The Application of Dynamic Reduction in Modelling an Exhaust System as a Flexible Body

SIMPACK User Meeting 2001

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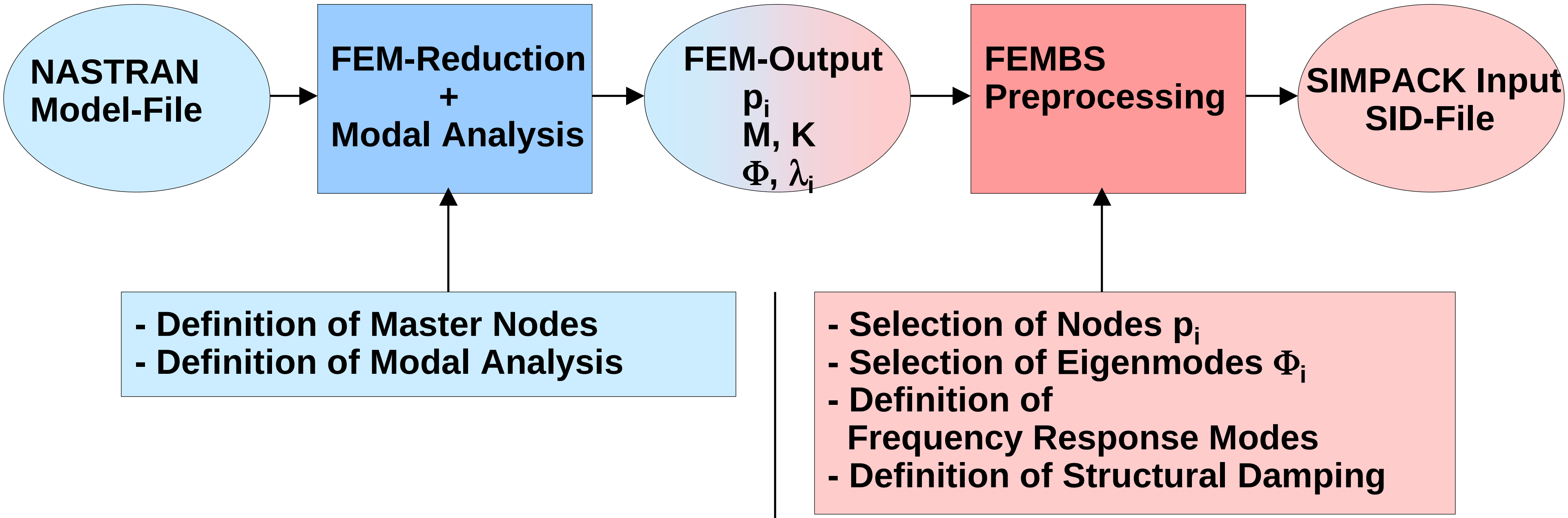
BMW Group

Contents

Flexible Bodies in SIMPACK

Application Pattern for NASTRAN



FEM-Postprocessing
NASTRAN

MBS-Preprocessing
SIMPACK/FEMBS

Static Reduction

FEM-Model Equations

$$\mathbf{M_f}\,\ddot{\mathbf{u}}_\mathbf{f} + \mathbf{K_f}\,\mathbf{u_f} = \mathbf{P_f}$$

Dimension nf: **Physical FEM-Degrees of Freedom**

Separation of **Master Nodes $\mathbf{u_a}$** from **Internal Nodes $\mathbf{u_o}$**

$$\begin{bmatrix} M_{aa} & M_{ao} \\ M_{oa} & M_{oo} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{u}}_\mathbf{a} \\ \ddot{\mathbf{u}}_\mathbf{o} \end{bmatrix} + \begin{bmatrix} K_{aa} & K_{ao} \\ K_{oa} & K_{oo} \end{bmatrix} \begin{bmatrix} \mathbf{u_a} \\ \mathbf{u_o} \end{bmatrix} = \begin{bmatrix} \mathbf{P_a} \\ \mathbf{P_o} \end{bmatrix}$$

Elimination of Internal Nodes

$$\mathbf{u_o} = -K_{oo}^{-1}\left[K_{oa}\mathbf{u_a} + M_{oa}\ddot{\mathbf{u}}_\mathbf{a} + M_{oo}\ddot{\mathbf{u}}_\mathbf{o} - \mathbf{P_o}\right]$$

$$\ddot{\mathbf{u}}_\mathbf{o} = -K_{oo}^{-1}K_{oa}\ddot{\mathbf{u}}_\mathbf{a}$$

Guyan Approximation:
Static Solution 2x differentiated

Reduced Model Equations

$$\mathbf{M_{aa}}\,\ddot{\mathbf{u}}_\mathbf{a} + \mathbf{K_{aa}}\,\mathbf{u_a} = \mathbf{P_a}$$

Dimension na: **Master Nodes-Degrees of Freedom**

Dynamic Reduction

Approximation of Internal Nodes

$$\mathbf{u_o} = -K_{oo}^{-1}[K_{oa}\mathbf{u_a} + M_{oa}\ddot{\mathbf{u}}_\mathbf{a} + M_{oo}\ddot{\mathbf{u}}_\mathbf{o} - \mathbf{P_o}]$$

$$\ddot{\mathbf{u}}_\mathbf{o} = -K_{oo}^{-1}K_{oa}\ddot{\mathbf{u}}_\mathbf{a} + \Phi_{oq}\ddot{\mathbf{u}}_\mathbf{q}$$

Generalised Coordinates and **Form Functions**

Reduced Model Equations

$$\begin{bmatrix} \mathbf{M_{aa}} & \mathbf{M_{aq}} \\ \mathbf{M_{qa}} & \mathbf{M_{qq}} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{u}}_\mathbf{a} \\ \ddot{\mathbf{u}}_\mathbf{o} \end{bmatrix} + \begin{bmatrix} \mathbf{K_{aa}} & \mathbf{0} \\ \mathbf{0} & \mathbf{K_{qq}} \end{bmatrix} \begin{bmatrix} \mathbf{u_a} \\ \mathbf{u_q} \end{bmatrix} = \begin{bmatrix} \mathbf{P_a} \\ \mathbf{P_q} \end{bmatrix}$$

Dimension na+nq: **Master Nodes - DoF + Generalised Coordinates**

➡ **The Dynamics of Internal Nodes** is taken into account by **Generalised Coordinates** and **Form Functions**

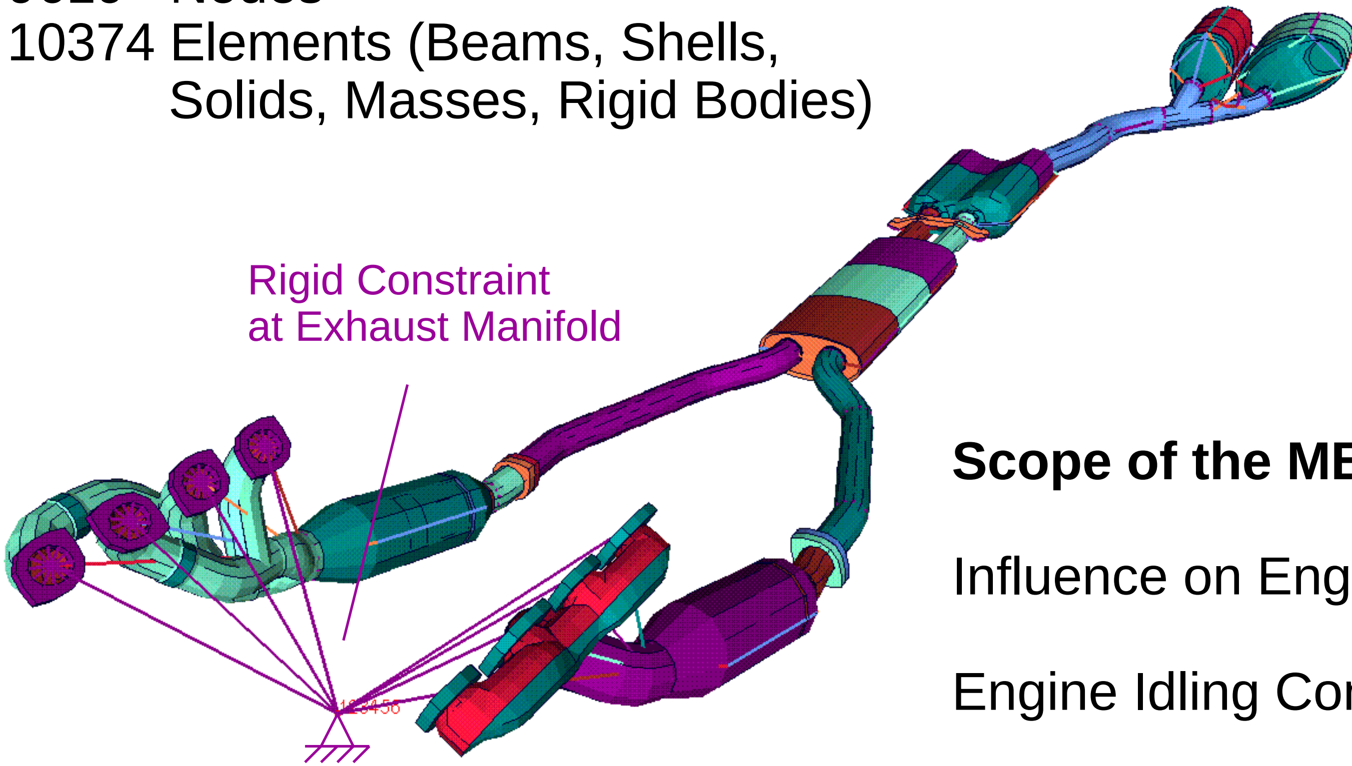
Properties of the Reduction

	Static	Dynamic
Stiffness Matrix	Exact ++	Exact ++
Mass matrix	Rigid body characteristics exact +	Rigid body characteristics exact +
Eigenfrequency,-modes	Dependant on distribution of Master Nodes --	Controllable by the number of frequencies considered ++
Modelling Effort	Dense distribution of master nodes and check of the Eigenfrequencies is necessary --	Minimum number of Master Nodes at the coupling nodes to the MBS is possible ++

Exhaust System Example

FEM-Model

9619 Nodes
10374 Elements (Beams, Shells, Solids, Masses, Rigid Bodies)



Coupling with the MBS by
Rigid Joint at Exhaust Manifold and
Elastic Force Elements

Scope of the MBS-Simulation

Influence on Engine Shake (5-30Hz)

Engine Idling Comfort (20-60Hz)

Isolation of Structure Borne Noise
Boom at low Frequencies (< 100Hz)

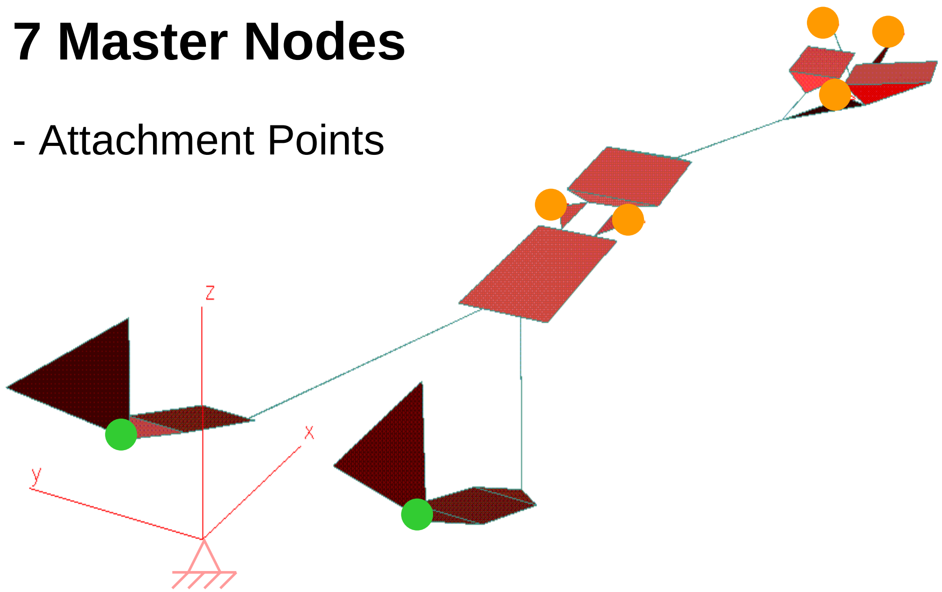
➡ **Dynamics up to 100Hz**

FEM-Model Reduction

Alternatives with Different Number of Master Nodes

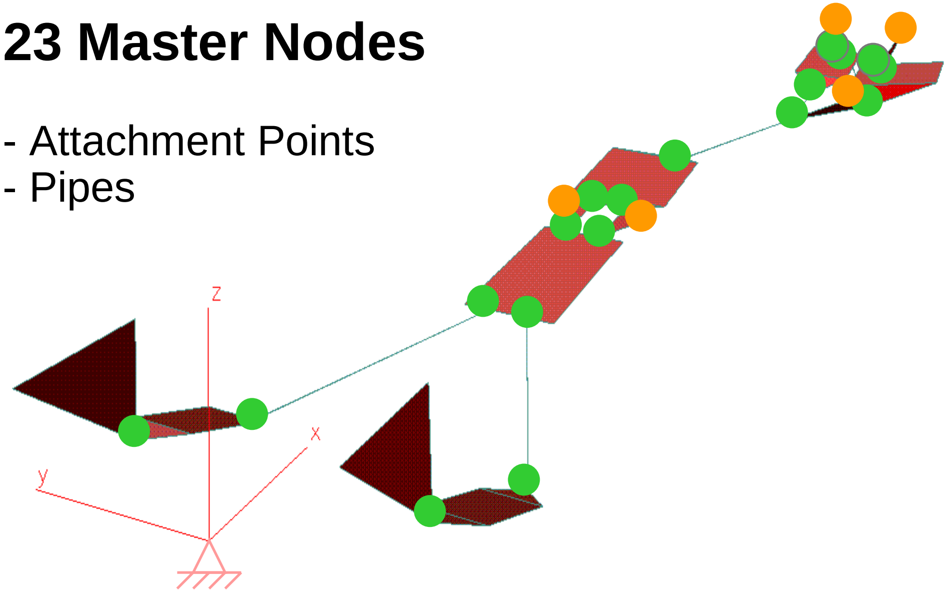
7 Master Nodes

- Attachment Points



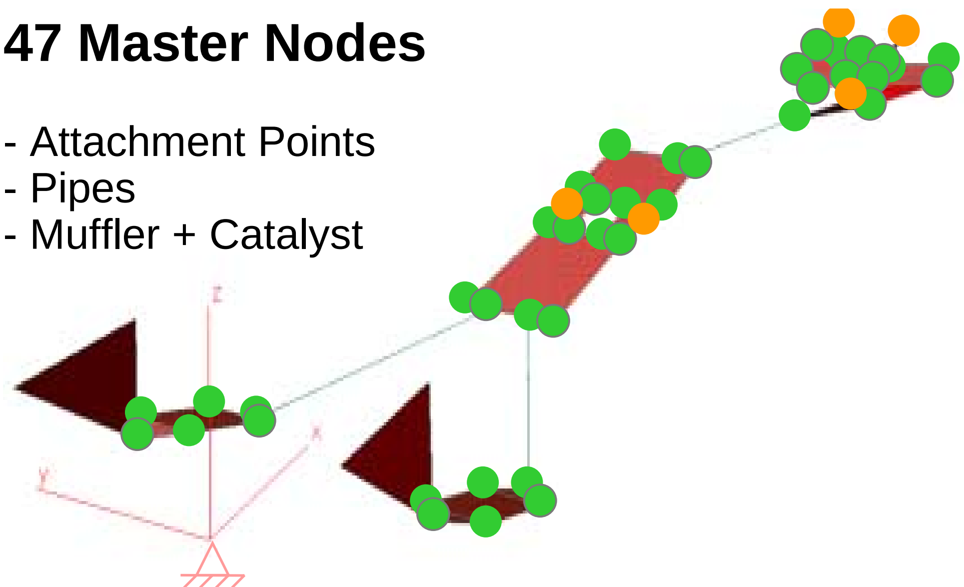
23 Master Nodes

- Attachment Points
- Pipes



47 Master Nodes

- Attachment Points
- Pipes
- Muffler + Catalyst



Master Nodes

- Coupling Nodes
- Additional Master Nodes

Model Quality of the FEM-Reduction

Constrained Exhaust System without Mounts

		FEM	Static Reduction			Dynamic Reduction EigenFrequncies to 300Hz		
Nodes		9619	7	23	47	7	23	47
Number of Eigen Frequencies	1	1,6	1,6	1,6	1,6	1,6	1,6	1,6
	2	3,5	3,5	3,5	3,5	3,5	3,5	3,5
	3	9,7	9,8	9,7	9,7	9,7	9,7	9,7
	4	15,8	16,1	15,8	15,8	15,8	15,8	15,8
	5	24,0	27,6	24,1	24,0	24,0	24,0	24,0
	6	28,8	31,8	28,8	28,8	28,8	28,8	28,8
	7	32,1	36,0	32,2	32,1	32,1	32,1	32,1
	8	41,7	49,0	41,9	41,7	41,8	41,7	41,7
	9	58,0	70,5	58,5	58,2	58,1	58,1	58,1
	10	74,6	99,8	75,1	75,0	74,8	74,7	74,7
	11	85,3	135,4	87,3	85,7	85,5	85,4	85,4
	12	87,3	151,3	88,3	87,5	87,4	87,4	87,4
	13	110,4	172,4	112,6	110,9	110,7	110,5	110,5
	14	116,2	242,9	126,5	116,9	116,5	116,3	116,3
	15	129,1	261,3	133,1	130,4	129,6	129,3	129,3
	16	148,4	340,5	153,7	149,6	150,5	148,8	148,7

Relative Error

5% < f
2% < f < 5%
f < 2%

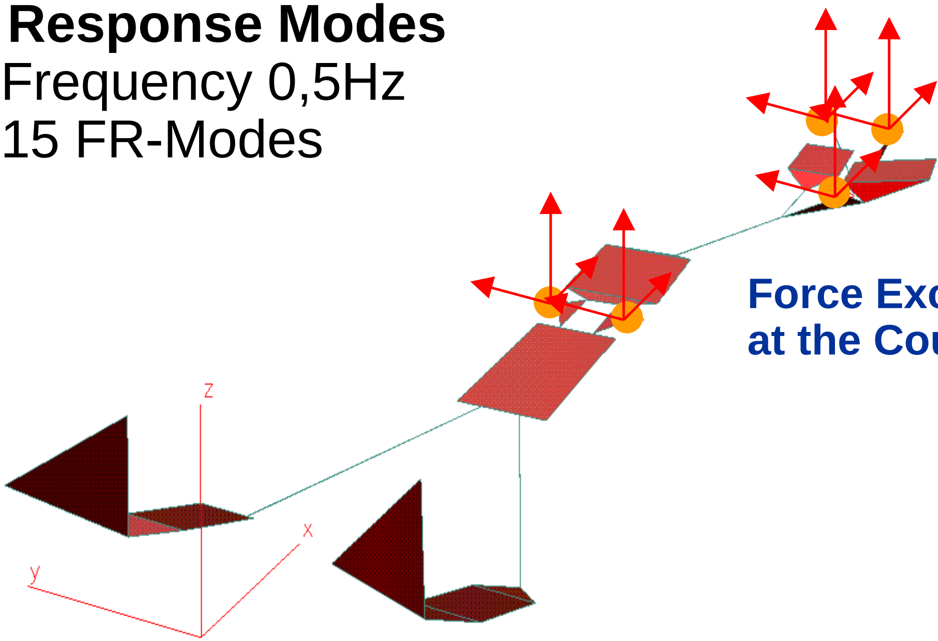
Eigenfrequencies of FEM-Model and Reduced Models evaluated with NASTRAN

➡ **Static: Model quality dependant on number and distribution of master nodes**
Dynamic: Model quality independant of the master nodes

FEMBS Preprocessing

Eigenmodes
- fe < 155Hz

Frequency Response Modes
- Excitation Frequency 0,5Hz
- Maximum 15 FR-Modes



Force Excitation x,y,z at the Coupling Nodes

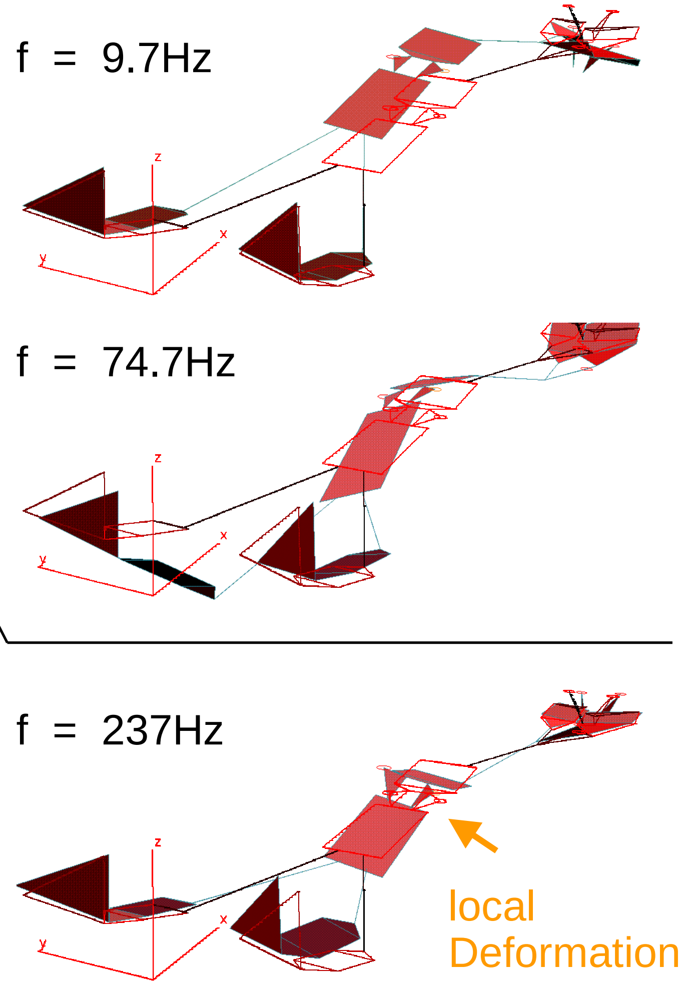
- Maximum Frequency of the Flexible Body
  fr < 500 Hz -> 5 FR-Modes
  fr < 1000 Hz -> 11 FR-Modes
  fr < 1800 Hz -> 15 FR-Modes

Influence of Frequency Response Modes

Constrained Exhaust System without Mounts

FEMBS Modes		FEM	MBS - Dynamic Reduction (47 Nodes) fe < 155Hz	fe < 155Hz fr < 500z	fe < 155Hz fr < 1000z	fe < 155Hz fr < 1800z	
Number of Eigen Frequncies	1	1,6	1,6	1,6	1,6	1,6	Eigenmodes
	2	3,5	3,5	3,5	3,5	3,5	
	3	9,7	9,7	9,7	9,7	9,7	
	⋮	⋮	⋮	⋮	⋮	⋮	
	14	116,2	116,3	116,3	116,3	116,3	
	15	129,1	129,3	129,3	129,3	129,3	
	16	148,4	148,7	148,7	148,7	148,7	
	17	157,7		215,5	215,5	215,5	Frequency Response Modes
	18	171,0		236,9	236,9	236,9	
	19	192,4		345,8	345,8	345,8	
	20	217,2		412,8	412,8	412,8	
	21	260,8		479,6	479,6	479,6	
	22	264,3			579,1	579,1	
	23	272,7			⋮	612,1	
	24	288,6			960,7	⋮	
	25	304,7				1789,8	
	⋮	⋮					

Eigenfrequencies of the Flexible Body in Comparison to FEM

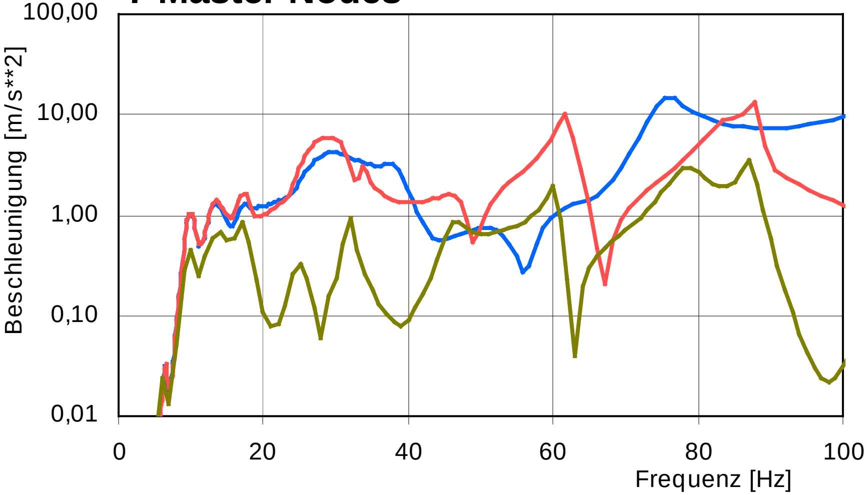


➡ **Frequency Response Modes** create **High Frequency Eigenmodes** as correction for missing FEM-Modes to describe **Local Deformations** at the coupling nodes.

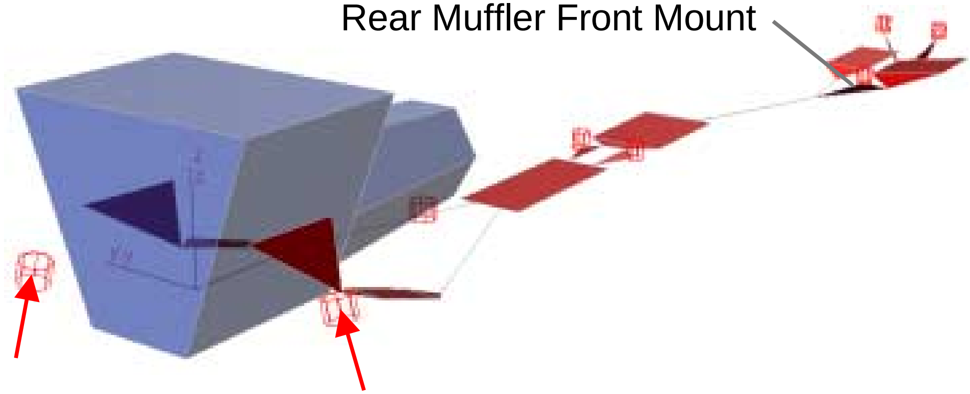
Validation of the Coupled MBS

Comparison of the Reduction Alternatives

7 Master Nodes

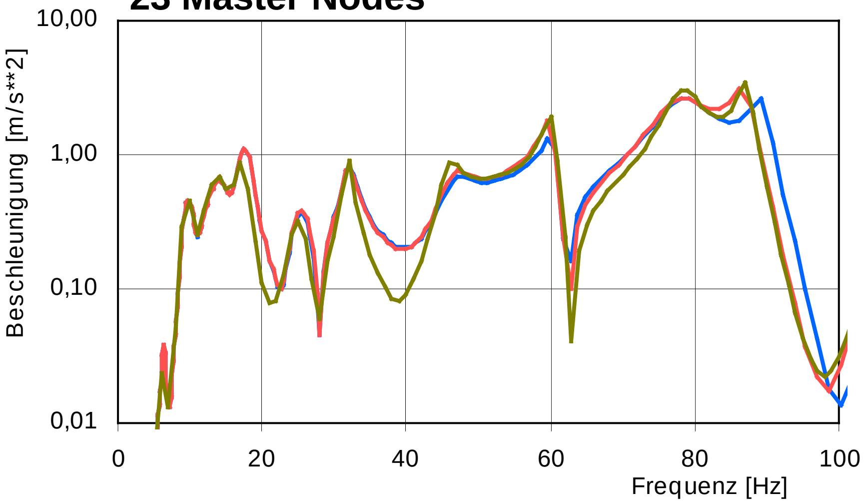


Vertical **Acceleration** at the Rear Muffler Front Mount

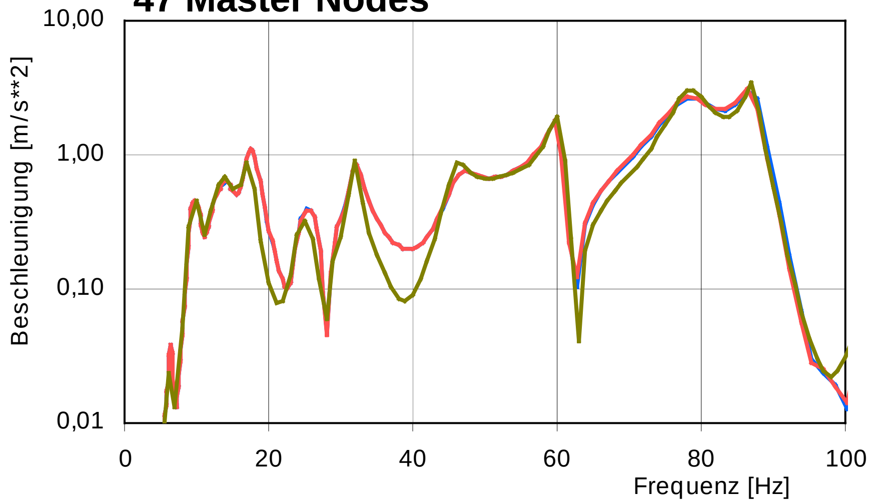


Force Excitation at Engine Mounts in Phase 200N

23 Master Nodes



47 Master Nodes



Linear Response Analysis Comparing Reduction Alternatives (without Frequency Response Modes)

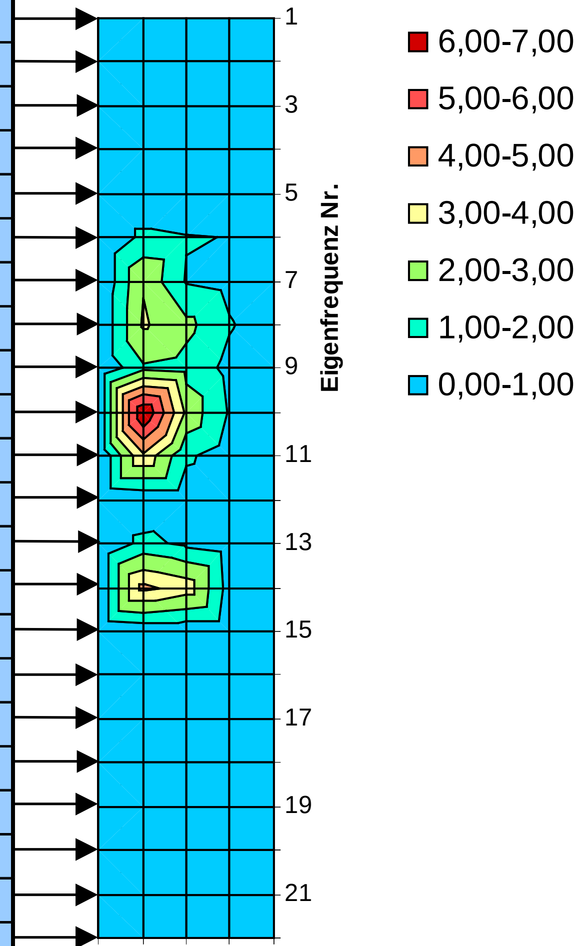
FEM — **Static Reduction** — **Dynamic Reduction**

Validation of the Coupled MBS

Influence of Frequency Response Modes

		FEM	MBS - Dynamic Reduction (47 Knoten)			
FEMBS Modes			fe < 155Hz	fe < 155Hz fr < 500Hz	fe < 155Hz fr < 1000z	fe < 155Hz fr < 1800z
Number of Eigen Frequencies	1	5,8	5,8	5,8	5,8	5,8
	2	6,4	6,4	6,4	6,4	6,4
	3	9,3	9,3	9,3	9,3	9,3
	4	10,3	10,3	10,3	10,3	10,3
	5	12,8	12,8	12,8	12,8	12,8
	6	13,8	13,9	13,9	13,9	13,9
	7	⇨ 16,4	16,8	16,5	16,5	16,4
	8	⇨ 17,3	17,8	17,7	17,5	17,4
	9	⇨ 23,9	24,4	24,3	24,1	24,0
	10	⇨ 24,8	26,7	25,5	25,0	25,0
	11	⇨ 28,5	29,6	28,8	28,6	28,5
	12	31,7	31,8	31,8	31,8	31,7
	13	⇨ 45,8	46,4	46,2	46,0	45,9
	14	⇨ 50,3	52,5	52,1	50,6	50,6
	15	59,9	60,0	60,0	60,0	60,0
	16	78,3	77,8	77,8	78,1	78,1
	17	86,6	86,9	86,9	86,9	86,9
	18	88,7	88,6	88,6	88,7	88,7
	19	112,2	112,0	112,1	112,4	112,4
	20	117,7	117,8	117,8	118,0	118,1
	21	130,4	130,6	130,6	130,7	130,7
	22	150,7	151,0	151,6	151,6	151,5

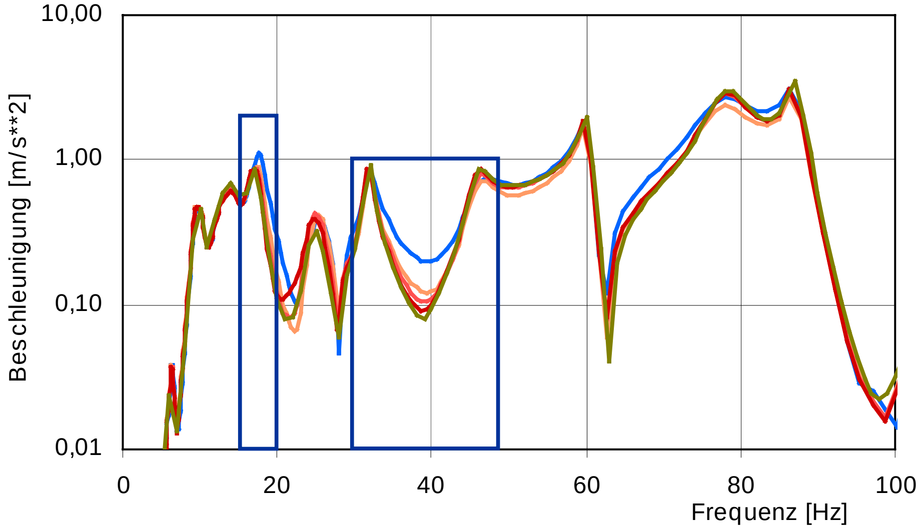
Relative Error [%]



Eigenfrequencies of the Coupled MBS in Comparison to FEM

Validation of the Coupled MBS

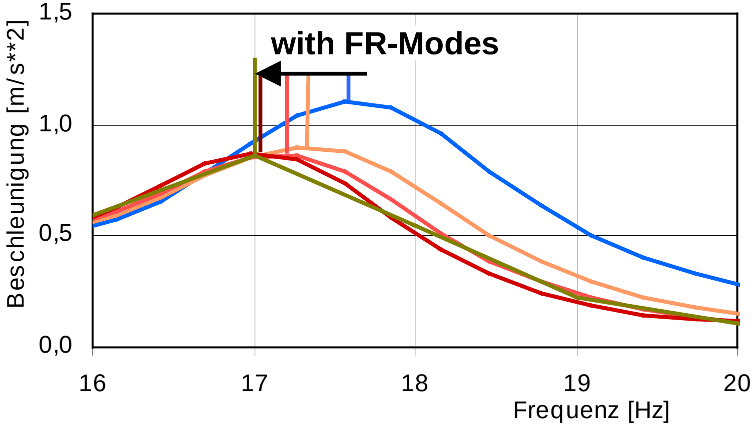
Influence of Frequency Response Modes



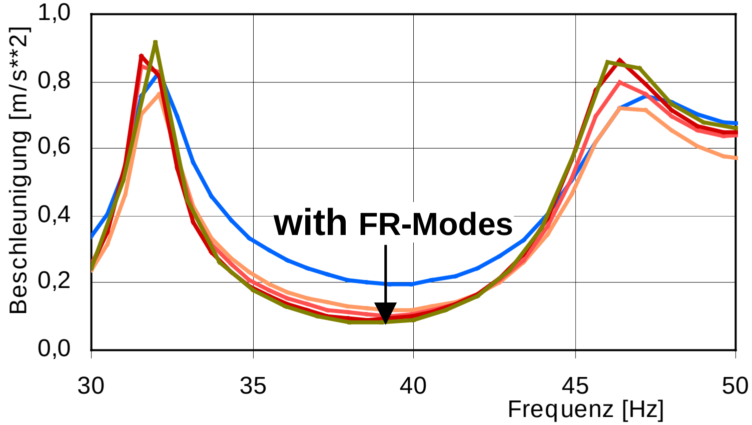
Linear Response Analysis

Veritical Acceleration at Rear Muffler Front Mount due to **Force Excitation** in Phase at Engine Mounts

- Without FR-Modes
- 5 FR-Modes up to 500Hz
- 11 FR-Modes up to 1000Hz
- 15 FR-Modes up to 1800Hz
- FEM



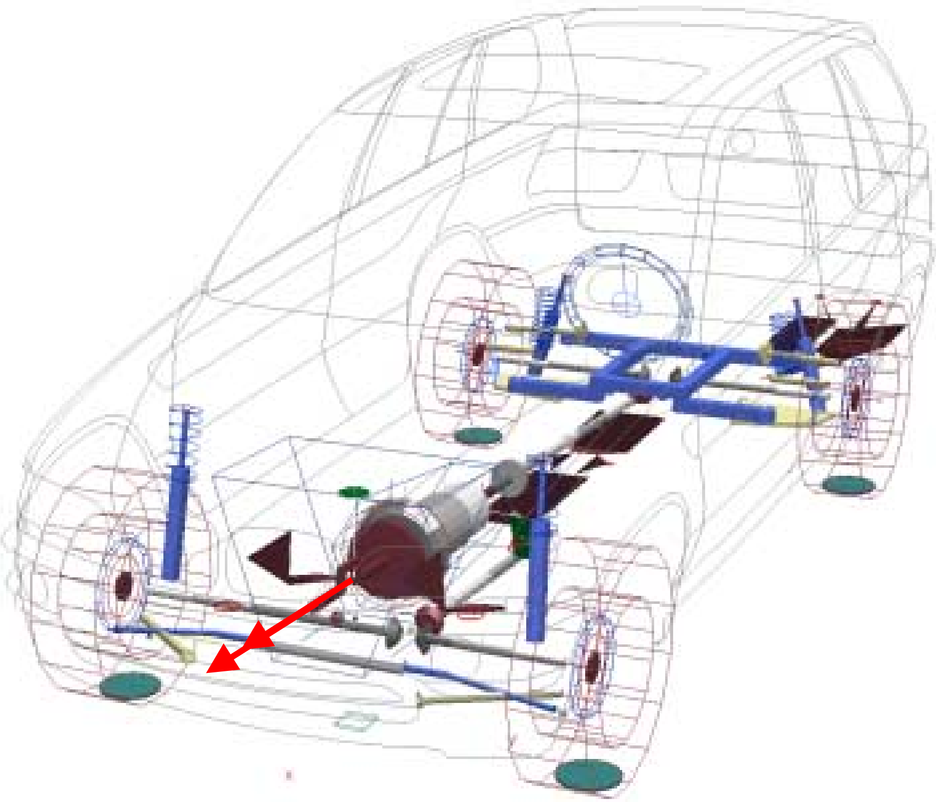
Improvement of Resonant Frequency



Improvement of Amplitude

MBS Full Vehicle Model

Principle Analysis of Engine Idling Comfort



Full Vehicle Model for Ride Analysis

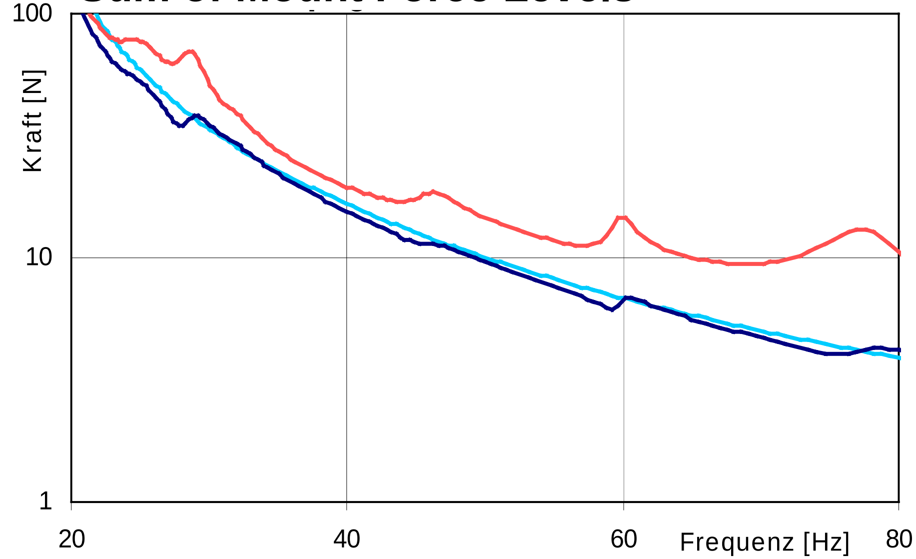
- Chassis	**84 Bodies**
- Drive Train	**110 Joint DoF**
- Engine Mounting System	**38 Constraints**
- Exhaust System	**67 Additional ODE**

Linear Response Analysis

Mount Forces (Engine, Gearbox, Exhaust) due to **Excitation** by Alternating Torque 30Nm, 20-80Hz about the Engine Longitudinal Axis

- Engine-/Gearbox (Model without Exhaust)
- Engine-/Gearbox (Model with Exhaust)
- Engine-/Gearbox and Muffler Mounts

Sum of Mount Force Levels



Summary

- The **Advantages** of the **Dynamic Reduction** are
  - Simplification of the FEM-reduction and
  - Accurate Modelling independent of the number of master nodes

- The generation of a flexible body with ‚**too few Master Nodes**‘ results in incorrect frequency responses in the coupled MBS.

  Possible cause
  - FEM-model reduction in **Constrained Condition** leads to inaccurate **Mass Distribution**

- Possible improvements from INTEC
  - Implement the dynamic reduction in **FEMBS**
  - Investigate the problems of ‚**too few Master Nodes‘**