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Ground breaking Simulation Solutions

physics on screen

Comparison of the Numerical Accuracy of Superelements and FRF-Assembly

BETA CAE

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Content

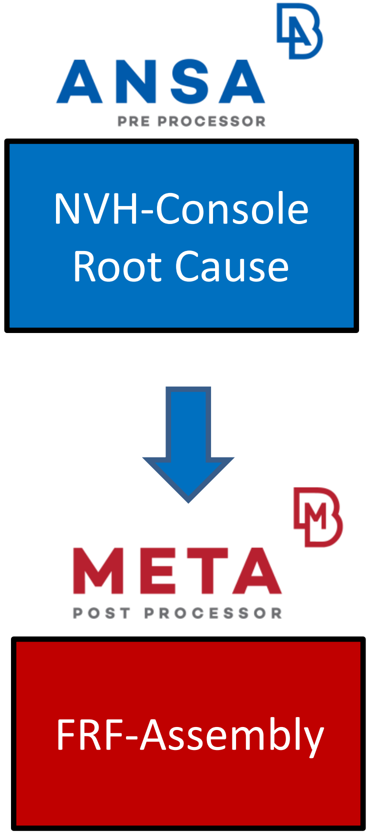
Motivation

NVH-Console

- **NVH-Console** (NVH-C) unified environment embedded in ANSA, which **facilitates the complete NVH development process**.
- NVH-Console supports **both** FRF-Assembly and Superelement (SE) method.
- BUT, the main **root cause analysis** types of NVH-Console, e.g. TPA analysis, are performed in META deploying FRF-Assembly method.
- Bottom line, most NVH-Console runs are using FRF-Assembly as a reduction method in the background.

Motivation

- Accuracy of FRF-Assembly is crucial for NVH-C accuracy.
- CAE customers are usually used to Superelement method and similar techniques and doubt the capability of FRF-Assembly.



Substructuring – Background (1)

References

[Rix] De Klerk, Dennis, Daniel J. Rixen, and S. N. Voormeeren. "General framework for dynamic substructuring: history, review and classification of techniques." *AIAA journal* 46.5 (2008): 1169-1181.

[Ren] Ren, Y., and C. F. Beards. "On substructure synthesis with FRF data." *Journal of Sound and Vibration* 185.5 (1995): 845-866.

[MSC] MSC Nastran 2022.4. "Superelements and Modules User's Guide." *Hexagon AB. Sweden* (2022).

[Viz] Vizzini, Simone. *CMS methods in complete NVH analysis*. Master's. thesis. Chalmers University of Technology, Department of Applied Mechanics, Division of Dynamics, Sweden, 2014.

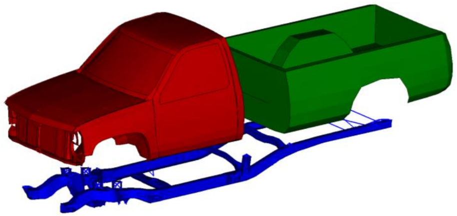
Substructuring – Background (2)

Superelements (SE)

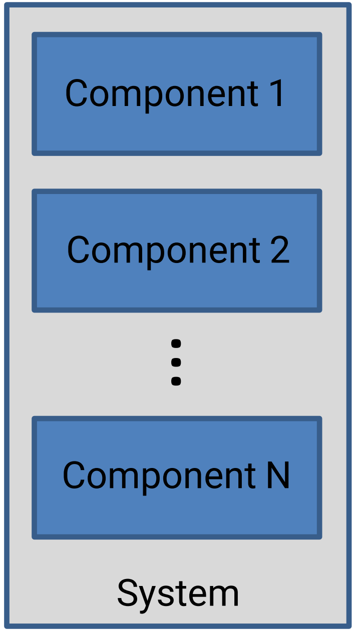
- **Component Mode Sythensis (CMS)** method, physical DOFs of each component are represented through a reduced system of modal coordinates. Component SE are assembled to calculate system response.
- **Craig-Bampton SE** is an enhancement of the static **Guyuan Reduction** method. Static constraint modes are augmented by supported normal component modes [MSC].
- N.B.: Craig-Bampton SE is base for Automatic Multi Level Substructuring (AMLS).

FRF-Assembly

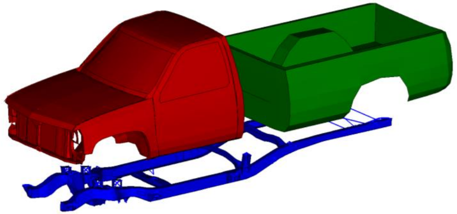
- FRF-Assembly assembly is **Frequency Based Substructuring (FBS)** method, components are represented by their Frequency Response Functions (FRF). Component FRFs are combined to the system response.
- FBS methods were original developed in the **experimental community**, still used in interactive NVH-simulator devices.
- **META FRF-Assembly Tool** deploys an FBS technique introduced by Ren et al. [Ren]



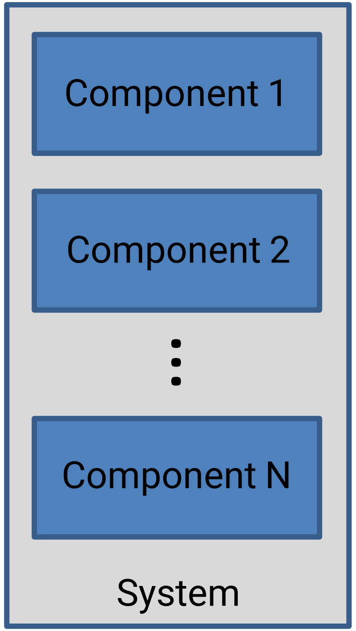
Example: 3 components



Substructuring – Background (3)



Example: 3 components



Advantages Substructuring (SE/FBS)

- Allows evaluating the dynamic behavior of structures that are too large or complex to be analyzed as a whole.
- **Reduces turn-around time** if just one component to be changed in the development process.
- Allows to maintain **confidentiality** as component can be exchanged as SE or FRF.

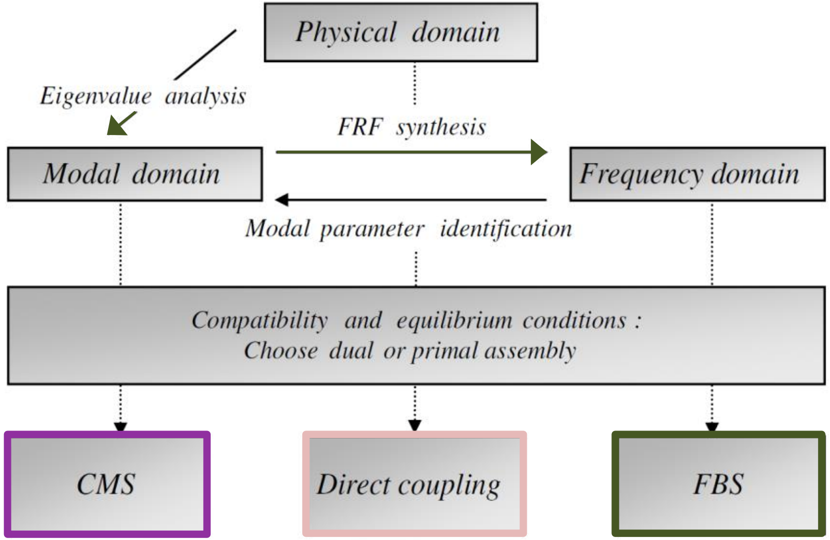
Advantages FRF-Assembly (FBS)

- Calculated FRFs and measured FRFs can easily be combined. This enables Test-CAE **Hybrid Models** and the usages of **Blocked Forces** measurements.
- Facilitates several root cause analysis types, e.g. **Transfer Path Analysis** (s. NVH-Console)

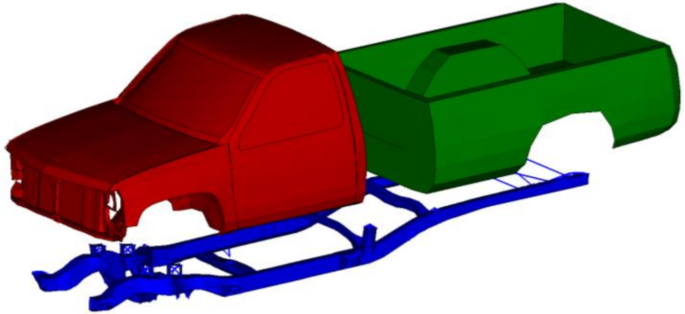
Advantages SE

- Can be used to speed up Nastran SOL200 optimization runs, if the design variables (DV) of the optimization are inner parameters of one or more components.

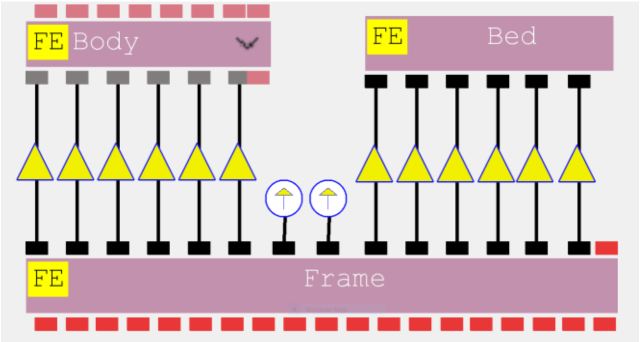
Substructuring – Background (4)



Representation of system dynamics in three domains [Rix]



Physical domain (FE-Model)



Representation in NVH-Console Diagram View

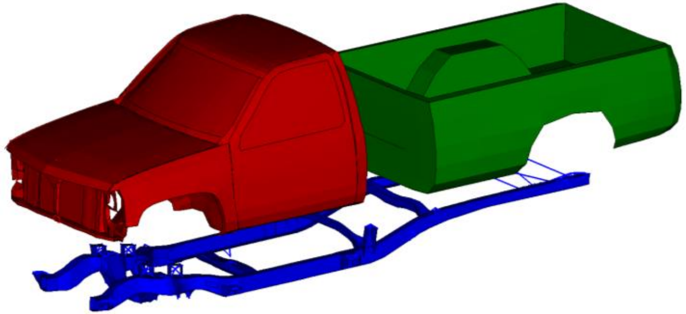
General Aspects

General System/Model Features

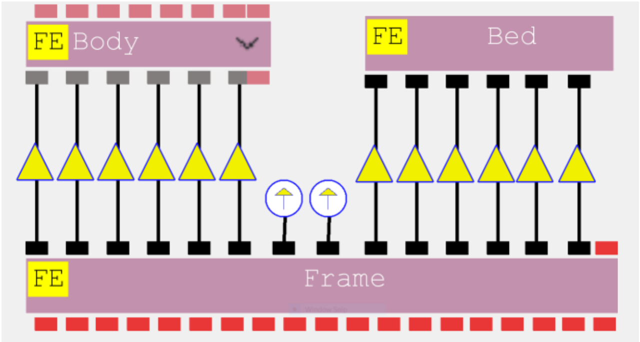
- Model/System consists of N > 1 **components**:
  - E.g. Model A: body, frame, bed
- Components are connected in **NVH-C** with spatially separated node-to-node **connectors**, e.g. bushes, hydro mounts, rigid connectors, etc. (NVH-C requirement)
  - E.g. Model A: rigid connectors only
- All components use **structural damping** in material cards of shells/solid/beams or in property cards of bush elements.

FE-Calculation

- Solver: Nastran 2022.x, Block Lanczos
- Direct coupling ('Full FE') and FRF component runs are modal solutions SOL111, not direct FRF calculation SOL108
- Set up Nastran calculation decks within **NVH-C**



Model A with 3 components



NVH-Console Model

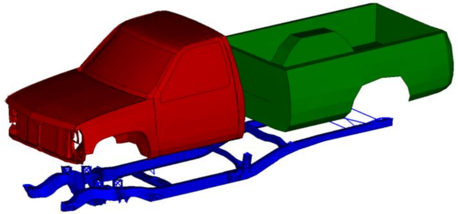
Model A: Results

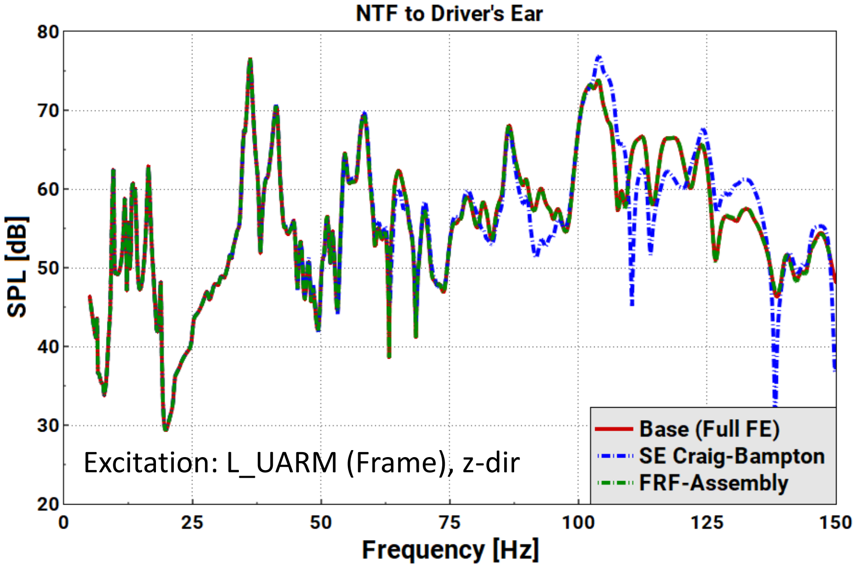
Features

- Size (w/o cavity)
  - 7.000 elements/grids
  - 550 modes
- Cut-off frequency: 200Hz

Observation

- **Perfect correlation** between reference (Full FE/direct coupling) and FRF-Assembly for the entire frequency range.
- Perfect correlation between reference and SE Craig-Bampton only for low frequencies. At higher frequencies significant deviations.





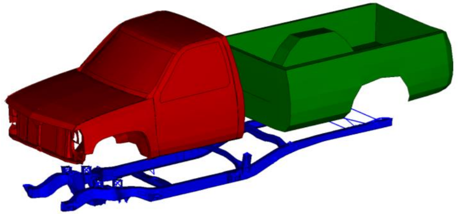
Influence Damping Assumptions (1)

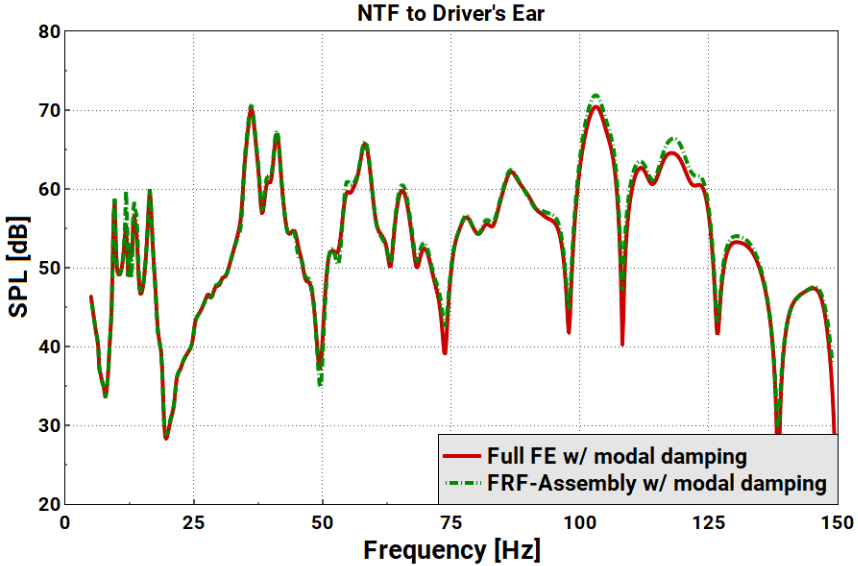
Observation

- Perfect correlation for FRF-Assembly was achieved with **structural damping** applied as **material damping** (s. last slide).
- If **modal damping** is used in exactly the same way in all components and in the system analysis perfect correlation cannot be achieved!
- Differences between Full FE and FRF-Assembly are small but noticeable and can be more pronounced in other systems.

Possible Explanation

- Modal damping is strongly connected to the modes.
- The system modes are different than the component modes, therefore the damping mechanism is not identical.





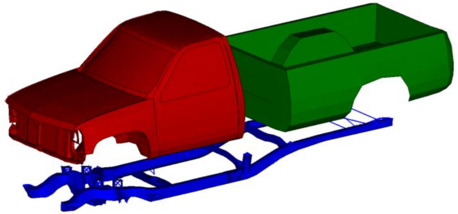
Influence Damping Assumptions (2)

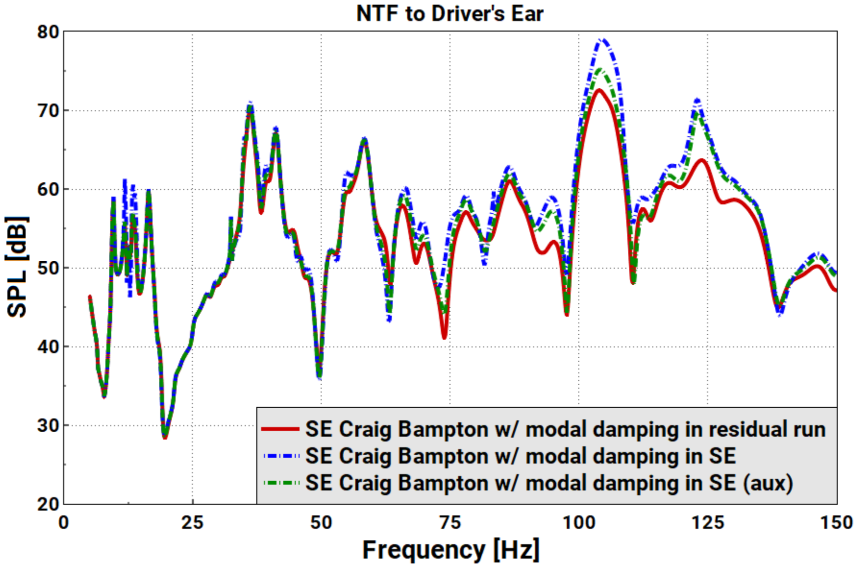
Observation

- **Craig-Bampton** with **modal damping** shows differences depending on whether the modal damping is applied on the system or on the components.
- There are noticeable differences in the entire frequency range, even at low frequencies, where Craig-Bampton with structural damping correlates perfectly.
- Even if *'param,sesdamp,aux'* is used instead of *'param,sesdamp,yes'* the use of modal damping introduces an numerical error in the assembly process.

Possible Explanation

- Damping of the constraint (static) modes might be the issue.





Influence Damping Assumptions (3): Summary

Observation

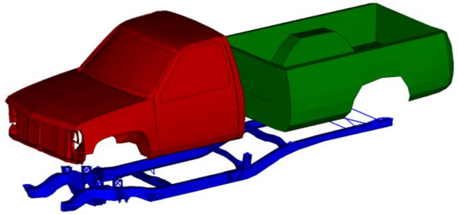
- **Structural damping** delivers the **highest numerical accuracy** for all substructuring methods.
- **Modal damping** always introduces a **numerical error** in substructuring methods FBS and SE.
- Additionally, different structural damping at different materials allows to put the damping at the geometrical position, where damping material is technically applied. Also, often approximate damping values for certain materials are known. Therefore, structural damping seems to be the best choice modelling wise.
- N.B.: As the **cavity** is not part of the substructuring process, the **fluid damping** mechanism does not influence the correlation. Modal damping for the fluid can be used without deteriorating the numerical accuracy.

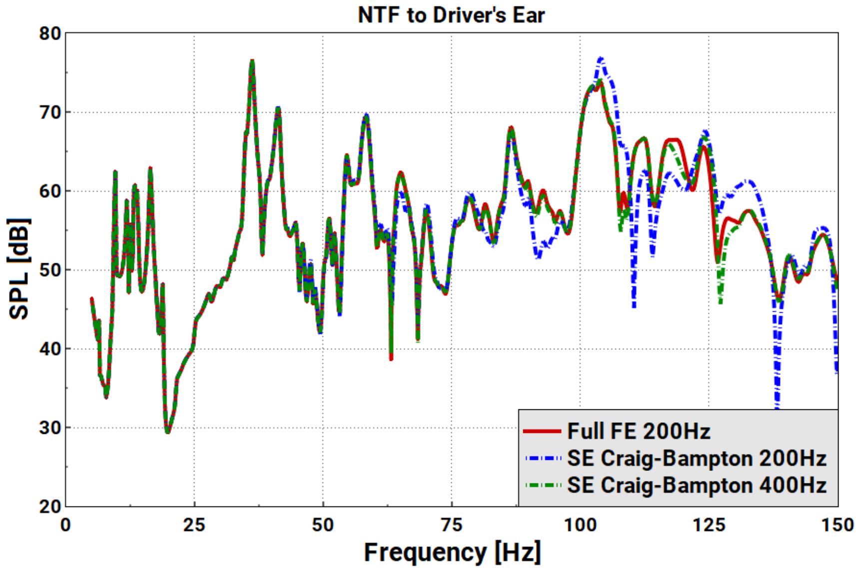
Lesson Learned (1)
Always use structural damping in FBS and SE
for the structural parts

Convergence of Craig-Bampton SE

Observation

- If the cut-off frequency for the SE component analysis is significantly increased the correlation of the Craig-Bampton method improves.
- However, even for 400Hz cut-off for all components the correlation is not perfect.



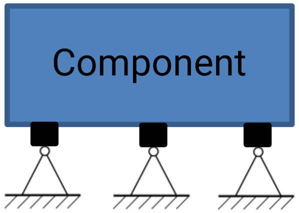


Lesson Learned (2)
Craig-Bampton SE converges slower than FRF-Assembly

Boundary Conditions (BC) in Superelement Analysis (1)

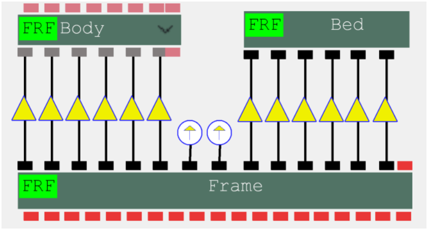
Standard BC

- **Craig-Bampton SE**: Modal solution (SOL103) for component reduction
  - Normal modes **supported/fixed** at interface nodes
  - **Constraint** modes (static Guyuan vectors)
- **FRF calculation**: Modal solution (SOL111) using
  - **Unsupported** normal modes (free-free)
  - **Unsupported** residual vectors (inertia relief vectors)

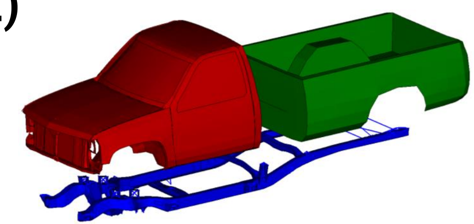


Alternative BC in SE

- **Craig-Chang SE**: Replace ASET w/ CSET in Craig-Bampton SE
  - **Unsupported** normal modes
  - **Unsupported** residual vectors (inertia relief vectors)
- References: [Rix, MSC, Viz]

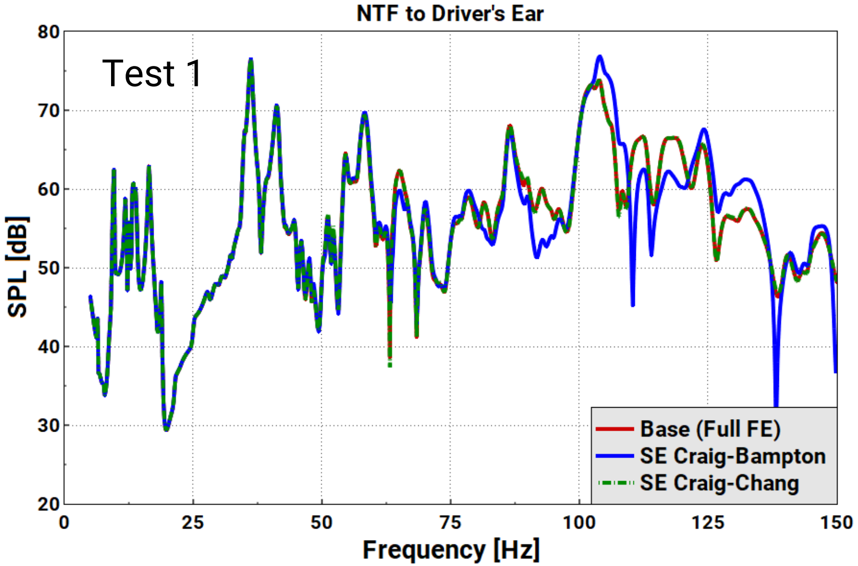


Boundary Conditions in Superelement Analysis (2)

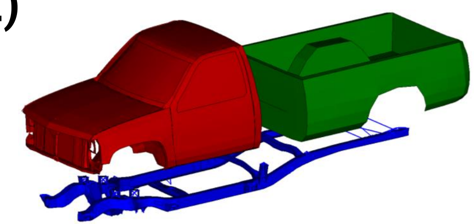


Observation

- **Test 1:** If the SE is performed according to **Craig-Chang** with unconstraint normal modes and residual vectors, also the SE method **correlates perfectly.**

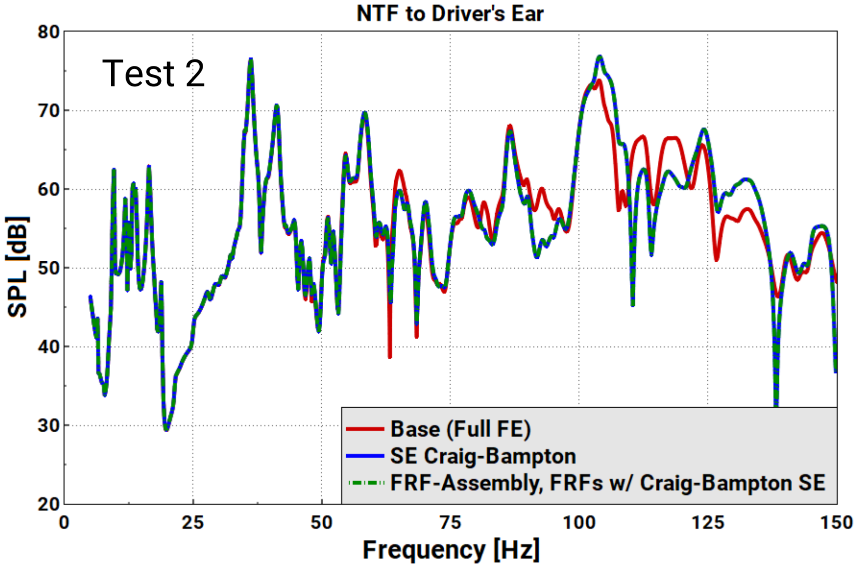


Boundary Conditions in Superelement Analysis (2)



Observation

- **Test 1:** If the SE is performed according to **Craig-Chang** with unconstraint normal modes and residual vectors, also the SE method **correlates perfectly.**
- **Test 2:** If the FRFs for the components are calculated with the Craig-Bampton SE, the FRF-Assembly shows the same correlation as the results for the assembled Craig-Bampton superelements.



Lesson Learned (3)
BCs used in the component analysis are the main driver for accuracy, NOT the assembly method

Boundary Conditions in Superelement Analysis (3)

Important

- Numerical accurate calculation of **residual vectors** is crucial for FRF-Assembly and Craig-Chang!
- Results from [Viz] support the all findings presented in this investigation regarding the influence of BC in SE method (Craig-Bampton vs. Craig Chang)

Reference

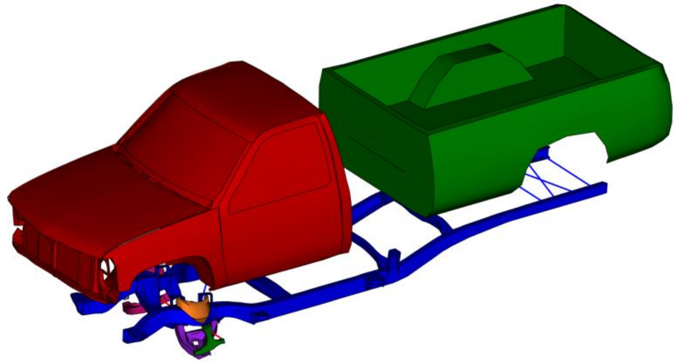
[Viz] Vizzini, S. I. M. O. N. E. *CMS methods in complete NVH analysis*. Diss. M. Sc. thesis. Chalmers University of Technology, Department of Applied Mechanics, Division of Dynamics, Sweden, 2014.

Verification of Results with Different Models

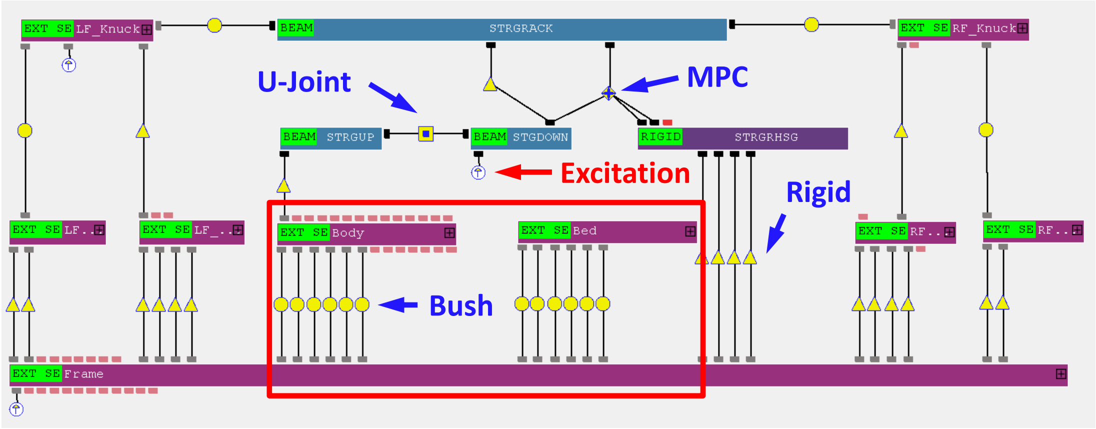
Model B – Enhanced Truck

Features Model B

- Size similar to Model A
- Significant bigger number of components: 13
- Different connector types Rigid, CBUSH, U-joint, MPC (s. NVH-Console) with very **different connector stiffness**
- Different component types Rigid, Beam, FE (s. NVH-Console) with very different **component stiffness and mass**



Model B FEM

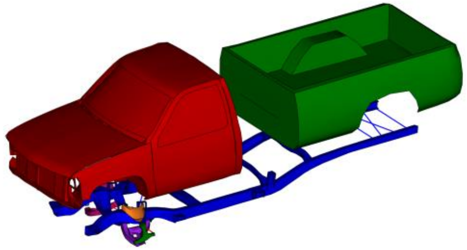


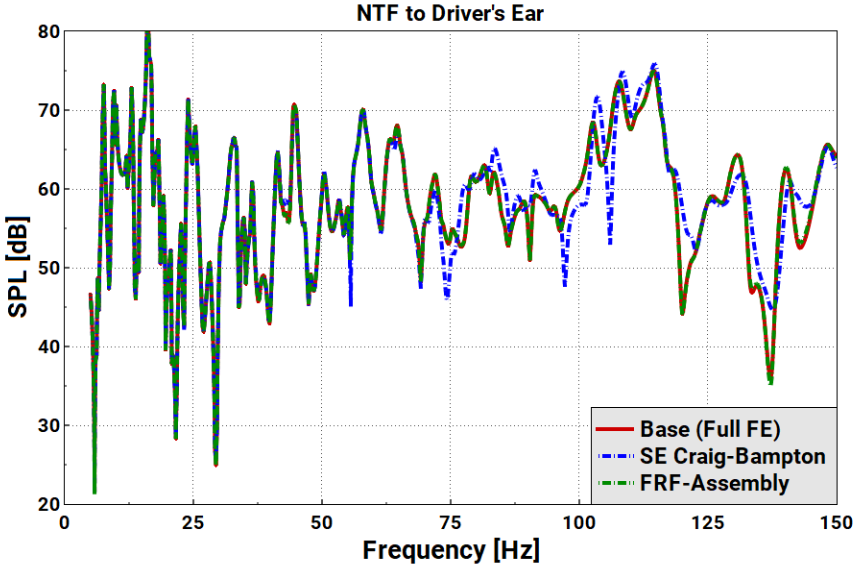
Model B NVH-C

Model B – Results

Observation

- Also the enhanced truck with more components shows exactly the same behavior as Model A:
  - Perfect correlation for FRF-Assembly.
  - SE Craig-Bampton shows less accuracy for higher frequencies.
- Agreement with [Viz]: Just marginal influence of connector stiffness on the above findings.

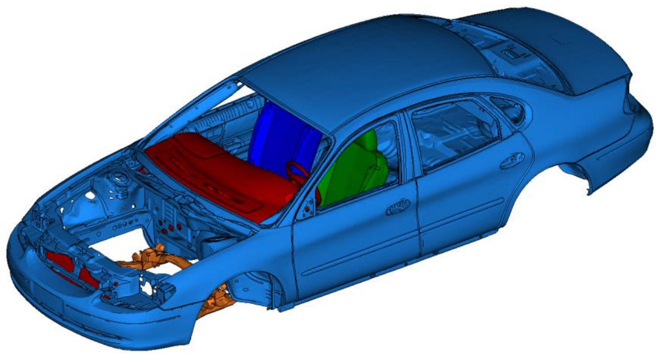




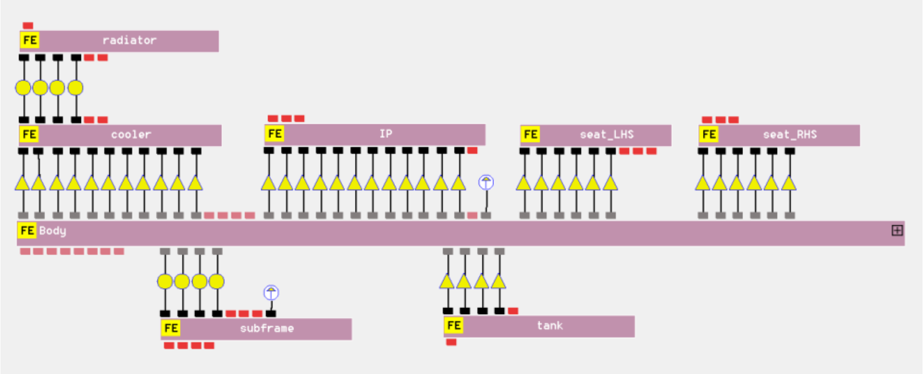
Model C – Taurus Trimmed Body

Features

- Model C consists of 8 components
- Size (w/o cavity)
  - 750.000 elements/grids
  - 4.700 modes
- Cut-off frequency: 600Hz
- Different structural damping for different materials, e.g. for IP (s. pic below)
  - Steel (red): GE = 0.04
  - Plastic (blue): GE = 0.1
  - Leather (green): GE = 0.2



Model C FEM



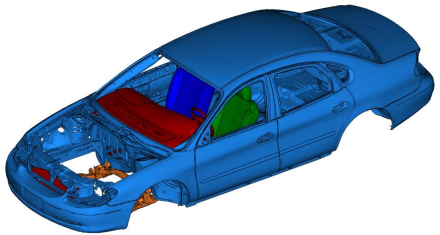
Model C NVH-C

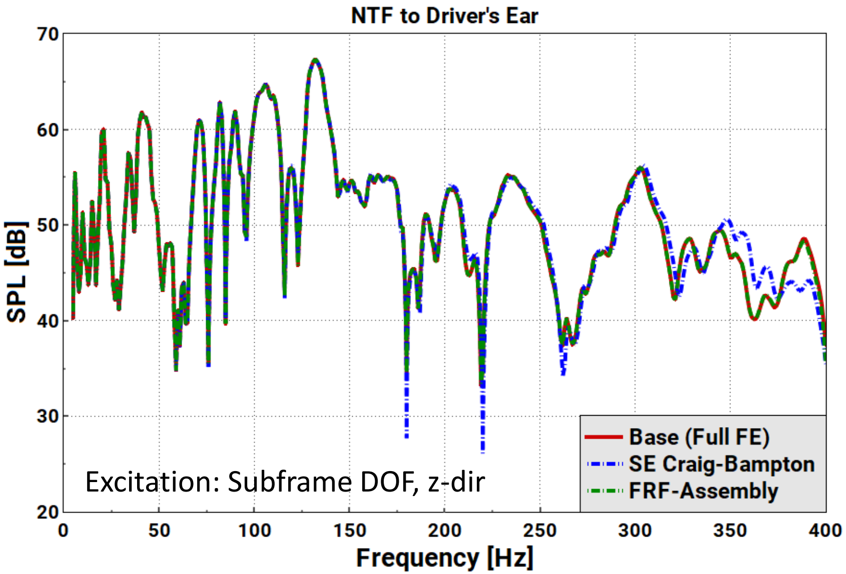
IP Model C

Model C – Results

Observation

- Also Model C shows the same behavior as Model A/B:
  - Perfect correlation for FRF-Assembly.
  - SE Craig-Bampton shows less accuracy for higher frequencies.

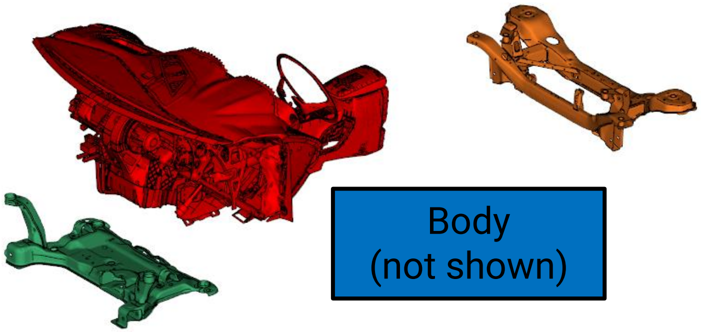




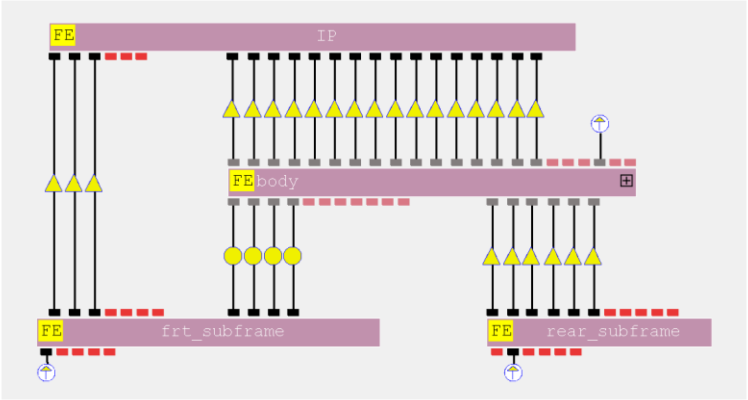
Model D – Trimmed Body

Features

- Consists of 4 components:
  - Body, IP, front and rear subframe
- **Production NVH TB model,** realistic modelling of interface and attachment points
- Front subframe bushes **very stiff**, rear subframe/IP attached **rigidly** to body
- Size (w/o cavity)
  - 1.400.000 elements and 1.200.000 grids
  - 4800 modes
- Cut-off frequency: 600Hz
- Different structural damping for different material



Model D FEM

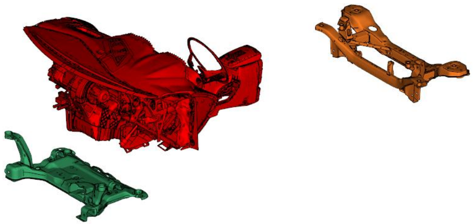


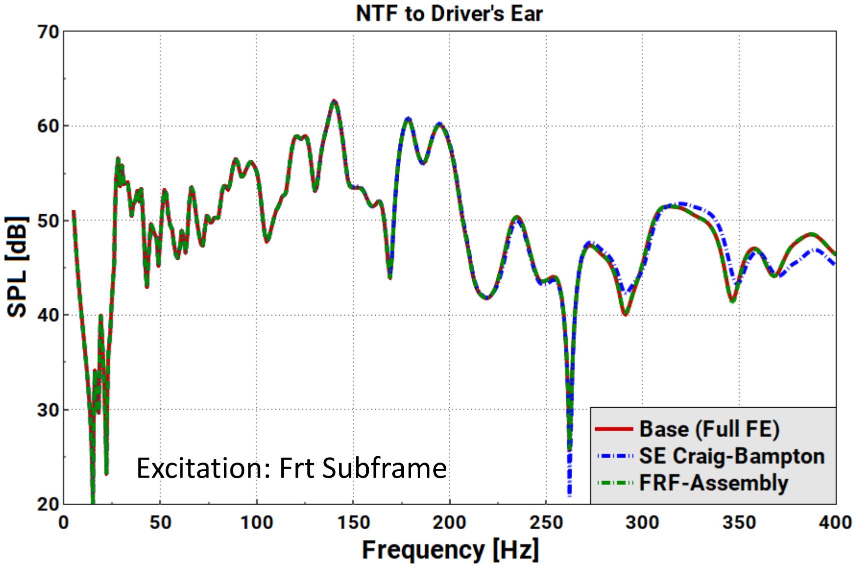
Model D NVH-C

Model D – NTF Results

Observation

- Also Model D shows the same behavior as Model A/B/C:
  - Perfect correlation for FRF-Assembly.
  - SE Craig-Bampton shows less accuracy for higher frequencies.

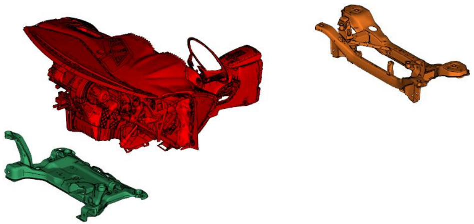


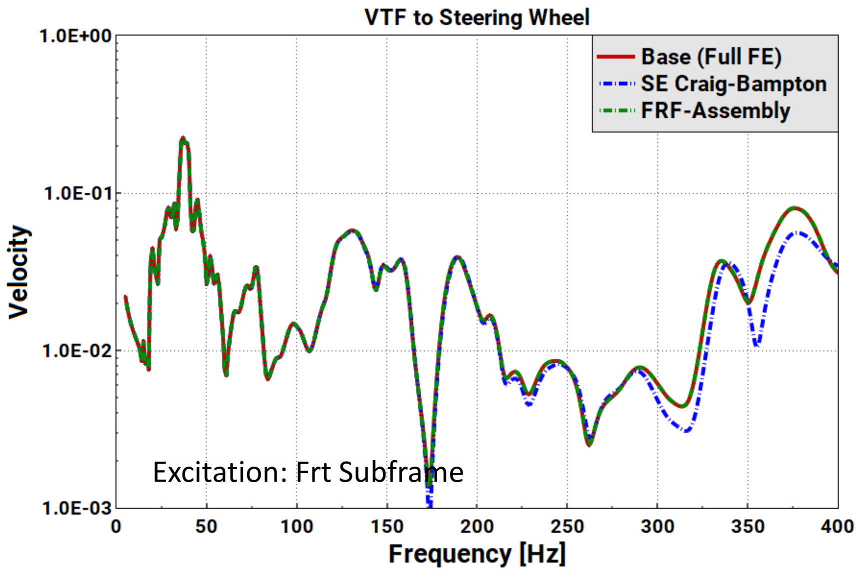


Model D – VTF Results

Observation

- Most of the **tactile transfer functions (VTF)** show the same behavior as the acoustic transfer functions (NTF):
  - Perfect correlation for FRF-Assembly for the entire frequency range.
  - SE Craig-Bampton shows less accuracy for higher frequencies.

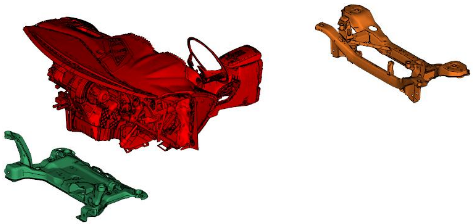


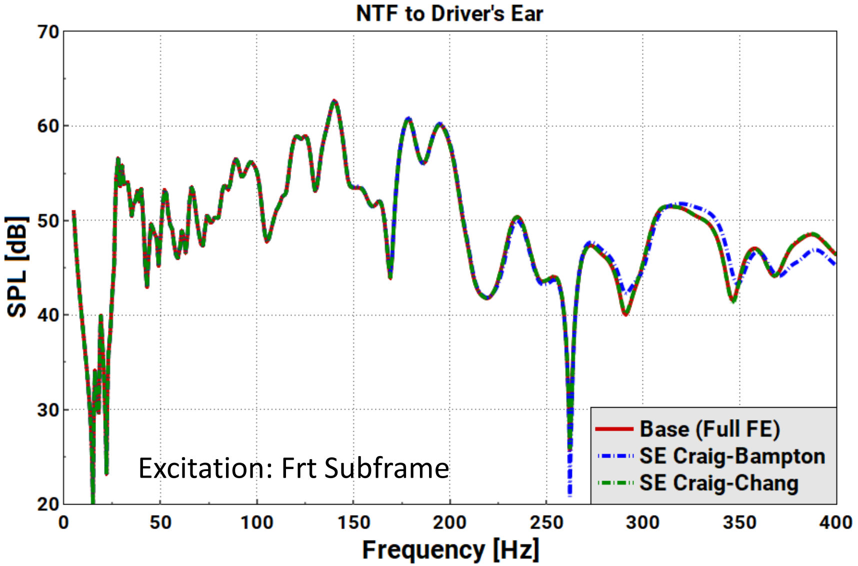


Model D – BC in SE Comparison

Observation

- Also Model D shows the same behavior as Model A:
  - Perfect correlation for SE, if the Craig-Chang method is used.



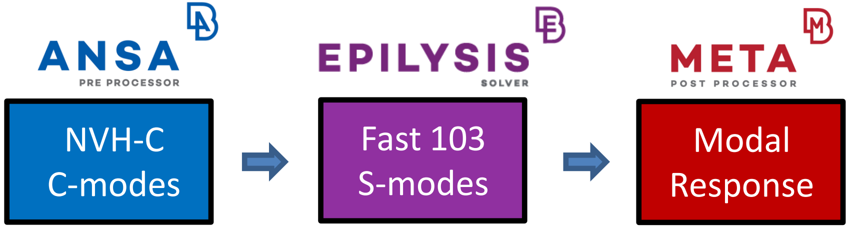


All models investigated support the Lesson Learned (1-3)

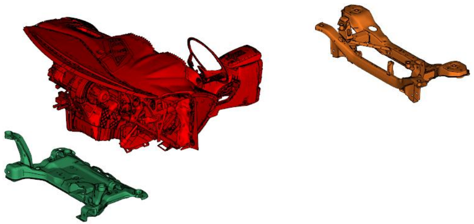
Model D – Fast SOL103 in Epilysis

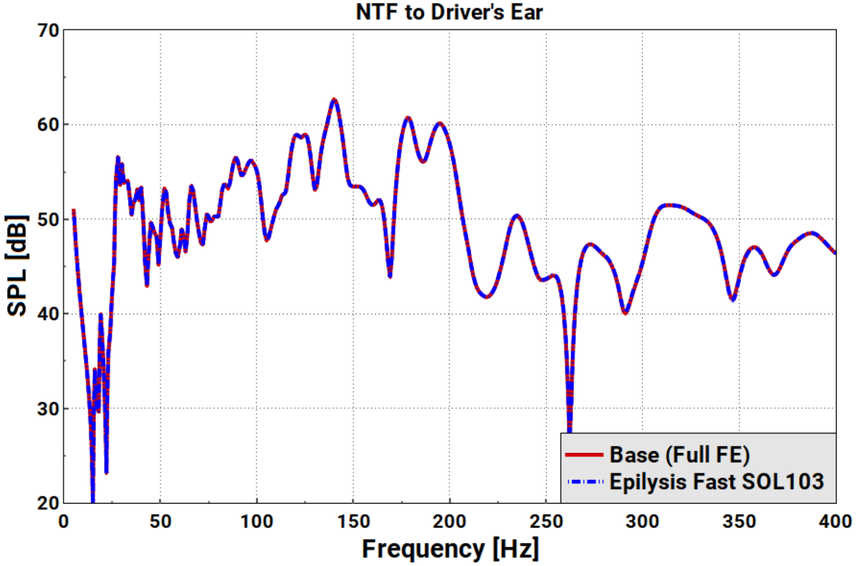
Fast SOL103 Method (Modal Models)

- **CMS method** in Epilysis to calculate system (S) modes out of components (C) modes (SOL103)
- Works with unconstraint normal component modes and residual vectors **similar to Craig-Chang.**
- N.B.: **Faster turn-around time** than SE.
- Can be easily **set-up from NVH-C.**
- Results can be **used in META Modal Response** to calculate the system response.
- **Numerical accuracy** as Craig-Chang and FRF-Assembly.



Workflow Fast SOL103





Visit the Epilysis Booth!

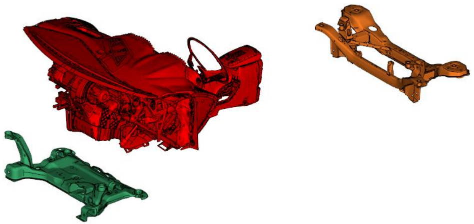
Model D – Solver Epilysis/AMLS

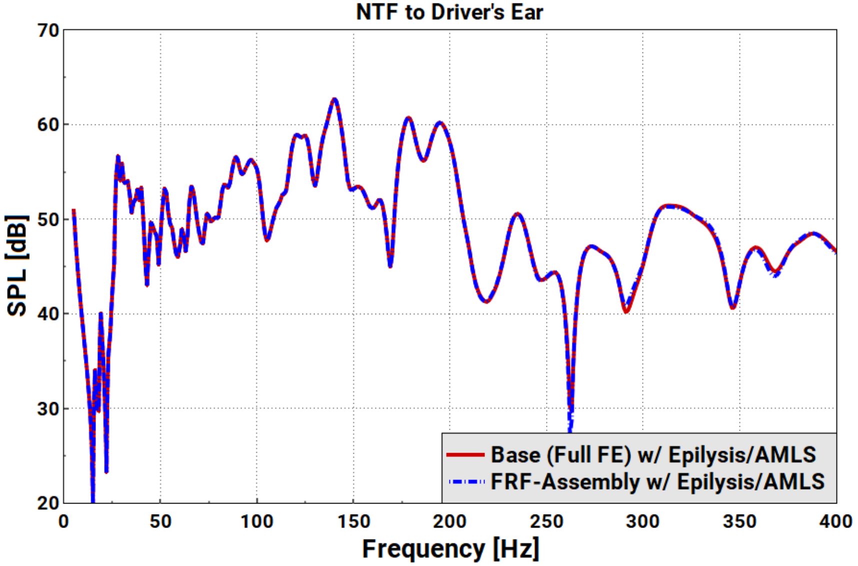
Motivation

- Presented results were all calculated with Nastran **Block Lanczos** (BL) solver because:
  - BL is the most accurate solver
  - Customers are used to Nastran
- In order to show the high accuracy of the FRF-assembly method can also be achieved for other solvers set-ups:
  - Epilysis solver (v24.0.0)
  - AMLS instead of BL for Body and System FRFs

Observation

- Using Epilysis/AMLS a nearly perfect correlation can be achieved.
- This proves high numerical accuracy of Epilysis/AMLS, e.g. for residual vectors and in general for component FRF calculation.





Visit the Epilysis Booth!

Summary

Findings

- Most important result for NVH-C users: **FRF-Assembly is a numerically accurate method!**
  - More than the presented models were investigated: The conclusions were always the same!
  - FRF-Assembly numerical accuracy has been proven in a lot of cases by comparing with Nastran SOL111 one-shot runs.
- **LL1: Use structural/material damping** in order to achieve highest possible numerical accuracy for all substructuring methods.
- **LL2: Craig-Bampton SE converges significantly** slower in all models investigated with respect to the cut-off frequency used in the modal analysis for the components.
- **LL3: Boundary Conditions are main driver for different accuracy** between Craig-Bampton SE and FRF-Assembly for higher frequency ranges. **Craig-Chang SE** method has the same numerical accuracy as FRF-Assembly in all cases investigated. (Remember: CSET instead of ASET!)

BETA
SIMULATION SOLUTIONS

Stay connected

Backup

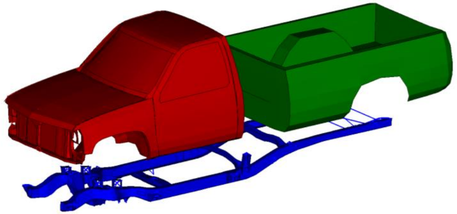
General Analysis Workflow

Analysis Types/Nastran Solutions

- **Base Run/Reference (Direct Coupling)**
  1. System: Nastran modal frequency response (SOL111)
- **Superelement (CMS)**
  1. Components: Nastran external SE run (SOL103)
  2. System: Nastran residual SE run (SOL111) using the external SE for each component
- **FRF-Assembly (FBS)**
  1. Components: Nastran modal frequency response FRF (SOL111)
  2. System: META FRF-Assembly using the component FRFs

Solver: Nastran 2022.x, Block Lanczos

N.B.: All calculations are set up within **NVH-Console**



Example: 3 components

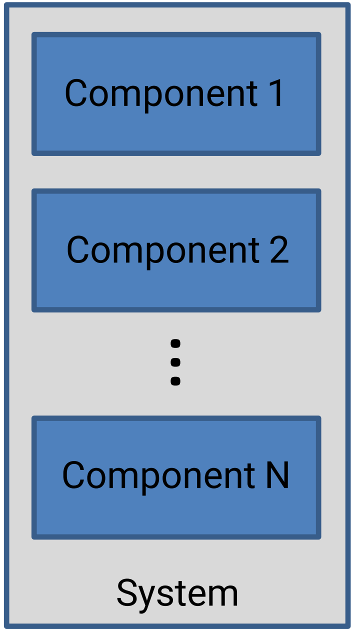
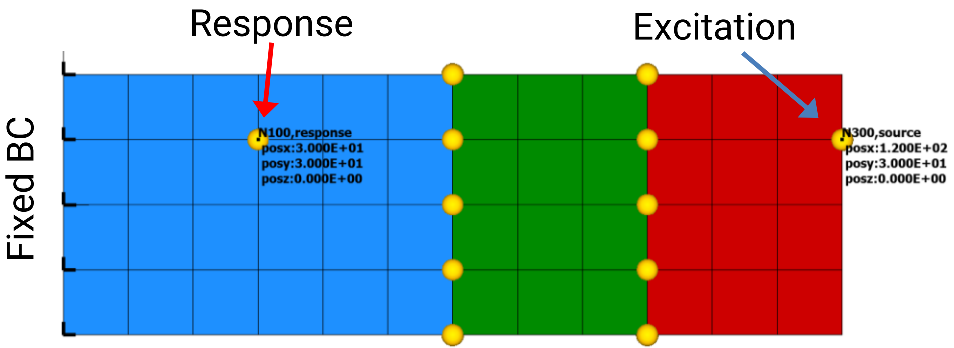


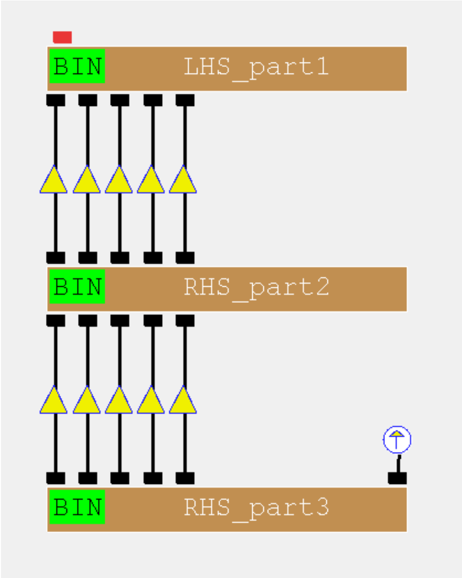
Plate Example

Motivation

- Verification of findings for a model that does not contain single, separated node-to-node connections.
- The example consists of a steel plate which is divided into 3 parts and constrained at one side



FE Model



NVH-C Model

Plate Example – Results

Modelling set-up

- Comparison against Nastran SOL108 as this is considered as the most accurate solution.
- Cut-off frequency for all runs 10kHz.

Remarks

- The investigated scenario (cutting a component in 3 parts) is not the common scenario used in NVH-C.

Observation

- Perfect correlation for FRF assembly and SE.