

NVH Simulation & Measurement Approach for Wacker Neuson's Construction Machines

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Wacker Neuson
Group

Agenda

1. Introduction
2. Structure-borne noise & vibrations
3. Air-borne noise & vibrations
4. Liquid-borne noise & vibrations
5. Validation
6. Summary & Outlook

Introduction

- Wacker Neuson locations and products
- New wheel loader platform



Introduction

Production Locations

NORTH AMERICA

MENOMONEE FALLS (USA)



R&D, production

- Generators, pumps, heaters, lighting
- Rollers, trench rollers
- Skid steer loaders, compact track loaders

NORTH AMERICA

USA (Menomonee Falls)

EUROPE

Germany (Reichertshofen, Korbach, Pfullendorf)
Austria (Linz)
Serbia (Kragujevac)
Spain (Zaragoza)

ASIA

PINGHU (CHN)



Production

- Excavators
- Floor saws
- Vibratory plates
- Vibratory screeds
- M-series products

EUROPE

KORBACH (GER)



R&D, production

- Articulated
 - Hoftracs
 - Wheel loaders
 - Telescopic wheel loaders
- Telehandlers

PFULLENDORF (GER)



R&D, production

- All-wheel steered
 - Loaders
 - Telescopic wheel loaders
- Telehandlers

REICHERTSHOFEN (GER)



R&D, production, academy

- Internal vibrators, external vibrators, frequency converters
- Vibratory rammers, vibratory plates, rollers

HÖRSCHING (AUT)



R&D, production

- Tracked and wheeled excavators
- Track and wheel dumpers

SARAGOSSA (ES)



R&D, production

- Internal vibrators, frequency converters, screeds
- Vibratory rammers, vibratory plates, rollers

KRAGUJEVAC (SRB)



Production

- Steel components

Introduction

Products and Services

Construction equipment

Concrete technology



Compaction



Pumps



Demolition



Generators & lighting



Compact machines

Excavators



Dumper



Skid steer loaders



Telehandlers



Wheel loaders



Services¹



Concrete specialists



ConcreTec



Used machines



Academy



Repair & maintenance



Spare parts



Financial solutions



EquipCare



eStore



Rental

¹ The range of services rendered varies depending on the market and brand.



Introduction

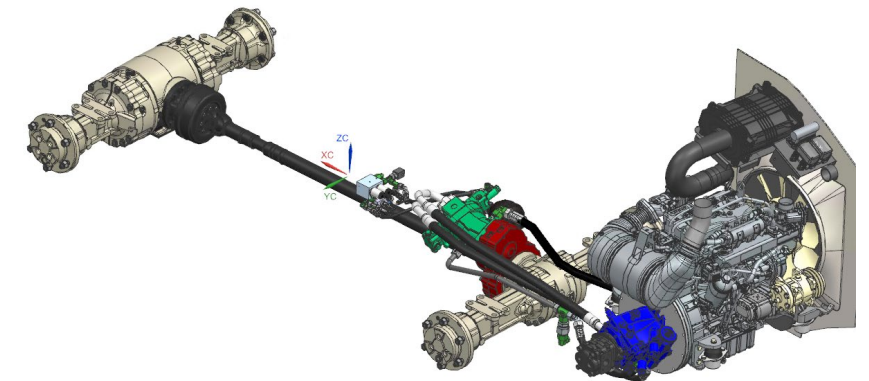
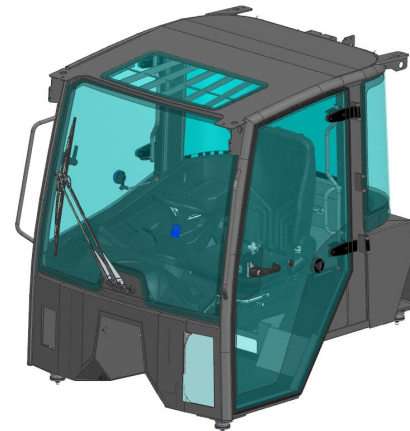
New wheel loader platform

Renewals compared to previous models:

- Platform 4t – 8t machines: common parts strategy
- Transverse engine installation
- New cabin platform for high driver comfort:

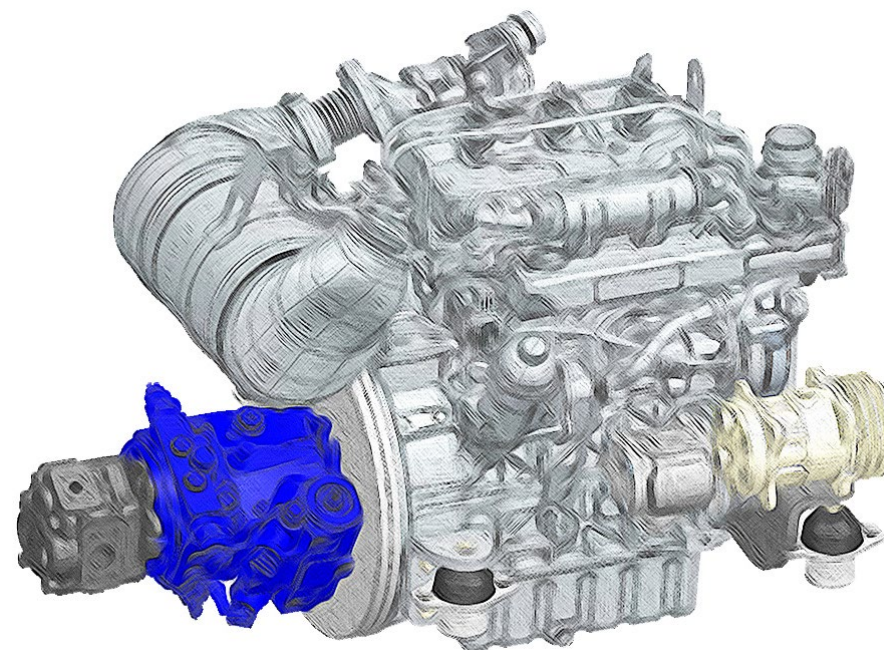
Powertrain & drivetrain (sound sources):

- Diesel engine, cooling fan
- Gear pump (implement pump)
- Axial piston pump (driving pump)
- Axial piston motor (driving motor)
- Transfer gear box
- Axles (differential gears, planetary gears)
- Tires



Structure-borne noise & vibrations

- Engine isolation
- Local dynamic stiffness of chassis & cabin
- Acoustic & vibrational transfer functions



Structure-borne noise & vibrations

Engine isolation

Simulation approach:

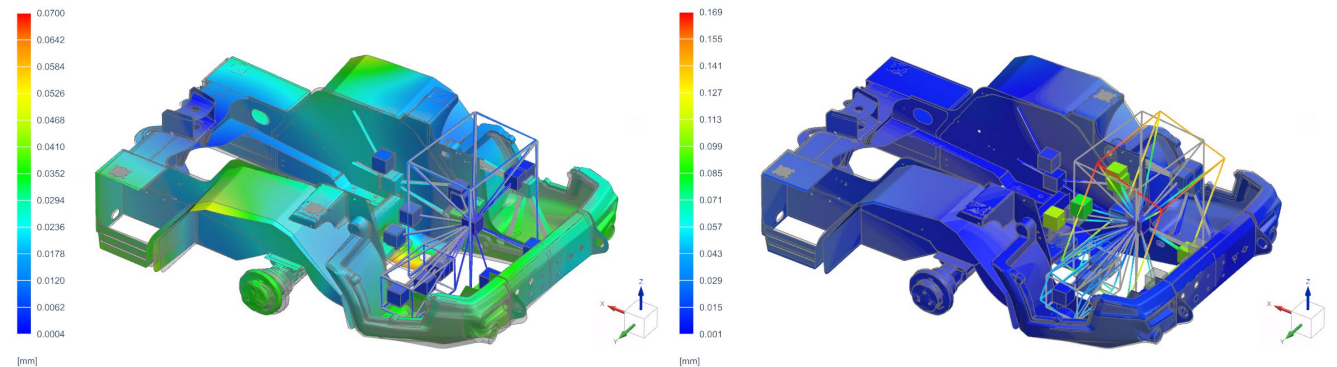
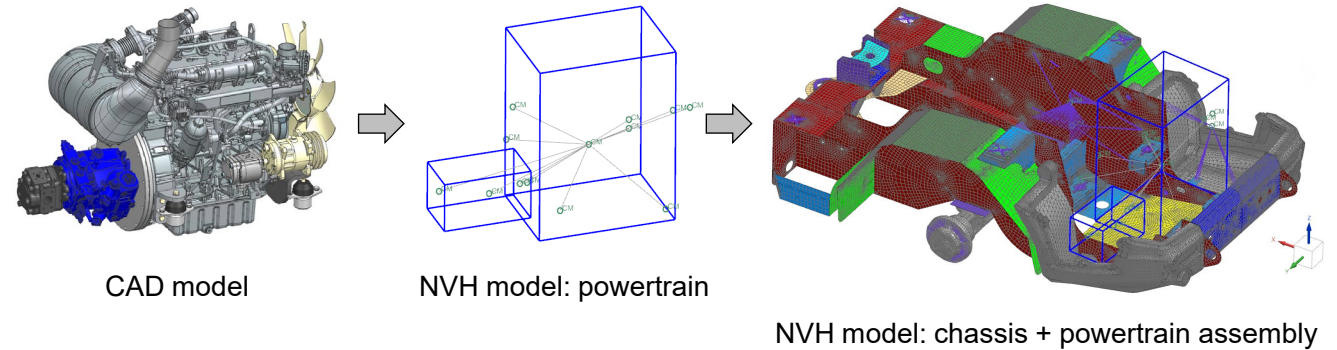
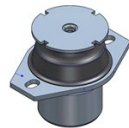
- Powertrain: rigid body model
- Chassis with engine mount brackets: FEM
- Engine mounts: dynamic stiffness and damping

Targets:

- Symmetric static loads for all engine mounts
- Work load 50 – 70% of max. load limit
- Eigenfrequency criteria

Optimization potentials:

- Engine mount type: elastomer/hydro mounts
- Shore hardness
- Engine mount positions



Mode 7: Side walls ✗

Mode 8: Pitch ✓

Structure-borne noise & vibrations

Local dynamic stiffness (LDS) of chassis & cabin

Simulation approach:

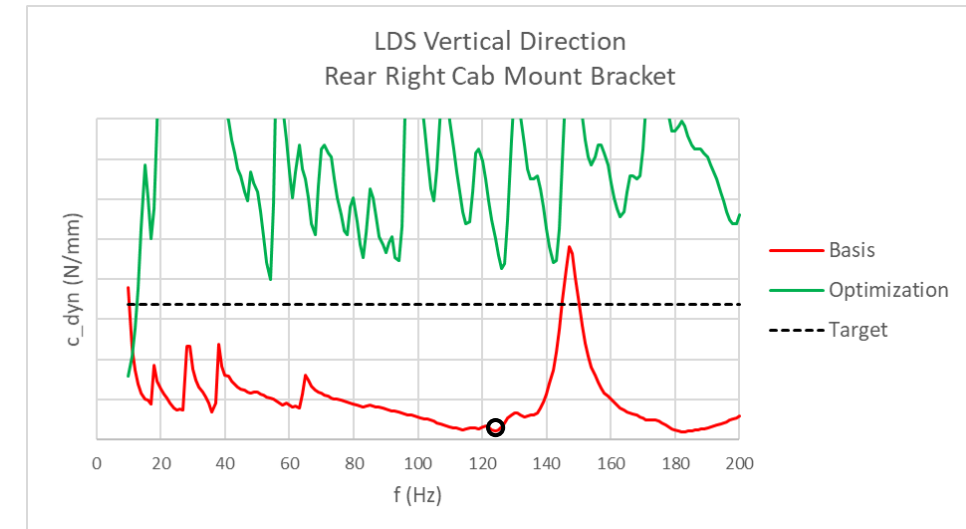
- Structural models of chassis and cabin frame
- Inputs: unit forces at engine & cabin mount connections
- Outputs: displacements at excitation points
- Frequency response simulation: stiffness over frequency

Targets for good isolation:

- Stiffness of engine & cabin mounts ↓
- Structural stiffness of chassis & cabin frame ↑
 - Stiffness targets based on dynamic mount stiffness

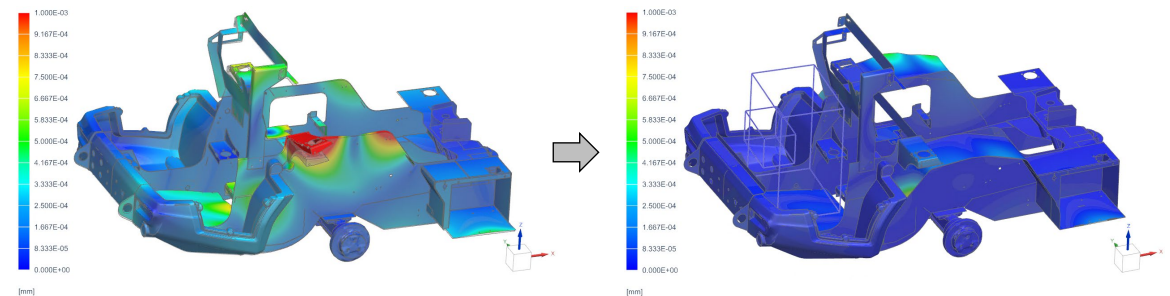
Optimization potentials:

- “Local” reinforcements: brackets, ...
- “Global” reinforcements: frame side walls, ...



LDS rear right cabin mount bracket:
Basis vs. Optimization

Operating deflection shape (ODS) with unit forces:



Basis @ critical frequency 125 Hz

Optimization @ critical frequency 125 Hz

Structure-borne noise & vibrations

Acoustic transfer functions (ATF's) & Vibrational transfer functions (VTF's)

Simulation approach:

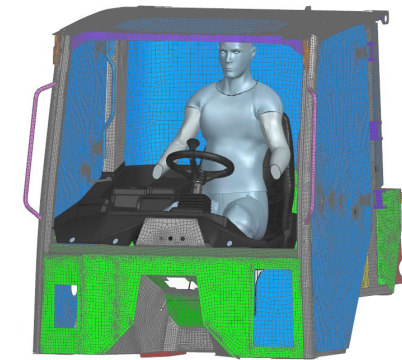
- Structural cabin model with cavity (air volume) and fluid-/structure interaction
- Inputs: unit forces at cabin mount connection points
- Outputs (ATF): sound pressure at driver's ears
- Outputs (VTF): vibration velocities at comfort points
- Frequency response simulation: transfer functions

Targets:

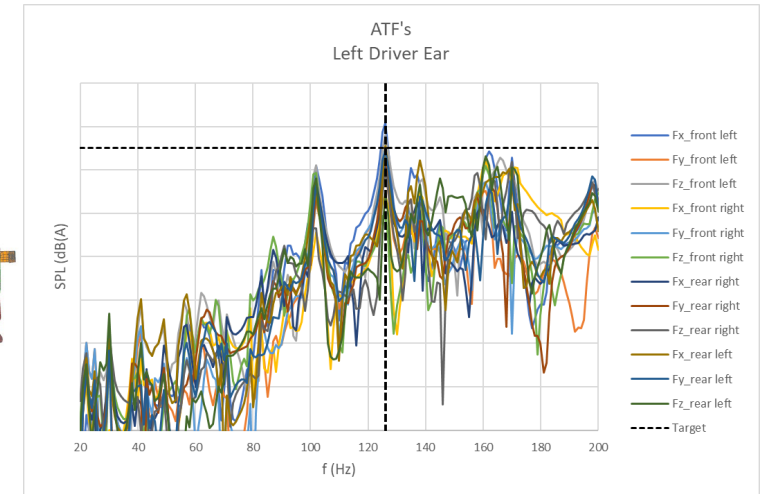
- Sound pressure < engineering target
- Peaks shifted to “non-critical” frequencies ($\neq$ excitation)

Optimization potentials:

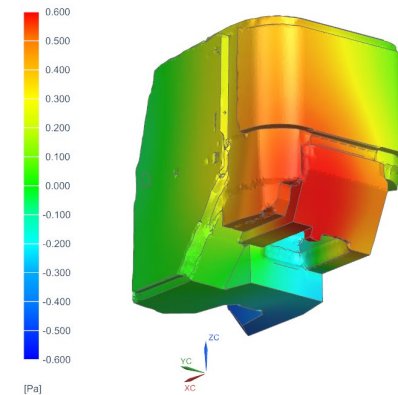
- Stiffness optimization of frame and large surfaces (roof, rear wall, bottom), glasses, ...
- Structural damping (glass type), absorption (insulation material)



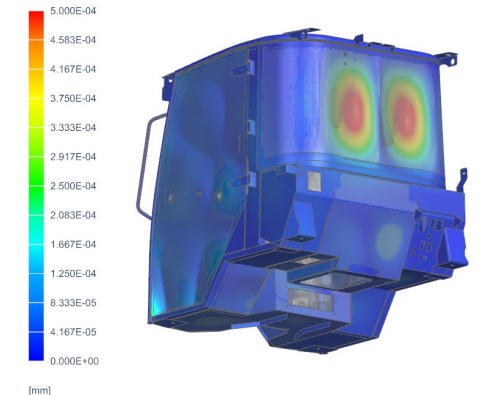
NVH model: cabin structure and cavity (hidden)



ATF's left driver ear



Cavity mode @ 125 Hz
Diagonal mode → left ear's sensitivity



ODS @ 125 Hz, unit force rear left
cab mount → monitored during validation

Air-borne noise & vibrations

- Fan noise
- Cabin isolation



Air-borne noise & vibrations

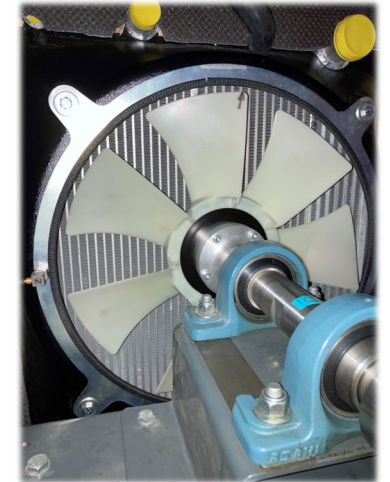
Fan noise

Approach:

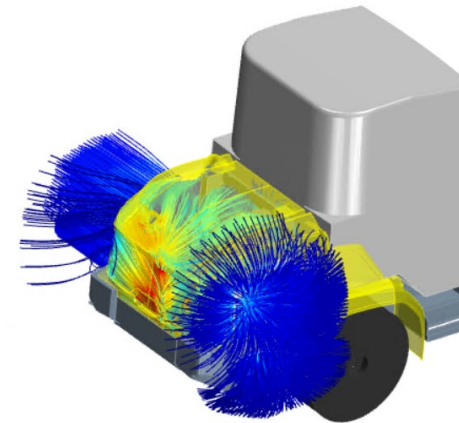
- Optimization of acoustic & cooling performance on test rig
 - Fan, shroud, cooler, engine silhouette
- Operating point (pressure and air flow) regulated by opening area
 - CFD simulation machine (underhood)
 - Iterative CFD simulations test rig
- Acoustic measurements
 - Sound intensity
 - Eigenfrequencies shroud, fan blades
- Thermal measurements:
 - Cooler temperatures inlet/outlet
 - Air flow



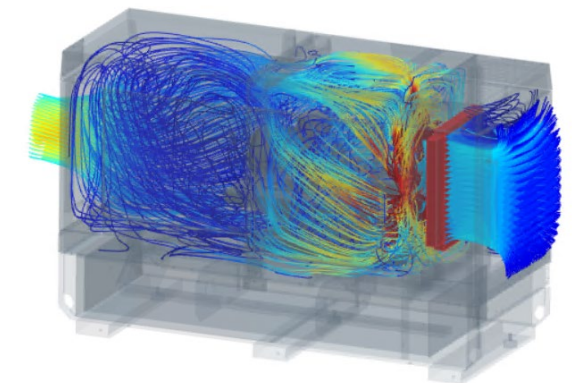
Fan/cooler test rig



Test rig: interior view
(w/o engine silhouette)



CFD simulation machine



CFD simulation test rig

Air-borne noise & vibrations

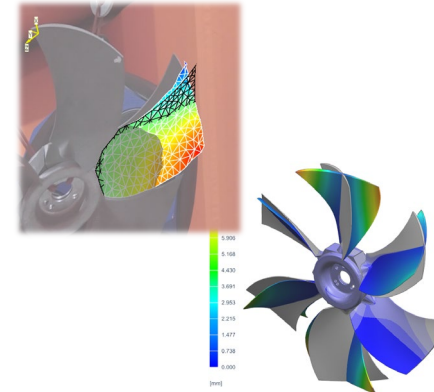
Fan noise

Targets:

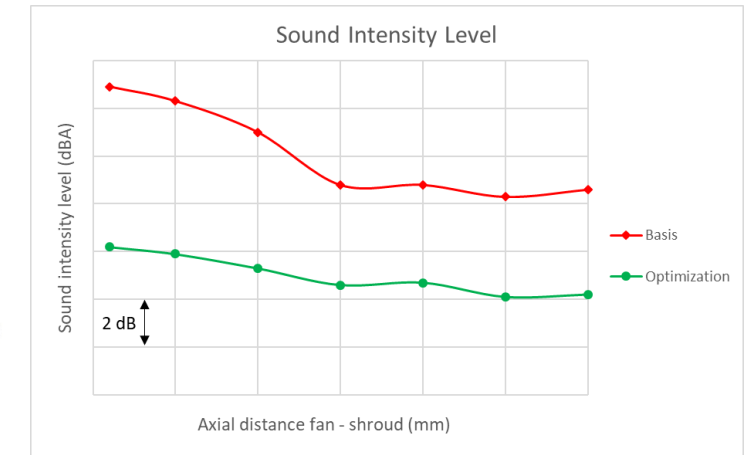
- Test rig
 - Optimized setting for highest possible noise reduction
- Machine
 - Fulfilment of ISO standard for LwA
OND 2000/14/EG, ISO 6395, ISO 3744
- Sound power test rig $\neq$ sound power machine

Optimization potentials:

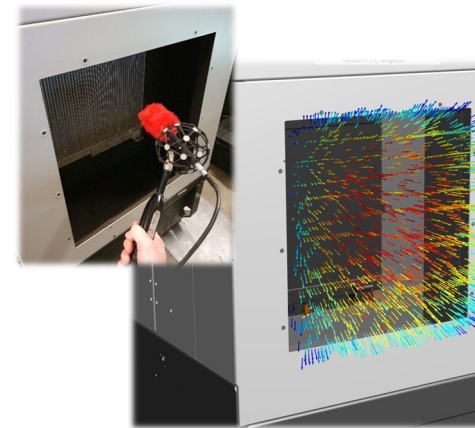
- Parameters:
 - Fan type (blade geometry), fan speed
 - Cooler type
 - Immersion depth fan/shroud
- Trade-off: cooling performance vs. acoustics



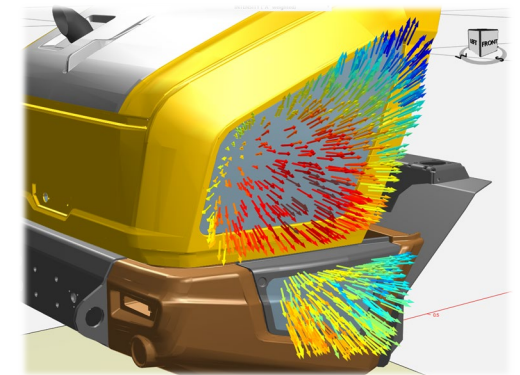
Mode shape of fan blade @ critical frequency: external measurement with laser vibrometer vs. simulation



Optimization results: sound intensity cooler



Measured sound intensity test rig



Measured sound intensity machine

Air-borne noise & vibrations

Cabin isolation

Approach:

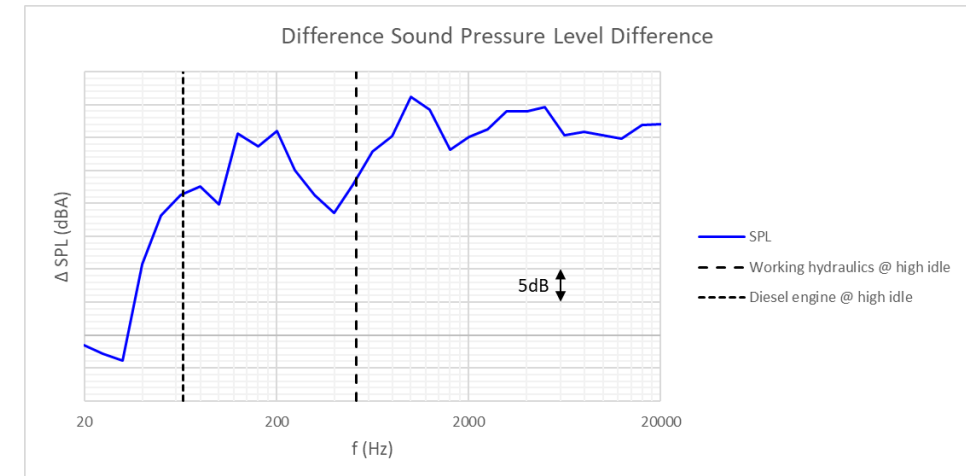
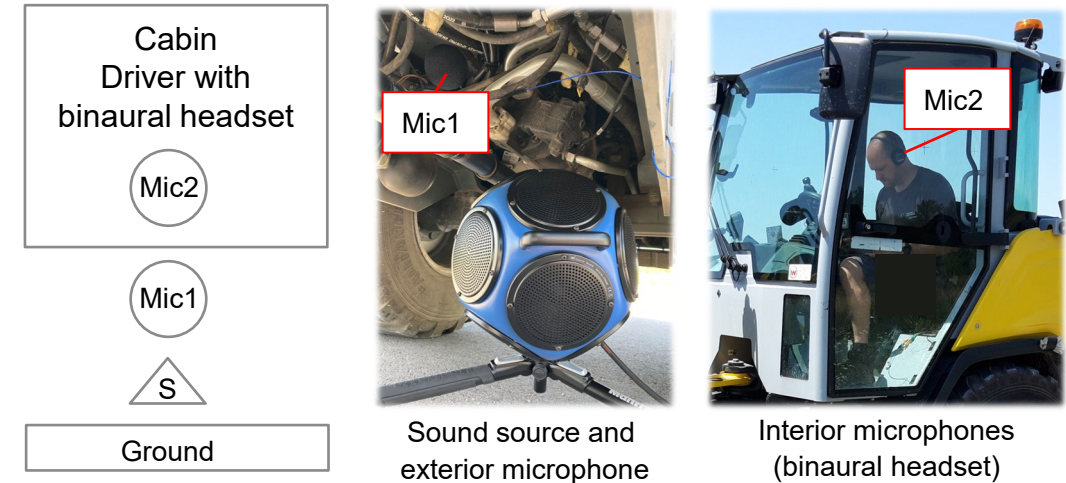
- Exterior sound pressure level SPL_1
 - Broadband excitation with omnidirectional loudspeaker → white noise
 - Microphone at sound source
- Interior sound pressure level SPL_2
 - Microphone at driver's ears (binaural headset)
- Acoustic transfer function p_{Mic1}/p_{Mic2} or $SPL_{Mic1} - SPL_{Mic2}$

Targets:

- Frequencies with low isolation should not be excited

Optimization potentials:

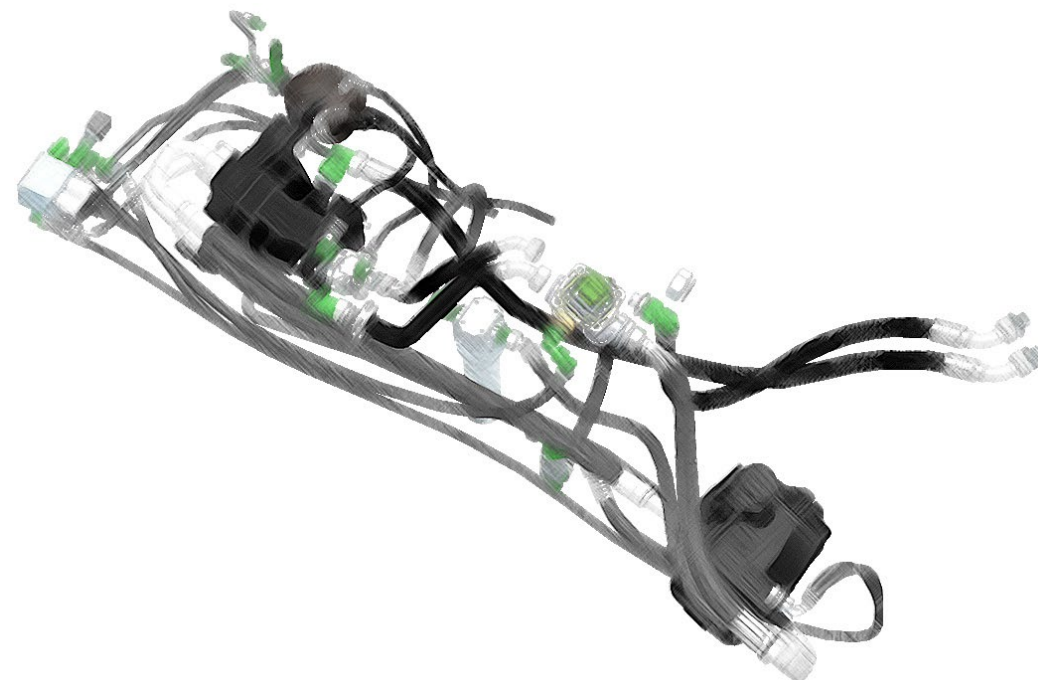
- Closing of gaps and openings
- Appropriate insulation material in cabin



Cabin isolation: Δ sound pressure level

Liquid-borne noise & vibrations

- Working hydraulics / steering noise



Liquid-borne noise & vibrations

Working hydraulics / steering noise

Approach:

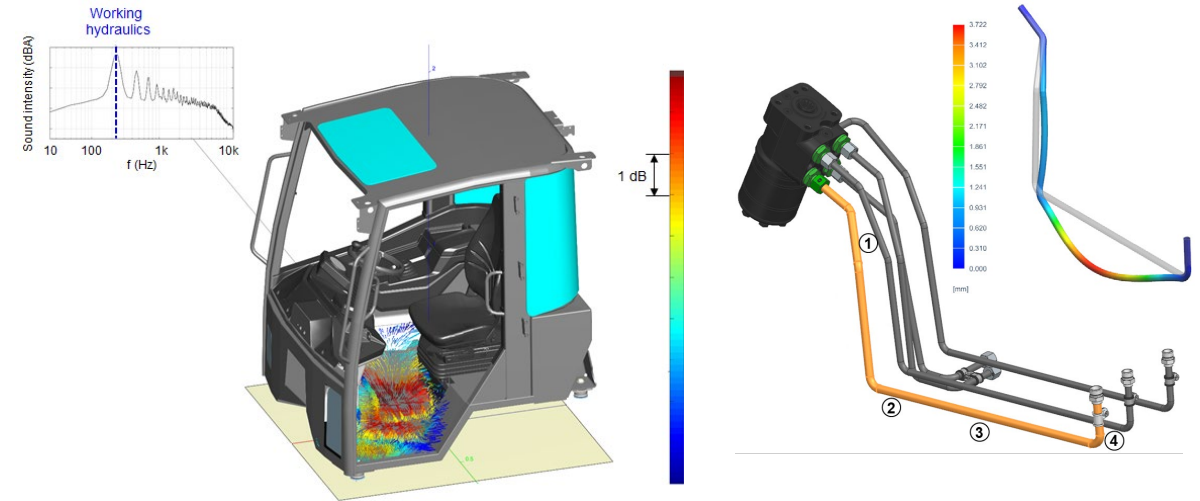
- Sound source localization of annoying cabin noise
 - Sound intensity measurements → steering pipes
 - Excitation: pressure pulsations from implement pump
- Cross check with:
 - Eigenfrequency simulation
 - Vibration measurements

Targets:

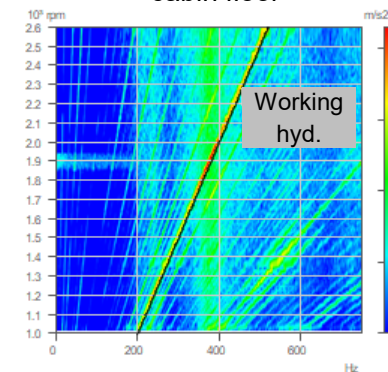
- Elimination of annoying noise → subjective improvement

Optimization potentials:

- Hydraulic hose instead of critical steel pipe
- Decoupling of other steel pipes
- Silence pump (costs!)

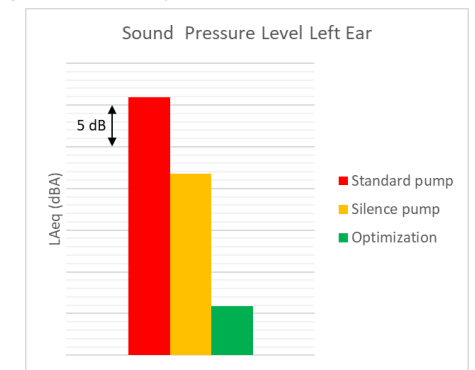


Sound intensity measurements
cabin floor



Campbell diagram of accelerations
at critical pipe

Steering orbitrol with steering pipes
Eigenfrequency simulation of critical pipe



Optimization results:
Sound pressure level

Validation

- Exterior noise
- Interior cabin noise
- Influence of structural stiffness
- Eigenfrequencies cabin cavity (air), rear glass



Validation

Exterior noise

Approach:

- Validation of fan noise optimization on test rig
- Comparison with measured sound power in free field
 - LwA according OND 2000/14/EC, ISO 6395
 - Consideration only of working cycle (no driving)

Results:

- Basis vs. optimization:
 - Test rig / sound intensity: -4.7%
 - Machine / sound intensity: -3.8%
 - Lower potential due to other sound sources
 - Machine / sound power: -3.4%
 - Difference between standstill and working cycle



Sound intensity measurement test rig



LwA measurement free field

Validation

Interior cabin noise, influence of structural stiffness

Approach:

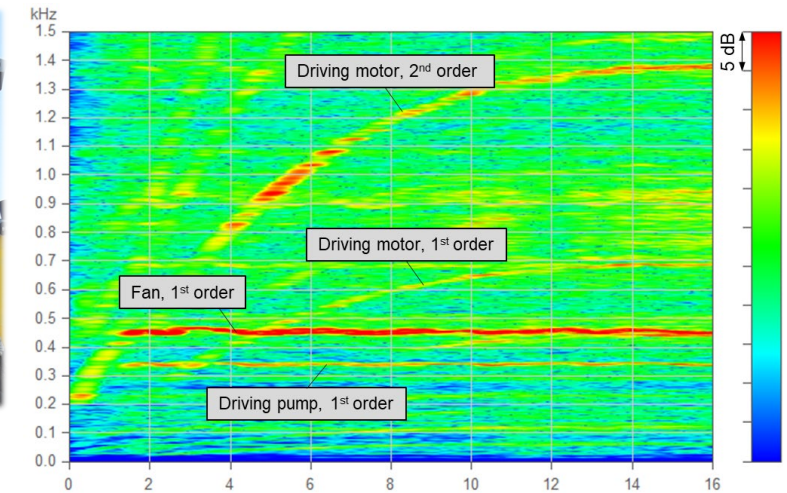
- Cabin noise measurements, vibration measurements
 - Stationary operating points, engine runup, working cycle, driving cycle
 - Sound pressure @ driver's ears
 - Vibrations @ comfort points
- Validation of structural stiffness simulation
 - Relative comparison: basis machine vs. machine with structural reinforcements according simulation results

Results:

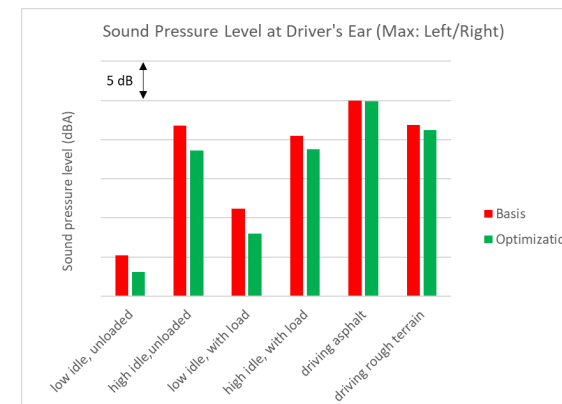
- Ranking of sound sources in cabin
- Influence of chassis stiffness (after fan optimization):
 - Sound pressure reduction: max. -4.8%
 - Accelerations seat console: max. -59%



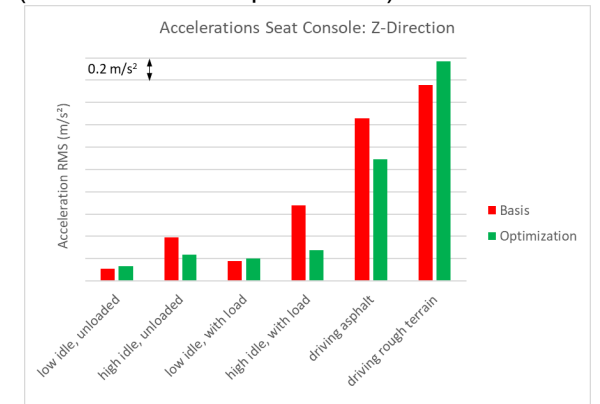
Binaural headset
Acceleration sensor seat console



Spectrogram left driver's ear, accelerated driving
(before fan noise optimization)



Stiffness influence in sound pressure



Stiffness influence in seat console vibrations

Validation

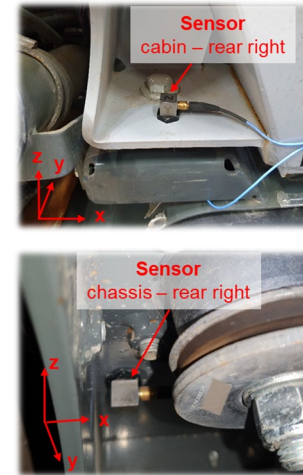
Interior cabin noise, influence of structural stiffness

Approach:

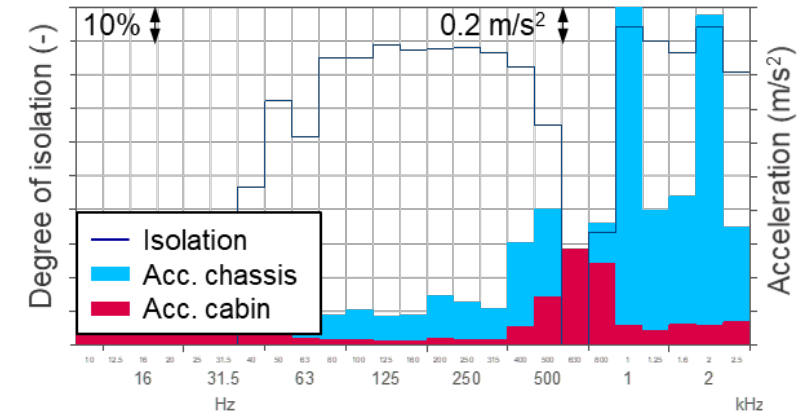
- Cabin mount isolation
 - Stationary operating points, engine runup, working cycle, driving cycle
 - Accelerations chassis / cabin side
- Experimental modal analysis of certain components

Results:

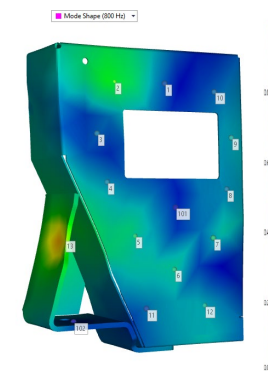
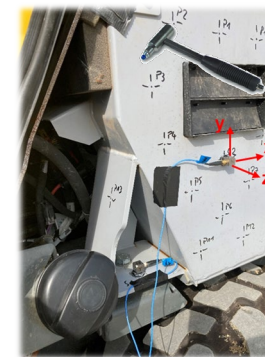
- High isolation degrees in all scenarios at all 4 cabin mounts, in all directions
- Frequency range of isolation as simulated
- Weak point at rear right cabin mount @ 800 Hz
- Excitation from 2nd order of working hydraulics
- Eigenfrequency of cabin mount bracket and side wall detected → potential for structural improvement



Acceleration sensors



Terz spectrum of accelerations (z), isolation
Driving on rough terrain, constant speed



Experimental modal analysis
Rear right cab mount bracket and side wall, mode shape 800 Hz

Validation

Eigenfrequencies cabin cavity (air), rear glass

Approach:

- Validation of simulated cavity mode and rear window
- Sound source:
 - Omnidirectional loudspeaker in cabin, white noise
- Microphones:
 - Left driver ear and reference signal
- Acceleration sensors:
 - Rear window S1, S2

Results:

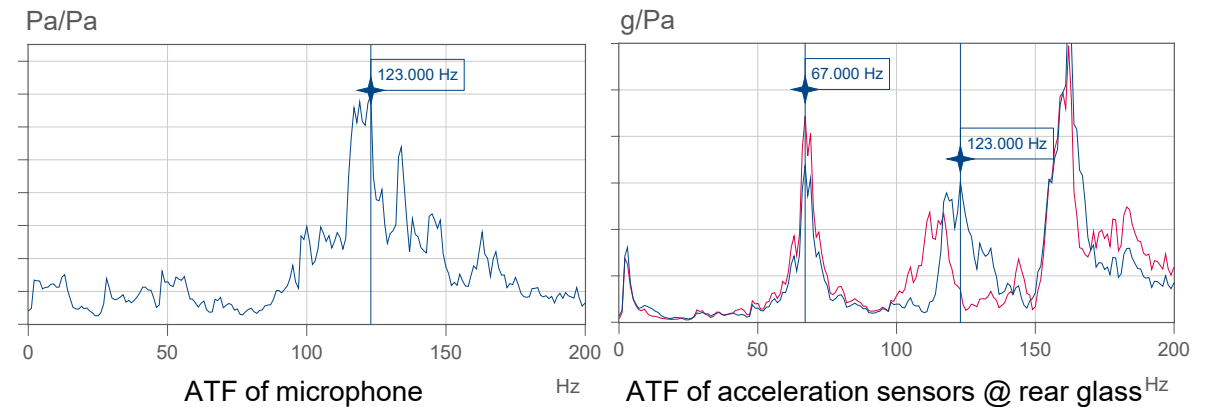
- Peak in ATF of microphone: 123 Hz
- Peaks in ATF's of acceleration sensors: 67 Hz, 123 Hz
- Uncertainties: glass material data, gluing connections etc.
- Cavity mode validated, but not critical during operation



Measurement setup in cabin: loudspeaker, microphone, acceleration sensors



Acceleration sensors rear window



Summary & Outlook



Summary & Outlook

Ranking of sound sources

Ranking of sound sources:

- Ranking before optimizations
 1. Fan
 2. Hydrostatic drivetrain
 3. Steering hydraulics

Approach:

- Ranking during measurements on prototype
- Noise prediction in virtual phase with available tools not possible → future approach



Summary:

- Approach before prototype “**virtual phase**”
 - Hybrid simulation / measurement approach
 - Simulation: eigenfrequencies, local dynamic stiffness, frequency response functions for structure & fluids
 - Measurements: fan noise (test rig)
- Approach with prototype “**hardware phase**”
 - Measurements of current status: exterior microphones, binaural headset at driver’s ears, vibrations comfort points
 - Sound source localizations: sound intensity measurements
- Optimization: **hybrid approach simulations + measurements**

Outlook:

- **Predicted cabin noise & vibration**
 - Excitation database: measured blocked forces determined via C-TPA
 - NVH models: assembly of substructures with more accurate connections
- } virtual prototype assembly



Thanks to ECS team for
cooperation in NVH simulation!

Thank you for your attention!

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