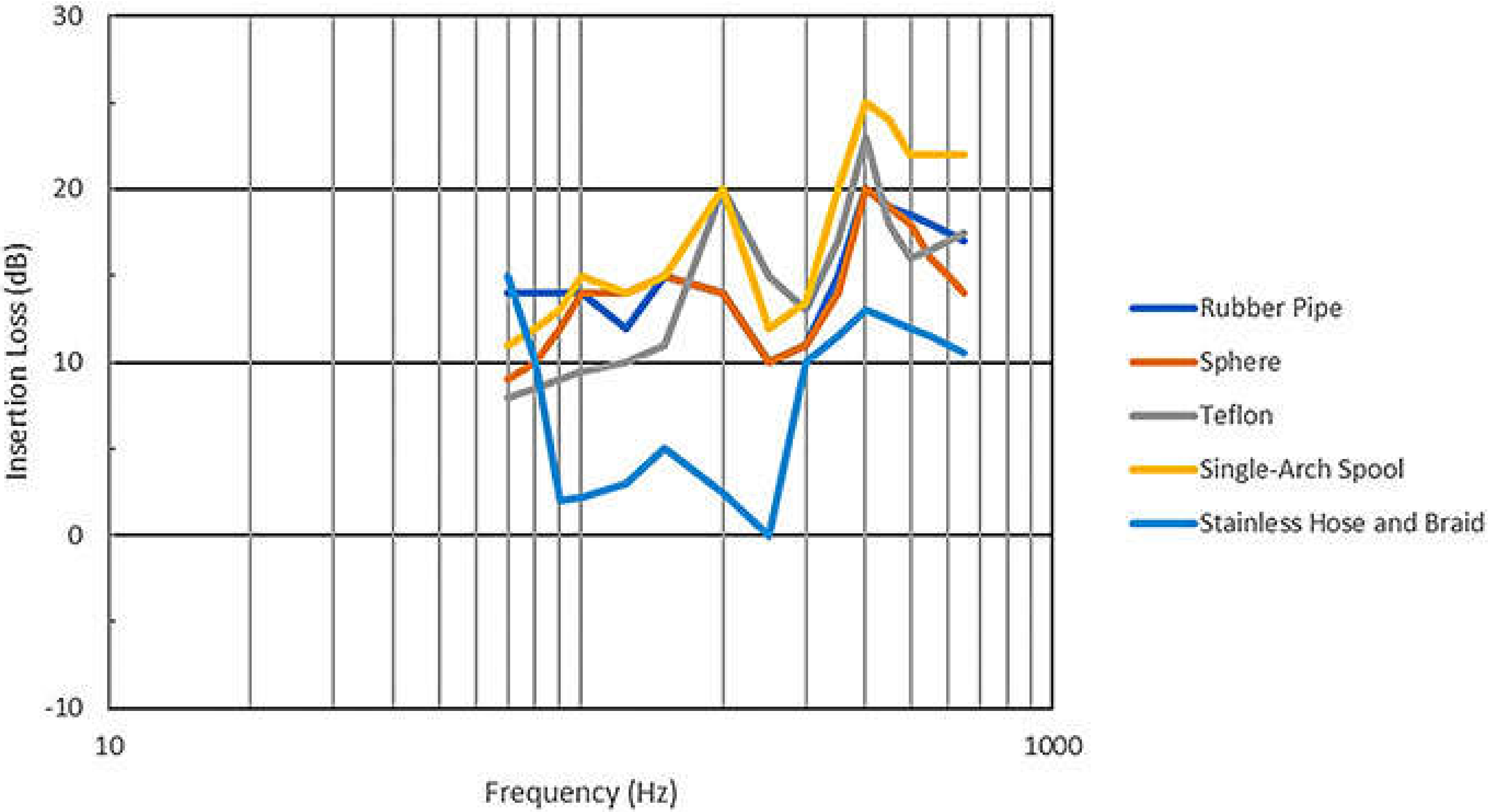
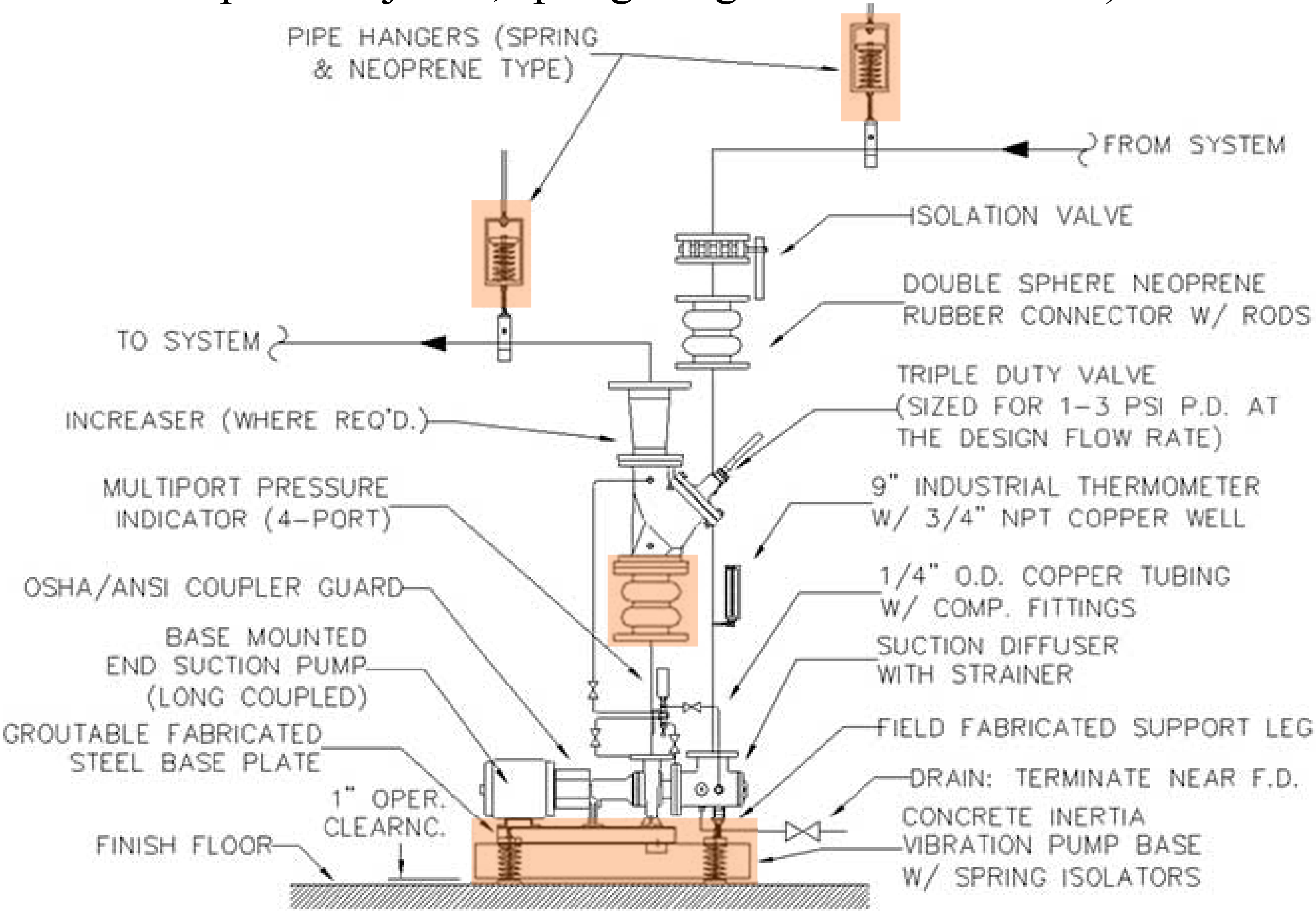
(Source: https://www.pumpsandsystems.com/isolation-noise-vibration-hvac-plumbing-piping-systems)

Insertion loss (represents the amount of vibration reduction from the source to the receiver) for various pipe connectors



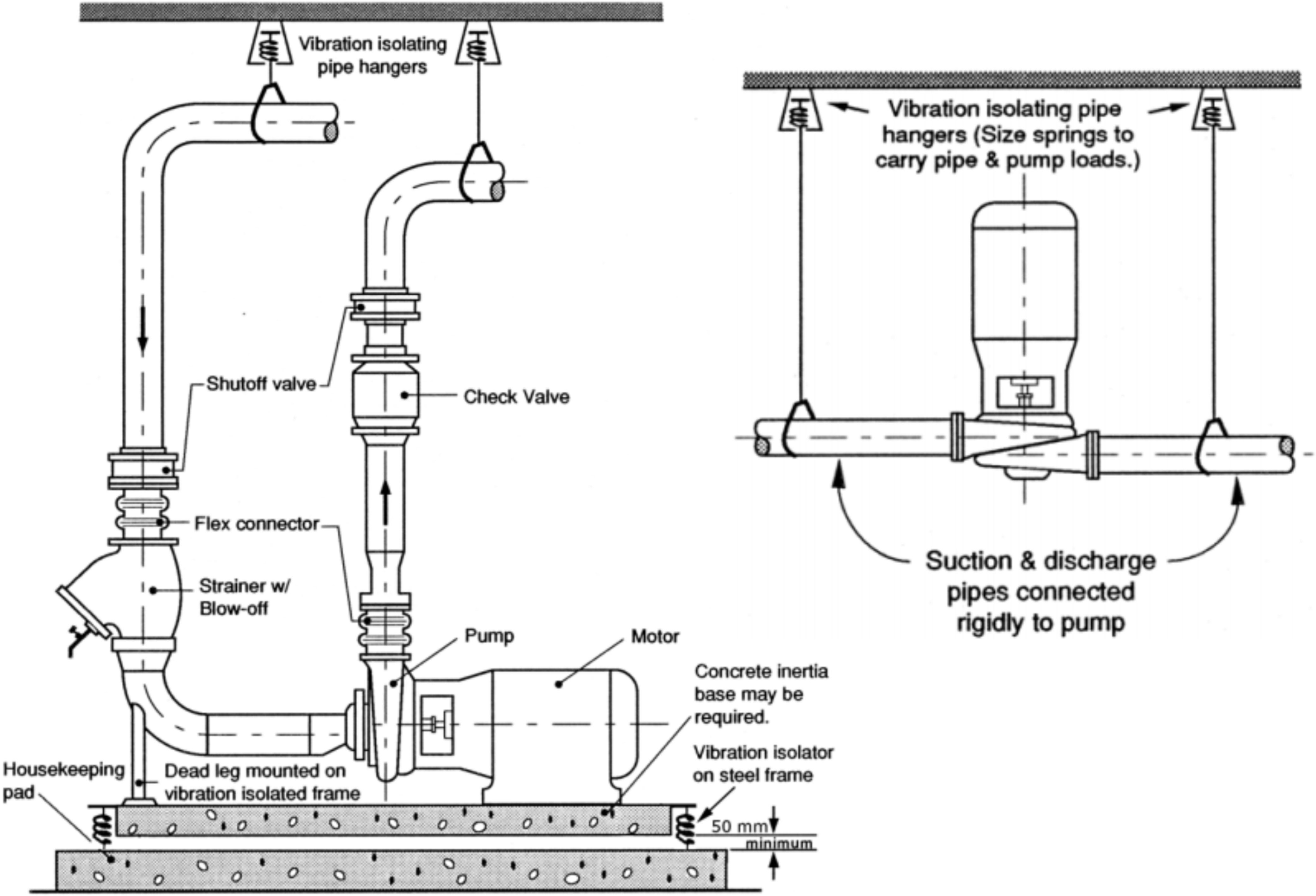
(Source: https://www.pumpsandsystems.com/isolation-noise-vibration-hvac-plumbing-piping-systems)

Typical standard detail for a base-mounted HVAC pump (with neoprene spherical joints, spring hangers and inertia base)



(Source: https://www.pumpsandsystems.com/isolation-noise-vibration-hvac-plumbing-piping-systems)

Proper installation of an end-suction pump and an inline pump



(Source: Schaffer M. E., 2011. *A Practical Guide to Noise and Vibration Control for HVAC Systems*, 2nd Edition (SI))

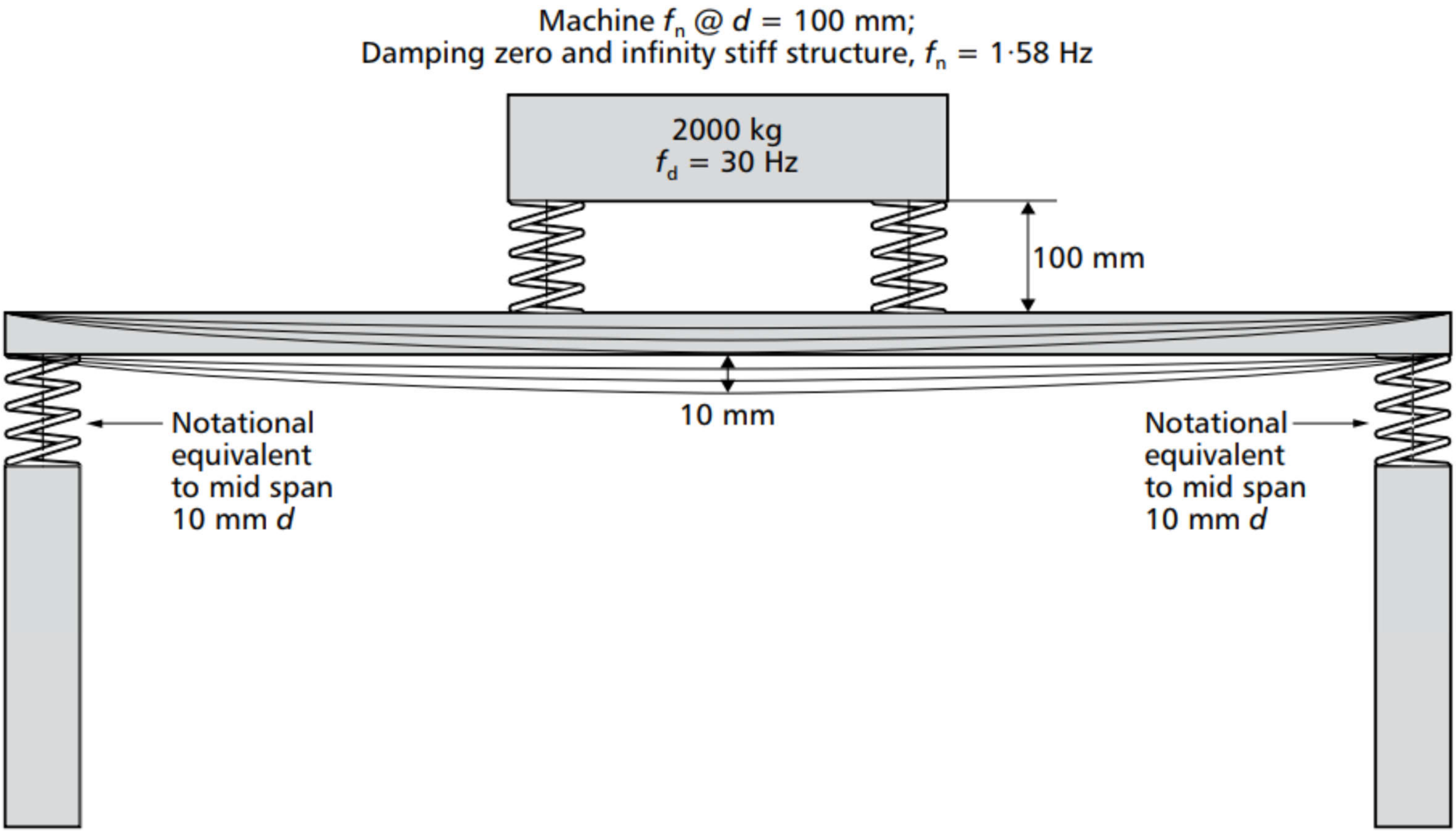
Vibration control

- How pipe layout affect noise and vibration?
  - Flange effects (and other heavy components like valves and rigid supports)
  - Pipe support effects (stiffness)
  - Pipe bend effects (e.g. elbows)
  - Pressure effects (of the fluid medium)
  - Control rod effects (can “short circuit” the vibration isolation of the rubber joint)
- Flexibility of connectors in both axial and circumferential directions to absorb vibration

Vibration control

- Major factors on vibration isolation
  - 1. The equipment type, drive-type (direct, gear or belt), rotation speed rpm, and motor kW rating
  - 2. The mass & location of the vibrating component(s) within the equipment enclosure or on the equipment skid
  - 3. The nature of the equipment's vibration --vertical or horizontal, rotating or reciprocating
  - 4. The location of the equipment relative to nearby noise & vibration-sensitive areas
  - 5. The stiffness of the building structure supporting the isolated equipment (usually related to the column spacing & beam depth)
  - 6. The spacing between isolator mounting points

Isolated machine interface with a wide span floor

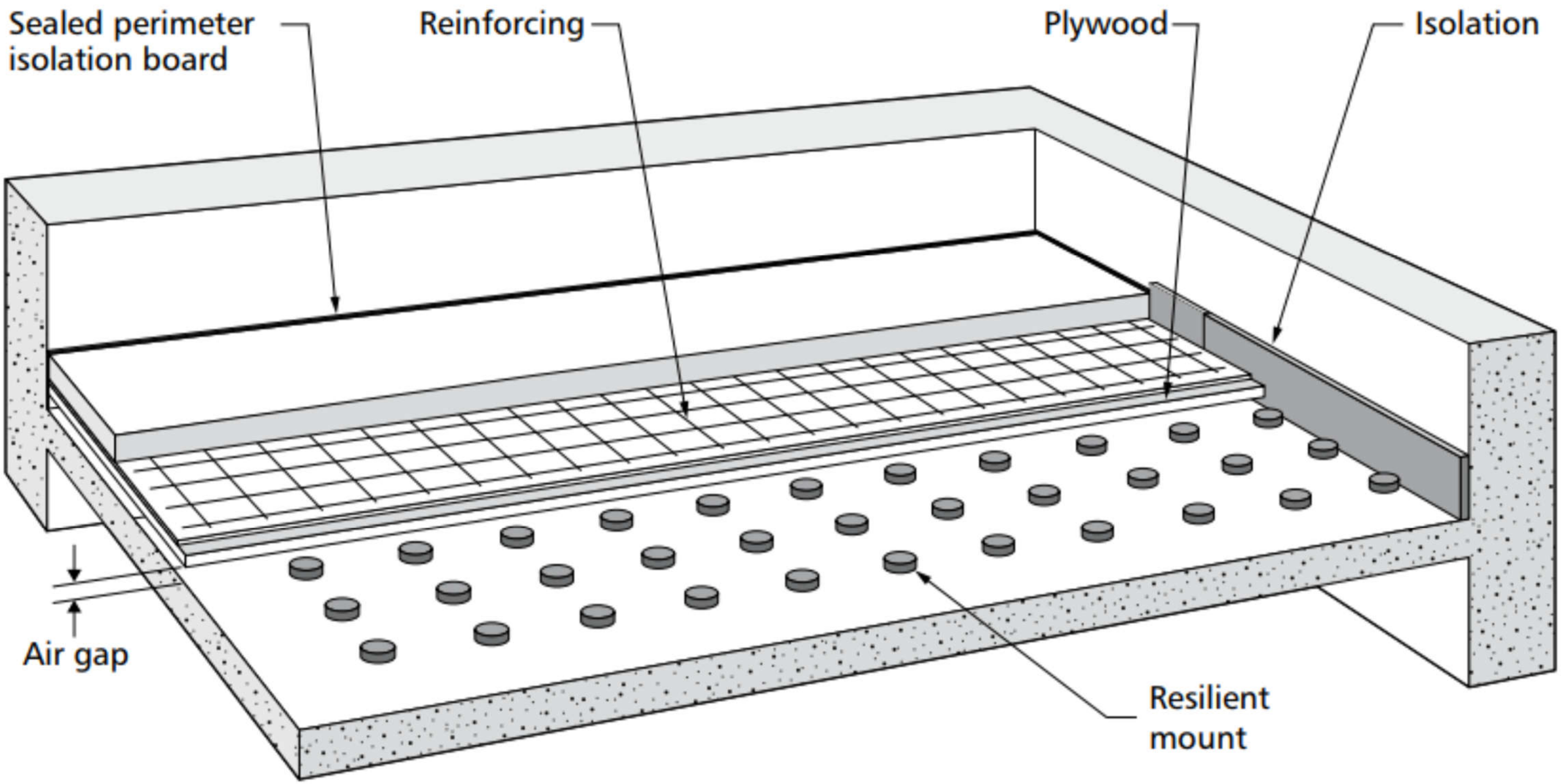


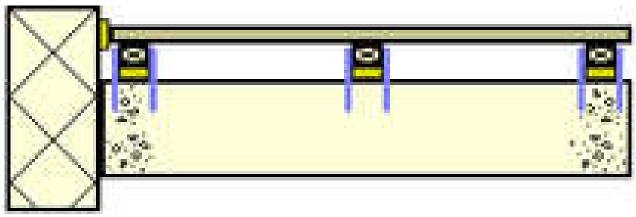
(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

Vibration control

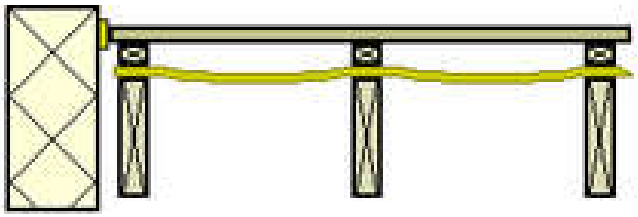
- Building structure planning: <u>floating floors</u>
  - Structural sound control -- flooring material “floats” over the subfloor & underlayment
  - Vibration & impact sound insulation of floors
  - Floating floors are used both to provide vibration isolation and to increase sound transmission loss, e.g. for plantrooms immediately adjacent to conference suite
  - Acceptable noise levels depend on the room usage (theatres and recital halls will have stricter noise requirements than offices or gymnasiums)

A basic floating floor arrangement



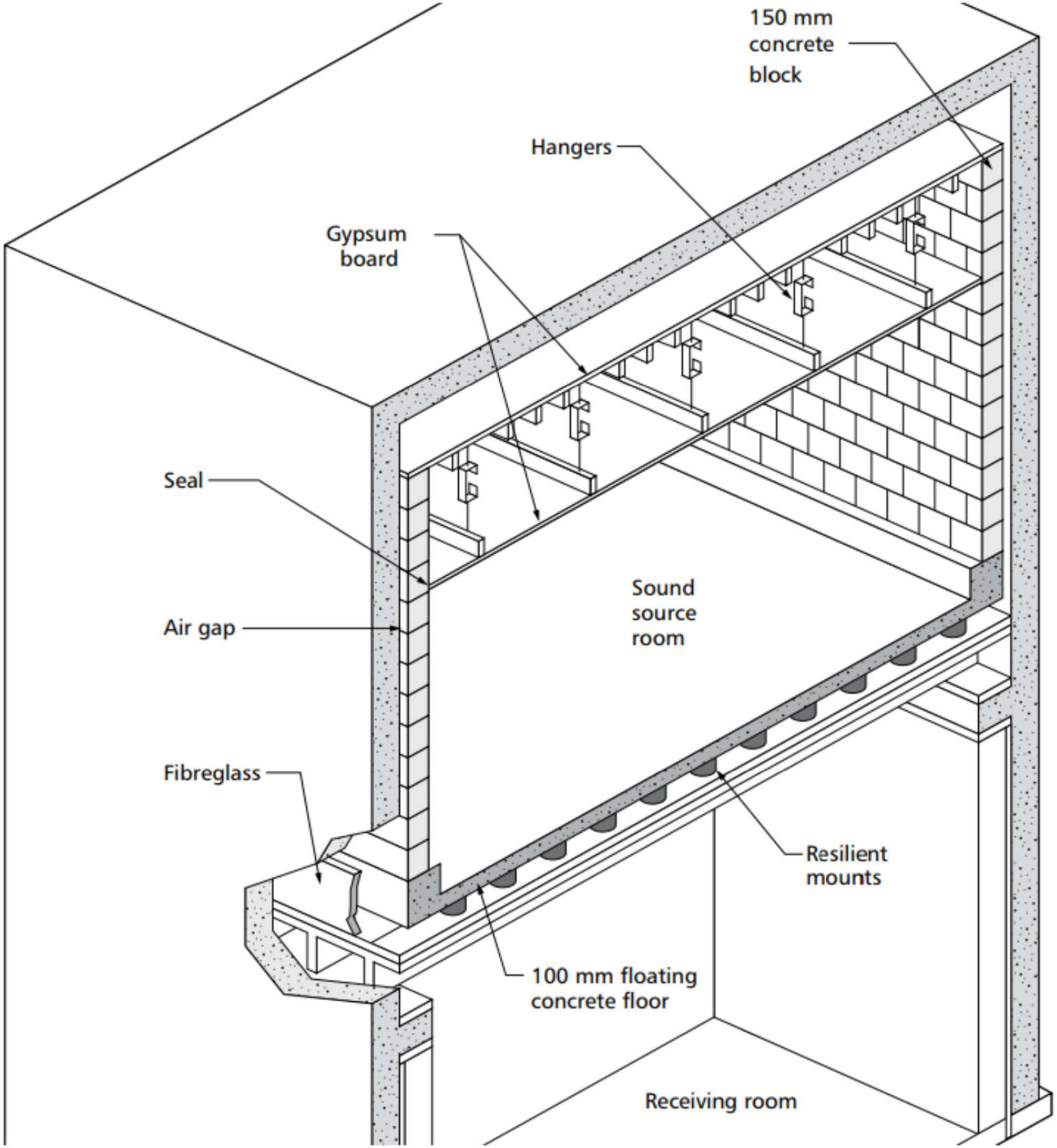


Floating floor over concrete



Floating floor over joists

(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)



A complex 'box in a box' floating floor arrangement

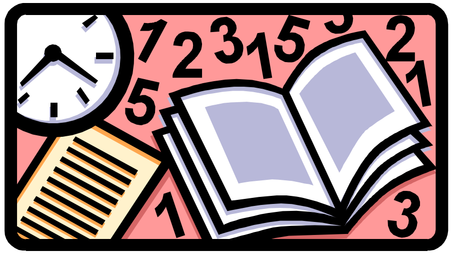
(Source: CIBSE, 2016. *Noise and Vibration Control for Building Services Systems, CIBSE Guide B4: 2016*, Chartered Institution of Building Services Engineers (CIBSE), London.)

Further Reading

- Training videos:

  - HVAC Training - Noise Control (24:43) https://youtu.be/yUBPe9BY3h4
  - Sound Fundamentals (24:22) https://youtu.be/DhpBqhIeiic
  - Webinar Recording: Understanding & Reducing Air System Noise (36:58) https://youtu.be/SktbXN9jBcE
  - Webinar Recording: Vibration Isolation for Mechanical Systems (20:41) https://youtu.be/MCBnZ83C75A
- HVAC Systems Noise Control https://www.cedengineering.com/userfiles/HVAC%20Systems%20Noise%20Control.pdf
  - Section-1 The Fundamentals of Acoustics
  - Section-2 Noise Rating Methods

References



- ASHRAE, 2019. *ASHRAE HVAC Applications Handbook 2020*, SI edition, Chp. 49 Sound and Vibration Control, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.
- CIBSE, 2016. *Noise and Vibration Control for Building Services Systems*, CIBSE Guide B4: 2016, Chartered Institution of Building Services Engineers (CIBSE), London.
- Crocker M. J. & Arenas J. P., 2021. *Engineering Acoustics: Noise and Vibration Control*, Wiley, Hoboken, NJ. https://doi.org/10.1002/9781118693902
- Schaffer M. E., 2011. *A Practical Guide to Noise and Vibration Control for HVAC Systems*, 2nd Edition (SI), American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA.