Advanced testing and simulation techniques in Ride and Handling body deformation

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Agenda

1. Introduction to bodyflex methodology
2. Theoretical background
3. Typical project overview
4. Application cases
5. Conclusions & Outlooks

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1

Introduction to Bodyflex methodology

Introduction

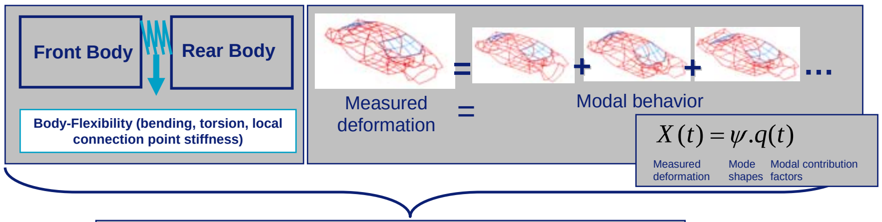
LMS Engineering has developed a test based process to support the understanding of the body flexibility on the ride & handling performance

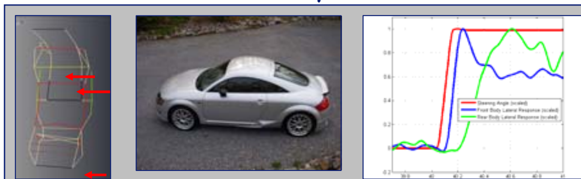
Today many automotive constructors are looking for ways to differentiate their vehicles with respect to competition and **create a brand image**. Functional performance engineering has therefore become even more important and the focus has shifted from individual performance engineering towards **multi-attribute engineering**. The impact of the body design in NVH has always been easy to understand. For ride & handling however it is much more difficult to engineer the body towards a better performance.

LMS engineering has therefore developed a technology that allows to **decompose specific targets for ride & handling into body flexibility contributions** which are typically represented by body modes. For impact harshness this comes down to a decomposition in frequency domain of the total vibration response into body modal contributions. For handling maneuvers the body decomposition is done in time domain and allows a **real time visualization of the body deformation** while performing the maneuvers, allowing to make clear relations between subjective feeling and objective measures and to set clear targets for the body component. In both ride & handling performance, state of the art measurement (e.g. strain gauges) and processing (e.g. body modal analysis including global modes and local modes) technologies are used.

Background

- ***Body flexibility influences the body force-distribution and therefore the vehicle dynamics****.*
  However, ***this influence is difficult to quantify using standard measurement technology***
- *Using a* ***strain-data based technology*** *the time-domain body forces as well as the body deformations can be identified, which allows a thorough analysis of the effect of the body-flexibility on the ride and handling performances.*



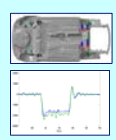


Body Flexibility impacts the Body Force Distribution & Vehicle Dynamics

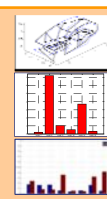
Goals for body-flexibility projects

- Goal 1: advanced handling parameter identification
  - Detail vehicle information additional to yaw-rate, lateral acceleration, etc
  - Based on operational strain (suspension links) or based on forces

- Goal 2: time-domain force-identification
  - Force-distribution in operational condition (on suspension links or body)
  - Time-domain force validation for MBS-models



- Goal 3: body-deformation identification
  - Visualization of body-deformation during a maneuver
  - Decomposition into mode contributions (torsion / bending)
  - Weak-point identification (global or local body stiffness)
  - Identify the relation of the body-flexibility to the handling performance



Effect of Body flexibility on R&H
Some References

Advanced testing and simulation techniques in handling body deformation Paper # IMECE2008-67408

Kouichi Miyagawa, Yoshiyuki Maruyama, Masataka Nasada
Daihatsu Motor Co., Ltd., Ikeda, Japan
Giancarlo Conti, Paolo di Carlo, Valerio Cibrario
LMS Italiana, Torino, Italy

Improving the vehicle dynamic performance by optimizing the body characteristics using body deformation analysis
Chassis Tech Conference Munich 2010, LMS Theo Geluk, J. Van Herbruggen G. Conti,
Hyundai J.H. Park, J.S. Jo,

Analysis of the Contribution of Body Flexibility to Handling and Ride Comfort Performances

20090529 JSAE Society Automotive Engineers of Japan
Masafumi Kyuse - Kohei Umehara - Honda R&D Co. LTD
Rabah Hadjit - Theo Geluk - Peter Mas – LMS International

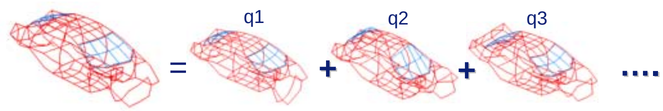
Body load identification and weak spot analysis to evaluate different body concepts for better balancing of vehicle dynamics and NVH

February 2009 Chassis.tech Munich
AUDI - Dr. E. Plank, A. Guellec
LMS - P.Mas, T.Geluk

2 Theoretical background

Contribution of Body Flexibility to Handling and Ride Comfort Performances

- **Purpose: Analyze the contribution of each flexible mode of the body to the total deformation during handling maneuver (time domain contribution) or ride comfort (frequency domain contribution).**



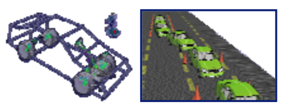
Total deformation   Modal behavior

Total deformation → X; Mode shapes → ψ; Modal contribution factors → q

$$\underset{nx1}{X} = \underset{nxm}{\psi} . \underset{mx1}{q}$$

n = number of responses
m = number of modes

Handling



$$X(t) = \psi . q(t)$$

$$X(\omega) = \psi . q(\omega)$$

Solving *q(t)* or *q(ω)* Direct matrix inversion

- <u>**Direct matrix inversion method:**</u>

Time domain	$q(t) = \psi^{-1}.X(t)$
Frequency domain	$q(\omega) = \psi^{-1}.X(\omega)$

Modal model → ψ^{-1}; Operational measurement → $X(\omega)$

- **Requirements:**
  - The responses x(t) can be accelerometers or strain gauge responses:
    - In <u>handling</u> maneuvers the signals are very low frequency, <u>strain gauges</u> need to be used
    - For <u>ride comfort</u> <u>accelerometers</u> can be used
  - Overdetermination of 4 if accelerometers to 8 for strain gauges

Solving *q(t)* or *q(ω)*
Modal forced response

- **Modal forced response:**
  - General equation of motion

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)=F(t) \qquad \text{(matrix equation)}$$

  - Through transformation to modal domain using $x(t)=\psi.q(t)$

$$\Rightarrow \lceil m_\rfloor \ddot{q}(t)+\lceil c_\rfloor \dot{q}(t)+\lceil k_\rfloor q(t)=f(t) \qquad \text{(set of uncoupled equations)}$$

for a system with proportional damping

Solve for each mode shape to obtain $q(t)$ →

Time domain

$$m_r\ddot{q}_r(t)+c_r\dot{q}_r(t)+k_rq_r(t)=f_r(t)$$

Frequency domain

$$-m_r\omega^2Q_r(\omega)+j\omega c_rQ_r(\omega)+k_rQ_r(\omega)=F_r(\omega)$$

$r=1..m$

m = number of mode shapes

m_r = modal mass mode r

c_r = modal damping mode r

k_r = modal stiffness mode r

$f_r=\psi_r^{\,T}F(t)$ = modal force

Required input data

Solving *q(t)* or *q(w)*
Modal forced response

- **Modal forced response:**
  - The external forces are required, and can be obtained from matrix inversion:

Frequency domain: $F_{oper}(\omega)=H(\omega)_{FRF}{}^{-1}.X_{oper}(\omega)$ — Frequency domain forces through inversion and matrix multiplication

Time domain: $F_{oper}(t)=h^{-1}(t)_{impulsresponse}\otimes X_{oper}(t)$ — Time domain forces through inversion, iFFT and convolution

Is obtained through inversion of FRF matrix and inverse FFT:

$$h^{-1}(t)_{impulsresponse}=iFFT(H(\omega)_{FRF}{}^{-1})$$

Comparison of methods: advantages / disadvantages

	Direct matrix inversion $q(t) = \psi^{-1}.X(t)$	Modal forced response $m_r\ddot{q}_r(t) + c_r\dot{q}_r(t) + k_r q_r(t) = f_r(t)$
ADVANTAGES	• Easy mathematics • No body load needed	• Extra information: effect of body loads on modal contribution • Modal contribution not dependent on number of modes shapes • Lower overdermination needed of strain gauges for force identification (2 is enough) • No strain needed in modal matrix

DISADVANTAGES	• Impractical for strain gauges:
	  • Modal matrix should contain strain
	  • Overdetermination for strain gauges very high
	  • Location of strain gauges very critical (points of maximum modal strain needed)
	• Impractical for accelerometers
	  • Acceleration signal saturated with rigid body behavior
	  • Quality of modal contribution factors dependent on number of mode shapes
		• Solve differential equation for time domain
		• Body load needed
		• Quality of modal contribution factors is dependent on force estimation quality

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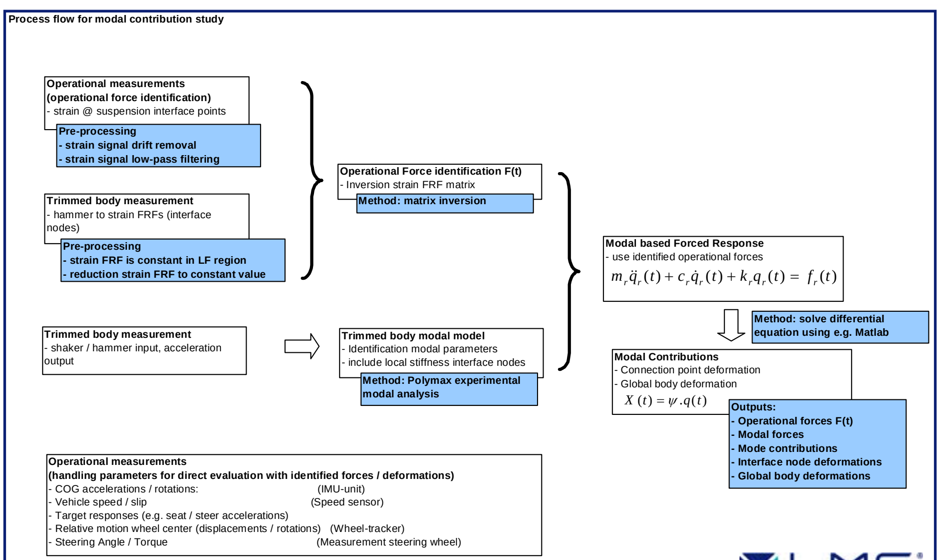
Overview body flexibility process



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Body Modal Contribution Analysis for Ride comfort

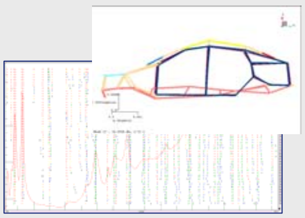
STEP1 - operational measurements

Cleat at chassis dyno

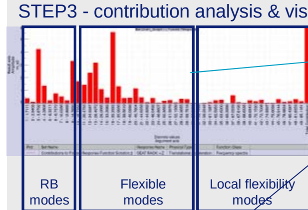
Operational response

Modal contribution at selected frequency

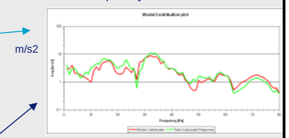
STEP2 - body modal measurements



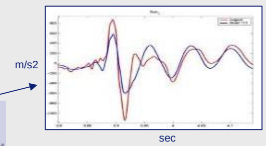
STEP3 - contribution analysis & visualization



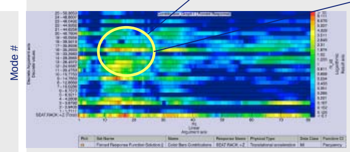
Frequency domain contribution



Time domain contribution



Modal contribution at all frequencies



$a(\omega) = \sum \varphi(\omega) q(\omega)$

→ Modal response

→ Modal excitation (identified by matrix inversion)

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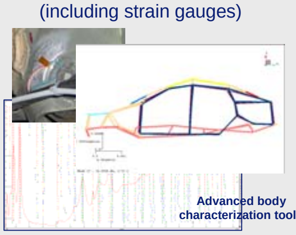
Body Modal Contribution Analysis for Handling

STEP1 - operational measurements (including strain gauges)

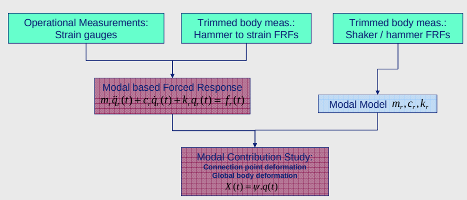
High performance portable system for R&H system

STEP2 - body modal measurements (including strain gauges)

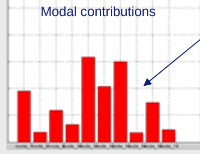


Advanced body characterization tools

STEP3 - contribution analysis & visualization



Modal contributions



Real time visualization of body flexibility

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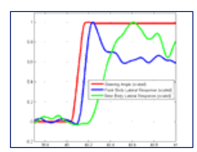
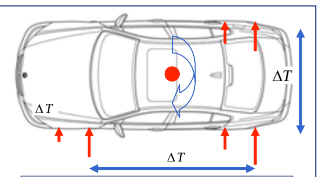
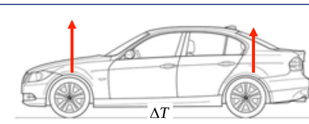
3 Typical project overview

Advanced handling parameter identification



- Standard handling parameters:
  - Mostly defined in the vehicle-COG:
    - → describing the *combined effect* of all forces acting on the vehicle
    - → global parameters
- Additional handling parameters: based on strain-signals / body-forces
  - Parameters for local vehicle responses (front, rear, left, right) in different directions
  - Provide additional insight in vehicle behavior – parameters can also be used as extra input for a subjective – objective correlation



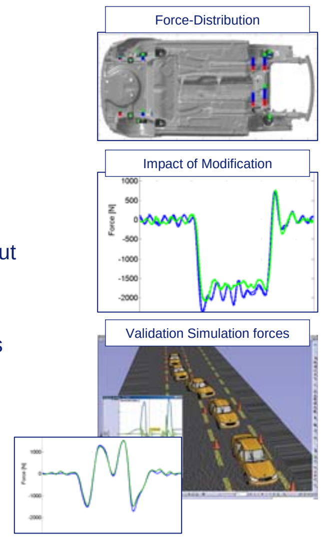


mobile system LMS Test.Lab

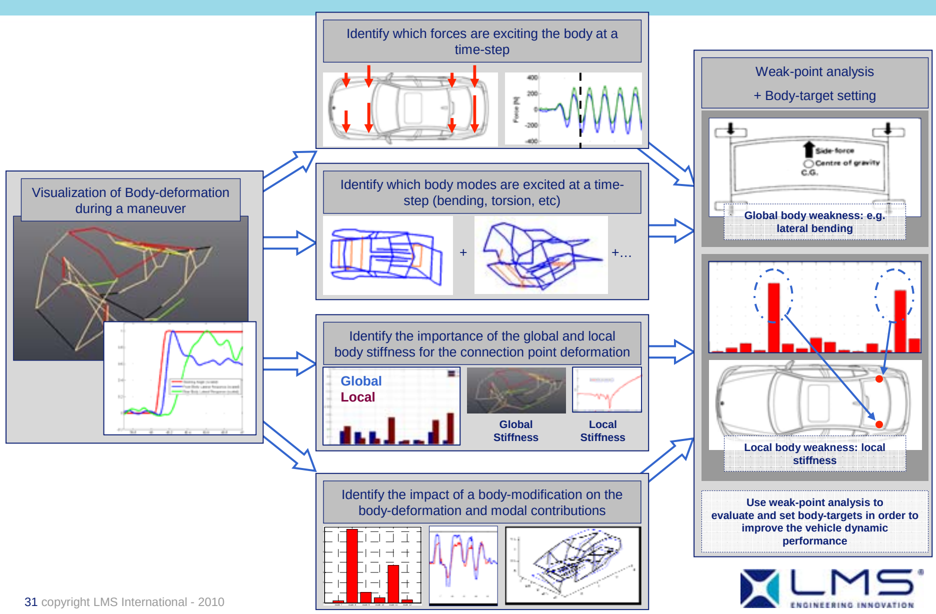
When Body-Forces are used: these parameters can be used to evaluate the impact of **body-modifications** on the vehicle dynamic behavior

Time-domain force identification

- Force-distribution at any time during the maneuver
  - Is distribution as expected – desirable?
  - Identify input nodes with highest force-levels
- Impact of a body-modification on the force-distribution
  - Change in force-amplitude
  - Change in force-phase (time-delay) to the applied input
- Validation of MBS-model
  - Validate simulation results with estimated body-forces



Body-deformation identification



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Application cases

Examples from:
- **Ride-comfort Audi**
- **Handling Hyundai**

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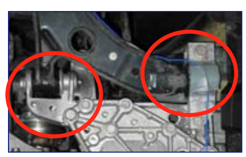
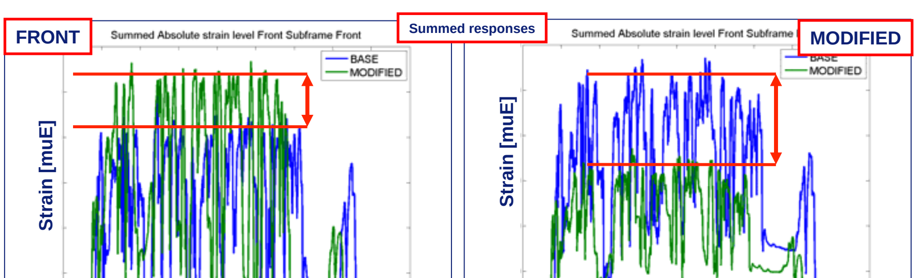
Operational results
Comparison Base Vehicle VS Modified Vehicle

- **Steering-Handling Track**
  - Comparison summed operational strain:
    - Front subframe front connection
    - Front subframe rear connection



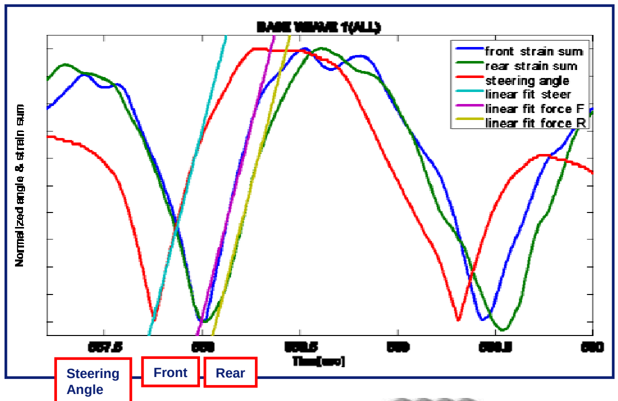


Front subframe shows a high influence due to the body modification. At the front connection the total strain level increases, while at the rear a large decrease in the summed operational strain results from the modification

Audi LMS ENGINEERING INNOVATION

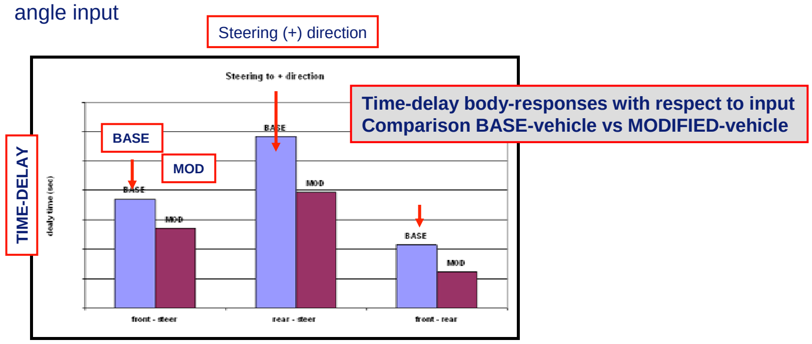
Operational results
Comparison Base Vehicle VS Modified Vehicle

- **WEAVE-test**
  - Comparison BASE-vehicle VS Modified-vehicle
  - Evaluation of response timing during weave-test
  - Response time-delay of summed front and rear strain with respect to steering-angle input



Operational results
Comparison Base Vehicle VS Modified Vehicle

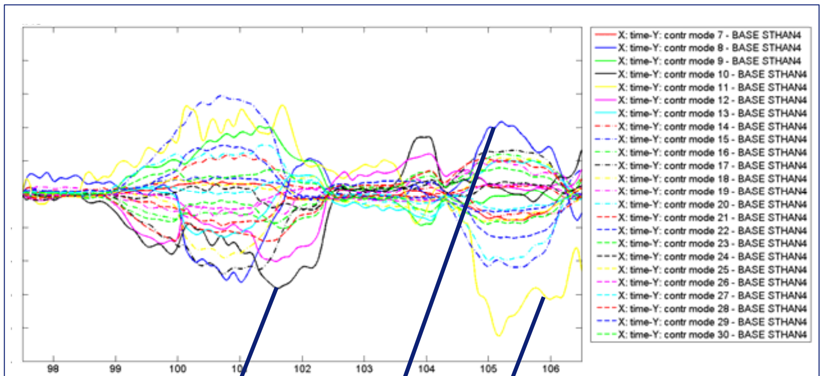
- **WEAVE-test**
  - Comparison BASE-vehicle VS Modified-vehicle
  - Evaluation shows the averaged result of multiple periods and multiple runs
  - Response time-delay of summed front and rear strain with respect to steering-angle input



All time-delays are decreased for the modified body, indicating an increased responsiveness

Time domain forces – Modal Contributions

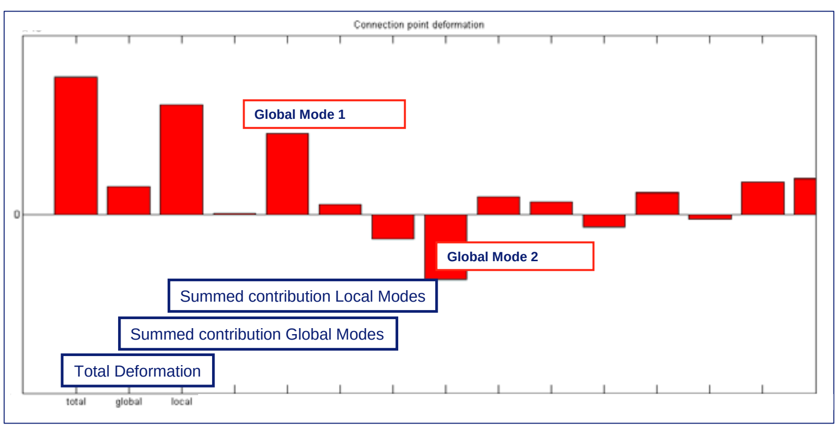
- **BASE-vehicle modal contributions – Global Modes**



Global Mode 1 **Global Mode 2** **Global Mode 3**

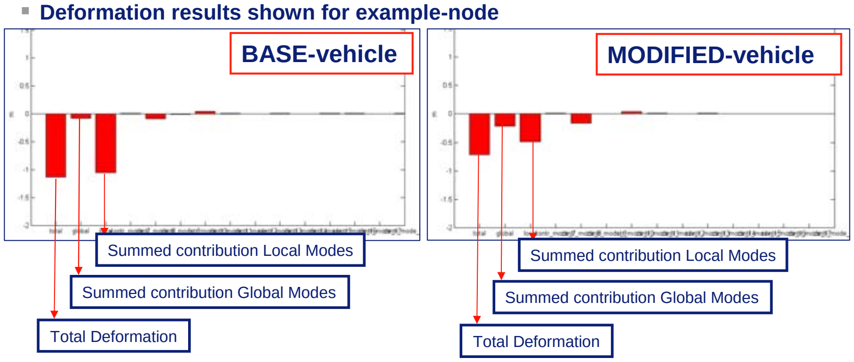
Time domain forces – Modal Contributions

- **Is body-deformation resulting from global modes or local modes?**



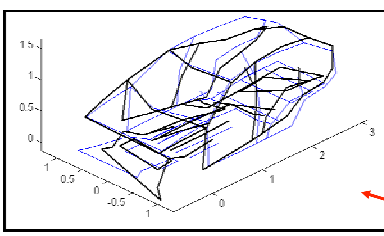
Time domain forces – Modal Contributions

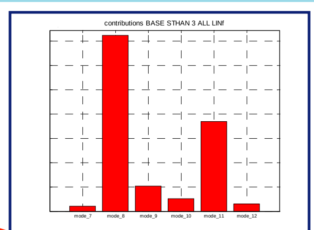
- **Is body-deformation resulting from global modes or local modes?**
- **Deformation results shown for example-node**



Effects of body-modification:
→ Reduction of total deformation amplitude
→ Reduction contribution of local flexibility to the deformation

Time domain forces – Body Deformation – Example Results (Base vehicle)



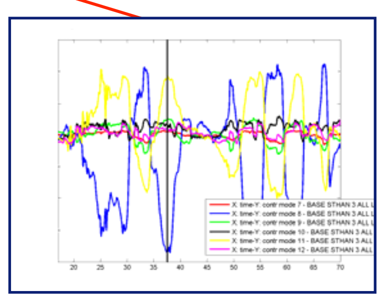


Body deformation at indicated time

Deformation calculation performed with a selection of modes: 25 global modes. No residual vectors (local stiffness) are taken into account

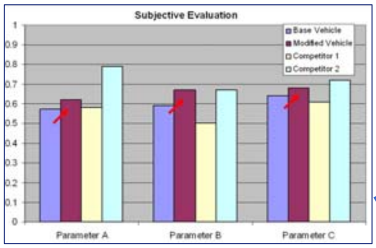
Using all visualization options a clear overview is obtained

- What are the most contributing modes
- How is the contribution of mode '1' with respect to the contribution of mode '2', e.g. opposite phase
- Which points have the largest deformation levels
- How does the total body-deformation look like when a selected set of global modes is included in the calculation



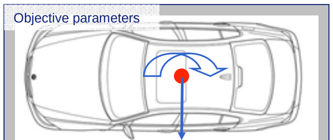
Handling vs BodyFlexibility parameters

- The subjective evaluation of Base and Modified vehicle has shown significant differences as an effect of the applied body-modifications



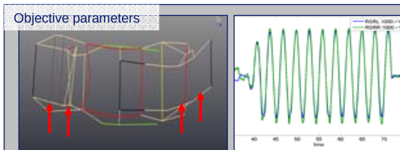
Evaluate effect of the applied body-modifications using the measured objective parameters
- Amplitude (peak-to-peak, RMS, …)
- Phase (time-delays)

Objective parameters



Lateral Acceleration, Yaw-rate, Slip-angle, …

Objective parameters

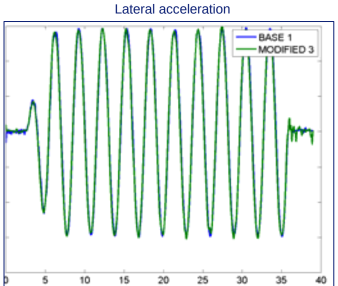


Suspension-to-Body interface forces

Handling vs BodyFlexibility parameters
Handling parameters

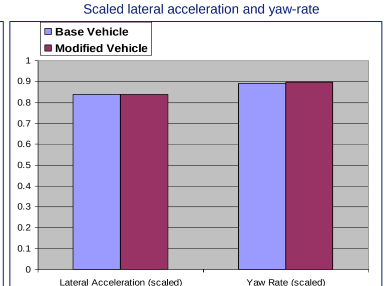
- Lateral acceleration and Yaw-rate in Weave-test

Lateral acceleration



Time-trace comparison Base vs Modified vehicle

Scaled lateral acceleration and yaw-rate

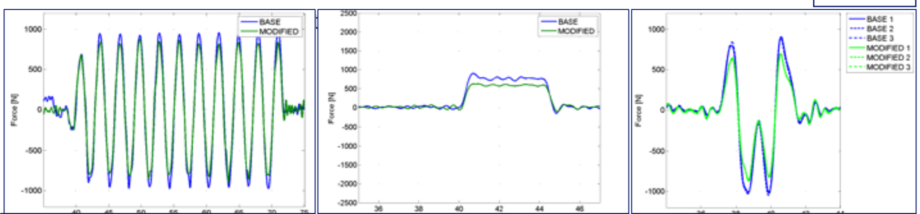


Amplitude comparison Base vs Modified vehicle

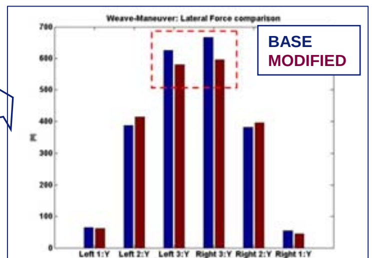
The differences (amplitude or time-delays) that are found in handling parameters are small and mostly close to measurement repeatability

→ This data is difficult to use to evaluate the impact of applied body-modifications

Handling vs BodyFlexibility parameters
Body-force parameters



Body-force in Weave-test | Body-force in Step-Steer | Body-force in ISO Lane Change



RMS-values of 6 body-forces in Weave-test

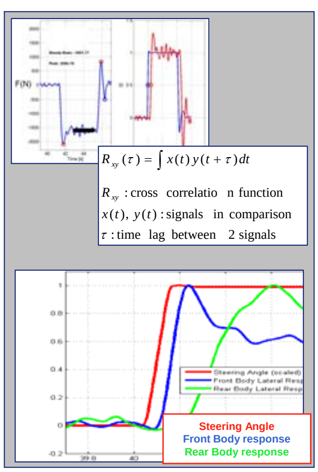
Significant differences in identified body-force amplitudes in <u>all</u> maneuvers that are evaluated.

Differences between body-forces >> measurement variation.

These results enable a direct evaluation of the impact of an applied body-modification

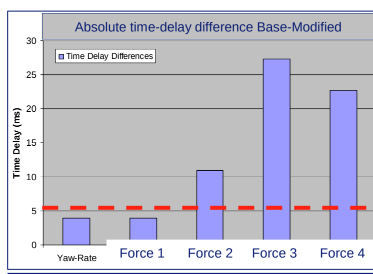
Handling vs BodyFlexibility parameters
Body-force parameters

- Identification of the time-delays with respect to the steering-input is done by using cross-correlation for the weave-test and ISO Lane Change and the 50% steady-state value for the Step Steer maneuver



$$R_{xy}(\tau) = \int x(t)\,y(t+\tau)\,dt$$

R_{xy} : cross correlation function
$x(t),\ y(t)$: signals in comparison
τ : time lag between 2 signals



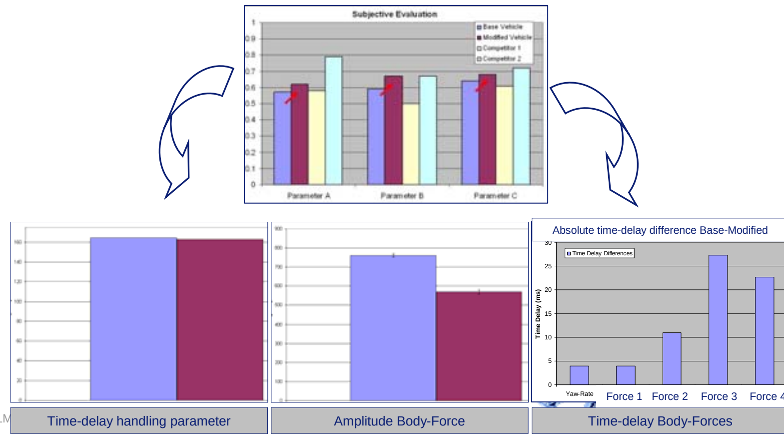
Threshold measurement repeatability (~5ms variation)

Time-delay evaluation of the Base and Modified vehicle shows significant changes in body-force responses, indicating a *<u>quicker</u>* or more *<u>delayed</u>* force-build-up on different suspension-to-body interface nodes

As with the amplitude evaluation, these results enable a direct evaluation of the impact of an applied body-modification

Handling vs BodyFlexibility parameters
Body-force parameters

- Subjectively, differences are identified between Base & Modified vehicle
  - Parameters as lateral acceleration, yaw-rate, etc show minimal variations, mostly close to measurement variations.
  - Body-force parameters show significant changes, both in amplitude and time-delay, as an effect of the applied body-modifications



5 Conclusions & Outlooks

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Conclusions

- **The presented methodology allows to:**
  - Estimate the time-domain forces during a handling maneuver
  - Analyze the body-deformation during a handling maneuver
  - Analyze the modal contributions to the deformation
- ***Bodyflex methodology* confirms body structure has a large effect both on ride AND handling performances**
- **Strain-gauge approach allows to have objective evidence of the subjective driver perception**
- **A SW tool has been developed to post-process RT the operational measurements vs the main modal contribution factors**

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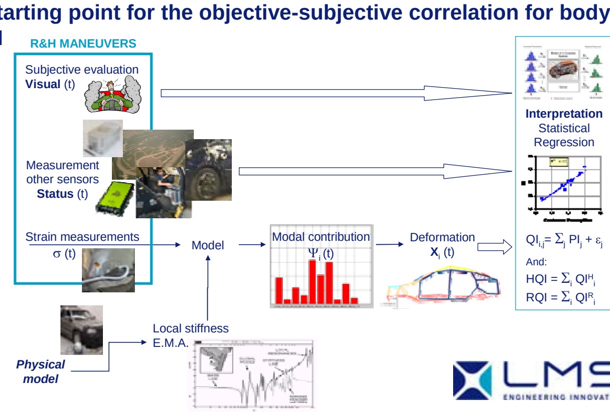
Outlooks

- **General conclusions (still TBC)**
  - Front body modes are mainly effected by local deformations (point mobilities)
  - Rear body modes are mainly effected by global rear end deformations
- Strain-gauge approach allows to have objective evidence of the subjective driver perception…
  …which represent the **starting point for the objective-subjective correlation for body structure effect in R&H**



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Thank you !