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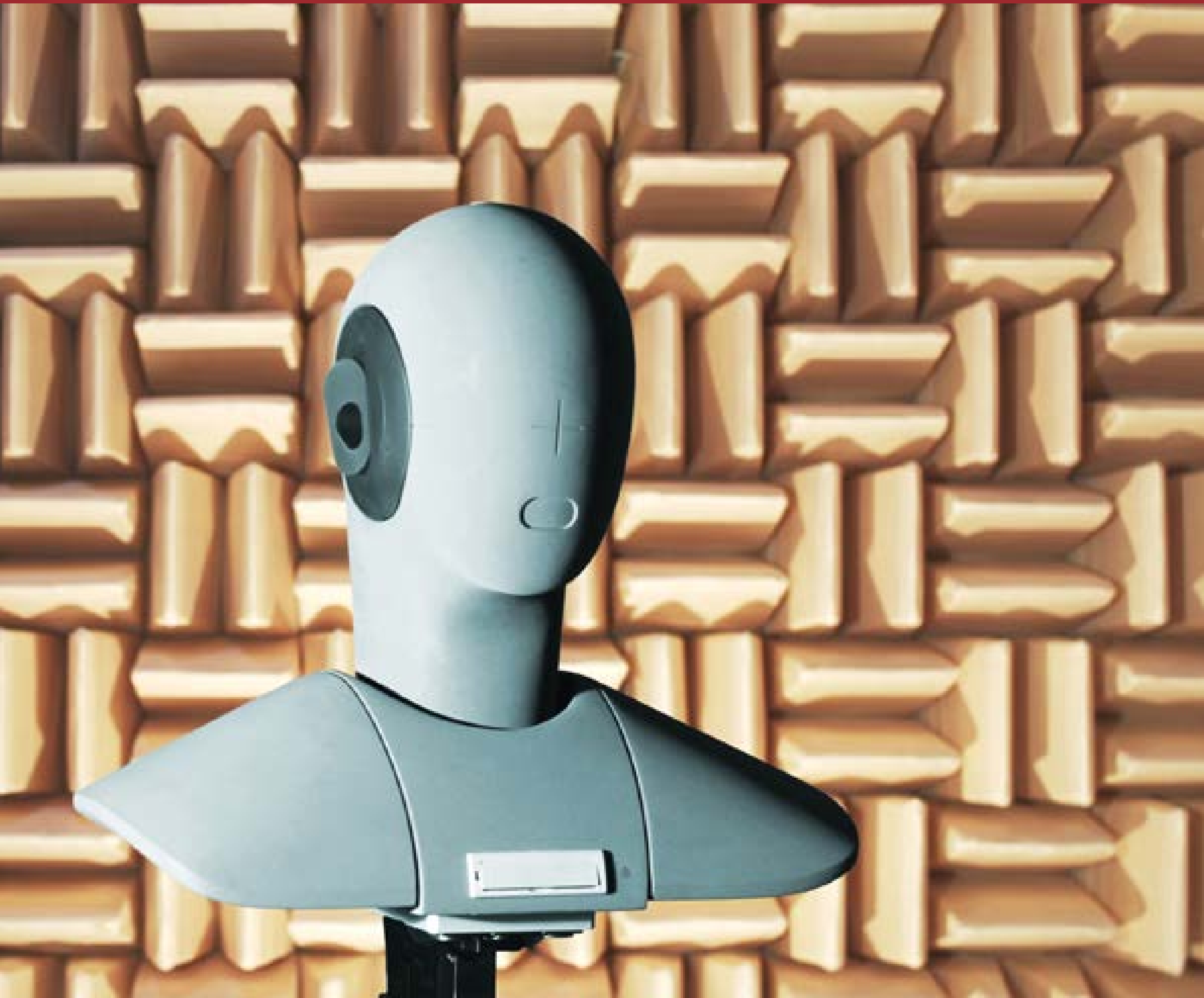
ACOUSTICAL ENGINEERING

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ACOUSTICAL ENGINEERING: THIS IS WHAT THE FUTURE SOUNDS LIKE

Acoustical Engineering is an interdisciplinary science dealing with the mathematical and physical basics of acoustical phenomena of noise excitation, noise generation and sound propagation, and the influencing of sound in various media. In addition to the actual analysis of sound events, sound perception by the human ear plays an important role as well as the effect of sound on the human organism.

Noise as unwanted and uncomfortable sound is consciously or subconsciously perceived by humans and may cause impairment of health. Thus, manufacturers of noise emitting machines, vehicles, engines and plants are always responsible for reducing the noise emissions of their products to a bearable amount by applying suitable technical solutions. In the automotive industry in particular, essential parts of the series development process have comprised noise reduction, noise optimization and the design of a vehicle- or brand-specific sound (sound design). In order to implement noise optimization measures into the design process as early as possible, it is necessary to obtain information about sound sources and their positions and contributions to the overall sound already at an early product stage.

The Department of Acoustical Engineering at the Fraunhofer Institute for Machine Tools and Forming Technology IWU conducts research in acoustics and vibration technology in the following areas, among others:

– Machine acoustics
– Vehicle acoustics
– Railway acoustics
– Building acoustics and room acoustics
– Psychoacoustics

On a total surface area of approx. 1,000 m² at the Dresden branch of the institute, several acoustic laboratories and acoustic test facilities are available as well as extensive equipment of acoustic measurement systems for performing detailed noise and vibration analysis within research projects.

IMAGE *Localization of sound sources in an air conditioning unit of a high speed train by using microphone array technologies*

Research topics

Our research activities focus on the following topics:

■ Acoustics of gearboxes and complete powertrains

The acoustical properties of powertrains are becoming more and more important as quality criteria of vehicles. Current developments in drive technology aim for achieving high performances in the generation and transfer of kinetic energy while using as few resources as possible. In this context, a focus lies on alternative drive concepts such as hybrid and electric drives.

In order to realize research activities in the area of gearbox acoustics, we apply various processes for measuring and simulation, which allow us to detect acoustical phenomena. Using the latest simulation processes enables us to evaluate and optimize production-dependent acoustical properties already in the development stage, or to specifically influence available structures. Furthermore, we use the detailed simulation models for acoustically evaluating tolerance variations due to deviations during production and assembly, or for designing active systems for reducing vibrations on transfer paths.

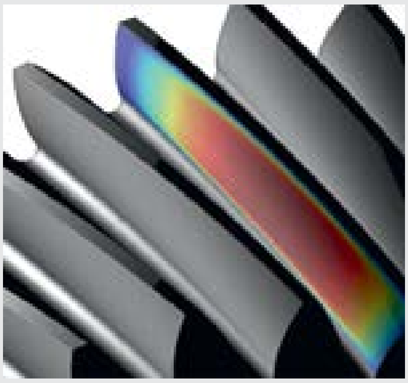
■ Acoustics of electric drive systems

Radial and tangential dynamic force components from the magnetic circuit of electric machines represent an essential mechanism of excitation of noise and vibrations. The noise radiation of the machine can be significantly reduced by magnetic circuit optimization or by the machine control. Moreover, the torque ripple of the drive can also be reduced as well as the resulting bearing reaction forces. In order to achieve integrated reduction, coupled loads and dynamic properties are represented in an abstracted manner, both in machine models and testing setups. For this purpose, we apply numerical simulations of the magnetic field with tools of the finite element method (FEM) or analytical approaches for calculating magnetic circuits. The abstraction into power-based coupling points of the subsystems allows the transfer into multi-domain overall systems. Measurement based validation takes place using classical modal analyses and special acoustical testing facilities for overall systems and subsystems. We can realize and verify simulated optimizations by applying real-time capable rapid control prototyping of the drive control.

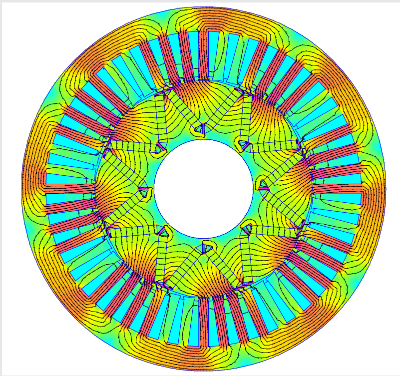
■ Structural dynamics

For effectively reducing noise and vibrations, it is often necessary to optimize structure-borne noise transfer paths and the noise radiation of components in addition to understanding the excitation mechanism. Acoustical component optimization, for example, can reduce undesirable noise. This can be achieved by passive measures such as the introduction of ribbing or by decoupling; furthermore, active solutions are also possible such as active vibration control (AVC).

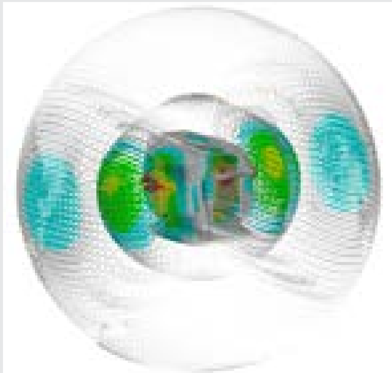
Depending on the frequency range to be considered, we utilize various simulation methods for designing active or passive measures against noise. In addition to the classical finite element method or modeling of multibody systems (MBS), these measures also include analytical approaches of computation (for example the four-pole theory) or energy-based simulations (statistical energy analysis – SEA, structural intensity – STI), which are developed at Fraunhofer IWU and validated by measured data.



Gear
- Gear design and optimization
- Transfer paths and components



Electric machine
- Control processes
- Optimization of magnetic circuits
- Interactions

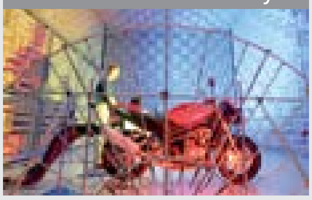


Structural dynamics
- Material properties
- Component optimization
- Sound transfer paths and noise radiation

Acoustical methods at Fraunhofer IWU

Active and passive systems

Processes of measurement and analysis



Modeling and simulation methods

Influences on production and quality assurance

IMAGE *Investigations of noise radiation in tires are conducted on a multi-axial vibration test rig.*

ACOUSTICS OF GEARBOXES AND COMPLETE DRIVE TRAINS

Our range of services

Our range of services comprises experimental determination, simulation-based representation and optimization of acoustical properties of powertrains and gearboxes. In addition to the numerical and experimental investigation of overall systems, we conduct fundamental investigations for describing noise transfer properties of individual system components and sources of excitation, for example the gear mesh of transmissions.

Our competences

Measurements

– Analysis of gearboxes by extensive vibro-acoustic measurements, for example analysis of operating deflection shapes (ODS)
– Detection of surfaces relevant for noise radiation
– Order analysis, also considering undulations on the gear flank ("ghost frequencies")
– Experimental modal analysis (EMA)
– Model updating

Simulation

– Analysis of gearboxes by multi-physical simulation (finite element simulation – FEM, multibody simulation – MBS, analytical approaches)
– Acoustical optimization considering degree of efficiency and strength
– Excitation prediction and calculations of load distribution considering the elastic behavior of shafts, bearings and gearboxes
– Optimization of gear flank topology for noise reduction and increase of load capacity
– Acoustical optimization of the gear body geometry
– Simulation-based analysis of deviations due to manufacturing and assembly processes
– Calculation of noise radiation of gearboxes
– Development of measures for reducing vibration/noise
– Design of active systems for vibration control (AVC) on relevant transfer paths

Testing

Test rig for gearboxes

– Fundamental investigations on high-speed gearboxes for vehicles and industrial applications (spur and helical gears) with arbitrary profiles regarding load and rotational speed
– Quasi-static measurement of transmission errors caused by gear mesh
– Investigation of efficiency by high-precision torque measurement at the input and output sides (power loss)
– Analysis of airborne noise and structure-borne noise at various points of operation (for example by using laser vibrometry or sound intensity mapping with microphone array technologies)
– Investigations on load capacity (Woehler curves of component, investigating types of damage such as scuffing, micropitting, small pits, wear and tooth fracture depending on various system parameters)

Technical data of test rig for gearboxes

– Maximum rotational speed: 10,000 min^{-1}
– Permanent maximum torque: 1,100 Nm (up to 1,650 min^{-1})
– Maximum power: approx. 190 kW
– High-precision measuring of angle of rotation
– Flexible setup:
  Setup 1: test housing with variable center distances for supporting various spur gears with tempered injection lubrication
  Setup 2: support of an external gearbox
  Setup 3: support of an entire E-powertrain, including vehicle engine and application of the respective wheel driving torque
– Vehicle energy system for 3-E operation (Setup 3) with battery simulation capacity (200 kW, 8 to 800 VDC)
– Optional location: semi-anechoic chamber

Reference projects

Gear excitation

The acoustical evaluation of power transmissions requires the detailed analysis of the gear mesh relations considering the dynamic behavior of the surrounding components like bearings, shafts and the gearbox housing. We use modern computing approaches to estimate the impact of these influencing parameters on gear mesh excitation. The objective is the minimization of excitation which, for example, can be achieved by micro geometry optimization of the tooth flanks.

Simulation of manufacturing in gear grinding

Especially in the case of vehicle transmissions, the requirements continuously increase for load capacity and dynamic behavior. A reason for the increasing demands can be found in the use of new electrical drives where no combustion engine exists, i.e. no masking effects occur. Nowadays, the specific application of tooth flank micro geometries is used to improve the load capacity of gears and the acoustic behavior of the gearbox. However, deviations of the target flank form can lead to significant changes in the predicted behavior. These deviations can be caused by the manufacturing process, for example the bias which occurs during the gear grinding process of gears with lead crowning. The use of manufacturing simulations enables the consideration of these deviations to improve the corresponding prediction models.

Numerical calculation of noise radiation

The acoustical properties of transmissions are important quality criteria. For evaluation of the acoustical behavior even within the development process, we use simulation methods considering the dynamic properties of the entire system which includes the excitation and transfer behavior as well as the simulation of the radiated sound. Our objectives are the identification of critical operation points and the structural optimization of the gearbox housing.

End-of-line vehicle correlation

In most cases, the acoustical behavior of vehicle components differs in the final implementation inside the vehicle structure and the end-of-line test rig in production. The differences are caused by the changing mounting conditions. Based on correlation analysis, we develop mathematical methods to characterize the component's acoustical behavior between test bench and vehicle. By applying specific and statistically verified end-of-line analyses (EOL), we can ensure constant high acoustical quality of gearboxes in various car body variants.

IMAGE *Acoustical test rig for gearboxes*

ACOUSTICS OF ELECTRICAL DRIVE SYSTEMS

Our range of services

We offer valid simulation approaches for the acoustic analysis and optimization of electric machines. The dynamic excitation of the machine is represented holistically – in interaction with control, and including the reaction with coupled loads and boundary conditions of bearings. For validation of the simulation models, we use different specialized test rigs. Target values are verified by experiments as well.

Our competences

Measurements

- Development of tests for determining the dynamic excitation of electric drives
- Measuring the excitation of airborne noise and structure-borne noise at various points of operation

Simulation

- Description of multidomain systems by abstracting partial systems and by power-based definition of interfaces, by applying the four-pole theory and by extending it to n-poles for multidimensional systems
- Numerical calculation of magnetic fields by using FEM and analytic calculation of magnetic circuits with efficient computing time, including magnetic circuit optimization
- Scalable electric machine models: fundamental model, extended fundamental model depending on position, characteristics of flux harmonics, skew modeling, current harmonics due to pulsing (Total Harmonics Distortion – THD)
- Time step simulation for designing controller and filter of the drive control and for modulation processes
- Drive and machine control close to the recitifier, field orientation and direct processes, real-time capable implementation and rapid control prototyping of the drive control
- Compensation process for reducing torque ripple and excitation of radial force in order to achieve improved vibro-acoustic drive behavior

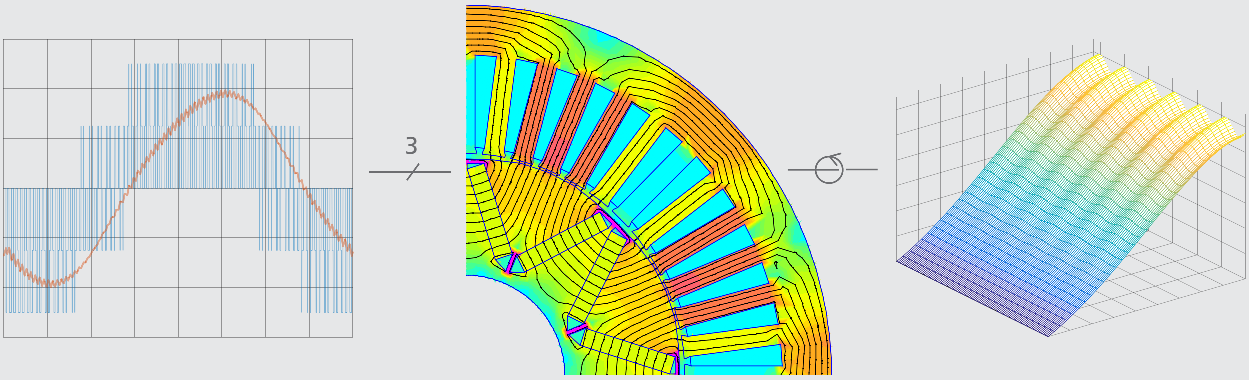
Testing

Test rigs

- Test rigs for drive systems (total systems or subsystems)
- Testing of component´s specifications in terms of airborne noise and structure-borne noise and additional specifications like electrical, hydraulical and mechanical values
- Customized test rigs for vehicle auxillary components and spezialized acoustical test rigs for electrial drives and components
- Test rig for electrical drive systems

Possible testing options

- Measuring of mounting forces according to the "blocked force" principle
- Determination of the free mounting velocity of a component for all degrees of freedom (DOF)
- Determination of the radiated sound power using enveloping surface methods or sound intensity probes
- Evaluation of the structure-borne noise by measuring the operational velocity and operational deflection shapes using 3D laser vibrometry
- Combined test rigs for driving or driven subsystems of vehicle auxillary components for separating acoustical contributions
- Load test rigs for acoustical evaluation of small electric drives
- Determination of performance parameters and of the efficiency range of electric drives
- Determination of electric characteristic values such as idle power and apparent power, power factor, current harmonics, pulsing patterns, THD values
- Determination of acoustic characteristic values such as torque ripple and surface velocity



Reference projects

Multidomain overall simulation and description of coupling points

The system components of an electric drive can be seprated in different physical domains like power electronics, magnetic circuit and mechanical structure. Additional systems can be coupled to the drive like transmission, fan wheel or linear guiding. All individual components of the mechatronic system influence its acoustical behavior and may interact with each other. In order to describe the overall system, it is necessary to identify and characterize the acoustically relevant effects of each physical domain. We seperate subsystems which are free of interactions to describe the relevant individual effects in an abstracted manner. Then the subsystems are coupled power-based using a flow- and a difference variable to describe the overall mechatronic system.

End-of-line testing for detection of production errors in electric vehicle drives

Selecting sensors, measuring positions and the actual testing program, and determining limit curves are major challenges in the automated end-of-line (EOL) testing of electric vehicle drives with integrated transmission and inverter. Preferably all errors which may occur are to be detected within a specific production cycle time. For this purpose, our employees catalog all potential errors at the manufacturer’s facilities, identify their characteristic error patterns by measurement and simulation, and ideally assign them to the matching cause in the production process. Subsequently, we support the manufacturer in developing a complete testing methodology and testing program. In order to evaluate the EOL measurement, strategies are examined that include dynamic limit curves, and reliably detect gradual exceedance of limit values.

Minimization of magnetic force harmonics in electric machines for vehicle drivetrains

The subjective noise perception of electric vehicles can be unfamiliar and uncomfortable because the combustion engine is no longer relevant as a noise source, and high frequency noise is increasing instead. The high frequency content is due to dynamic forces of the electric machine, which excite vibrations in the housing structures and the gear stage. Harmonic force orders result from the geometry of the magnetic circuit and have radial and tangential impact. They can be reduced by injection of vibration damping current harmonics, which results in reduced vibrations during vehicle operation.

During a research project extending over several years, numerical calculations of the magnetic field are carried out to identify the amplitudes and phases of the current harmonics. Furthermore, the field-oriented control is extended to inject these vibration damping current harmonics into the drive. Moreover, we identify the influences of the active vibration control on relevant parameters such as efficiency and torque ripple. The algorithm is then experimentally validated on a drive test bench using acceleration sensors to measure structure-borne noise.

IMAGE *Multidomain analysis – control, magnetic circuit, structural excitation*

STRUCTURAL DYNAMICS

Our range of services

We offer a broad range of solutions for the acoustical analysis and optimization of systems' structural dynamics. In addition to performing classic optimizations of structural dynamics, we also examine the application of active systems for noise and vibration reduction.

Our competences

Measurements
– Determination of dynamic parameters (forces, accelerations, displacements, sound pressure, sound power, noise intensity etc.) based on various measuring principles
– Experimental modal analysis and analysis of operational deflection shapes
– Experimental investigation of effective measures for reducing noise and vibrations
– Binaural measurements using an artificial head
– Localization of sound sources by using imaging techniques
– Determination of vibro-acoustic transfer paths

Simulation
– Simulation of the dynamic behavior of systems (numerical modal analysis, analysis of operational deflection shapes etc.)
– Simulation-based design of measures for reducing noise and vibrations, prediction of its absolute effect based on various simulation methods (FEM, BEM, MBS, analytical approaches)
– Simulating the noise radiation of systems
– Optimization algorithms for adjusting the dynamic properties (natural frequencies, noise radiation behavior, etc.)
– Simulation of active systems and their dynamic behavior in the overall system
– Sensitivity analyses regarding ideal excitation positions of active systems
– Simulating energy flows of structure-borne noise by applying various methods (structural intensity – STI, statistical energy analysis – SEA etc.)

Testing

Testing options
- Acoustical semi-anechoic chamber (class 1)
  – Lower frequency limit: 100 Hz
  – Internal dimensions: 8.7 x 6.1 x 5.4 m^3
  – Usable spatial volume: 284 m^3
- Laser vibrometry
  – 3D laser scanning vibrometer (PSV 400)
    - Contactless measurement of surface velocities
    - Frequency range: 0 to 1 MHz
    - Object size: starting from 1 mm^2
    - Evaluation regarding time and frequency range
    - Strain measurement
  – Vibrometer for rotating objects
    - High-precision and contactless measurement of torsional vibrations

Localization of sound sources by using microphone arrays
We are able to visualize sound sources through sound field mapping by using multiple microphone arrays (acoustic camera). Here the level of sound radiation is represented by color highlighting in an optical overlay image. By making sound events visible, sound sources are not only identified and localized, but it is also possible to quantify their contribution to the overall noise. As a result, a so-called noise source ranking can be calculated which comprises the ranking of all sound sources classified according to their sound power. By combining the two microphone array methods "acoustic holography" and "beamforming", we are able to analyze stationary or non-stationary sound events within a frequency range of approx. 80 Hz to 12,800 Hz. Various array geometries are available for analysis of a large variety of test objects.

Reference projects

Active solutions for reducing noise in rear axles

In several projects we developed different approaches to reduce the noise contribution from automotive rear axles – the so-called rear axle gear whine – inside the passenger compartment. Active systems were used to induce dynamic forces with phase opposition into the rear axle assembly in order to eliminate unwanted vibrations which are relevant for the interior noise. For example, a significant reduction of the noise contribution inside the vehicle can be achieved by an electrodynamic inertial mass actuator placed near the mounting of the rear axle transmission. Further development included piezoceramic patch actuators (piezopatches) that were applied on the rear axle subframe in order to minimize the transfer of structure-borne noise into the vehicle.

Describing the propagation of structure-borne noise in silencers for ships

Statistical methods can be used to calculate the propagation of structure-borne noise in silencers with dimensions typical for shipbuilding. Among other things, we developed a mathematical model that applies statistical energy analysis (SEA) to consider the reduced damping effect of silencers due to structure-borne noise. The vibration induction, the airborne noise excitation and the propagation of structure-borne noise in silencer components were investigated in this context with methods of experimental and analytical SEA. Moreover, suitable prediction models were developed. Validation of the models was carried out using test silencers and original-size silencers on a ship.

Structural intensity (STI) – processes of simulation and measurement

Reducing noise radiation of technical structures can often be achieved most effectively by systematically influencing the structure-borne noise. Damping layers or ribbing can be applied for this purpose. In order to achieve the maximum effect of these measures, the energy of structure-borne noise has to be known regarding its distribution and flow within a structural component. In a research project we investigated how to quantify and visualize energy flows of structure-borne noise from excitation to noise radiation by utilizing the structural intensity (STI). In this context we examined various methods for numerically and experimentally determining the structural intensity. For the measurement-based determination of the STI various methods have been compared, for example, the determination of the STI using surface velocities which have been measured using a 3D laser scanning vibrometer or optical strain measurements.

IMAGE *Visualized noise radiation of a vehicle door*

Editorial notes
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