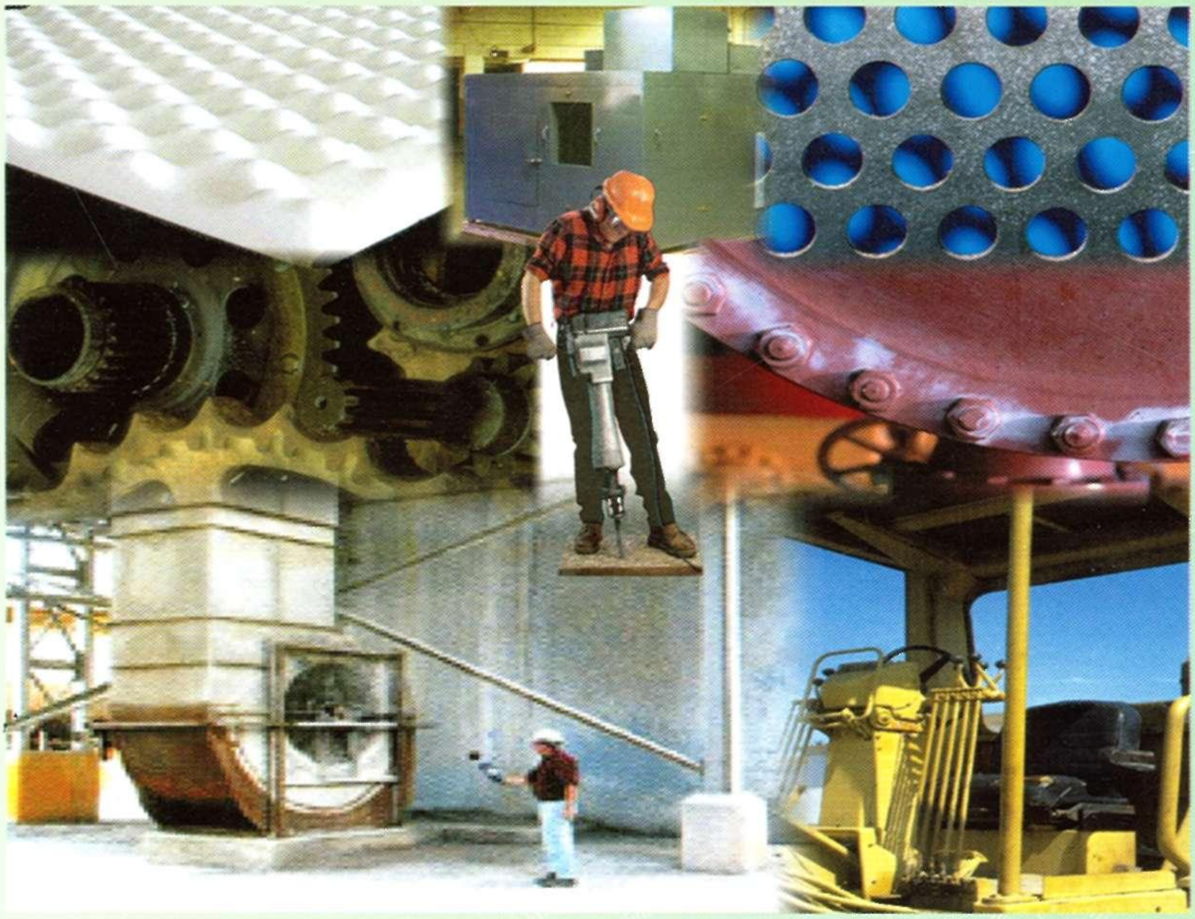

DOSH

Guidelines for Control of OCCUPATIONAL NOISE 2005

Department of Occupational Safety and Health, Malaysia

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FOREWORD

Concern about occupational noise continues to grow all the time as a resuit of increasing levels of noise exposure and greater understanding of the effects of noise, both auditory and extra-auditory. Increasing noise emission levels are to be expected as we consistently strive for increasingly faster and more economical ways to work, do business, travel or play; therefore noise exposure levels will likely continue to increase rapidly unless we make concerted efforts, on both technical and political fronts. We need to take urgent action to stem and reverse the tide of occupational noise induced hearing loss (NIHL) because it has the potential to become a serious workplace health issue as well as to significantly impair work efficiency and productivity.

Occupational noise control procedures may take such varied approaches as engineering, person-based hearing protective equipment (HPE) or administrative. As long as they are both practical and economically feasible, engineering methods would by far be the most desirable because: (1) they deal with predictable inanimate objects rather than relying on the uncertain behaviour of people, and therefore they tend to be much more effective and dependable; and (2) they ensure employee protection without imposing on him the burden and inconvenience of having to wear PPE, which is the highest goal in hazard control. Granted, it may not always be possible to obtain enough reduction with engineering methods, and it may be necessary in certain circumstances to employ a mixture of all aforementioned approaches to attain desired exposure levels. However, with the constant and rapid advances being made in technology and materials, the range of work situations in which engineering methods may be applied viably and the flexibility with which each application can be designed and implemented keeps increasing all the time.

It is now high time for industry to start weaning itself away from its traditional dependence on PPE — while not forgetting PPE's value as a stopgap, backup or last-resort measure — and move further up the hierarchy of hazard control strategies to more reliable and more effective long term protective measures. This would both free workers from the burden of discomfort and inconvenience that PPE tends to impose on them — an OSH ideal — as well as help take the standard of OSH in Malaysia up to a higher level. In many instances, and over a large portion of the whole spectrum of working environments, noise control by engineering methods can offer a practical, practicable and viable long term solution.

While engineering control of occupational noise requires some fundamental knowledge of acoustics, developing a solution to a problem would also depend upon a high degree of ingenuity, determination and commitment on the part of the person responsible for it. The general acoustical principles as applied to occupational noise control have been fairly well-established. Nevertheless, it may not always be possible to predict results of noise reduction techniques exactly. This is due in part to the complexities of noise sources, the varying working environments, and limitations due to operational and maintenance requirements. These uncertainties should not discourage the individual responsible for occupational noise control, however, since most occupational noise problems have been encountered and solved before and their results published.

Engineering-based noise control on noisy equipment already in operation may be relatively more challenging, but not unlikely, and definitely not impossible. Furthermore, it may not always be economically feasible to replace many long-life, noisy machines with quieter alternatives. Therefore, it is imperative that the most efficient use is made of existing as well as newly available noise control techniques. These techniques include the use of noise absorbing materials, enclosures or barriers, mechanical isolation, reduced driving force, driving system modification, and noise muffling.

These guidelines are intended to provide basic practical guidance to employers on how to comply with and implement the requirements of the Factories and Machinery (Noise Exposure) Regulations 1989 — as well as those of any new law on occupational noise that might be introduced in the future — particularly those pertaining to noise control, to an adequate degree. It is hoped that these guidelines would help achieve, especially in the long term, a significant and sustainable reduction in the incidence and severity of occupational NIHL.

Director General of Occupational Safety and Health
Malaysia
7 April 2005

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These guidelines have been compiled by DOSH Malaysia personnel and have been subjected to expert and peer reviews by a panel of experts and peers who have been and are still currently active in occupational noise control and/or occupational hygiene. DOSH Malaysia would thus like to take this opportunity to acknowledge and thank each and every one of them for their very precious contribution towards the preparation of these guidelines. These individuals are listed alongside their respective roles and organisations as follows:

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These guidelines are meant primarily for informative and instructive purposes only. Their main objective is to facilitate compliance with any national legislative requirement or relevant supporting standard pertaining to noise control, as a means of promoting good industrial hygiene practice and sustaining a healthful working environment, thereby positively contributing to worker health protection and corporate productivity. The examples given in them are neither meant to be presented as the only or the best solution to any specific problem, nor to be interpreted as endorsement of any particular firm, person, product, method etc. Rather, they are intended as basic practical guidance for the employer and other person or party acting on his behalf in developing adequate and effective noise control measures at work. In relation to this, DOSH Malaysia, as the publisher of these guidelines, hereby EXPLICITLY absolves itself of any blame, obligation or responsibility, whether direct or indirect, regarding any misinterpretation or misrepresentation one way or another and any loss or damage arising there from.

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1. INTRODUCTION

These Guidelines for Control of Occupational Noise (2005 edition) are intended as basic practical guidance to the employer in developing noise control measures, thereby helping him comply with the requirements of the Factories and Machinery (Noise Exposure) Regulations 1989 — as well as any new law on occupational noise that might be introduced in the future — particularly those pertaining to noise control, as a means of promoting good industrial hygiene practice and sustaining a healthful working environment, thus positively contributing to worker health protection and corporate productivity. These objectives will hopefully be achieved via stimulation and enhancement of: (1) the conceptual understanding of occupational noise control; and (2) its subsequent implementation; in Malaysian workplaces. For brevity, the guidelines assume a working understanding of sound and its basic principles. Nevertheless, for the reader who requires an introduction, or perhaps a refresher, Appendix 1 has been prepared with exactly these needs in mind.

2. PURPOSE

Although the existing Factories and Machinery (Noise Exposure) Regulations 1989 in their present form cover mostly only industries involved in: (1) manufacturing; (2) construction; and (3) mining and quarrying, these guidelines have been drawn up to cater to the noise control needs of all occupations falling within the purview of the Occupational Safety and Health Act 1994. It is hoped, therefore, that these guidelines will help achieve, especially in the long term, a significant reduction in the incidence and severity of occupational noise induced hearing loss (NIHL) in all occupations through the application of noise control principles. The guidelines should not in any way be construed to represent, indicate or suggest any upper boundary or limit on what quality of working environment in terms of noise control can be achieved in any undertaking. Rather, they should be seen more as a starting point for the employer to initiate companywide efforts striving continuously for better and better standards of noise control in his workplace all the time. In this respect too, professional noise control specialists would be expected to play a strategic and very important supporting role, particularly in relation to workplaces that may not have the resources or expertise to carry out meaningful and effective noise control measures on their own.

3. NOISE CONTROL - CONCEPT AND BASIC PRINCIPLE

As in all hazard control, noise control efforts should be approached according to the hierarchy of control strategies, i.e. using the paradigm:

source → path → receiver

Noise from most equipment comprises mainly waste energy. For this reason, as well as others related to efficiency, the best way to reduce noise is to tackle the problem at the source. Generally, reducing the noise at the source also offers the most options. Reduction at path would generally involve adding barriers or enclosing the equipment, but may also involve adding sound-absorbent materials. Reductions of more than a few decibels are difficult to achieve by these modifications. At the other end, reduction at receiver (i.e. affected employee) is achieved by either removing the employee from the sound field, limiting his working time in the area, or through the use of hearing protective equipment (HPE). While HPE is in principle really a reduction of noise at path, it is in practice usually considered as control at receiver. HPE is highly dependent on consistently appropriate human behaviour to work adequately, requires very robust management commitment and enforcement, and tends to be less effective. Thus, HPE ranks lowest in the hierarchy of noise control strategies and should NOT be relied upon as the primary means of noise control, but rather be treated as a means of last resort for controlling noise exposure — only to be used as a temporary or supplementary (i.e. backup) measure where other measures higher up the hierarchy of noise control strategies are pending or where they have been attempted and proven inadequate, ineffective or impracticable.

4. OVERALL NOISE CONTROL PROCEDURE

The mode of attack for tackling an occupational noise problem is somewhat similar to that for controlling any hazard in the working environment. Appropriate control measures include such things as change in plant design and layout, substitution of a less hazardous work method, reduction of the hazard at its source, and reduction of the hazard at its path of transmission. It has been proven helpful in the past to follow a structured method of analysis so that no possible control measure is overlooked. Thus the recommended method of approach goes according to the order outlined below.

(1) Plant planning (design and layout)

(2) Substitution (equipment, process, material)

(3) Engineering control
- Control at source (modification of noise generator)
- Control at path (modification of sound wave)

5. CONTROL BY PLANT PLANNING

One of the greatest opportunities for the industrial hygiene engineer in the field of noise control is to guide the design of new plants and the modernisation of existing ones. In this manner noise problems can be anticipated and prevented before they even arise. Successful planning for noise control involves: (1) knowledge of the noise characteristics of each machine and process; (2) proposed location of each noise source, operator, and maintenance man; and (3) selection of design criteria based on employee exposure time.

Engineering specifications for design and selection of equipment should incorporate a requirement for noise performance data. A sample equipment noise specification schedule is given in Appendix 6. In most cases, the machinery manufacturer is in the best position to reduce the noise of the machine at the source with built-in designs. It is expected that many such designs will not substantially increase the cost of the machine.

The acoustically important details of the building's load-bearing structure and work areas should be calculated and fixed early in the planning stage. The need for noise control depends first and foremost on the way the plant is designed and laid out. The structural design of the building often depends on where the machinery is placed and the need for insulation against both airborne and structure-borne sound. Towards this end, it is important to consider the following:

(1) The building's load-bearing structure, floors and machine foundation should be chosen so that all noise sources can be effectively vibration isolated. Heavy equipment demands stiff and heavy foundations, which must not be in direct contact with other parts of the building structure.

(2) Powerful noise sources should be enclosed by structures which give adequate airborne-sound insulation. Doors, inspection windows and other building elements where there is a risk of sound leakage require special attention.

(3) Rooms where there are sound sources and where personnel are present continuously should be provided with ceiling cladding (also wall cladding where high ceilings are concerned) which absorb the incident sound. Sound absorption characteristics vary widely for different materials which must therefore be chosen with regard to characteristics of the noise. Good sound absorption characteristics can OFTEN be combined with good thermal insulation.

(4) Office areas should be separated from building elements where vibrating equipment is installed by a joint of elastic material.

(5) Walls and ceiling construction, windows, doors etc. should be chosen so as to achieve the required sound isolation.

(6) Mounting noisy equipment on light or movable partitions should always be avoided. If ventilation for cooling systems must be mounted on such a light foundation in any case, e.g. a false ceiling, special effort must be made to obtain sufficient vibration isolation.

(7) In open-plan offices and large rooms where there are several office functions carried out in the same room, there must be a ceiling with high sound absorption; and soft carpeting on the floor is also beneficial. It should be noted that it is especially important to ensure that sound absorption is effective not only at the high frequencies, but also at the low and medium frequencies.

6. CONTROL BY SUBSTITUTION

6.1. Use Quieter Equipment

The first step in providing quiet workplace equipment is to make a strong effort to have equipment purchase specifications include noise emission limits. Even if the desired specifications may not always be available, or even achievable, at least these specifications will provide an incentive for the design and development of quieter products in the future. Again, reference can be made to the sample equipment noise specification schedule given in Appendix 6. Modification to equipment to reduce noise includes closer tolerances, better assembly, balancing of rotating machinery, redesign of components, and other quality control measures. Usually these changes must be left to the manufacturer of the equipment. However, users of equipment can specify the noise level that will be tolerated in new equipment purchases.

It would be reasonable to believe that new workplace noise regulations expected to be introduced in Malaysia in the future would likely include provisions for mandatory declaration of equipment noise emission levels by manufacturers. Many manufacturers worldwide already attempt to distinguish their products by emphasising their lowered noise emission levels, with cars being a good example. Purchasers of equipment, however, may not be aware of the cost advantages if quiet equipment is purchased — such as would be achieved by avoiding the need for a hearing conservation programme and preventing hearing loss among employees. The OSH professional should assure that both overall management and the purchasing department are aware of the value and importance of buying quiet equipment.

Quite often it is possible to substitute a quieter machine for a noisy one. Existing machines were probably selected because they were the most economical and efficient means of producing a desired product or service. Noise was very likely not considered as an important factor at the time of purchase. However, it may be more economical to pay more for quieter equipment now than to purchase cheaper noisy equipment that will require additional expenditure for noise control later. When acquiring new equipment, its type and speed should be selected on the basis of the applicable noise criteria. Some examples are given below.

(1) Replace high-frequency propeller or axial flow fan with squirrel cage type blower, which emits noise of lower frequency.
(2) Replace high speed fans or blowers with low speed types.
(3) Replace gear increasers with turbine drives, which are usually less noisy, where high speeds are concerned.
(4) Replace air ejector for removing parts from punch presses with a mechanical ejector.
(5) Replace a mechanical hopper vibrator — which are inherently noisy, where temperature and material will allow, with an internal pulsating-diaphragm type pneumatic feeder, which will greatly reduce the noise. Basically, the goal should be to shake only the part of the material handling system which impedes the flow. Avoid vibrators employing metal-to-metal impact.
(6) Replace pneumatic portable tools with electric tools.

(7) Replace a pneumatic riveting hammer with a hydraulic press. The exhaust of compressed air from the operation cylinder of pneumatic presses is usually noisy if unmuffled.

(8) If an impact tool must be used, choose the smallest one capable of doing the job.

(9) Replace mechanical presses with hydraulic presses

6.2. Use Quieter Processes

In many cases, changing the process can be one way of getting to grips with noise generation. This would require one to be aware of the availability of quieter processes for both actual production work as well as material handling. This would in turn involve cooperation between the employer, supplier, process designer and OSH professional. The following are several common examples.

(1) Replace percussion or impact riveting with: (i) welding, unless chipping is also required in the weld preparation; (ii) high strength bolts; or (iii) compression riveting.

(2) Replace chipping with grinding, Arc-air process or flame gouging.

(3) Replace cold working with hot working.

(4) Replace rolling or forging with pressing.

(5) Replace high-impact impulsive force (i.e. mechanical power) used for pile driving in building and construction with hydraulic power (Fig. 1).

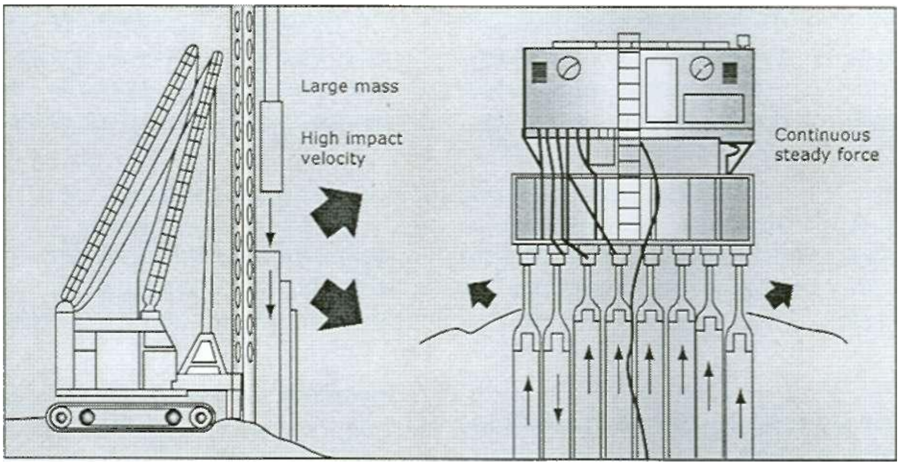


Fig. 1: Eliminating impact noise by substituting hydraulic power for impulsive force.

In most building and construction work, sheet piles are normally driven into the ground via the impact of a heavy mass (i.e. the pile driver) dropped from a great height, often powered up again by exploding a diesel charge. Hazardous local noise levels are generated both by the impact on the pile and from the explosion, and annoyance may be caused at distances of up to a few miles. In many situations, it is possible to use an entirely different technique (Fig. 1), which avoids impact altogether! A set of hydraulically operated rams is used to grip a number of sheet piles simultaneously. One pile is forced down at a time while the machine pulls upwards on all the rest, which anchor it to the ground. Vibration of the ram holding the pile being driven assists its progress. Impact is avoided completely, and noise levels can fall to as low as the hydraulic equipment allows.

6.3. Use Quieter Material

Materials from which buildings, machinery, piping and containers are constructed have a vital relation to noise control. Some materials have high internal damping and are called 'dead' materials, while others called 'live' materials have little internal damping and cause a ringing sound when struck. Some ways of using quieter materials are as follows:

(1) Replace acoustically Mive' materials with acoustically 'dead' (highly internally damped) materials. For instance, elastomers are good materials to use for bumpers. Good examples are gaskets, seals industrial truck tyres and rubber caps for hammer heads.
(2) Replace steel wheels on hand trucks with rubber or plastic tyres.
(3) Replace steel gears with fibre gears.

7. ENGINEERING CONTROL

7.1. Existing Equipment

If the need is to reduce the noise from existing machinery, consider both generation and radiation of sound for possible noise control measures. Once generated, the noise will be transmitted through: (1) the direct sound field; (2) the reverberant sound field; or (3) a structure-borne path. Finally, the only true measure for reducing noise exposure at the receiver is to reduce the amount of time the employee spends in the sound field. Providing a noise enclosure for the employee can also be considered as a receiver-based noise control measure. Proper maintenance of equipment must also be stressed, since virtually all mechanical equipment progressively becomes noisier as components undergo wear and tear.

7.2. Systematic Approach

The following systematic approach, comprising a variety of methods, could be used for controlling noise from existing equipment by the application of engineering principles. Each method will be discussed later in somewhat greater detail.

7.2.1. Control at source — generated noise

(1) Reduce impact noise.
(2) Reduce or eliminate aerodynamically generated noise.
(3) Reduce or eliminate any resonance effects.
(4) Modify or replace gears, bearings, bumpers or blades. This can help avoid or reduce metal-to-metal contact. Nylon gears, plastic bumpers and damping of blades have been proven effective.
(5) Separate the noisy elements that service the basic machine but need not be directly part of it, such as pumps, fans and air compressors, by moving them some distance away.
(6) Allow control of the speed of processes to enable practical work flow. This will reduce noise created by stop-start impact.
(7) Reduce unbalance in rotating systems.

7.2.2. Control at source — radiated noise

(1) Move the machinery to a new location as far away as possible from exposed employees.
(2) Provide vibration isolation to reduce the radiation of noise from the surface on which the machinery is mounted.
(3) For large heavy machinery, use an inertia block.
(4) Insert flexible connectors between the machine and any ductwork, conduit, or cables.
(5) Reduce or modify the surfaces that radiate noise.
(6) Apply vibration isolation to machine housing.
(7) Use active noise cancellation or active vibration cancellation.
(8) Use vibration isolation mountings, mufflers or silencers for air and gas flow.

7.2.3. Control at path — directly transmitted noise

(1) Provide a partial or full enclosure around the machine.
(2) Use sound-absorptive material.
(3) Construct an acoustical barrier to shield, deflect, or absorb noise energy. This is best done with dense and heavy materials, such as brick, concrete or steel using bracing or strategic reinforcing during construction of walls or machine enclosures to reduce resonant noise.
(4) Reduce the leakage paths permitting noise to leak from enclosures.

7.2.4. Control at path — reverberant noise

(1) Use sound-absorptive material, e.g. fibreglass, thick-pile carpet or acoustic tiles etc., on walls, ceiling or floor.
(2) Reduce reflections by moving equipment away from corners or walls.

7.2.5. Control at path — structure-borne noise

(1) Use ducts lined with sound-absorptive material.
(2) Use wrapping or lagging on pipes to increase their sound insulation.
(3) Reduce turbulence from liquid or gaseous flows.
(4) Add mufflers.

7.2.6. Control at receiver

(1) Use enclosure or control room to house the employee.
(2) Reduce the amount of time the employee is allowed to work in a high-noise area.
(3) Provide HPE to the employee.

8. REDUCING GENERATED NOISE

8.1. Reduce Impact Noise

Mechanical and material handling devices commonly produce noise from impact. This type of noise can be reduced by:

(1) Reducing the dropping height of goods collected in boxes or bins (Figs. 2 and 3).
(2) Using soft rubber or plastic to receive and absorb hard impacts, such as where panels are likely to be struck by materials during processing (Fig. 3).

(3) Increasing the rigidity of containers receiving impact goods and adding damping material — especially to large surfaces.
(5) Regulating the speed or cycle time of conveyors to prevent collisions and excessive noise.

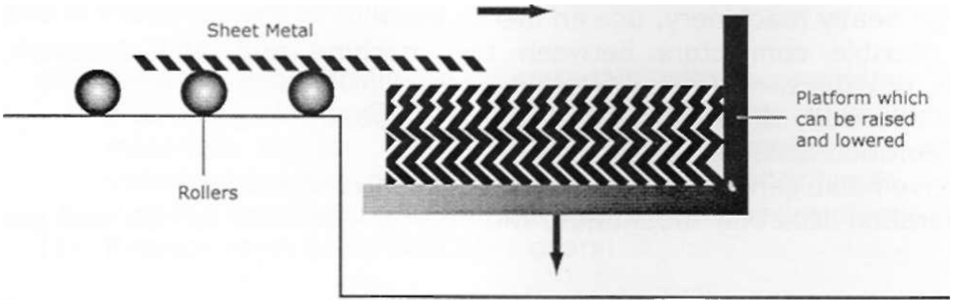


Fig. 2: Reducing drop height using adjustable platform.

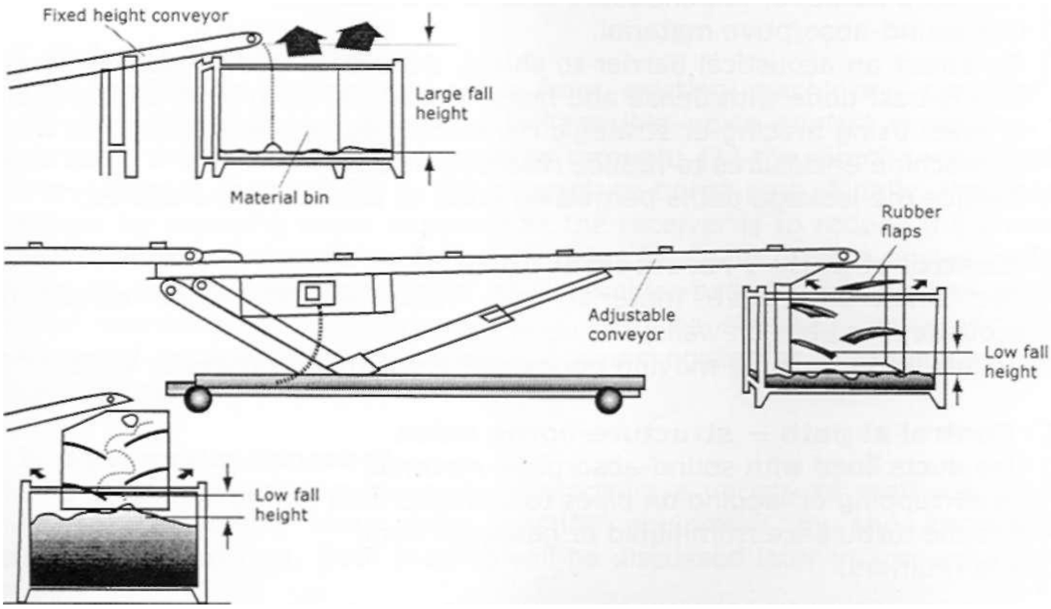


Fig. 3: Reducing drop height and using rubber flaps to slow down fall speed and absorb impact.

8.2. Reduce or Eliminate Aerodynamically Generated Noise

A wide variety of methods can be used to control aerodynamically generated noise.

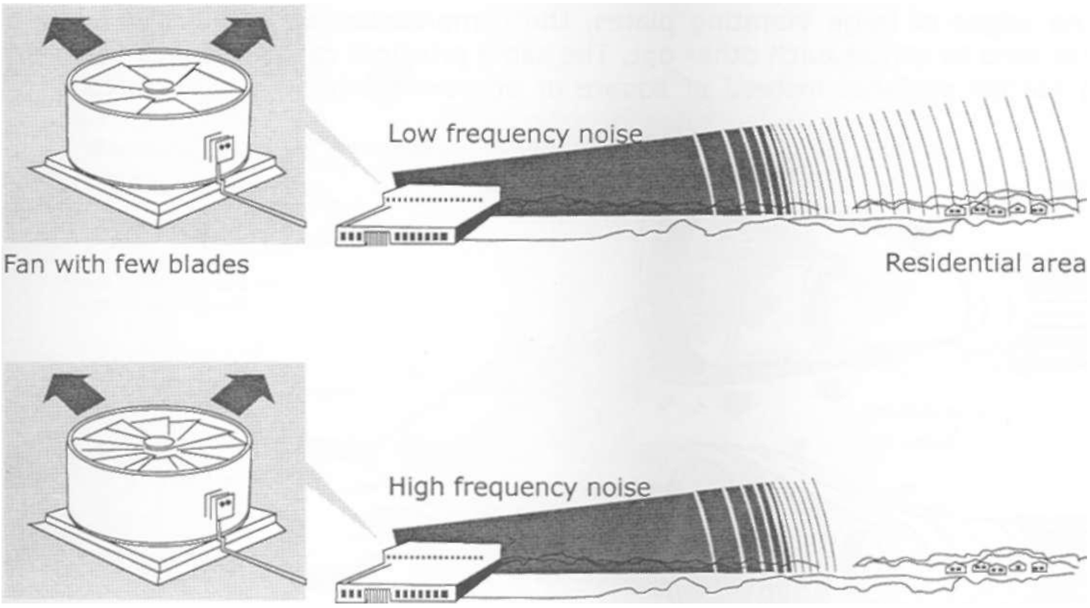
8.2.1. Change the character of the noise

Where great distances are involved, such as often happens outdoors, air reduces high-frequency sounds more than lower-frequency sounds. Atmospheric attenuation for pure tone sounds at 70% relative humidity and 10° C is given by:

$$A_{atm,f} = \frac{R}{1,000}\left[0.6 + 1.6\left\{\frac{f}{1,000}\right\} + 1.4\left\{\frac{f}{1,000}\right\}^2\right]$$

where r is the distance between the source and the receiver (m) and f is the sound frequency (Hz).

For community noise control (also applicable to outdoor working environments), replacing a noise source with one of higher noise frequency may reduce the sound level at typical property-line distances (Fig. 4). Note, however, that shifting to higher frequencies will likely bring the source into a sound frequency range where the ear is more sensitive. Therefore, careful consideration of perceived loudness must be made before applying this solution.



Fan with many blades Residential area

Fig. 4: Converting fan noise from lower to higher frequencies, which results in greater attenuation by atmospheric air.

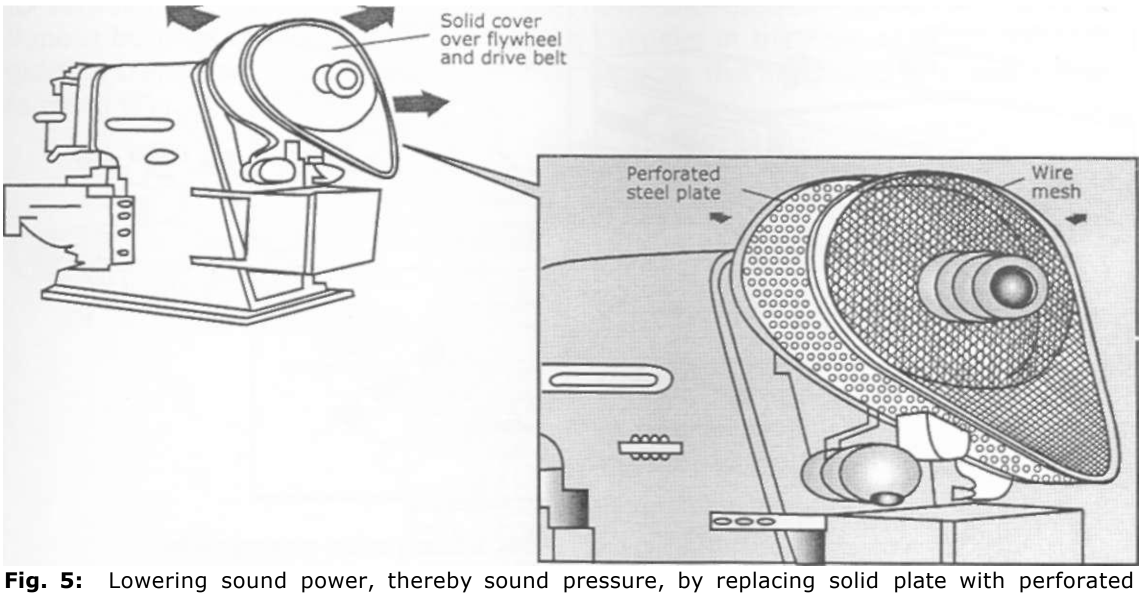


Fig. 5: Lowering sound power, thereby sound pressure, by replacing solid plate with perforated metal.

8.2.2. Reduce the surface area of the source

When large surfaces vibrate they will produce high sound levels. Consider replacing solid plates, wherever possible, with expanded metal, wire mesh or perforated metal (Fig. 5).

8.2.3. Change the source dimensions such that noise is cancelled out at the edges

At the edges of large vibrating plates, the compression and rarefaction sound waves tend to cancel each other out. The same principle can be applied by using long narrow surfaces instead of square or approximately square surfaces (Fig. 6).

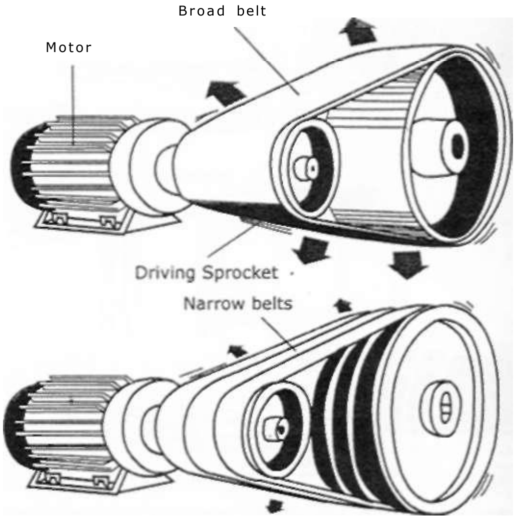


Fig. 6: Lowering sound power, thereby sound pressure, by replacing a single broad belt with several narrower belts.

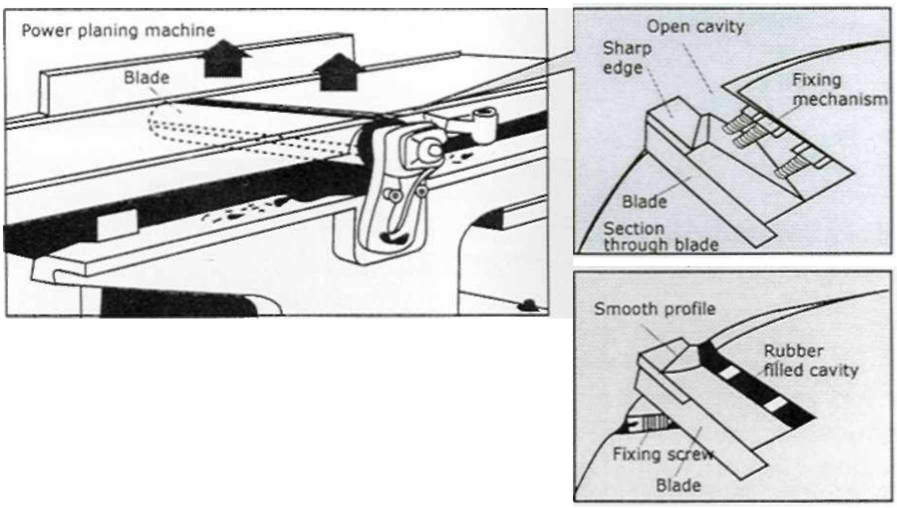


Fig. 7: Reducing wind tonal noise by filling out cavities around rapidly moving parts.

8.2.4. Reduce or remove interrupted-wind tonal noise

When air blows across an edge or opening with a cavity behind it, a loud tonal (i.e. pure tone) noise is produced due to standing-wave pressure vibrations via a phenomenon called Helmholz resonance. Wind-based musical instruments, e.g.

organ, flute etc., work by this principle, as does a man's mouth when he whistles. When tonal noise is produced by machinery due to this effect, it may be possible to eliminate the wind (i.e. the air flow) by filling out any hollow space, thus removing the noise created by it (Fig. 7).

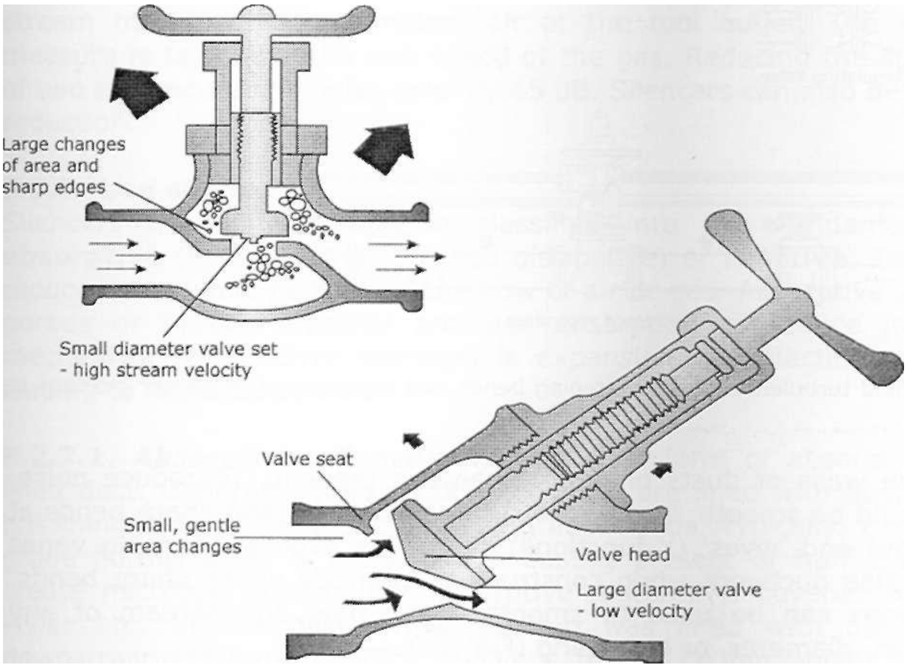


Fig. 8: Reducing fluid turbulence by straightening flow pathways.

8.2.5. Reduce turbulence in fluids

Smooth laminar flow in ducts or pipes does not generate noise. Fluid noise is due to turbulence. The more turbulent the flow, the greater would be the noise. Vapour bubbles can be created by abrupt changes in the flow of fluids. Providing gradual transition in cross-sectional area reduces the likelihood of these bubbles forming (Fig. 8).

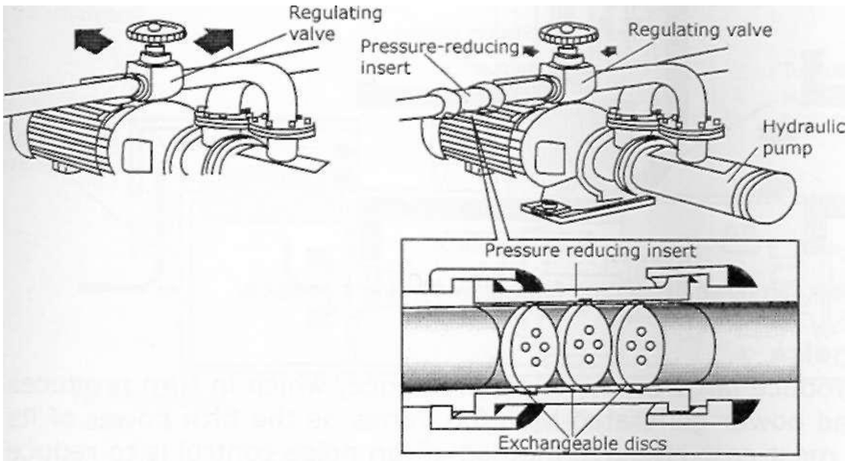


Fig. 9: Preventing vapour bubble implosion (cavitation) by reducing pressure in several smaller steps.

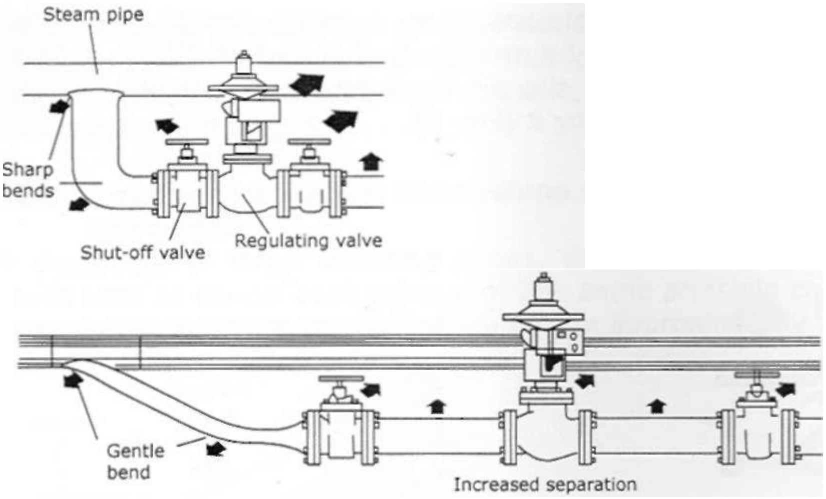


Fig. 10: Reducing fluid turbulence by straightening bends and transitioning diameter changes in fluid flow.

Turbulence at the walls of ducts or pipes is always present. To reduce noise, interior walls should be smooth, free of protrusions at joints, and sharp bends at 'tees' (T junctions) and 'wyes' (Y junctions) should be avoided. Turning vanes can be placed inside ductwork when construction methods utilise sharp bends. Straightening vanes can be used to smoothen the flow downstream of any change in direction, diameter, or branching (Fig. 10).

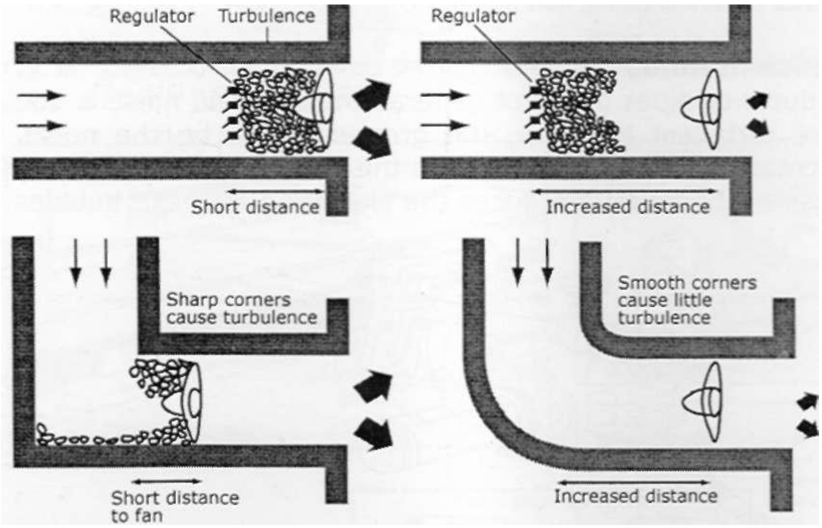


Fig. 11: Reducing ductwork fan noise by shifting fan to low turbulence region.

8.2.6. Reduce fan noise

Fans, in particular, produce large amounts of turbulence, which in turn produces noise. Since the sound power generated by a fan varies as the fifth power of its rotational speed, the most cost-effective method of fan noise control is to reduce this speed wherever possible. Wherever possible, when purchasing new fans, choose quieter designs. For instance, backward-curved blades on squirrel-cage fans are quieter than straight blades or forward-curved blades.

Fans mounted inside ductwork create significant noise, especially when mounted in regions where a great deal of turbulence is present. In-line duct fans should be mounted in low-turbulence regions of ductwork (Fig. 11).

Pneumatic equipment produces noise turbulence where the high speed gas stream mixes with the ambient air at the tool outlet. The simplest control measure is to reduce the exit speed of the gas. Reducing the speed by a factor of two can reduce the noise level by 15 dB. Silencers can also be used for further reduction.

8.2.7. Use silencers
Silencers or mufflers can be classified into two fundamental groups — **absorptive** (sometimes also called dissipative) or **reactive.** They are made to reduce noise while permitting the flow of air or gas. Absorptive silencers contain porous or fibrous material and use absorption to reduce noise. The basic mechanism for reactive silencers is expansion or reflection of sound waves, leading to noise cancellation.

8.2.7.1. ***Absorptive silencer:*** The simplest form of absorptive silencer is a lined duct. Generally, long sections of ducts are lined with absorptive material, but lining is particularly effective along duct bends. Typically, 2 - 5 cm acoustical grade fibrous glass is used. Where dust is present or humid conditions could create microbial growth, the absorptive material is covered with thin plastic, Mylar etc. In the past, HVAC ducting was lined with absorptive material downstream of fans in office buildings to reduce fan noise. Several of these installations have had severe microbial growth, inadvertently potentially contributing to other (non-acoustic) industrial hygiene problems.

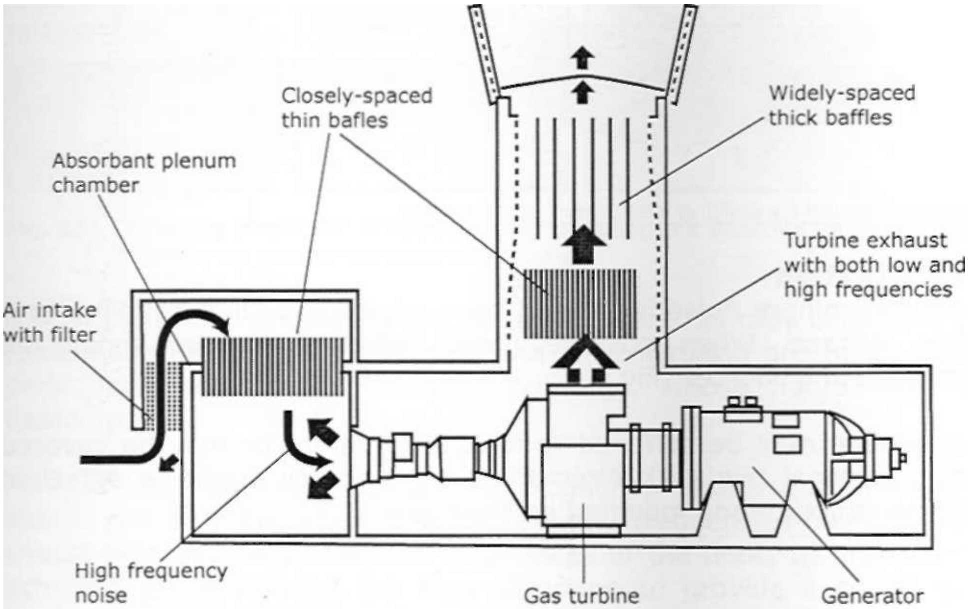


Fig. 12: Absorbent mufflers sized for dominant frequencies.

Another form of absorptive silencer comprises parallel baffles. Good design includes aerodynamically streamlined entrance and exit ends with perforated spaces filled with highly absorbent acoustic materials. The first few feet of length are highly absorbent; so the attenuation is not linear with length. Thick absorbent material with wide spaces between absorbers is effective for low frequencies, while thin material with narrow spaces is effective for higher frequencies. They should be considered for cooling and exhaust air whenever sources are to be enclosed (Fig. 12).

8.2.7.2. *Reactive silencer:* The simplest form of a reactive silencer is a single expansion chamber. As the air enters and leaves the chamber, the expansion and contraction in pressure cause reflection of sound waves. The reflected wave added to the incoming sound wave results in destructive interference, leading to noise reduction. This reduction only occurs when:

$$l = \frac{n\lambda}{4} \quad \text{where } n = 1, 3, 5 \ldots\ldots$$

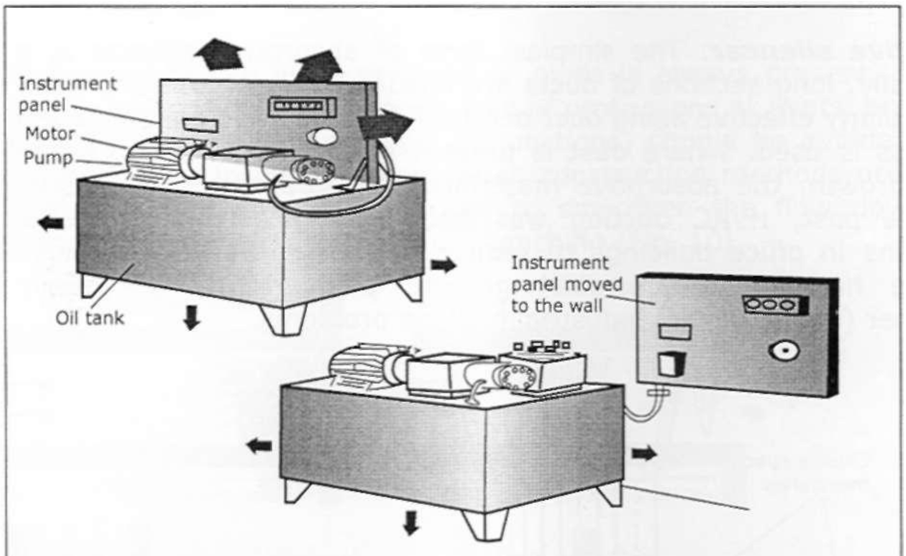


Fig. 13: Reducing vibration by shifting instrument panel to wall.

where l is the length of the muffler, λ is the wavelength of the tone, and n is an integer. This equation can be used to calculate the length needed for a reactive silencer.

8.3. Reduce Vibration

In many cases, machinery noise is created by a vibrating source coupling to a large radiating surface. When possible, large radiating surface should be detached from vibrating sources (Fig. 13).

The vibrating surface may be stiffened to limit the motion, or may be covered with a damping material (Fig. 14). Alternatively, the source might be detached from the building structure and mounted on the floor.

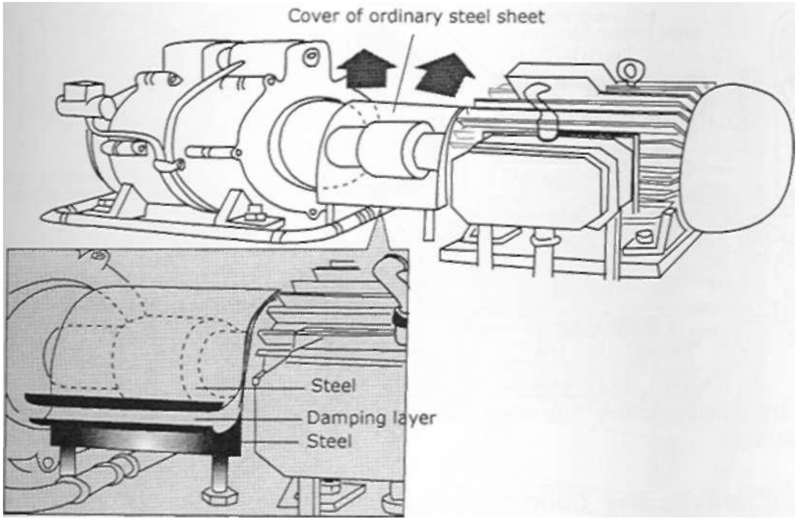


Fig. 14: Reducing vibration by putting damping on flexible panel.

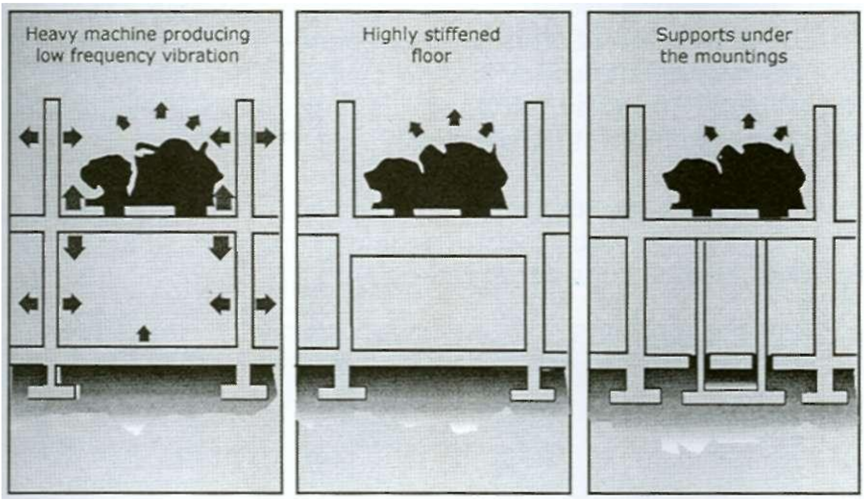


Fig. 15: Obtaining maximum isolation by (a) stiffening the floor structure; or (b) mounting the machine on ground-founded pillars.

A heavy machine producing low frequency vibration may cause the floor itself to resonate even though isolators of the correct rating are used. This problem is particularly common in concrete buildings, whose floors have low internal damping.

For the best isolation, the natural frequency of the machine on its isolators should not only be well below the exciting frequencies from the machine, but should also be lower than the resonances of the floor. In practice, this may be achieved by reinforcing the floor structure to provide a stiffer solid base, or mounting the machine on pillars founded directly in the ground (Fig. 15).

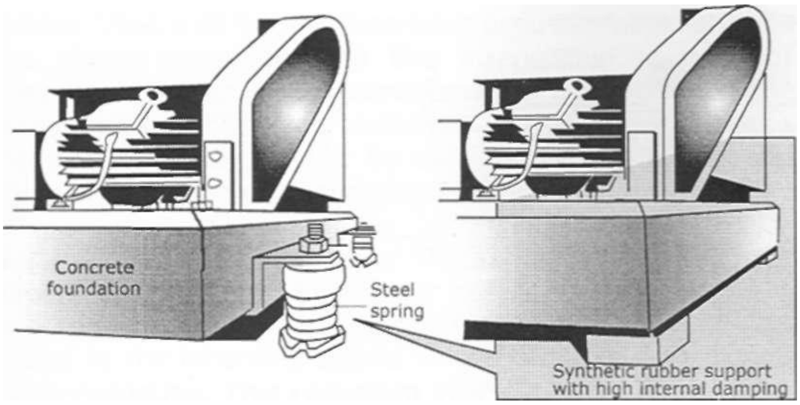


Fig. 16: Isolating vibration by placing heavy vibrating equipment on inertial block with vibration isolators and dampers.

When equipment is attached to the building structure, care must be taken to provide vibration isolation or the noise may be transmitted throughout the building by vibrating the building structural members. The equipment may be mounted on concrete inertia blocks or directly to steel frames. Regardless of the mounting, some form of vibration isolators are usually used (Fig. 16). The degree of isolation achieved with vibration isolators depends on the frequency of vibrations relative to the natural frequency of the system and the amount of damping built into the isolator. Formulae for determining the isolation achievable are provided by manufacturers of vibration isolators.

Vibration isolation may not be completely effective when noise is transferred through piping or conduits from the equipment. Flexible connectors to mount the tubing to the building must also be considered (Fig. 17).

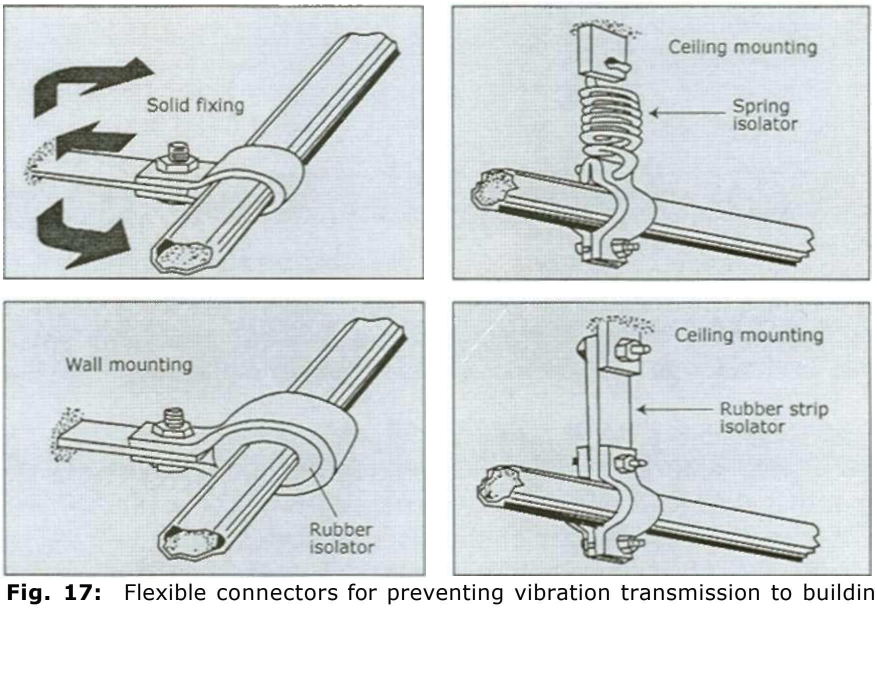


Fig. 17: Flexible connectors for preventing vibration transmission to building structure.

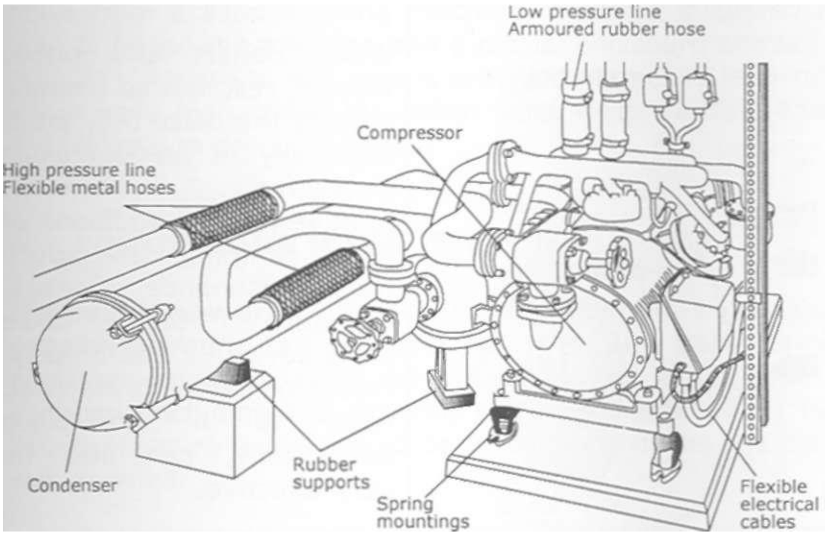


Fig. 18: Vibration isolation of pipework on refrigeration plant by use of flexible couplings.

For instance, refrigeration plant can be a serious noise source due to the large pressure changes in the fluid during its passage through the compressor unit. Careful vibration isolation of the entire plant is necessary, and all incoming and outgoing pipework should be isolated from the plant by flexible couplings (Fig. 18).

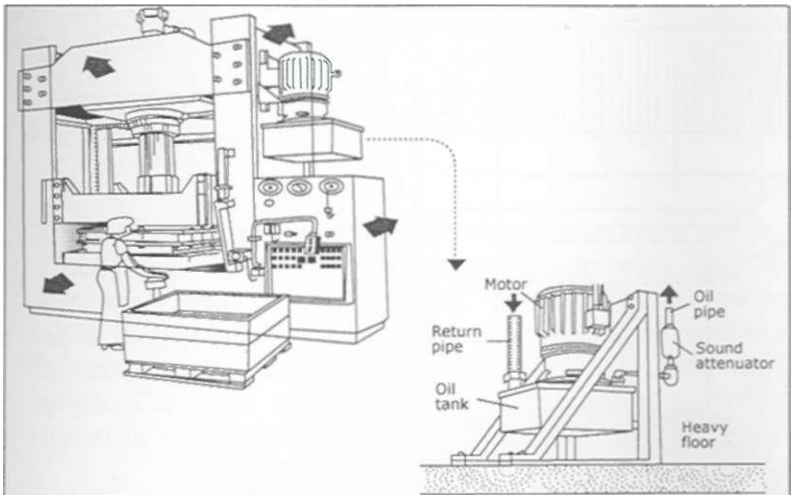


Fig. 19: Reducing vibration by shifting small service machinery onto isolators on a solid floor.

Small machinery, such as pumps and motors, serving much larger pieces of equipment such as hydraulic presses, machine tools, and turbines are often mounted directly on structural panels. Unfortunately, these are set into vibration, radiating high noise levels from the entire area of the machine.

The solution is to mount the small service machinery on isolators, away from the main frame of the large equipment, on a solid floor wherever possible (Fig. 19).

Pipework carrying fluids should be connected via flexible piping and should include attenuators to avoid the transfer of vibration back to the main structure of the large equipment.

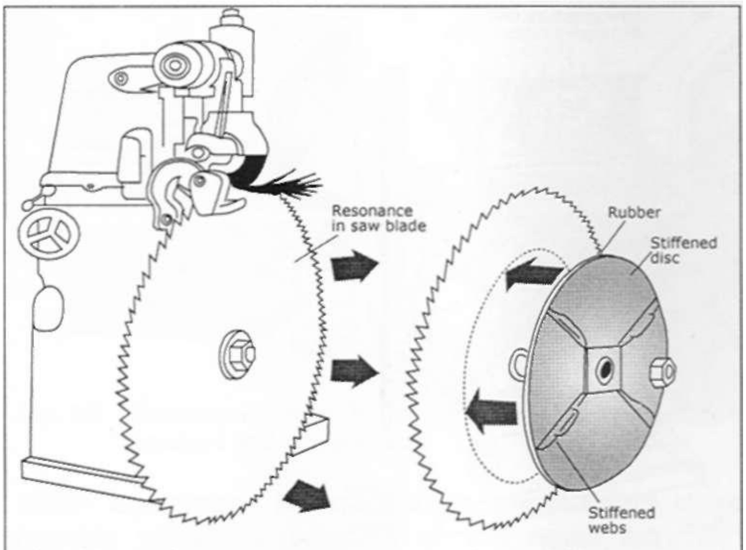


Fig. 20: Reducing resonance in a circular saw blade.

When panels and plates vibrate, resonances strongly amplify the noise they emit, especially in homogeneous structures. However, relatively small additions of extra damping can reduce the resonance peaks, therefore the noise radiated, enormously. Pieces of damping material, fixed to a work-piece temporarily, can also be very effective.

A circular saw blade in a sharpening machine is a good example. It generates a high level of noise because of resonance and very low internal damping. By fastening a disc of rubber damping material to the blade with a stiff disc during sharpening, both mass and damping is increased, thereby reducing amplification of the resonances (Fig. 20).

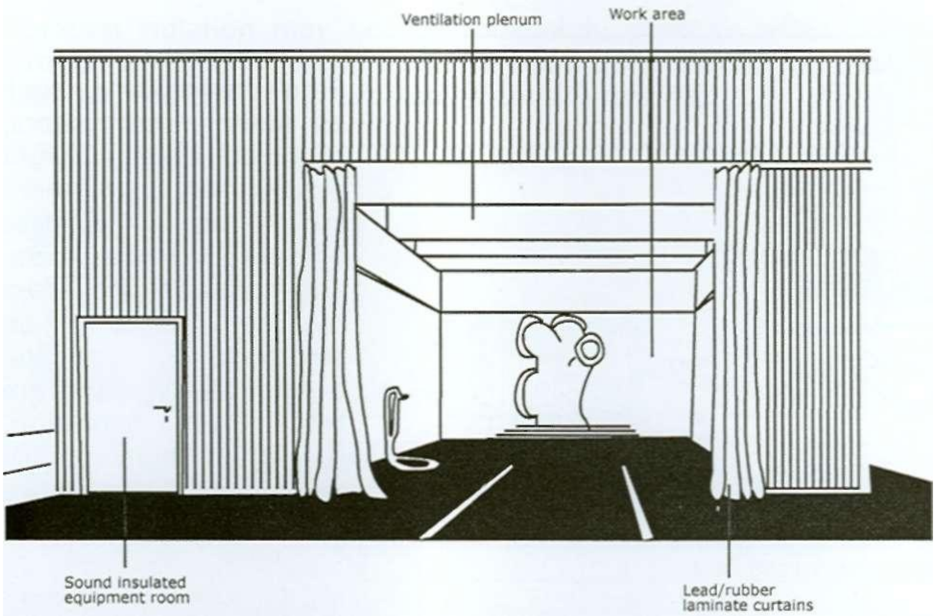


Fig. 21: Sand blasting machine, housed in a sound insulated machine room, with a partial enclosure erected around the work area.

When sound meets a wall, it sets the wall into vibration and sound is then radiated from the other side, the level of which is dependent on the **surface density** of the wall, i.e. its weight per unit surface area. In general, insulation increases along with the sound frequency or the wall thickness, until a point is reached where it begins to fall off due to coincidence. For example, to control noise from a sand blasting machine, a sound insulated machine room can be built to house the machine and a partial enclosure erected around the work area (Fig. 21). Access to this area is provided via heavy lead-rubber laminate curtains which have high sound insulation while being flexible and easy to fold to allow easy access to the work area.

9. CONTROLLING NOISE IN ROOMS

The **sound power** of a source is independent of its environment, but the **sound pressure** around the source is not (Fig. 22). Considering the equipment as a point source, if it could be suspended in midair away from any reflecting surfaces, including the ground, the equipment would be in a free field, and sound pressure levels would decrease by 6 dB as the distance from the source was doubled.

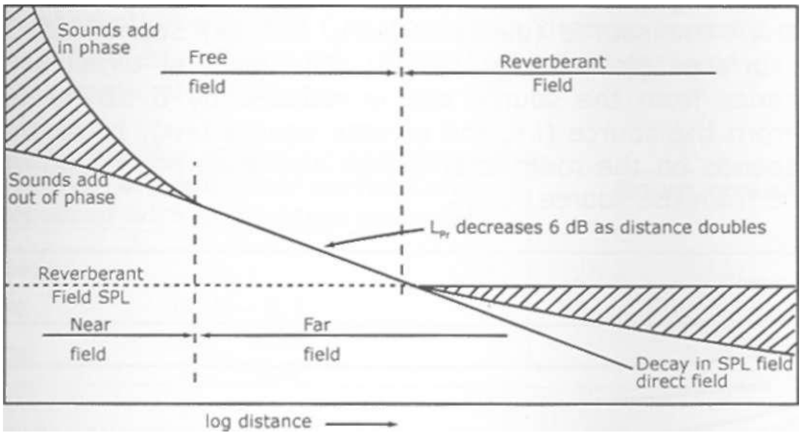


Fig. 22: Sound pressure levels in the near, free and far fields.

In practice, machinery is neither a point source nor in free-field conditions. Noise is usually emitted from all parts of equipment, and not all parts vibrate in phase with each other. Consequently, some parts will be moving in while other parts move out, leading to a partial cancellation of sound pressure. At other parts of the equipment, parts may be moving in phase, reinforcing the sound pressure levels. Close to a machine, in the near-field, sound pressure levels may be higher or lower than predicted from sound power and distance.

Outdoors, at distances about twice the longest dimension of the machine, these effects disappear, and the 'inverse square' law or the '6 dB decrease per doubling of distance' rule becomes valid. Indoors, reverberations from walls, floors, and ceilings will result in less of a decrease in sound pressure level as the distance increases than predicted in a free-field environment.

Noise sources should be kept away from walls. The worst placement is in the corners, where the reflections are greatest (Fig. 23).

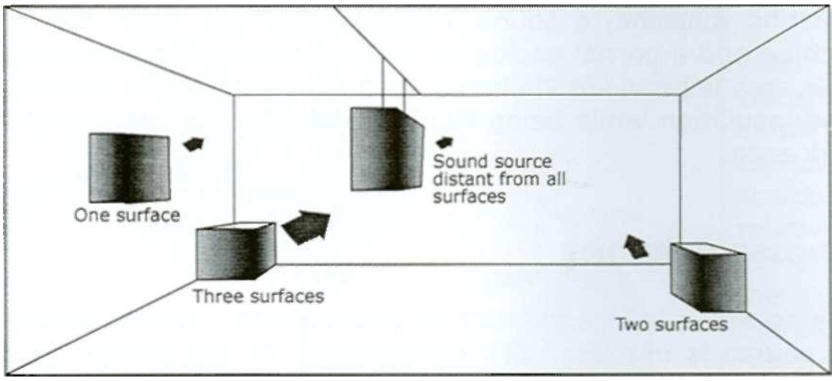


Fig. 23: Avoid placing equipment near walls and corners.

9.1. Treating Rooms with Absorbent Material

Absorbent material is used when it is desired to reduce noise within a particular environment. Sound reaching the ear consists of two components: (1) sound transmitted directly from the source (direct sound); and (2) sound reflected from all the room's surfaces (reverberant sound). The level of direct sound depends only on distance from the source and is reduced by 6 dB for each doubling of distance from the source (i.e. the inverse square law). In contrast, reverberant sound depends on the room shape, size and absorption, and does not depend on distance from the source.

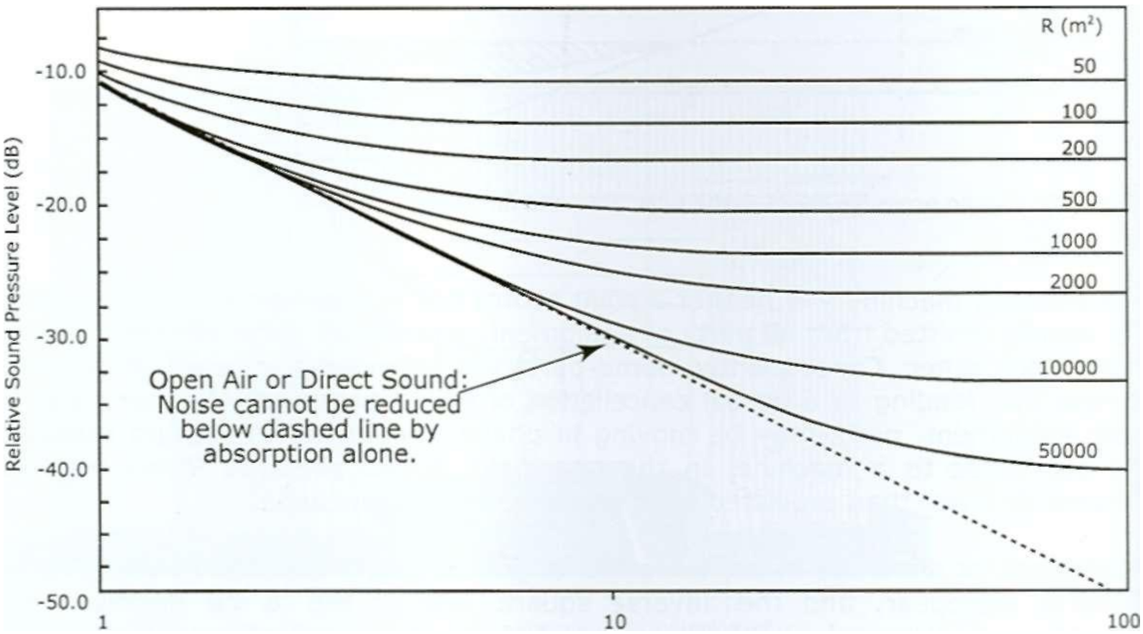


Fig. 24: Relative sound pressure level in a room as a function of room constant and source-receiver distance.

The unit for sound absorption in a room is the room constant R, in m^2.

The relative sound pressure level in a room can also be calculated using the Eyring theory, which for a point source is calculated as:

$$L_{Pr} = (L_{Pr})_1 - (L_{Pr})_2 = 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) \quad (1)$$

where L_{Pr} is the relative sound pressure level (dB); Q is the directivity factor (taken to be 1); r is the source-receiver distance; and R is the room constant (m^2).

From Fig. 24, we see that close to the source the sound pressure level is determined primarily by distance, whereas far from the source it is strongly influenced by the amount of absorption. Thus increasing the room acoustic absorption is not effective in reducing the sound level close to the source.

In practice, the room constant can be difficult to calculate or requires some relatively sophisticated equipment to measure. For a rough estimation of the room constant, determine the fraction of the total room surface area covered with absorption material (i.e. carpeting, drapes, acoustic ceiling tiles, absorbent wall panels etc.). From this, Table 1 can then be used to estimate the acoustic characteristic of the room.

Table 1: Estimation of room acoustic characteristic

Fraction of total room surface area covered with absorption material	Room acoustic characteristic
0	"Live"
0.1	"Medium-Live"
0.15 - 0.2	"Average"
0.3 - 0.35	"Medium-Dead"
0.5 - 0.6	"Dead"

In order to estimate the room constant, use the room acoustic characteristic and room volume (Fig. 25).

Example 1: A computer room measures 50 ft by 50 ft with a 10 ft ceiling height. The ceiling is made up of acoustic tile while some absorptive panels on the walls has an "average" room constant (R = 80 m^2). Installation of heavy carpeting was suggested to reduce the noise from a supplemental HVAC unit located about 15 ft (4.5 m) from the work stations of several employees. Estimate the reduction in noise which would be achieved.

Answer:
Floor area = 50 ft x 50 ft = 2,500 ft^2
Total room surface area = 2 x 50 ft x 50 ft + 4 x 50 ft x 10 ft = 7,000 ft^2
Increase in fraction of covered surface area = 2,500/7,000 = 0.36

Thus, heavy carpeting on the floor would increase the fraction of the room surface area covered by 0.36 — thereby changing the room reverberation characteristic from "average" to "dead" and increasing the room constant R to 300 (see Fig. 25). Using Eq. 1 or Fig. 24, the relative sound pressure level change is estimated to be 5 dB.

Note that the answer obtained to the above example problem is an extremely crude estimate, and it relies on a number of simplifying assumptions. A more accurate estimation may be made by measuring octave band sound pressure levels from the source and calculating the change in room constant at each octave band level from the absorption coefficients. In particular, for this example, the noise from the HVAC unit is likely to be predominantly in the low frequencies, where carpeting is not particularly absorbent. Most machinery is used inside buildings, and even outdoor equipment is seldom suspended above the ground. Consequently, in actual practice, free-field conditions seldom exist.

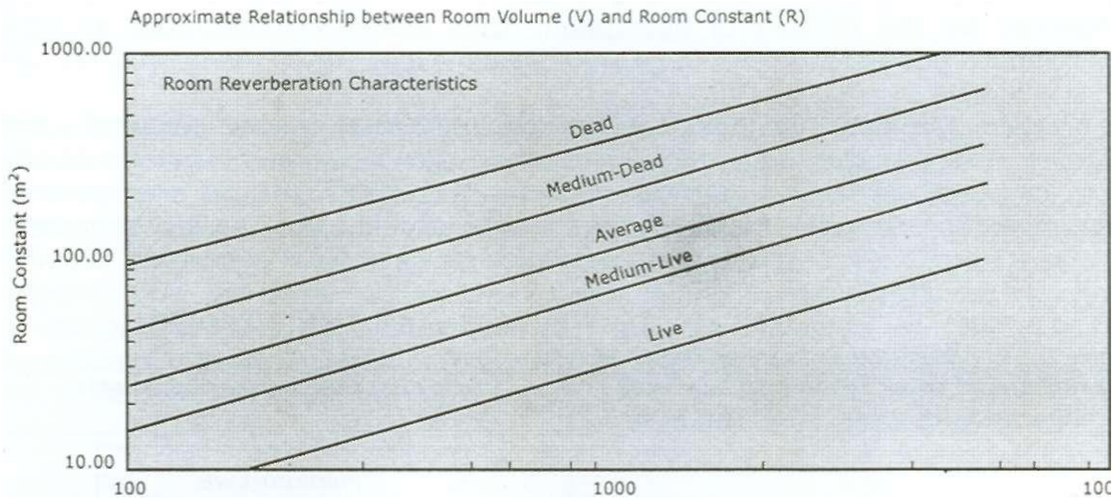


Fig. 25: Approximate relationship between room constant and room volume for a space with varying acoustic characteristics.

9.2. Sound Absorption Coefficients

Machines that contain cams, gears, reciprocating components, and metal stops are often located in large, acoustically reverberant areas that reflect and build up noise levels in the room. Frequently, the noise levels in adjoining areas can be reduced significantly by using sound-absorbing material on walls and ceilings. However, the amount of reduction close to the machines may be slight because most of the noise exposure energy is coming directly from the machines and not from the reflecting surfaces. The type, amount, configuration and placement of absorption material depends on the specific application — however, the choice of absorption material can be guided by the absorption coefficients listed in Table 2. An absorption coefficient of 1.0 means the material will absorb all sound impinging randomly on the surface; an absorption coefficient close to 0 means the material will absorb very little acoustic energy.

Table 2: Sound Absorption Coefficients of Surface Materials

Material	Frequency (Hz)					
	125	**250**	**500**	**1,000**	**2,000**	**4,000**
Brick: Glazed	0.01	0.01	0.01	0.01	0.02	0.02
Unglazed	0.03	0.03	0.03	0.04	0.05	0.06
Unglazed, painted	0.01	0.01	0.02	0.02	0.02	0.03
Carpet: Heavy (on concrete)	0.02	0.06	0.14	0.37	0.60	0.65
On 40 oz. hairfelt or foam rubber (carpet has coarse backing)	0.08	0.24	0.57	0.69	0.71	0.73
With impermeable latex backing on 40 oz. hairfelt or foam rubber	0.08	0.27	0.39	0.34	0.48	0.63
Concrete block: Coarse	0.36	0.44	0.31	0.29	0.39	0.25
Painted	0.10	0.05	0.06	0.07	0.09	0.08
Poured	0.01	0.01	0.02	0.02	0.02	0.03
Fabrics: Light velour: 10 oz/yard^2, hung straight, in contact with wall	0.03	0.04	0.11	0.17	0.24	0.35
Medium velour: 14 oz/yard^2 draped to half-area	0.07	0.31	0.49	0.75	0.70	0.60
Heavy velour: 18 oz/yard^2 draped to half-area	0.14	0.35	0.55	0.72	0.70	0.65
Floors: Concrete or terrazo	0.01	0.01	0.015	0.02	0.02	0.02
Linoleum, asphalt, rubber, or cork tile on concrete	0.02	0.03	0.03	0.03	0.03	0.02
Wood	0.15	0.11	0.10	0.07	0.06	0.07
Wood parquet in asphalt on concrete	0.04	0.04	0.07	0.06	0.06	0.07
Glass: Ordinary window glass	0.35	0.25	0.18	0.12	0.07	0.04
Large panes of heavy plate glass	0.18	0.06	0.04	0.03	0.02	0.02
Glass fibre: Mounted with impervious backing, 3 lb/ft^3, 1 in. thick	0.14	0.55	0.67	0.97	0.90	0.85
Mounted with impervious backing, 3 lb/ft^3, 2 in. thick	0.39	0.78	0.94	0.96	0.85	0.84
Mounted with impervious backing, 3 lb/ft^3, 3 in. thick	0.43	0.91	0.99	0.98	0.95	0.93
Gypsum board: 1/2 in. thick nailed to 2" x 4" s, 16" on centre	0.29	0.10	0.05	0.04	0.07	0.09
Marble	0.01	0.01	0.01	0.01	0.02	0.02
Plaster: Gypsum or lime, smooth finish on tile or brick	0.013	0.015	0.02	0.03	0.04	0.05
Gypsum or lime, rough finish on lath	0.14	0.10	0.06	0.05	0.04	0.05
Gypsum or lime, with smooth finish	0.14	0.10	0.06	0.04	0.04	0.03
Plywood paneling, 3/8 in. thick	0.28	0.22	0.17	0.09	0.10	0.11
Sand: Dry, 4 in. thick	0.15	0.35	0.4	0.5	0.55	0.8
Sand: Dry, 12 in. thick	0.2	0.3	0.4	0.5	0.6	0.75
Sand: Wet, 14 lb. H_20/ft^3, 4 in thick	0.05	0.05	0.05	0.05	0.05	0.15
Water	0.01	0.01	0.01	0.01	0.02	0.02
Air, per 10m^3 at 50% RH (for larger spaces, air attenuates sound — particularly the higher frequencies)				0.32	0.81	2.56

9.3. Noise Barriers and Enclosures

The amount of noise reduction that can be attained with barriers depends on the characteristics of the noise source, the configuration and materials used for the barrier, and the acoustic environment on each side of the barrier. It is necessary to consider all these complex factors to determine the overall benefit of a barrier.

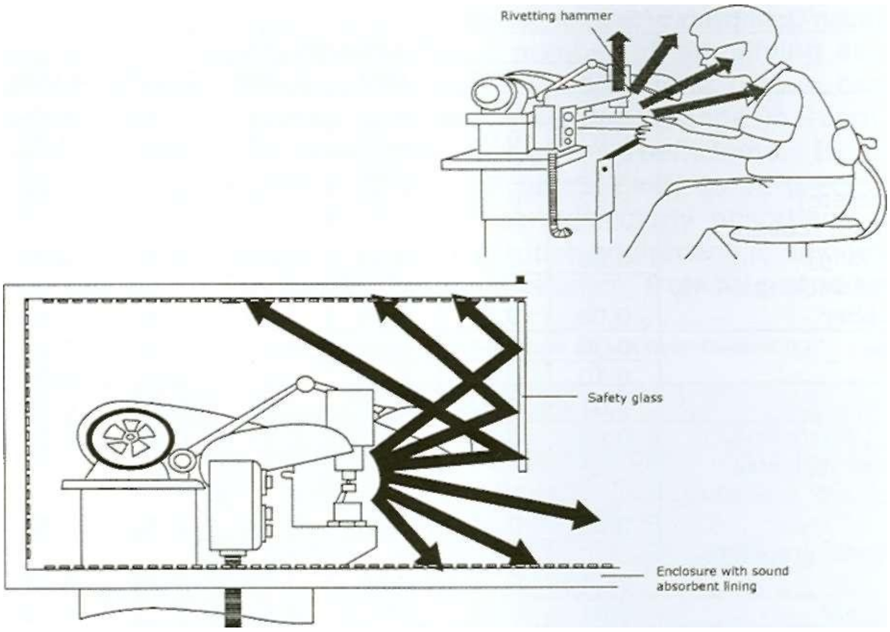


Fig. 26: Reducing high frequency noise with a barrier and partial enclosure lined with absorbent material.

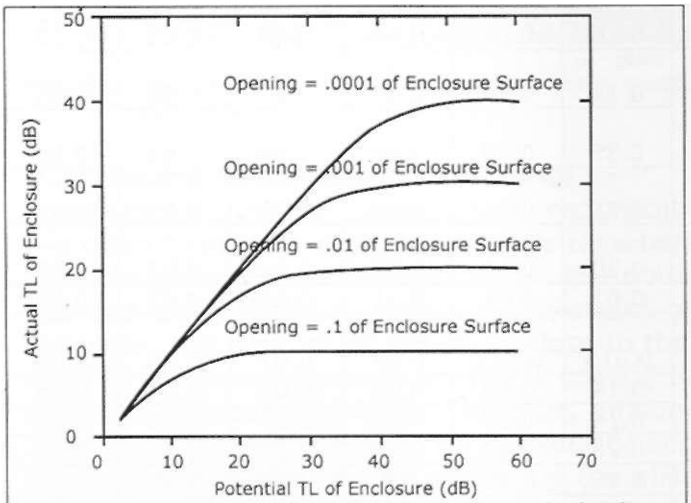


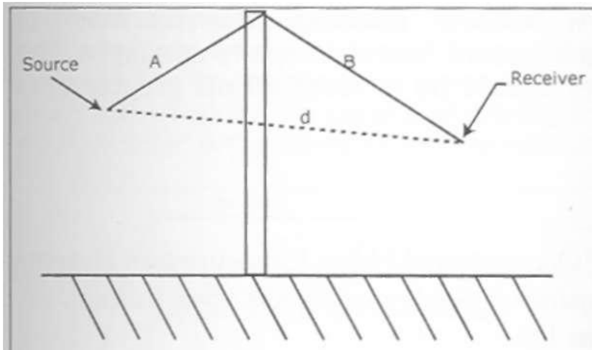
Fig. 27: Reduction in transmission loss (TL) if an enclosure has openings.

The noise reduction levels resulting from barriers or enclosures vary significantly. Single-wall barriers with no openings may provide as little as 2 - 5 dB reduction in the low frequencies and a 10 - 15 dB reduction in the high frequencies. Higher noise reduction levels are possible using heavier barriers with greater surface areas. Higher noise reduction levels may also be expected when the source and/or the persons exposed are close to the barrier. The effects of 2- or 3-sided barriers are difficult to predict on a general basis. However, well-designed partial enclosures may provide noise reduction levels of more than twice as much as single-wall barriers. Complete enclosures from simple practical designs may provide noise reduction levels in excess of 10 - 15 dB in the low frequencies and more than 30 dB in the high frequencies.

Partial enclosures (Figs. 26 and 27) must be lined with absorptive material to obtain maximum effectiveness. If the workers are not in the direct line of the opening, a shadow effect of 3 - 15 dB for high frequency sounds may be achievable. This shadow effect is limited to high frequency sounds where the dimensions of the enclosure are of the order of several times the wavelength of the noise.

9.3.1. Noise reduction obtained from use of noise barrier

If a sound source is in a room with a large amount of absorption (i.e. few reflections present), blocking the direct path with a partial barrier may provide adequate noise control. Indeed, this technique is more often used outdoors, since even a modest amount of reverberation will destroy the effectiveness of a shield. Based on theoretical considerations, the decrease in sound pressure level L_p in the shadow of a barrier is as given in Fig. 28, where N is a geometric factor; A + B is the shortest distance over the barrier between source and receiver; d is the linear (straight-line) distance between source and receiver; A is the wavelength of sound; and L_p is the decrease in sound pressure level.



$$\lambda\ (m) = \frac{344}{f\ (Hz)}$$

$$N = \frac{2}{\lambda}(A + B - d)$$

$$\Delta L_{Pr} = 20 \log_{10} \left[\frac{(2\pi N)^{1/2}}{\tanh\ (2\pi N)^{1/2}}\right] + 5$$

Fig. 28: Geometrical considerations for noise reduction, ΔL_{Pr}, by use of barriers.

Example 2: What is the expected further reduction in sound pressure levels at typical speech frequencies (500, 1,000 and 2,000 Hz) which would be obtained by increasing the height of a barrier between 2 telephone reservation agents from 4 ft. (1.22 m) to 5 ft. (1.52 m)?

Answer:

Distance between source and receiver of seated telephone agents is taken to be 1.05 m. Assume agents are seated 1.2 m apart. Therefore, d = 1.2 m, and for a 4 ft (1.22 m) barrier:

$A = B = [(0.6)^2 + (1.22 - 1.05)^2]^{1/2} = 0.624$ m

Similarly, for a 5 ft (1.52 m) barrier, A = B = 0.762 m

Using the above formulae or graphs, the results tabulated below are obtained:

Frequency (Hz)	S	N (@4 ft)	N (@5 ft)	ΔL_{Pr} (4 ft)	ΔL_{Pr} (5 ft)	Difference (dB)
500	0.7	0.1	1.0	7.0	12.9	5.9
1,000	0.3	0.3	1.9	8.6	15.8	7.2
2,000	0.2	0.5	3.8	10.7	18.8	8.1

Thus, under ideal conditions, the sound from the adjacent reservation agent could be reduced by approximately 6 - 8 dB further by increasing the barrier height from 4 ft. to 5 ft. In practice, there will be reflections from nearby surfaces (in particular from the ceiling and the floor), and end effects from the barrier will be important.

9.3.2. Recommendations for use of indoor barriers

(1) The barrier should be as close to the source or receiver as possible. However, the source should not touch the barrier to prevent transferring vibration.

(2) The barrier should extend beyond the line of sight of the source plus 1/4 wavelength of the lowest frequency sound of interest for attenuating the noise.

(3) Select a solid material without any holes or openings. Barriers made of material with more than 4 pounds per square foot are usually adequate. The transmission loss (TL) of the barrier should be at least 10 dB greater than the required attenuation.

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APPENDIX 1

INTRODUCTION TO SOUND

1. GENERAL

Technically, the sensation of sound results from oscillations in pressure, stress, particle displacement, and particle velocity in any elastic medium that connects the sound source with the ear. When sound is transmitted through air, it is usually described in terms of changes in pressure that alternate above and below atmospheric pressure. These pressure changes are produced when a vibrating object (i.e. sound source) causes alternating regions of high pressure (compression) and low pressure (rarefaction) that propagate from the sound source. The sound characteristics of a particular sound depend on the rate at which the sound source vibrates, the amplitude of the vibration, and the characteristics of the conducting medium. A sound may have a single rate of compression-rarefaction alternation (i.e. its frequency), but most sounds have many frequency components. Each of these frequency components, or bands of sound, may have a different amplitude.

2. FREQUENCY OF SOUND

Frequency is defined as the rate at which the waves of a sound are emitted from its source. Physically, it is measured by the number of times per second the pressure oscillates between levels above and below atmospheric pressure (Fig. 1). Frequency is denoted by the symbol f and is measured in Hz (Hertz), where 1 Hz = 1 cycle/second. Frequency is inversely related to the period (T), which is the time (in second) a sound wave requires to complete one cycle. The range of sound frequency over which normal young human adults are capable of hearing sound at moderate levels is 20 - 20,000 Hz. 'Pitch' or 'tone' is the sensation closely associated with frequency.

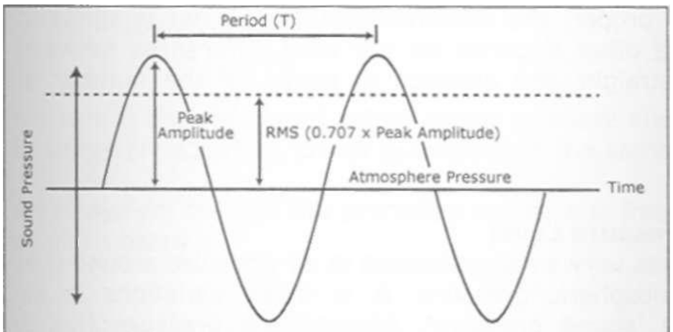


Fig. 1: Amplitude and frequency of a pure tone sound wave.

A sound may consist of a single frequency (i.e. a pure tone); however, most common sounds comprise many frequency components. It is generally infeasible to report the characteristics of all the frequencies emitted by noise sources; so measurements are made that include the sound energy from a broad range of frequencies.

Frequency weighting networks have been standardised for single-number assessments of sounds having properties similar to the response of the human ear. In addition to these broad-band weightings, the frequency range in acoustics is frequently divided into smaller ranges. The most common range of frequencies is the octave band, where the upper edge of the band is twice the frequency of the lower edge. One-third octave bands (i.e. where 3 bands are used to measure 1 octave) and narrower bands are also used.

3. WAVELENGTH OF SOUND

The distance a sound wave travels during one sound pressure cycle is called the wave-length (λ). The wavelength is related to the speed of sound (c) and its frequency (f) by:

$$\lambda = \frac{c}{f} \qquad (1)$$

where λ is the wavelength in metres (m), c is the sound speed in metres per second (m/s) and f is the frequency in Hertz (Hz).

For most applications in noise control for hearing conservation, it is sufficient to note that sound travels in air at approximately 344 m/s at normal atmospheric pressures and room temperatures.

Example 1

Calculate the wavelengths of sound waves of frequencies 20, 1,000 and 20,000 Hz.

$$@\ 20\ \text{Hz},\ \lambda = \frac{c}{f} = \frac{344\ \text{m/s}}{20/\text{s}} = 17.2\ \text{m}$$

$$@\ 1{,}0000\ \text{Hz},\ \lambda = \frac{c}{f} = \frac{344\ \text{m/s}}{1{,}000/\text{s}} = 0.344\ \text{m}$$

$$@\ 20{,}0000\ \text{Hz},\ \lambda = \frac{c}{f} = \frac{344\ \text{m/s}}{20{,}000/\text{s}} = 0.017\ \text{m}$$

When considering the behaviour of sound, one important characteristic is the ratio of the length of the item affected by the noise to the wavelength of the sound. For instance, a given sound will not efficiently couple to vibrations of the entire eardrum when its 1/4 wavelength is less than the dimensions of the eardrum. It is not surprising, therefore, that a sound of frequency greater than 20,000 Hz cannot be heard, since its % wavelength (i.e. 4.25 mm) is less than the 5 mm-diameter dimension of a typical human eardrum. As shown in the guidelines proper, the effectiveness of a barrier in shielding one side from a noise source on the other depends on the path differences between going around the barrier and the straight line distance in terms of the number of wavelengths.

4. AMPLITUDE OF SOUND

4.1. Sound Pressure and Sound Pressure Level

When a sound source vibrates, it causes very small variations in air pressure around (i.e. above and below) the ambient atmospheric pressure. It is these variations in air pressure that is referred to as the 'sound pressure'. Atmospheric pressure (i.e. 1 atmosphere) = 1.013 x 10^5 pascals (Pa) or 1.013 x 10^5 N/m^2. In direct comparison, the magnitude of sound pressure relative to air pressure is very small indeed — so small as to be practically negligible. For instance, the sound pressure resulting from normal speech at 1 metre distance from a talker would average about 0.1 Pa, i.e. 1 millionth of an atmosphere.

The range of sound pressures relevant to the human ear, and therefore commonly measured, is very wide. Sound pressures well above the ear pain threshold, i.e. about 20 Pa, can be found in some working environments, while sound pressures down to the threshold of hearing, i.e. about 20 μPa (micropascals) are used for hearing measurements. The range of common sound pressure exposures therefore exceeds 10^6 Pa. This range cannot be scaled linearly with a practical instrument while maintaining the desired accuracy at the low and high ends, because for it to be able to show "just noticeable differences" in hearing at sound pressures in noisy environments would require a scale many miles long! Therefore, in order to accommodate this wide range of sound pressure switl? a reasonable number of scale divisions and to provide a scale that responds more closely to the response of the human ear, the logarithmic decibel (dB) scale is used. The abbreviation dB is used with upper and lower case — "d" for deci, and "B" for Bell — in honour of Alexander Graham Bell. This measurement unit was first conceived at Bell Laboratories (USA) to facilitate calculations involving loss of signals in long lengths of telephone lines.

By definition, the decibel is a unit without dimensions; it is the logarithm to the base 10 of **the ratio of a measured quantity to a reference quantity when the quantities are proportional to power.** The decibel is sometimes difficult to use and to understand because it is often used with different reference quantities. Acoustic intensity, acoustic power, hearing thresholds, electrical voltage, electrical current, electrical power, and sound pressure level may all be expressed in decibels, each having a different reference. Obviously the decibel has no meaning unless a specific reference quantity is specified, or understood. Any time the term **'level'** is referred to in acoustics, decibel notation is implied.

Most sound-measuring instruments are calibrated to provide a reading (called root mean square or RMS) of sound pressures on a logarithmic scale in decibels. The decibel reading taken from such an instrument is called the sound pressure level (Lp_r). The term **'level'** is used because the measured pressure is at a particular level above a given pressure reference. For sound measurements in air, 0.00002 N/m^2 (1 N/m^2 = 1 Pa), commonly serves as the reference sound pressure. This reference is an arbitrary pressure chosen many years ago because it is approximately the normal threshold of young human hearing at 1,000 Hz. Since the eardrum responds proportionally to the intensity (i.e. energy per unit time per unit area) of the sound wave, and since sound intensity is proportional to sound pressure squared, sound pressure level is calculated from the square of sound pressure. Mathematically, sound pressure level, L_{Pr}, is written as follows:

$$L_{Pr} = 10 \log_{10} \left(\frac{p}{p_R} \right)^2 \qquad (2)$$

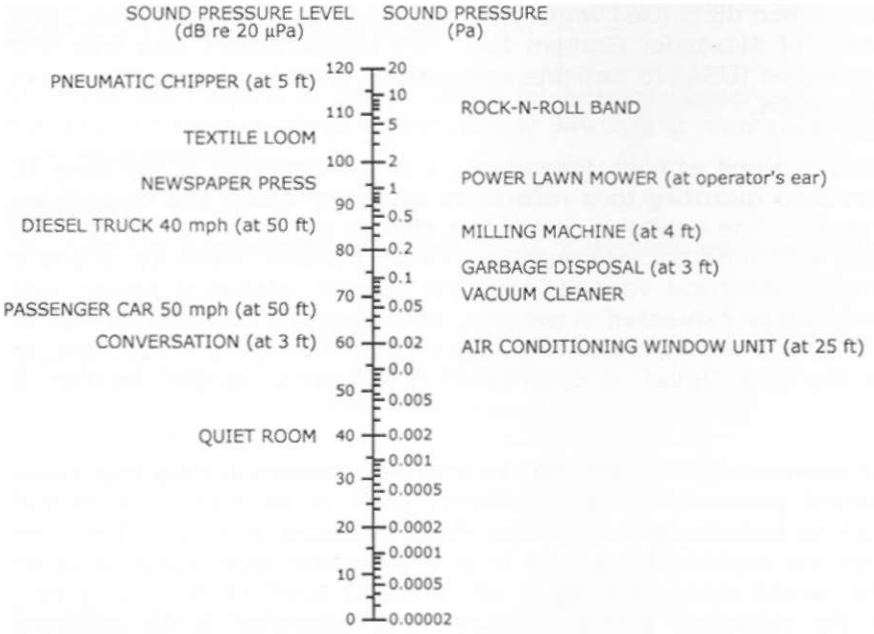
where p is the measured actual sound pressure and p_R is the reference sound pressure. In using this equation, p and p_R must be in the same units.

An equivalent form of the preceding equation is frequently found in acoustics text books, as given below:

$$L_{Pr} = 20 \log_{10} \left(\frac{p}{p_R} \right) \qquad (3)$$

Specifying sound pressure levels in this form tends to mask the fact that levels are ratios of quantities equivalent to power. For technical purposes, Lp_r should always be written in terms of decibels relative to the recommended reference sound pressure of 0.00002 N/m^2 (i.e. 20 μPa). Reference quantities for acoustic levels are specified in ANSI SI.8. The reference quantity should be stated at least once in every document.

Fig. 2 shows the relationship between sound pressure (in pascals) and sound pressure level (in dB re 0.00002 N/m^2). This diagram illustrates the advantage of using the decibel scale rather than the wide range of direct pressure measurements. It is of interest to note that any doubling of a sound pressure is equivalent to a 6-dB change in sound pressure level. For example, a range of 20 to 40 μPa, which might be found in hearing measurements, or a range of 1 to 2 Pa, which might be found in hearing conservation programmes, are both ranges of 6 dB. Measuring in decibels allows reasonable accuracy for both low and high sound pressure levels.



0.0002

fc-0.0001

1 0 ~- 0.0005

0 --0.00002

Fig. 2: Relation between A-weighted sound pressure levei and actual sound pressure.

4.2. Sound Intensity and Sound Intensity Level

Sound intensity at any specified location may be defined as the average acoustic energy per unit time passing through a unit area that is normal to the direction of propagation. For a spherical or free-progressive sound wave, the sound intensity may be expressed by:

$$I = \frac{p^2}{\rho c}$$

where p is the RMS sound pressure, p is the density of the medium, and c is the speed of sound in the medium. Sound intensity units, like sound pressure units, cover a wide range, and it is often desirable to use decibel levels to compress the measuring scale. To be consistent, sound intensity level, L_{Int}, is defined as

$$L_{Int} = 10 \log_{10} \left(\frac{I}{I_R} \right) \qquad (5)$$

where I is the measured actual sound intensity at some given distance from the source and I_R is a reference sound intensity, 10^{-12} Watt/m^2. In air, this reference sound intensity closely corresponds to the reference sound pressure of 0.00002 N/m^2 (i.e. 20 µPa) used for sound pressure levels.

Combining Eqs. 4 and 5 gives

$$L_{Int} = L_{Pr} \qquad (6)$$

4.3. Sound Power and Sound Power Level

Consider a vibrating object suspended in the air (Fig .3). The vibrations will create sound pressure waves that travel away from the source — decreasing by 6 dB as the distance from the source doubles. The sound power of this source is independent of its environment, but the sound pressure around the source is not.

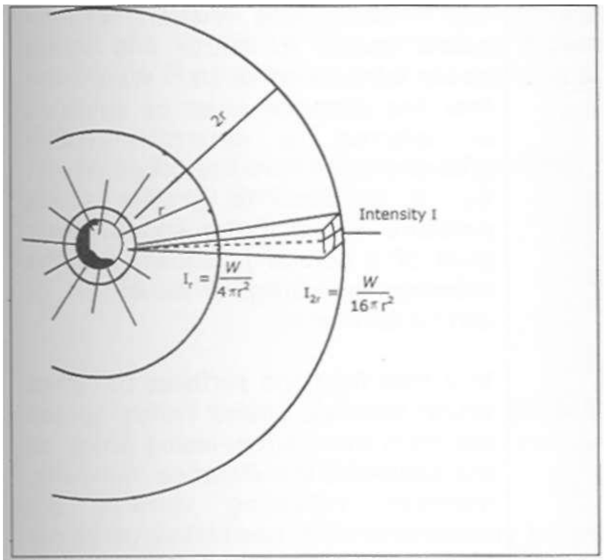


Fig. 3: Pulsating object suspended in air (i.e. free-field)

Sound power (represented by *Q)* is used to describe the sound source in terms of the amount of acoustic energy that is produced per unit time (Watts). Sound power is related to the average sound intensity produced in free-field conditions at a distance r from a point source by:

$$Q = I_{avg} 4 \pi r^2 \qquad (7)$$

where I_{avg} is the average sound intensity at a distance r from a sound source whose sound power is W. The quantity $4\pi r^2$ is the area of a sphere surrounding the source over which the sound intensity is averaged. The sound intensity decreases with the square of the distance from the source, hence the well-known inverse square law.

Units for sound power are also usually given in terms of decibel levels because of the wide range of powers covered in practical applications. For consistency, sound power level, L_{Pow}/ is defined as

$$L_{Pow} = 10 \log_{10} \left(\frac{Q}{Q_R} \right) \qquad (8)$$

Choosing a reference surface area S_R of 1 m^2 derives a convenient expression for sound power level, L_{Pow}/ as follows:

$$\frac{Q}{Q_R} = \frac{I_{avg} 4 \pi r^2}{I_R S_R} = \frac{I_{avg}}{I_R} \; \frac{4 \pi r^2}{S_R}$$

$$10 \log \left(\frac{Q}{Q_R} \right) = 10 \log \left(\frac{I_{avg}}{I_R} \right) + 10 \log \left(\frac{4 \pi r^2}{S_R} \right)$$

$$L_{Pow} = L_{Int} + 10 \log \left(\frac{4 \pi r^2}{S_R} \right), \text{ and since } L_{Int} = L_{Pr} \text{ (i.e. from Eq. 6):}$$

$$L_{Pow} = L_{Pr} + 10 \log \left(\frac{4 \pi r^2}{S_R} \right) \qquad (9)$$

where Q is the sound power of the source in Watts (1 Watt = 1 N m/sec) and Q_R is the reference sound power (10^{-12} Watt, from $Q_R = I_R S_R$).

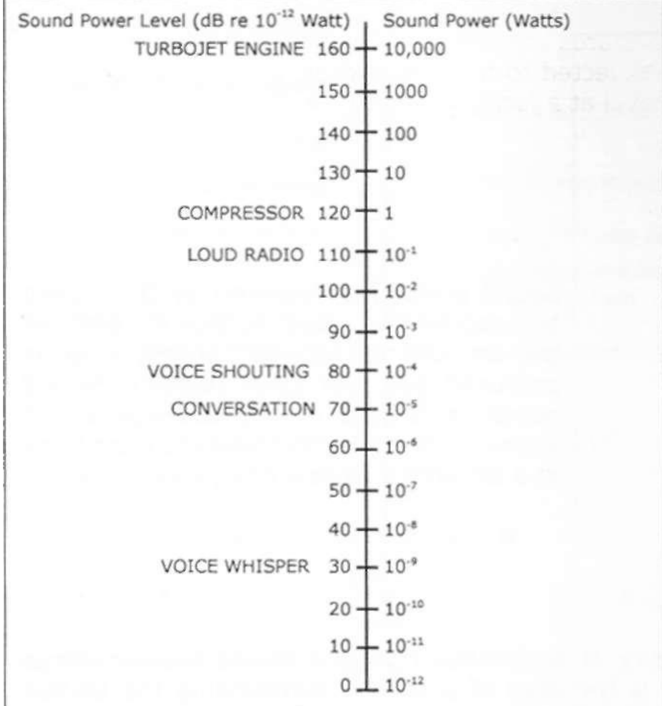
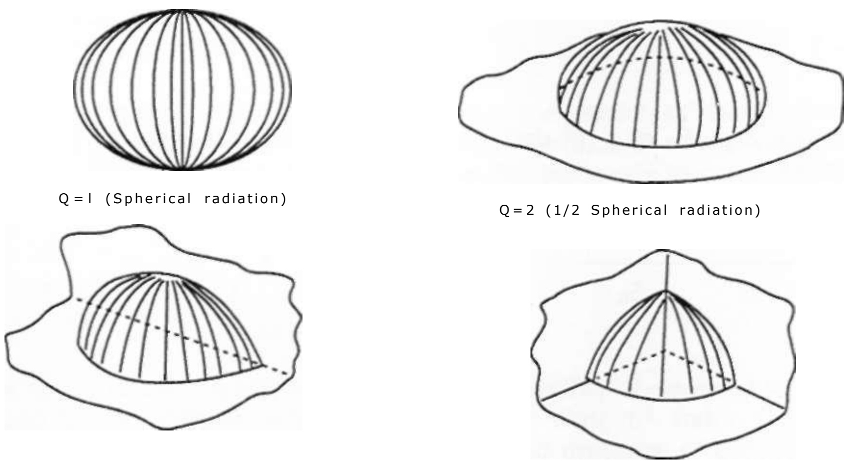


Fig. 4: Relation between sound power level and sound power.

Fig. 4 shows the relation between sound power in Watts and sound power level in dB re 10^{-12} Watt. Note that the distance must be specified or inferred to determine sound pressure level from the sound power. Eq. 9 is used to predict sound pressure levels if the sound power level of a source is known and the acoustic environment is known or can be estimated.

In a free field (no surfaces to reflect sound waves), sound waves spread out from the source, losing power as the square of the distance. Normally, however, reflecting surfaces are present or the sound source is not omnidirectional. A reflecting surface will increase the sound intensity since the volume in which the sound radiates is reduced.

The **directivity factor** (Q) is a dimensionless quantity used to describe the ratio of volume to which a sound is emitted relative to the volume of a sphere with the same radius (Fig. 5).



Q=I (Spherical radiation)

Q=2 (1/2 Spherical radiation)

Q=4 (Radiation from floor and wall)

Q=8 (Radiation into 1/8 sphere)

Fig. 5: Directivity factor (Q).

4.4. The Relationship between Sound Power, Sound Intensity and Sound Pressure

The resolution of noise control problems requires a practical knowledge of the relationship between sound pressure, sound intensity, and sound power. For example, consider the prediction of sound pressure levels that would be produced around a proposed machine location from the sound power level provided by the machine.

Example 2
The manufacturer of a certain machine states that this machine has an acoustic power output of 1 W (Watt). The machine is expected to be mounted on the floor of a factory workroom. Predict the sound pressure level at a location 10 m from the machine.

Answer
For an omnidirectional source in a free field, putting $I = I_{avg}$ and combining Eqs. 4 and 7 gives the sound pressure as:

$$p = (I_{avg}\, \rho\, c)^{1/2} = \left(\frac{Q\, \rho\, c}{4\pi r^2}\right)^{1/2}$$

$$p = \left[\frac{(1 \text{ N m/s}) \times (1.18 \text{ kg/m}^3) \times 344 \text{ m/s}}{4\pi \times (10 \text{ m})^2}\right]^{1/2} = 0.32 \text{ N/m}^2$$

However, since the source will actually be sitting on the floor, reflections will double the sound pressure, giving an actual sound pressure of 0.64 N/m^2. The estimated sound pressure level, using Eq. 2, will thus be

$$L_{Pr} = 10 \log_{10} \left(\frac{0.64}{0.00002}\right)^2 = 90 \text{ dB (re } 2 \times 10^{-5} \text{ N/m}^2)$$

Admittedly, there are few truly free-field situations, and few omnidirectional sources; so the above calculation can only give a rough estimate of the absolute value of the sound pressure level. However, comparison or rank ordering of different machines can be made, and at least a rough estimate of the sound pressure level is available. Noise levels in locations that are reverberant, or where there are many reflecting surfaces, can be expected to be higher than that predicted because noise is reflected back to the point of measurement.

Table 1: Common dB 'levels' in sound measurement, their definitions and the relevant reference quantities.

Level (dB)	Definition	Relevant Reference Quantity	
		SI Units	Imperial Units
Sound Pressure Level, L_{Pr}	$L_{Pr} = 20 \log_{10}(p/p_R)$	$p_R = 2 \times 10^{-5}$ N/m²	$p_R = 2.9 \times 10^{-9}$ lb/in²
Sound Power Level, L_{Pow}	$L_{Pow} = 10 \log_{10}(Q/Q_R)$	$Q_R = 10^{-12}$ Watt	$Q_R = 5 \times 10^{-10}$ lb in/s
Sound Intensity Level, L_{Int}	$L_{Int} = 10 \log_{10}(I/I_R)$	$I_R = 10^{-12}$ Watt/m²	$I_R = 5.71 \times 10^{-15}$ lb/in s
Sound Exposure Level, L_{Exp}	$L_{Exp} = 10 \log_{10}(E/E_R)$	$E_R = (2 \times 10^{-5}\ N/m^2)^2$ s	$E_R = 1 \times 10^{-18}\ lb^2/in^4$ s

REFERENCES

(1) Lichtenwalner, C. P. & Michael, K., "Occupational Noise Exposure and Hearing Conservation", in *Handbook of Occupational Safety and Health,* 2nd Edition, ed. DiBerardinis, L. J., John Wiley & Sons Inc.

APPENDIX 2

ENGINEERING-BASED NOISE CONTROL - OVERVIEW AND GENERAL MEASURES

1. NEW EQUIPMENT AND WORKPLACES

(1) The purchase of new equipment, the design of the area in which it is to be installed and the design of new workplaces, generally, provide opportunities for cost-effective noise control measures.

(2) Invitations to tender for the supply of new equipment should specify a maximum acceptable level of noise emission. If equipment is to be purchased directly, without tender, noise emission data should be obtained from suppliers to enable the equipment with the lowest practicable noise level to be selected.

(3) New workplaces, and installation sites for new equipment in existing workplaces, should be designed and constructed to ensure that exposure to noise is as low as practicable.

(4) If new equipment is likely to expose people in the workplace to excessive noise, design features should incorporate effective engineering noise control measures to reduce noise to as low a level as practicable.

(5) Where equipment is to be designed for a particular workplace, designers should:

(a) obtain agreement with the client on goals for noise, be aware of the noise control policy for that workplace and establish a budget that will allow for effective noise controls at the design stage;

(b) consider the effect on overall noise levels of building reverberation, the building layout and the location of workstations relative to equipment;

(c) consider the transmission of noise through structures and ducts;

(d) design for acoustical equipment rooms and control rooms where appropriate; and

(e) design acoustic treatments for external environmental control in a way that will reduce internal noise and vice versa.

2. EXISTING EQUIPMENT AND WORKPLACES

(1) Once a noise assessment has been carried out and the necessity to reduce the noise exposure of employees is established, the task of controlling the noise can be addressed. Priority should be given to those noise sources that contribute to the highest noise exposures affecting the largest number of people. Noise exposure levels should be reduced to, or below, the Permissible Exposure Limits specified in the Factories and Machinery (Noise Exposure) Regulations 1989 wherever the Permissible Exposure Limits are exceeded. Even if the Permissible Exposure Limits cannot be met, any practicable reduction in noise levels should be carried out. Further reductions in noise levels should be carried out wherever practicable. The need for noise control should be taken into account when deciding on production methods or processes. There are two basic engineering noise control measures for controlling noise levels:

- engineering treatment of the noise source; and
- engineering treatment of the noise transmission path (including enclosure of the operator).

3. ENGINEERING TREATMENT OF THE SOURCE

(1) Engineering treatment of the source is the preferred method of permanently removing the problem of noise exposure due to machinery or processes at the workplace. Since all noise-emitting objects generate airborne energy (noise) and structure-borne energy (vibration), the treatment of these noise problems may require modification, partial redesign or replacement of the noise-emitting object. Subjective inspection or acoustical measurement of the device can identify how and where the noise is generated. Some problems can be solved by relatively inexpensive and simple procedures, although some are difficult. The advice from specialists may be beneficial in providing best results. These guidelines include references to some of the simpler methods of noise control that might be achieved.

(2) When seeking a solution to a noise problem, an understanding of the operation of the machine or process is necessary in considering the possible treatment of the noise at source. Engineering noise control measures can be specifically targeted at the machine and its parts, or towards the actual processes, including material handling systems.

(3) General noise control solutions, and examples of particular engineering noise control measures which can be carried out on machines, are provided below:

(a) Eliminate or replace the machine or its operation by a quieter operation with equal or better efficiency, for example, by replacing rivets with welds.

(b) Replace the noisy machinery by installing newer equipment designed for operating at lower noise levels. Machinery power sources and transmissions can be designed to give quiet speed regulation, for example, by using stepless electric motors. Vibration sources can be isolated and treated within the machine. Cover panels and inspection hatches on machines should be stiff and well damped. Cooling fins can be designed to reduce the need for forced airflow and hence fan noise.

(c) Correct the specific noise source by minor design changes. For example, avoid metal-to-metal contact by the use of plastic bumpers, or replace noisy drives with quieter types or use improved gears.

(d) A high standard of equipment maintenance should be provided to facilitate compliance with the Factories and Machinery (Noise Exposure) Regulations 1989 and, going a step further, reduce noise levels to as low as practicable. Badly worn bearings and gears, poor lubrication, loose parts, slapping belts, unbalanced rotating parts and steam or air leaks all create noise which can be reduced by good maintenance. Equipment resulting in excessive noise levels should be repaired immediately.

(e) Correct the specific machine elements causing the noise by a local source approach, rather than by consideration of the entire machine as a noise source. For example, adding noise barriers, noise enclosures, vibration-isolation mountings, lagging to dampen vibrating surfaces, mufflers or silencers for air and gas flows, or reducing air velocity of free jets. These may be considered as a solution for the individual noise-producing elements of the total operation.

(f) Separate the noisy elements that need not be an integral part of the basic machine. For example, move pumps, fans and air compressors that service the basic machine.

(g) Isolate the vibrating machine parts to reduce noise from vibrating panels or guards.

(4) In addition to engineering changes to machinery and parts, processes can be modified to reduce noise. Specific means of modification include the use of processes that are inherently quieter than the alternatives, for example, mechanical pressing rather than drop forging. Metal-to-metal impact should be avoided or reduced, where possible, and vibration of the surfaces of the machine or the material being processed should be suppressed. This can be achieved, for example, by the choice of suitable materials, by adequate stiffness and damping or by careful dynamic balancing where high speed rotation is used.

(5) Material handling processes, in particular, can also be modified to ensure that impact and shock during handling and transport are minimised as far as possible. This may be achieved by:

(a) minimising the fall height onto hard surfaces of items collected by tables and containers;

(b) fixing damping materials to, or stiffening, tables, walls, panels or containers where they are struck by materials or items during processing;

(c) absorbing shocks through the provision of wear resistant rubber or plastic coatings;

(d) using conveyer belts rather than rollers, which are more likely to rattle; and

(e) controlling the speed of processes to match the desired production rates, thereby obtaining a much smoother work flow and less likelihood of noise generation due to stop-start impact noise.

4. ENGINEERING TREATMENT OF THE NOISE TRANSMISSION PATH

(1) If it is not possible to change or modify the noise-generating equipment or processes by engineering treatment of the source, engineering treatment of the noise transmission path between the source and the recipient, in this case the employee, should be investigated.

(2) Engineering treatment of the noise transmission path includes isolating the noise-emitting object(s) in an enclosure, or placing them in a room or building away from the largest number of employees, and acoustically treating the area to reduce noise to the lowest practicable levels.

(3) Alternatively, it may be desirable to protect the operator(s) instead of enclosing the sound sources. In this case, design of the soundproof room or sound-reducing enclosures should still follow the same principles.

(4) The principles to be observed in carrying out engineering treatment of the noise transmission path are listed below:

(a) Distance is often the cheapest solution, but it may not be effective in reverberant conditions.

(b) Erect a noise barrier between the noise source and the listener, in some instances a partial barrier can be used to advantage. In cases where either area has a false ceiling, care should be taken to ensure that the dividing wall extends to the true ceiling and that all air gaps in the wall are closed and airtight.

(c) Once the acoustical barrier is erected, further treatment, such as the addition of absorbing material on surfaces facing the noise source, may be necessary.

(d) Materials that are good noise barriers, for example, lead, steel, brick and concrete, are poor absorbers of sound. The denser and heavier the material, the better the noise barrier.

(e) Good sound absorbers, for example, certain polyurethane foams, fibreglass, rockwool and thick pile carpet, are very poor barriers to the transmission of sound.

(f) Walls and machine enclosures must be designed to minimise resonances which will transmit acoustical energy at the resonant frequency to the protected area. This can be achieved by placing reinforcement or bracing in strategic areas during construction or modification.

(g) Reduce, as far as possible, the reverberation of the room where noise is generated by the introduction of acoustically absorbent material(s). The presence of reverberation in a room shows the need for absorbing material. Excessive reverberation produces unpleasant and noisy conditions, which can interfere with speech communication.

(5) These principles can be utilised in the following way:

(a) using a sound-reducing enclosure which fully encloses the machine(s);

(b) separating the noisy area and the area to be quietened by a sound-reducing partition;

(c) using sound-absorbing material on floors, ceiling and/or walls to reduce the sound level due to reverberation; and

(d) using acoustical silencers in intake and exhaust systems associated with gaseous flow activity, for example, internal combustion engine exhaust systems or air conditioning systems.

5. INSPECTION AND MAINTENANCE OF CONTROLS

(1) A system should be established to ensure regular inspection and maintenance of vibration mountings, impact absorbers, gaskets, seals, silencers, barriers, absorptive materials and other equipment used to control noise.

REFERENCES

(1) National Code of Practice on Noise Management and Protection of Hearing at Work (Australia).

(2) Factories and Machinery (Noise Exposure) Regulations 1989 (Malaysia).

APPENDIX 3

COMMON NOISE CONTROL DESIGNS AND TECHNIQUES

The selection of a particular noise reduction design is dictated by the characteristics of the specific noise problem. Care should be exercised to adopt the most effective technique for each problem. This appendix gives descriptions of common noise control methods frequently applied to problems in process plants. A list of comments is also provided to enhance the noise control knowledge.

1. ENCLOSURES

Noise from certain sources may be most effectively reduced by acoustically enclosing the source. Sound transmission loss characteristics of a composite partition composed of panels of different materials is a function of the total percentage of area occupied by each material and its transmission loss factor. Transmission loss characteristics of various commonly used materials for enclosures are available in most noise control handbooks.

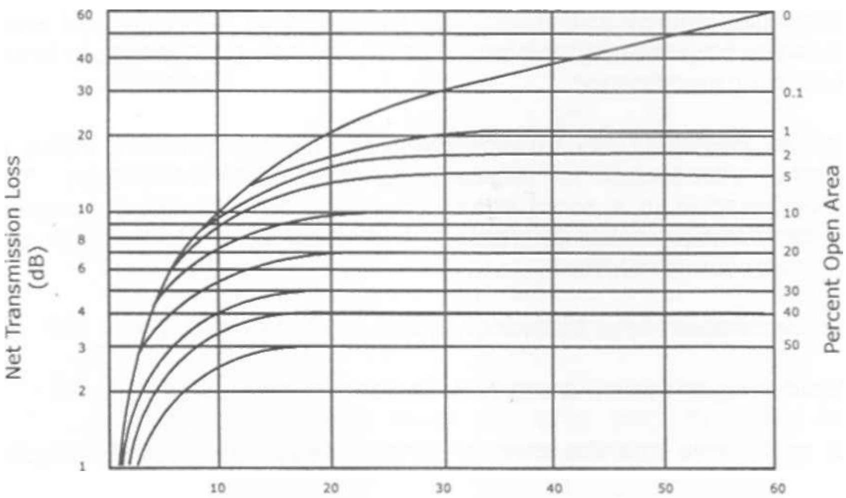


Fig. 1: Effects of open area on potential noise reduction of an enclosure

Leaks or open areas in the enclosure create significant reduction in the overall transmission loss of a panel, as illustrated, in Fig. 1. For example, if an enclosure with a 60-dB expected noise transmission loss or noise reduction has an opening that represents 1.0% of the total area, the effective net noise transmission loss is reduced from 60 to 15 dB. The values shown in Fig. 1 are only an indication of loss of effectiveness. To contain equipment requiring cooling air, an' enclosure must have openings for air intake and exhaust. Such openings must be acoustically treated, as shown in the example of Fig. 2.

For maintenance purposes disassembly of an enclosure should be given careful design consideration. Lift-out panels, panels mounted on overhead tracks, or merely large, well-positioned enclosure doors with chain hoist accessibility can often solve equipment removal and maintenance problems.

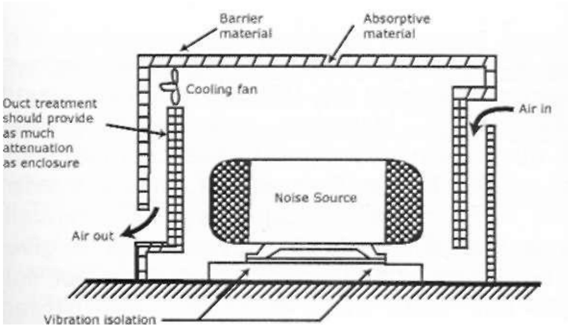


Fig. 2: Concept design of enclosure for a noise source requiring cooling air.
(source: Guidelines on Noise, American Petroleum Institute Medical Research Report No. EA7301)

Quite often, thinner panels may be employed to absorb high frequency noises; however, for frequencies below 250 Hz, 4-in. thickness panels with a heavy type material septum is recommended. Panels should also be vibration isolation mounted to avoid the transmission of low frequency vibration to the floor or attachment structures.

2. ROOM TREATMENTS

For equipment housed in buildings or rooms, consideration should be given to the noise reverberation reduction through the addition of absorptive treatments to the room, particularly if it has hard, acoustically reflective surfaces. The choice of an effective treatment is dictated primarily by the available area and noise absorptive of room surfaces.

Room treatment will not be significant in the proximity of the noise source; however, it can be beneficial in reducing total area noise levels, especially rooms containing several noise sources. In most cases, the resulting noise reduction is usually not >3 dB.

Quite often in industry, area noise reverberations are increased by 3 to 4 dB merely by painting the cement block walls with a heavy, pore sealing paint, which significantly decreases the noise absorption of the walls. If area cosmetics are desired, colour-tinted cement blocks and water-based non-pore sealing paint are available.

3. REACTIVE AND DISSIPATIVE SILENCERS

Silencers or mufflers can be considered simply as a duct or pipe that has been acoustically treated or shaped specifically to reduce noise transmission in the contained medium. The noise may originate from a machine source or it may be flow-generated. Sources include blow downs to atmosphere, draft fans, vacuum pumps, pelletisers, chillers, blowers, compressors, piping systems, pressure reduction valves, turbines, reciprocating engines, and other equipment. The characteristics of gas flow noise vary widely; therefore, a thorough analysis of the spectral content of gas flow noise is an important first step in the choice and application of a silencing mechanism. There are 2 basic types of silencers: (1) **reactive;** and (2) **dissipative.** These are categorised by the manner in which noise reduction is achieved.

3.1. Reactive Silencers

The acoustical properties of a reactive silencer are governed primarily by its internal configuration and the reduction of flow velocity by providing an expansion chamber. Reactive silencers are designed to take advantage of sound reflections *from* abrupt changes in shape and resonances of added branches or cavities to a pipe or duct. These reactive mechanisms obstruct the acoustical passage by impedance mismatch of acoustic energy flow within the pipe or duct. Reactive silencers are most effective at low frequency and limited spectral bandwidth applications.

3.2. Dissipative Silencers

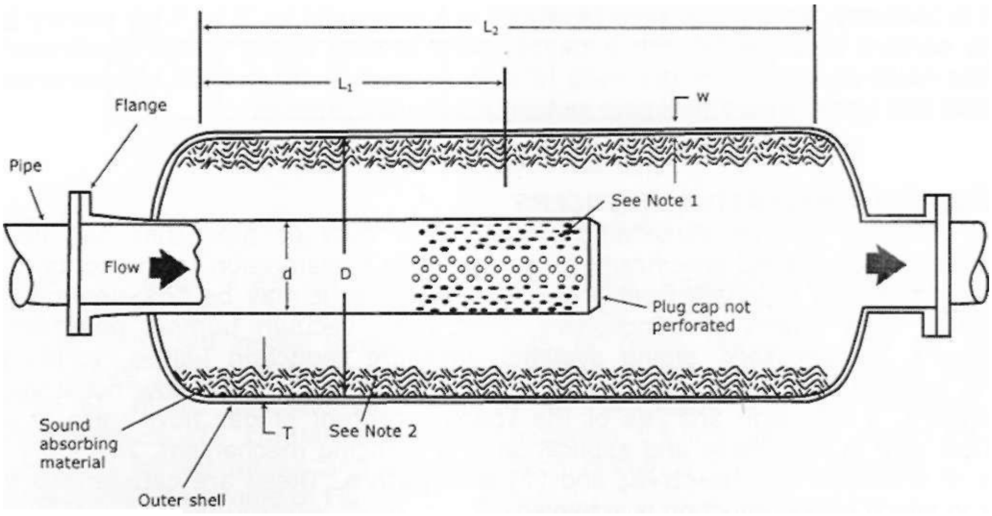
The second basic type of silencer *for* noise is the dissipative (also called absorptive) silencer. Its acoustical properties are governed primarily by the presence of sound-absorbing material that dissipates acoustic energy. Materials such as *rock* wool, fibreglass, and felt, when deployed within a duct, form a dissipative silencer. Maximum absorption of such materials usually occurs at the higher frequencies, yet dissipative silencers usually have a relatively wideband noise reduction capability. A potentially undesirable feature of this type of silencer is that if improperly designed *for* a given service, bits of the absorptive material may be drawn into the gas stream. This not only eventually degrades silencer performance but also may endanger downstream equipment. Thus, care should be exercised to ensure that silencer design is compatible with service requirements.

The distinction between reactive and dissipative silencers is conceptual. In practice, all silencers achieve some noise reduction by both reactive and dissipative means. Certain silencers, however, are designed as combination reactive-dissipative devices *for* a specialised application.

In all muffler employment considerations, the back pressure increase in the duct must be considered and its effect on the total plant and equipment design specifications.

4. PIPING NOISE SILENCERS

Pulsating flow created by the intake and discharge of reciprocating compressors and pumps is a frequent and serious source of noise and vibration. Devices called "snubbers" or "pulse traps" are used to buffer this pulsating flow by providing both an expansion chamber and dissipative elements in the associated piping system. The performance of such devices is a function of the system in which they are installed; therefore, an analysis of a complete piping system should be performed to ensure operational compatibility and acoustical performance.



Note 1: Hole diameters should be spaced as closely as possible and yield a total open area greater than twice the piping cross-section area.

Note 2: Sixteen (16) gauge (or heavier) noncorrosive steel with at least 50% perforated open area and backed by 16 x 16 or 18 x 14 noncorrosive wire mesh.

Fig. 3: General design features of an in-line silencer.
(source: Guidelines on Noise, American Petroleum Institute Medical Research Report No. EA7301)

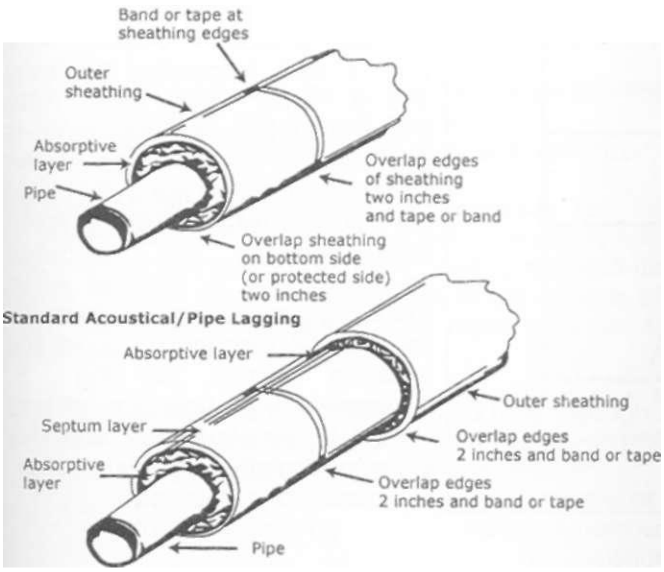
In-line silencers are useful in reducing gas stream noise within the body of the silencer and thus reducing the level of downstream noise propagation. These silencers are available in a wide variety of designs. Fig. 3 presents a general description of this type of silencer. Table 1 below lists the primary design characteristics of an in-line silencer.

Table 1: Primary Design Characteristics of an In-Line Silencer

1. Sound absorption - probably the single most important characteristic; the absorptive material should cover as much area as practical
2. Limitation of turbulence re-excitation as the gas leaves the silencer - can be achieved by avoiding sharp edges or area restrictions
3. Suppression or avoidance of resonances
4. Wide-band attenuation
5. Construction suitable to avoid external radiation of sound
6. No serious pressure loss in net flow
7. Construction suitable to withstand operating pressures
8. Simplicity of installation

4. ACOUSTICAL LAGGING

Acoustical lagging of noise sources, principally pipelines, valves, and ducts, consists of encapsulating the source with treatments that provide a combination of sound barrier and sound absorption mechanisms to obtain the maximum noise reduction. The optimum lagging design is dependent upon the spectral content of the radiated noise as well as the level of noise reduction required. All designs should avoid any mechanical coupling between pipe or duct surface and outer shell treatment and should have a layer of resilient absorptive material between the pipe, duct, or valve surface and the outer shell treatment. Increased thickness of material or a heavier composite material is required for low frequency performance. For thin-shelled pipes or ducts, a vibration damping material with adhesive backing should be directly applied on the surface. Fig. 4 illustrates typical acoustical lagging designs. For a 20-dB reduction, two 2-in. layers of 6 lb/ft^3 absorptive materials with at least a 1.0 lb/ft^3 septum interposed between layers is an average requirement.



Pipe Lagging Using Sandwiched Septum Layer for High Noise Level Reductions

Fig. 4: Typical acoustical lagging designs for noise radiating pipelines
(source: Guidelines on Noise, American Petroleum Institute Medical Research Report No. EA7301)

5. VIBRATION ISOLATION AND DAMPING

The application of vibration isolation and damping techniques are generally required to silence structure-borne noise. A relatively small vibrating machine, pipe, or other mechanism, when closely coupled to a floor or panel and then radiates the vibration acoustically, can often produce objectionable noise levels. Structure-borne noise refers to the transmission through structures of mechanical vibrations that produce airborne noise when a panel or other structure is set into motion and radiates sound.

Vibration suppression or reduction is generally accomplished by the installation of vibration mounts that combine the properties of resilience and vibration damping to provide two fundamental mechanisms for control:

(1) Dissipation and reduction of vibrational energy generated within the system by conversion of that energy into heat.

(2) Mechanical decoupling or removing the vibration paths of the system from its mounting structure and floor.

The process for selecting a particular vibration isolation or damping design is described in detail in the literature supplied by manufacturers of such vibration isolation devices.

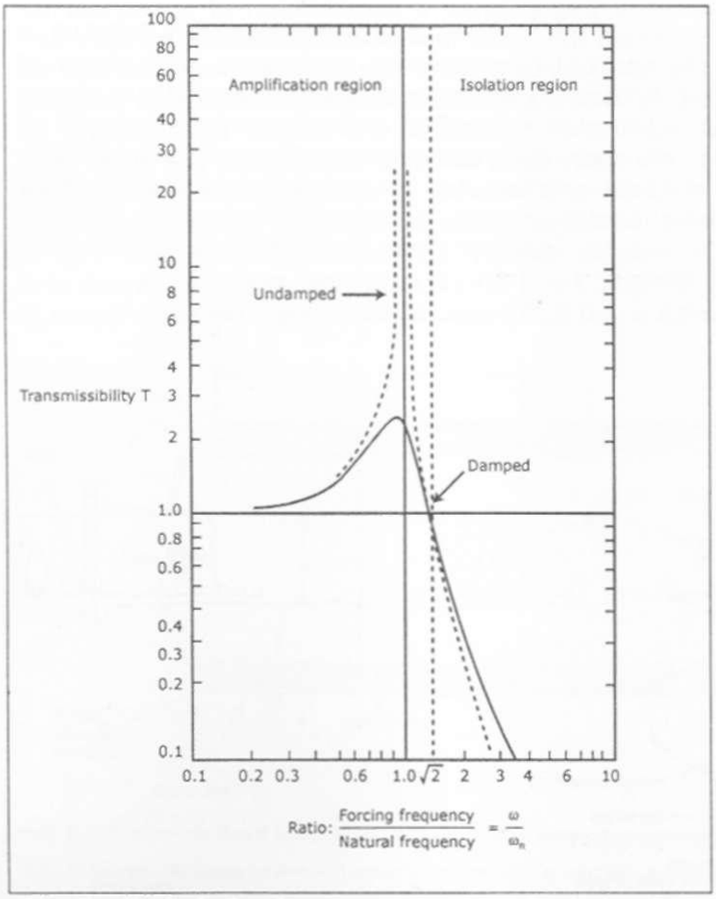


Fig. 5: Typical vibration response of a mechanical system mounted on viscous vibration dampers.

Fig. 5 illustrates typical features of the response of a mechanical system mounted on viscous dampers. The ordinate represents the transmissibility of the mounting (T) which is the ratio of transmitted force to driving force and the abscissa is the ratio of the forcing frequency to the resonance or natural frequency of the system. The magnitude of the transmissibility in the figure at the ratio of $\omega/\omega_n = 1$ approaches $T = 1$ with increasing damping and a higher ω/ω_n ratio. Note that if the frequency ratio ω/ω_n is less than 2, amplification of the transmitted force will result and the mounts will do more harm than good. In summary, transmissibility is reduced when the forcing frequency, ω, exceeds the natural frequency, ω_n in the isolation region of Fig. 5. Equipment vibration consultants should be employed for effective vibration isolation and damping.

Viscoelastic materials typically are the most versatile and effective materials in providing the desired vibration damping and ultimate noise reduction, especially for thin structures. To determine what surfaces may require treatment by application of viscoelastic materials, it is necessary to measure vibration levels. For those surfaces having high vibration levels relative to other surfaces, decisions should be made as to the type(s) of appropriate treatment. If the surfaces are easily accessible and continuous, a lagging treatment may be employed; if the surfaces are irregular or not easily accessible, the application of damping materials may be the most expedient noise reduction approach. The characteristics of applied damping materials vary significantly with temperature and frequency; therefore, the manufacturer's data should be consulted prior to selection and application.

Coil springs are another form of vibration isolation. Coil springs are employed primarily for the isolation of vibrating motion that have a low forcing frequency and where elastomeric mounting pads are not very effective. Coil springs are a transmission path for high-frequency vibrations and have large static deflections, therefore, design precautions must be taken in the proper selection of spring-type vibration isolation equipment mounts.

6. MOTOR NOISE REDUCTION

Noise from electric motors is predominantly generated by cooling fans. The cooling fan is the dominant noise source in totally enclosed fan-cooled-type motors up to about 200 hp and thus the radiated noise level does not vary significantly with load. Motor noise levels vary with manufacturers. Personal computer fan noise has probably been recognized by many individuals, and the application of discussed noise abatement techniques would reduce these noise levels for most computers.

Noise reduction may be achieved by installing an acoustically treated air intake shroud. Such devices are commercially available for many motor sizes and configurations, or may be designed and fabricated to satisfy unique requirements. Substantial noise reduction can also be achieved by installing an enclosure around the motor using previously discussed enclosure principles. With a motor-driven pump the loudest noise quite often is in the coupling guard area. This guard is usually made of sheet metal, so with vibration damping of the coupling guard or the installation of a guard acoustical lining, the noise level would be significantly lowered.

7. CONTROL VALVE NOISE REDUCTION

Valves are generally the primary sources of noise radiated by piping systems. Noise generation by valves is caused by at least one of three mechanisms:

(1) Turbulent eddy interaction with solid surfaces
(2) Turbulent mixing and cavitation
(3) Shock-turbulence interaction and vibration

Regardless of the generating mechanism, the in-pipe valve-generated noise field is propagated downstream and decays very slowly with distance from the valve. Because of the mass of the valve wall, little noise is radiated directly from the valve. As a result, the piping system itself becomes the prime source of externally radiated noise. Effective noise control of valve generated noise may be approached by one or more of three methods:

(1) Change the dynamics of fluid flow through the valve
(2) Change the dynamics of fluid flow downstream of the valve and absorb acoustic energy by installing an in-line silencer
(3) Intercept and absorb acoustic energy at the outside pipe wall surface with acoustical lagging

The first method is the most effective and involves the employment of special design type valves that limit the localized flow velocities by forcing the flow to travel through a plurality of passages. Quiet valves are available. However, cost tradeoffs should be examined with comparisons to low cost acoustical lagging and the employment of in-line silencers.

8. NOISE CONTROL DESIGN — THE LAST WORD

Even with a great deal education in the field of noise control, real life industry experience has shown that it is only after many years of practical noise control involvement that a feel for cost-effective noise control is developed. Formal education trains the individual in theoretical and laboratory principles; however, only extensive field (i.e. practical) experience can give one the skills and good judgement to be able to obtain cost-effective noise control solutions fairly rapidly. For a summary of some simple but potentially very useful advice on noise control, see Appendix 4.

REFERENCES

1. McGuire, J., Industrial Plant Noise Abatement, in *The Work Environment (Volume One) - Occupational Health Fundamentals,* ed. Hanson, D. }., Lewis Publishers.

APPENDIX 4

PEARLS OF WISDOM - NUGGETS OF KNOWLEDGE ON NOISE CONTROL DESIGN

(1) One of the most common noise problems associated with fluid flow is that of venting high pressure gas to the atmosphere. When the ratio of absolute pressure upstream of the pressure reducing (PR) valve is 1.9 or greater, the port velocity in the valve will be sonic and the sound power level will vary directly with the quantity of gas flow. Such valves are called choked valves. Calculations for choked and non-choked valves provide basic data for specifying mufflers to control this noise.

(2) In order to reduce turbulent flow and subsequent high noise levels, the flow velocity should be reduced to a minimum. Additional noise reduction may be obtained by streamlining the equipment design. For example, the use of multiple opening nozzles to replace a single opening nozzle results in the reduction of the exit noise. Noise in the higher frequency octave bands are effectively reduced with substitution of multiple opening nozzles.

(3) Surfaces radiating low frequency sounds can sometimes be made less efficient radiators by dividing them into smaller segments or otherwise reducing the total area. The employment of perforated or expanded metal can often result in less efficient sound radiation from sheet metal guards and cover pieces.

(4) The response of a vibrating member to a driving force can be reduced by damping the member, increasing its stiffness, or increasing its mass. When the frequency of the driving force is equal to the natural frequency of the member (including floors) being vibrated, a large surface displacement results with highly amplified noise levels. This phenomenon is known as "resonance".

(5) Changing the stiffness of the mount is the simplest method of altering the natural frequency of a system. The second parameter that must be known in designing an isolation system is the frequency of the vibration being isolated. If many frequencies exist, the lowest frequency is the one which must be considered. This is known as the forcing frequency.

(6) Structural steel can transmit noise sources greater distances than air. Structure-borne noise sources or vibrating surfaces should be taken strongly into design considerations. It should also be remembered that a flexible pipe or hose for a hydraulic pump may expand and contract at the piston or gear frequency of the pump to radiate sound.

(7) A noise source may radiate sound energy into air; this may cause a plate or sheet metal panel to vibrate, which in turn then reradiates sound energy.

(8) At 1,000 Hz, the wavelength of sound is approximately 1 ft. At lower frequencies the wavelengths become longer while at higher frequencies the wavelengths become shorter. At 200 Hz, a wavelength is 5.65 ft, while at 2000 Hz, a wavelength is 0.565 ft. Therefore, when the dimensions of a noise-radiating surface are comparable to the wavelength of the sound being emitted, the surface becomes a relatively efficient radiator. If the radiator is greater in size than 3 or more wavelengths, it becomes a very efficient radiator. On the other hand, if the dimensions of the radiating surface are reduced to one third or less of a wavelength, this radiating surface becomes a relatively inefficient radiator.

(9) A good example of sound radiation: a tuning fork vibrating at 256 Hz (middle C) radiates a sound wave having a wavelength of approximately 4 ft. Because the

radiating surface of the tuning fork prong is approximately 1/4 in. wide or 1/100 of the wavelength, it does not radiate sound very efficiently or effectively; however, if the base of the tuning fork is held in contact with a relatively large surface, such as a table top, the sound level is increased or amplified and the tone heard loud and clear. The reason, of course, is that the greater surface area of the table is more able to radiate sound having a 4-ft wavelength. A piano, for instance, is an excellent radiator of sound energy. Likewise an extruder or compressor with low forcing frequency noise can have its sound radiated effectively through a supporting floor area. Vibration isolation of an extruder or compressor or large pieces of vibrating equipment is therefore necessary.

(10) Surfaces that are small in comparison to the wavelength of the emitted sound radiate the sound relatively uniformly in all directions, whereas surfaces that are large in comparison to the wavelength are very directive sound sources. An example is to compare a "tweeter" (small loudspeaker) which produces high frequency sounds in a high-fidelity sound system to a bass speaker called a "woofer." The bass speaker will be very directive if used to reproduce higher frequency sounds.

(11) In general, vibrating surfaces are very directive at high frequencies and less directive at low frequencies, since a wavelength of a sound wave is inversely proportional to its frequency. When studying equipment design it is important to keep in mind the directivity properties of the sound emitting surface and its relationship to the wavelength of the sound being produced. For example, a manufacturer may build a machine and then install covers or side panels to dress up the product. The manufacturer is then surprised that the sound is higher than before the side panels were placed on the machine. The panels in this case not only increased the radiating surface, but because the sizes of the panels were comparable to the wavelength of the sound being produced, they radiated the sound more efficiently than the structural members of the machine. This amplifying effect may be desirable with pianos, where the sounding board of a piano is employed to amplify sound; however, it is not a desirable design technique for industrial equipment. A large percentage of equipment manufacturers are not familiar with these very basic principles. In cases of a metal cover, the panel should be perforated with holes to reduce the radiating surface, or the panel can be acoustically damped or structurally modified. The sound level produced by a radiating panel may be reduced by 3 or more dB each time the radiating surface is halved. Disconnecting a significant vibrating part from the radiating area would, of course, significantly reduce the noise levels produced.

(12) If a machine moving member has less surface to compress the air in front of it to create sound, there will be less mechanical energy converted into sound.

(13) Fan speed reduction significantly reduces noise levels. A 2:1 reduction in fan speed can result in a 16 dB reduction in noise level. If the velocity of an air stream can be reduced by 50%, the noise level can drop by 20 dB.

(14) Laminated construction is likely to have high internal damping which is helpful in controlling resonant vibrations. "Damping" is used to describe the conversion of resonant vibration energy into heat energy. This is an effective mechanism for noise control because, once converted to heat, vibration energy is no longer available for generation of airborne noise.

(15) Pumps operating at 3,600 rpm are likely to produce more noise than similar larger pumps operating at 1,800 rpm for a given rating.

(16) A preventive equipment maintenance program, in addition to preventing equipment

breakdown and maintaining product quality control, has a desirable by-product — the prevention of increased noise levels that would result from excessive wear of moving parts. Periodic machine vibration checks and the employing of a vibration accelerometer might be worthwhile during equipment maintenance checks.

(17) The application of periodic forces or impulses may cause a machine to vibrate with a frequency that mayor may not be the natural frequency of the vibrating body. When the period of the forced vibration is the same as that of the free vibration, the two effects reinforce each other and large amplitudes of the vibrating body result in "resonance." Most mechanical structures resonate at a series of frequencies that become closely spaced at high frequencies. There are instances in which machines cannot be operated at certain speeds because of resonance; this on occasion results in structural failure.

(18) When the frequency of the driving force coincides with the natural frequency, transmission of vibration force is increased rather than reduced by isolators. To counteract resonant vibration, damping is added to many isolators to increase energy dissipation. This is done with some sacrifice in the effectiveness of the isolator at other frequencies.

(19) Acoustical damping is more effective at high frequencies than at low frequencies because damping is accomplished by internal friction of the material as it is stretched or compressed by the vibrating motion.

(20) A technique for determining the presence of resonant vibrations and need for damping is to vary the speed (rpm) of equipment to above and below normal speed; listen for increased noise or changes in pitch, which may indicate that resonances are occurring and that damping treatment may be a useful measure for noise reduction. Instrument techniques may also be used to determine vibration levels and node patterns.

(21) The response of a vibrating part to a driving force above the resonant frequency can be reduced by damping the member, improving its support, increasing its mass or stiffness, or in general, reducing its resonant frequency.

(22) The noise transmission loss from 2 or more walls separated by air spaces is usually significantly greater than predicted on the basis of mass law attenuation. It is important that walls should not be solidly tied together in order to gain advantage of air space. Staggered wall studs are also recommended.

(23) Partial noise enclosures are most effective in reducing high-frequency noise and least effective at low frequencies.

(24) Barrier walls provide a noise shadow effect for high frequencies but are less effective for low frequency, long wavelength types of noise. Barriers are most effective when either the noise source or the receiver or both are close to the barrier wall. The attenuation and advantages of a barrier should always be compared to those of an enclosure with regards to ventilation, noise reduction requirements, and cost.

(25) Mass theory states that noise transmission loss should increase by 6 dB for each doubling of partition weight.

(26) Relatively low noise transmission losses result when the frequency of the sound energy is coincident with resonant partition vibrations.

(27) Small openings in sound barriers or enclosures greatly reduce their effectiveness.

For example, a 1-in. hole will transmit slightly more sound energy than the entire surface of a 4 x 12 ft sheet lead barrier rated for a 40-dB transmission loss. Door crack openings and ventilation ducts are often noise passages. Commercially available special rubber seals for doors may be used to avoid excessive noise leaks.

(28) The reverberant noise level in a room decreases 3 dB for each doubling of the total absorption. In most applications, installations of absorptive materials provide <10 dB of noise reduction, and significantly <10 dB with regard to worker noise exposure levels.

(29) It is impractical to acoustically treat more than 50% of a room surface area because the noise reduction gained by going beyond this percentage is slight. If room treatment is necessary, treatment of 20 to 50% of the boundary surface area is considered a practical approach.

(30) A good muffler for a hydraulic system is a flexible hose or an accumulator inserted in the line at the pump discharge. The flexible hose can then expand and contract in response to the hydraulic pulsations. The hose diameter is small compared to the wavelength of the sound generated by pressure fluctuations in the hydraulic fluid; therefore, the hose does not radiate noise efficiently.

(31) A double wall noise enclosure can provide improved noise reduction over a single wall enclosure of the same weight.

(32) Vibration isolators must be placed correctly with respect to the centre of gravity of the machine. In cases of instability, i.e., "rocking" the effective centre of gravity may be lowered by mounting the machine on a heavy mass and isolating the mass and the machine on a so-called "floating floor."

(33) Coil springs are employed in vibration isolators primarily for the isolation of vibrating motion having a low forcing frequency. Consequently, coil springs must usually have relatively large static deflection. This introduces the danger of instability, with the possibility that the mounted equipment may fall sideways unless precautions are taken to assure stability of the equipment and isolator assembly. Instability is likely to result if the lateral stiffness of the isolator is too small or the static deflection is too large. Coil springs possess practically no damping; therefore, transmission at resonance is extremely high. Coil springs also allow high frequency surges to pass through the equipment being protected. Springs also have a transmission path for high frequency vibration, resulting in excessive noise levels. Rubber pads are employed at the bottom of spring isolators to overcome some of these deficiencies. Side-restrained metal spring isolators are available to avoid difficulties.

(34) Since there is little inherent damping of resonant vibrations in most structural elements, external damping must be made to reduce vibrations. External damping can be applied in several ways: (a) by interface damping (letting two surfaces slide on each other under pressure — the dry friction producing the damping effect); (b) by application of a layer of material with high internal losses over the surfaces of the vibrating element; (c) by designing the critical elements as "sandwich" structures. (Damping through the use of "sandwich" structures refers to a layer of viscoelastic material placed between 2 equally thick plates or to a thin metal sheet placed over the viscoelastic material that covers the panel.)

REFERENCES

1. McGuire, J., Industrial Plant Noise Abatement, in *The Work Environment (Volume One) - Occupational Health Fundamentals,* ed. Hanson, D.]., Lewis Publishers.

APPENDIX 5

DESIGN CRITERIA FOR NEW PLANT

The preparations necessary to ensure that the design of a new plant meets criteria for allowable noise limits should begin in the early stages of planning. Noise specifications should be established for selection. The initial step in planning for an acoustically acceptable plant is to specify an acceptable noise environment for the plant and its surroundings. The initial step in planning for an **acoustically acceptable** plant is to specify an acceptable noise environment for the plant and its surroundings. For example, if a maximum plant level is set at 85 dB(A) in all areas, then all equipment must meet at least an 80 dB(A) criterion at 3 ft or 1 m. This is considered to be an effective criterion since the physical spacing required for equipment seldom results in a composite or total noise level of > 5 dB above individual source levels. Unless more detailed analysis or spacing is available is available or known, these limits should be employed. It is also recommended that a maximum total energy 90 dB criterion be set for all equipment to discourage equipment design practices that result in equipment with low frequency (below 1,000 Hz) noise levels.

Using the fulfilment of 85 dB(A) 8-hour LEQ (i.e. the Action Level) criterion of the Factories and Machinery (Noise Exposure) Regulations 1989, as a matter of fact, may still not eliminate the existence of significant noise levels below 1,000 Hz, which a dB(A)-based regulatory regime discounts. If the engineering control process is only focused mainly on shifting high frequency noise to low frequency (below 1,000 Hz) noise, the low frequency levels will increase. Subsequently, if low frequency noise energy causes more speech-frequency-range hearing loss than high frequency noise energy — which some experts believe, then this would mean that noise regulations can be complied with by employing some noise control techniques which will result in increased employee hearing losses! This could be the unfortunate result of honest engineering intentions that do not delve deep enough into occupational health principles and implications. Therefore, a limit on equipment total energy noise levels should therefore be set and 90 dB has been determined to be a reasonable limit for this purpose.

Noise projections should be made in the early plant design stages with reliable equipment noise data, and this should be observed field data rather than data supplied by the equipment manufacturer. The task of combing noise sources and levels is a critical activity whether it is performed manually or by computer programmes. In this type of activity the employment of computer aided engineering design drawings (i.e. CAD) has been employed very effectively with colour-coded noise projection interfaces. The reduction of these engineering design drawings with noise projections allows for quick reference in summary reports. Noise limits should apply to typical or maximum operating modes. If there is more than one mode of operation, the limits should apply to the noisier condition. The resulting specifications to equipment manufacturers and engineering companies should be very clear as to the conditions assumed. Noise specifications should be designed with tolerances or built-in margins for unavoidable variations in noise levels. Several factors to be considered in setting tolerances are listed in Table 1.

General guidelines for site selection and plant layout are listed in Table 2. In determining plant layout, these general guidelines should be observed whenever possible.

Table 1: Factors to be considered in setting noise control tolerances.

Most manufactured equipment is built to operate within a noise range; however, some units will exceed a specification based on the median value.

Equipment noise levels tend to increase with age, wear and tear, lack of maintenance and increased load, etc.

The measured equipment composite noise level may be increased by reflection from nearby objects.

Equipment specified to meet an overall noise power level limit may produce a noise level that exceeds the specification when measured in a certain direction.

An engineering allowance may be necessary where overall design procedures are not precise.

Noise limits for individual sources must be set at a lower level to insure that the composite noise level for an area does not exceed the total noise level criteria.

It should be realised that noise levels quoted by equipment manufacturers are usually lower than actual field-experience noise levels.

Table 2: General guidelines for site selection and layout.

Locate process areas or known noise sources at maximum distances from more sensitive plant areas; for example, large furnaces can often be placed near plant boundaries away from administrative offices and adjacent community areas.

Utilise acoustical shielding situations offered by large structures such as storage tanks.

Take advantage of hills, large neighbouring structures, wooded areas, etc, to screen noise.

In determining site location, the following factors should be considered:

- Proximity to existing housing or light industries and general topography
- Proximity to unoccupied land, to possible development, and to industrial neighbours
- Local codes, regulations or standards
- Transport of raw and finished products

These guidelines and factors should, of course, be integrated with other considerations, future expansions, regulations etc.

REFERENCES

1. McGuire, J., Industrial Plant Noise Abatement, in *The Work Environment (Volume One) - Occupational Health Fundamentals,* ed. Hanson, D. J., Lewis Publishers.
2. Factories and Machinery (Noise Exposure) Regulations 1989.

APPENDIX 6

PLANT AND EQUIPMENT NOISE SPECIFICATIONS

The most effective and economical approach to noise control is to include noise control features as an integral part of the plant design. Such an approach is most efficiently handled by proper use of equipment performance and design specifications. Performance specifications require that the proposed equipment will satisfy the selected criterion; design specifications indicate to the supplier specific noise control features known to be effective and compatible with plant operations. A sample equipment noise specification schedule is given in Table 1.

Table 1: Noise Specifications to the Equipment Supplier

Equipment noise level limitations, noise testing procedures, and noise data documentation requirements. These limitations and requirements should apply to all stationary and mobile equipment and machinery that produce continuous, intermittent, and impulse noise.

Provisions for a uniform method of conducting and recording noise tests to be made on equipment.

Requirements that the equipment manufacturer and the engineering contractor guarantee to meet the noise limits set forth in the specification.

Statements indicating that if the noise survey of a completed plant indicates that an item of equipment is producing noise levels that exceed equipment specifications, the equipment manufacturer, subcontractor, or engineering contractor will be responsible for the extra cost of treating the equipment to bring noise levels within the equipment and plant specification requirements.

Agreements that all equipment manufacturers and engineering companies will be penalised if the equipment and plant and/or site noise specifications are not met.

Pre-bid and final test noise measurements shall be made on the purchased equipment and test data will be made available and determined acceptable by the buyer or their representative prior to shipment with authorised signatures.

Reservation of the right to send qualified representatives to the equipment manufacturing plant to observe or conduct noise tests.

Maximum acceptable noise levels for the plant site perimeter, plant area perimeters, and interior plant areas including production areas, control rooms, offices, laboratories, etc.

Maximum acceptable vibration levels for all equipment, and noise reverberation levels for all work and process areas.

Instrumentation and measurement techniques.

Pre-bid equipment noise level data sheets requiring equipment noise specification guarantee signature and buyer approval signature.
Final test noise level data sheets requiring equipment noise specification guarantee signatures and witness/or noise data acceptance signatures.

In selecting equipment for a new plant or for equipment replacement or additions to an existing facility, satisfactory noise limits often can be obtained by proper attention to specific design features of the equipment. The prescribed equipment specifications may sound stringent. However, successful activities in all plants that have followed the criteria have not only been rewarding but also cost-effective. A summary of some of these design features are shown in Table 2.

Table 2: Desirable Features of Equipment Design for Noise Reduction

Equipment	Source of Noise	Design Features
Heaters	Combustion at burners	Acoustic air intake plenum
	Inspiring of premix air at burners	Inspirating air intake silencer Acoustic air intake plenum
	Draft fans	Air intake silencer or acoustic plenum lagging
	Ducts	Lagging
Motors	TEFC cooling air fan WP II cooling air openings	Acoustic fan shroud, unidirectional fan, and/or intake silencer
	Mechanical and electrical	Enclosure
Airfin coolers	Fan	Lower rpm (increased pitch). Tip and hub seals. Increased number of blades. Decreased static pressure drop. More fin tubes.
	Speed changer	Belts in place of gears.
	Fan shroud	Streamlined air flow. Damping and stiffening.
Centrifugal compressors	Discharge piping and expansion joints	In-line silencer and/or lagging.
	Antisurge bypass system	Quiet valves, reduced velocity, and streamlining. Lagged valves and piping. In-line silencers.
	Intake piping and suction drum	Lagging.
	Air intake/air discharge	Silencer.
Screw compressors (axial)	Intake and discharge piping	Silencers and lagging
Speed changers	Gear meshing	Enclosure, constrained damping on case, or lagging
Engines	Exhaust	Silencer (muffler)
	Air intake	Silencer
	Cooling fan	Enclosed intake and/or quieter discharge
Condensing turbine	Expansion . joint on steam discharge line	Lagging
Atmospheric exhausts and intakes	Discharge jet	Discharge silencer
	Upstream valves	Quiet valve or silencer
Piping	Leading pipe	Lagging
	Excess velocities	Limited velocities
		Smooth, gradual changes in size and direction
		Lagging
	Valves	Limited velocities
		Constant velocity or a quiet valve
		Divided pressure drop
Pumps	Cavitation of fluid	Enclosure
Flares	Steam jets	Multiport on air injectors

REFERENCES

(1) McGuire, J., Industrial Plant Noise Abatement, in *The Work Environment (Volume One) - Occupational Health Fundamentals,* ed. Hanson, D. J., Lewis Publishers.

APPENDIX 7

SELECTION OF NOISE CONTROL MATERIAL

***Note:** This guide on selection of noise control material has been extracted and adapted from a USA source. Accordingly, some adjustments may have to be made as appropriate to suit the local conditions in Malaysia.

There are 4 types of materials most often used in noise control: absorbers and isolators for airborne sound, and vibration isolators and damping materials for controlling vibration solid borne sound. Material selection also needs to take account of non-acoustic considerations (i.e. regulatory and environmental factors).

1. ABSORPTION MATERIALS

With absorption, small amounts of sound energy are changed into correspondingly small amounts of heat energy. Suitable materials are usually **fibrous, lightweight and porous.** The fibres should be relatively rigid. If a cellular material is used, the cells must intercommunicate. Foams should be reticulated to the proper degree.

Examples of absorbent materials are: acoustical ceiling tile, glass fibre and foamed elastomers. Physically, the flow resistance of fibrous materials is the most important characteristic. For optimum results, the flow resistance must usually be increased as the thickness of the absorbent decreases, to maintain peak absorption. Absorbent materials are employed in several applications including muffler linings, wall, ceiling and enclosure linings, wall fill and absorbent baffle construction.

The flow resistance can be sensed — rather crudely — by attempting to blow through the material. Comparison with an accepted material of the same thickness provides a personal calibration. The effectiveness of an acoustically absorbent material is measured by the absorption coefficient. Ideally, this is the fraction of the sound energy flowing toward the material that would be absorbed by it. A material with an absorption coefficient of 1 (100%) would "soak up" the entire sound incident on it. Industrially useful acoustically absorbent materials have coefficients above 60% in the frequency range from 500 Hz and up.

Absorbent materials on room surfaces reduce the amount of reverberant sound in a working space and thus reduce the effects of reflected sounds. It is very important to recognise that absorbents materially affect the transmission of sound, thus, they should never be used as shields or barriers or enclosure walls. The reduction of reverberant sound pressure levels that could be expected by addition of an absorbent material is given as approximately 10 times the logarithm of the ratio of the room constant obtained after adding the absorbent material, divided by the original room constant. It is relatively simple, then, to estimate the new sound level from the new sound pressure levels. Table 1 shows average absorption coefficients of various absorbent materials.

Table 1: Sound absorption coefficients of common acoustic materials

Material*	Frequency (Hz)					
	125	**250**	**500**	**1,000**	**2,000**	**4,000**
Fibrous glass						
4 lb/ft[3], hard backing						
1 inch thick	0.07	0.23	0.48	0.83	0.88	0.80
2 inches thick	0.20	0.55	0.89	0.97	0.83	0.79
4 inches thick	0.39	0.91	0.99	0.97	0.94	0.89
Polyurethane foam						
(open cell)						
1/4-inch thick	0.05	0.07	0.10	0.20	0.45	0.81
1/2-inch thick	0.05	0.12	0.25	0.57	0.89	0.98
1 inch thick	0.14	0.30	0.63	0.91	0.98	0.91
2 inches thick	0.35	0.51	0.82	0.98	0.97	0.95
Hairfelt						
1/2-inch thick	0.05	0.07	0.29	0.63	0.83	0.87
1 inch thick	0.06	0.31	0.80	0.88	0.87	0.87

* For specific grades, see manufacturer's data; note that the term NCR when used is a single-term rating that is the arithmetic average of the absorption coefficients at 250, 500, 1,000 and 2,000 Hz.

Note that for each doubling in the amount of absorption, you can expect a 3 dB noise reduction in reverberant levels. The first 3 dB reduction is therefore relatively cheap to obtain, you must add twice as much material to obtain a second 3 dB reduction. Note also that the ultimate noise reduction potential would be limited. You would not be able to reduce the sound level to below that which would be obtained if there were confining walls present in the workspace.

The absorption coefficient depends not only on the material but also on what is in front and at the back of it. Most coefficients are stated for an unobscured front but with a rigid impervious backing spaced various distances away from the material. Noise control engineers use designations of the Acoustical and Insulating Materials Association (USA) to describe the material mountings:

(1) Cemented to backing with about 1/8 in. air space
(2) Spaced [3]A in. away by furring strips
(4) Laid directly on surface - very little air space
(7) Suspended 16 in. from the backing

When the mounting is not specified, usually it is No. 1 or 4.

Absorbent materials may have special facings. For resistance to grease and water that would clog pores, a thin plastic film covering is often used. Such films, as well as perforates vinyl or sheet metal facings, tend to produce a maximum in the mid frequency absorption coefficient. Absorbents protected by a film still have exposed edges. These may be sealed by a latex paint that anchors it self to the pores of the absorbent and closes the edges. Some thin construction materials, notably plywood, can show increased low-frequency absorption by panel resonance, if they are not securely fastened down.

The standard reverberation-room method of measurement of absorption coefficient (ASTM 0423-66, or latest version) essentially subjects the absorbent to sound from all angles. Data on absorption coefficients cannot be regarded as useful and meaningful unless they have been obtained in this standard fashion.

2. TRANSMISSION LOSS MATERIALS

The sound isolation properties of materials are stated in terms of transmission loss. As with absorption, the concept of energy flow is used, here it is the energy transmitted through the material, relative to that flowing toward it. Transmission loss is 10 log (incident energy)/(transmitted energy) and it ideally increases with frequency at the rate of about 5 to 6 dB per doubling of frequency. The standard measurement for determining transmission loss is made in accordance with ASTM E90:99 or ISO140/l:1997 & ISO140/3:1995. Data on the transmission loss of materials appearing in advertising literature cannot be regarded as meaningful unless they have been determined in this standard manner. In Malaysia, only a few laboratories are known to have the capability for testing transmission loss of building materials, namely those of: (1) Universiti Teknologi Malaysia (Skudai); (2) Universiti Kebangsaan Malaysia (Bangi); (3) Universiti Malaysia Sabah; and (4) Universiti Institut Teknologi MARA (Shah Alam).

As a result of the search for a single number to indicate the average full transmission loss, the concept of sound transmission class (STC) was developed. It is useful specifically in assessing the degree to which intelligible speech is prevented from being transmitted through a wall. Use the STC with caution in industrial work, however, because the noise spectrum can be much different from that of speech. You will need the transmission loss in each octave band for the proper application of isolating materials.

3. DAMPING MATERIALS

Damping materials are used to reduce resonance effects in solids. Essentially, damping materials are absorbents for solid-borne sound, converting the vibrational energy into heat. They are used in many applications. If a machine panel (such as a belt guard) is subjected to vibration, it will radiate sound strongly at its resonant frequencies. Damping the panels or guards can reduce this radiated sound. In another application, parts that fall into (and are carried along) metal chutes can excite the chute panels by repeated impact. Installing damping materials along the chute surfaces will reduce the noise, but these materials must be selected with heat resistance and mechanical integrity in mind. Damped stock tubes are available for quieting screw operation. Panels for isolating enclosures can transmit large amounts of sound in certain frequency regions. Damping can help retain transmission loss in those regions.

There are two types of damping materials: (1) homogeneous layer; and (2) constrained layer. A homogenous-layer material is sprayed or **trawled** on in a relatively thick coat, depending on the thickness and type of metal to be damped. A constrained-layer material consists of a thin layer of the actual damping material with a backing of thin metal or stiff plastic. The mechanical action is one of making the damping layer much more effective than if it were homogenous. Constrained-layer damping materials can be purchased as an adhesive/metal-foil tape combination, where the adhesive is selected for its energy loss properties as well as its adhesion. These damping tapes are especially useful on thin panels (1/16 in. steel or less)

4. VIBRATION ISOLATORS

Vibration isolators act on the same principle as isolators for airborne sound: introducing into the transmission path a material whose wave-transmitting properties are as different as possible from the medium carrying the wave. For vibration in solids, such materials are spring-like. Examples include resilient elastomer and metal springs, elastomer pads and in extreme cases, air springs. The weaker the spring, usually the greater is the isolation. Solid rubber or rubber-fabric pads are not too effective because the displacement is small and is not proportional to the load.

If an isolator is too weak vertically, it may not be laterally stable. Side-restrained metal spring isolators are available to avoid this difficulty. In extreme cases, it may be necessary to use many isolators, all acting along lines that pass through the centre of gravity of the machine. Vibration isolators can also be used when the vibration situation is reversed, i.e., when a delicate mechanism is to be protected from external shock and vibration.

The proper amount of damping is needed with vibration isolation in many applications. Steel springs alone are highly undamped; if they rest on elastomer pads, there is much improvement.

5. MATERIAL SELECTION

The most commonly used materials for control of noise in industry are absorbers and transmission loss materials for airborne sound and vibration isolators and dampers for structure-borne sound. Besides acoustical aspects, selection of materials is also governed by other factors. These factors may be broadly classified as environmental and regulatory. Environmental factors include:

(1) Moisture, water spray, water immersion
(2) Oil, grease, dirt
(3) Vibration
(4) Temperature
(5) Erosion by fluid flow

Regulatory factors include:

(1) Lead-bearing material forbidden near food processing lines
(2) Restrictions on materials that may be in contact with foods being processed-glass, Monel or stainless steel permitted
(3) Requirements for material not to be damaged by disinfection
(4) Firebreak requirements on ducts, pipe runs shafts
(5) Flame spread rate limits on acoustically absorbing materials
(6) Fire-endurance limits on acoustically absorbing materials
(7) Restrictions on shedding of fibres in air by acoustically absorbing materials
(8) Elimination of uninspectable spaces in which vermin may hide
(9) Requirements for secure anchoring of heavy equipment
(10 Restrictions on hold sizes in machine guards (holes can reduce radiated noise of vibrating sheets)

A good example of the influence of these factors is seen in the selection of **adsorbent** materials for use inside machine enclosures. It is typical of ordinary maintenance practice to over lubricate rather than to install or service oil or grease seals. Hence, it is common to find oil and grease deposits on machines, often with dirt, metal chips and other debris. Such deposits greatly degrade the performance of absorption coatings, which are porous materials that easily wick oil and water. However, absorbent materials are now available with a thin imperforate skin or film covering of Mylar, Saran or Tedlar which prevents fluid wicking. Nevertheless, the sheer weight of grease deposits will degrade higher frequency performance even without wicking; fire hazards will also be increased. Therefore, the film must be strong enough that the deposits can be cleaned off with a cloth wet with warm detergent, plus mild rubbing. Such maintenance will be necessary with machine enclosures lined with absorbent materials. The time between cleanings can be greatly lengthened if oil and grease seals are installed or if deflecting shields are used on severe oil spray such as those from impacting parts in a punch press.

Curtain types of isolating materials such as lead-loaded vinyl are convenient for constructing an enclosure rapidly. Where leaded materials cannot be used as in some stages of food processing, a barium-loaded type is available. Monel and stainless steel are the only common metals usually permitted in contact with food products.

Fibrous absorbing materials in shop-made silencers and mufflers can be eroded by high-speed gas flow, say, above 15 m/s (50 fps). The fibres may pose a health hazard and can also interfere with machine operations. The situation is worsened if vibration is present, as it tends to break and shake out small fibres. The material used should have some bonding agent to hold fibres securely in place. In addition, the absorbent can be covered with wire screen or perforated metal. If the latter is used, the ratio of open screen to total area should be greater than 0.3. The effective absorption will be decreased if lesser open areas are used. Foamed absorbent materials shed much less than fibrous types, but all need sealing of raw edges by a film-making paint or by a thin plastic cover.

Fire resistance is often required by building codes. Absorbent materials are available with several degrees of resistance. With suitable materials, fire breaks are sometimes unnecessary in isolating walls that are filled with absorbent material. Since local building codes may not be applicable to structures that can be described as a part of the machine, prudent language must be used in describing the function of enclosure.

Last but definitely not least, a most important non-acoustical factor in the selection of noise control material is net cost. You must always be aware of this factor and should design so that labour-plus-material cost is minimised. A part of the net cost is the loss in production while a machine is being treated, so time to restore production must be considered too. Ease of maintenance must also guide the selection. Achieving a viable design means that material selection cannot be accomplished on a purely acoustical basis.

REFERENCES

(1) Industrial Noise Control Manual, Revised Edition, National Institute of Occupational Safety and Health (USA).

(2) Kejuruteraan Semangat Maju Sdn. Bhd., Subang Jaya, Malaysia.

APPENDIX 8

SELECTING AND USING A NOISE CONTROL CONSULTANT*

***Note:** This guide on selecting and using a consultant has been extracted and adapted from a USA source. Accordingly, some adjustments may have to be made as appropriate to suit the local conditions in Malaysia.

1. KNOWING WHEN A CONSULTANT IS NEEDED

Having read the guidelines proper would hopefully have set you some way towards being able to deal with some noise problems on your own. That would be the ideal case. However, if you are still unsure of the solution, if preliminary measures have proved unsatisfactory, or if the challenge is beyond your capability in terms of expediency, resources or expertise, it may be time to consider the use of a professional noise control consultant.

A consultant may be needed when the machine to be quietened is complex, with many noise sources of approximately equal strength. Locating the sources and obtaining their relative noise strengths will perhaps call for more sophisticated equipment and procedures than you may have. If you find that the A-weighted sound level at all points at a constant distance from the machine (but within the critical distance) covers a range of 5 dB or less, this is likely to be the case.

You may also need a consultant for unusual situations. With belt-driven blowers, for example, you may find a slow but considerable variation in sound level. Another is impact noise, as from a punch press, where several events take place in rapid succession. A narrow-band analysis of a tape recording is usually required. Inadvertent tuning of some part of the machine may lead to pure tone ringing that is difficult to locate. For such situations, using a consultant is often the most rapid way of getting results.

If you have installed noise control measures on your own that do not work, you may (albeit reluctantly) have to use a consultant to correct the situation. Although this may be a painful decision, it will usually occur but once. You should document the situation thoroughly and use the consultant to supply information on what went wrong.

Sometimes you may be approaching a lawsuit, where data must be obtained and presented (as an expert witness) by a disinterested third party. Many consultants can provide this complete service.

Once you have decided to obtain a consultant, how do you proceed? You should first be warned that currently there is no legal restriction on anyone offering services as an "acoustical consultant" or a "noise control consultant". Consequently, it is up to you to vet prospective applicants to avoid those who are unsuitable because of: (1) lack of training or experience; as well as (2) simple venality or greed.

2. SELECTING AN ADEQUATE CONSULTANT

People declaring themselves as consultants can be broadly classified according to **whether or not** they have a special interest in recommending a particular acoustical product or solution. Both types, properly used, have their special advantages and disadvantages. "Special-Interest Consultants" are individuals who vary in their backgrounds from product salesmen to specialist professionals who are quite capable in their line of business. Members of this group, who are most commonly indicated by the degree or their association with manufacturing or retail sales of acoustical products, should be used directly only if, by use of the techniques described in previous chapters, you have satisfied yourself that their solution is applicable to your problem. In this case, you have progressed to the point where the "consulting" aspect consists mainly of soliciting proposals for design and installation. The main problem remaining is to write your contract in such a way that you are guaranteed (to the extent possible) a solution to your problem that is cost effective. The advantage of using this group directly is that you avoid consultant costs. In effect, to a certain extent, you are in this way acting as your own consultant.

The disadvantage in dealing with a product-oriented special-interest consultant is that a costly mistake, out of proportion to the independent consultant's fees, is rendered more likely. Examples abound of cases in which a small fortune was spent in implementing a particular solution, only to find that no good was done (a common mistake is to use acoustical tile - a material good for absorbing reverberant noise - in situations where reverberant noise is not the problem). If there are any doubts in your mind as to the proper method for solving your problem, then an "Independent Consultant" (one free from ties to a particular line of products) should be called in. Since this independent consultant is what is usually meant by the word "consultant", it is this type of professional that will be discussed for the remainder of this Appendix. The word "independent" will be dropped.

In choosing a consultant, an ideal first step would be to inquire of any specialist professional organisation in the noise and acoustical field that is interested in the qualifications of its members. In the context of Malaysia, however, information on such an organisation is at the moment not readily available. The next best option would be to try the Institution of Engineers, Malaysia (IEM), or the Institute of Physics, Malaysia, both of which may have members active in noise and acoustical control. Alternatively, you could get in touch with the relevant faculty of a local tertiary institution. As another option, you could request a candidate's business resume and obtain references from satisfied customers, trade or industry associations etc., then follow these up. The relevant government authorities could be another possible information source. With a bit of effort on your part, these would provide an adequate approach to selection. On the other hand, you might like to get in touch with a professional noise control organisation overseas, say in USA, Europe, Australia, Japan etc., some of which might have Malaysian-based individuals among their membership. For that, the relevant foreign Embassy or High Commission may be able to give you some leads. Examples are:

(1) Institute of Noise Control Engineering (INCE), P. O. Box 1758, Poughkeepsie, New York 12601, USA.

(2) National Council of Acoustical Consultants (NCAC), 8811 Colesville Road, Suite 225, Silver Spring, Maryland 10910, USA.

You can also question the prospective consultant yourself. A series of guide questions is given in Section 3 below. These questions are rather completely presented here. Nevertheless, you may wish to ask only those that are pertinent to your particular task.

3. GUIDE QUESTIONS

3.1. Education

(1) What tertiary academic institutions did you attend?
(2) What courses did you take bearing on acoustics?
(3) What degrees did you receive? When?
(4) In what special conferences, seminars, symposia, or graduate courses in acoustics have you been involved, either as a student or as an instructor?

3.2. Experience

(1) For how many years have you been professionally active in acoustics?
(2) Please supply a list of recent clients that you have served, preferably in my geographical area, and on problems similar to those in which I am Interested.

(3) What teaching or training have you done in acoustics, and to what groups - university, industry, trade associations, civic groups, engineers, symposia?

3.3. Statur

(1) Are you now an Independent Consultant? For how many years? Full time or part-time?

(2) If part-time:
   (a) Who is your chief employer or in what other business ventures are you involved?
   (b) Is your employer aware and does he approve of your part-time activity as an acoustical consultant?
   (c) May we contact your employer concerning you?
   (d) What restrictions does your employer place on you as a part-time acoustical consultant?

(3) Are you associated with the manufacture or sale of a product that could create a conflict of interest in your activities as an acoustical consultant?

3.4. Professional Affiliations

(1) Of what engineering or scientific societies or associations are you a member?

(2) What is your present grade of membership and length of time in that grade, for each association?

(3) Have you been accorded any professional honours in these associations, such as offices, committee chairmanships, awards, or prizes?

(4) Are you a registered Professional Engineer? In what disciplines?

(5) Of what professional consulting associations are you or your firm a member?

(6) Of what trade associations, chambers of commerce, or similar business groups are you or your firm a member?

3.5. Special Capabilities

(1) In what areas of acoustics do you specialise?
- Noise measurement and control
- Architectural acoustics
- Hearing conservation
- Shock and vibration measurement and control
- Non-destructive testing

(2) What equipment do you have for conducting acoustical measurements: (1) in the field?; and (2) in the laboratory?

(3) With what national standards do you comply in conducting your acoustical measurements?

(4) Are you listed by any governmental or trade association body as an acceptable or certified acoustical test laboratory?

(5) What equipment do you have for the absolute calibration of test apparatus?

(6) Can you serve as an expert witness, either for your client or as a friend of the court? What experience have you had?

3.6. Business Practice

(1) Please indicate your fee structure. Do you handle this by hourly charges, estimates for total job, retainer charges, or all of these?

(2) If you use a contract form, please supply a sample.

(3) In your charges, how do you treat such expenses as travel, subsistence, shipping, report reproduction, and computer time? (Note: Consultants will usually charge to you the time spent during travel for work done for you Monday - Friday, 9:00 a.m. to 5:00 p.m. There may be a charge for use of highly specialised and expensive equipment.)

(4) What insurance and bonding do you have?

(5) Are you operating as an individual, partnership, or firm?

(6) What statements do you have in your contracts covering commercial security, liability, patent rights?

(7) What restriction is there on the use of your name in our reports, in litigation, and in advertisements?

(8) What is the character and extent of reports that you prepare? Can you give examples?

(9) What facilities do you have for producing design shop drawings on devices that you may develop for the specific purposes of a consulting task?

(10) Where is your principal office? Do you have branch offices? Where?

(11) What size is your staff? What are the qualifications of your staff members? Who will be working on this project?

4. THE PROPOSAL

Once you have selected a consultant, you can arrange to obtain his services in several ways. With most professional people a verbal commitment is sometimes all that is necessary. However, you may wish to request a written proposal that spells out the steps to be taken in the solution of your problem.

Often, in a larger job, proposals from several points of view are evaluated and used as one of the bases for the final selection of the consultant. In this case, answers to pertinent questions in the preceding section may be sought in the proposal rather than in the Interview. If so, evaluation of the proposal from this point of view is self-evident from the above discussion. If the questions you are interested in are not answered to your satisfaction, do not hesitate to ask for further clarification. In the discussion below, we are concerned with the section of the proposal that outlines the consultant's approach to your problem.

Aside from background qualifications of the consultant, the proposal should answer the questions:

1. How much is the service going to cost? Smaller jobs are often bid on an hourly basis, with a minimum commonly specified of a half day's work, plus direct expenses. Larger jobs are usually bid at a fixed amount, based on the work steps described.

2 What is the consultant going to do? The answer to this question may range all the way from a simple agreement to study the problem to a comprehensive step-by-step plan to solve it.

3. What will be the end result? The answer to this question is all too often not clearly understood; the result is usually a report that specifies the consultant's recommendation. If you do not want to pay for the preparation of a written report, and a verbal one will do, specify this in advance. Since the recommendations often call for construction to be carried out by others, whose work is not subject to the consultant's control, results usually cannot be guaranteed. Rather, an estimate of the noise reduction to be attained is all that can be expected. If the consultant is to provide drawings from which the contractor will work, you must specify sketches or finished drawings. Generally, sketches are sufficient. If special materials are required, the consultant should agree to specify alternative selections if possible. If you want a guaranteed result, experimental work will usually be necessary.

In the case of a proposal to quieten machine noise, the proposal, if detailed, will probably call out the following steps:

1. Determine the daily noise dose, so that the amount of reduction required is known.
2. From diagnostic measurements, determine the location and relative strength of the major noise sources on the machine in question, all other competing noise sources being more than 10 dB below the intended noise.
3. Design preliminary noise control means; discuss design with production people for possible interference with access to the machine.
4. Prepare and submit final recommendations in a report, with construction data.
5. In a post-report conference, resolve any questions or compromises; submit memorandum of conference.
6. If experimental work is needed, it can be added between 3 and 4 above.

5. OTHER SERVICES

If you wish, the consultant can also, as an additional service, provide monitoring of construction (of the noise control system) to determine compliance with specifications. The consultant can also make post-installation measurements to confirm predictions and supply oral briefings as needed. By working with the consultant during his measurements, you can learn a great deal about how to handle the special situation for which he has been retained. However, he brings to the job an instrument that is most difficult to reproduce: ears trained to listen and to guide the use of the physical instruments. It takes much practice and not a little aptitude to achieve this condition. This aspect of a consultant's expertise is most difficult to replace.

If the consultant is to serve as an expert witness for you, you will find that he is not automatically on your side. Rather, he is more like a friend of the court, devoted to bringing out the facts he has developed, with careful separation of fact from expert opinion. Complete frankness is needed if you want to avoid unpleasant surprises. For example, the consultant may be asked by the opposing attorney for a copy of his report to you. Thus, this report should be prepared with this eventuality in mind.

If the consultant is retained to develop a quieter machine for you, there should be a meeting of minds on handling of patent rights. Ordinarily the patent is assigned to the client, with perhaps a royalty arrangement for the inventor.

For many situations, the consultant will need photographs and plans of machines and shop layout to facilitate his evaluation. Permission to obtain these data can be handled in a manner consistent with your industrial security system. A qualified consultant will not have to be told to regard this material as private, not to be divulged to others without your prior consent. If you regard him as the professional person he is, your association with him can be fruitful to all concerned.

6. ADDITIONAL ADVICE — THE LAST WORD

Even with a great deal of education in the field of noise control, real life industry experience has shown that it is only after many years of **practical noise control involvement** that a feel for cost-effective noise control is developed. Formal education trains the individual in theoretical and laboratory principles; however, only extensive field (i.e. practical) experience can give one the skills and good judgement to be able to obtain cost-effective noise control solutions fairly rapidly. Therefore, whatever a candidate consultant's academic background and qualifications, it may not be such a bad idea to look beyond his formal training and education when selecting a professional noise control consultant.

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(1) Industrial Noise Control Manual, Revised Edition, National Institute of Occupational Safety and Health (USA).

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