Simulation of containment-tests at a generic model of a large-scale turbocharger with LS-DYNA

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Overview

- Introduction
  - Company Profile
  - Why simulate Containment-Tests
- Motivation
- Containment Simulation today
- Generic Model
- Studies
  - different approaches of modeling bursting scenario of compressor flywheel
  - effect of lode-angle-parameter on the damage and failure behavior of the housing structures
- Summary
Introduction - Company Profile

- 1992 Founded (managing partner: Prof. Dr.-Ing. W. Feickert and Prof. Dr.-Ing. A. Huß)
- Based in Liederbach / Frankfurt a.M.
- Providing CAE services for several branches: automotive industry and its components suppliers, machine and plant construction, aerospace, consumer goods, chemical industry

- Fields of activity:
  - Simulation explicit and implicit FE-Method
    - Linear and nonlinear structural mechanics
    - Dynamic
    - Optimization
    - Thermal Transport
    - Fluid Dynamic
    - Crash
    - Drop Test
    - Containment Test
  - Software- und Product Development
    - Software Development
    - AutoFENA 3D
    - FKM inside ANSYS
    - WB/FKM
    - WB / Weld
    - ASME-Tool
    - Buckling-Tool
    - Product Development
    - Concept Development
  - Experimental Services
    - Durability Testing
    - Acceleration Measurement
    - Modal Analysis
    - Temperature- und Strain Gauge- Measurement
  - Software -Training
    - Training Courses and Webinars
    - ANSYS
    - LS-DYNA
    - FKM Assessment

- Since 2010 office in northern germany (near Hamburg)
- Since 2015 office in Düsseldorf
Introduction – Why simulate Containment-Tests

Why simulation techniques are used?

- Hardware test: extremely high kinetic energy
  - very dangerous \(\rightarrow\) high safety precautions necessary
    - Example: A rotor with a mass of 20 kg rotates with 26,000 min\(^{-1}\) corresponding approximately 840,000 J of kinetic energy. In a car side crash about 105,000 J of kinetic energy have to be dissipated.
  - very expensive and time consuming
  - duration of damage process: approximately 2-15 ms
  - comprehension of high-speed deformation processes is restricted
  - possibilities for measurements and improvements are limited

- using explicit finite element technique
  - reduce/minimize number of hardware tests
  - possibility to look into the machine during crash and analyze and comprehend load chains
  - nowadays essential tool used from the early stage of the development process of a turbocharger up to its certification and also afterwards accompanying the whole machine-life
    - Develop a safe design with regard to burst loads
    - Analyze and understand damage process, load chains and the causal correlations in the machine in detail
    - Qualify design concerning modified boundary or operating conditions
Simulation concepts and methodologies are developed continuously

- Problem:
  - turbocharger structures become more and more complex and sophisticated
  - the bursting and damage procedure should predicted as exact as possible
  - increasing demand in the precision of the CAE model (e.g. all cast structures are meshed with 3D elements, preferably hexahedrons)
    - strong increase in effort for modeling
    - strong increase of computing time
  - Further investigations (e.g. new approaches for different idealizations of certain areas, new material laws, different boundary conditions or robustness studies) at a model of a specific turbocharger and on that high level of detail is not really economical.

→ The idea of a generic CAE model of a large-scale turbocharger was born
What are the tasks today?

- compressor impeller burst and turbine wheel burst or blade loss scenarios and combinations of both
- several load cases and structure variants
  - different burst scenarios, rotational velocities, impact positions, impeller/blade sizes, different design sizes (not scaled ideally)
- lead to complex and varying load paths and high loadings in different sections
- long load chains with multiple sites of fracture
Containment-Simulation Today

- detailed model of the whole turbocharger is necessary which is able to accurately represent all areas
  - fine mesh with 3D-elements (preferably Hexahedrons) for structure parts and fasteners
    - min. 3 – 5 elements over wall thickness
    - consider cast radii
    - consider ribs
  - reduce connection via tied contacts
  - impeller: separate wedges (merged over 50-60% of height beginning from the top of the impeller \(\rightarrow\) closer reproduction of the real weakening)
  - boundary conditions: pretensions, internal pressure, propulsion of rotor
  - complex material models:
    - differentiation of behavior under tension and compression load with consideration of strain-rate dependencies (e.g. MAT124)
    - multi-axial fracture including damage (*MAT_ADD_EROSION – GISSMO)

- FE-Data:
  - > 5 million nodes
  - > 5 million elements
  - 4.5 mm average element length
  - ca. 0.5 mm min. element length
  - very small timestep
  - simulation time: 8ms \(\rightarrow\) calculation time: ca. 40-60 h (16 CPU-Cores)
Example: material law for a cast housing: *MAT124 + *MAT_ADD_EROSION (GISSMO)

- Stress-strain diagramm (quasistatic)
- Strain rate dependency

Damage

\[ \Delta D = \frac{n}{\varepsilon_I(\eta, \xi)} \cdot D \left( \frac{1}{n} \right) \Delta \varepsilon. \]

Damage accumulation [1]

Material instability:

\[ \Delta R = \frac{n}{\varepsilon_I(\eta, \xi)} \cdot F \left( \frac{1}{n} \right) \Delta \varepsilon. \]

Failure

Typical failure curve for metal sheet [3]

- 3D: add. lode-angle-dependency \( \rightarrow \) failure surface

Influence of element size on stress-strain curve [2]

- Strain rate dependency of failure strain and material instability

Generic Turbocharger Model

Requirements:
- usable for compressor and turbine damage
- as simple as possible
  - reduce simulation time
  - quick and easy modifiable
  - possible parameterization
- as accurate as possible
  - depict the principle behavior of real containment tests with all its complex load chains

Objective:
- no assessment of containment safety
- influence check (A-B-comparisons)
- robustness studies
- test new approaches (modeling, material, BC´s)
- benchmark new software releases or other codes

- mass = 2300 kg
- max. diameter d = 1160 mm
- Rotational speed n = 14340 1/min = circumferential velocity 475 m/s
Generic Turbocharger Model

- Turbocharger is build up modular: **3 sections and rotor:**
  - Compressor
  - Bearing
  - Turbine
  - Rotor
  2 versions of each (coarse and fine - differentiation of compressor and turbine containment)

- **rotational symmetric structure**
  - no inlet and outlet openings

- **no base / foot structure**
  - mounting via BC´s at lower area of circumference of turbine casing

- silencer heavy idealized
  - back plane/flange + lumped masses
  - retention mass inertia
**Generic Turbocharger Model**

### Compressor section:
- 2.1 Million Elements
  - Compressor Casing
  - Diffuser
  - Impeller (diameter 634 mm; 68.5 kg)
  - Compr. Cover / Labyrinth Disk

### Bearing section:
- 1.0 Million Elements
  - Bearing Casing
  - Bearing Parts

### Turbine section (coarse version):
- 0.18 Million Elements
  - Turbine Nozzle Ring
  - Gas Admission Casing

#### FE-data:
- 3,85 million nodes
- 3,3 million elements
- 5-6 mm average element length
- 1,0 mm min. element length

#### Simulation time:
- 8 ms →
  - calculation time: ca. 12 h
  - (16 CPU-Cores)
Study 1 - Modeling bursting scenario and pretension of compressor wheel

➢ Modeling of bursting scenario:
  o 1 – Compressor wheel
  o 2 – Clamping Nut
  o 3 – Clamping elements / rotor parts
  o 4 – deformable shaft
  o 5 – rigid shaft with turbine wheel

➢ 3 approaches of modeling bursting scenario:
  Var 1: Detached Segments
    - formerly used
  Var 2: 60% Merged
    (partial node connection)
    - Currently used
  Var 3: Slotted
    (analog test procedure)
    - under discussion

Start of fracture on rear side
Study 1 - Modeling bursting scenario and pretension of compressor wheel

- Affect fracture time → different trajectories
- Elimination effect of fracture time lead to divergence of only 3-4° after fracture
- Marginal influence on CG-velocities

<table>
<thead>
<tr>
<th></th>
<th>$T_{\text{frac}}$ [ms]</th>
<th>$E_{\text{int}}$ [kJ]</th>
<th>$E_{\text{kin}}$ [kJ]</th>
<th>$E_{\text{int,erod}}$ [kJ]</th>
<th>$E_{\text{kin,erod}}$ [kJ]</th>
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<td>2380</td>
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+0.2% slot
Study 1 - Modeling bursting scenario and pretension of compressor wheel

Synchronized at fracture point: Relative x-displ. after fracture

Complete fracture
Study 1 - Modeling bursting scenario and pretension of compressor wheel

- Pretension:
  - Radial pretension
  - Axial pretension
  - Combined pretension

- Var 1: DETACHED

<table>
<thead>
<tr>
<th>Pretension Type</th>
<th>$T_{\text{det}}$ [ms]</th>
<th>$E_{\text{det}}$ [kJ]</th>
<th>$E_{\text{prox}}$ [kJ]</th>
<th>$E_{\text{det,net}}$ [kJ]</th>
<th>$E_{\text{prox,net}}$ [kJ]</th>
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</table>

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Study 1 - Modeling bursting scenario and pretension of compressor wheel

- Var 2: 60% Merged

<table>
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<tr>
<th>Variant</th>
<th>$T_{opt}$</th>
<th>$E_{opt}$</th>
<th>$E_{init}$</th>
<th>$E_{init,red}$</th>
<th>$L_{init,red}$</th>
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<tr>
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<td>10.3</td>
<td>2.8</td>
<td>1.7</td>
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- a = 95 mm

- No effects on velocities of segment center

- N2
Study 1 - Modeling bursting scenario and pretension of compressor wheel

- Var 3: SLOTTED

- no effects on velocities of segment center
- small effect on fracture time → different trajectories
- elimination effect of fracture time lead to divergence of <1° after fracture

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<tr>
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<th>( E_{\text{int, erod}} ) [kJ]</th>
<th>( E_{\text{kin, erod}} ) [kJ]</th>
<th>( \Delta E_{\text{kin}} ) [%]</th>
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<td>2.3</td>
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</tbody>
</table>
Study 1 - Modeling bursting scenario and pretension of compressor wheel

- review results in complete turbocharger model (generic model):
  - Implemented rotor variants:
    - **Var 1**: DETACHED: 3 separate segments of compressor wheel without pretension
    - **Var 2**: 60%MERGED: partially coupled segments without pretension
    - **Var 3**: 60%MERGED_AxRadPre: partially coupled segments; axial + radial pre-stressed
    - **Var 4**: SLOTTED70_AxRadPre: Slotted compressor wheel (a=70mm); axial + radial pre-stressed
  - evaluation of simulation on the basis of energies, displacements and kinematic of compressor insert piece, compressor casing, bearing casing and labyrinth disk

![Graphs showing energy distribution over time](image.png)
Study 1 - Modeling bursting scenario and pretension of compressor wheel

- Kinematic:

0: V1: Detached
1: V2: 60% Merged
2: V2: 60% Merg + Pret
3: V3: Slot70 + Pret
Study 1 - Modeling bursting scenario and pretension of compressor wheel

➢ Bearing Casing + Labyrinth Disk:

- V1: DETACHED
  - V4: SLOT70+PRET
    - V3: 60%MERG+PRET
    - V2: 60%MERG

eff. plast. strain

X-displ. [mm]
Study 1 - Modeling bursting scenario and pretension of compressor wheel

- **Insert Piece:**
  - V1: DETACHED
  - V2: 60%MERG
  - V3: 60%MERG+PRET
  - V4: SLOT70+PRET

- **Compressor Casing:**
  - V1: DETACHED
  - V2: 60%MERG
  - V3: 60%MERG+PRET
  - V4: SLOT70+PRET
Study 1 - Modeling bursting scenario and pretension of compressor wheel

- implementation of bursting scenario:
  - small influences on energy balance (red. 2-3%)
  - difference in time till fracture (depending on slot depth) → variance of segment kinematic
    - small divergence in radial and tangential movement and segment rotation: trajectories differ < 4°
    - obvious influence on axial movement / overturning (in particular Var1)

- axial pretension → no significant influences

- radial pretension → reduced $E_{\text{internal}}$ for fracture + reduced loss of $E_{\text{kinetic}}$
  - no influence on degree of damage of compressor wheel
  - small influence on time till fracture → small variance of segment kinematic (overturning)

- pretension eliminates peak in triaxiality at the beginning
Study 1 - Modeling bursting scenario and pretension of compressor wheel

- influences in complete turbocharger model (generic model):
  - small differences in global energies + partially heavy differences in energies of main assemblies
  - different impact loads on surrounding parts: differences in plastic strain, axial displacements and damage
  - different kinematic of compressor wheel
    • in particular Var1 (DETACHED) differ from the rest significantly
    • marginal divergences between Var2 and Var3 (60%MERGED with and without Pretension)
    • small divergences between Var3 (60%MERGED+PRET) and Var4 (SLOTTED70+PRET)
  - initial splitted or only slotted impeller make the great difference; the kind of modeling the slot is secondary
  - axial pretension → no influence; radial pretension → small influence

- compressor bursting: prefer variant with partially merged segments (coupling over ca. 60% of height beginning from the top of the impeller) without pretension
  (good kinematic + heaviest loads on surrounding structure + no slot-modeling and implicit analysis needed)
Study 2 – Effect of lode-angle-parameter on the failure behavior in a CT-Simulation

- Example: material law for a cast housing: *MAT124 + *MAT_ADD_EROSION (GISSMO)

Extension: Lode angle dependence

Lode angle parameter:
\[ \xi = \frac{27}{2} \frac{J_3}{\sigma_{YM}^3} \]

Lode angle parameter (only for plane stress):
\[ \xi = -\frac{27}{2} \eta \left( \eta^2 - \frac{1}{3} \right) \]

Failure

3D: add. lode-angle-dependency → failure surface
Different behavior in the kinematics if the 3D stress state is considered.

More damage due to the radial impact in the model with lode angle dependence.

Due to less damage in the first model the axial forces get bigger and the screws start to fail.
Study 2 – Effect of lode-angle-parameter on the failure behavior in a CT-Simulation

- **Results – Comparison with/without lode angle dependence:**
  - Results of the labyrinth disk
    - triaxiality: -0.5 to -0.2
    - lode angle parameter: -0.55 to -0.2
    - → failure strain differ strongly from that of the approach with only plane stress dependence.
    - Shows possible differences if a 3D stress state is considered in the failure model. More damage in the model with lode angle dependence.

- **Lode angle dependence:**
  - significant influence on the behavior of failure
  - strong dependency of shape of the failure surface
  - more possibilities to adjust the failure behavior to test data
  - more material tests necessary, which cover different stress states
Summary

- models become more and more complex → high effort for meshing + long calculation time → cost driver
  - studies of modifications and improvements (e.g. in material laws, meshing, geometry, boundary conditions, simulation methodology) are very expensive and long-lasting

- the developed generic model has proved itself a very helpful instrument
  - depicts the principle behavior of real containment tests with all its complex load chains
  - enables studies, sensitivity and robustness analyses in a fast and efficient way
  - improvements, new features and simulation approaches can be tested and assessed comprehensively before considering them in a detailed containment simulation

- kind of implementation of bursting scenario can affect simulation results significantly
  - Currently used approach is very good and efficient

- Lode angle dependence is a very important point
  - can have strong influence depending on shape of the failure surface and the existing stress state
  - more effort for validation needed
Thank you for your Attention?