Powertrain NVH Analysis with BK Connect

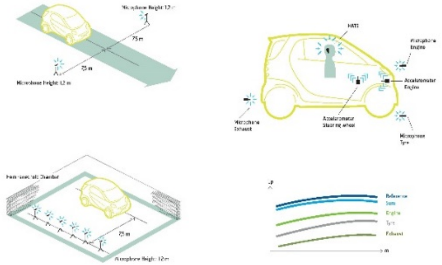
Bert van Amerongen
(Special thanks to Nick Prgomelja and Francisco Sanchez)

Bert van Amerongen: Product Owner BK Connect

Responsible for Pass-by solutions
Active member of ISO WG 42

36 years with HBK (Brüel & Kjær)
1 Oct 1987

Favorite product

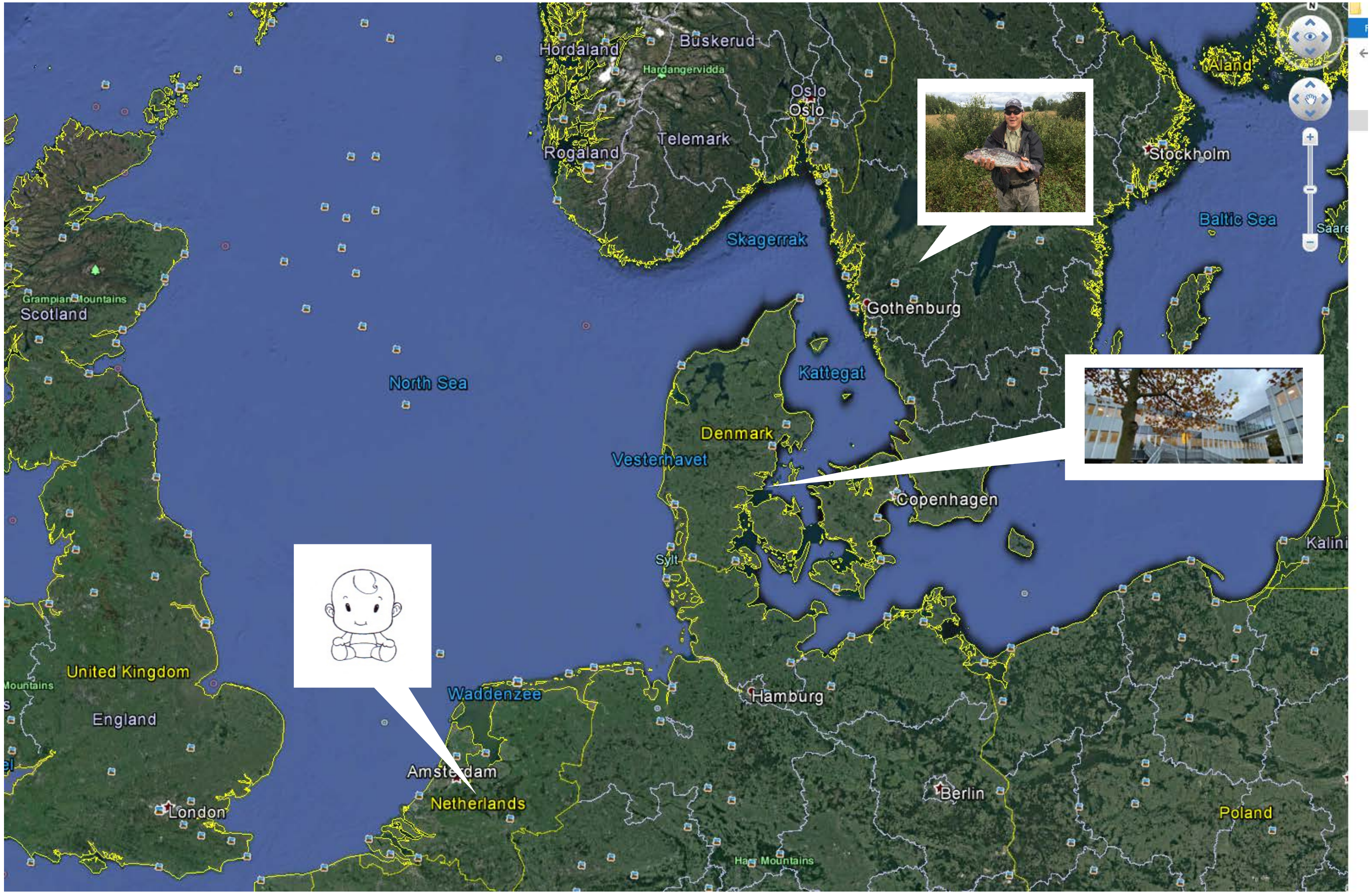


Contact me if…

- You need help with pass-by solutions
- ISO Pass By standard related questions
- …

UNRESTRICTED

Dutchman, living in Sweden, working for HQ in Denmark



UNRESTRICTED

HOTTINGER BRÜEL & KJÆR

Agenda

POWERTRAIN NVH ANALYSIS

- NVH intro
- NVH from ICE vs. EV
- NVH Analysis tools
- Inverter Noise
- Order analysis vs Order tracking
- Auto tracker
- Data sharing between NVH analysis software (BK Connect)

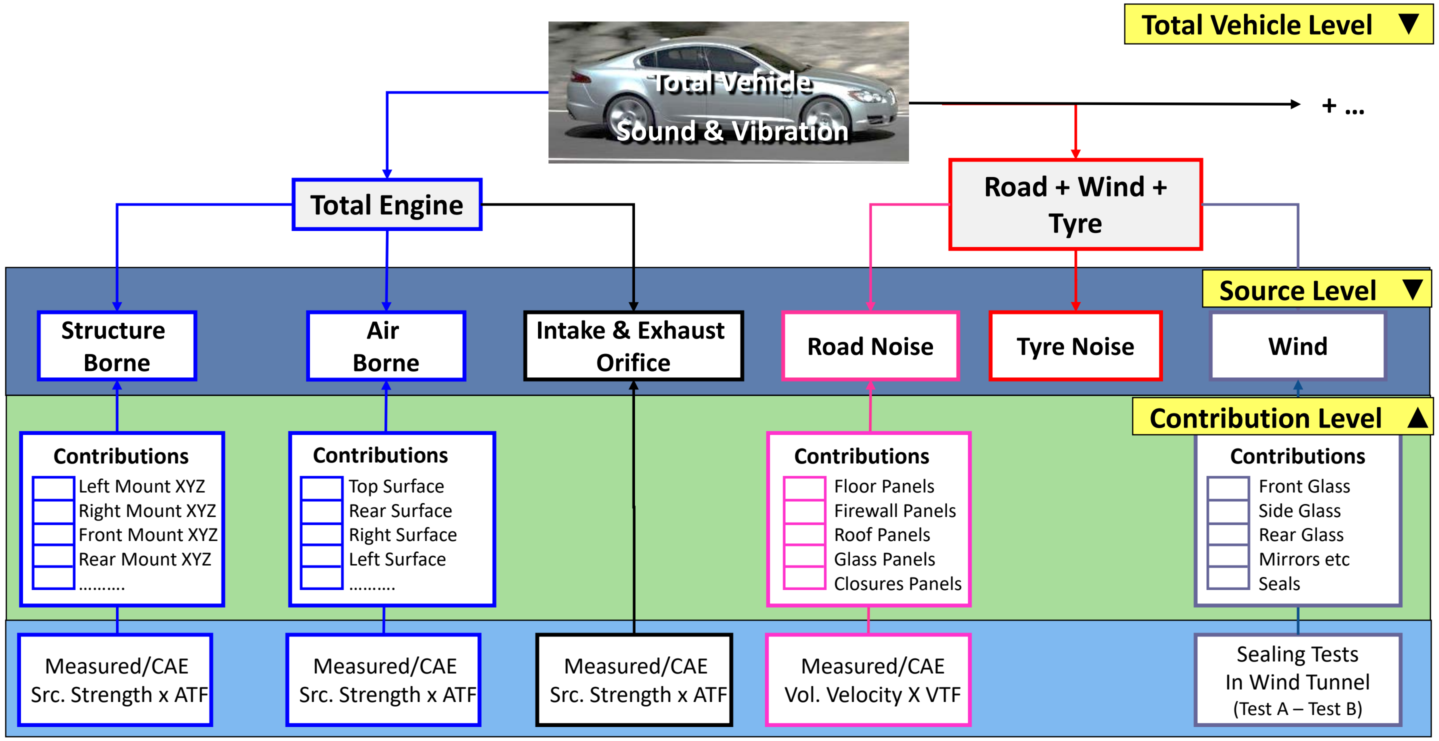
What are the challenge's we are facing by analysing NVH.

- Over years, we accepted the sound cause by NVH as part of our soundscape.
- Sound caused by NVH can be recognized and in many cases admired. It becomes a brand of itself.
- We even identified local preferences what sound will be preferred in: USA, Asia or Europe.
- We talk about the “receiver” and his perception: driver (passengers) or pedestrians (surrounding community)
- Warning sounds: AVAS Acoustic Vehicle Alert Systems (join our Pass-by webinar the 6th of December)
- We try identifying the “Path” which facilitate this “perception”
- To summarize: **We are applying objective methods to quantified subjective preferences.**

UNRESTRICTED

HOTTINGER BRÜEL & KJÆR

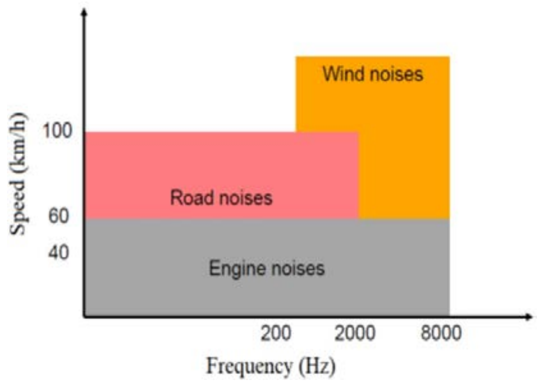
ICE (Internal Combustion Engine) “standardize” approach

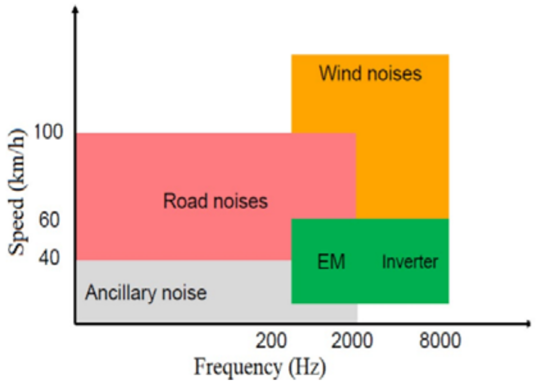


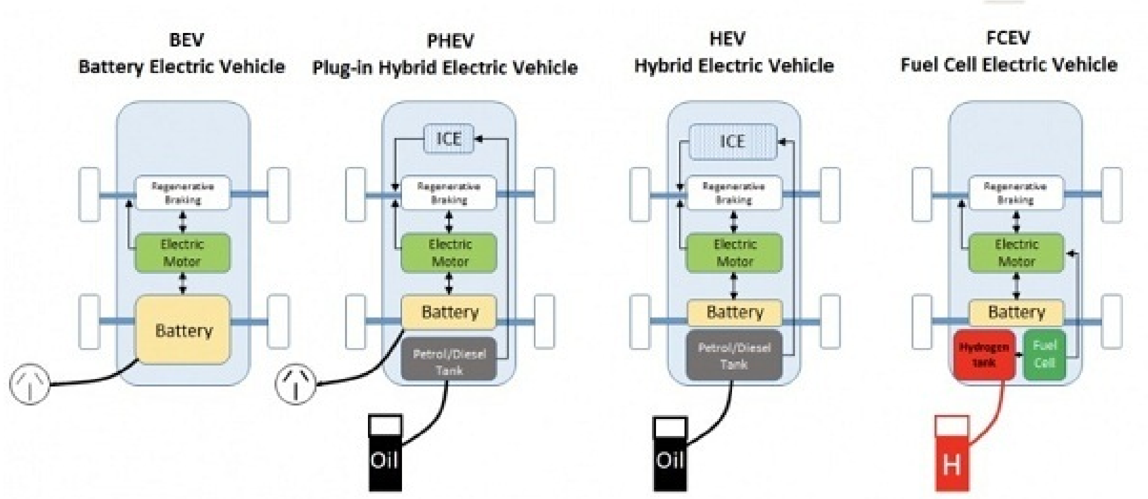
- We can identify the noise sources as:
  - powertrain (motor, auxiliary, transmission),
  - chassis,
  - road,
  - tyre and wind
- The Path can be:
  - Structure borne
  - Air borne

UNRESTRICTED

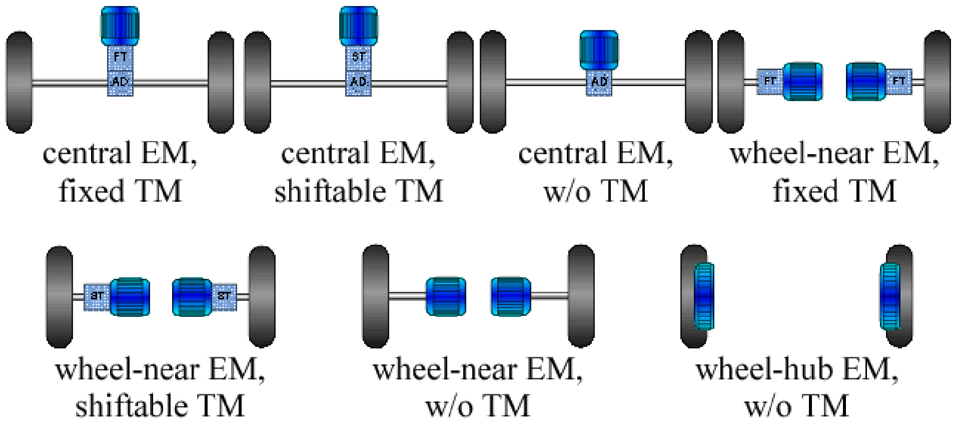
EV not so much.







- ICE has a low frequency signature,
- EV has high frequency signature
- From construction point of view EV can be:
  - Retrofitting Platform
  - Hybrid Platforms
  - Dedicated EV Platforms
- Number of different E-drive configuration



HBK HOTTINGER BRÜEL & KJÆR

UNRESTRICTED

ICE vs EV Source model

ICE Vehicle

Powertrain Other
- Intake
- Exhaust
- Turbocharger
- Throttle
- Fuel Injectors
- PCV
- EGR
- Evaporative Emissions
- Oil Pump
- Idle Air Bypass
- Fuel Supply
- Power Steering
- Brake Boost
- Alternator
- Cooling Pump and Fan
- AC Compressor and Fans
- Complex Automatic Transmission

Powertrain
- Pistons
- Rods
- Crankshaft
- Valvetrain

Chassis
- Doors and Power Locks
- Window Adjustors
- Seat Adjuster
- WS Wipers
- Brakes
- Parking Brake
- Power Steering
- Switches
- Fuel Tank
- Sound System
- Pedals

Electric Vehicle

Powertrain
- Motor Rotor

Powertrain Other
- Oil Pump
- Electric Power Steering
- Brake Boost
- Cooling Pumps and Fans
- Simplified Automatic Transmission
- AC Compressor
- Invertor/Charger/Controller

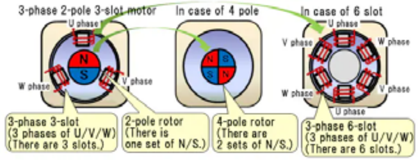
Chassis
- Doors and Power Locks
- Window Adjustors
- Seat Adjuster
- WS Wipers
- Brakes
- Parking Brake
- Power Steering
- Switches
- Sound System
- Pedals
- Battery

HBK HOTTINGER BRÜEL & KJÆR

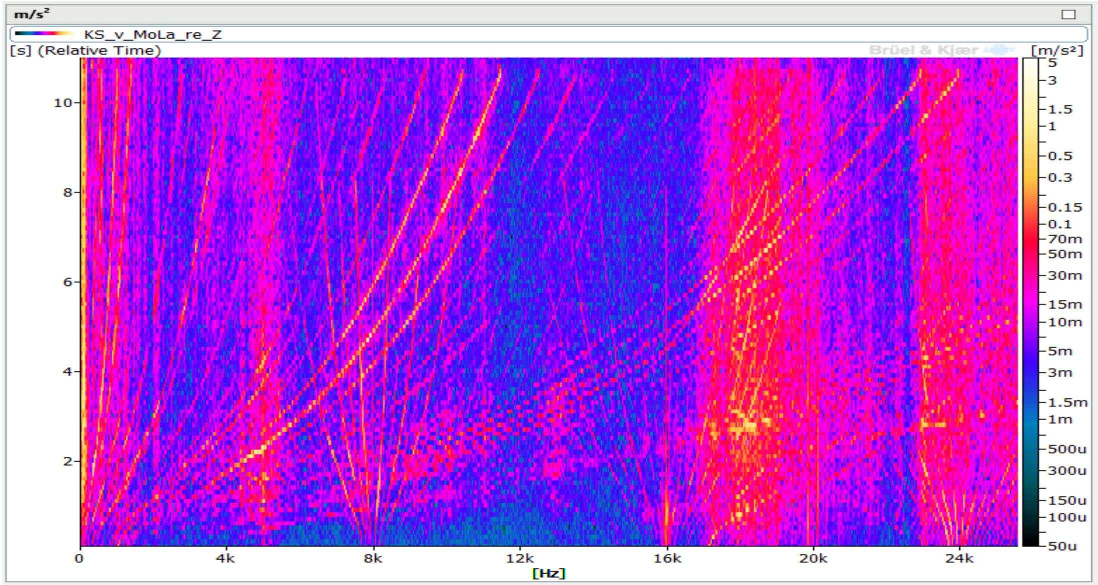
UNRESTRICTED

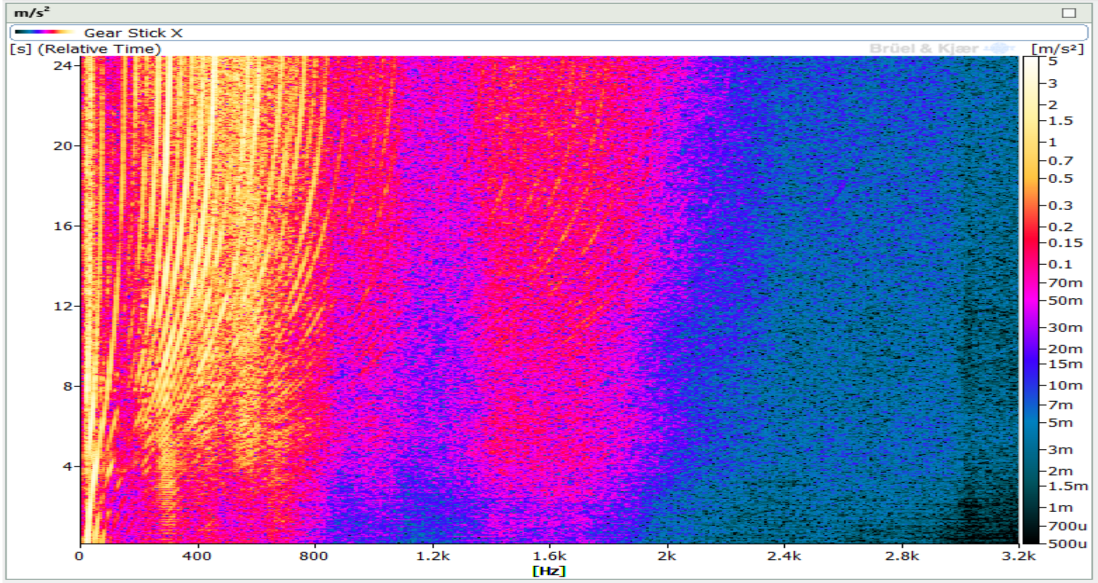
EV Noise Sources and Paths

- Battery
  - Cooling system (Fan or Pump)
- Inverter PWM / Harmonics
  - Voltage
  - Current
- Electric Motor Slotting
  - Harmonics influences
  - Torque ripple



- Transmission / Gears Gear mash (planetary arrangement)
- Breaking (Recuperation - motor running in generator mode)
  - Torque vibration



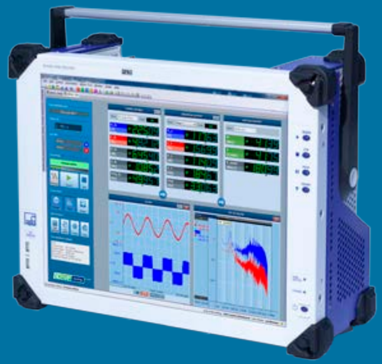


HBK HOTTINGER BRÜEL & KJÆR

UNRESTRICTED

NVH Analysis Tools at HBK

Data recording



Genesis

LAN-XI

Analysis for R&D

BK Connect

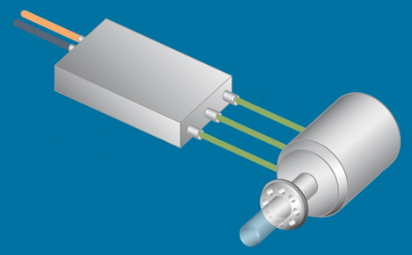
- Measurement Setup and Data Recorder
- Data processing and general signal analysis

Analysis for EOL

Discom
- All-in-one solution for EOL testing

UNRESTRICTED

Acquisition of all signals with one system

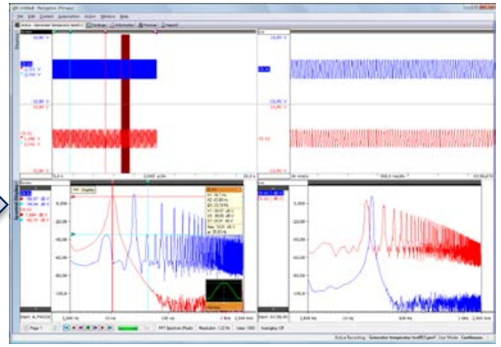


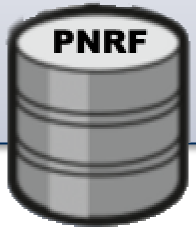
Measurement object

Voltage
Current
AND
Acceleration

ALL signals, time-synchronous and continuous
recorded with **Genesis**

Time and
FFT display
in **Perception**





Post-process analysis in
BK Connect

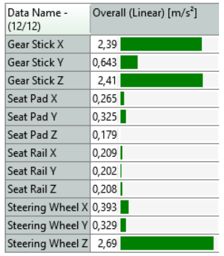
UNRESTRICTED

HBK
HOTTINGER BRÜEL & KJÆR

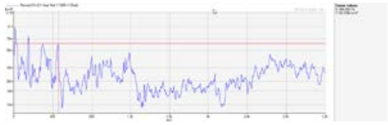
NVH analysis of electromechanical data sets

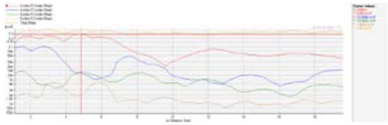
The results ca be single values, curves or even higher dimensional objects like spectrograms.

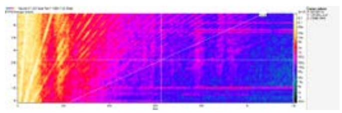
Source	Examples	Result Types
Time Signals	Peak, RMS, Crest	Single value
Spectra	Order spectra (synchronous and mix), fixed frequency spectra	Curve (Spectra)
Single orders taken from spectrum (or sums of orders, band sums)	Gear mesh order value H1, side bands, Order sum Hx, specifically selected orders	Single value
Orders tracked over ramp	Gear mesh order track RPM track	Curve (track)
Values computed from tracks	Speed bands, differences	Single Values
Spectra tracked over ramp	Spectrogram	Spectrogram
Short Time and Modulation analysis	Short time spectrogram, Modulation spectrogram, modulation content	Spectogram, spectrum, single values

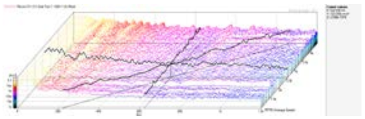


Data Name - (12/12)	Overall (Linear) [m/s²]
Gear Stick X	2,39
Gear Stick Y	0,643
Gear Stick Z	2,41
Seat Pad X	0,265
Seat Pad Y	0,325
Seat Pad Z	0,179
Seat Rail X	0,209
Seat Rail Y	0,202
Seat Rail Z	0,208
Steering Wheel X	0,393
Steering Wheel Y	0,329
Steering Wheel Z	2,69









UNRESTRICTED

HOTTINGER BRÜEL & KJÆR

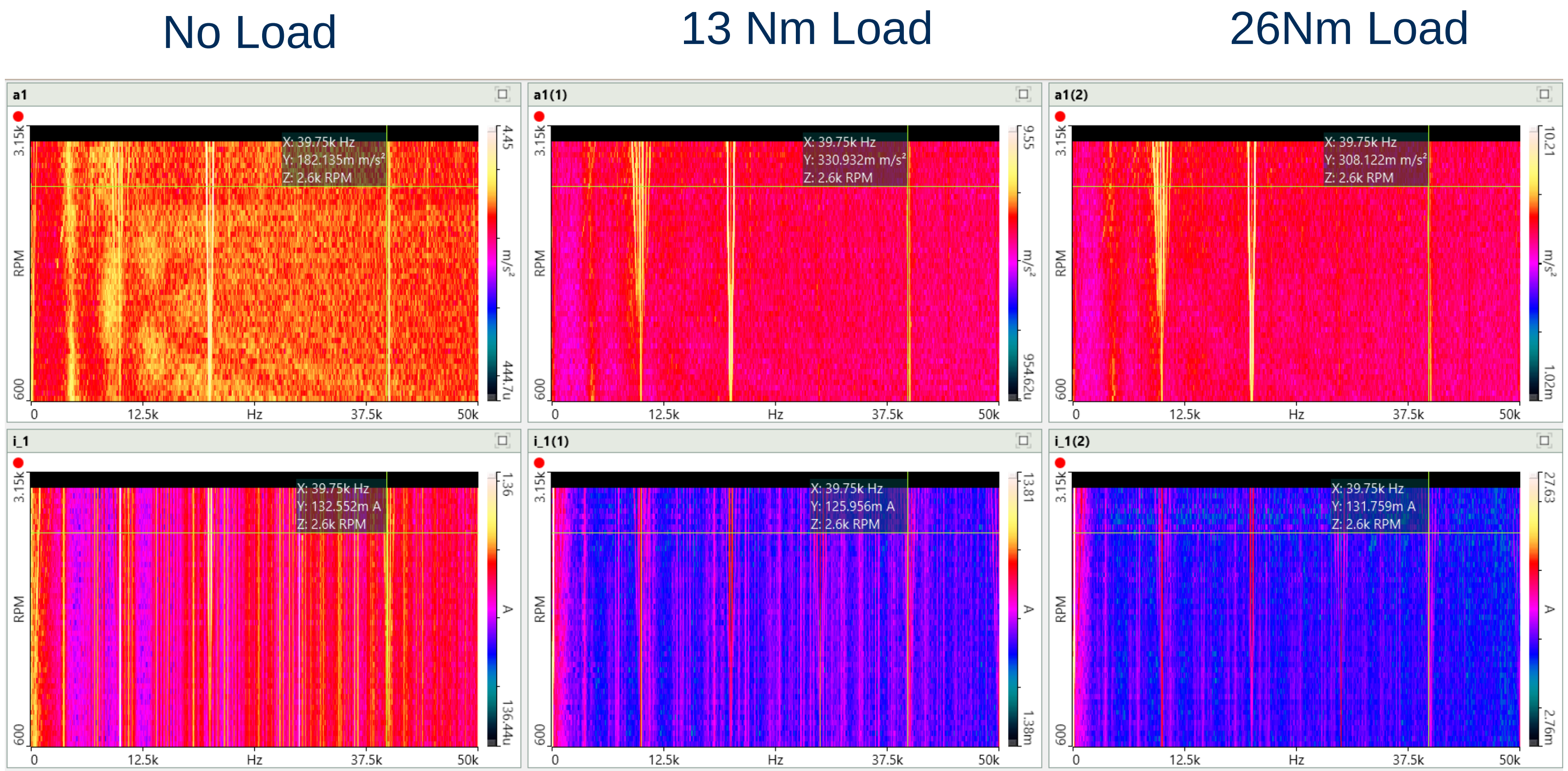
Frequency spectrum from Ramps Test

- A ramp test is often portrayed with a spectrogram showing:
  - X - Frequency (Hz)
  - Y – Speed (RPM)
  - Contour – Amplitude

- 3 ramps are plotted. 0, 13, 26 Nm from 0 to 3k RPM

- Acceleration and current are shown

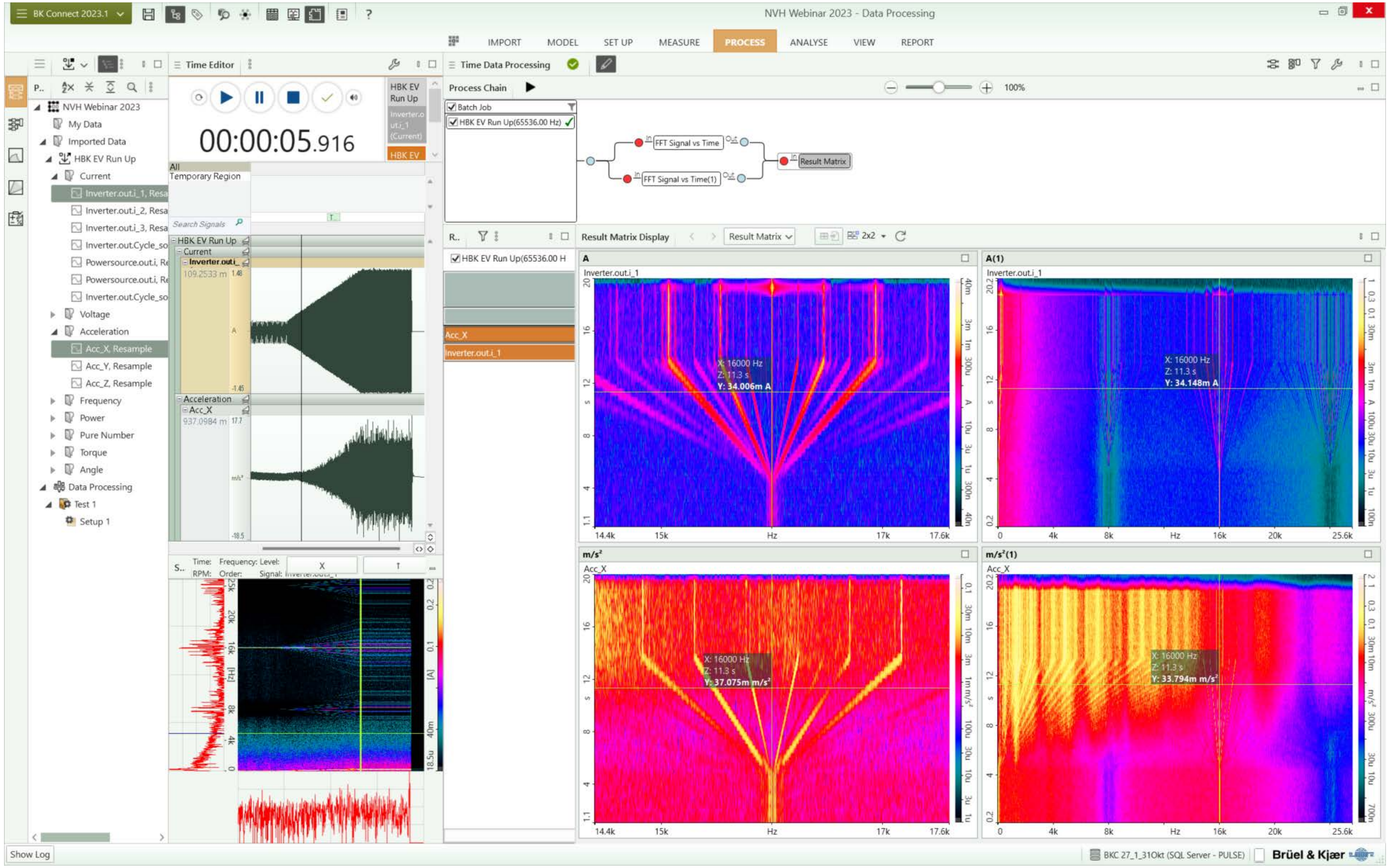
- We can see fundamental, switching frequency, and field frequency shown in both spectra



Full spectrum plots of acceleration and current for 3 loading points during ramp tests from 0-3000RPM

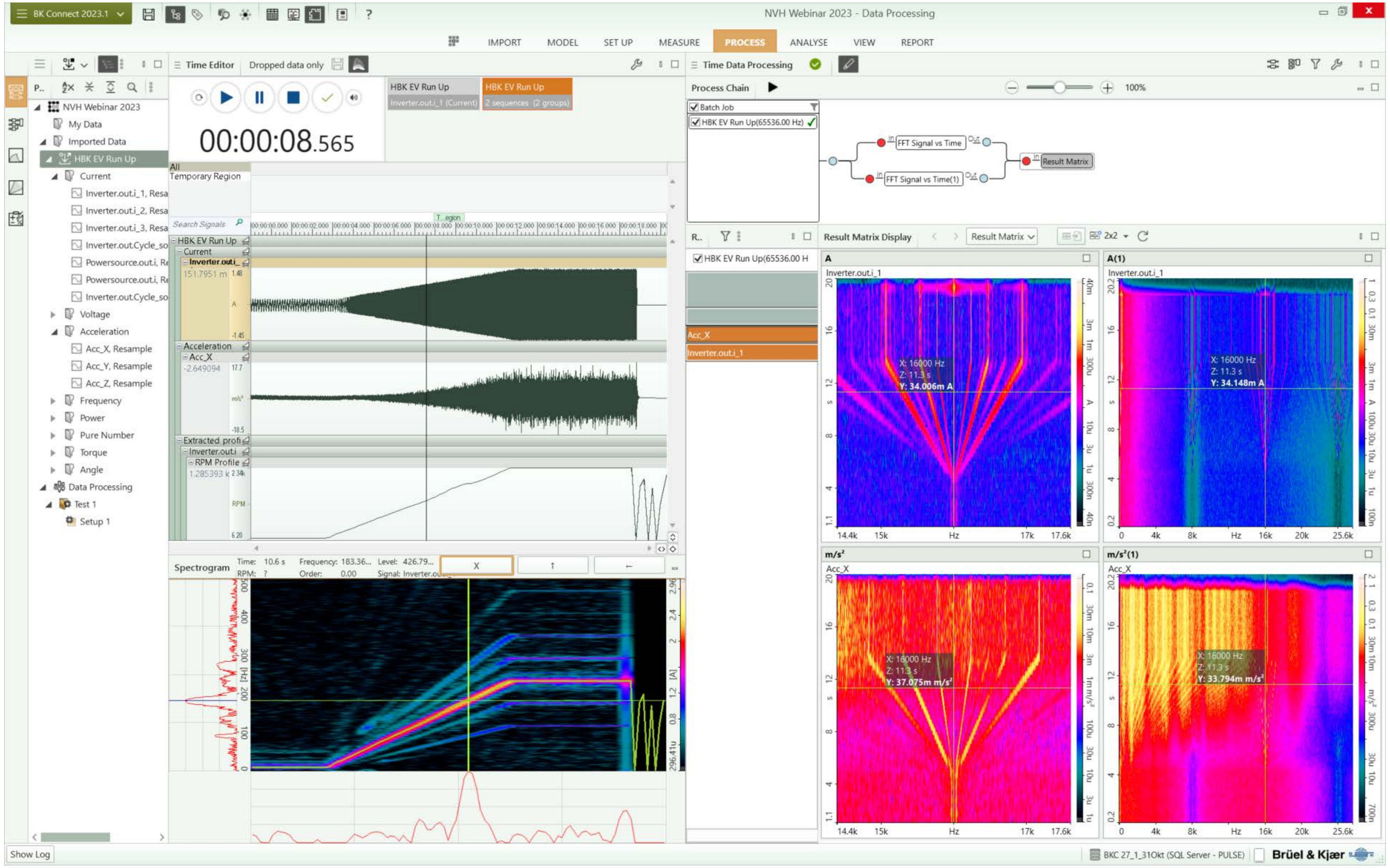
UNRESTRICTED

Acceleration signal vs Current



HBK
HOTTINGER BRÜEL & KJÆR

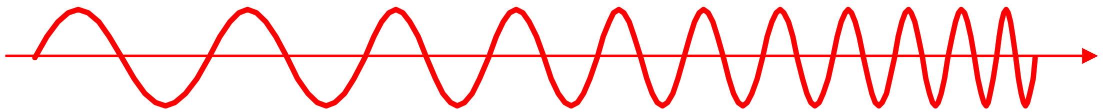
Auto Tracker



UNRESTRICTED

Analysis with and without tracking

a) Original signal

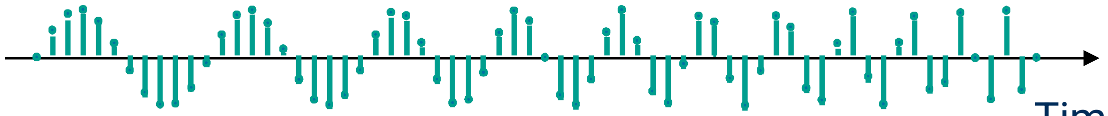


Time

b) Fixed sampling rate

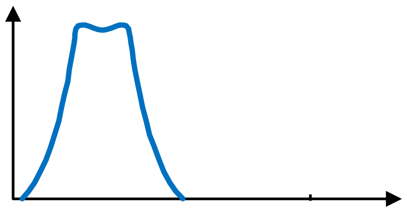
f_s = 2,56 x f_{max}

Analysed samples



Time

Spectra without tracking



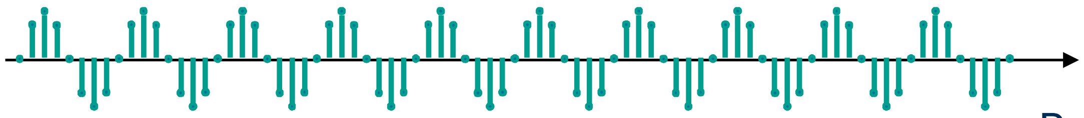
f_{max}

Frequency

c) Sampling rate adapted to the speed

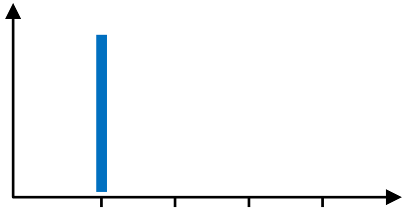
Example: f_s = 8 x $f_{fundamental}$

Analysed samples



Revolutions
(Period)

Spectra with tracking



1 2 3 4

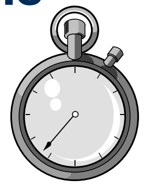
Orders

UNRESTRICTED

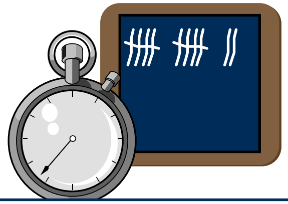
HBK HOTTINGER BRÜEL & KJÆR

Order Tracking vs. frequency-based order analysis

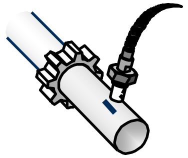
Frequency analysis
Time: When?
Related to the clock
[Sek]



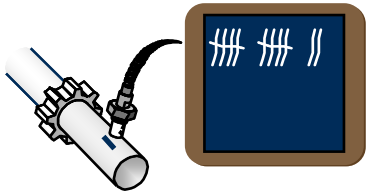
Frequency spectrum:
How often?
[per second]



Order Tracking Analysis
"Time": When ?
Based on the rotation of the shaft
[rotation]



Order spectra:
How often?
[per revolution]



	Frequency analysis	**Order Tracking Analyse**
Signal	Time [Sek]	Revolutions [revolution]
Spektrum	Frequency [Hz] [per second]	Harmonic [Orders]] [per revolution]

UNRESTRICTED

Modular software for all your testing and analysis needs

BK Connect applications are user-centric and modular. Each core application can function as a stand-alone tool, or can be combined

General purpose analysis software

- Measurement setup and data recording
- Data processing and signal analysis
  - FFT, CPB, Order..
  - Angle Domain Analysis
- Data Management and Reporting

Structural dynamics software

- Modal measurements and analysis
- Shock response spectrum analysis
- Correlation
- Operating Deflection Shapes

Acoustics

- Sound Power Mea
- Array analysis
- Sound quality metrics

UNRESTRICTED

HBK
HOTTINGER BRÜEL & KJÆR

Applets, Applications and Templates

Acoustic Camera.BKConnectApplet
Type: BKConnectBackup file

CPB FFT Overall Analysis - Processing.BKConnectApplet
Type: BKConnectBackup file

CPB FFT Overall Analysis.BKConnectApplet
Type: BKConnectBackup file

FFT Analysis - Processing.BKConnectApplet
Type: BKConnectBackup file

FFT Analysis.BKConnectApplet
Type: BKConnectBackup file

Hammer Impact.BKConnectApplet
Type: BKConnectBackup file

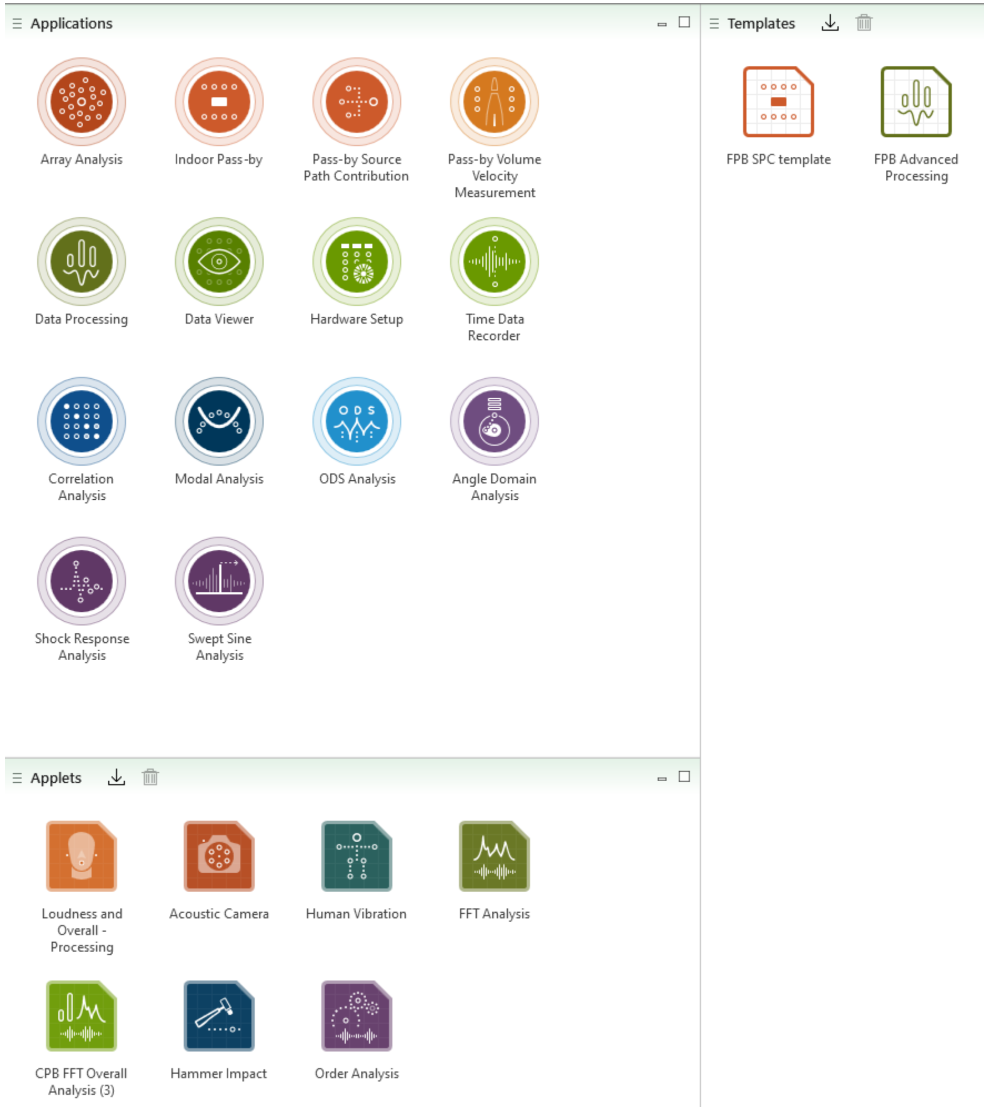
Human Vibration.BKConnectApplet
Type: BKConnectBackup file

Loudness and Overall - Processing.BKConnectApplet
Type: BKConnectBackup file

Loudness and Overall.BKConnectApplet
Type: BKConnectBackup file

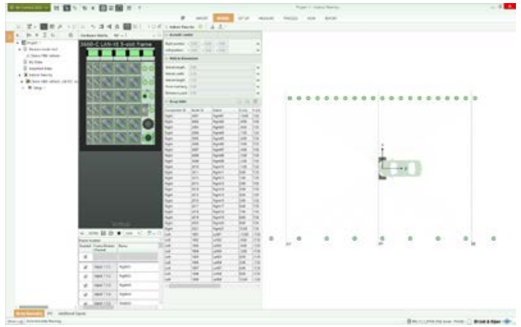
Order Analysis - Processing.BKConnectApplet
Type: BKConnectBackup file

Order Analysis.BKConnectApplet
Type: BKConnectBackup file

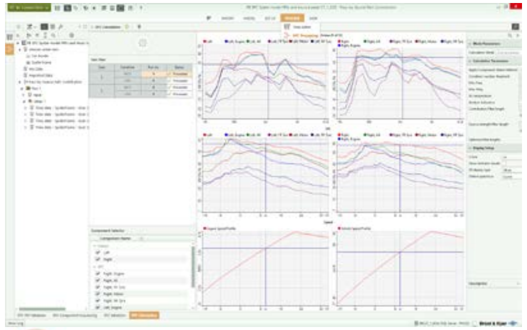


UNRESTRICTED

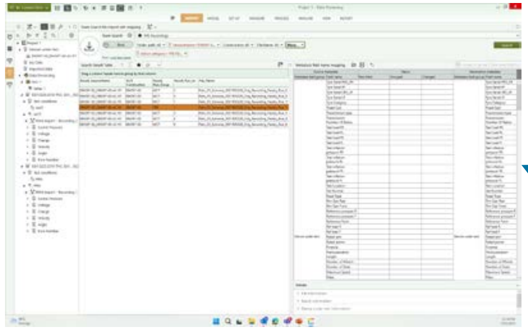
Team Server Connects!?



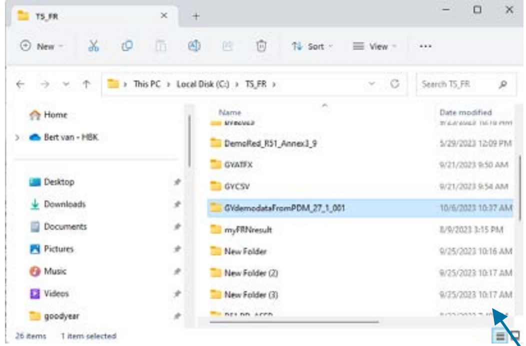
Pass By



Pass By SPC

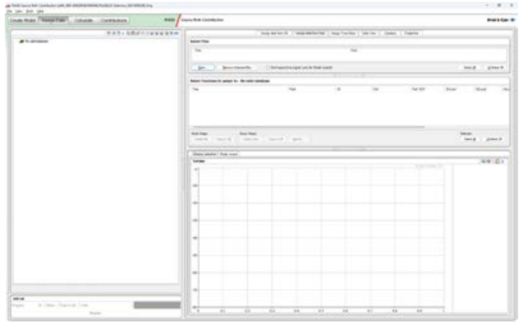


BKC

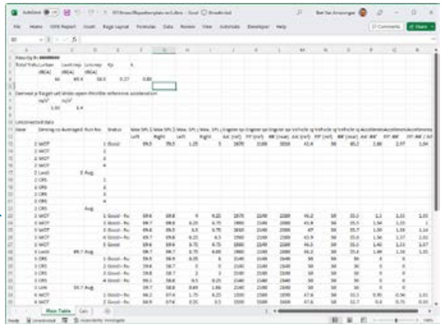


File repository

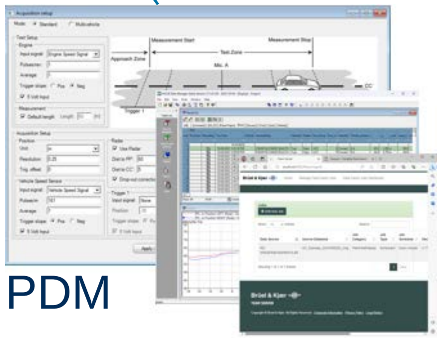
CSV
XML
ATFX
BKC



SPC



Other (incl. Python)



PDM

UNRESTRICTED

Q&A

Thank You

hbkworld.com I bksv.com I hbm.com I hbmprenscia.com

Bert van Amerongen
Product Owner

bertvan.amerongen@hbkworld.com

HBM Brüel & Kjær

www.hbkworld.com | © HBK – Hottinger, Brüel & Kjær | All rights reserved

HBK HOTTINGER BRÜEL & KJÆR

Structural Dynamics Testing in NVH

APPLICATIONS AND SOLUTIONS

Niels-Jørgen Jacobsen
Product Manager
Structural Dynamics and Array Acoustics

November 29, 2023

www.hbkworld.com | © HBK – Hottinger, Brüel & Kjær | All rights reserved

CONFIDENTIAL - EXTERNAL

Introduction of Niels-Jørgen Jacobsen

- Joined Brüel & Kjær in 1986 after graduating from the Technical University of Denmark
- Product manager –
  Structural Dynamics and Array Acoustics
- Previous positions
  - Software developer
  - Software project manager
  - Application specialist
  - Manager of Vibration Specialist Group
- Member of the Permanent Committee and the Scientific Committee of IOMAC
- Enjoy long-distance running, active travels, good food & wine, opera, classical and rock music - and a lot of other things

HBK
HOTTINGER BRÜEL & KJÆR

Contents

- Brief introduction to structural dynamics testing
- Selected applications
  - Operating Deflection Shapes (ODS) Analysis
  - Experimental Modal Analysis (Classical Modal Analysis)
  - Operational Modal Analysis (OMA)
- Overview of structural dynamics solutions from Hottinger Brüel & Kjær (HBK)
- Q&A

CONFIDENTIAL - EXTERNAL

HOTTINGER BRÜEL & KJÆR

Brief introduction to structural dynamics testing

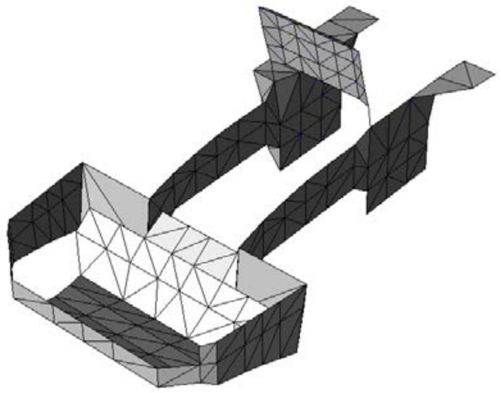
CONFIDENTIAL - EXTERNAL

What is structural dynamics testing?

- **Observation** of the **actual dynamic behaviour** of a structure under **operating conditions**
  - **Deflection patterns** as a function of **time** or at specific **frequencies or orders (ODS analysis)**

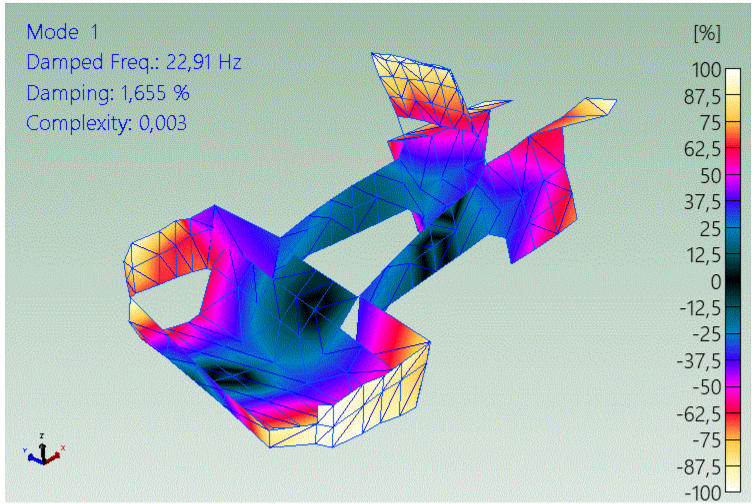
- Creation of a mathematical model describing the **inherent dynamic properties** of a structure, so its **behaviour** can be **predicted** in various situations
  - The **modal parameters**: Natural frequency, damping ratio and mode shape **(Modal analysis)**

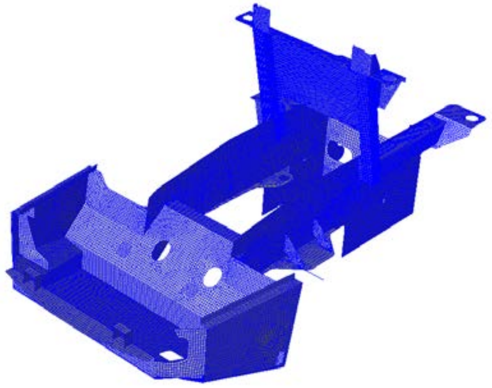
The Digital Twin



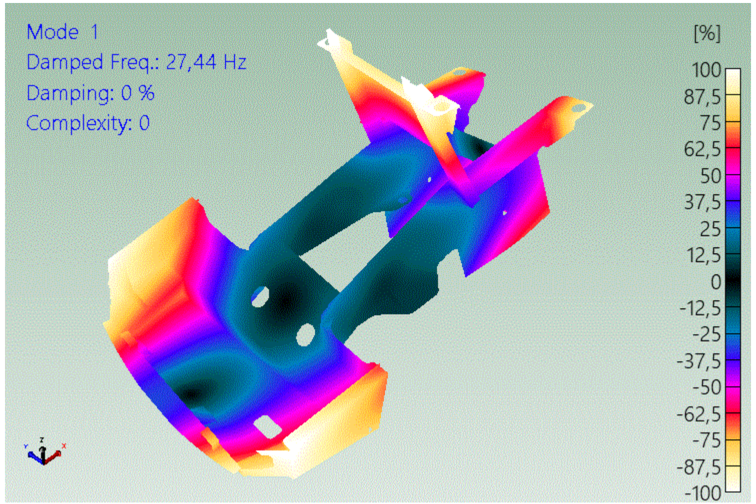
Test model
- 209 nodes
- 288 elements

Test
- Impact hammer in fix DOFs
- 3 triax accels. roved in 70 measurements





Nastran FE model
62.276 nodes
62.222 elements
6 DOFs in all nodes



Pre-test analysis using FE model is often used to optimise test setup and execution
Test-FE model correlation is often used to improve the development of FE models

HBK
HOTTINGER BRÜEL & KJÆR

CONFIDENTIAL - INTERNAL

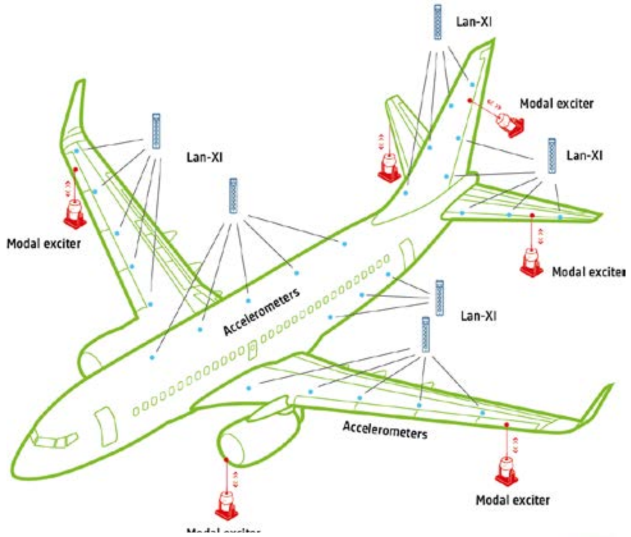
How to perform structural dynamics measurements

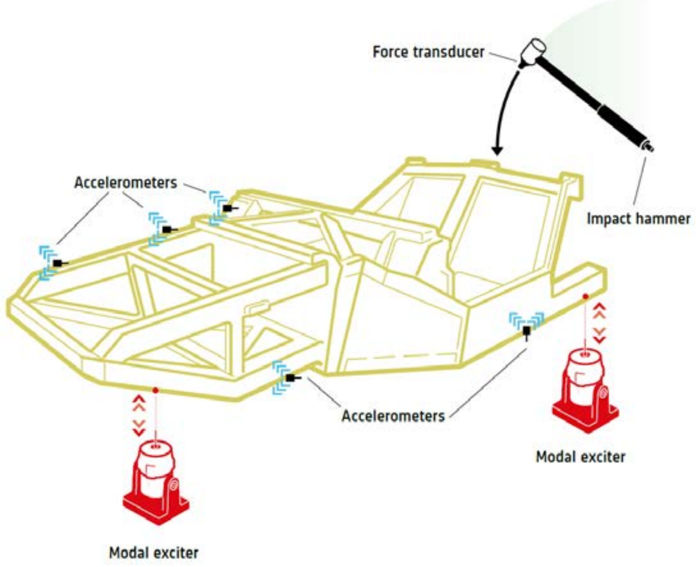
- The structure is excited by **unmeasured natural forces** (ODS[1], OMA[2]) or **measured applied forces** (classical modal analysis) in one or more points and directions (Degrees-of-Freedoms: **DOFs**)

- **Artificial forces** are either applied using a dedicated **impact hammer** that also measures the applied force, or by using one or more **modal exciters (shakers)** and measuring the applied forces using force transducers

- The result is measured in a number of response DOFs, typically using uniaxial or triaxial **accelerometers**

- Tests are performed from **2-channel impact testing** using, for example, one hammer and one accelerometer, to large modal surveys with more than **10 modal exciters** and **1000 response DOFs**





1) Operating Deflection Shapes
2) Operational Modal Analysis

HBK HOTTINGER BRÜEL & KJÆR

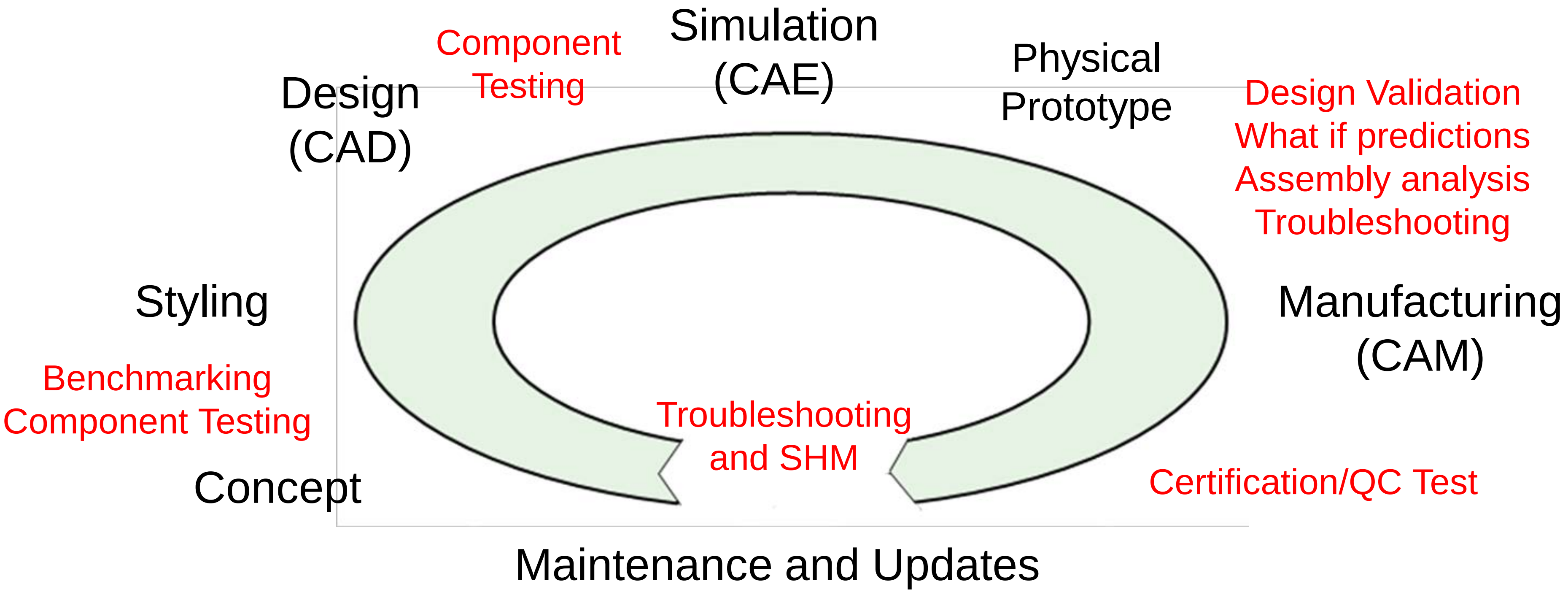
CONFIDENTIAL - INTERNAL

Why and when do we perform analysis of structural dynamics?

To understand and **improve** safety, reliability, performance, consumption and comfort

Design validation, certification testing, QC testing, troubleshooting, prediction of “what if” scenarios, benchmarking, structural health monitoring and much more

Product Development Cycle



CAD: Computer Aided Design
CAE: Computer Aided Engineering
CAM: Computer Aided Manufacturing
QC: Quality Control
SHM: Structural Health Monitoring

CONFIDENTIAL - INTERNAL

Selected applications

Operating Deflection Shapes (ODS)

Experimental Modal Analysis (EMA) – Classical Modal Analysis

Operational Modal Analysis (OMA)

HBK
HOTTINGER BRÜEL & KJÆR

CONFIDENTIAL - EXTERNAL

ODS Analysis – An example of signal analysis

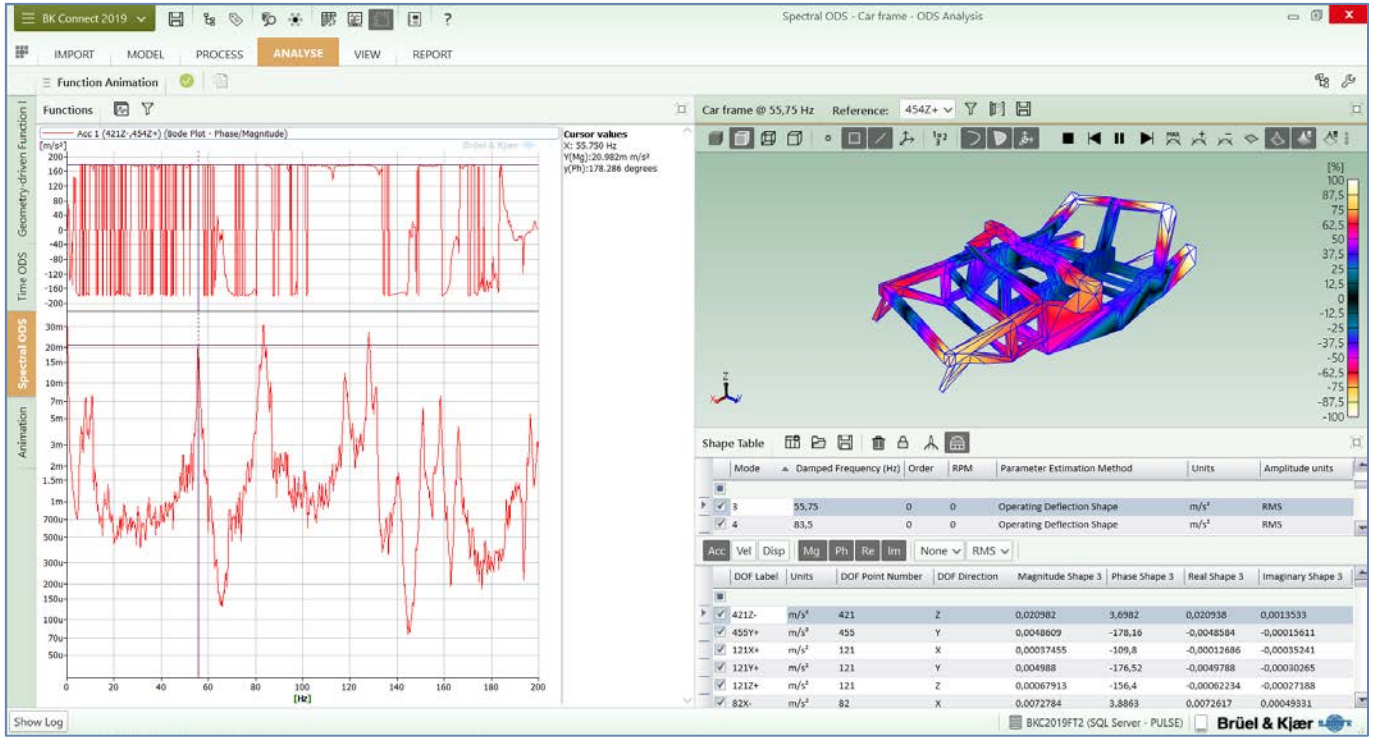
Determination and visualization of the vibration pattern of structures under operating conditions

Operating conditions
- Speed, Load, Temp., Pressure, Flow, ...

Vibration signals
- Stationary
- Quasi-stationary
  - » Slightly varying speed or excitation level
  - » Run-up/down tests
- Transient

Types
- Time ODS, Spectral ODS (freq., order) and Non-stationary (Run-Up/Down) ODS

Results
- Geometry animated in different DOFs
- Table of Shapes for different frequencies/orders
  - Acceleration, Velocity and Displacement
- Table of deflection pattern at different time instances



ODS analysis answers the questions:

How does the structure actually vibrate?

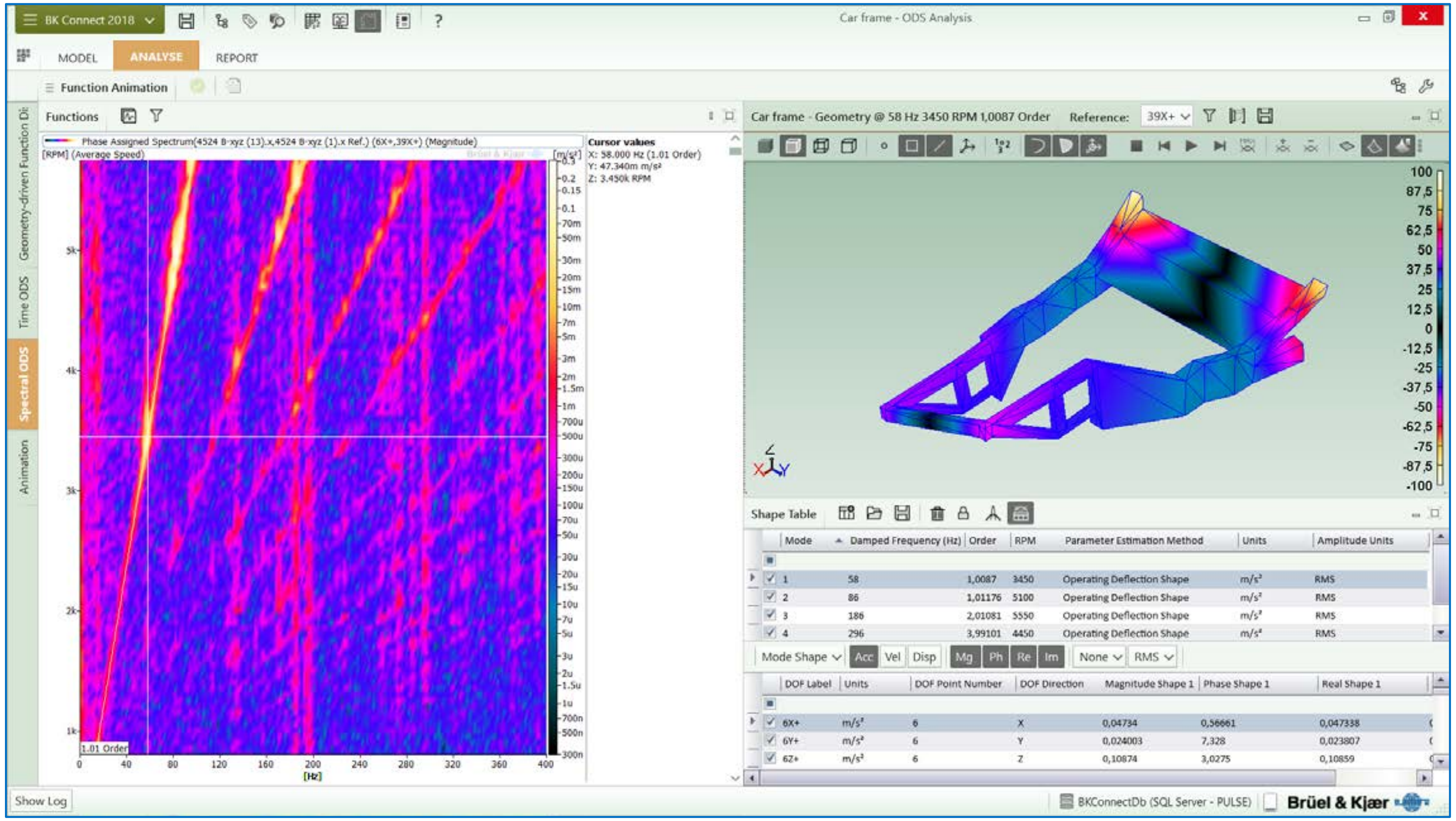
What is the actual absolute motion of one DOF vs. another?

HBK HOTTINGER BRÜEL & KJÆR

CONFIDENTIAL - INTERNAL

Example – Run-Up ODS (frequency-based) of a Car Frame

- Sports car frame excited by a small engine running from 0-6k RPM (0-100 Hz)
- Measurement made using 20 triaxial accelerometers
- Reference in right front corner
- Simplified geometry with 154 nodes
- Interpolation in 134 nodes
- Engine speed measured using a tacho probe
- Frequency range: 400 Hz
- One frequency/RPM combination animated at a time



Structural resonances (natural frequencies) are seen as vertical lines.
Orders (multipla of engine speed) are seen as oblique lines.

CONFIDENTIAL - INTERNAL

Classical Modal Analysis – An example of system analysis

To obtain a mathematical model of the dynamic properties of a structure
by experimental means using hammer or shaker excitation *(modal testing)*

Controlled measurements

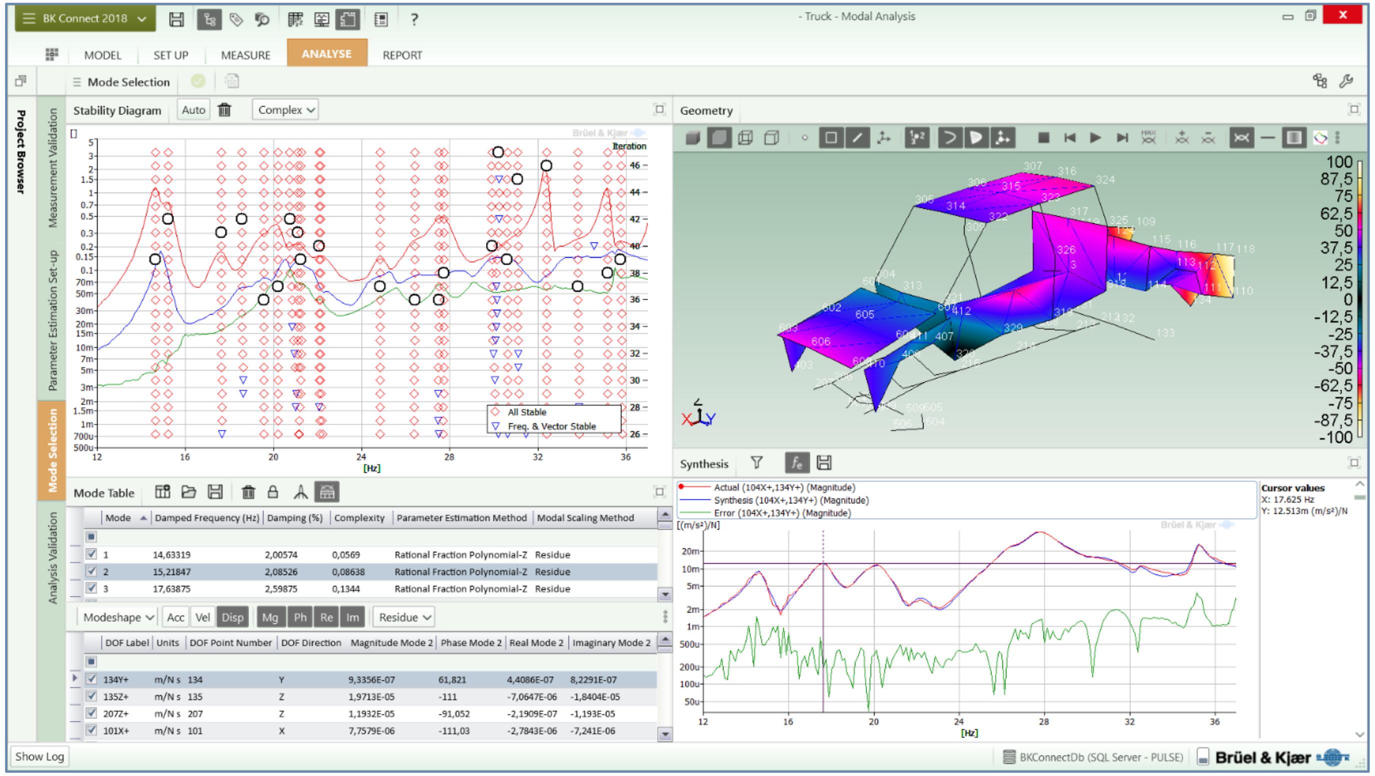
- Boundary conditions
- Excitation signals
- Environmental conditions

Excitation signals

- Sinusoidal (fixed, sweep, step)
- Random (continuous, burst, pseudo …)
- Transient (impact)
- …

Results – Modal Parameters

- Natural Frequencies
- Modal Damping
- Mode Shapes



Classical Modal Analysis answers the question:

What is the structure's inherent dynamic properties?
How can they be improved?

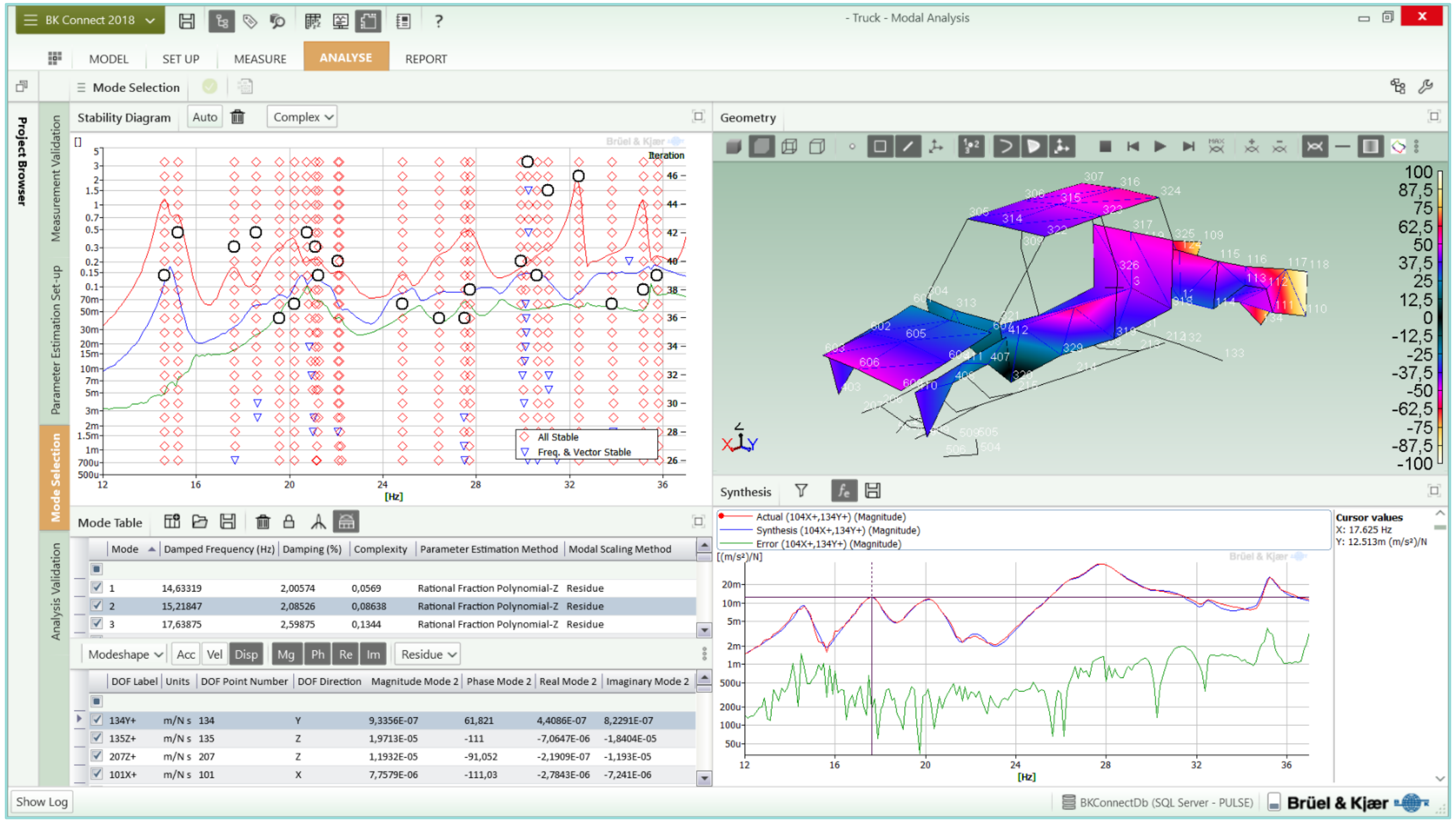
HOTTINGER BRÜEL & KJÆR

CONFIDENTIAL - INTERNAL

Brief Demo – Classical Modal Analysis of a Partly Trimmed Truck

Configuration

- Partly trimmed truck (heavily damped modes, non-linear behaviour)
- 3 shakers and 330 response DOFs (110 triax (4524-B)) => 990 FRFs



Operational Modal Analysis (OMA) – An example of system analysis

To obtain a mathematical model of the dynamic properties of a structure by experimental means using unmeasured natural excitation *(modal testing)*

In-operation measurements (in situ)

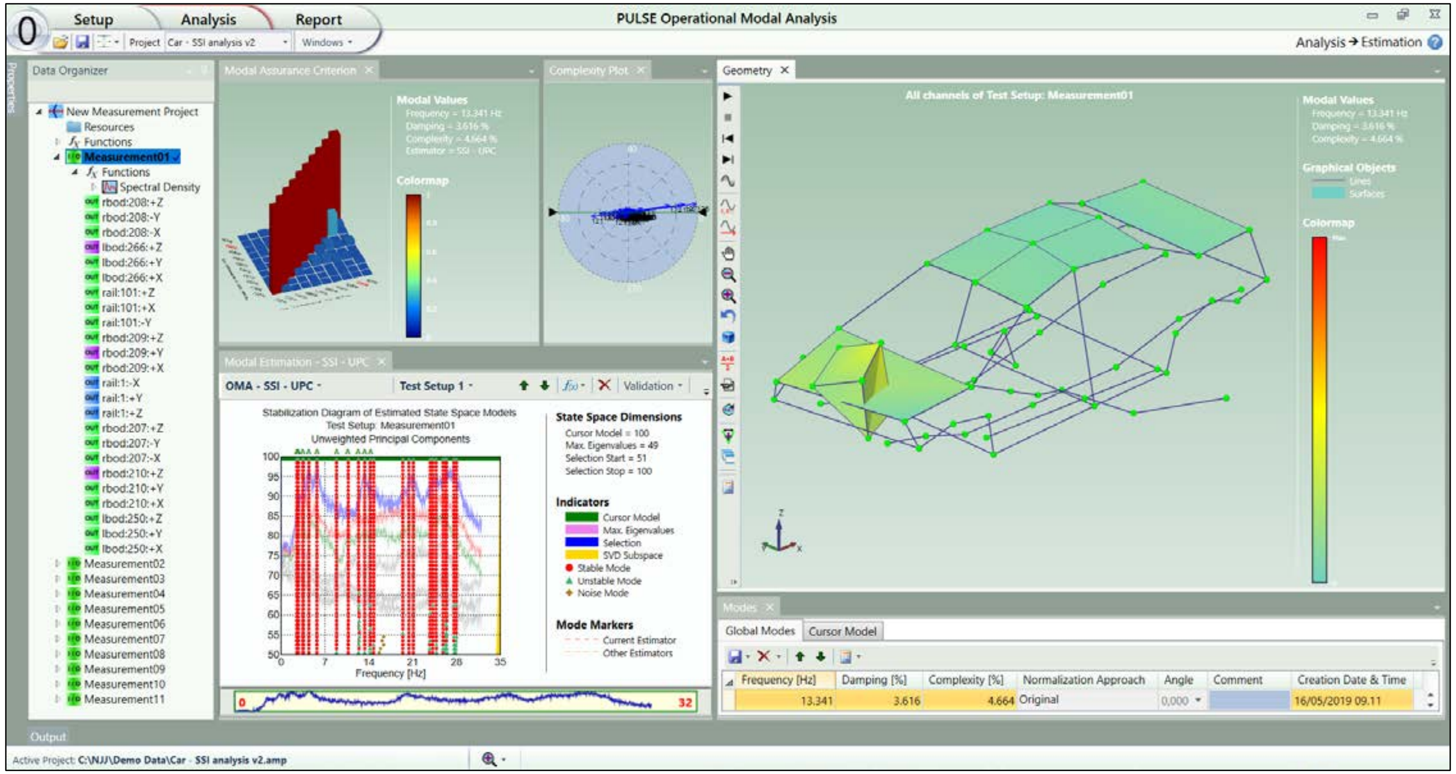
- True boundary conditions
- Actual excitation signals
- Actual environmental conditions

Broad-banded ambient or self-generated natural excitation signals

- Ride and handling, powertrain testing, chassis/body testing, suspension ...
- Cars, trucks, trains, trams, motorcycles …

Results – Modal Parameters [1)]

- Natural Frequency
- Modal Damping
- Mode Shape



Operational Modal Analysis answers the questions:

What is the structure's inherent dynamic properties?
How can they be improved?

1) Extracted using dedicated OMA modal parameter identification techniques

CONFIDENTIAL - INTERNAL

HBK HOTTINGER BRÜEL & KJÆR

Overview of HBK solutions for structural dynamics testing

CONFIDENTIAL - EXTERNAL

Solution Overview

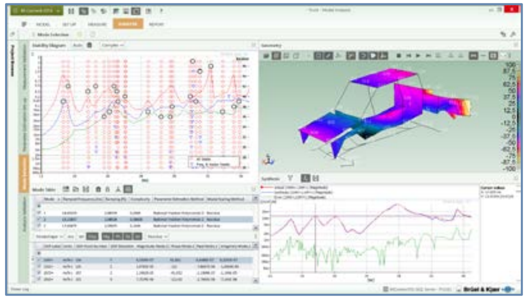
Complete measurement and analysis chain from exciters and sensors to correlation software

Modal Exciters and Hammers | Transducers | Data Acquisition Hardware | Pre-test Analysis Software | Measurement Software | Analysis Software | Correlation Software

Nastran® (MSC, NX, NEi)
Ansys®, Abaqus®, Ideas

BK Connect and OMA/SHM software

Nastran® (MSC, NX, NEi)
Ansys®, Abaqus®, Ideas



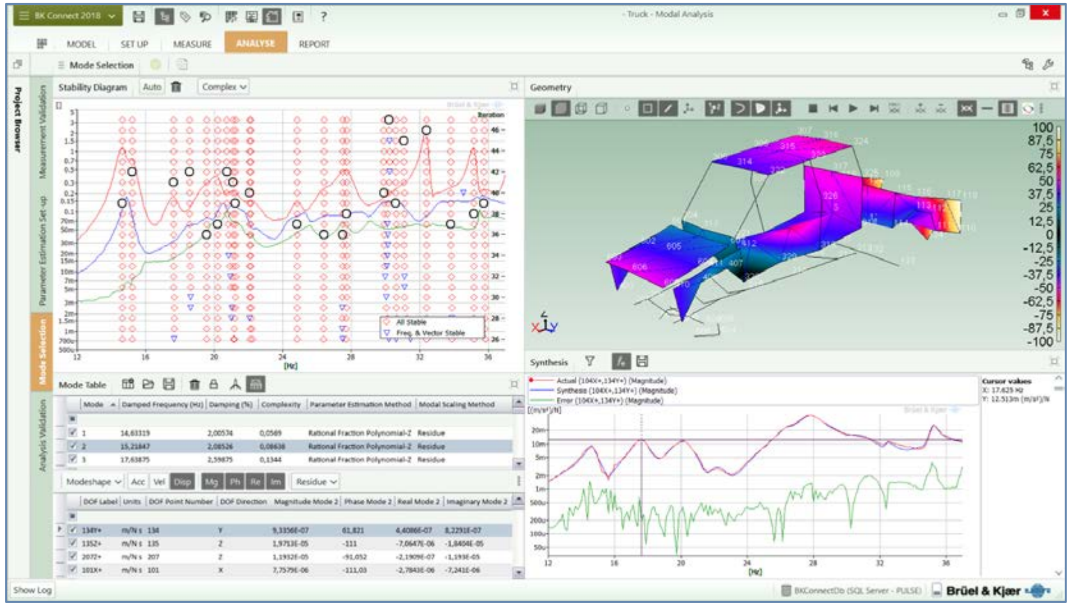
Shortens time from concept to manufacturing and beyond by covering the complete measurement and analysis chain with seamlessly integrated products.
Results you can trust, increased productivity and reduced risk of error.

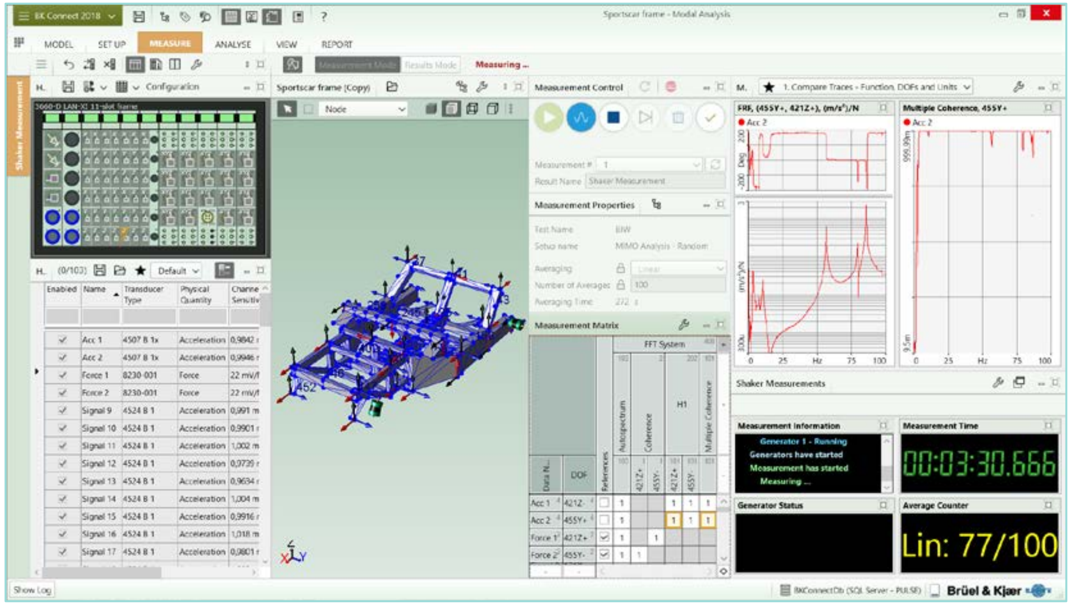
HBK
HOTTINGER BRÜEL & KJÆR

CONFIDENTIAL - EXTERNAL

Applications for Test and Test-FEA Integration

- Pretest-analysis based on FE Models
- Transducer Smart Setup App
- Mobility testing – Hammer Impact Applet
- Geometry-guided measurements
- ODS Analysis
  - Time
  - Spectral (frequency or order-based)
  - Run-up/down (Non-stat.) ODS
- Classical Modal Analysis
  - Modal identification using hammer or shaker (SIMO/MIMO) excitation (continuous, burst, pseudo and periodic random, swept sine, chirp …)
- Stepped Sine Measurement and Analysis
  - Feedback software loop with alarm/abort levels directly from hardware
- Operational Modal Analysis
  - Modal identification from measured responses only
- Model Correlation of test and FE models
  - Geometry alignment, CrossMAC and Cross-Orthogonality, Mode Pairing
- Structural Health Monitoring
  - Damage detection, mode tracking and drift analysis
- Normal Mode Tuning (NMT)
- Shock Response Analysis
  - Compatible with the ISO 18431–4:2007 standard
- …





HBK
HOTTINGER BRÜEL & KJÆR

CONFIDENTIAL - EXTERNAL


Q&A

Thank You

https://www.hbkworld.com/en/solutions/applications/structural-dynamics

www.hbkworld.com | © HBK – Hottinger, Brüel & Kjær | All rights reserved

CONFIDENTIAL - EXTERNAL