ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

ANALYSIS OF NOISE CONTROL MEASURES ON OUTDOOR MACHINERY USING EQUIP+

Michael Dittrich

TNO Science and Industry
Stieltjesweg 1, 2628 CK, Delft, the Netherlands
michael.dittrich@tno.nl

Abstract

Noise control of different types of outdoor machinery covered by EU Directive 2000/14/EC such as construction machines, generators and other equipment powered by internal combustion engines requires knowledge of the noise path model and the potential noise control measures. As there is often a trade-off between different design parameters and cost, it is of use to the designer to be able to study the effect of various combinations of noise control measures.The noise path model consists of the main sound sources, noise paths and radiators, described in terms of their spectral contribution to the total sound power or sound pressure level. It also can include the dependency on operating conditions (speed, load, power), and relevant design parameters such as enclosure parameters, intake and exhaust design, elastic mount stiffness, damping materials and others. It is illustrated how the EQUIP+ noise path modeller can be used to assist in this process. Examples of component-based noise path models are shown with the main acoustic characteristics and influence parameters.

INTRODUCTION

Outdoor machinery is a well-known source of environmental and occupational noise. European Directive 2000/14/EC [1] requires noise marking for 57 types of equipment used outdoors, and additionally, sets noise limits for 22 of these. It brings together a number of previous separate Directives covering noise emission from some types of machinery such as lawnmowers, compressors and construction equipment, adding several new ones, such as cooling equipment on vehicles, glass recycling containers and piling equipment.

Article 1 of the Directive states: “The aim of this Directive is to harmonise the laws of the Member States relating to noise emission standards, conformity assessment procedures, marking, technical documentation and collection of data concerning the noise emission in the environment of equipment for use outdoors. It will contribute to the smooth functioning of the internal market, while protecting human health and well-being.” Directive 2005/88/EC [2] is an amendment to 2000/14/EC, adapting the stage II limits for Article 12 equipment by 2-3 dB, in force from January 2006.

The provision of noise information is also consistent with the requirements of the Machinery Directive 98/37/EC and CE-marking. Quieter machinery not only benefits the environment but also the workplace, both for the operator and the bystander of machinery.

In this article some of the noise sources and noise-relevant design parameters for this type of machinery are discussed, and the characteristic noise path models and typical noise reduction solutions are elaborated. This is done using the EQUIP+ tool for noise path modelling and low noise design of machinery, which is intended to assist designers with respect to low noise design.

OUTDOOR MACHINERY GROUPS

Outdoor machinery covered by the 2000/14 Directive includes machines that can be divided into a number of groups shown in table 1. Most equipment types are mobile or self-propelled. Many have an internal combustion engine as power source and are used in construction or municipal works, goods handling and gardening.

For the 22 equipment types that have noise limits, these limits are given either as a constant or as a function of a relevant noise parameter in the form

$$L_{Wlim} = L_{Wref} + a \lg x \qquad (1)$$

where L_{Wref} is a reference value, x a relevant parameter such as e.g. installed power and a is an empirically determined coefficient. The sound power is measured under test conditions described in the Directive having some relation to real operating conditions. For some machines and power ranges a single value $L_{Wlim} = L_{Wref}$ is given, and above a certain power level the coefficient is

$$L_{Wref} + 11 \lg P_{mech} \qquad (2)$$

for net installed mechanical power P_{mech} in kW (mostly combustion engines),

$$L_{Wref} + 11 \lg m \qquad (3)$$

for total oscillating mass m in kg (breakers),

$$L_{Wref} + \lg P_{el} \qquad (4)$$

for electrical power P_{el} in kW,

$$L_{Wref} + 2 \lg P_{mech} \qquad (5)$$

for net installed mechanical power P_{mech} in kW for compressors,

$$L_{Wref} + 11 \lg L \qquad (6)$$

approximately, for the cutting width L (cm) of lawnmowers and trimmers.

Table 1 - Outdoor machinery groups from the 2000/14 Directive.
(ICE stands for Internal Combustion Engine)

	Subject to sound power limits and noise marking	**Subject to noise marking only**
Construction	- Compaction machines, vibratory - Paver-finishers - Concrete breakers and picks, hand-held - Graders - Construction winches, ICE - Tracked dozers, loaders, excavator-loaders - Wheeled dozers, loaders, excavator-loaders - Excavators - Landfill compactors	- Compaction machines (explosion) - Paver-finishers, with screed - Concrete or mortar mixers - Construction winches, electric - Conveying and spraying machines for concrete and mortar - Drill rigs - Hydraulic hammers - Joint cutters - Piling equipment - Pipe layers - Road milling machines - Trenchers - Truck mixers - Building site band saw machines - Building site circular saw benches
Cranes/ Lifting	- Builders hoists, ICE - Lift trucks, counterbalanced, ICE - Mobile cranes - Tower cranes	- Builders hoists, electric - Arial access platforms, ICE - Conveyor belts - Lift trucks, counterbalanced, ICE (lift cap. < 10 t)
Power generation	- Power generators (< 400 kW) - Welding generators - Hydraulic power packs	- Power generators (≥ 400 kW)
Compressors	- Compressors	
Pumps		- Equipment for loading and unloading silos or tanks on trucks - Water pump units
Municipal		- Combined high pressure flushers and suction vehicles - High pressure flushers - Suction vehicles - High pressure water jet machines - Power sweepers - Snow removing machines - Piste caterpillars - Refuse collection vehicles - Mobile waste containers - Glass recycling containers
Cooling		- Cooling equipment on vehicles
Garden maintenance	- Lawn mowers - Lawn and lawn edge trimmers - Motor hoes	- Brush cutters - Grass/grass edge trimmers, ICE - Hedge trimmers - Chain saws, portable - Leaf blowers and leaf collectors - Scarifiers - Shredders/chippers

The formulas for noise limits are approximations based on empirical data related to net installed power. For the purpose of noise control and low noise design, the various noise sources, their contributions and relevant design parameters must be taken into account. The EQUIP+ tool allows this type of analysis.

THE EQUIP+ TOOL

EQUIP+ is a software tool developed by TNO including a noise path modeller and a low noise design manual, used as an aid to the designer to develop quieter machinery. General design rules can be found in the manual, whereas a noise path model is required to describe the noise situation in terms of the relevant components, main influence parameters and noise control measures. EQUIP+ provides some basic generic calculation models for typical noise sources, however for specific machines often some experimental feedback is required to tune and verify the model. Before actually building a calculation model, the visual noise path model should be correct, i.e. the noise generation mechanisms, relevant components, receiver type and noise paths should be known. A valid noise path model is in itself a major step towards understanding how to achieve a low noise design.

In the visual representation of the noise path model (see figure 1), square icons represent the relevant components, the blue round icons represent the noise generation mechanisms and the red round icons represent the receiver (sound pressure or sound power). The noise paths are given by different linetypes, solid for structure-borne noise, dashed for airborne noise and dash-dot for liquid-borne noise. Any type of calculation model can be attached to this visual model, potentially including the main influence parameters such as engine speeds, power, dimensions, materials, damping and others.

COMMON COMPONENTS AND NOISE SOURCES

For many of the machine types in the 2000/14/EC Directive, there are a number of frequently occurring components which are relevant for noise emission, listed in table 2, with their typical noise sources and radiators, and some main influence parameters.

Operating conditions such as power setting, speeds, loading and mounting have a major influence on the noise emission. For tools, also the noise contribution from the workpiece may need to be taken into account. For the machinery in the Directive, the measurement conditions are often performed under load, at nominal or maximum speed or at conditions of maximum noise production.

To achieve a noise reduction it is often necessary to combine noise control measures on different paths and parts of the machine, especially if more than one noise path is involved. In addition, spectral information needs to be taken into account to ensure a good balancing of noise control measures. One-third octave data is a suitable level of detail for this purpose.

Table 2 - Common noise relevant components for outdoor machinery

Components	**Noise generation**	**Noise Radiation**	**Main influence parameters**
Combustion engines	Pressure variation, mechanical contact, unbalance forces	Direct, via exhaust and inlet and via mounts and attached components	Engine rpm, load, stroke volume, number of cylinders, type
Cooling fans and suction devices	Turbulence and blade interaction	Via ducts	Fan speed, diameter, efficiency
Compressors	Pressure variation, mechanical contact, unbalance forces	Direct, via outlet, inlet and via mounts and and attached components	Rpm, pressure load, stroke volume, number of cylinders, type
Electric motors	Often cooling fan, also electromagnetic	Cooling vents and housing, attached components	Rpm and Torque, type of motor, number of fields, current
Hydraulic pumps and motors, valves, pipes and hoses	Fluid turbulence, mechnical contact	Housing, piping, hoses and attached components	Rpm, pressure load, flow rate
Gear transmissions	Gear forces	Housing	Rpm and tooth number of fastest stage, load, gear type and quality
Cutting and impacting elements	Impact forces	Impacting and attached components	Masses and velocities of impact, contact elasticity
Elastic mounts	Not applicable	Sometimes from mount itself	Stiffness (dynamic), mobility ratio
Support frames and plates	Not applicable	Beams and plates	Material, thickness and geometry, damping
Enclosures and covers	Not applicable	Outer casing and openings	Covered area, open area, absorbent area
Exhaust/outlets and intakes with silencers	Potentially flow noise	Orifice and casing	Cross-section ratio, internal absorption

GENERIC NOISE PATH MODELS

Two examples of noise path models are shown here to illustrate the noise sources, transmission paths and influence parameters of a diesel engine powered machine and a lawnmower. It should be emphasised that a feedback of experimental data is important to tune such a model for a given machine type.

Diesel engine unit

An example of a noise path model is given here for a diesel powered machine with a support frame, a cooling fan and an enclosure (figure 1).This type of noise path model is typical for a range of combustion engine powered machines and equipment covered by the Directive. Other components and noise sources can easily be added.

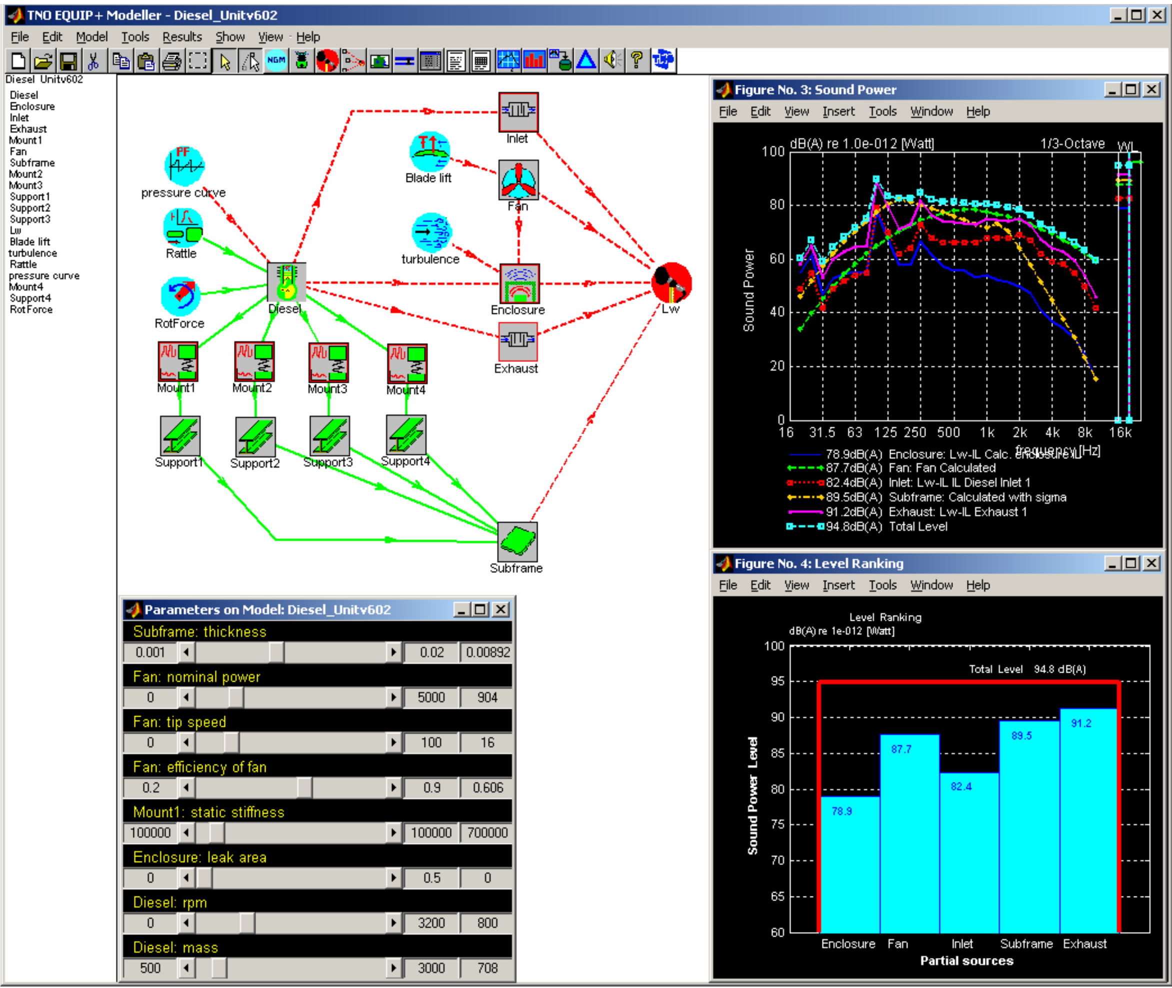

Figure 1 - Component-based noise path model of a diesel-powered machine in EQUIP+, including engine, mounts and subframe, enclosure, intake, exhaust and fan. Slidebars on various influence parameters are shown on the lower left. The overall and spectral ranking is given on the right.

The noise path model shows only the noise-relevant components and the main transmission paths, airborne and structure-borne. The main influence parameters chosen for this model are: thickness of the subframe; nominal power of the cooling fan; tip speed of the cooling fan; efficiency of the cooling fan; stiffness of the engine mounts; engine rpm; engine mass.

The main task to achieve a low noise design is to obtain a minimum sound power by balancing the contributions from the main sound radiators, in this case the subframe, the inlet and exhaust, the enclosure and the fan. These contributions are expressed in terms of sound power. The power at the receiver L_W is the energy sum of the sound powers from the main radiators. In table 3 some examples of basic formulas used for parametric calculations are shown, originating from various literature sources.The examples given here are indicative and can of course be refined. The noise level can be minimised by finding optimal parameter configurations.

Table 3 – Examples of basic formulas for parametric calculation in the noise path model.

Engine	$L_W(f) = 57 + 10\lg\left(\frac{NP(1+\frac{P}{m})}{\left(\frac{1000}{f}\right)+\left(\frac{f}{1000}\right)}\right) + 20\lg\frac{n}{N}$ (7)
Fan	$L_W(f) = L_{Wsp} + 10\lg\left(\frac{P_e(1-\eta)\left(\frac{u_0}{c}\right)^{1.5}}{1+\left(\frac{St}{St_0}\right)^m}\right)$ m=1.7 (8)
Plate	$L_W = 20\lg F - 20\lg\lvert Z_{in}\rvert + 20\lg\lvert H_v\rvert + 10\lg\sigma + 10\lg(\rho c S)$ (9)
Enclosure	$D = 10\lg\left(10^{-\frac{Da}{10}} + 10^{-\frac{Db}{10}}\right)$ $D_a = R - 10\lg(\frac{S_{tot}}{A})$ $D_b = 10\lg(1+\alpha\frac{S_{tot}}{S_{leak}})$ $A = \alpha S_{cov}$ $S_{tot} = S_{cov} + S_n$ (10)
Elastic mounts	$Z = \frac{k}{j\omega}$ (11)
Exhaust/intlet	$L_W = L_{Win} - IL$ (12)

The key to the variables is as follows: Lw=sound power level; n,N=rpm and nominal rpm; f=frequency; m=mass; P=mechanical power; P_e=electrical power; η=fan efficiency; u=tip speed; c=speed of sound; St=Strouhal number; F= force; Z= impedance; Hv=velocity transfer; σ = radiation efficiency; S=area; D= attenuation; α = absorption factor; R= sound insulation index; k= stiffness; ω=angular frequency; L_{Win}=input power at inlet; IL=insertion loss.

Lawnmower
Another example of a noise path model is shown for a lawnmower in figure 2.
Although a smaller machine, the noise path model has similarities to the previous

example except that the rotating blade is present as a sound source.

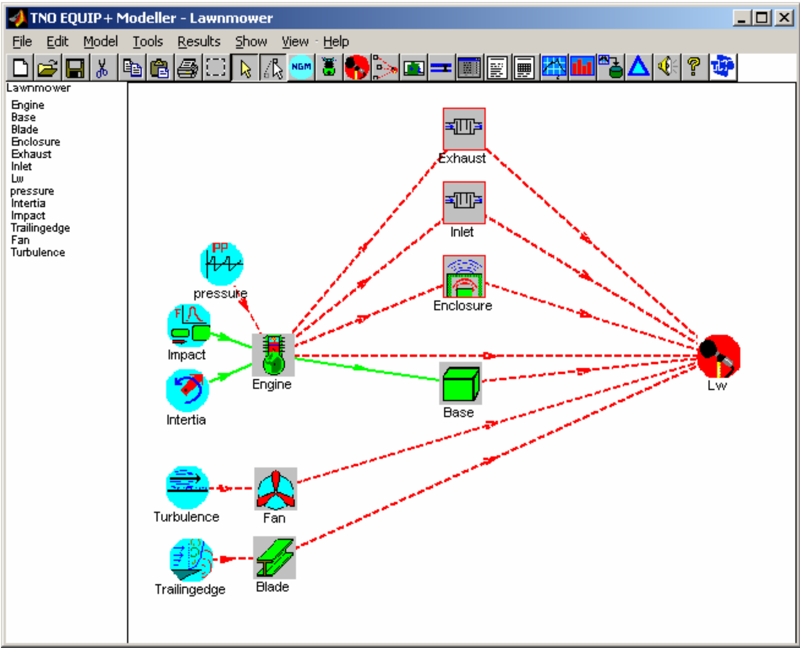

Figure 2 – Noise path model of a lawnmower, combustion engine powered.

SUMMARY

Low noise design of outdoor machinery can be approached with parametric noise path modelling, starting with general noise path models for typical machinery groups such as those for combustion-engine powered equipment and others. Such models include one third octave spectral data, obtained from models or from measurement.

REFERENCES

[1| Directive 2000/14/EC of the European Parliament and of the Council of 8 May 2000, on the approximation of the laws of the Member States relating to the noise emission in the environment by equipment for use outdoors.
[2] Directive 2005/88/EC of the European Parliament and of the Council of 14 December 2005, amending Directive 2000/14/EC on the approximation of the laws of the Member States relating to the noise emission in the environment by equipment for use outdoors.
[3] "Position paper on guidelines for the application of the European Parliament and Council Directive 2000/14/EC on the approximation of the laws of the Member States relating to the noise emission in the environment by equipment for use outdoors",
EU DG Environment, Brussels 2002.
[4] EQUIP+ User Manual, Modelling Manual, TNO 2003.