CIRP Journal of Manufacturing Science and Technology 5 (2012) 337–347

Contents lists available at SciVerse ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Noise investigation in manufacturing systems: An acoustic simulation and virtual reality enhanced method

Jan C. Aurich [a,*], Xiang Yang [a], Simon Schröder [b], Martin Hering-Bertram [c], Tim Biedert [b], Hans Hagen [d], Bernd Hamann [e]

[a] Institute for Manufacturing Technology and Production Systems (FBK), University of Kaiserslautern, P.O. Box 3049, D-67653 Kaiserslautern, Germany
[b] Fraunhofer Institute for Industrial Mathematics (ITWM), Fraunhofer-Platz 1, D-67663 Kaiserslautern, Germany
[c] Rhine-Waal University of Applied Sciences, Landwehr 4, 47533 Kleve, Germany
[d] Computer Graphics and HCI Group, University of Kaiserslautern, P.O. Box 3049, D-67653 Kaiserslautern, Germany
[e] Institute for Data Analysis and Visualization (IDAV), University of California, 1 Shields Avenue, Davis, CA 95616-8562, United States

ARTICLE INFO

Article history:
Available online 7 October 2012

Keywords:
Noise investigation
Manufacturing systems
Sound simulation
Visualization
Virtual reality
CAVE

ABSTRACT

Even though the noise issue in manufacturing is widely discussed from legal and health aspects, there is still no comprehensive method to simulate and analyze it. In this paper, a novel concept to investigate the noise level is proposed. Therefore a simulation method and the virtual reality (VR) implementation are involved. Acoustic measurements in real factory provide validation data for a realistic simulation. Furthermore, a representation of simulation results in the virtual environment is visualized in a Cave Automatic Virtual Environment (CAVE). The analysis and evaluation of potential noise reduction are realized by using described methods.

1. Introduction

In manufacturing environments, employees are stressed by different influences during their work. Negative impacts are typically noise emitted by the machining processes, chemical solvent polluted air, heat from thermo forming, or extreme low/high level of humidity in some special industry. Therefore, to analyze and optimize the working environment of manufacturing systems is an essential and urgent issue.

To protect health and safety of the employees, there are existing laws and guidelines to observe. For example, the Federal Ministry of Labour and Social Affairs of Germany (BMAS) provides a set of limits for noise and vibration levels, which are established within Germany's Occupational Safety Law 'Arbeitssicherheitsgesetz' [1], German ordinance 'Lärm- und Vibrations-Arbeitsschutzverordnung' [2] and other additional guidelines.

Regarding such limits and guidelines, various investigation methods are implemented in industry. However, a comprehensive and low cost approach is not found. In this paper, the noise in a factory is analyzed by using an acoustic simulation and virtual reality (VR) supported method. To realize the acoustic simulation, the essential data are collected from a factory. The geometric modeling and acoustic measurements provide basic simulation input data. To understand the output data from simulation, different visualization methods are implemented. VR is then used as visualization environment, which enhanced the analysis capabilities. This method provides a new viewpoint to fulfill the noise diagnosis and noise reduction requirements of factory planning.

The paper is organized as follows. In the next section, some related work in fields of noise issues, sound simulation and the current VR applications are shown. Section 3 introduces the data acquisition step, which involves the geometric modeling and experimental acoustic measurement. In Section 4, an interactive sound visualization framework and its implementation are presented. The visualization effect is shown with both non-immersive and immersive VR systems. Last section concludes the paper and provides an outlook for future research.

2. Related work

2.1. Noise in manufacturing systems

In a factory, the noise from machinery, powered tools or other activities influences employees' health and can even cause

* Corresponding author. Tel.: +49 631 205 2618; fax: +49 631 205 3304.
E-mail addresses: aurich@cpk.uni-kl.de (J.C. Aurich), yang@cpk.uni-kl.de (X. Yang), s_schroe@informatik.uni-kl.de (S. Schröder), martin.hering-bertram@hochschule-rhein-waal.de (M. Hering-Bertram), t_biedert09@informatik.uni-kl.de (T. Biedert), hagen@informatik.uni-kl.de (H. Hagen), hamann@cs.ucdavis.edu (B. Hamann).

1755-5817/$ – see front matter © 2012 CIRP.
http://dx.doi.org/10.1016/j.cirpj.2012.09.010

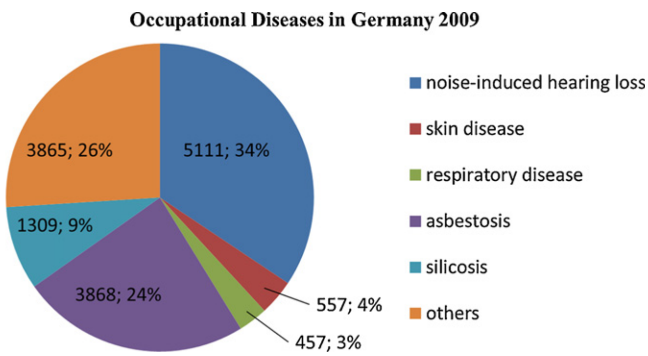

Fig. 1. Recognized occupational diseases in Germany, 2009.

diseases. It became one of the most frequent occupational hazards. According to the investigation of Federal Institute for Occupational Safety and Health (BAUA), about five million employees are exposed to noise in Germany. Fig. 1 shows the recognized occupational diseases and patient rates in 2009. Which is based on the German Statutory Accident Insurance (DGUV) provided data. About 34% occupational diseases belong to noise-induced hearing loss and the accident insurances pay about 170 million Euros every year for those cases. Especially in metal manufacturing enterprises, the proportion of noise related diseases is 41% from all recognized occupational diseases cases [3].

For the determination and analysis of noise effects in manufacturing systems, three main issues are taken into account, (1) the occupational safety, (2) negative health impacts, and (3) preservation of work performance. The following two cases show the first issue. According to ISO guidelines [4], for work safety the loudness of warning signal in industry must be 15 dB over the ambient noise. The warning signal could be ignored because of high noise level that causes accidents. Another case is the communication issue among workers. The quality of lingual communication is deteriorated because of noise [5], which causes potential unsafeties as well. The issue (2) is health damages related, which result from exposure to repeated noise or over loud noise. The healthy damage could be various, such as stress and tiredness, dizziness, hearing damage, temporary/permanent hearing loss, and other heart diseases. More noise caused health risks such as physiological effects or the risk of accidents refer to Kryter [6] and guidelines [7,8]. Much research work on issue (3) has been done to determine the influence of noise on employees' performance. The results of studies pointed to similar conclusion. Different authors found a significantly poorer performance when employees are exposed to noise [9–11].

The costs paid for the negative effects of noise to employees are large. Embleton [12] summarized these negative effects and discussed the cased costs: "Such costs include not only the financial compensation or damages that must be paid, and the reduced enjoyment of everyday life for those with a hearing loss, but also less quantifiable factors such as reduced productivity, increased stress, disturbed speech communication and risk of accidents for a large number of workers." Regarding these three noise-induced issues, different methods and instruments are deployed in practice. According to the application areas, these methods are classified into three categories [13]. They are implemented to control/reduce (a) noise emission, (b) sound propagation and (c) sound pollution. In manufacturing systems, (b) and (c) related methods are often used. Important methods in (b) are for example changed room shape, optimized division among work areas, and the use of sound absorbing building material. The methods in category (c) are basically workstation related, such as, rearrangement of workstations and placement of sound shielding around workstations.

Adjusting or rescheduling a manufacturing system is expensive and time consuming. Therefore, it is necessary to take the noise issue into account, during the planning and design stage of the manufacturing systems. In proposed approach, the computer aided tools are integrated. Through the modeling of noise source and the simulation of noise propagation, the understanding and evaluation of noise influence in a factory is enhanced. The simulation results allow the user to analyze and select appropriate methods from categories (a) to (c) regarding the three main issues (1) to (3) and statutory regulations.

2.2. Acoustic modeling and simulation

In order to determine the influences of noise, the acoustic simulation is implemented in many different areas. The simulation methods are divided briefly into numerical simulation and geometric methods. The numerical methods are based on solving wave equations, such as Finite Element Methods (FEM), Boundary Element Methods (BEM) and Finite Difference Time Domain (FDTD). The geometric methods us a simplification of sound propagation processes. They are for example the image source method, ray tracing and beam tracing related methods. Compared with the numerical methods, the geometric methods improve the computational performance of sound simulation significantly but at the cost of simplifying assumptions. A survey and comparison of those methods is also given in existing literatures [14–17].

Due to the computation complexity, the introduced wave-based and geometric methods are not practical and efficient for large geometric models. An improved geometric approach named "Phonon Tracing" is developed [16,18], which is implemented in this paper. This method is inspired by photon tracing method, which considers the light particles called photons and simulates photo-realistic image. Analogous to seeing light as particles called photons, sound sources emit sound particles are called phonons. The phonon tracing is a geometric acoustics method, which needs geometric data as input. The 3D models of factories, facilities, and different machines are generated, which are input to an integrated scene graph. Besides the geometric data, the following input data is needed:

- a triangulated scene with tagged surface material
- absorption coefficients/functions for different materials
- position of one or more sound sources
- emission distribution of the sound sources
- sound energy of the sound sources
- number of phonons to be traced
- number of reflections to be traced
- the threshold energy of phonons at the end of simulation.

Using the given sound emission level, the distribution of sound energy is regarded as a sphere surface, which was illustrated in Fig. 2 left. From defined sound source, the phonons are sent out and go as a ray to the surfaces (boundary of medium) they meet. Number of phonons is defined by user. A high number of phonons provide simulation data with higher details for visualization and auralization. However, the human ear is not capable to locate the origin of a sound source as exactly as the eye locates a light source. Therefore, a lower number of phonons are sufficient for auralization and efficient for simulation as well. The sound speed in air is considered as constant value 314 m/s. The phonons from sound source intersect with the surfaces and locate at the intersection point, contributing to the global phonon map. The new phonons are reflected with specular with respect to the local surface normal and contribute to the phonon map at the next interaction. The absorbed energy is calculated using absorption coefficients.

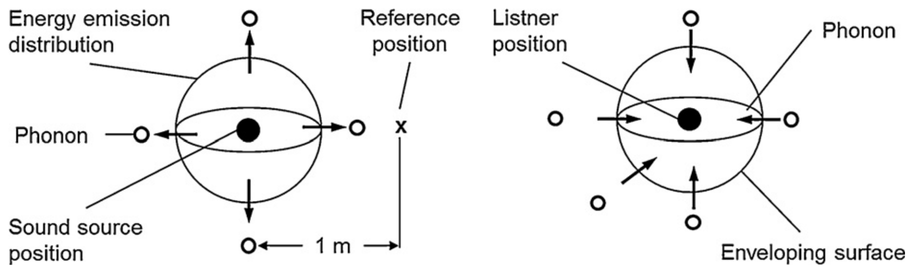

Fig. 2. Modeling of phonon tracing and phonon collection.

Calculating the influence of all phonons to a particular listener position, the information of all reflection positions is collected and weighted according to their distance to the listener. For each listener position an enveloping surface is created for phonon collection (see Fig. 2 right). The phonons which fly through this enveloping surface are documented and calculated together to sound pressure level. The human ear can distinguish sound frequencies in the spectrum from 20 to 20,000 Hz, but cannot sense the equal sound pressure at different frequencies equal. Hence, the finite impulse response (FIR) filters for each listener position are implemented in phonon collection step. The filter bank is generated by using 214 samples. To limit the non-causal effect the widest filters for 40, 80, 160 and 320 Hz are combined to one together. That means totally seven FIR filters are predefined, namely 320, 640, 1280, 2560, 5120, 10,240, and 20,480 Hz, which cover from the range from 40 to 20,480 Hz. The produce of FIRs is made in advance to reduce the computing time. The collection is cut off after 6.5^{-3} s. Afterwards, the energy sum of collected phonons is calculated to estimate the corresponding sound pressure level.

Tracing the pressure for different frequency bands and using a Dirac impulse as sound source this calculation provides the room's impulse response. This simulation process needs to be repeated only when the sound sources and listener positions are changed. In our paper, the simulation is used to calculate the sound pressure level at arbitrary listener positions. The simulation and visualization are implemented then in a virtual environment.

2.3. VR applications

VR is a comprehensive and widely developed technical concept, which is widely implemented for scientific visualization, education and training, operation in hazardous environment, space exploration, entertainment, etc. [19]. A common definition was made by Sutherland [20] as 'a system that can display information to all senses of the user with an equal or bigger resolution than the one that can be achieved in a natural way so that the user cannot say that the artificial world is not real'. Immersion, interaction and imagination are commonly understood as three main features of VR [21], which distinguish VR systems from other computer systems and embody the advantages of VR systems. In recent years VR technology is improved significantly and shows following changes, such as increased hardware speed and reduced acquisition costs; increased demand of applications in industry; or development of the Virtual Reality Modeling Language (VRML)/ Extensible 3D (X3D) standard.

The VRML standard is accepted by International Organization for Standardization [22] and widely used for VR applications, e.g. the assembly design, machining process simulation, evaluation and visualization of planned facility, or training of employees parallel to the running production [23,24]. For these reasons, VRML is used in here for modeling and visualization.

VR systems are classified into non-immersive and immersive systems: the former include desktop based systems or a power wall system, and the later head mounted displays (HDMs) or Cave Automatic Virtual Environment (CAVE). Compared with immersive system a non-immersive system has lower sense of situational awareness, lower field of regard, less scale perception and sense of immersion. However, a non-immersive VR has advantages of lower costs, shorter development time and better implementation conditions. A CAVE system is a VR system, which enables an immersive perception and interactive manipulation of virtual environments. Fig. 3 left illustrates a typical 4-wall CAVE system, which consists of 8 projectors. Each wall is projected by two projectors and three mirrors are used to reduce the projection length.

At the Institute for Manufacturing Technology and Production Systems (FBK), this system offers an immersive virtual environment more than 17 m^3. Passive stereo technology with circular

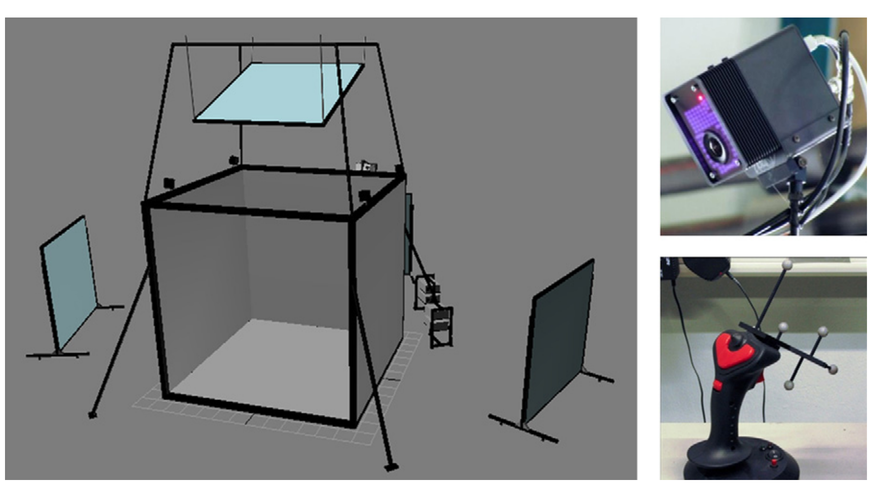

Fig. 3. Illustrated CAVE system at FBK institute.

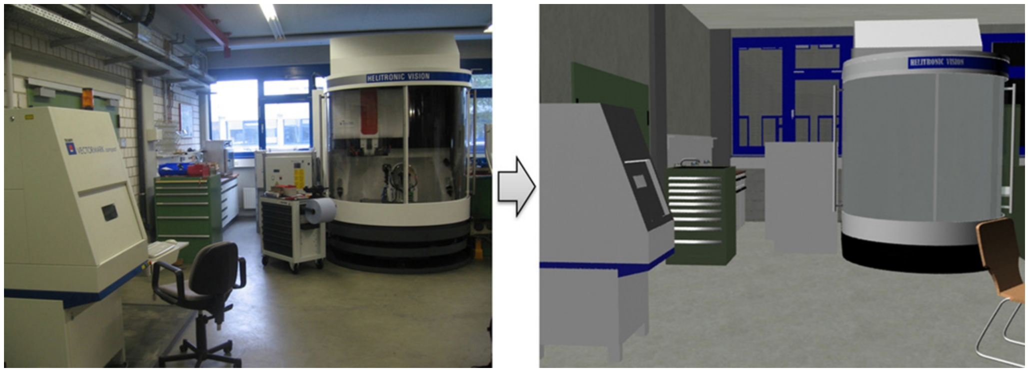

Fig. 4. Geometric modeling of a manufacturing factory.

polarization is used for stereoscopic rendering of the 3D environment. This CAVE is operated by a VR cluster, which contains 1 master and 8 client workstations. The user position is tracked through the tracking markers on the 3D glassed by four IR-cameras above the CAVE (see Fig. 3 right). The user can interact with the system via different input devices, such as a fly stick or wireless keyboard. At FBK, both non-immersive and immersive VR systems are implemented to satisfy different demands of research and industrial projects [25,26].

3. Data acquisition and modeling

3.1. Geometric modeling

The elementary data from a real factory is the geometric data which contains the geometric information of manufacturing facilities, machines, transporters, layout, etc. The shape, location, material feature, textures, and other information of single object in a manufacturing system are summarized and further described by 3D-modeling. According to the measured data, 3D geometric models are generated, which is illustrated in Fig. 4. A geometric model of environment provides the following information:

- Environment features, such as the building geometries and layout
- Geometries, coordination, positions and orientations of each single object
- Object surface features, such as material, texture, and color
- Manufacturing process-based interrelationships among the objects

In this paper, the FBK mechanical engineering laboratory is used as a reference data source for an approach development. Compared to visible light, the audible sound has wavelengths between 0.2 and 17 m. Thus the reflections are primarily specular on large and smooth surfaces. And, the diffractions occur often around big objects (such as lathes), while small objects (such as water bottles) have little effect on the sound propagation. Therefore, the 3D geometric models for sound simulation need less detail than the models for computer graphics. In addition to CAD software, the modeling software '3ds Max' is used to improve the visual effect of a virtual environment. The number of polygons is optimized to balance the visual effect and computing performance. The object surface material features are tagged using material libraries.

3.2. Acoustic measurement

Sound sources in a manufacturing system are commonly considered as running machines and their power supply systems. The features of sound sources are directly related with machine types, machining processes, machining tool selection, work piece materials, etc. Acoustic measuring provides necessary data for characterization of sound sources and supplementary data for sound pressure level evaluation. To do it, two types of measurements are implemented: sound power measuring and sound pressure level measuring.

3.2.1. Measurement of sound power

Sound power is one of the most essential sound features which indicates the total energy of a sound wave per unit time and measured in watts. It is a technical feature of a machine to describe the total emitted energy as sound waves. Usually the sound power could be estimated through sound pressure measurement or sound intensity measurement. A comparison of these two methods to determine sound power is made by Schirmer [27] and Möser [28]. In this paper, the sound intensity method is used because of its accuracy.

A so-called enveloping surfaces method is implemented. The measurements are undertaken around a selected machine, namely directly facing the five surface sides: front, back, left, right, and top, with a measurement distance to the machine 0.5 m. According to the guideline, each surface the measurement should be repeated at least 10 times per square meter [29]. To do it, all of the 5 to be measured surfaces and 247 measuring points of the lathe are firstly defined and draw as sketch, which is shown in Fig. 5 left. Based on this blue print, a grid is made as support equipment to undertake the measurements around the lathe (see Fig. 5 right). This grid is made by several wood frames and thin cords, which defines the sub-surfaces for measuring and helps the operator to find the right position to place the intensity probe.

A sound intensity probe, which shown in Fig. 6 left, is often used for sound intensity measuring. This probe is made by two condenser microphones and a distance holder between them. Its construction could refer to [30]. The sound intensity could be determined by using the difference of two measured sound pressure levels, which are recorded by the both microphones [31]. Before measurement a microphone calibration using a pressure calibrator is needed (see Fig. 6 right). Using the support grid the sound intensity measurements are repeated in the middle of each sub-surface. The machining speed during measurement is 1120 rpm without work piece. The sound power of each sub-surface is visualized in Fig. 7 in 2D and 3D. The point of maximum sound power level, which was estimated near the cutting tool before the measurement, is actually shown close to the electric motor. Especially near the back side of the motor, the sound power level reaches 82.9 dB because the back cover is thinner as the front one. Due to the reflexion of floor, the sound power level shows a higher value of 86.3 dB at the bottom of the electric motor. The 3D representation enables further a straightforward understanding of

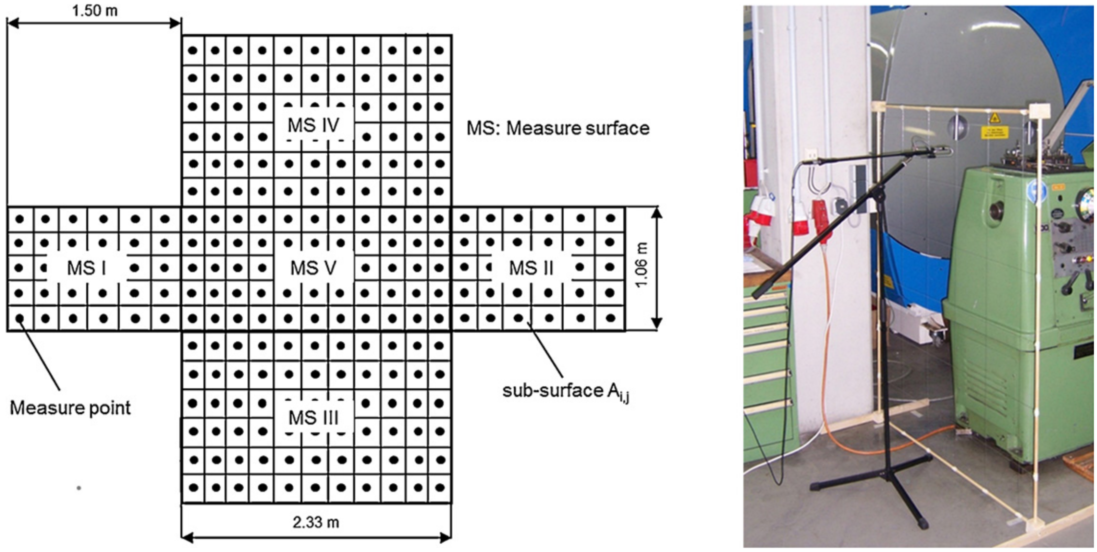

Fig. 5. Sound power measurement blue print and support equipment.

Fig. 6. The sound intensity probe and the calibrator.

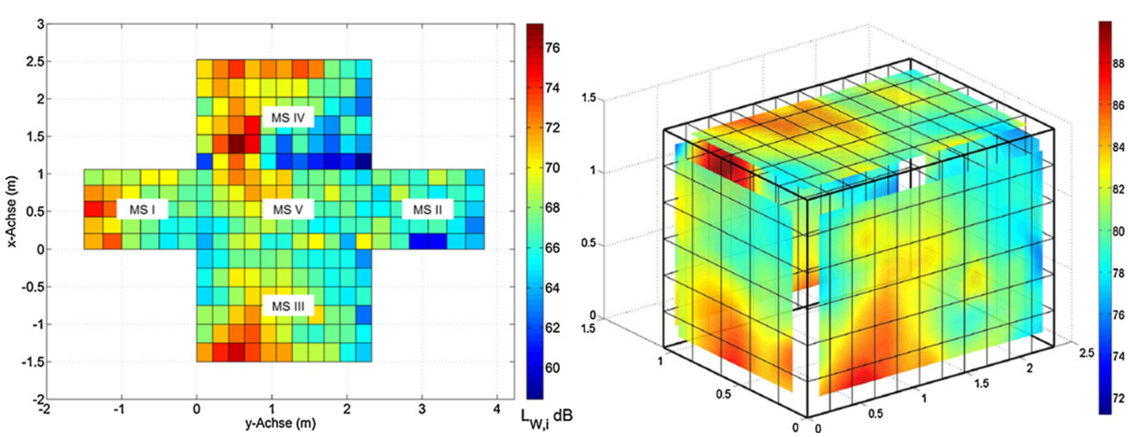

Fig. 7. Visualized sound power level in 2D and 3D.

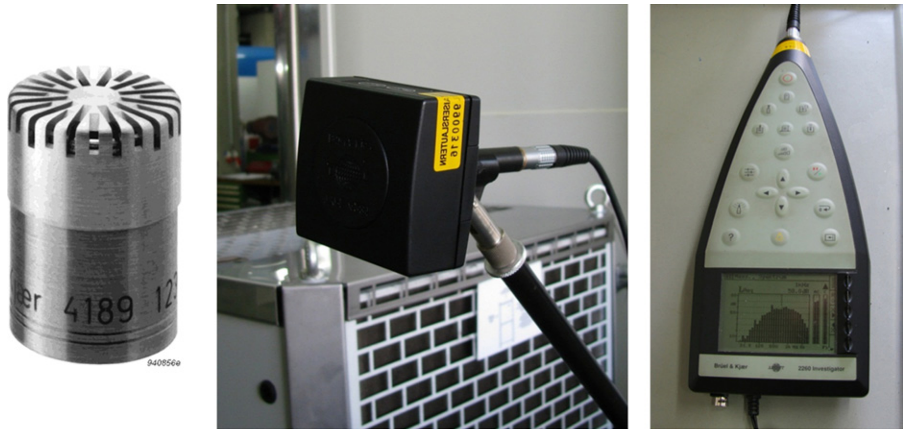

Fig. 8. Microphone, calibrator and measurement setting.

Fig. 9. Sound pressure level measurement in a factory.

sound power distribution of the sound sources. The total power of a sound source is estimated by sum of all the parts.

3.2.2. Measurement of sound pressure level

The sound pressure level is measured by using the sound level meter 'Investigator' from company Brüel & Kjær (Type 2260). According to ISO 11202 [32], the acoustic pressure level is determined by measurements of continuous sound pressure level, sound from foreign sources and maximal sound pressure level. A combined measurement design is based on DIN series 45635, for example the measurement for a lathe is according to DIN 43635-1 [33]. For each single sound source the measurements are made at 11 different positions and at 3 typical machining predecessors, idling, normal machining and high speed machining.

The calibration (Fig. 8 middle) is done before the microphone (Fig. 8 left) is used. A portable display allows the measurement setting, the measurement results storage and visualization (see Fig. 8 right). During measurement, the microphone is positioned by using a tripod with an extension arm. The microphone position is adjusted of 10 mm to the operation position with the same height. In Fig. 9, the microphone is for example placed facing the control panel or operation side. The measurement is undertaken at 11 common operation positions in a factory, as the lathe 1 is in operation. Fig. 10 right shows the 11 positions based on the factory layout and Fig. 10 left shows the sound pressure levels at these positions. The nearest position (4) shows the highest sound pressure level and position 9 in the farthest corner shows the lowest sound pressure level. In the main, an inverse relation between distance to sound source and the sound pressure level is found. Still, the sound pressure level could not simply be estimated by the distance to the sound source. Due to the different amount and size of objects between sound source and measured positions, as well as the reflection surfaces around the measuring position, unexpected high sound pressure level are found at some positions (e.g. 1, 2 and 8). These values are to be compared with the simulation in the next section.

4. Interactive sound simulation and visualization in VR

4.1. The framework

The objective is to have an application for interactive noise investigation in virtual manufacturing environments. To do this, a software tool is implemented. First, a VRML supported framework for the implementation is introduced. VRML is used as front-end to the user, which provides capabilities for rendering complex scenes, animating objects, and interaction with the user. Another advantage of VRML is that it is a well-established standard

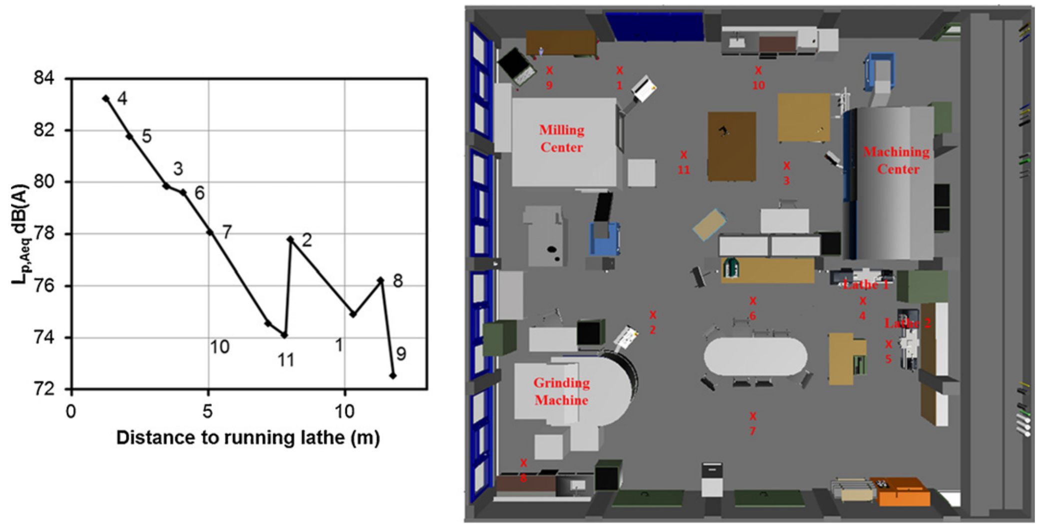

Fig. 10. 11 position measurement in a factory.

supported by any important platform and operating system. Although VRML also provides programming interfaces through JavaScript and Java, a server/client concept is enabled. With this, an existing C++ implementation of the acoustic simulation can be used and extended for the purposes.

Fig. 11 illustrates a framework to realize the interactive sound simulation and visualization. The information flows firstly from modeling software to VRML editor and then loaded into a web server generated viewer application. All the objects are modeled with '3ds Max' and then exported in VRML standard. By using 'VrmlPad' as VRML editor, the Sensors, Events or other interactions are constructed directly in VRML files. At the same time, Java and JavaScript codes are embedded into VRML. This enables the geometric changing, interactive user interface, performing a simulation and building data interfaces. After these steps, the necessary data and coding for applications are prepared.

The simulation application acts as web server, loading the model of the room and adding user interface elements. The resulted VRML code is delivered to VRML compliant VR platform via a HTTP port, which is generated at the start of the application. Preferring a non-immersive VR system, the visualization can take place by a simple web browser, using a local or web-based VRML viewer application. For an immersive VR, VRML is a compatible file format for CAVE software. That means, this VRML based application is platform independent and can be performed in virtual environments with different immersion degrees. Users can choose suitable access forms depending on their needs and existing hardware devices. In the next chapter the implementation is demonstrated on desktop based non-immersive and CAVE-based immersive systems.

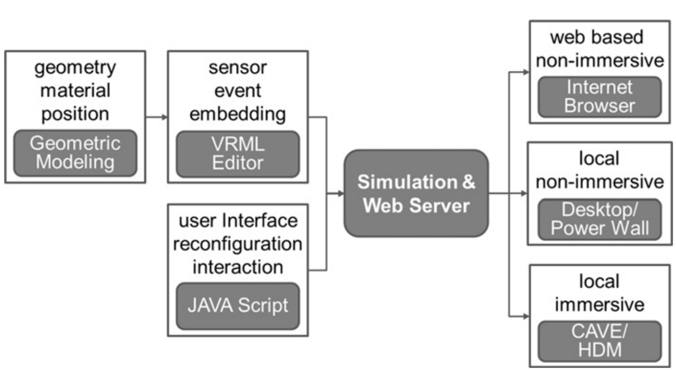

Fig. 11. The VRML supported software framework.

4.2. Simulation input and setting

The sound simulation, the phonon tracing method, requires several input parameter settings. As it is a geometric approach, the algorithm needs the geometric model of the room and the objects inside. Each surface is assigned one material with specific absorption properties. Usually, the material's absorption coefficients are taken from coefficient tables. The parameters which are necessary for simulation are listed:

- a triangulated scene graph with tagged surface material
- absorption coefficients/functions for different materials
- position of one or more sound sources
- sound energy and emission distribution of the sound sources
- number of the phonons to be traced
- number of reflections to be traced
- the threshold energy of phonons at the end of simulation.

For this sound source, the position and the sound pressure at 1 m distance is needed. Better results are achieved by providing either an anechoic signal of the sound source, i.e. of the simulated machine, or the sound pressure level of several frequencies. Furthermore, the user may specify an arbitrary number of listeners from which only the position is needed. Number of phonons is defined by user. A high number of phonons provide simulation data with higher details for visualization and auralization. However, the human ear is not capable to locate the origin of a sound source. Therefore, a lower number of phonons are sufficient for auralization and efficient for simulation as well. The sound speed in air is considered as constant value 314 m/s. More details to simulation setting could be found in [16].

4.3. Software implementation

The simulation process needs to be repeated when the sound sources and listener positions are changed. To simplify the simulation parameter setting, a software tool is developed. The implementation is done using C++ and Qt develop environment. Qt provides facilities for an easy graphical user interface for starting the web server on selected network ports and generating an initial VRML file, which is to be opened by the VRML viewer application.

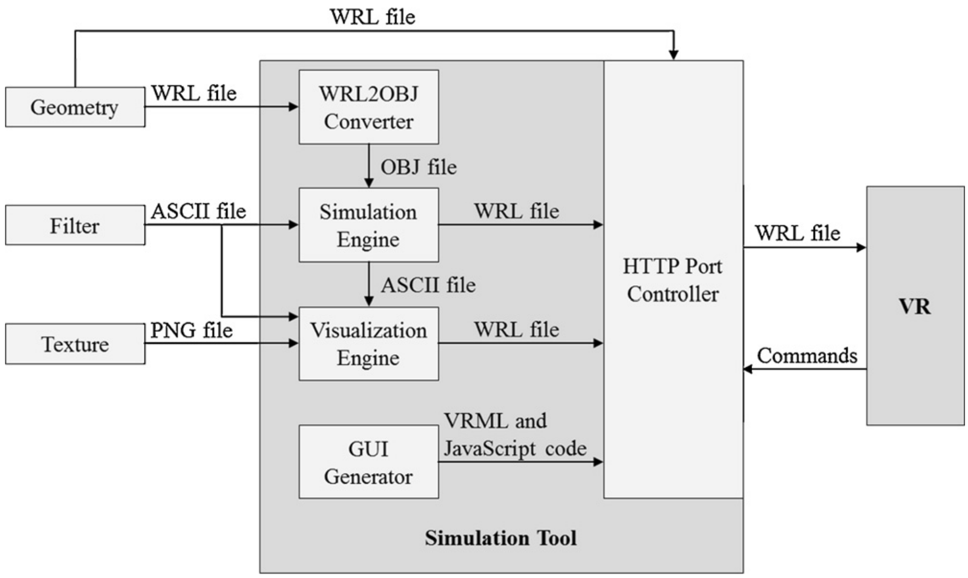

Fig. 12. Function diagram of simulation and visualization software tool.

Additionally, Qt provides a simple interface for managing network sockets which is for example an HTTP connection. All Qt code is platform independent and portable to major operating systems.

The web server loads the VRML model file and adds additional VRML code with user interface elements for interaction with the server from within the scene graph. Buttons and sliders are implemented using VRML and JavaScript. Their visual appearance is modeled using simple VRML geometry. This geometry is connected to a 'TouchSensor' for buttons and to a 'PlaneSensor' for sliders. These sensors emit events which are routed to 'Script Nodes' containing simple interaction logic written in JavaScript. Commands are sent back to the server by loading a special URL which encodes the action. Then, the simulation is calculated by the server and delivered to the viewer again. This communication is done via HTTP connections. The viewer opens a new connection using an HTTP request asking for a file encoding commands in the filename. The server does its calculation and answers with a new VRML file delivered by this existing HTTP connection.

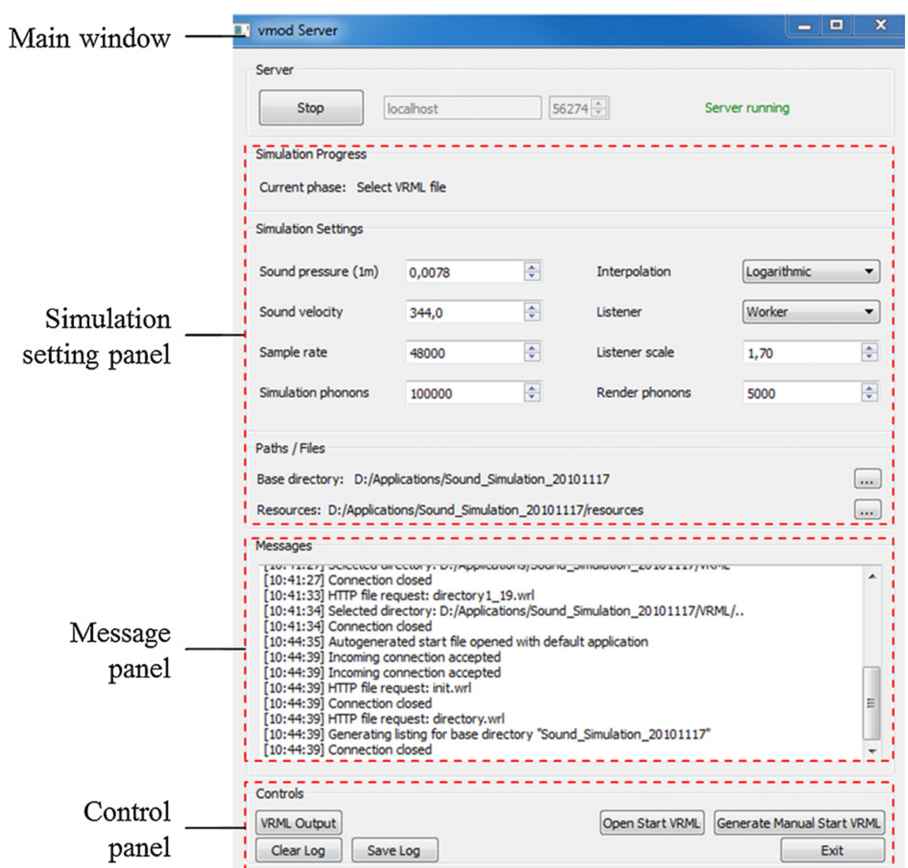

Fig. 13. User interface of web server.

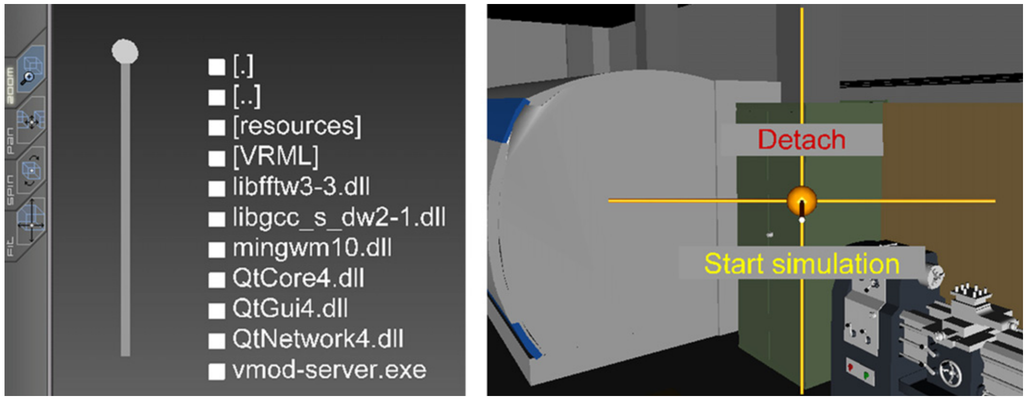

Fig. 14. User interface for file navigation and sound source placement.

Fig. 12 illustrates the data flows and functions within this software tool. Five main functions modules are included: "WRL2OBJ Convertor", "Simulation Engine", "Visualization Engine", "GUI Generator", and "HTTP Port Controller". The "WRL2OBJ Convertor" transforms WRL files to OBJ files for "Simulation Engine". Based on the generated OBJ file and given surface absorption coefficients the "Simulation Engine" executes and computes the phonon tracing processes. The results after simulation could be transferred to the "Visualization Engine" or via TCP/IP to VR system directly. In "Visualization Engine", the SPLs are calculated according to the given listener positions and FIR filter files, and then a new WRL file is generated. This file could be visualized in VR systems as well. The "GUI Generator" provides additional VRML and JavaScript code to create straightforward user interface in virtual environments. All communications between simulation software tool and VR systems are connected through HTTP by using the "HTTP Port Controller".

Fig. 13 illustrates the user interface of web server and the different panel parts are marked with red lines. The main window panel allows the web server to select and start/stop a HTTP port. The current server status is shown as well. With the simulation setting panel, the parameter settings for simulation and visualization can be made, such as the sound pressure or to be used phonon amount. The file path and used geometric file name are also displayed in this panel. The message panel displays the processing messages. Using the control panel, the user is able to generate a start file, to output the computing messages, or to store the simulation results as VRML file.

4.4. VR interface and visualization

Sound simulation is firstly implemented using the VRML Viewer 'Instant Player' and 'Cortona3D Viewer', which enables the user to navigate and manipulate a VRML scene graph in a desktop-based workspace. In Fig. 14 two modules are shown. The left module shows the file system navigation. The needed geometric file could be selected from a local or a network database. After loading the model per URL address into the viewer application, the user can explore the room placing the sound source and starting the acoustic simulation. The 3D interface helps the users to locate the sound source. This module is shown in Fig. 14 right.

When the simulation is done, the software switches to the phonon collection step. The user interface is shown in Fig. 15. The users can investigate the sound propagation inside the room by looking at animated phonon paths. The playback speed can be adjusted using the '++' and '–' buttons, and the current simulation time step can be selected by a slider. And, one or more listeners are placed in the room according to operation positions. The listener geometry can be customized. Afterwards, the phonon collection step can be performed.

The tool enables the user to interactively place and remove listeners depicted by workers. Then, a command for the calculation of the sound levels at the listener positions is issued. The scene in Fig. 16 is updated with corresponding colors for the listeners according to the sound pressure level: green for low sound pressure levels <80 dB, yellow/orange for critical sound pressure

Fig. 15. Phonon propagation visualization and listener placing.

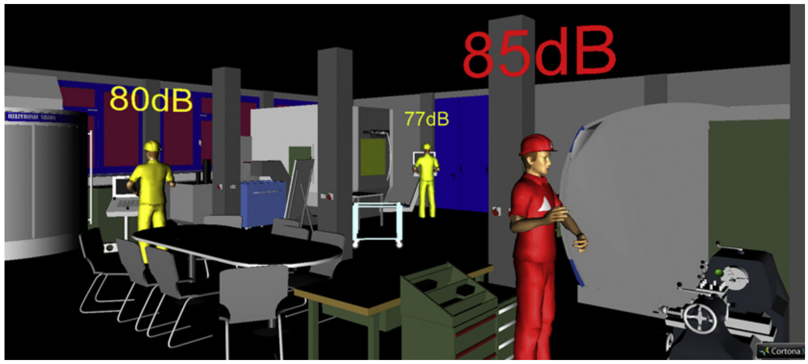

Fig. 16. Visualization of sound pressure level at different positions.

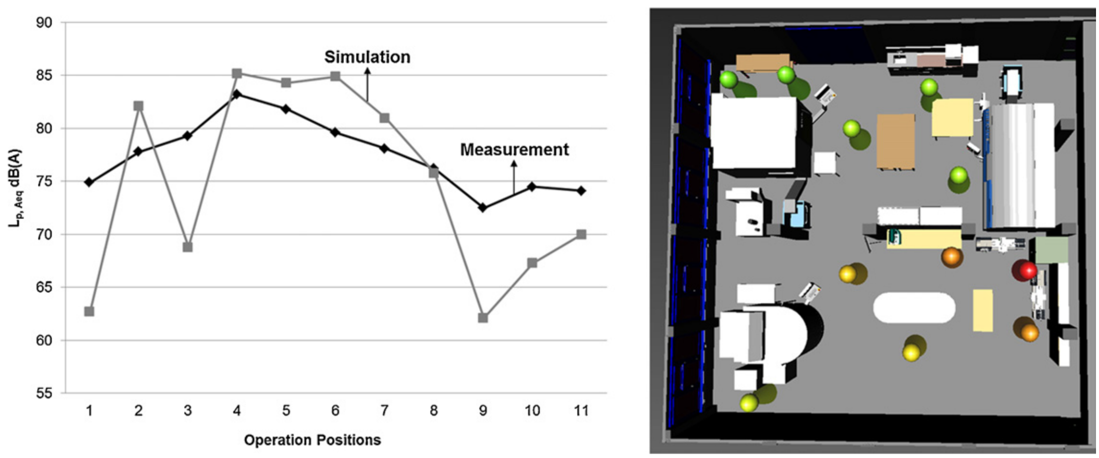

Fig. 17. Comparison between measurement and simulation results.

levels <84 dB and red if the sound pressure level is too high according to the standard [2].

According to the positions, which are used to implement the sound pressure level measurement (see Fig. 10), the simulation is made. The result and comparison with measurement is shown in Fig. 17 left. The considerable differences between the simulation and measurement are probably caused by 2 reasons. First, the values of the deviated absorption coefficients of different materials inside the room are estimated. The facilities are mostly non-standard and old. Thus, the absorption coefficients can only be estimated, but not selected from the existing database. Second, compared to the wave-based methods, the phonon tracing method as well as other geometric methods fails in the low frequency range. Due to the limitation of geometric methods, a combined approach could provide more ideal and more accurate simulation. For example, Deines suggested an additional wave-based method implementation to simulate the sound wave propagation at low and middle frequencies [16]. The simulated values are visualized with different colors and viewed comprehensively (see Fig. 17 right).

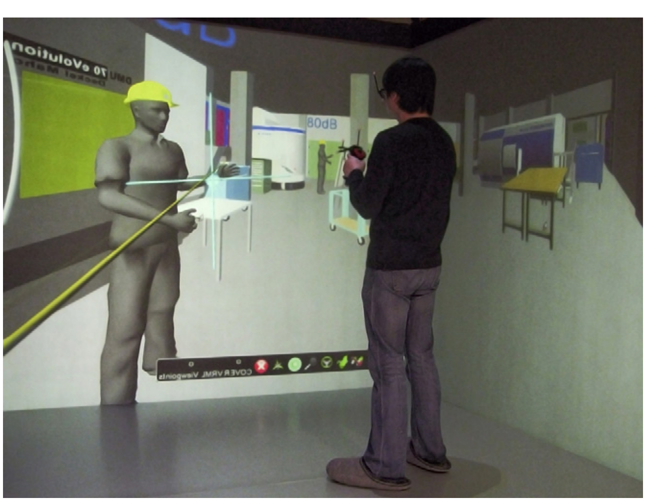

Fig. 18. Visualization in CAVE.

This application is further implemented in CAVE. The simulation server opens a HTTP port for COVISE modules and gets feedback from COVISE. The two necessary COVISE modules are 'VRML renderer' and 'VR' modules. The former enables the VRML visualization of a scene graph in CAVE and the latter provides basic interaction functions, such as the navigation and user tracking. Fig. 18 shows the basis user interface and the added interface element by simulation software tool. Using the three button fly stick, the user could use this software more convenient as using a desktop display and mouse.

5. Conclusions and future work

This paper introduces a new method for interactive and fast noise investigation, specifically in manufacturing environments, e.g. the machine halls. The experimental acoustic measurements provide essential data for simulation and evaluation. The sound simulation and visualization methods are integrated to a comprehensive approach. Based on this approach, the implemented software tool can be used to determine the noise level, for example at the operation positions, and easily test different improvement scenarios. Thus, noise in manufacturing environments can be reduced testing different suggestions from worker without applying all of them in reality and stalling production. This approach reduces downtime during improvement processes and allows for testing of more improving scenarios. Further, the software tool provides facilities to check the noise level considering different federal regulations.

Up to this point, the basic interactions, which facility sound investigation for the user, is to be extended in the future. First, the simulation supports the placement of only one sound source. Usually, production halls contain several machines running at the same time. Therefore, a development to include multiple sound sources is proposed. Further, changing acoustic properties of the room is very cumbersome as it involves changing the original room model. This has to be extended to provide interactive adjustment of absorption coefficient, e.g. for simulation of different construction materials. And a collaborative computing architecture, which is based on the web server approach, is considered to improve the computing performance.

Acknowledgments

This work was funded by the German Science Foundation (DFG) within the International Research Training Group (IRTG) 1131 Visualization of Large and Unstructured Data Sets Applications in Geospatial Planning, Modeling, and Engineering.

References

[1] BMAS (Federal Ministry of Labour and Social Affairs of Germany). 2006, Gesetz über Betriebsärzte, Sicherheitsingenieure und andere Fachkräfte für Arbeitssicherheit (ASiG), .
[2] BMAS (Federal Ministry of Labour and Social Affairs of Germany). 2007, Verordnung zum Schutz der Beschäftigten vor Gefährdungen durch Lärm und Vibrationen (Lärm- und Vibrations-Arbeitsschutzverordnung - LärmVibrationsArbSchV), .
[3] Schmischke, H., 2009, Lärm am Arbeitsplatz in der Metall-Industrie (BGI 688), Heymanns, Köln.
[4] ISO 7731, 2003, Ergonomics – Danger Signals for Public and Work Areas – Auditory Danger Signals.
[5] ISO 9921, 2003, Ergonomics – Assessment of Speech Communication.
[6] Kryter, K.D., 1994, The Handbook of Hearing and the Effects of Noise: Physiology, Psychology, and Public Health, Academic Press, Boston.
[7] VDI (Verein Deutscher Ingenieure), 1988, VDI 2058 Blatt 2, Assessment of Noise with Regard to the Risk of Hearing Damages, VDI Manual Noise Reduction.
[8] VDI (Verein Deutscher Ingenieure), 1999, VDI 2058 Blatt 3, Assessment of Noise in the Working Area with Regard to Specific Operations, VDI Manual Noise Reduction.
[9] Sherwood, N., Griffin, M.-J., 1990, Effects of Whole-Body Vibration on Short-Term Memory, Aviation Space and Environmental Medicine, 61/12: 1092–1097.
[10] Sundstrom, E., et al, 1994, Office Noise, Satisfaction, and Performance, Environment and Behavior, 26/2: 195–222.
[11] Ljungberg, J.K., Neely, G., 2007, Stress, Subjective Experience and Cognitive Performance during Exposure to Noise and Vibration, Journal of Environmental Psychology, 27:44–54.
[12] Embleton, T.F.W., 1997, Technical Assessment of Upper Limits on Noise in the Workplace, The International Institute of Noise Control Engineering, No. 97-1.
[13] Probst, W., 2002, Anwendung der Geräuschemissionsangabe in der Praxis. Wirtschaftsverl, NW, Verlag für Neue Wiss., Bremerhaven.
[14] Rabenstein, R., et al, 1997, Acoustic Rendering of Buildings, in: Proceedings of the 5th International IBPSA Conference Building Simulation (vol. 2, Prag), pp.181–188.
[15] Svensson, U.P., 2002, Modelling Acoustic Spaces for Audio Virtual Reality, in: Proceedings of the 1st IEEE Benelux Workshop on Model based Processing and Coding of Audio (MPCA) (Leuven, Belgium), .
[16] Deines, E., 2008, Acoustic Simulation and Visualization Algorithms, PhD thesis, University of Kaiserslautern.
[17] Siltanen, S., et al, 2010, Rays of Waves? Understanding the Strengths and Weaknesses of Computational Room Acoustics Modeling Techniques. in: Proceedings of International Symposium on Room Acoustics (ISRA2010) (Melbourne, Australia), .
[18] Bertram, M., et al, 2005, Phonon Tracing for Auralization and Visualization of Sound, in: Proceedings of IEEE Visualization (VIS'05), pp.151–158.
[19] Gigante, M.A., 1993, Virtual Reality: Definitions, History and Applications, in Earnshaw RA, Gigante MA, Jones H, (Eds.) Virtual Reality Systems. Academic Press, London, San Diego, p. 1993.
[20] Sutherland, I.E., 1965, The Ultimate Display, in: Proceedings of the IFIP Congress (New York, USA), pp.506–508.
[21] Burdea, G., 1993, Virtual Reality Systems and Applications, Electro'93 International Conference (Edison, New Jersey), .
[22] ISO/IEC 14772-2, 2004, The Virtual Reality Modeling Language International Standard.
[23] Oliveira, D.M., et al, 2007, Virtual Reality System for Industrial Training, IEEE International Symposium on Industrial Electronics (Vigo, Spain), pp.1715–1720.
[24] Brecher, C., Witt, S., 2009, Interactive Analysis of the Structural Mechanic Behaviour of Machine Tools, Production Engineering, 3/4–5: 475–481.
[25] Aurich, J.C., et al, 2005, Models for VR-based Reconfiguration of Manufacturing Systems – Basic Demands and Requirements, in: Proceedings of the ProSTEP iViP Science Days (Darmstadt, Germany), .
[26] Aurich, J.C., et al, 2009, Improvement of Manufacturing Processes with Virtual Reality based CIP Workshops, International Journal of Production Research, 47:5297–5309.
[27] Schirmer W, (Ed.) (2006), Technischer Lärmschutz. 2nd edition. Springer, Berlin.
[28] Möser, M., 2007, Technische Akustik. 7, erw. und aktual. Aufl., Springer, Berlin.
[29] ISO 9614-1, 2009, Acoustics – Determination of Sound Power Levels of Noise Sources using Sound Intensity; German version, November 2009.
[30] Brüel & Kjaer (Ed.), 1991, Handbuch Schallintensitätskalibrator Typ 3541, Brüel & Kjaer, Naerum.
[31] Henn, H., et al, 2008, Ingenieurakustik, 4. überarb. und erw. Aufl., Vieweg + Teubner, Wiesbaden.
[32] ISO 11202, 2010, Acoustics – Noise Emitted by Machinery and Equipment – Determination of Emission Sound Pressure Levels at a Workstation and at Other Specified Positions Applying Approximate Environmental Corrections.
[33] DIN 45635-1, 1984, Geräuschmessung an Maschinen; Luftschallemission, Hüllflächen-Verfahren; Rahmenverfahren für 3 Genauigkeitsklassen.