Comfortable earth moving machinery

Knowledge and experiences from the Eurocabin project

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5 Interior noise and vibration reduction

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5.1 Introduction

Interior noise and vibration is one of the design aspects of machines. This becomes of major importance when the machine and man operate together for a long period (i.e. working day). The EuroCabins project investigates the ergonomics of cabins of earth moving machines. Interviews with a representative selection of operators have shown that noise and poor seat comfort are important aspects where improvements are needed.
This chapter briefly introduces the state of art around this topic, divided in:

1. interior noise;
2. hand-arm and whole-body vibration.

The chapter, based on a literature search and TNO projects, will give the designer some directions to go in optimizing these comfort aspects of the earth moving machines. First the state of knowledge for both areas is described. Next to pragmatic solutions new advanced developments will set new targets for noise and vibration reduction, i.e. active control systems. These will be presented in the paragraph after. Concluding remarks, a list of (internet) links and standards and the references will complete the paper.

5.2 State of knowledge

Reduction of the workload by increasing the comfort level has been subject of many studies. It is therefore impossible to give a complete overview of the developments in the past and present. Literature has been studied and from this study some developments have been selected for this chapter. More detailed information can be found through the references, the internet links and the standards.
The next paragraphs describe the state of knowledge for the area of interior noise and body vibration.

5.2.1 *Interior noise*

Requirements and standards

By legal requirements the maximum noise level for a workplace is set to 80 dB(A). Additional to this requirement comfort, market or company targets may set the admissible maximum value of interior noise to a lower level. To interpret the value of interior noise correctly it is important that this value is determined according approved measurement standards and that the operating conditions are well defined.

The noise level measured at the driver's ear is defined by the

- the noise level of the sources (like engine, fan, hydraulic pump and motors, hydraulic valves);
- the transmission of the noise;
- the design of the cabin.

Optimal reduction can however only be achieved if noise reduction is integrated in the whole design process. In the next paragraph a method for low noise design will be presented. This type of noise can be classified as structural and has a repetitive character. Following to this, so called *squeak and rattle*, which can also cause inadmissible increase of the workload, will be discussed too.

The design process

The design process consists of the following stages:

- package of demands;
- conceptual design;
- detailed design;
- prototyping.

- Package of demands

  In contrast to the standards for the noise level on the place of work, no specific demands are available for the noise level exposed to the operator of earth moving machines. The investment in noise reduction is therefore a deliberation between costs and the added value to the product form marketing's point of view.
- Conceptual design

  The design systematic has been developed in the European Brite-Euram project Equip (Dittrich, 1999). This development includes a software package (briefly introduced later in this paragraph). This systematic tool is supplementary to ISO Technical report 11688-1/2 for design of low noise machinery and equipment ISO (1998;2000). The choices made in the conceptual design are essential for the obtainable comfort level with respect to noise and should be applied for:

- engine (type of engine, position, mounting in the chassis),
- hydraulics (pump + valves, cylinders, tubes),
- pneumatics (pump + valves, cylinders, tubes) and
- electrical components.

Basic rules to minimise the noise level are:

- apply low noise active sources: engine (by using a gas engine or an electrical motor instead of a diesel engine), fan (optimized blade geometry, efficiency, minimum tip speed, smooth flow, no close obstacles in flow), transmission (use a belt instead of gear wheel transmission), pumps/motors/valves (use gear pumps if possible) and in general minimise rpm, loading and flow velocities, tip speed and turbulence;
- balance noise emission of various sources to avoid excessive noise control (and cost). This can only be done by first assessing by measurement the ranking of sound radiators for a particular machine;
- minimise noise transmissions through:
  1. air-borne (AB) paths like leaks, panel and window insulation engine enclosure.
     Use absorption in engine housing and in cabin; sealing of leaks; optimized window and panel insulation for cabin (materials + design); selection and positioning of best intake + exhaust muffler with cap;
  2. structure-borne (SB) paths like engine mounts, cabin mounts pump/motor and valve mounting. Use effective elastic mounts for engine, cabin and hydraulics; avoidance of resonance;
  3. liquid-borne (LB) paths like hydraulic hosing and piping hydraulic damper/resonator by optimized dimensioning and positioning of piping and hoses;
- minimise sound radiation from radiators to cabin surface like the engine exhaust and intake (keep distant and direct away from cabin), fan and cooling intake turbulence engine radiation and hydraulics radiation;
- apply or optimize elastic isolation, engine enclosure and absorption and damping materials where effective. Integrate noise damping in conceptual design;
- detect and avoid obvious noise control errors such as leaks (cabin), unnecessary transmission through the structure, resonance, rattle, squeak,

high turbulence, and direct excitation of the cabin (air-borne or structure-borne).

- Detail design

  In the detailed design stage further reduction can be obtained by checking the design on unnecessary clearance, noise leaks and reasoning panels.

  Example

  For reducing the noise by the engine an "Engine near-field shield" (Wolf & Portal 2001) can be applied. The shields consist of a basic load bearing body (generally made of a polyamide compound) in conjunction with an absorption element made of acoustically effective polyurethane foam. The fastening of the neutralising components consists of an elastomeric mixture corresponding to the vibration technological requirements. For the functionality a distinction has been made between frequency in the range of the engine levels and higher frequency engine noise (i.e. combustion noise). In order to minimise the excessive and unavoidable noise resulting from the design of components in the area of the lower engine levels, it is necessary to employ a sufficiently rigid structure for the cover as well as suitable insulation of structure-borne noise by means of tuneable decoupling elements. Depending on the on the frequency a reduction can be obtained up to 8 dB (Yamaki et al., 1999).

- Prototyping

  However the possibilities are limited in this stage of the design, measurements of the noise level may lead to a further optimization. Possible solutions can be found in relocating components and the use of damping and absorbing materials.

Diagnostic measurement techniques for source identification and ranking are for example:

- sound intensity measurement,
- order analysis and
- vibration measurements.

Applicable calculation techniques are dynamic and acoustic finite element calculation and Statistical Energy analysis. It is however most important to create a visual noise path model of the machine, indicating the relevant components generating the noise, AB/SB/LB transmission paths and radiators, and the receiver (operator ear position). Once this is clear, even without detailed measure-

ments or calculations, a first proposal for noise control measures can be made. TNO's EQUIP+ software for noise path modelling provides a tool to perform this task (see figure 5.1).
This development partly took place within the Brite-Euram project 'EQUIP' (Dittrich, 1997). The resulting software is now in part available for industrial application. The Noise Path Modelling System is based on a library of:

- noise generation mechanisms;
- generic machine and structural components;
- acoustic devices (enclosures, isolators, etc.);
- receivers.

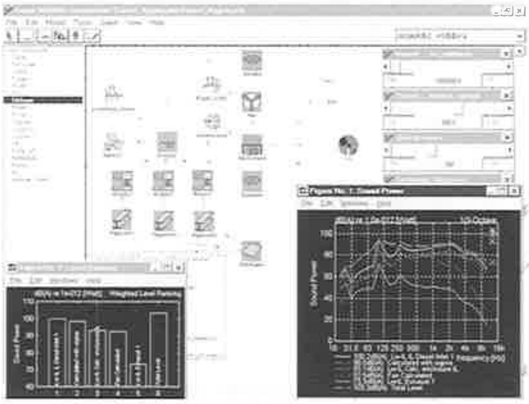

Figure 5.1 Noise path model of a diesel engine aggregate

Focussed on the cabin only vibro-acoustic optimization can be done using Multi-Disciplinary Optimization (MDO) techniques (Miccoli, 1999). This technique, integrated in Computer Aided Engineering (CAE) tools, creates Response Surface model (RSM) of each design output as function of the design input. With a minimal of simulation runs it turns out possible to identify the most critical design inputs, quantify how the design inputs influence the design outputs, detect correlated design outputs, predict design output values for untried design input values and estimate the manufacturability of the product with regard to the design outputs. Figure 5.2 shows the earth moving machine cab 3D structural model.

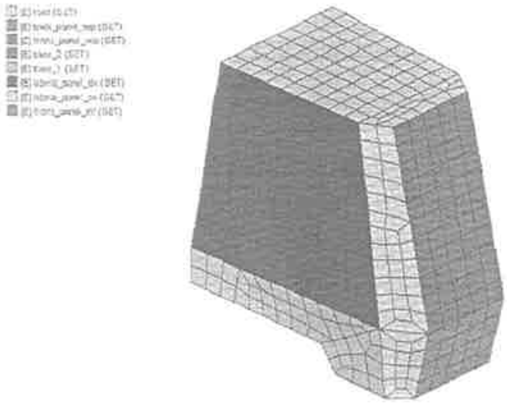

Figure 5.2 The earth moving machine cab 3D structural model

Squeak and rattle noise

Not mentioned in the previous part is the non-repetitive noise of Squeak and Rattle (S&R) (Automotive Engineering, 2001). S&R noise is highly dynamic, presenting difficulties for some types of analysis. Furthermore, S&R events measured in real driving environments often have other, higher-level acoustic events. For example, when a vehicle crosses a large, abrupt road irregularity, a non-S&R acoustic event usually will be generated by the impact. There also can be a corresponding S&R event, but at a very low level compared to the acoustic impact. This low relative level merely adds to the analysis difficulty. Many squeaks and rattles occur from sliding contact between interior plastic parts. A tensile tester was used to measure the friction force of a plastic sliding on itself. When stick slip occurred during sliding, amplitude of the stick slip was used to describe the tendency for the sliding pairs to make noise. The plastics examined are polypropylene (PP), polycarbonate (PC), acrylonitrilebutadienestyrene (ABS), polyamide 6 (PA6), polyoxymethylene (POM), PC/ABS blend and ABS/PA blend. PP had the lowest stick slip amplitude. The ranking of the test materials, according to increasing stick slip amplitude, are PP, ABS, PC/ABS, PC, ABS/PA, POM, and PA6.

5.2.2 *Vibration (body)*

Vibration control in drivers' seat is a permanent research topic. Not only the importance of prolonged exposure to excessive vibration influence us stressed but also the importance of exposure to occasional large bumps is inevitable in reality.

Requirements and standards

A guide for the evaluation of human exposure to whole-body vibration in the range 0-80 Hz is described in the ISO standard 2631. In this range the standard distinguishes two ranges:

- 0.5 Hz to 80 Hz for health comfort and perception and
- 0.1Hz to 0.5 Hz for motion sickness.

Limits are given for use according to the three general recognisable criteria of preserving comfort. These limits are influences by the measuring position and also scaled by frequency weighting curves. The frequency weighting curve is defined per direction (x , y and z) and for respectively the exposure to health, comfort, perception and motion sickness.

The design process

General rules like those that have been discussed for the interior noise are also applicable for the whole body vibration. Further to this a special area is the driver seat comfort. Here a compromise should be found between comfort and control. A stiff seat spring reduces the comfort but increases the controllability and prevents for the motion sickness.

Research (Hogget et al., 1995) has shown that for standard driver seats with air spring a strong coherence between the input and output signal is found for frequency up to 2 Hz. With increasing frequency up to about 10 Hz this coherence drops down to zero. The transfer function is very much depending on the configuration of the driver chair. One of the problems comes from the height control of the chair. A combination of reducing height with an upward vertical acceleration may result in high acceleration shocks. These can be prevented by a case sensitive height control or by adding additional damping at the end of the stroke.

A compromise between comfort and controllability has been found in for example electro pneumatic active seat suspension systems (Stein, 2000). The vibration control is facilitated by a combination of a 'sky hook' feed back loop and a feed forward loop working in the so-called 'sky cloud' principle, compensating for base vertical vibration. The system is especially of interest for vehicles with an unsprung chassis like earth moving machines.

In order to optimize the seat comfort, computer aided techniques like vehicle dynamics simulations can be of great help. Here the following stages should be distinguished:

- modelling the vehicle as a whole;
- definition of the movements of the vehicle (for example by logging them on a existing vehicle at work) and the seat relative to the vehicle;
- analysis of the effects of the present configuration on comfort, etc. and motion sickness;
- validation of the model;
- optimization the seat suspension (or maybe also the cabin mounting to the chassis) with respect to comfort, etc. and motion sickness.
  Human sensing models as presented in paragraph 5.3 can be of great help to an objective rating of the present and future configuration.

Thus an solution could be found in replacing some components or if necessary revising the complete design of the seat suspension by for example replacing it by an active suspension. In this way, the use of computer simulation can give the necessary data to decide for the optimum between costs and performance.

5.3 Future design challenges

Future design of cabins may be improved by use of following developments:

1. development op active systems;
2. application of sensing human model in simulations.

Not worked out here but a general future design challenge is the reduction of the noise by optimizing conventional solutions (§ 5.2.1) and the deliberation between costs and added value to the product from marketing's point of view.

Development of active systems

Active control is sound field modification, particularly sound field cancellation, by electro acoustical means. In its simplest form, a control system drives a speaker to produce a sound field that is an exact mirror image of the offending sound (the "disturbance"). The speaker thus "cancels" the disturbance, and the result is no sound at all. In practice, of course, active control is somewhat more complicated (Ruckmann, 2001).

The name differentiates "active control" from traditional "passive" methods for controlling unwanted sound and vibration. Passive noise control treatments include "insulation", silencers, vibration mounts, damping treatments, absorptive treatments such as ceiling tiles, and conventional mufflers like the ones used on today's automotive application. Passive techniques work best at middle and high frequencies, and are important to nearly all products in today's increasingly

noise-sensitive world. But passive treatments can be bulky and heavy when used for low frequencies. The size and mass of passive treatments usually depend on the acoustic wavelength, making them thicker and more massive for lower frequencies. The light weight and small size of active systems can be a critically important benefit; see later sections for other benefits (Ruckmann, 2001).
The most successful demonstrations of active control have been for controlling noise in enclosed spaces such as ducts, vehicle cabins, exhaust pipes, and headphones. Note, however, that most demonstrations have not yet made the transition into successful commercial products.

Application of sensing human model in simulations

Research of the rating of the comfort level earth moving construction equipment (Kumar et al., 1999) has compared the subjective and objective rating of comfort. In this research three pieces of earth moving construction equipment have been used by each operator. The equipment was grouped into three size categories (small, medium and large). Both static and dynamic activities were evaluated. The psychophysical ratings of the vibration level have been compared with the objective measures. The study demonstrated that the size of the equipment and activity were significant determinants of the psychophysical ratings. Also the psychophysical ratings of vibration levels and discomfort correlated well. But weaker correlation was evident between subjective ratings and quantitative vibration levels.
A better understanding of the subjective ratings can be achieved by application of human models in simulations. These kind of models have been developed for the MADYMO multi body simulation package (Oudenhuizen et al., 2000). A range of MADYMO human models has been developed and validated for impact simulation. These include multibody full body models, multibody detailed segment models, FE segment models and a full FE human model. The human models are multi-directional and are therefore applicable for frontal, lateral and rearward impact.
The multibody mid-size male model is currently being validated with the aim to develop a virtual-testing-tool which can predict comfort in automotive driving conditions. Using the human model in a virtual test environment instead of tests with dummies has the following advantages:

- the human model accurately represents the geometry of the human body, which is important in the analysis of pressure distributions;
- the effects of muscle activity can be incorporated in human models;
- virtual testing is a relative cheap and efficient tool in the design process.

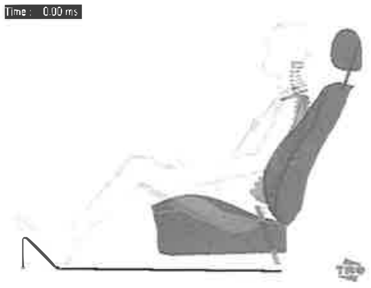

Figure 5.3 The MADYMO multibody model

The MADYMO human model will be used to model the interaction between the human and the vehicle, with the objective to predict mechanical parameters that are related to the subjective feeling of comfort. Both static and dynamic comfort are considered. The static comfort analysis focuses on the prediction of posture, joint angles, joint forces and torque, and seat pressure. The dynamic comfort analysis includes predictions of the dynamic body motion due to vibrations, joint forces and torque, seat pressure, and accelerations. A number of vibration tests with volunteers has been performed to validate the human model for dynamic comfort. Next to the multibody human model, detailed FE sub models will be used for the pressure analysis. The multibody human model is presented in figure 5.3.

5.4 Concluding remarks

This chapter has presented all kinds of measures which can be taken to reduce the noise and vibration focussed on earth moving vehicles. It has shown that targets only can be reached if noise and vibration reduction is incorporated in all development stages of the vehicle.

For the reduction of noise and high frequency vibration a pragmatic solution like the use of a noise path model can already lead to good results. Computer aided techniques are relevant too. In the low frequency vibration with respect to seat comfort aided techniques are a necessity to reach the optimum between comfort and controllability of the earth moving machines.

Concluding this chapter it is clear that both noise technology and vibration technology give enough chances to come to a significant improvement. If a manufacturer wants to apply these, is however a deliberation between costs and the added value to the product form marketing's point of view.

5.5 Internet links and international standards

Internet links

- www.sae.org
- www.NVHmaterials.com

International Standards

- Interior noise:
  - ISO/DIS 6394: 1995
    Acoustics. Measurement of airborne noise emitted by earth moving machinery. Operator's position. Stationary test condition
  - ISO 6396:1993
    Acoustics. Measurement at the operator's position of noise emitted by earth-moving machinery. Dynamic test conditions
- Exterior noise (not discussed in this paper):
  - ISO 6395/DAM 1: 1996
    Acoustics. Measurement of exterior noise emitted by earth-moving machinery. Dynamic test conditions
  - ISO/DIS 6393: 1995
    Acoustics. Measurement of exterior noise emitted by earth-moving machinery. Stationary test conditions
- Body vibration:
  - ISO 2631-1: 1997
    Mechanical vibration and shock – Evaluation of human exposure to while body vibration- Part 1 general requirements

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