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COORDINATOR:
TNO Institute of Applied Physics, Delft, The Netherlands
M.G. Dittrich

PARTNERS:
BeSB GmbH Schalltechnisches Büro, Berlin, Germany
Caterpillar, Belgium
CETIM, Senlis, France
CIAT, Culoz, France
FAUN Umwelttechnik, Nurnberg, Germany
Institut fur Maschinenwesen TU Clausthal, Germany

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The EQUIP Project: Methodology and a Computer Tool for Low Noise Design

M.G. Dittrich[1], D. Haje[2], M. Bockhoff[3], U. Trautmann[4]

[1] TNO Institute of Applied Physics, P.O. Box 155,2600 AD Delft, The Netherlands
2) Institut fur Maschinenwesen, TU Clausthal, Robert-Koch-Straße 32, 38678 Clausthal-Zellerfeld, Germany
3) Centre Technique des Industries Mecaniques (CETIM), 52, Avenue Felix Louat, BP 67-F-60304 Senlis Cedex, France
4) BeSB GmbH, Undinestraße 4, D-12203 Berlin, Germany

Abstract

A methodology and a knowledge-based system for low noise design have been developed within the Brite-EuRam project EQUIP, that provide the designer with new tools to assist in designing low noise machinery and equipment. The methodology was based on an analysis of the design process, identifying the main activities and the flow of information relevant for noise control, and an inquiry in industry providing actual requirements from design engineers. An approach for component-based noise path modelling has been developed, enabling the designer to describe and model a machine or a structure in terms of acoustics. This type of noise path model consists of relevant mechanical components, noise generation mechanisms, a receiver and links between these. All relevant data can be associated with this noise path model, such as formulas, measured and calculated data, requirements, design rules and noise control measures. A limited set of components and noise generation mechanisms has been defined, which covers most machinery noise situations.

The computer toot consists of a noise path modeller with help facilities, database browsers, calculation facilities and a macro facility. Depending on the design phase, either a qualitative or a quantitative approach can be taken. The designer can set requirements, identify low noise design principles and components, perform noise level calculations and spectral ranking, and assess combinations of noise control measures.

In parallel to the methodology development noise control work was carried out on 3 different types of machine: excavators, municipal vehicles and water chillers. Noise reductions of 5-11 dB(A) were achieved by applying the methodology in a systematic way.

Two specific measurement methods were developed for characterisation of structure-borne sound sources, the pseudo-force method and the reception structure method.

The EQUIP project was funded within the Brite/EuRam programme of the European Commission, DG XII, and was carried out jointly by CETIM(F), IMW TU Clausthal (D), BeSB Schalltechnisches Buro (D), Caterpillar Belgium, CIAT (F), FAUN (D) and TNO Institute of Applied Physics (Coordinator, NL).

1. Introduction

In this article the overall results of the EQUIP project are presented. EQUIP stands for *Work MEthodology for Development of QUIet Products,* a Brite-EuRam project supported by the European Commission/DGXII. A methodology and a knowledge-based system for low noise design have been developed ([1-4]) that provide the designer with new tools to assist in designing low noise machinery and equipment. These are intended to help machine manufacturers to reduce noise emission levels, time-to-market, R&D and material costs. The development of these tools was carried out concurrently with noise control work on machines produced by three industrial partners, thereby taking into account to the practical needs of industry. The products involved in the project are excavators, cooling equipment and municipal vehicles. The tools and methods developed were tested in the companies involved in the project and applied to the products mentioned.

The need for these tools stems from the fact that since the EEC Directive 89/392 on machinery safety has come into force, noise emission is one of the aspects that has to be taken into account in the design of many machine types. More manufacturers of machines, equipment and vehicles than previously therefore now need support in low noise design, to avoid trouble-shooting at the product prototype stage. Not only legislation, but also customer demand increasingly includes noise emission as a product quality aspect, which is frequently specified in contracts.

A review of measurement methods relevant for low noise design was performed, Two specific measurement methods for characterisation of structure-borne sound sources were developed and applied, the pseudo-force method and the reception structure method.

2. Methodology for Low Noise Design

A methodology for low noise design was developed, intended to fit into current design practice in the mechanical engineering industry. The following steps were taken to develop this methodology:

- the theory of design methodology was evaluated, to examine existing methodology and to integrate acoustic knowledge into the design process;
- an inquiry in industry was held, to evaluate current design practice and designers' needs with respect to acoustics;
- acoustically relevant design information and machine types were structured;
- the designer-acoustician interface was structured;
- the methodology was tested in industry.

From the evaluation of the theory of design methodology it was shown that various design approaches exist, consisting of distinct phases and utilizing specific tools and methodic work steps. [n the modem methodologies these tools and steps are suitable for computer application. An extensive description of the design methodologies and theories, and the influence of noise requirements on the design process is given in [12].

Inquiry in industry

An inquiry in industry was undertaken [13] to gain a better knowledge about the design process in general and the acoustical problems different companies have to deal with. The intention was to improve the design process at those points where acoustical knowledge is integrated. Therefore, it appeared important to learn where and when acoustical problems occur and to what extent, as well as who is in charge of solving those problems. The inquiry covered company data, the design process and the integration of acoustic knowledge, computer environment and product

specific data. A total of 27 companies from various industrial sectors participated. All of the companies deal with acoustic problems, regardless of product type. A representative group of companies was interviewed, covering different industrial sectors, suppliers and end-product manufacturers, and large and medium sized companies. The companies belong to the following sectors: construction equipment, office machines, hydraulics, ventilation systems, internal combustion engines, bearings, gear transmissions, and the electrical, plant, vehicle, civil, aircraft and mechanical engineering sectors.

Plant engineering, vehicle engineering, construction equipment, ventilation and cooling systems and aircraft engineering, are sectors in which noise emission is a critical design requirement. A number of noise sources occurs frequently, as illustrated in figure 1.

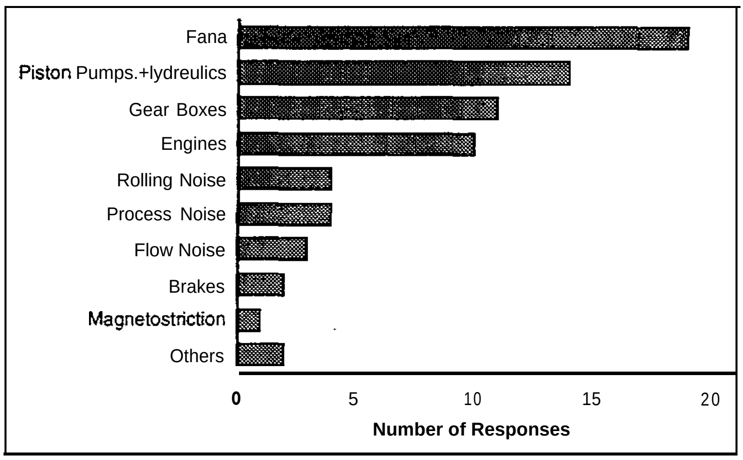

***Figure 1** Main noise sources*

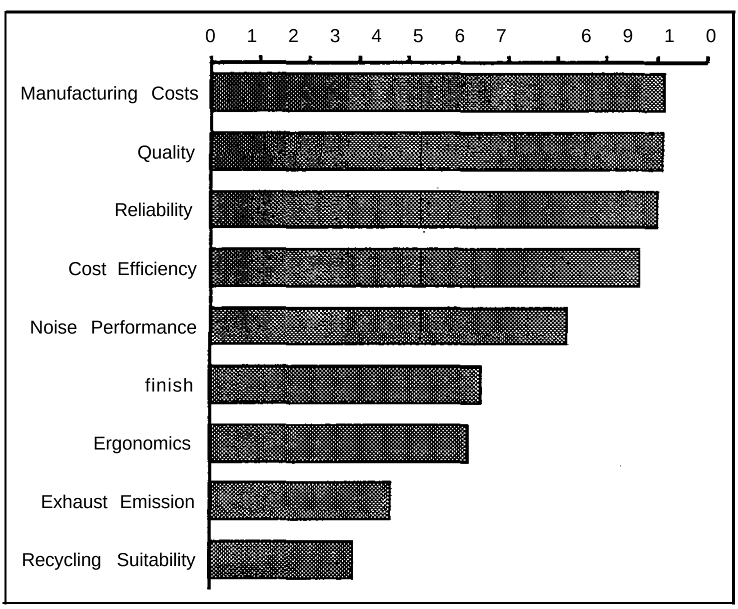

***Figure 2** Importance of different product aspects*

All of the companies interviewed consider noise behaviour an important product requirement besides production costs, quality, cost efficiency and reliability (figure 2). In general, customer and legal requirements for noise emission can be difficult to comply with.

Structuring of Information and Machine Types

From the Inquiry in Industry it was shown that the designer needs a knowledge based system that, in order to support the design of low noise products, should present various types of acoustic information about machines or components. To allow this, all relevant information, be it of a general kind or specific to a machine, a component, or a noise generation mechanism, be it related to noise requirements, noise production, noise reduction, design methodology, measurement methods, has to be available to the consulting system in a suitable manner. Therefore, an information model was generated (see [15]) which allows access to all relevant information related to an entity (e.g. product, component, mechanism). The model also defines attributes for each of the components and mechanisms which are acoustically relevant. With this model, the knowledge based system can provide the user with all information needed for low noise design.

The information model, which is used to map acoustic knowledge, has been described in the standardized modelling language EXPRESS, part of a standard for the exchange of product data (STEP). Tools exist which are capable of automatically generating a database structure from an EXPRESS file. For filling the database, forms were developed for collecting information of various types. These forms are directly related to the information model.

The information model contains ‘entities’, or modelling elements, which are the building blocks with which a product can be described in terms of acoustics. Important entities are

‘Component’, which can represent any mechanical component,
'NGM', which represents a physical noise generation mechanism,
'Receiver', which represents the noise emission quantity, for instance sound power or sound pressure level.

The entity ‘component’, whose attributes are described in figure 3, is the supertype of the following entities, to which all relevant components **are** assigned either directly or indirectly by subgroups:

- group
- displacement_machinery
- hydrodynamic_machinety
- acoustic_device
- fluidic_device
- electrical_ machinery
- structure
- torque_converter
- linear_actuator
- guidance_system.

Each ‘component’ can also be decomposed into its individual subcomponents and noise generation mechanisms by means of the entity ‘group’. The first level of subclasses (subtypes) of ‘component’ is shown in figure 3, according to the EXPRESS-G representation. Figure 4 shows a further decomposition for the lowest level of ‘acoustic_devices’. The EXPRESS schema contains at least 57 components and 29 noise generation mechanisms.

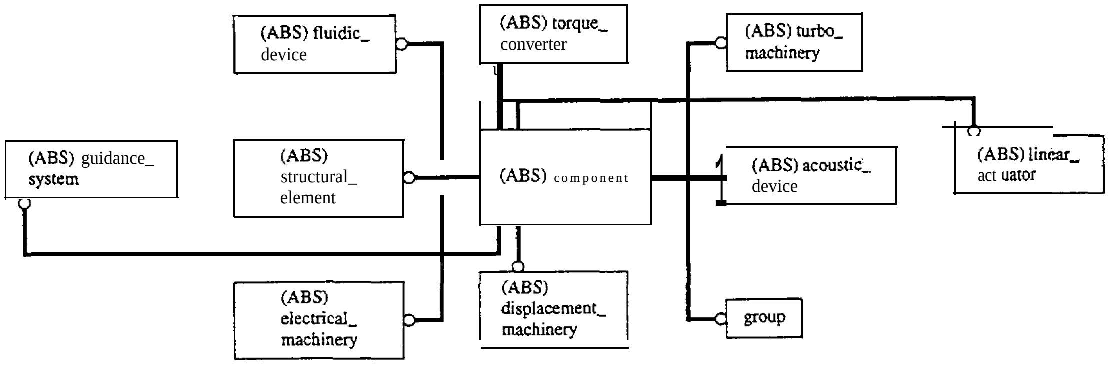

Figure 3 Subclasses of 'Component' (EXPRESS-G representation)

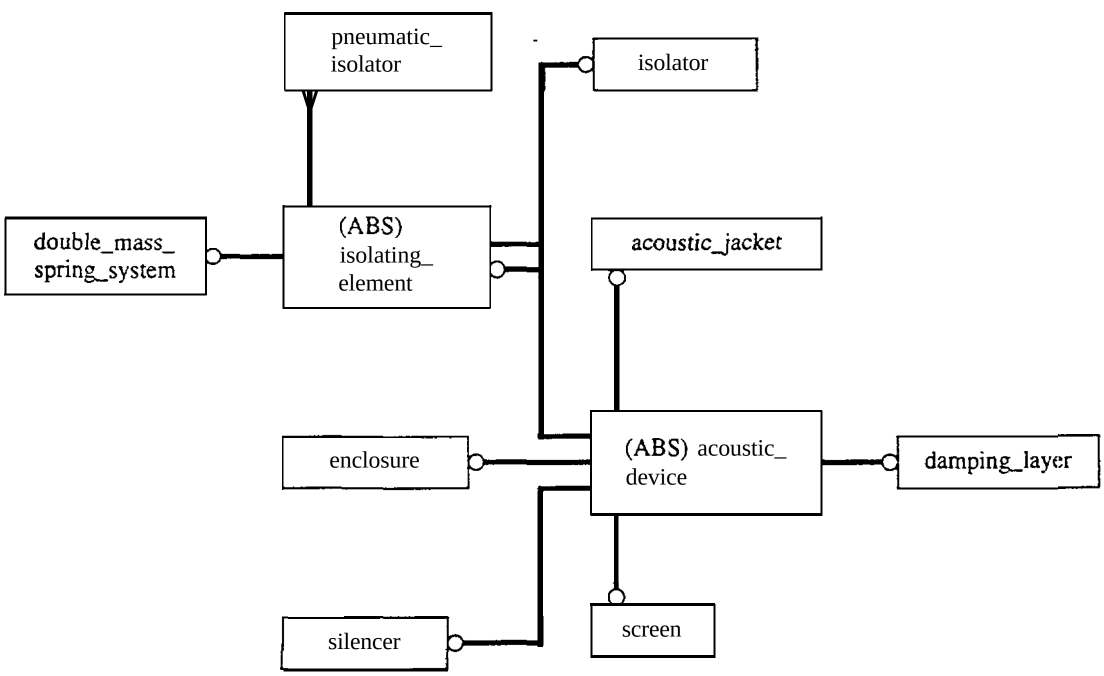

Figure 4 Structuring of acoustic devices (EXPRESS-G representation)

Structuring of the designer-acoustician interface

After defining the relevant information for low noise design, the information flow and activities particular to low noise design were analysed and mapped ([16]). Here, the methodology which designers or acousticians must apply to develop low noise products was formally described using the SADT technique (Structured Analysis and Design Technique).

Overall Activity AO of the SADT Diagram

The activity AO 'Design a Low Noise Product' is the overall activity which is described within the EQUIP project, see figure 5. It deals with the design of new products as well as optimization of existing ones. It is described from the designer's perspective.

The 'Design Task' (input AO - I1) describes what is to be designed, and it consists of functional requirements (function, speed, power, size, usage,...), operational requirements (noise level, exhaust emission,..,) and business requirements (maximum costs, parts or components that may or may not be used, e.g. engine types,...).
'Acoustic Experience and Knowledge' (AO - Cl) controls all activities of low-noise design. It consists for example of strategies, experience, design rules, design examples, estimation formulae, procedures, measurement methods, component information, documents, and it is of fundamental importance for the design process. The specific knowledge needed to perform the various sub-activities is shown in the decompositions of the AO box (Node A0), where the knowledge involved is specified.

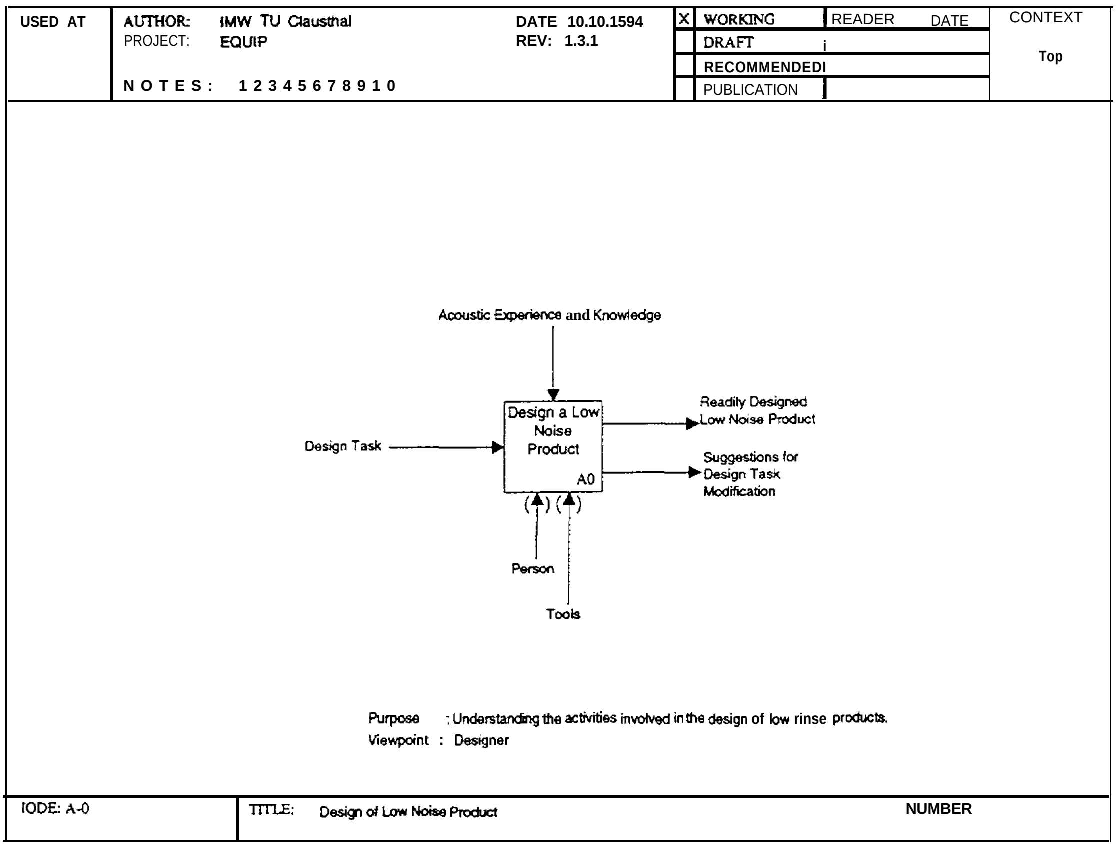

Figure 5 *EQUIP SADT Model, Node A-O*

A 'Readily Designed Low Noise Product' (output AO - 01) is the output of the design **process,** if a design was achieved which meets all requirements, i.e. **if functional, operational and business** requirements are fulfilled. The output 'Suggestions for Design Task Modification' (AO - 02) occurs if the design task is not feasible, e.g. if cost constraints or other business requirements prevent the fulfillment of the requirements. The mechanism arrow AO - Ml ('Person') represents the person performing the activities, e.g. a designer or an acoustician. 'Tools' (AO - M2) are any hardware and software tools applied for solving the problem.

The **Activities Al to A5 of the SADT Diagram**

Figure 6 shows the decomposition of the activity AO into five subactivities (Al- A5). A detailed description of the information flow (input, output and control) can be found in [16].

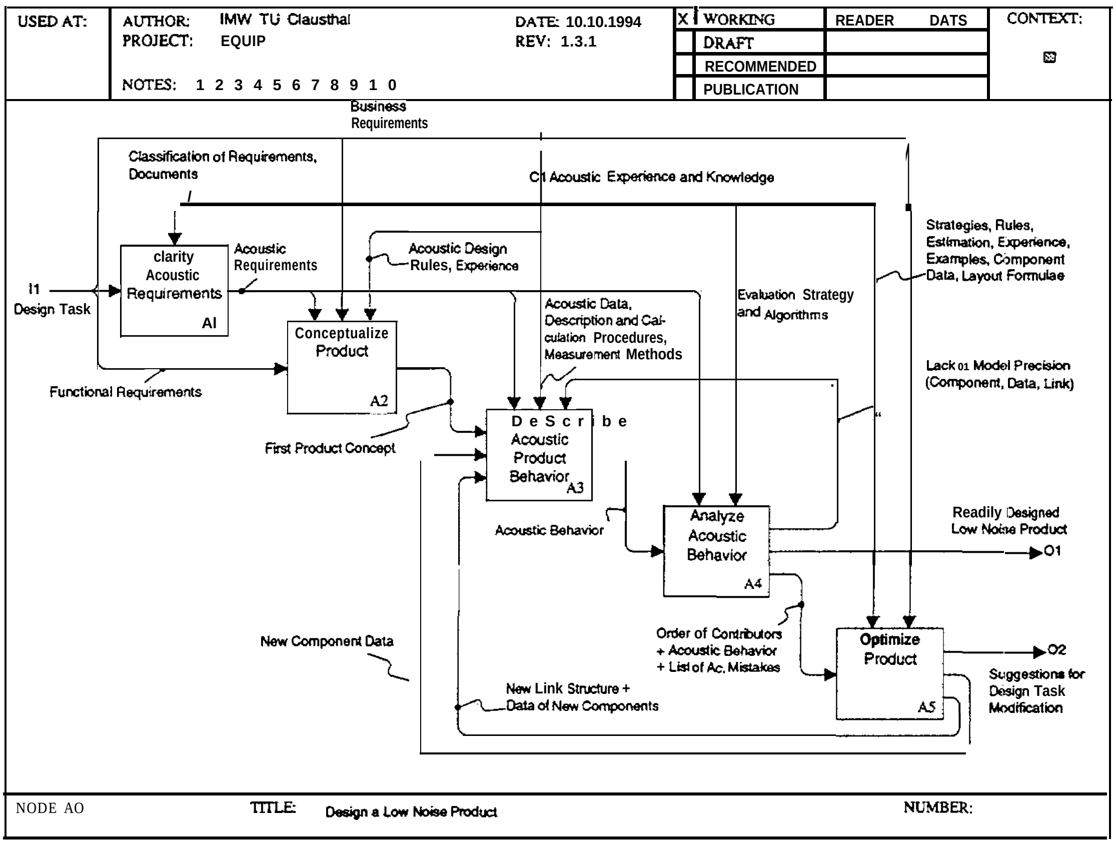

Figure 6 EQUIP SADT Model, Node A 1-A5

Clarify Acoustic Requirements, Al

Activity Al 'Clarify Acoustic Requirements' (see figure 3.8) covers the clarification of all acoustic requirements which the product must fulfil. The type of product (e.g. hydraulic excavator), the extension of the market (e.g. Europe, USA) and the type of requirements (e.g. legal requirements, market requirements) have to be considered before one can select requirements from documents or elaborate requirements (e.g. based on the market situation or in view of competitor products). It is important that levels as welt as measurement methods (including operation conditions) are specified to achieve unambiguous requirements.

Conceptualize Product, A2

During activity A2 'Conceptualize Product' the designer is supported in the very first steps of the design process. When the designer has to break down the overall function of the product into sub-functions and realize these by specific components and processes, the system should present general and product specific design rules. Examples for general design rules are the "General principles for low noise design of machines". Beyond others, these principles are: "Start with noise reduction at the predominant noise sources and radiators", "Implement noise control measures as close to the source as possible", "Replace inherently noisy processes by quiet ones", "Take account of the strong influence of rotational speed on noise".

Describe **Acoustic Product Behavior, A3**
The activity A3 'Describe Acoustic Product Behavior' covers the description of the product's acoustic behaviour. It starts at a very rough overall level and becomes more detailed during the development process. It is performed by means of for example measurements, estimations or database queries on component data. Its aim is to generate, validate and check an acoustic flow model of the product. This model can be used in the following activities to describe the product's acoustic behaviour and to compare different possible optimization measures.

Analyze Acoustic Behavior, A4
Activity A4 'Analyze Acoustic Behavior' covers the analysis of the acoustic product behaviour. It consists of a check of acoustic requirements and ranking of contributors. The requirement check compares the acoustic behaviour (from A3) with the acoustic requirements (from Al).

Optimize Product, A5
Activity A5 'Optimize Product' includes ail steps which are undertaken for product optimization purposes. The first step is to select optimization measures, whereas the second step is the optimization itself. The optimization measures are selected by considering the order of contributors, the list of acoustic mistakes, functional requirements, and business requirements, helping the user to optimize noise relevant contributors, considering the overall function, the contributors specification and the business constraints. The optimization can either be related to separate components / processes (with related mechanisms) or to the product link structure.

The SADT model, which was worked out in more detail than the 'top level activities' described above [16], was used to specify the software, Libraries and procedures for low noise design were designed on this basis.

The methodology was tested with the industrial project partners. It was found that component-based noise path modelling is easy for designers to use and to understand when investigating acoustic problems. Discussions with the designers brought out further requirements for the software, such as ease of use, cost-related aspects, and database availability.

3. Software and Knowledgebases

A system architecture was developed which uses the Noise Path Model as a central medium to which all relevant data for the knowledge based system is attached ([5,17]). Various types of library were defined, in which the different types of knowledge and data are stored, for example:

- Design examples
- Acoustic characteristics of components
- Noise control measures
- Acoustic mistakes
- Emission data

General help on low noise design
- Terminology, acoustics, methodology and system
Fluids and solids library
Standard components
Noise generation mechanisms
Documents, including requirements and measurement methods
Calculation routines
Acoustic data: levels, spectra, time signals and level histories
Scenarios (procedures).

The main system modules are

- A Modeller, illustrated in figure 7. This is the main program module, with which noise path models can be created. This is the starting point for any low noise design activities and allows instantiation of any kind of acoustic model including noise generation mechanisms, components, and receivers. Components can be decomposed (detailed at a lower level). Requirements and operating conditions can be set.

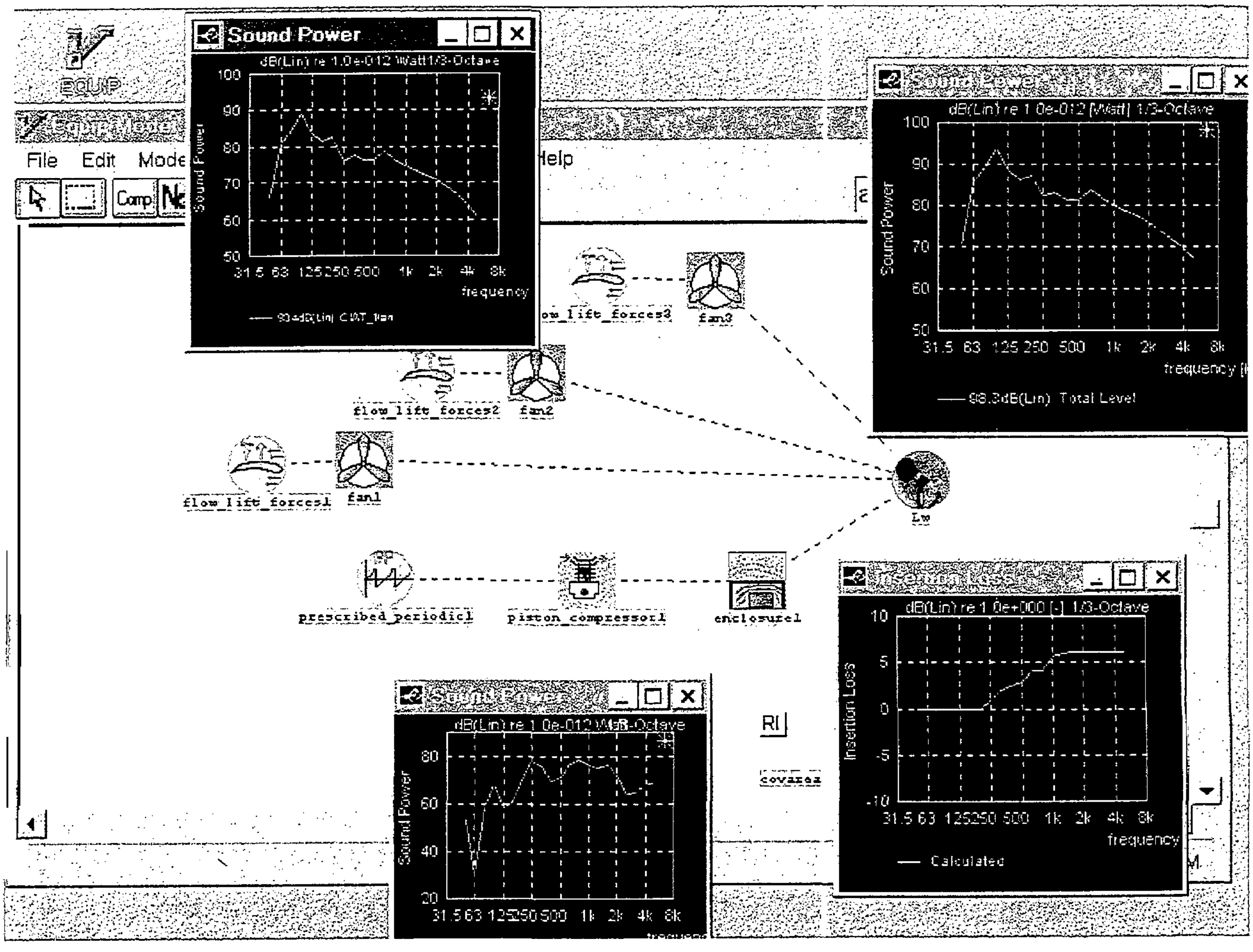

Figure 7 *EQUIP Modeller with noise path model Including NGMs, components and receiver*

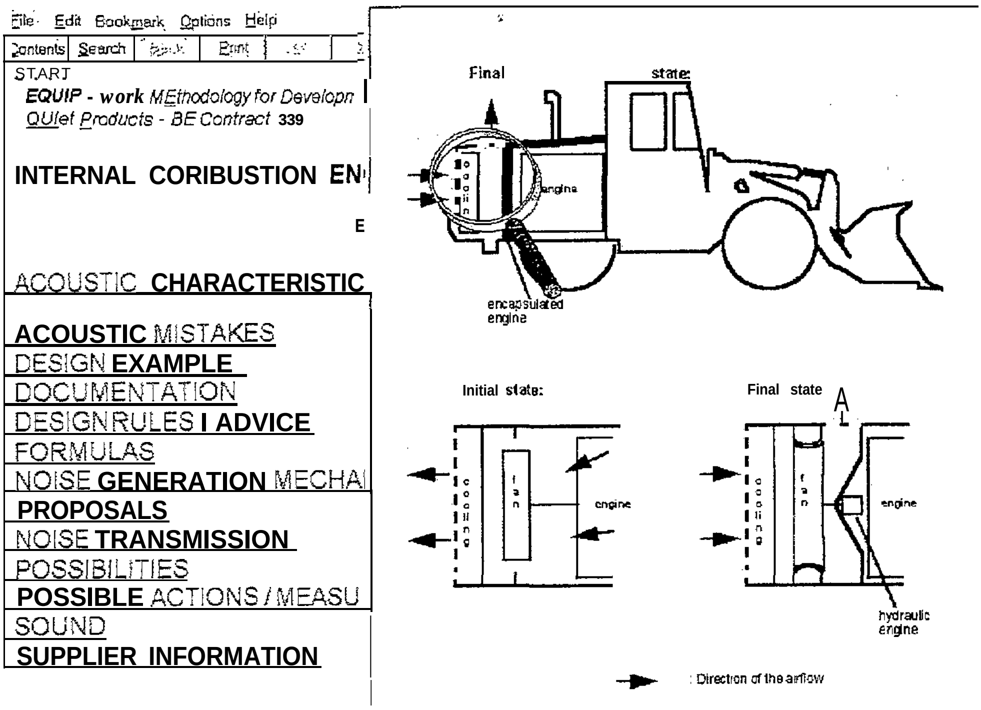

Figure 8 *Example of EQUIP Help facilities: combustion engine design example*

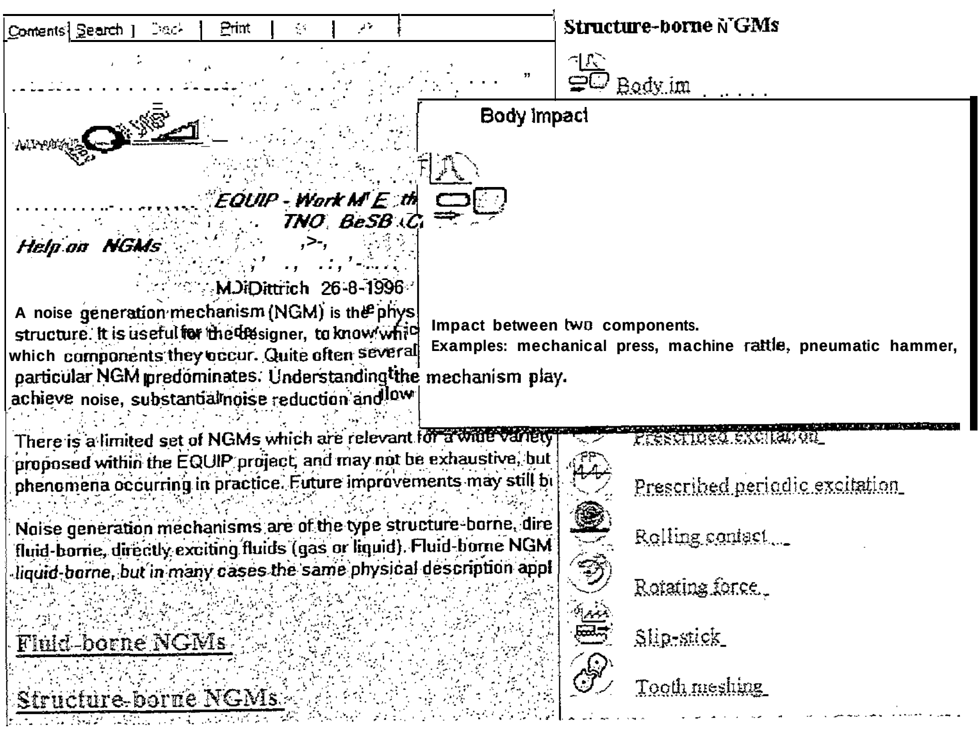

Figure 9 *Example of EQUIP Help facilities: help on Noise Generation Mechanisms (NGMs)*

A help system, consisting of hypertext help facilities on various topics, such as help on how to use the program, help on the components (figure 8) and NGMs (figure 9), help on general low noise design rules, acoustic and system terminology.
A database management system, for filling, accessing and querying various libraries mentioned above.
Calculation facilities, consisting of libraries and linked calculation programmed, which consist of analytical and statistical formulae for noise generation, transmission and radiation.
A scenario manager, a kind of macro facility, which is intended to guide the designer through various activities defined with SADT.

The system has been designed in such a way, that company or branch-specific and user-specific databases and libraries can be linked in.

4. Development of Low Noise Machines

In parallel to the methodology development noise control work was carried out on 3 different types of machine: excavators (see [8-11]), municipal vehicles (figure 10) and water chillers. Noise reductions of 5-11 dB(A) were achieved by applying the methodology in a systematic way.

Figure 10 *FAUN VEGA Sweeper*

The machines in the project were in different stages of the design cycle. For each machine, the following was undertaken:

analysis of the noise requirements, including definition of the relevant noise emission quantity, measurement method and operation conditions;

creation of noise path models, including selection of noise-relevant components and noise generation mechanisms;
assessment of measured data and noise path ranking (radiators);
identification, selection and combination of cost-effective and feasible noise control measures;
evaluation of the implemented measures.

Typical noise sources in the machines analysed were reciprocating machines such as diesel engines and piston compressors, fans, hydraulic components and suction nozzles.

Noise reductions of 5-11 dB(A) were achieved on the machines involved in the project.

These reductions were achieved by balanced application of noise control measures indicated in table 1.

Component	Noise control measures
Reciprocating machinery	Local encapsulation, improved resilient mounting
Fans	Optimisation of flow
Suction nozzle	Optimisation of flow geometry
Hydraulic components	Quieter gearpump, resonance damper
Cabin	Optimisation of elastic mounting

Table 1: Applied noise control measures.

5. Measurement Methods

A review of vibro-acoustic parameters and corresponding measurement methods relevant for low noise design was performed. This was done to assess to what extent procedures are established. for acquiring data which is required during the low noise design process. Measurement procedures for parameters such as sound pressure and sound power are well defined, but parameters such as structural damping, input power, and others are less standardised. The review confirmed that the basic principles for the determination of these parameters **are more or less known,** but that corresponding measurement methods are not yet developed in all cases to a level of industrial applicability. Several reasons can be given for this lack :

simplifications in theoretical models limit practical use (for example: machine feet considered as "point-sources")
mounting of measurement devices sometimes necessitates changes of the machine structure and may modify the operating conditions (for example : force transducers between source and receiver, anechoic terminators for liquid,...)
special test rigs, needed for determination of some parameters, do not allow to simulate real load conditions (for example: resiliently mounted components)

For structure-borne noise more measurement methods are available than for fluid-borne noise, but some of these methods seem to be less developed than the corresponding procedures for the characterization of fluid-borne noise.

From the review it was concluded that measurement methods which still need further development are:

- input force,
- input power,
- loss factor,
- transfer mobility,
- radiation efficiency,
- total sound transfer.

Priority was given to develop those methods which are relevant when designing machinery with built in components which are structure-borne noise sources, and can interact with the structures on which they are mounted. These parameters describe the "source strength" of sources of structure-borne noise. Two specific measurement methods for characterisation of structure-borne sound sources were developed and applied, the pseudo-force method and the reception structure method.

Source description independent from the test environment

The first method is called the 'Equivalent forces' or 'Pseudo forces' method, and is independent of the test environment [18]. It provides a set of equivalent forces which characterise the structure-borne source strength of components irrespective of the structure they are mounted on.

It consists of

- measuring operational vibrations on the source
- measuring impact response FRFs on the stationary source
- and then deriving by matrix decomposition and inversion a set of pseudo forces which represent the fundamental internal excitation forces exerted.

Once these forces are known, they can be used as an indication of the most important excitation directions, and also be used to calculate vibration response levels on receiver structures. This" information can be used in both qualitative and quantitative terms and is useful for the designer when selecting components and designing their mounting to other structural parts.

This method was applied on a hydraulic pump which was characterised both on a test rig and mounted in a vehicle, running under similar operating conditions. It was possible to quantify a set of forces in six degrees of freedom which generate the same vibration levels as the real operational forces (figure 1 1).

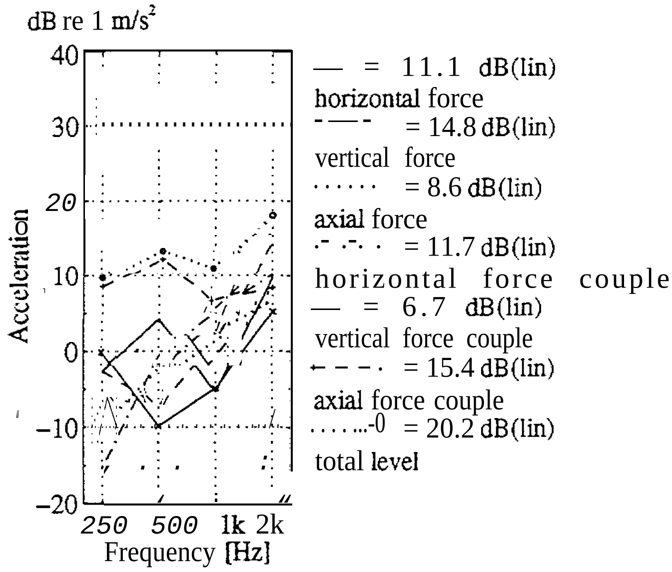

Figure 11 Contributions to the average vibration level in* octaves *on a vehicle mounting structure for each pseudo force

Source description depending on a specific test environment

The second kind of measurement method called the reception plate method depends on a specific test environment. An equivalent reception structure is required, that has similar acoustic characteristics to the real machine structure. The basic idea was to" reduce the size of the reception structure to formats which are:

representative for real mounting and operating conditions,
or at least compatible with industrial environments.

It was found that the method can be set up with reception structures of relatively small size, Limits for size reduction and a condition for source impedance (in relation to properties of the structure) have been worked out and presented in the form of charts [19].

6. Conclusions

A methodology for low noise design has been developed, which brings specific acoustic knowledge and procedures closer to the designer. H is based on an inquiry in industry and on feedback from designers and acousticians. A corresponding prototype knowledge-based system for systematic low noise design has been developed and tested. It has wide scope for futher industrial application, potentially providing designer engineers with a novel and practical tool. Substantial noise reductions of 5-11 dB(A) were achieved on excavators, municipal vehicles and water chillers New measurement methods for low noise design enabling source characterisation of structure-borne noise of components were developed and tested.

7. Acknowledgements

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Delft, February 1997

TNO-TPD-TU Delft

Ir. M.G. Dittrich

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