TECHNICAL REPORT

ISO TR 11688-1

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Acoustics — Recommended practice for the design of low-noise machinery and equipment —

Part 1:
Planning

Acoustique — Pratique recommandée pour la conception de machines et d'équipements à bruit réduit —

Partie 1: Planification

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Contents

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the Internation Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of technical committees is to prepare International Standards, but in exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

— type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;

— type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;

— type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 11688-1, which is a Technical Report of type 3, was prepared by Technical Committee ISO/TC 43, *Acoustics*, Subcommittee SC 1, *Noise*.

ISO 11688 consists of the following parts, under the general title *Acoustics — Recommended practice for the design of low-noise machinery and equipment*:

— *Part 1: Planning* [Technical Report]

— *Part 2: Introduction into physics of low-noise design*

Introduction

This International Technical Report provides a guideline for the design of low-noise machinery. Most of the existing International Technical Reports prepared in ISO/TC 43/SC 1 specify methods for the measurement and/or evaluation of noise. The final objective of this International Technical Report, however, will be noise control in existing machinery and noise control at the design stage.

It is important that non-acoustic engineers are engaged in noise control practice. It is of great importance for these engineers to have a basic knowledge of noise generation and propagation characteristics and to understand the basic principles of noise control measures. Hence, this International Technical Report also serves as an introduction into acoustical terms, and as a basis to the acquisition of further knowledge in noise control.

It is strongly required to support the dissemination of the design rules given here through standardisation.

Such considerations have led to the preparation of International Technical Reports in the area of noise control.

Acoustics — Recommended practice for the design of low-noise machinery and equipment —

Part 1: Planning

1 Scope

This International Technical Report is an aid to understanding the basic concepts of noise control in machinery and equipment.

The recommended practice presented here is intended to assist the designer at any design stage to control the noise of the final product. Methodical development of products was chosen as a basis for the structure of this document (see Clause 4).

The list of design rules given in this International Technical Report is not exhaustive. Other technical measures for reducing noise at the design stage may be used if their efficacy is identical or higher.

To solve problems going beyond the scope of this International Technical Report, the designer can refer to the bibliography in Annex D, which presents the general state of acoustic handbooks at the time of publication. Furthermore, reference is made to the numerous technical publications dealing with acoustical problems.

2 References

ISO 3744:1994, *Acoustics — Determination of sound power levels of noise sources using sound pressure — Engineering method in an essentially free field over a reflecting plane.*

ISO 3746:—[1)], *Acoustics — Determination of sound power levels of noise sources — Survey method employing an enveloping measurement surface over a reflecting plane.*

ISO 4871:—[1)], *Acoustics — Declaration and verification of noise emission values of machinery and equipment.*

ISO 9611:—[1)], *Acoustics — Characterization of sources of structure-borne sound with respect to the airborne sound radiation of connected structures — Measurement of velocity at the contact points of machinery when resiliently mounted.*

ISO 9614-1:1994, *Acoustics — Determination of sound power levels of noise sources using sound intensity — Part 1: Measurement at discrete points.*

ISO 9614-2:—[1)], *Acoustics — Determination of sound power levels of noise sources using sound intensity — Part 2: Measurement by scanning.*

1) To be published.

ISO 11200:—[1)], *Acoustics — Noise emitted by machinery and equipment — Guidelines for the use of basic standards for the determination of emission sound pressure levels at the work station and at other specified positions.*

ISO 11689:—[1)], *Acoustics — Systematic collection and comparison of noise-emission data for machinery and equipment.*

3 Definitions

For the purpose of this International Technical Report the following definitions apply:

3.1 *Airborne, liquid-borne and structure-borne noise:* Sound propagating through air, a liquid or a solid structure, respectively.

3.2 *Active noise components:* Components of machinery, which generate noise. In many cases these are the power converting devices generating mechanical work from power resources, such as electrical, mechanical or magnetic energy, hydraulic pressure, internal forces, or friction. Other noise "components" may be regions with non-steady flow and contact surfaces between moving parts.

3.3 *Passive noise components:* Components which transmit noise generated by the active components; they do not contain noise sources but can be dominating radiators of noise. Typical passive components are structural parts and covering panels of machinery.

3.4 *Periodic noise:* A noise event which is periodically repeated. Typical sources of periodic noise are gear wheels and piston machines. It is characteristic for periodic noise that it exhibits a line spectrum.

3.5 *Tonal noise:* Noise which is dominated by one or several clearly distinguishable tone(s).

3.6 *Broad band noise:* Noise generated by either single shocks, i.e. short duration pressure pulses or impacts, or by turbulence in an air or fluid flow. The characteristics of broad band noise are that the frequency analysis shows a continuous spectrum over a large frequency range.

3.7 *Force excitation:* The excitation force is independent of the properties of the excited structure; an example of this is the effect of a light and flexible source on a relatively stiff and heavy structure.

3.8 *Velocity excitation:* The excitation velocity is independent of the properties of the excited structure; an example of this is a light and flexible structure excited by a relatively massive source.

3.9 *Quasi-static response:* Response of the machine at frequencies below the lowest resonant frequency.

3.10 *Resonant response:* Response in a frequency range of distinct resonances.

3.11 *Multi-resonant response:* Response in a frequency range with many resonances.

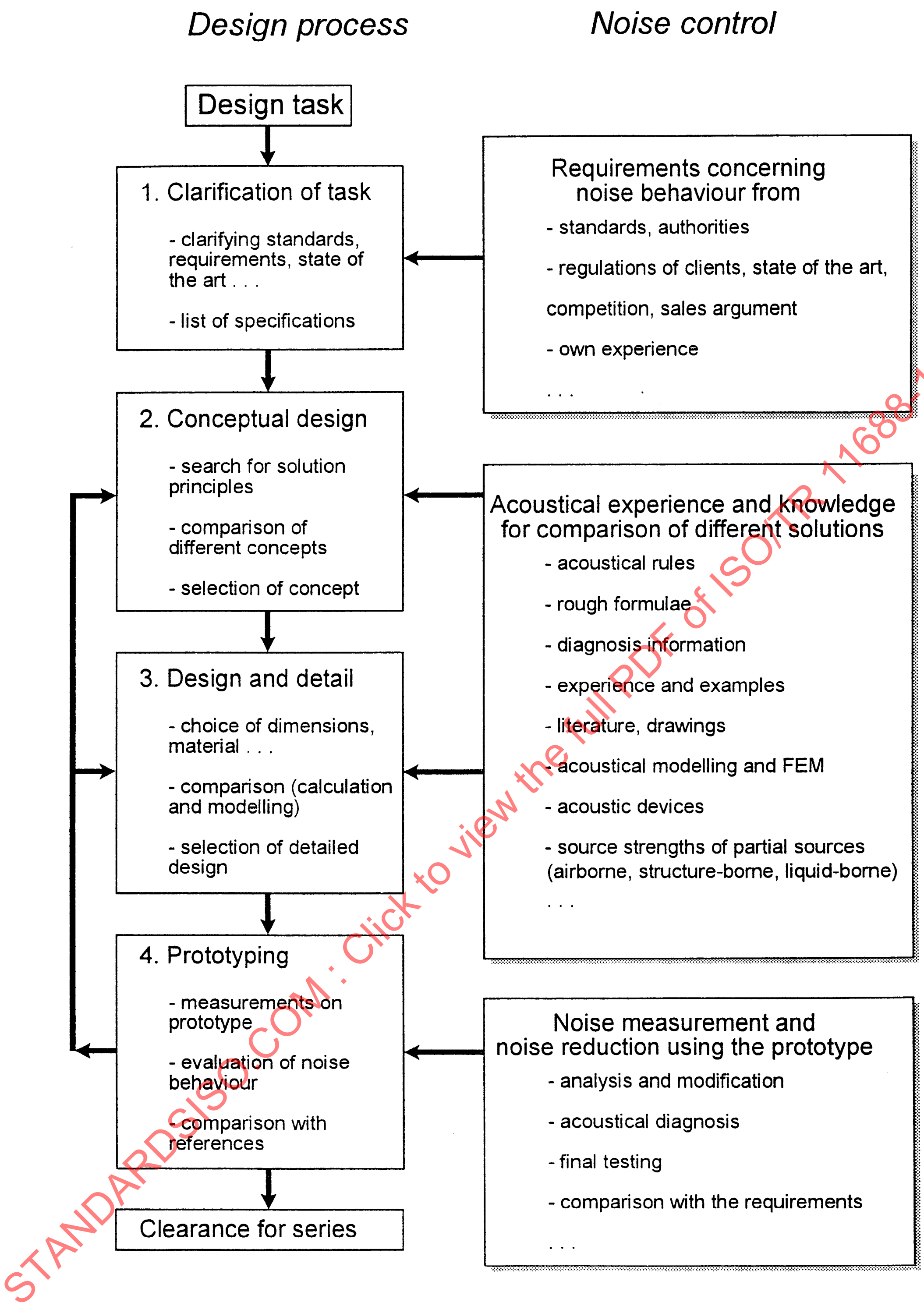


Fig. 1: Stages of the design procedure; support of design process by noise control methods

4 Methodical design and acoustic aspects

Methodical design is an operational approach which makes use of information from a variety of disciplines, for example machine acoustics. This way a basis is set for achieving targets and making decisions in design and development.

The design procedure can be divided into four phases (listed below) which are increasingly specific (see Fig. 1). Increase of information from phase to phase makes it possible to sort alternative solutions with respect to specific design criteria such as low noise level. The phases of systematic design are:

1. **Clarification of task:** Make a list of requirements which is the controlling document for the whole design task. Include noise specifications in this list with reference to legislation, the state of the art, competitors' products, client demand or the weighting of machine noise as a company sales argument. (See Annex B.)

2. **Conceptional design:** This phase of the design process concentrates mainly on achieving the desired objectives. Little information is available about the final product at this stage and the noise behaviour is often assessed by comparison to known designs.

3. **Design and detail:** As the design and choice of individual components progress, quantitative estimates of noise behaviour can be made through the selection of design options.

4. **Prototyping:** Measurements on the prototype allow quantification of major noise sources and sound paths. This may indicate specific measures leading to design changes. Compliance with the requirements can be confirmed by measurements.

The following procedure can be applied in each of the four phases described above. It is very important to follow the methodology of eliminating the most dominant noise problems in the earliest possible stage of design:

- The first step of the process is determining the major sources of noise in the machine and establishing a priority list or scheme (see 5.2).

- Once the major sources are recognised, a more detailed analysis of the noise mechanisms must be carried out (see 5.3).

- The next step is analysing and describing the direct radiation of noise from the sources to the receiving position(s), and the transmission through the structure to the radiating surfaces (see 5.4).

- The final step is to analyse the radiation from those surfaces and to determine the various contributions to the sound pressure level at the receiving position(s).

- Evaluate which combination of noise control measures is optimal.

In designing low-noise machinery one should try to identify the basic acoustic mechanisms involved by consideration of the causal chain (Fig. 2).

All design processes have a recursive element. So at every phase a decision has to be made as to whether the next phase can be entered or whether previous steps shall be repeated.

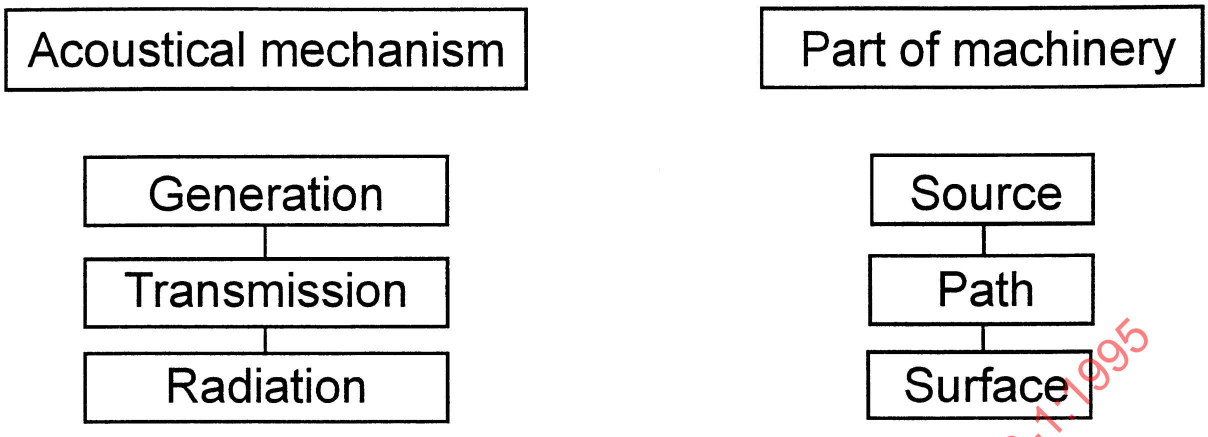


Fig. 2: Causal chain of noise generation

An illustration of how the different noise mechanisms are connected is shown in Fig. 3. The first priority in noise control is to identify the source. Different types of sources are shown in the first and second ring with key words corresponding to the headlines of the following clauses.

Once the source type is determined, transmission through the particular medium will take place as seen in the third ring. Finally the noise will radiate into free air or excite a structure. The figure can be used to show that every sound source has its own characteristics, its specific transmission path through the structure and excitation of the radiating surfaces. To control the noise from a machine with many different types of sources, it is necessary to analyse each noise source, transmission path and radiating surface on its own to be able to evaluate the relative importance. The next clause shows an example of such a machine.

5 Conceptual and detailed design

5.1 General

Since a design solution always comprises the choice of a physical operating principle and the choice of a functional system, it is possible to make the following general comments for the choice of design concepts.

- With a high degree of probability, the mode of operation with the lowest speed and acceleration will provide the best acoustic solution.

- For a given operational principle the noise from a machine can be reduced by altering the mass, stiffness and damping of the structure. Design parameters such as material, shape, position, number of elements, dimensions, structure and type of connections can have a large effect on the noise emission. If applied in the proper way such alterations may reduce the vibration and/or radiation of the machine.

- Steady flow of gases and liquids is quieter than unsteady flow.

Both in the conceptual phase and in the detailed design, the procedure described in Clause 4 and elaborated further in the following clauses can be used for diagnosis and noise control measures. In the conceptual phase only rough estimates, common design rules or a comparison with existing solutions is possible. In the detailed design phase the results of detailed calculations, modelling and survey experiments can be applied.

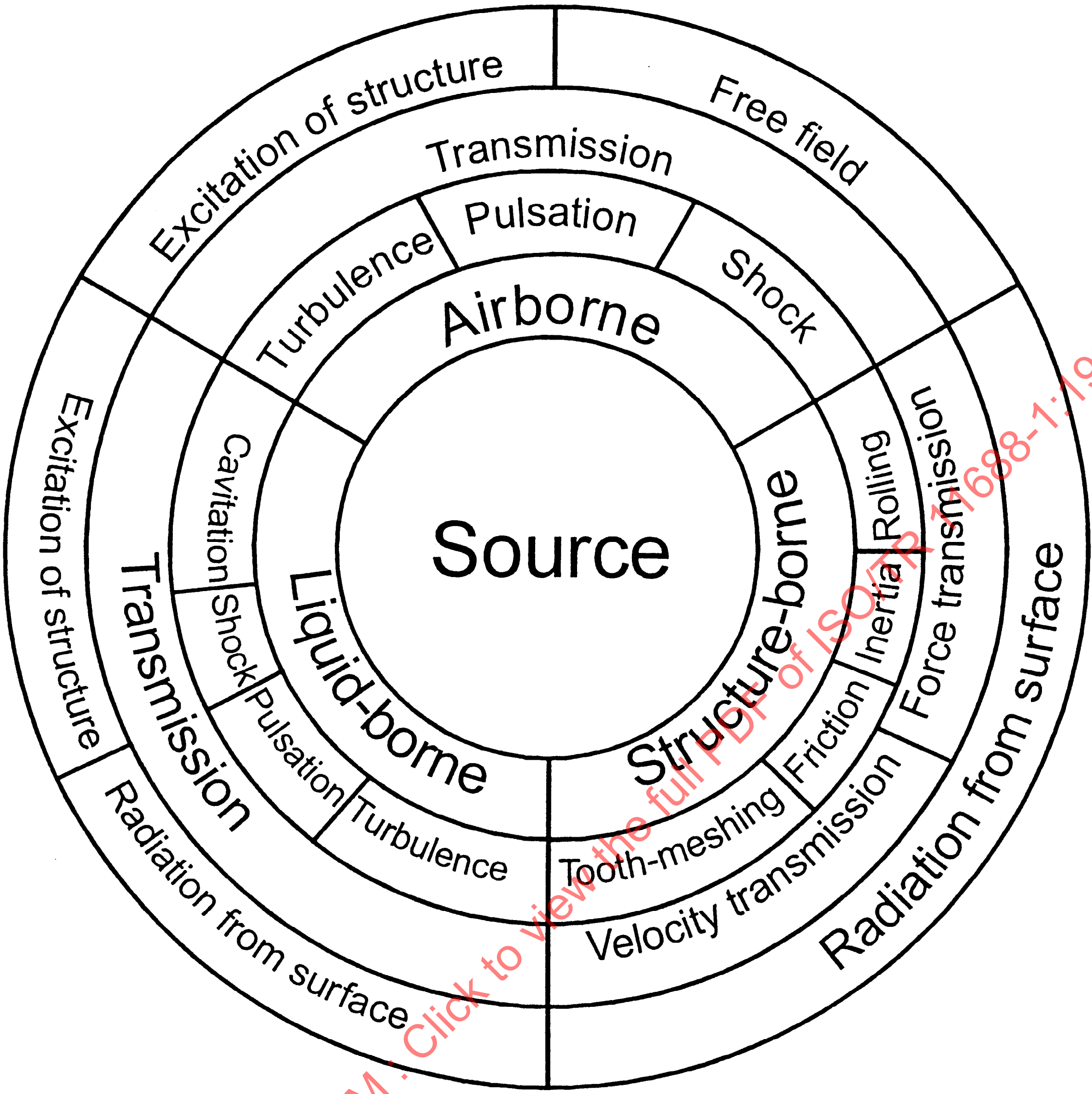


Fig 3: Basic model of noise generation in machines

5.2 *Basic steps*

5.2.1 Acoustical modelling and ranking

The noise behaviour in machinery with different noise sources can be visualised by an acoustic model of the machine (see Fig. 2). To elaborate this model, the designer must first divide the machine into active and passive noise components.

The active and passive noise components may have the capability of generating, transmitting and radiating airborne, liquid-borne and structure-borne noise. Therefore it is necessary to analyse the noise components for these three types of noise. The purpose of subdividing the noise components is the identification of the dominating noise sources, transmission paths and radiating surfaces.

Then the designer must analyse along which paths noise can be propagated. Structure-borne, liquid-borne and airborne sound paths shall be considered. Furthermore, possible direct radiation of airborne sound from the individual active components must be considered.

Finally the sound radiating surfaces of the machine must be identified.

When the most important noise sources with their transmission paths are identified, an analysis of the process parameters must be carried out. The dominant noise contributions have to be controlled first. It is recommended to control the sources first before dealing with transmission paths and the radiating surfaces.

Severe noise problems can be caused by the coincidence of driving frequencies and resonances in the active and passive components.

General design rules:

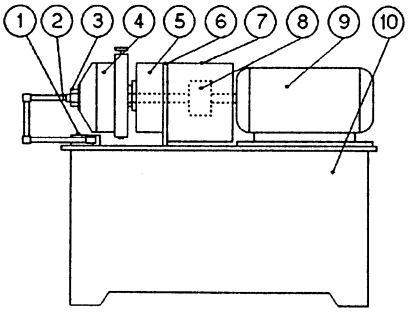
- Divide machine into active and passive noise components;
- Locate airborne, liquid-borne and structure-borne noise sources;
- Locate the airborne, liquid-borne and structure-borne sound paths;
- Locate the sound radiating surfaces;
- Identify the strongest contributions (sources, transmission paths, radiating surfaces).

5.2.2 Example

The purpose of this example is to demonstrate how acoustic modelling and noise source ranking can be carried out.

Fig. 4 shows a hydrostatic power pack having active noise components such as: electric motor, hydraulic pump and a valve.

They are all connected to the reservoir in a closed circuit.



1) Relief valve
2) Outlet tube (12 mm)
3) Reduction fitting (25 mm - 12 mm)
4) Pump
5) Vibration-isolated flange
6) Mounting flange
7) Cover
8) Vibration-isolated coupling
9) Electric motor
10) Reservoir

Fig. 4: Hydrostatic power pack

The power pack has active noise sources representing airborne, structure-borne and liquid-borne noise sources.

To visualise the transmission of noise from the different noise sources in the machine a block diagram, Fig. 5, is drawn which in graphical form illustrates the noise mechanisms of the power pack.

A list of the noise sources, paths and surfaces is shown in Tables 1 to 3

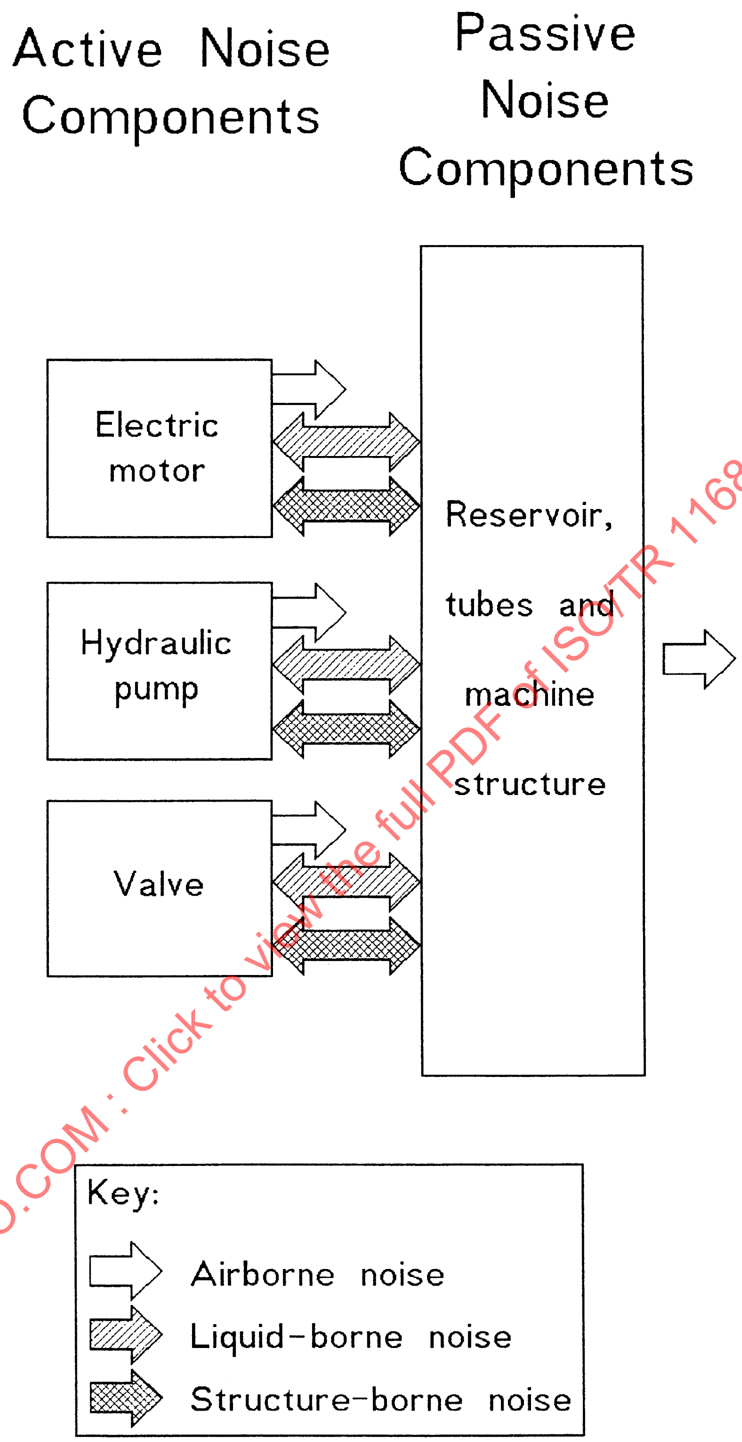


Fig. 5: Acoustical model of power pack

Table 1: Hydrostatic power pack; noise sources

Key:
A Airborne noise + Major contributor
S Structure-borne noise - Minor contributor
L Liquid-borne noise

Component	Source	A	S	L
Electric motor	Magnetic field		-	
	Fan	+		
	Unbalance		-	
Hydraulic pump	Pumping		+	+
	Unbalance		-	
Relief valve	Flow restriction			-
	Valve instability		-	-

Table 2: Hydrostatic power pack; transmission paths

Key:
A Airborne noise + Major contributor
S Structure-borne noise - Minor contributor
L Liquid-borne noise

Component	Path	A	S	L
Electric motor	Mounting points		+	
	Shaft		-	
Hydraulic pump	Mounting points		+	
	Shaft		-	
	Fluid connections		-	
Relief valve	Mounting points		-	
	Fluid connections		-	
Coupling	Coupling elements		+	
Tubes	Steel tubes		-	
	Fluid			-
Reservoir	Mounting points		+	
	Plates		-	
	Fluid			-

Table 3: Hydrostatic power pack; radiating surfaces

Key:
A Airborne noise + Major contributor
S Structure-borne noise - Minor contributor
L Liquid-borne noise

Component	Radiating surface	A	S	L
Electric motor	Housing	+		
Hydraulic pump	Housing	-		
Tubes	Walls	-		
Reservoir	Walls	+		

A number of experiments were carried out on the power pack to identify the different sources, paths and radiating surfaces concerning noise emission. The main results are shown in Table 4 as sound power measurements in a reverberant room. All experiments were done under the same operating conditions.

Table 4: Hydrostatic power pack: effect of noise control measures

Power pack noise control 1500 rpm; 180 bar		L_{WA} in dB
1	All transmission paths are present as in Fig. 5.	90
2	A separate frame supporting the motor and the hydraulic pump is suspended by vibration isolators on the reservoir lid. The reduction in structure-borne sound transmission to the reservoir/machine structure results in a small reduction in sound power.	89
3	The motor and pump frame is decoupled from the reservoir. The connection from the pump to the valve is made with a 2 m long hydraulic hose. This step gives a further reduction of 3 dB due to the reduction of structure-borne transmission to the reservoir.	86
4	The reservoir is removed from the reverberation room, eliminating the airborne radiation from it. This does not result in a further noise reduction, leadidng to the conclusion that the reservoir was already sufficiently decoupled in step 3.	86
5	The hydraulic pump is mounted on a conical flange on the electric motor, which included a vibration isolator. The fan is taken off the electric motor, and watercooling is provided. This results in a reduction of 1 dB.	85
6	Finally the electric motor is encapsulated to reduce the airborne noise radiated from its surface.	81

The conclusions from the experiments were as follows:

- The sound pressure level of the airborne noise radiated from the surface of the hydrostatic pump alone was 9 dB less than the sound power from the complete pack;
- The major noise sources were structure-borne and liquid-borne contributions from the hydrostatic pump;
- The dominant structure-borne noise transmission paths were those between the pump and motor and pump and resevoir;
- The dominant radiating surfaces were those of the electric motor and the reservoir.

The hydraulic pump used in this example is not typical of the equipment currently available. Replacing the hydraulic pump with one having less structure-borne and liquid-borne source strengths would have reduced the overall sound power level.

5.3 Control of noise sources

5.3.1 Airborne noise sources

All streaming gases (e.g. air) can cause noise by turbulence, shock and pulsation.

Turbulence

Turbulence is a noise generating mechanism which has many different forms. Turbulence can create pure tone components in flows over a cylinder, such as a chimney pipe. Tones are also generated by flow over a cavity which is seen for instance in a flute or in cutters in woodworking machines. In channel flows, noise can be generated by sharp corners, struts or valves.

Flows with high velocities at the nozzle exit or the tips of fans generate vortices due to the shear forces in the contact region between the air which is not moving near the nozzle and the exciting flow. This gives rise to broad band noise. The noise level and the spectrum of the noise depend on the flow velocity, the viscosity of the medium and the geometry of the nozzle.

Reductions are achieved by lowering the flow velocity in the contact region. This can be done by lowering the pressure difference, by using larger diameters or by providing a bypass flow, e.g. in nozzles or tube exits.

Noise sources are localised by analysing the flow system for possible obstacles. Reduction is effected by changing diameters of rods, by introducing spoilers on chimney stacks, by aerodynamic shaping or by reduction of flow velocity.

A fan should be designed to operate with the tip speed as low as possible. Use variable speed instead of throttling. Too little clearance between rotor and housing can increase noise generation.

Turbulence behind obstacles is avoided by removing obstacles, by minimising their number or by aerodynamic shaping (avoid sharp edges).

Changing the geometry of nozzles or valves by using a branched or slit type will increase the frequency of the generated sound which makes sound absorption and isolation easier.

Design rules to control turbulence in gases:

- Reduce operating pressure;
- Reduce pressure drops;
- Minimise flow speed;
- Optimise the jet outlet design to minimise velocity changes across a jet;
- Minimise tip speed of rotors;
- Avoid obstacles in the flow;
- Improve flow geometry.

Shock and pulsation

In piston machines, volume and pressure pulsations occur because of an uneven volume flow. Since these machines contain rotating components, pulsation occurs at frequencies proportional to the rotational frequency, generating **tonal noise.** Reductions are obtained by reducing the rotational speed, and in high pressure machines by reducing the operating pressure, if possible.

Shocks are generated by the fast release of a pressurised medium into a low pressure region. This happens during the opening and closing of valves and in high pressure pneumatic motors and pumps. Shock noise is reduced by slowing down the pressure-time variation either by reducing the pressure difference or by increasing the rise time. Quasi-stable shocks are generated in supersonic gas flows, for example in exhaust valves. These are reduced by reduction of the flow velocity.

By designing throat area variations at the opening of valves in such a way that only slow temporal variation can occur, the noise can be minimised. Compression of trapped fluid in for instance piston or gear pumps should be avoided through equalisation channels.

Single shocks from valves are **broad band** sources (generation of many frequencies). But shocks can occur periodically, for instance in high pressure pumps and motors, resulting in periodic noise with frequencies at the rotational frequency and multiples of this.

Stable shocks generated in valve exhausts due to velocities exceeding the normal speed of sound in air cause intense broad band noise. This can be avoided by reducing the flow velocity.

Design rules to control shock and pulsation in gases:

- Reduce speed of pressure change;
- Avoid obstacles near a rotor.

5.3.2 Liquid-borne noise sources

Like air, liquids can also generate noise by turbulence, pulsation and shock. Therefore the same rules as those mentioned in 5.3.1 can be applied.

Design rules to control liquid-borne noise sources:

- Reduce pressure drops;
- Minimise flow velocity;
- Avoid obstacles in the flow;
- Improve flow geometry;
- Reduce speed of pressure change.

<u>Cavitation</u>

Cavitation occurs in liquids when the static pressure drops below the vapour pressure. This may happen for instance in valves and pumps. In the region where the pressure is below the vapour pressure, cavitation bubbles grow. During recompression the bubbles implode, giving rise to high pressures. Since recompression often occurs by stagnation of flows on a surface, cavitation cannot only cause noise but can also be strongly erosive.

Cavitation can be avoided, for example, by reducing the pressure drop per valve stage. Introducing more stages can lead to the desired total pressure drop.

Cavitation is a broad band noise source.

Design rules to control cavitation:

- Reduce pressure drop;
- Reduce flow velocity;
- Increase static pressure;
- Improve flow geometry to avoid cavitation;
- Do not allow flow velocities exceeding 1,5 m/s;
- Keep suction lines short;
- Place the reservoir higher than the pump inlet;
- Use components with low flow resistance, e.g. sieves, valves etc.

5.3.3 Structure-borne noise sources

Impact

Impact noise is one of the most dominant noise sources in machinery. Many noise generating mechanisms can be treated as periodic impacts. The most important parameters in impact noise are the mass and speed of the impacting bodies and the duration of the impact.

The frequency analysis of one impact noise event shows that it is broad band noise dominated by high frequencies because of the short duration of the impact. Periodic impacts generate periodic noise. The spectrum shows the impact frequency and multiples of it.

Design rules to control impact noise:

- Increase impact time;
- Decrease impact velocity;
- Minimise the mass of the free impacting body;
- Increase the mass of the fixed body;
- Avoid loose components with alternating loads.

Tooth meshing

Tooth meshing as a special form of impact noise occurs for example in gearboxes and chain drives. Important parameters are the period of contact of the contacting elements, the force-time-variation during contact and the stiffness of the contacting elements (teeth). Tooth defects can cause an additional force variation and thereby increase the noise. Tooth meshing mostly results in the generation of pure tones (multiples of the meshing frequency).

Measures to influence tooth meshing are geometrical changes of teeth and contacting surfaces (profile relief at the tips and the ends of teeth, helical gears) to increase the contact ratios, improvement of the accuracy of gearing and adjustment or increase of the number of teeth. The number of teeth of the wheels in contact with each other should be chosen so that the same pair of teeth meet as seldom as possible (for instance by using prime numbers). Bending in teeth and shafts has to be taken into consideration with respect to geometrical changes. Gear wheel tooth profiles can be optimised for a limited load range, but not for all possible loads.

In case of low loads (e.g. in gears of household appliances), plastics can be used as material for gears. At high specific loads, a change of material has no significant effect on noise generation.

Design rules to control structure-borne noise caused by tooth meshing:

- Increase contact time;
- Use helical gears;
- Increase number of teeth;
- Improve quality (alignment, tooth accuracy);
- Use plastics for low loads.

Rolling

Noise generated by rolling is a result of roughness or irregularities in the contact region of the rolling surfaces. Rolling noise is encountered in roller and ball bearings, in conveyer systems, rail and road vehicles. Rolling noise also depends on the flexibility in the contact region.

The frequency content of rolling noise is broad band. When there are periodic elements in the excitation (e.g. in roller bearings), which is often the case, there may be tonal components as well.

Design rules to control rolling noise:

- Maintain smooth rolling surfaces;
- Use proper lubrication;
- Use precision roller bearings;
- Minimise tolerances in housing (fit of bearing);
- Use friction bearings;
- Increase flexibility in the contact area.

Inertia

The acceleration of mass induces forces which can result in noise generation by a variety of effects as for example impact, rolling, friction or pulsation. Inertia forces are induced by oscillating masses or by unbalanced or rotating parts. In some cases (e.g. a crank mechanism) inertia forces can cause excitation of parts of the machine structure with multiples of the rotation frequency. Beware of rolling noise if roller bearings are carrying inertia forces.

Inertia forces can be reduced by balancing, reducing the speed of revolution, the accelerated masses or the acceleration itself. In some cases single-plane balancing of disc-shaped rotors is sufficient, in all other cases dynamic balancing is necessary.

Design rules to control structure-borne noise caused by inertia:

- Minimise inertia forces by balancing of rotors or counterbalancing of moving masses;

- Minimise accelerated masses;
- Improve steadiness of motion.

Friction, self-excitation

Mechanisms where friction causes stick-slip phenomena are potential noise sources. The variations in force encountered here act as an impact type which can excite the resonances of the structure and assume the form of self-excitation of resonances. Friction created noise as seen in the squeaking of brake discs, hinges etc. is very dependent on material selection and lubrication.

In principle sliding generates broad band noise, but because of the excitation of resonances of the structure there are often strong tonal components in the generated sound.

Design rules to control structure-borne noise caused by friction and self-excitation:

- Control the friction by proper material selection;
- Control the friction by proper lubrication;
- Increase damping of the structure which can be self-excited.

Magnetic fields

Magnetic fields are used for example in electric motors to generate driving forces for rotation. The non-uniform variation of moment during one revolution resulting in force variations on the bearings and the static parts of the motor causes vibrations.

Magnetically induced noise is load dependent. It can be dominant in the case of a good thermal design of the electric motor and if low-noise bearings are applied. For drives with variable speed controlled by converters, high frequency noise may be generated.

Transformer noise consists of twice the mains frequency (50 Hz) and multiples of this up to about 600 Hz. Structure-borne noise generated in the transformer core by magnetic phenomena (e.g. magnetostriction which depends on material selection) is transmitted by the cooling medium and the mounting points and is radiated by the housing.

The windings of electrical transformers have to be fixed carefully to avoid vibrations causing low frequency sound.

Design rules to control structure-borne noise caused by magnetic fields:

- Choose number of slots to avoid excitation of resonances in stator and rotor;
- Avoid that slots are parallel to poles;
- Minimise tolerances in shape and position of the magnetic core to obtain a good degree of symmetry of the magnetic field;
- Optimise the shape of poles;
- Consider magnetically induced noise caused by converters of drives with variable speed;
- Select transformer core material to reduce structure-borne noise generation.

5.4 Noise transmission

5.4.1 Airborne noise transmission

Airborne noise generated in parts of the machine is transmitted to the environment. There are several means to control this transmission:

- acoustic enclosures;
- acoustic screens;
- silencers;
- sound absorption.

The physical phenomena used in these noise control measures are reflection and absorption.

Acoustic enclosures

These are closed sound insulating covers. Even small openings must be sealed. Covers are usually made of thin sheet metal to provide reflection of the noise. To improve the noise reduction of the enclosure a sound absorbent lining with porous material inside is necessary (thickness depends on the lowest frequency of interest).

The basic design of machines is either completed by enclosures, or existing machine covers are modified to act as acoustic enclosures. If openings are necessary (ventilation, flow of material, cables etc.) they should be equipped with silencers. Openings for maintenance purposes shall be closed carefully during operation.

To avoid structure-borne noise transmission into the cover sheets vibration isolation at the mounting points should be used (see 5.4.3).

Design rules to control airborne noise transmission by enclosures:

- Enclose noise sources totally, even small gaps or holes (e.g. slits, joints) are important and must be sealed;
- Use solid sheets (sound insulating material) for the outer shell of the enclosure;
- Use absorbent material inside;
- Use silencers at openings for ventilation, cables, pipes, transport of material etc.;
- Avoid rigid connections between enclosure and machine; minimise number of mounting points;
- Enclosure of components can be effective.

Screens

Screens can be mounted near small machine components with high noise emission. Their efficiency is much lower than that of enclosures and highly dependent on direction and distance. They are, however, useful for achieving a noise reduction within a restricted area (operator position).

Their effect is restricted to frequencies for which the length and width of the screen are at least equal to or larger than the wavelength of the airborne sound.

Design rules to control airborne noise transmission by means of a screen:

- Use solid sheets (sound insulating material) for the screen;
- Use screens for operator positions;
- The side of the screen facing the machine should be supplied with a sound-absorbent cover.

Silencers

Silencers are components which prevent the transmission of airborne sound via openings.

Absorption silencers are of the type "porously lined channel". They are frequently combined with enclosures and fans in order to ensure heat removal without reducing the efficiency of the enclosures. The working principle of reflection silencers is the reflection of sound at sudden changes of the cross-sectional area of pipes (normally used in internal combustion engines, intake and exhaust). Silencers are usually a combination of absorption and reflection types.

The expansion noise of pneumatic valves is controlled by expansion silencers.

Design rules to control airborne noise transmission by silencers:

- Use absorption silencers for broad band noise;
- Avoid velocities of flowing medium greater than 20 m/s in absorption silencers;
- Use reflection type silencers for low frequency noise;
- Use pneumatic expansion silencers for compressed air outlets.

5.4.2 Liquid-borne noise transmission

Transmission of liquid-borne sound usually takes place in pipes and tubes. Noise control can take place at the inlet to the system, within the system or at the outlet. The means of control are reflection and absorption. Reflection is obtained at the ends of the system through changes in cross-sectional area of the tube or hose, or by changing the rigidity of the pipe wall by using a combination of hoses and tubes. Absorption of liquid-borne sound is provided by hoses, steel-wool filled or gas filled accumulators. Hoses reduce liquid-borne sound but increase airborne sound.

Design rules to control liquid-borne noise transmission:

- Use a combination of tubes and hoses;
- Use silencers.

5.4.3 Structure-borne noise transmission

The transmission of structure-borne noise from the sources to the radiating surfaces can be influenced by changes of the mass, stiffness and damping distribution of the transmitting structure. The strategy chosen is dependent on a number of circumstances, such as:

- Increase of weight allowed or not?

- Force excitation or velocity excitation (or excitation of an intermediate character)?
- Narrow band or broad band excitation?
- Low frequency, mid frequency or high frequency excitation? These frequency ranges are connected with quasi static response, resonant response and multi-resonant response of the structure, respectively.

If increase of weight is allowed the addition of mass, especially near the excitation area, may be very effective, especially for the multi-resonant range and for force excitation.

In the case of force excitation an increase of input impedance by adding mass in the excitation area is very effective, especially for the multi-resonant range.

If the excitation has a velocity character, adding mass in the excitation range does not help. In that case isolation of the source is a more suitable measure.

When the excitation occurs in a limited number of narrow frequency bands, i.e. by a periodic signal, a change of resonant frequencies by redistribution of mass and stiffness may be useful, provided that the problem arises in the resonant frequency range. Addition of damping may also be effective in this case.

For broad band excitation a shift of resonant frequencies is not effective and a broad band reduction of transmission should be the aim.

In the low frequency range (with quasi-static response) the only measure that can be effective is vibration isolation (see below).

In the mid frequency range (with distinct resonant response) the following measures may be effective (depending on the type of excitation):

- Adding mass in the excitation point;
- Increase of damping;
- Isolation of the source;
- Reflection at discontinuities, see Fig. 6.

In the high frequency range (with multi-resonant response) the following measures may be effective:

- Increase of mass or stiffness in the excitation area;
- Isolation of the source;
- Discontinuities (see Fig. 6) in combination with extra damping on their source side.

Increase of damping alone is not very effective in this case.

It is useful to consider two of the above mentioned measures in some more detail:

- Vibration isolation;
- Damping.

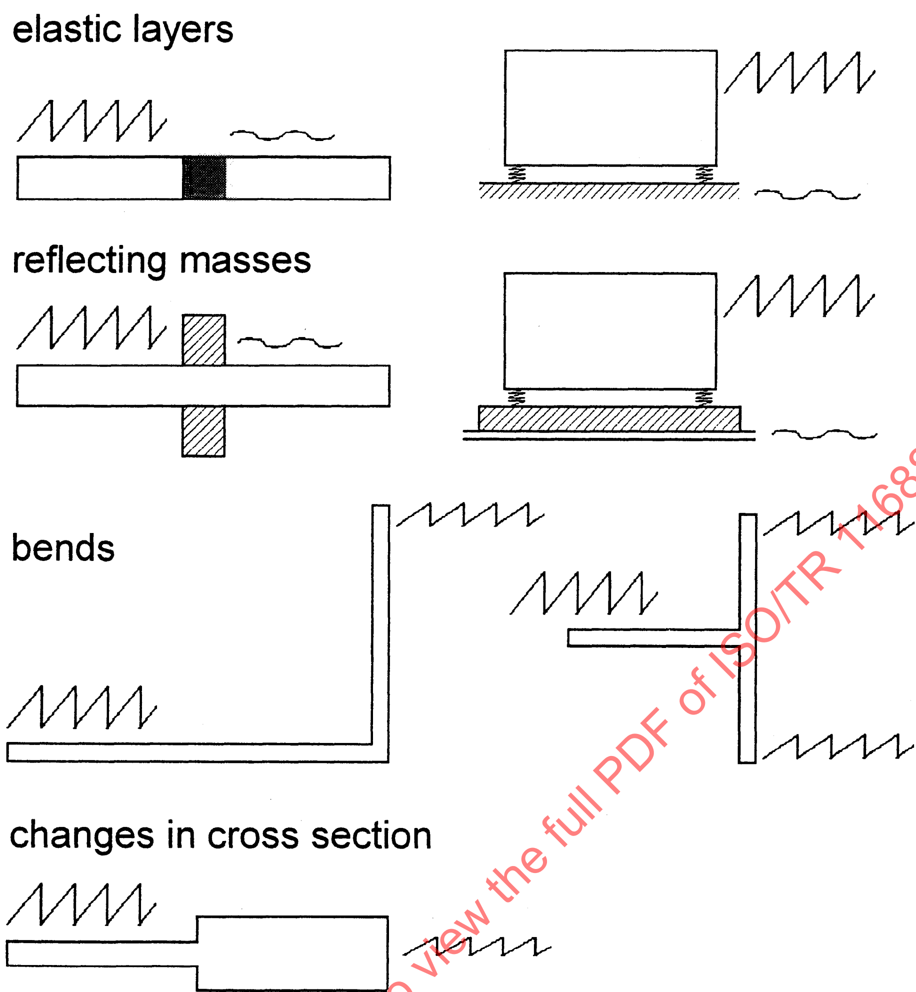


Fig. 6: Reflection of structure-borne sound at discontinuities

Vibration isolation

Vibration isolation is identical to the local introduction of a relatively low stiffness. It can be realised with the aid of isolators (which are resilient elements made of rubber, air bellows, helical steel springs or otherwise), or with the aid of resilient layers (made of rubber, cork or another "soft" material).

A significant amount of isolation can only be obtained when there is sufficient impedance mismatch on the receiver side, e.g. when the structure on the receiver side of the isolator or layer is sufficiently stiff and heavy. Increase of foundation impedance is equally important as decrease of isolator (or layer) stiffness.

Vibration isolation can be applied in various ways:

- By isolating the source;
- As a discontinuity in the transmission path (see Fig. 6);
- By isolating the outer covering structure from the rest of the machine; such a structure could be an acoustical enclosure which is applied to reduce the airborne sound radiation from the original surface.

Design rules for the control of structure-borne sound transmission by vibration isolation:

- Use elements or layers which are sufficiently resilient;
- Apply a sufficiently stiff and heavy foundation.

Damping

The addition of damping is used to dissipate more structural vibration energy. It is especially effective in the resonant response range in combination with structural discontinuities and when applied in the excitation area (i.e. close to the source).

The application of extra damping is only effective when the original damping of the structure was relatively low, which is often not true. Due to various mechanisms complicated machines are often considerably damped without a special damping treatment.

Structural damping can be added in various ways such as

- A special damping layer;
- Damped sandwich plates instead of a single plate;
- An additional plate with a limited number of point connections (the damping is caused by flow in the thin air layer between the two plates);
- Use of a material with more internal damping;
- Tuned dampers in the form of damped mass-spring systems.

The latter type of dampers is only useful when it is the aim to suppress a limited number of resonances.

Design rules for the control of structure-borne sound transmission by damping:

- Add additional damping when the original damping is low;
- Apply damping for reduction of transmission in the resonant response range;
- Apply damping near the source;
- Consider additional damping for thin plates. (It is difficult to damp stiff and heavy structures.)

5.5 *Noise radiation*

5.5.1 Radiation of airborne noise from openings

Airborne noise may be radiated through intake or exhaust openings, e.g. of an enclosure or at the end of a pipe. The noise has a certain directivity, usually resulting in the highest levels occurring along the axis of the pipe. In open spaces or in a free field such openings can be modified to reduce the noise in certain directions.

Design rules to control airborne noise radiation:

- Place the openings on the proper side (directivity of sound propagation);
- Use a silencer or a screen at the opening.

5.5.2 Radiation of structure-borne noise

Radiation from machine surfaces depends on area, shape, flexibility, mass and damping. With respect to radiation it is advantageous to design those parts of the machinery that are subjet to load as compact as possible, because small size and high stiffness and mass will reduce the radiation of noise.

To reduce radiation reduce the radiating area, or change stiffness, mass or damping of the structural part under investigation.

Radiation from a surface can also be reduced by applying panels with a low radiation efficiency. Another possibility is the application of sound proof panels which consist of a resilient layer and a thin plate.

Design rules to control structure-borne noise radiation:

- Reduce radiating area;
- Apply covers with low radiation efficiency for the dominant frequencies:
  - Thin plates instead of thick plates;
    (Warning: be careful if this cover is force excited)
  - Perforated plates;
  - Covers with damping layers.

6 Low-noise prototyping

6.1 General

Measurements on the prototype allow the detection of major noise sources and specific measures leading to design changes in the detailed design and approach phases (see Fig. 1). The compliance with limit values contained in the list of requirements (see Clause 4 and Annex B) can be confirmed by measurements.

6.2 Detection

The first step comprises an analysis by measurement aimed at detecting

- major noise sources and determining their classification (mechanisms of noise generation);
- noise transmission paths from the source to the receiver or through the structure to radiating surfaces;
- noise radiating machine parts (openings, plates).

In general, the analysis begins with relatively simple procedures facilitating a rough identification of the noise sources and their spatial, temporal and spectral classification. In-depth studies, connected with the assessment of the noise sources and transmission paths, are only carried out on selected components of the machine.

A list of measuring methods for acoustic tests on prototypes can be found in ISO/CD 11688-2 (at present under preparation). The selection of suitable test methods is dependent on various criteria:

- The measuring procedures are in part specifically configured for the analysis of the model of noise generation (see Fig. 3):
  - internal noise sources;
  - noise transmission path inside the machine;
  - noise radiating parts of the machine.
- Certain measuring methods can only be applied when the operating conditions of the machine (e.g. speed) can be varied, or when design changes can be effected (selective blocking or shielding, variation of elastic mounting, substitution of partial sources etc.).
- Most test methods provide qualitative results indicating the acoustic behaviour of the machine prototype, and form the basis for comparative studies (separation of different causes of noise, determination of fundamental transmission paths). Some procedures permit quantitative estimation of the radiated sound power of a particular noise source and/or a particular outer part of the machine.

6.3 Evaluation

Evaluation of the detected noise sources is carried out by establishing a priority list of major sources. In this process, the noise sources are listed and their fundamental characteristics are recorded (sound power level, sound pressure level at a reference measuring point, time function, frequency spectrum, position in the machine).

The establishment of the rank order of the sources can be carried out with the aid of measurements on the prototype, or the noise emission data on which the design is based can be used. This is necessary not only to deduce further actions for noise control on the machine, but also to provide traceability of all modifications made and their effects on the overall noise emissions of the machine.

In the planning of noise control measures for partial noise sources with the intention of reducing the overall noise level, a number of special features must be taken into account:

- It is not necessary to eliminate a dominant partial noise source completely, for the overall noise will then be determined by the remaining partial noise sources. In general, it will be sufficient to reduce a dominant component to approximately 5 dB below the residual noise. Further influencing of that partial noise source has only minor effects on the total noise level.

- When there are several partial noise sources approximately equal in strength, the noise control measures must be applied to all these noise sources. Reduction of individual noise sources will only have a marginal effect on the overall noise level.

- The relations stated above only apply to incoherent partial noise sources, i.e. sources not excited by the same source of excitation.

6.4 Modification

The aim of noise control measures is to reduce the noise emissions from partial noise sources in the order of priority established in the evaluation. Partial noise sources are each composed of an internal source, a transmission path and noise radiating machine parts, and therefore all these three components can be influenced.

For individual partial noise sources, it may under certain circumstances be necessary to determine more profound interactions with respect to excitation, transmission or radiation (sub-balance), in order to be able to identify the internal noise sources and take action on all three steps of noise generation. The machine-acoustical design rules are applicable here (see Clause 5).

In general, noise control measures are most effective when implemented close to the internal source. In principle the resulting order of priority is as follows:

1. Internal noise source

2. Transmission structure

3. Radiating machine parts

In practice the methods may be connected with technical and economical arguments.

The priority list of major noise problems (see 6.3) must be updated to reflect the noise control measures taken.

7 Final testing

The purpose of final testing is to confirm the level of noise control achieved on the machine. This testing covers measurement of the parameters stipulated prior to the start of design work (see Clause 4 and Annex B).

The measurement methods for the determination of the sound power level of machines are described in International Technical Reports (see Clause 2) and in noise test codes for specific machines. Above and beyond this, sound pressure level measurements can be carried out at specified positions.

During final testing, the machine must be

- operated with the specified accessories;
- set to operating parameters in accordance with the design requirement list;
- isolated from other plant components (e.g. connected ducts or pipework, which also radiate noise).

Annex A

Summary of design rules

General design rules:

- Divide machine into active and passive noise components;
- Locate airborne, liquid-borne and structure-borne noise sources;
- Locate the airborne, liquid-borne and structure-borne sound paths;
- Locate the sound radiating surfaces;
- Identify the strongest contributions (sources, transmission paths, radiating surfaces).

Airborne noise sources:

Design rules to control turbulence in gases:

- Reduce operating pressure;
- Reduce pressure drops;
- Minimise flow speed;
- Optimise the jet outlet design to minimise velocity changes across a jet;
- Minimise tip speed of rotors;
- Avoid obstacles in the flow;
- Improve flow geometry.

Design rules to control shock and pulsation in gases:

- Reduce speed of pressure change;
- Avoid obstacles near a rotor.

Liquid-borne noise sources:

Design rules to control liquid-borne noise sources:

- Reduce pressure drops;
- Minimise flow velocity;
- Avoid obstacles in the flow;
- Improve flow geometry;

Design rules to control cavitation:

- Reduce pressure drop;
- Reduce flow speed;
- Increase static pressure;
- Improve flow geometry to avoid cavitation;
- Do not allow flow velocities exceeding 1,5 m/s;
- Keep suction lines short;
- Place the reservoir higher than the pump inlet;
- Use components with low flow resistance, e.g. sieves, valves etc.

Structure-borne noise sources:

Design rules to control impact noise:

- Increase impact time;
- Decrease impact velocity;
- Minimise the mass of the free impacting body;
- Increase the mass of the fixed body;
- Avoid loose components with alternating loads.

Design rules to control structure-borne noise caused by tooth meshing:

- Increase contact time;
- Use helical gears;
- Increase number of teeth;
- Improve quality (alignment, tooth profile);
- Use plastics for low loads.

Design rules to control rolling noise:

- Maintain smooth rolling surfaces;
- Use proper lubrication;
- Use precision roller bearings;
- Minimise tolerances in housing (fit of bearing);
- Use friction bearings;

- Increase flexibility in the contact area.

Design rules to control structure-borne noise caused by inertia:

- Minimise inertia forces by balancing of rotors or counterbalancing of translating masses;
- Minimise accelerated masses;
- Improve steadiness of motion.

Design rules to control structure-borne noise caused by friction and self-excitation:

- Control the friction by proper material selection;
- Control the friction by proper lubrication;
- Increase damping of the structure which can be self-excited.

Design rules to control structure-borne noise caused by magnetic fields:

- Choose number of slots to avoid excitation of resonances in stator and rotor;
- Avoid that slots are parallel to poles;
- Minimise tolerances in shape and position of the magnetic core to obtain a good degree of symmetry of the magnetic field;
- Optimise the shape of poles;
- Consider magnetically induced noise caused by converters of drives with variable speed ;
- Select transformer core material to reduce structure-borne noise generation.

Airborne noise transmission:

Design rules to control airborne noise transmission by enclosures:

- Enclose noise sources totally, even small gaps or holes (e.g. slits, joints) are important and must be sealed;
- Use solid sheets (sound insulating material) for the outer shell of the enclosure;
- Use absorbent material inside;
- Use silencers at openings for ventilation, cables, pipes, transport of material etc.;
- Avoid rigid connections between enclosure and machine; minimise number of mounting points;
- Enclosure of components can be effective.

Design rules to control airborne noise transmission by means of a screen:

- Use solid sheets (sound insulating material) for the screen;
- Use screens for operator positions;
- The side of the screen facing the machine should be supplied with a sound-absorbent cover.

Design rules to control airborne noise transmission by silencers:

- Use absorption silencers for broad band noise;
- Avoid velocities of flowing medium greater than 20 m/s in absorption silencers;
- Use reflection type silencers for low frequency noise;
- Use pneumatic expansion silencers for compressed air outlets.

Liquid-borne noise transmission:

Design rules to control liquid-borne noise transmission:

- Use a combination of tubes and hoses;
- Use silencers.

Structure-borne noise transmission:

Design rules for the control of structure-borne sound transmission by vibration isolation:

- Use elements or layers which are sufficiently resilient;
- Apply a sufficiently stiff and heavy foundation.

Design rules for the control of structure-borne sound transmission by damping:

- Add additional damping when the original damping is low;
- Apply damping for reduction of transmission in the resonant response range;
- Apply damping near the source;
- Consider additional damping for thin plates. (It is difficult to damp stiff and heavy structures.)

Airborne noise radiation:

Design rules to control airborne noise radiation:

- Place the openings on the proper side (directivity of sound propagation);
- Use a silencer or a screen at the opening.

Structure-borne noise radiation:

Design rules to control structure-borne noise radiation:

- Reduce radiating area;
- Apply covers with low radiation efficiency for the dominant frequencies:
  - Thin plates instead of thick plates;
    (Warning: be careful if this cover is force excited)
  - Perforated plates;
  - Covers with damping layers.

Annex B

Noise control requirements for design

B.1 Noise emission quantities

The following quantities are used for specifications of noise emission of machinery, e.g.

- Main quantities
  - A-weighted sound power level L_{WA};
  - A-weighted emission sound pressure level L_{pA} at the work station (operator position) or at specific positions;
  - Other quantities as defined in ISO-Standards and legislative regulations;

- Additional quantities
  - A-weighted surface sound pressure level $\overline{L}_{pAf}$ at a distance from the machine;
  - C-weighted peak emission sound pressure level L_{pCpeak};

- Additional information can be obtained from:
  - Sound pressure spectra (e.g. in one-third-octave bands) at selected measuring points;
  - Impulsiveness;
  - Directivity index *DI*, if necessary.

The measurement procedures for these quantities are described in International Standards (e.g. ISO 3740-series, ISO 11200-series, ISO/DIS 9614 parts 1 and 2).

If versions of the design have to be compared at a prototype stage (see Clause 6) it is possible to use simplified procedures, e.g. only one microphone position instead of many positions around the machine.

B.2 Noise specifications

B.2.1 Emission values

Noise emission values, representing the noise control requirements for the design, should be determined according to the following principles:

Determine

- whether or not a specific ISO standard for noise measurement exists for that kind of machine; if not, which ISO guide for noise measurement should be applied;

- the noise quantities for which emission values have to be set up in accordance with the relevant standard.

The emission values for noise specifications can be determined with the help of:

- Noise limits (or recommended noise limits) required by machine buyers;

- Noise limits (or recommended noise limits) contained in regulations of international organisations (e.g. ECE-regulation for cars, ICAO-Annex 16 for airplanes, IEC-regulation for rotating electrical machines) or in national standards