

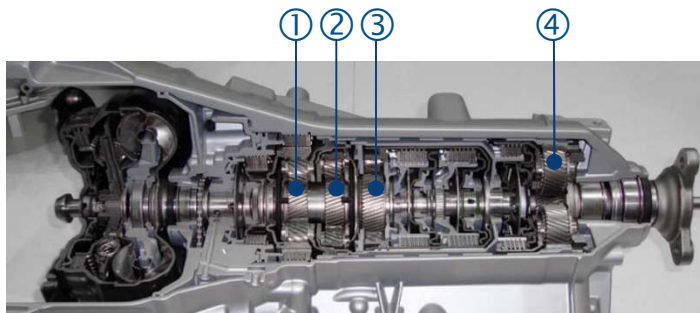


**3DEXPERIENCE®**

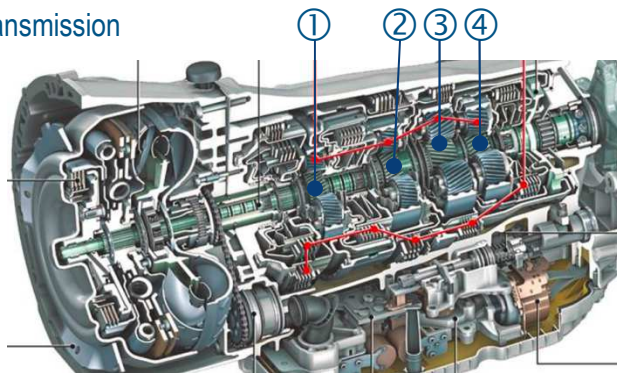
# Planetary Gear System

Gear Whine (Transmission/Differential)

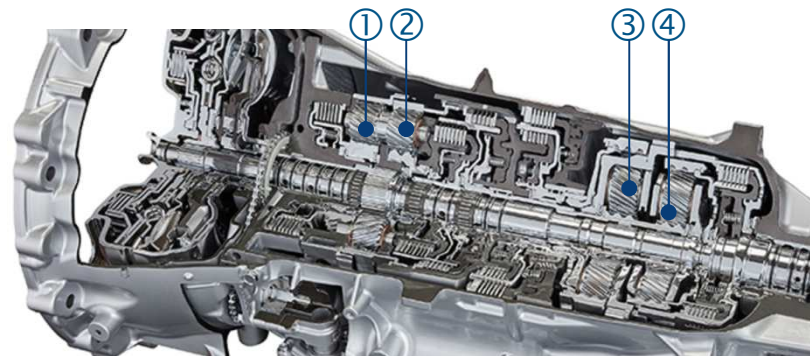
# Planetary Gear Sets in Automatic Transmissions



ZF – 8 speed – Automatic Transmission  
with 4 planetary gear sets

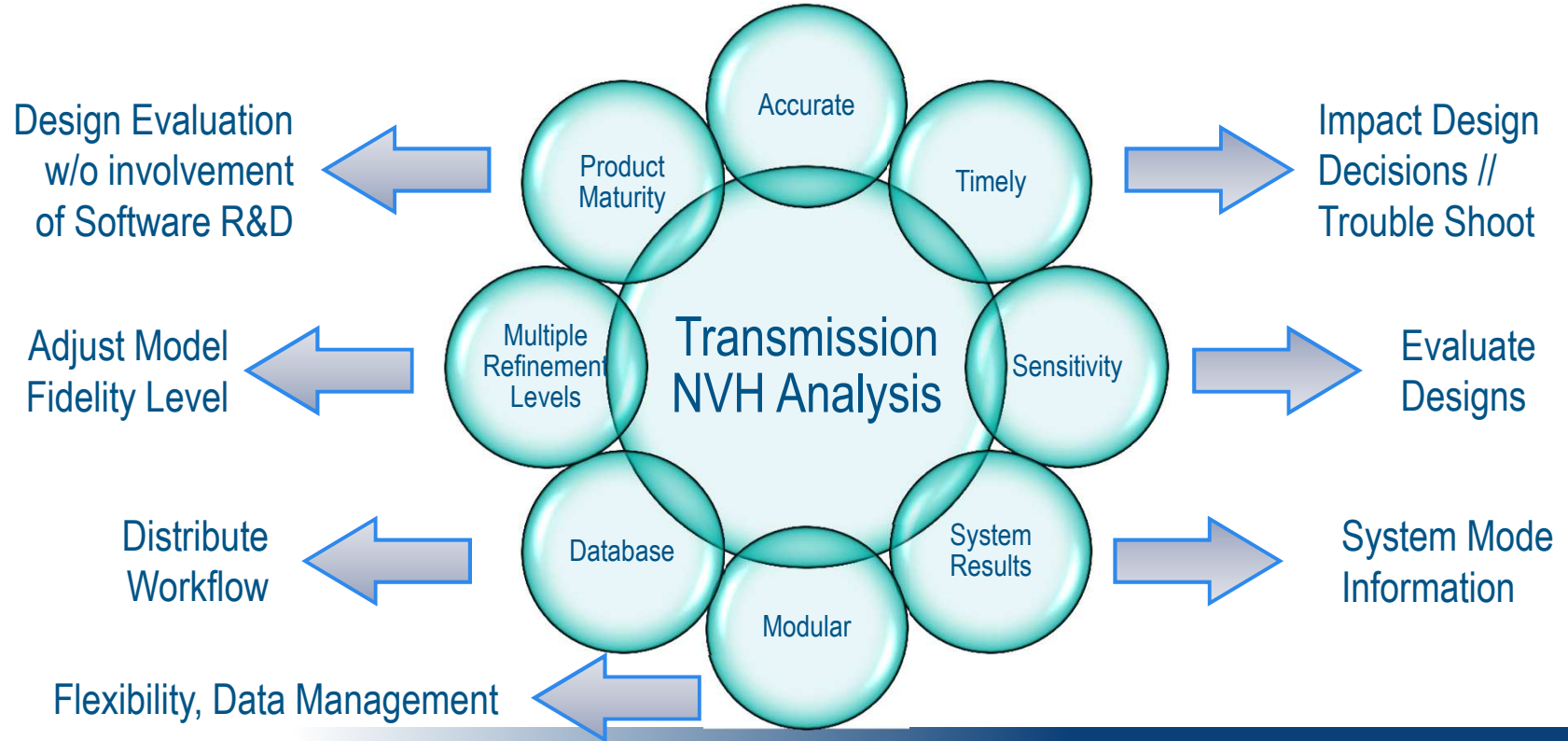


Mercedes – 9 speed – Automatic Transmission  
with 4 planetary gear sets



Toyota – 10 speed – Automatic Transmission  
with 4 planetary gear sets

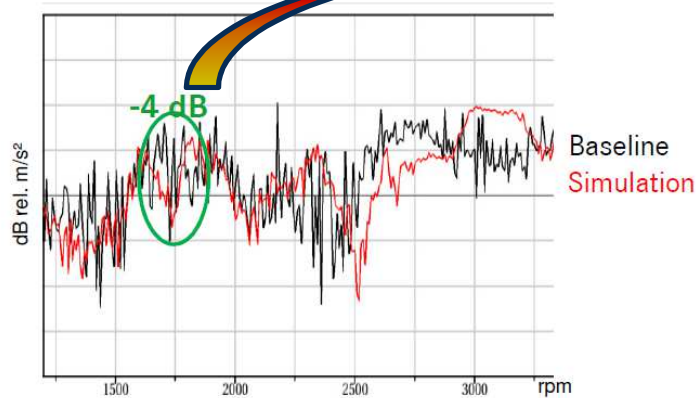
# Demands on System Analysis Tool



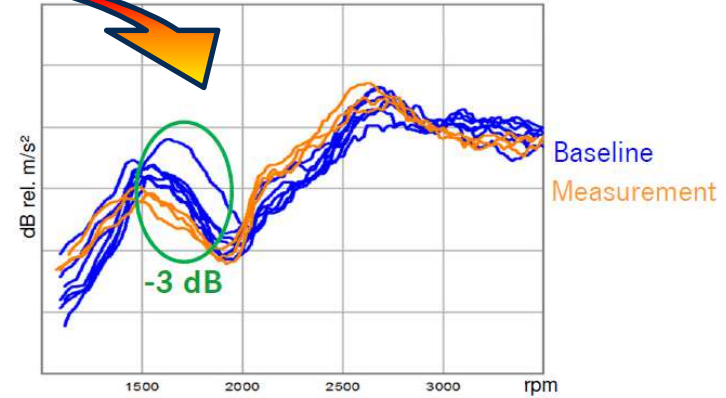
# Gear Whine Analysis at Mercedes-Benz

SIMPACK User Conference in Augsburg, October 2014

Result MBS-Simulation



Result End-of-line Testrig



By using a system level approach, the SIMPACK customer was able to isolate the influencing factor of the gear whine problem in a specific speed range. The SIMPACK model was able to provide a design solution to reduce the impact of gear whine.

# Gear Whine Example using SIMPACK

## SIMPACK User Conference 2014: Mercedes-Benz



### Simulation Methods for NVH-Development of a Double Clutch Transmission Gearbox

SIMPACK User Meeting 2014

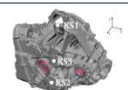


Alexander Neubauer  
Mercedes-Benz Cars Development  
Daimler AG, Stuttgart

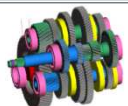


### 2.1 Methodology for NVH-Simulation of DCT Gearbox

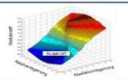
#### SIMPACK- Pre



- flexible gearbox housing
- modal materialdamping
- external nodes for evaluation of structure borne sound
- rigid body elements for gearshaft mounting

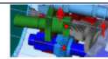


- flexible gearshafts
- switchable gears
- bearings with 6 DOF
- synchrodes as dummy bodies
- rigid gearwheels with detailed macro- and microgeometry
- gearwheels with material data
- analytical gearpair contact simulation (ISO 6336)

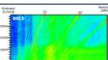


- Taper roller bearings with stiffness in 3D-Map from the supplier (BEARINX-MAP)
- bearing properties from KISS-SOFT interface (input from CAD)

#### SIMPACK-Post



- transmission error
- eigenfrequency analysis
- Detailed analysis of mechanism
- correlation with end-of-line testrig measurements
- Evaluation of accelerations on defined housing locations
- detailed analysis of gearorders



- Campbell plots for gear rattling and whining
- 3D-map to describe rattling sensitivity of a gearbox for a switched gear
- Creation of targets for structure borne sound level on defined housing locations
- Operational mode shape analysis of the gearbox housing (excitation at bearing locations with constant velocity)

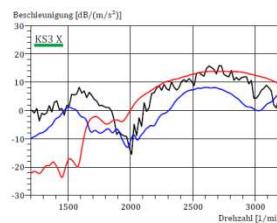
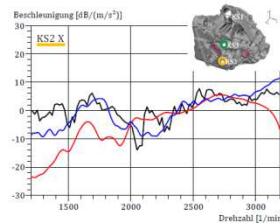
Alexander Neubauer | Daimler AG | 09 October 2014

5

Mercedes-Benz

### 3.3 Correlation End-of-line to Simulation

#### DCT coast 2nd gear order



- Measurement end of line (EOL)
- Model with nonlinear bearing stiffness (FE43)
- Model with 3D-Map (BEARINX)

good correlation between measured housing structure borne sound level in the gear order at the end of line (EOL) testrig and in MBS-simulation

Alexander Neubauer | Daimler AG | 09 October 2014

10

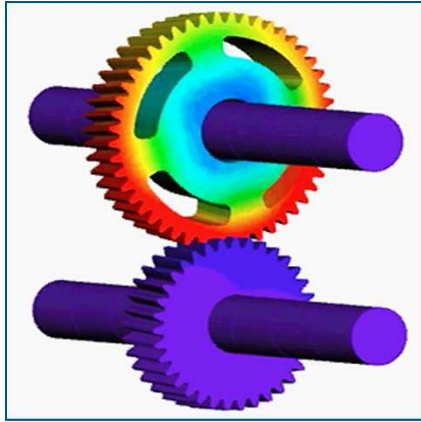
Mercedes-Benz

[http://www.simpack.com/fileadmin/simpack/doc/usermeeting14/Day\\_2\\_Room-1/04\\_UM14\\_Daimler\\_Neubauer\\_Simu-NVH-Develop-Double-Clutch-Trans-Gearbox.pdf](http://www.simpack.com/fileadmin/simpack/doc/usermeeting14/Day_2_Room-1/04_UM14_Daimler_Neubauer_Simu-NVH-Develop-Double-Clutch-Trans-Gearbox.pdf)

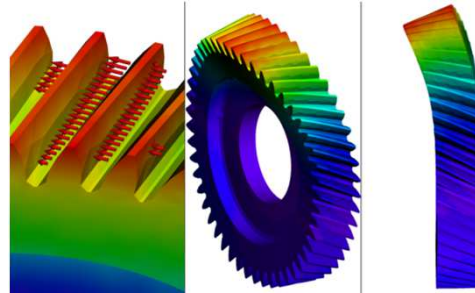
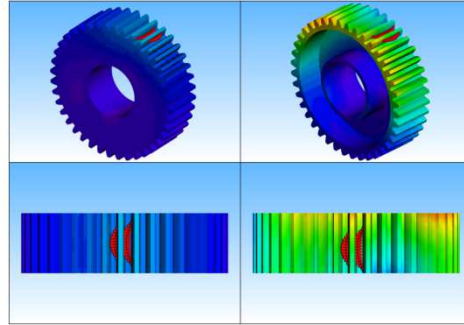
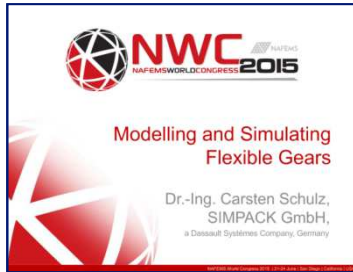
[www.simpack.com](http://www.simpack.com) → Downloads → User Meeting Presentations → Drivetrain →



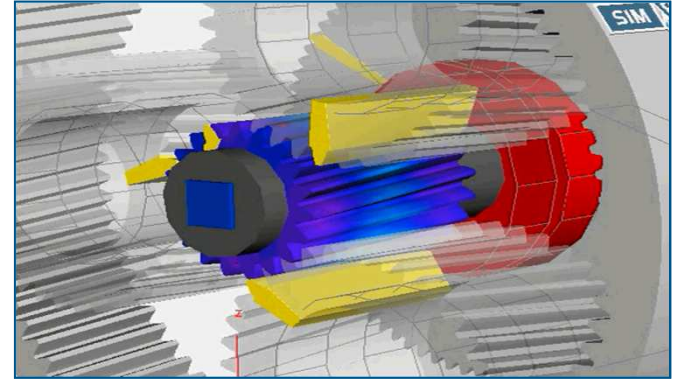
# Flexible Gears under Dynamic Loading Conditions



Non-standard gear design



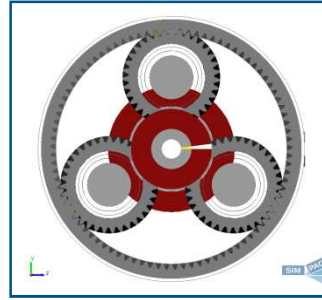
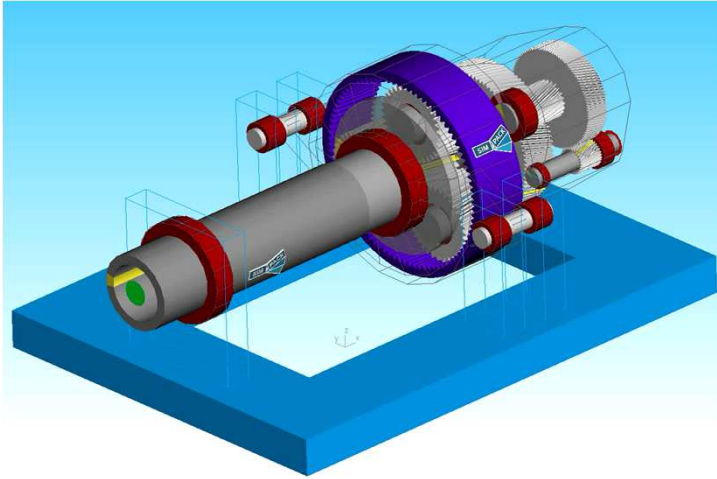
load and geometry dependent deformation



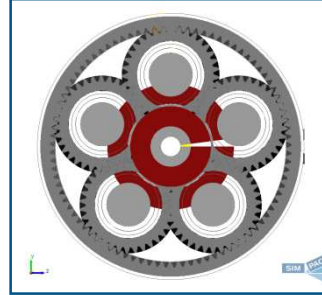
load distribution along the flank width

... by utilizing the Craig Bampton Method for linearizing FE models

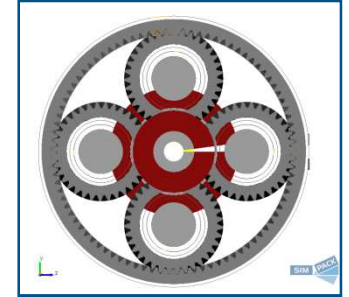
# Simpack System Model: Wind Turbine Gear Box



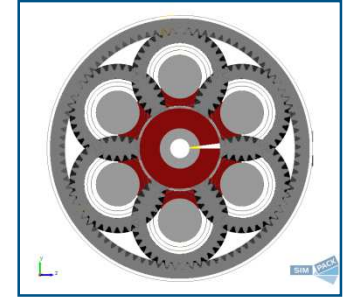
3 planets



5 planets



4 planets



6 planets

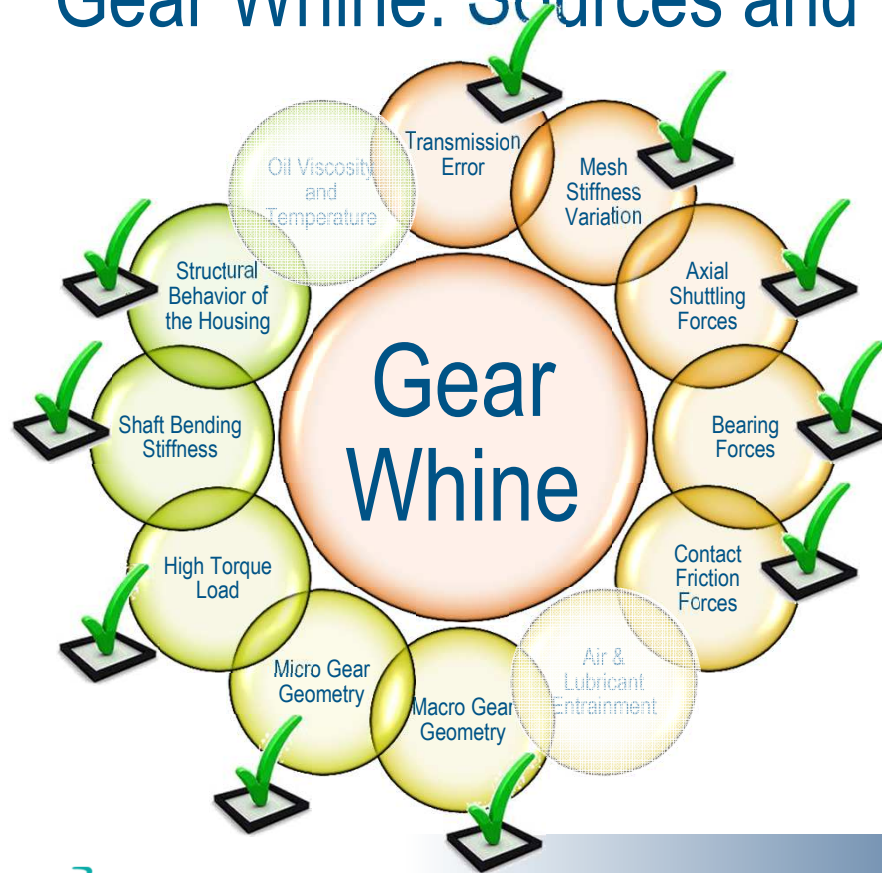
# Gear Whine: Sources and Factors



Sources and factors described in the literature that influence and impact gear whine

The complexity of this noise phenomena requires a system level view to capture all the different aspects and coupled effects of the mechanical system

# Gear Whine: Sources and Factors



**SIMPACK** covers the physics of all these factors described in the literature for sources that can cause gear whine and factors that influence gear whine.

# Gear Whine Evaluation

## Planetary Gear Set Configurations

### ► Number of Teeth

▷ Ring Gear = 89

▷ Sun = 19

▷ Planet = 35

### ► Gear Design: helical

### ► Load Case:

▷ constant speed (1,000 rpm @ sun)

▷ constant load (50 kN @ carrier)

### ► Number of planets: 3, 4, 6

► Focus of the results is on the **ring gear support** (forces and moments), as this is the main transfer path of the planetary gear set to the outside

► Expected main order content at ring gear support

▷ 3 planets: 90 (and multiples of 3)

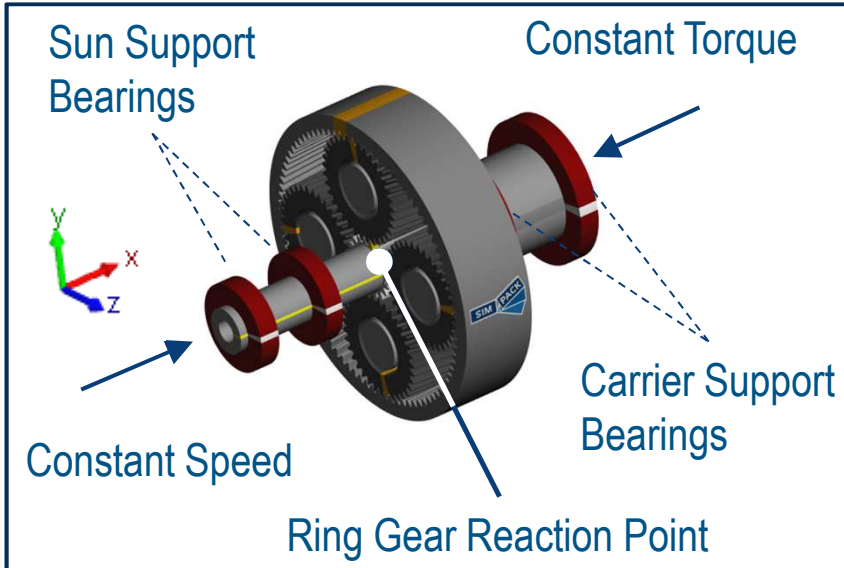
▷ 4 planets: 88 (and multiples of 4)

▷ 6 planets: 90 (and multiples of 6)

# Analysis Setup and Output

## Duration and Signal Characteristic

- ▶ 110 rev's of the sun, torque ramp-up
- ▶ 20 kHz signal for sufficient FFT



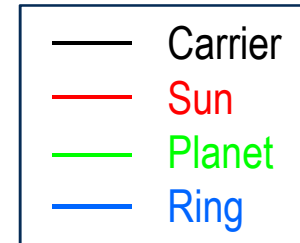
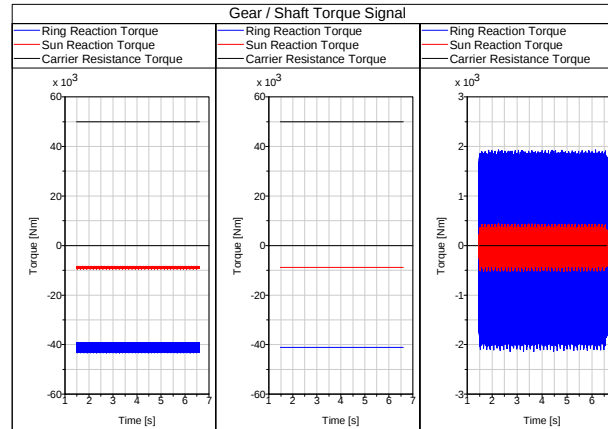
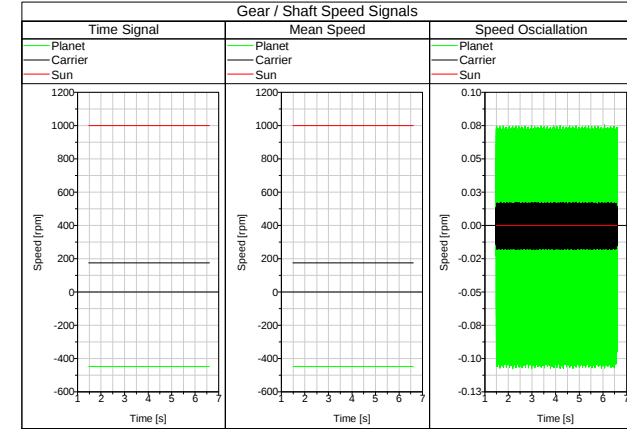
## Result Output (selection)

- ▶ Speed and torque signals
- ▶ Gear contact forces (animations)
- ▶ Order content at ring gear reaction point
  - ▷ Forces in x-, y- and z-direction
  - ▷ Moments in x-, y- and z-direction
- ▶ System mode evaluation using ODS



# Result Examples for 3 Planets – Speed & Torque

- ▶ 3 Planets
- ▶ Nominal
  - ▷ Ring Eccentricity = 0.0 mm
  - ▷ Carrier Eccentricity = 0.0 mm
  - ▷ Titling Angle =  $0.0^\circ$
- ▶ Rigid ring gear



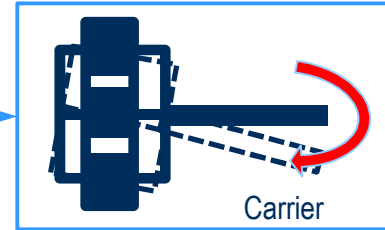
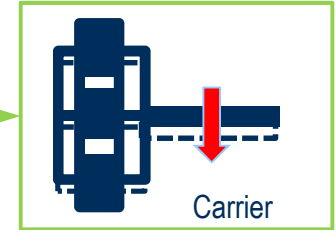
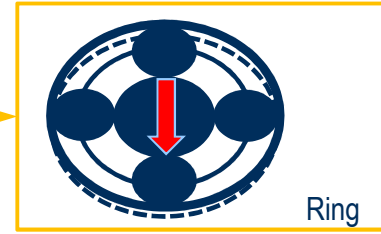
# Result Comparison of the 3 Configurations

| Nominal Conditions                      | 3 planets                 | 4 planets                 | 6 planets                 |
|-----------------------------------------|---------------------------|---------------------------|---------------------------|
| Carrier speed oscill. amp. [rpm]        | +0.075 / -0.107           | +0.089 / -0.092           | +0.098 / -0.061           |
| Ring torque oscill. amp. [kNm]          | +1.9 / -2.1               | +1.2 / -1.1               | +0.3 / -0.3               |
| areas of concern under 1,200 Hz [Hz]    | 264, 519, 783, 1045       | 258, ..., 784, 1044       | 264                       |
| areas of concern under 1,200 Hz [order] | 90, 177, 267, 357         | 88, ..., 268, 356         | 90                        |
| Planet bearing force [kN]               | 1.5 [35 <sup>th</sup> ]   | 1.0 [35 <sup>th</sup> ]   | 0.7 [35 <sup>th</sup> ]   |
| Carrier bearing force [kN]              | 0.17 [90 <sup>th</sup> ]  | 0.40 [88 <sup>th</sup> ]  | 0.12 [90 <sup>th</sup> ]  |
| Ring reaction force [kN] – radial       | 1.0 [177 <sup>th</sup> ]  | 3.0 [268 <sup>th</sup> ]  | 1.3 [90 <sup>th</sup> ]   |
| Ring reaction force [kN] – axial        | 0.24 [267 <sup>th</sup> ] | 0.07 [356 <sup>th</sup> ] | 0.02 [2.5 <sup>th</sup> ] |
| Ring reaction moment [kNm] – radial     | 1.2 [90 <sup>th</sup> ]   | 1.3 [88 <sup>th</sup> ]   | 1.1 [90 <sup>th</sup> ]   |
| Ring reaction moment [kNm] – axial      | 1.7 [267 <sup>th</sup> ]  | 0.4 [356 <sup>th</sup> ]  | 0.07 [2.5 <sup>th</sup> ] |

# Gear Whine Evaluation

## Design Study

- ▶ Nominal (perfect alignment)
- ▶ Radial Ring Gear Eccentricity
- ▶ Radial Carrier Eccentricity
- ▶ Carrier Tilting Angle
- ▶ Ring Gear: Rigid vs. Flexible

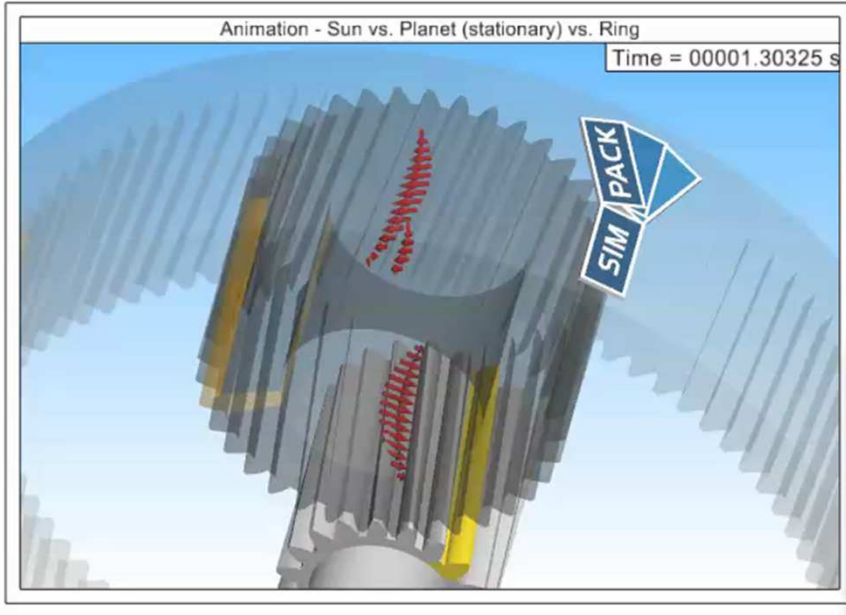


# Analysis Matrix for Single Planetary Gear Set

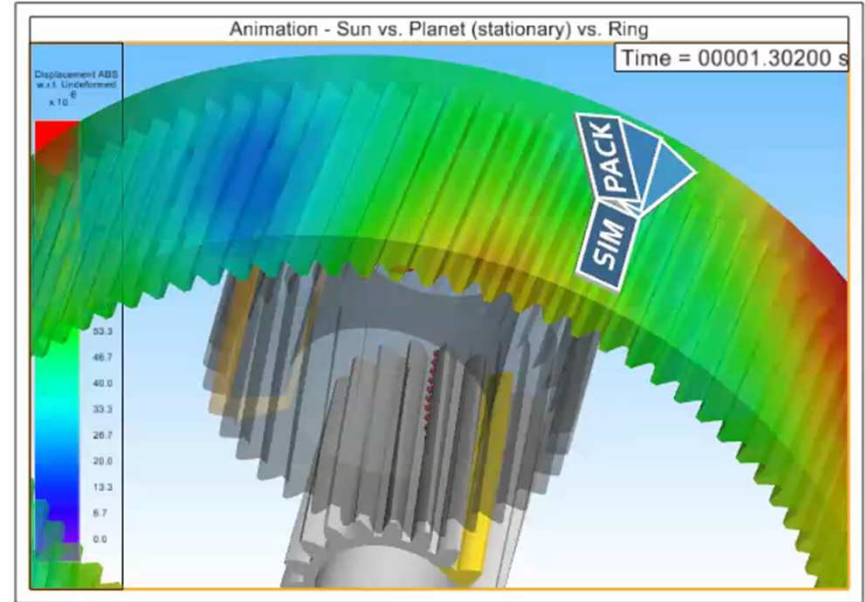
| # of runs | # of Planets | Ring Eccentricity | Carrier Eccentricity | Carrier Tilting | Ring Gear |          |
|-----------|--------------|-------------------|----------------------|-----------------|-----------|----------|
|           |              |                   |                      |                 | Rigid     | Flexible |
| 1         | 3            | 0.0 mm            | 0.0 mm               | 0.0 deg         | x         |          |
| 2         |              | 1.0 mm            |                      |                 | x         |          |
| 3         |              |                   | 1.0 mm               |                 | x         |          |
| 4         |              |                   |                      | 0.3 deg         | x         |          |
| 5         |              | 0.3 mm            | -0.3 mm              | 0.2 deg         | x         |          |
| 6         |              | 0.0 mm            | 0.0 mm               | 0.0 deg         |           | x        |
| 7         |              | 1.0 mm            |                      |                 |           | x        |
| 8         |              |                   | 1.0 mm               |                 |           | x        |
| 9         |              |                   |                      | 0.3 deg         |           | x        |
| 10        |              | 0.3 mm            | -0.3 mm              | 0.2 deg         |           | x        |

\* applied eccentricities and tilting angle where determined by available clearance in the planetary gear sets

# Gear Forces – Animation



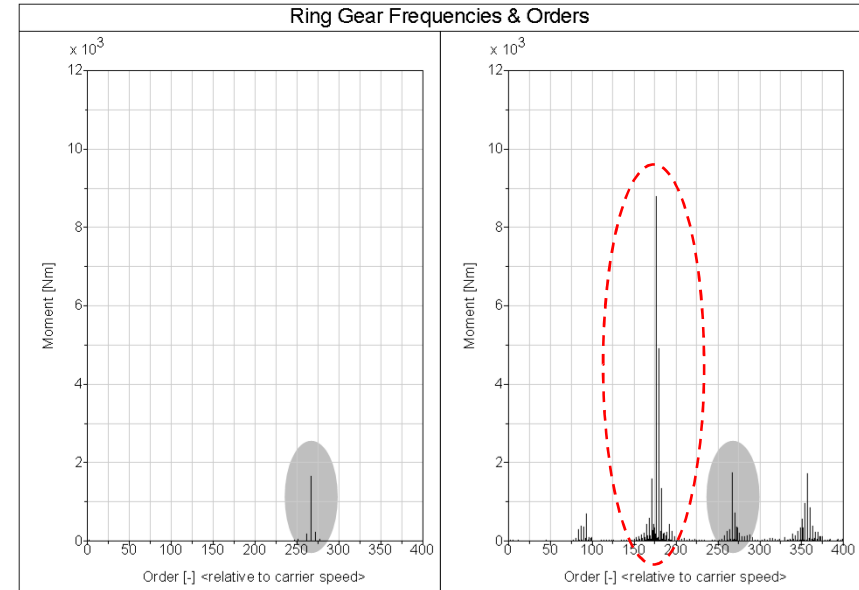
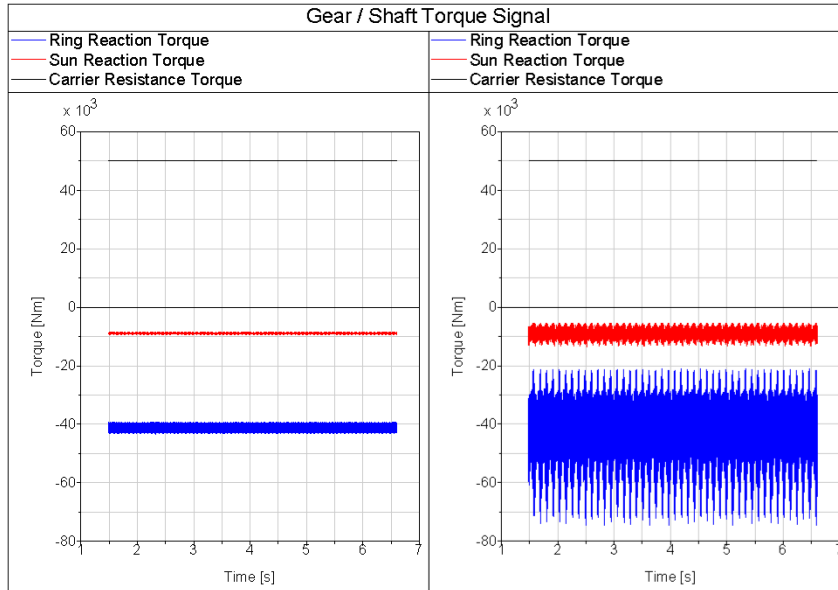
# 1: Nominal Conditions



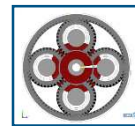
# 10: Eccentricities, Tilting and Flexible Ring Gear



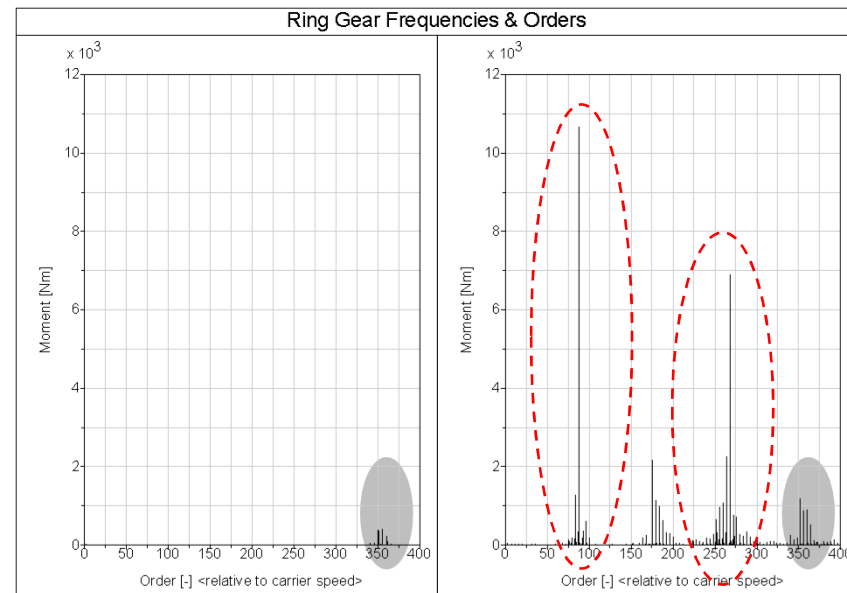
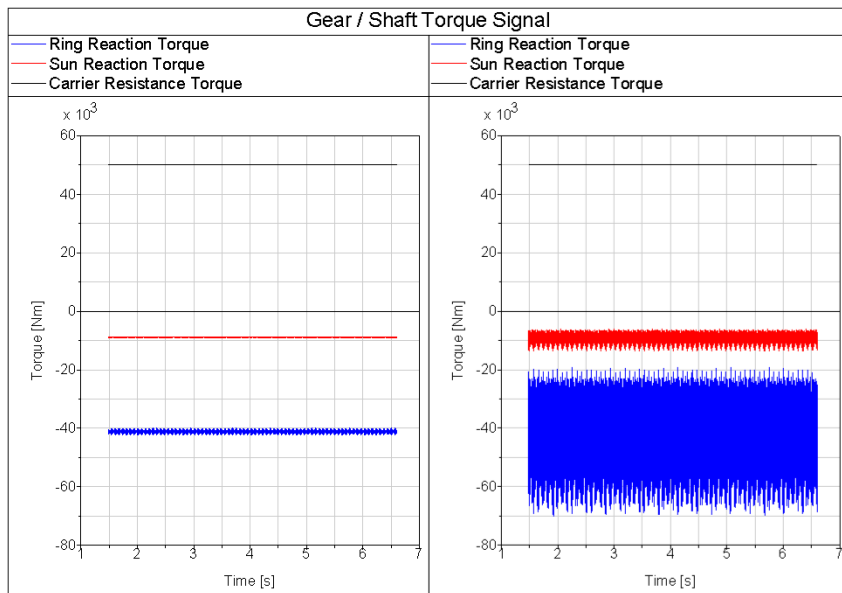
# Torque Reaction Comparison between #1 and #10



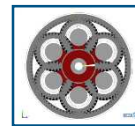
The analysis would have completely missed the system behavior, by not considering the complexity of the system and neglecting eccentricities, offsets, misalignments and compliance in the system.



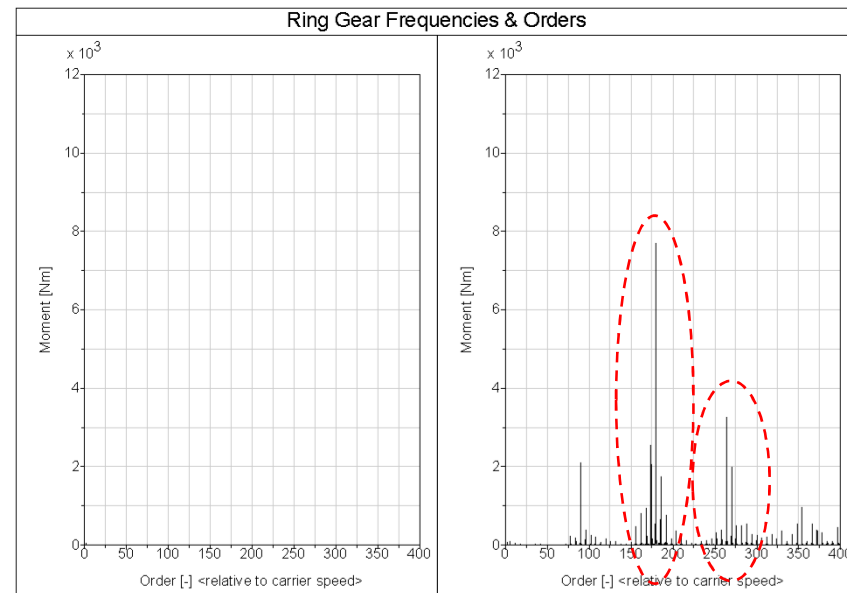
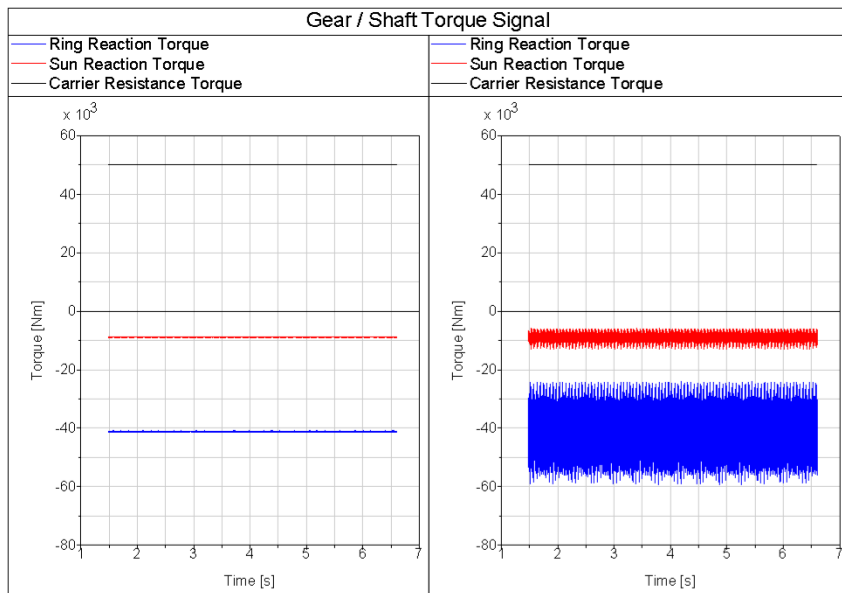
# Torque Reaction Comparison between #1 and #10



... with different implications for the different designs, here for the 4 planets



# Torque Reaction Comparison between #1 and #10



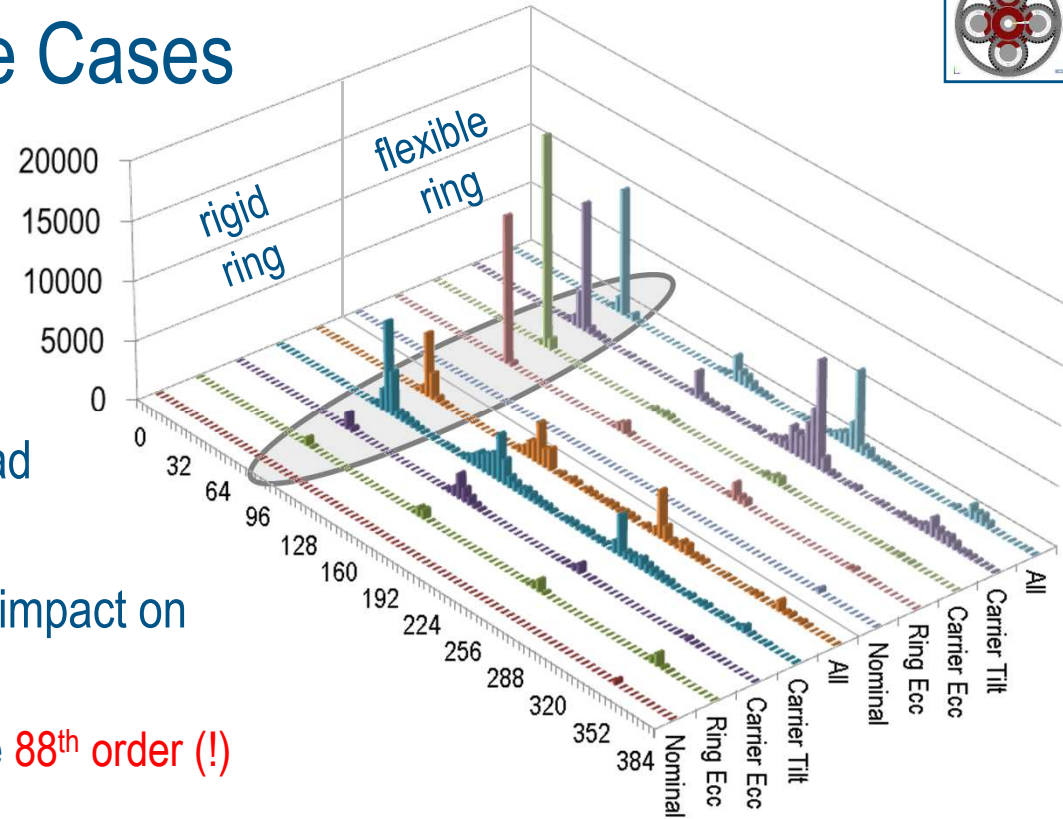
... here for the 6 planets



# Comparison of all the Cases

## Torque Reaction (4 planets)

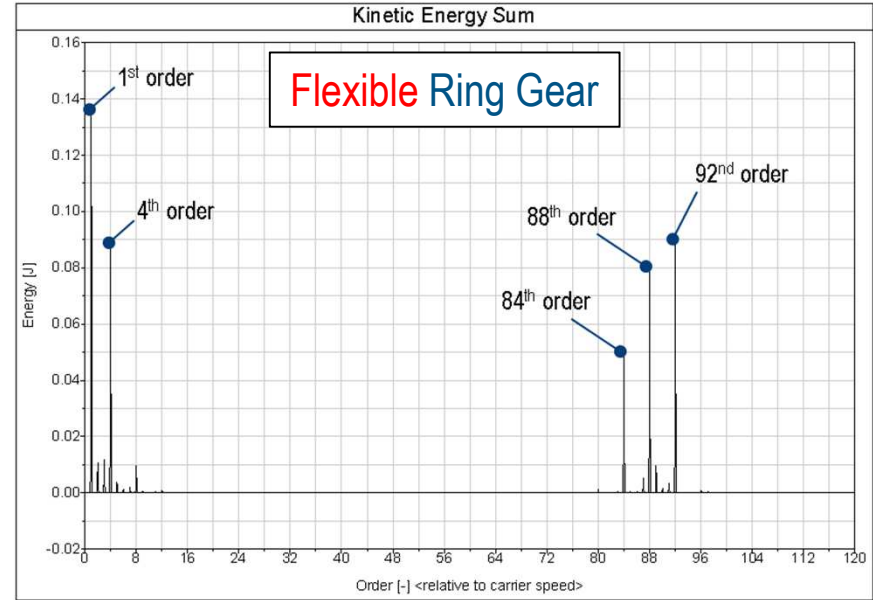
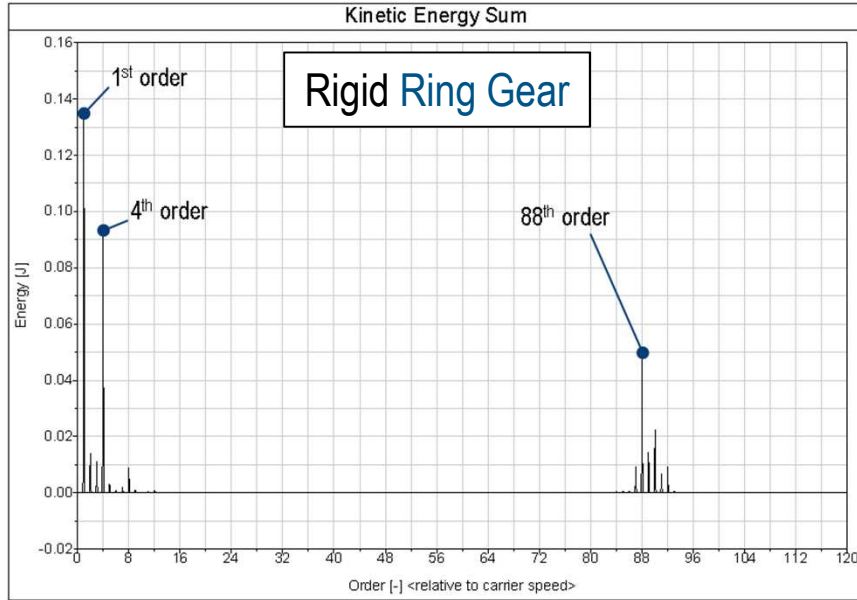
- ▶ Nominal conditions does not show any significance in the result comparison
- ▶ Carrier tilt shows biggest spread of response frequencies
- ▶ Flexible ring gear shows most impact on system frequency response
  - ▷ in respect to the response at the 88<sup>th</sup> order (!)
  - ▷ in regards of overall amplitude

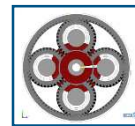


\* results are shown only in side band order content (4, 8, 12, 16, ..., 400)



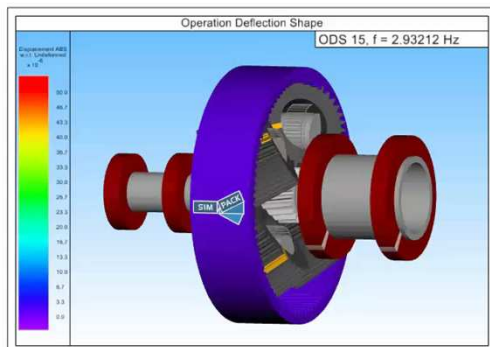
# System Model Evaluation with ODS for #10



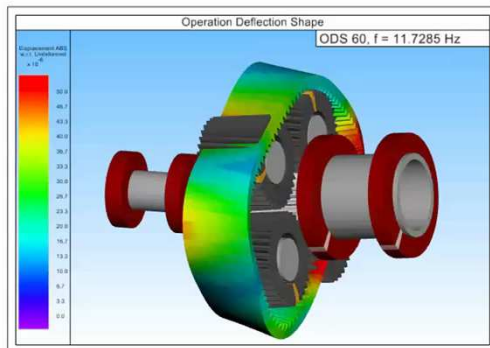


# ODS - Operation Deflection Shapes

## Low Frequency Modes

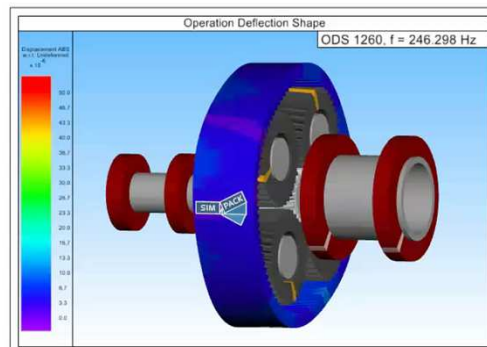


1<sup>st</sup> order



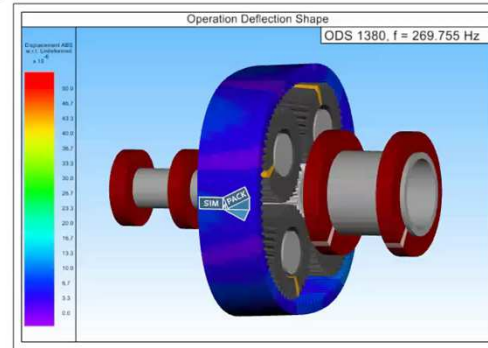
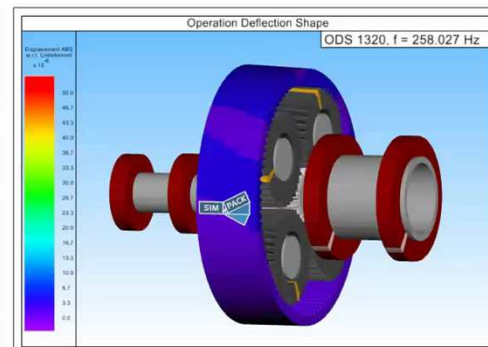
4<sup>th</sup> order

## Main Gear Order Modes



84<sup>th</sup> order

88<sup>th</sup> order



92<sup>nd</sup> order

\* results are shown with a mode shape scaling factor of 500

# Gear Whine Evaluation

## Other 'required' studies to explore design space

- ▶ Bearing Characteristic (non-linear, 3D, clearance, ...)
- ▶ Gear profile modifications & tolerance range
- ▶ Structural Compliance
  - ▷ Carrier
  - ▷ Sun shaft
  - ▷ Sun gear
  - ▷ Planet gear
- ▶ Planet misalignment (angular, radial)
- ▶ Load cases
  - ▷ Different speeds (Run-up)
  - ▷ Different load conditions (load sweep)
- ▶ .

The list of required DOE's can get long, fast!

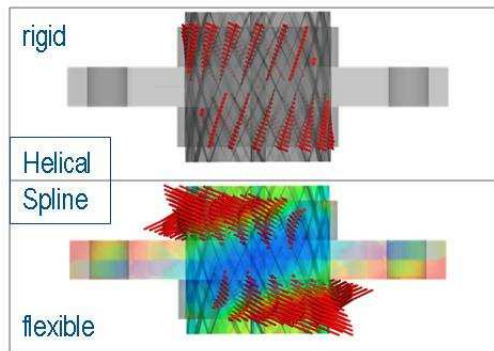
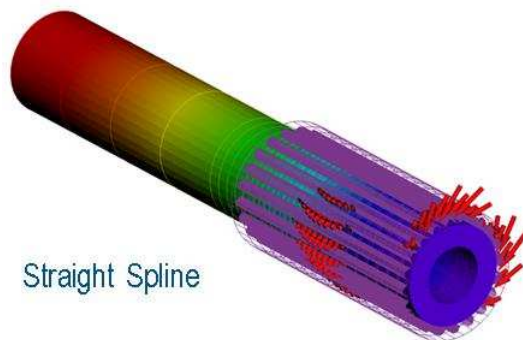
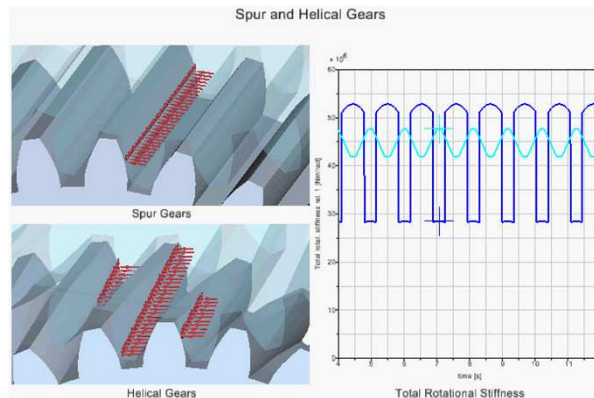
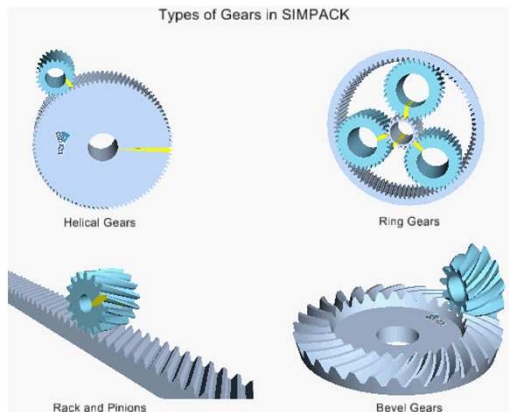
Essential to have a very efficient numerical solution available!

The analyses were performed on a 3 year old laptop with limited virtual memory (16 GB) and limited number of treads (4) for 6.6 sec simulated time

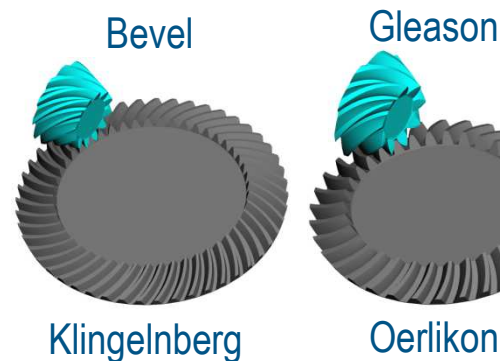
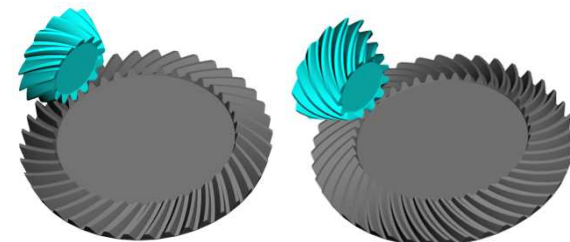
- Rigid Ring: 10-15 min
- Flexible Ring: 20-30 min

Simpack 2017.4

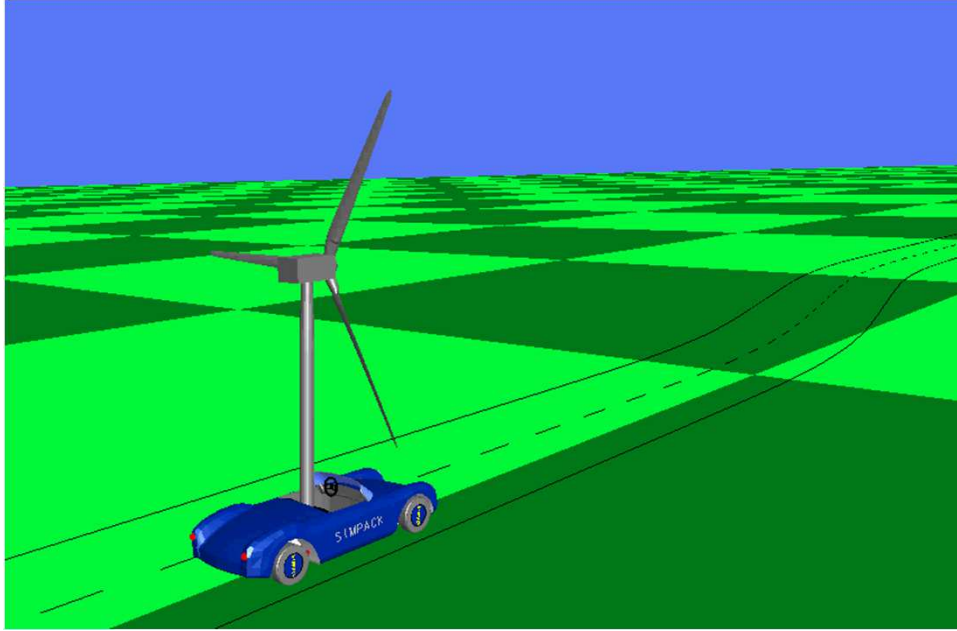
# Gear Module – Overview



## Bevel & Hypoid



# Simpack – Possible to simulate almost anything



Simpack  
provides the means  
to eliminate  
analysis assumptions  
... one-by-one.

