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Advanced Engine Dynamics Using MBS And Super Element Approach: Application To Twin-cylinder Boxer Engines

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Topics of the study

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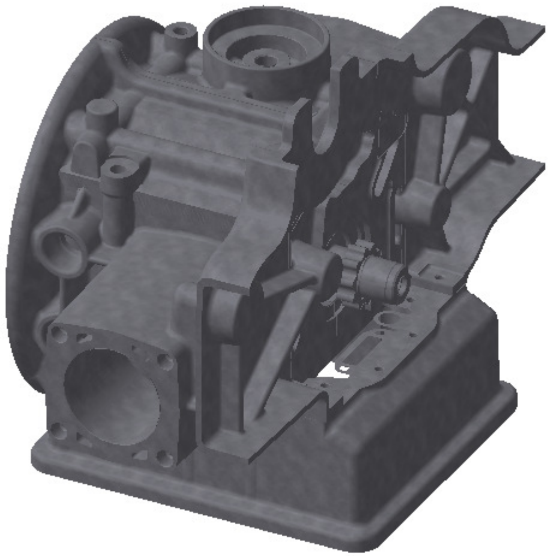
- Dynamic simulations of a twin–cylinder boxer engine using rigid or flexible parts models
- Strains and stresses analysis of engine crankshaft thanks to the finite element approach
- Application of super element technique to reduce the size of the problem and to improve the computing time of simulations

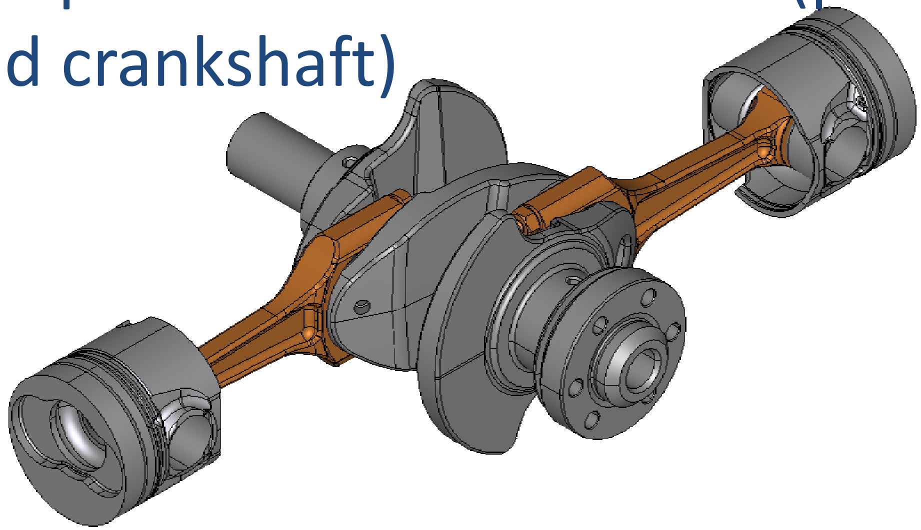
Twin-cylinder boxer engine

- Twin-cylinder boxer engine:
  - Flat engine with opposed cylinders and pistons moving in phase (reaching their top dead center simultaneously)
  - Naturally balanced, do not require balance shafts
  - Low center of gravity



Engine model

- Engine model is made with real geometry coming from the CAD model of a prototype engine (provided by Breuer Technical Development)
- Engine model is simplified, only the most significant mobile parts are kept for the simulations (pistons, connecting rods and crankshaft)



Simulation software

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- Engine simulations are performed using finite element approach with SamcefField MECANO software developed by Samtech and the university of Liège

SAMCEF FIELD

Rigid multibody model

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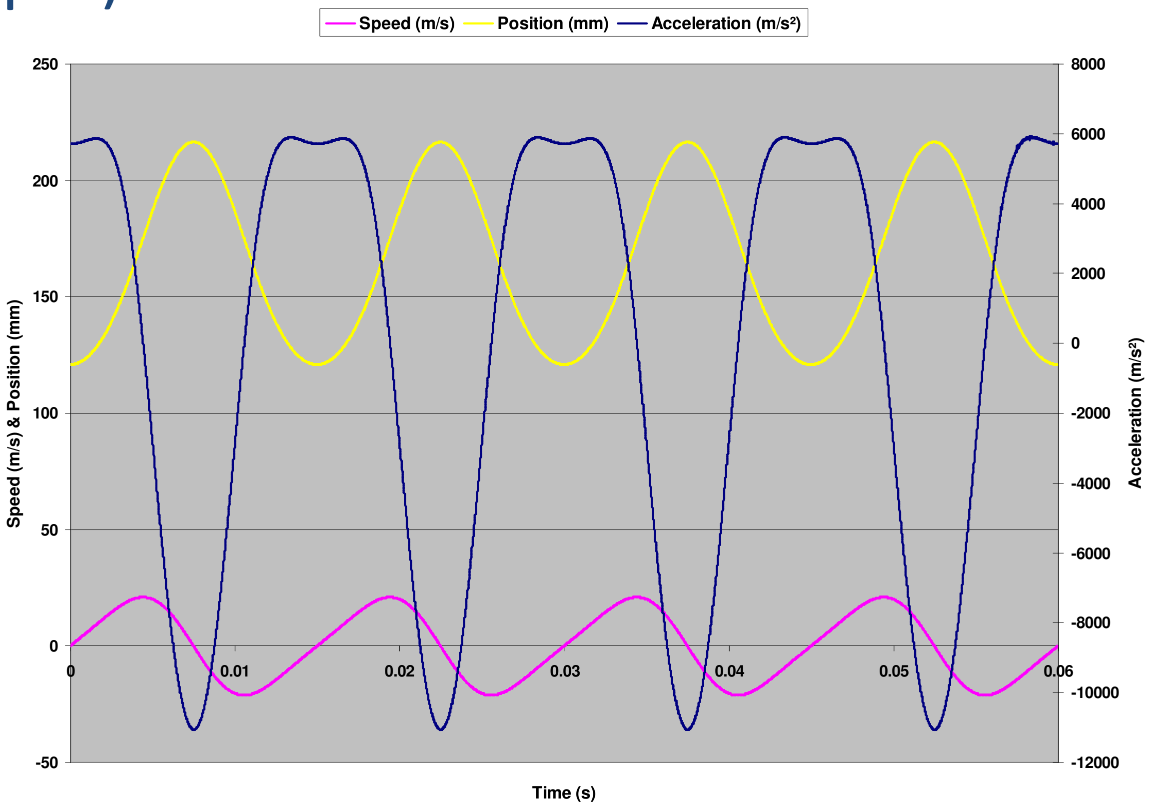
- All parts are considered as rigid
- Three simulations are performed:
  - Kinematic simulation with imposed crankshaft rotation speed => position, speed & acceleration
  - Dynamic simulation with imposed crankshaft rotation speed => inertia forces and moments
  - Dynamic simulation with imposed crankshaft speed and gas pressure effect => total forces acting on each part of the engine

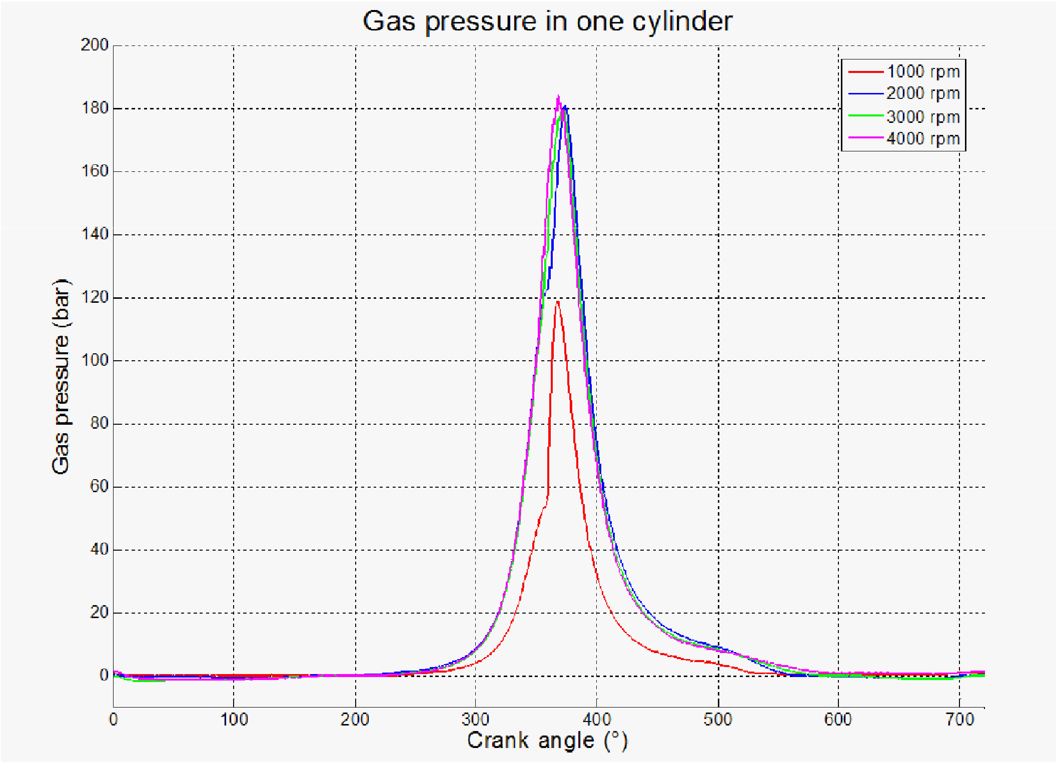
Rigid multibody model

- Kinematic simulation with imposed crankshaft speed (4000 rpm)



Gas pressure model

- Gas pressure inside a cylinder (experimental data)



Rigid multibody model

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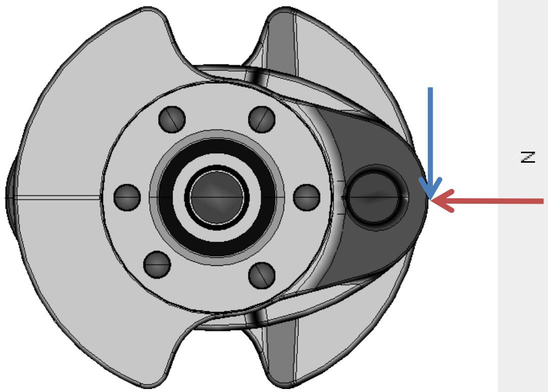
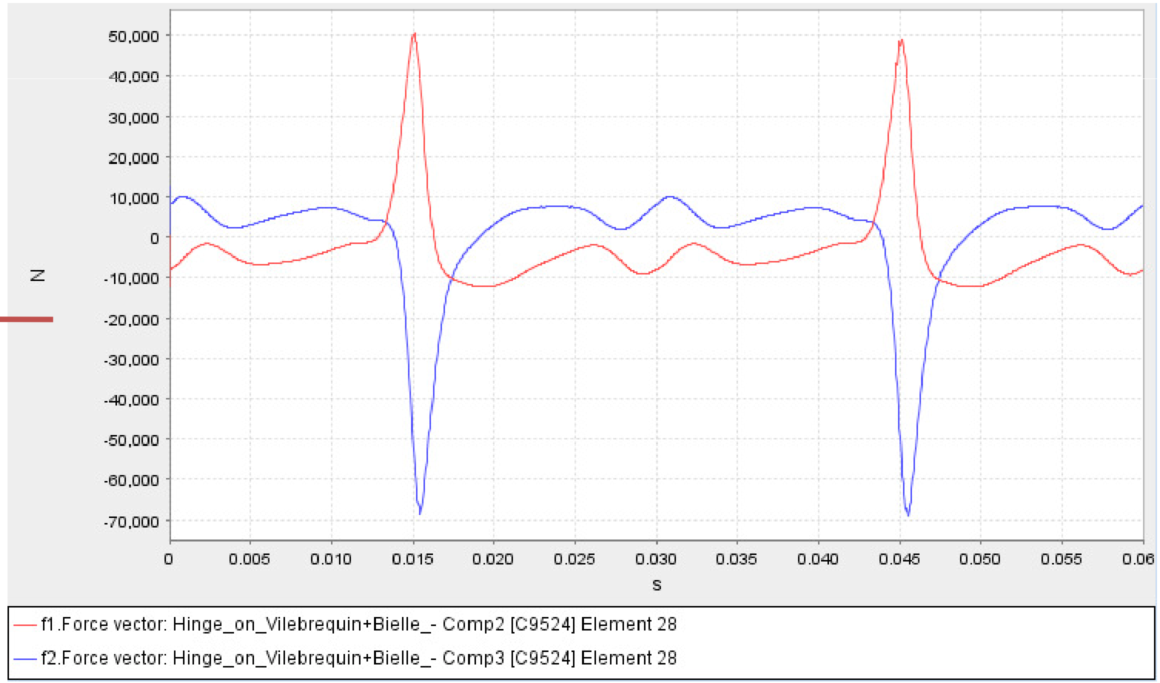
- Dynamic simulation taking into account the gas pressure force
  - Radial (red) and tangential (blue) forces acting on one crankpin





Flexible multibody model

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- Simulation of flexible engine parts thanks to the finite element approach
  - Dynamic multibody simulation with pistons and connecting rods considered as rigid bodies and crankshaft meshed with flexible finite elements
  - Crankshaft strains and stresses are calculated for the complete engine cycle

Flexible multibody model

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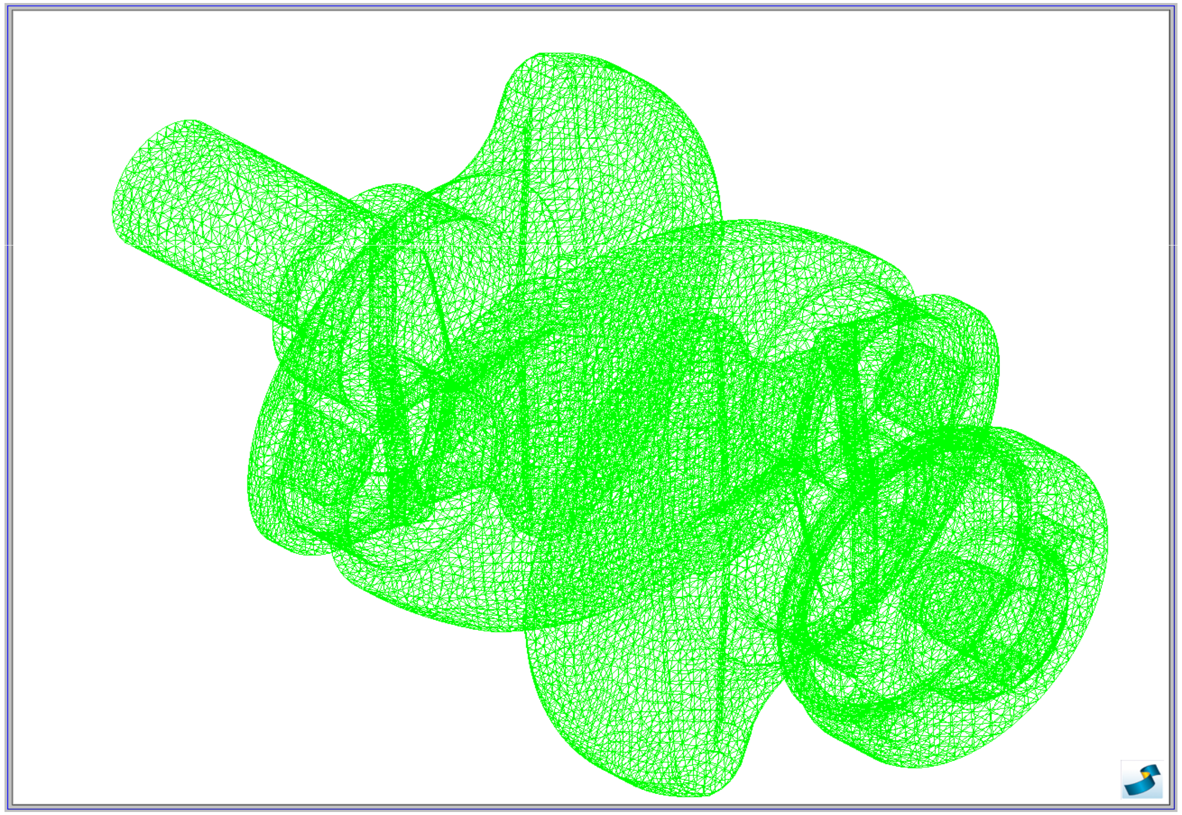
- Dynamic simulation of the engine
  - Crankshaft is meshed with 283700 first order tetrahedral elements of 3 mm average size (good compromise between result accuracy and computing time)
  - Rigid hinge model of bearing surfaces is used
  - Chung-Hulbert time integration algorithm
  - Maximal constraint (Von Mises criterion) occurs at time 15.78 ms (corresponding to a crankshaft angular position of 18.7 degrees after the TDC) and its value is 444.8 Mpa

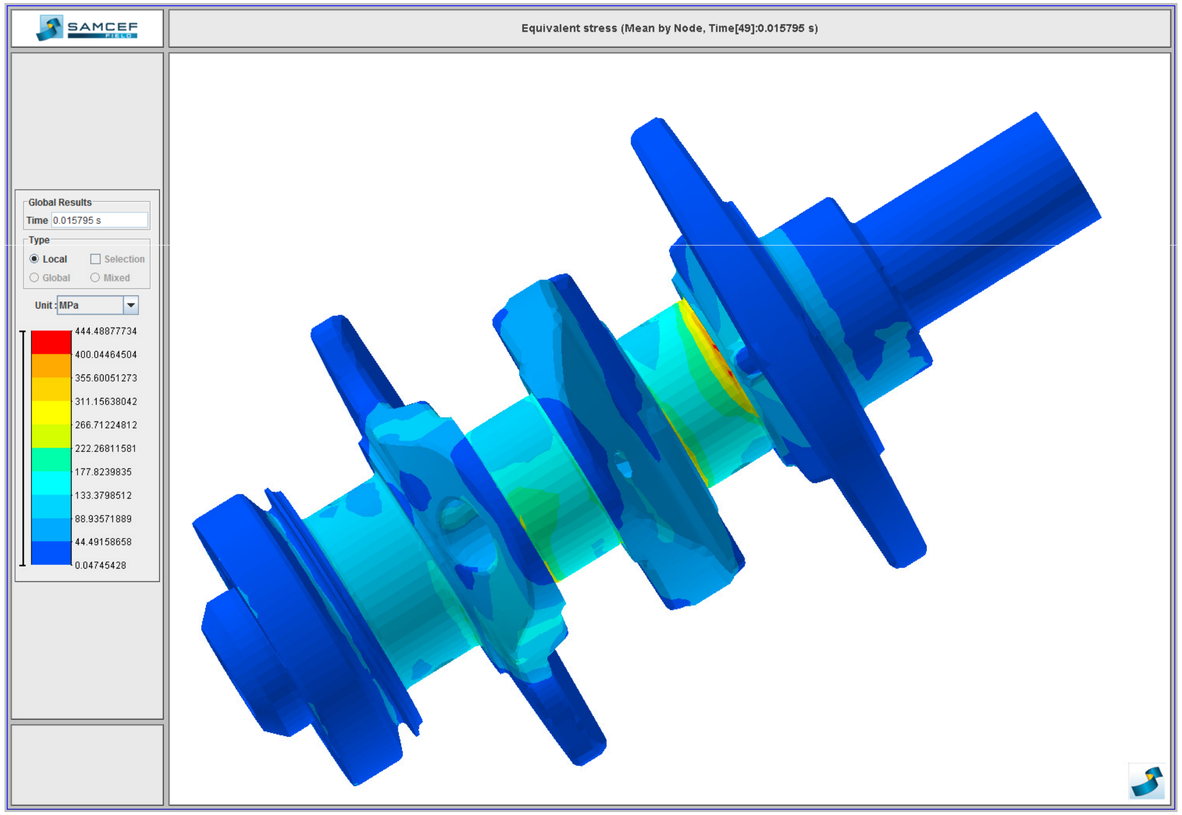
Flexible multibody model

- Crankshaft mesh:



Flexible multibody model

- Crankshaft stresses



Flexible multibody model

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- Simulations using fully detailed crankshaft geometry take a lot of time (13 hours per engine cycle for the previous model) and computing resources
- Need for simplified models:
  - Beam models
  - Simplified geometry 3D models
  - <u>Super element models</u>

Super element approach

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- Substructure technique used to reduce the size of a problem
- Nonlinearities are assumed concentrate in the joints
  - Motion (especially rotation) and the deformation of a body can be decoupled
  - Deformations of the body remain small and linear in a local frame attached to the body
  - The body is represented by a super element containing the internal modal information and linked to other bodies allowing to keep a relatively simple global dynamic model

Super element approach

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- Simulations using super element technique require 3 steps:
- Creation step:
  - Super element of the crankshaft is created by deleting some DOF and keeping only the boundary DOF and a reduced set of eigenmodes (Craig-Bampton condensation method)
  - The mass matrix and the stiffness matrix of the crankshaft are reduced and assembled with the rest of the system like an usual finite element

Super element approach

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- Calculation step:
  - Super element is assembled in the global system
  - A dynamic multibody analysis of the global system (the engine in this case) is performed
  - Results from the global simulation are obtained (position, speed, acceleration, force, moment…)

Super element approach

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- Results recovery step:
  - Some specific results of the crankshaft, for instance strains and stresses, can be recovered by a dynamic analysis of the super element

Super element approach

- Advantages of the method
  - Faster calculation
  - Needs less computing resources
- But also
  - Recovery of specific results only at required time
  - Direct decoupling of the displacement coming from the deformation and from the rotation

Super element crankshaft model

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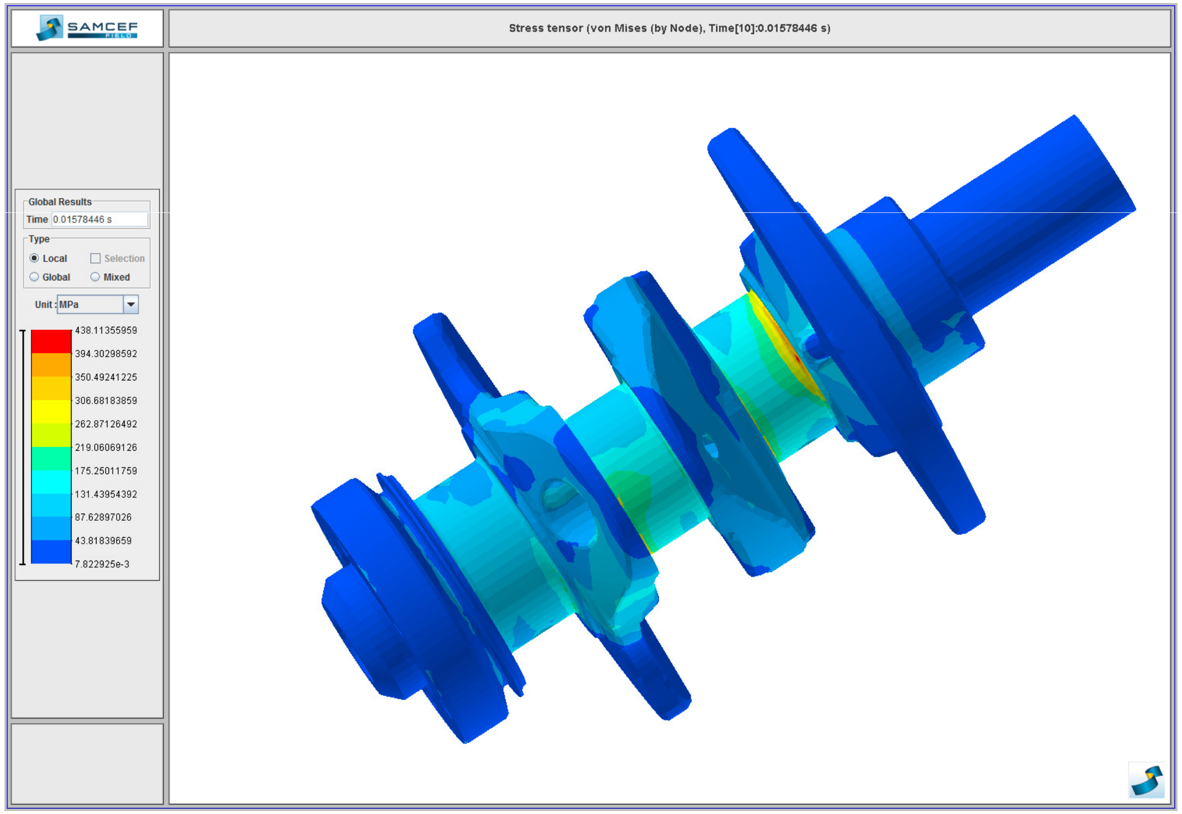
- Dynamic simulation of the engine using a super element model of the crankshaft
  - Super element is created with the crankshaft meshed with 283700 first order tetrahedral elements of 3 mm average size and keeping 25 eigenfrequencies
  - Rigid hinge model of bearing surfaces is used
  - Chung-Hulbert time integration algorithm
  - Total time of the simulation (including creation and recovery of the super element) is 3.25 hours

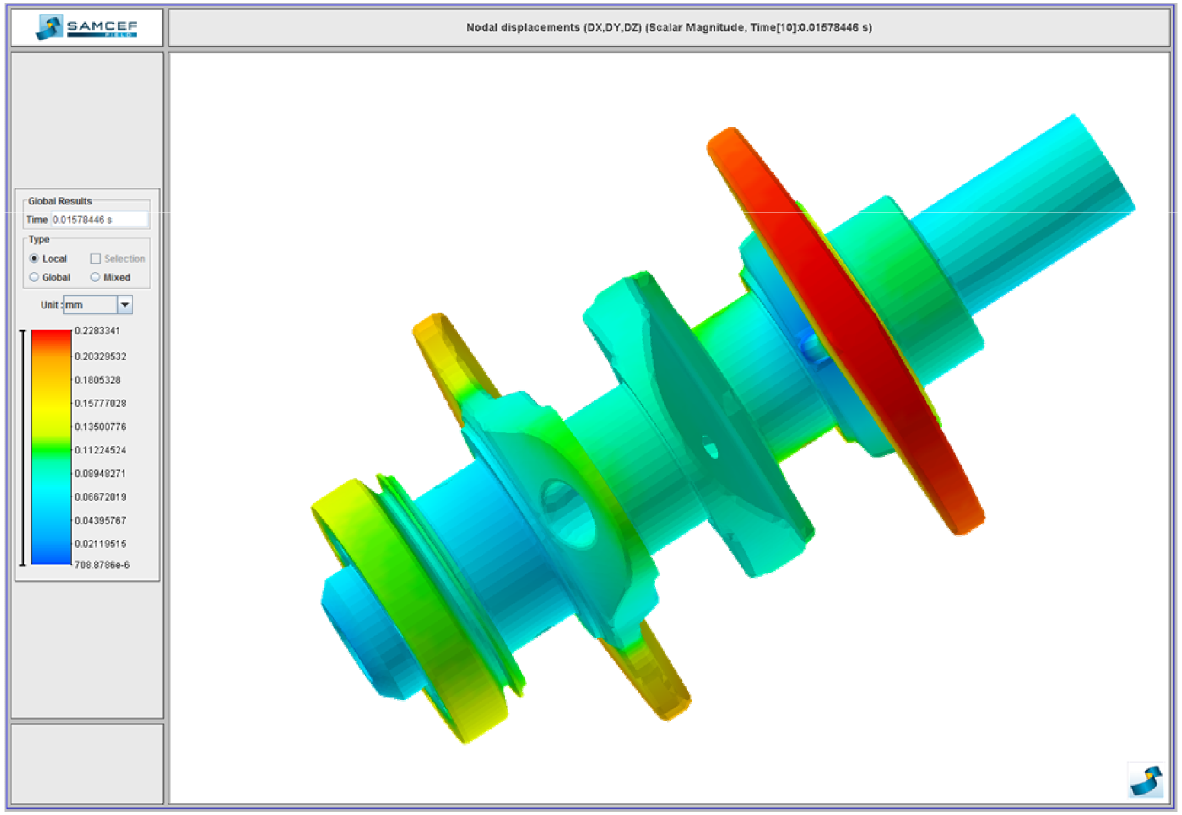
Super element crankshaft model

– Maximal stress (Von Mises criterion) occurs at time 15.78 ms and its value is 438.1 Mpa



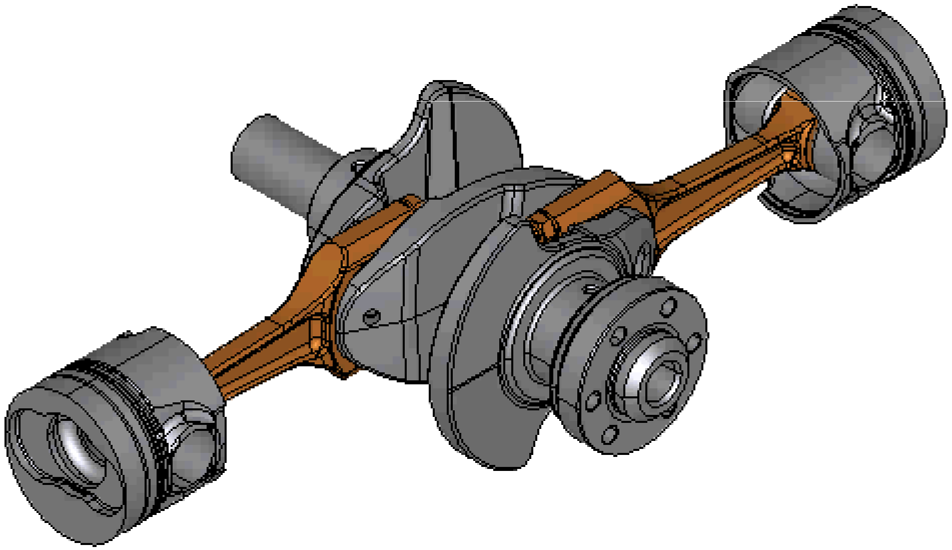
Super element crankshaft model

– Maximal displacement occurs at time 15.78 ms and its value is 0.228 mm



Super element crankshaft model

– Engine rotating motion



Super element crankshaft model

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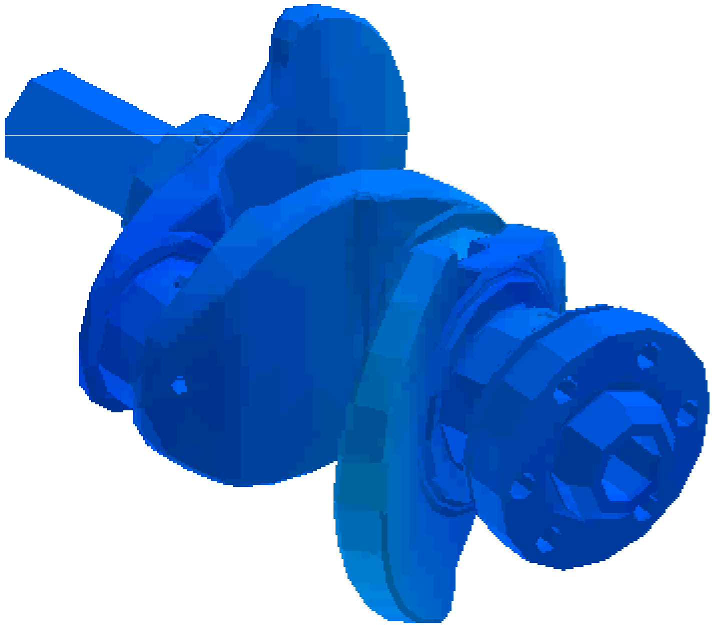
– Deformation of the crankshaft (15926 elements)

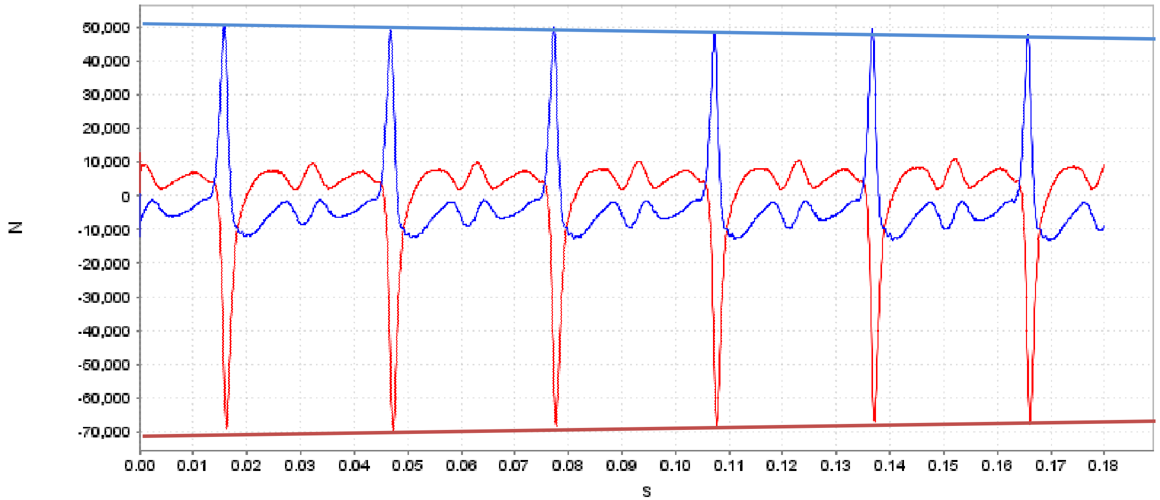


Variable speed simulations

- A super element model of the crankshaft is used in a variable speed engine simulation
- Simulation is similar to the constant speed one, except that the prescribed rotation speed varies, in this case, from 3800 rpm to 4200 rpm in 0.18 seconds and the force due to the gas pressure that has been adapted to remain in phase with the crankshaft rotation

Variable speed simulations

- Radial (blue) and tangential (red) forces acting on one crankpin
- The maximal value of the peak forces (radial and tangential) decreases at each rotation because the inertia force is increasing and is opposed to the force generated by the gas pressure when the engine speed is increasing



Variable speed simulations

- The main effect of the speed variation is the variation of inertia forces
- When the speed is increasing, the inertia force generated by the pistons and connecting rods increases also. Since this force is opposed to the gas pressure force, the total force coming from the connecting rods and acting on the crankpins is reduced => crankshaft strains and stresses decrease
- The inertia force due to the crankshaft is also increasing => crankshaft strains and stresses increase

Variable speed simulations

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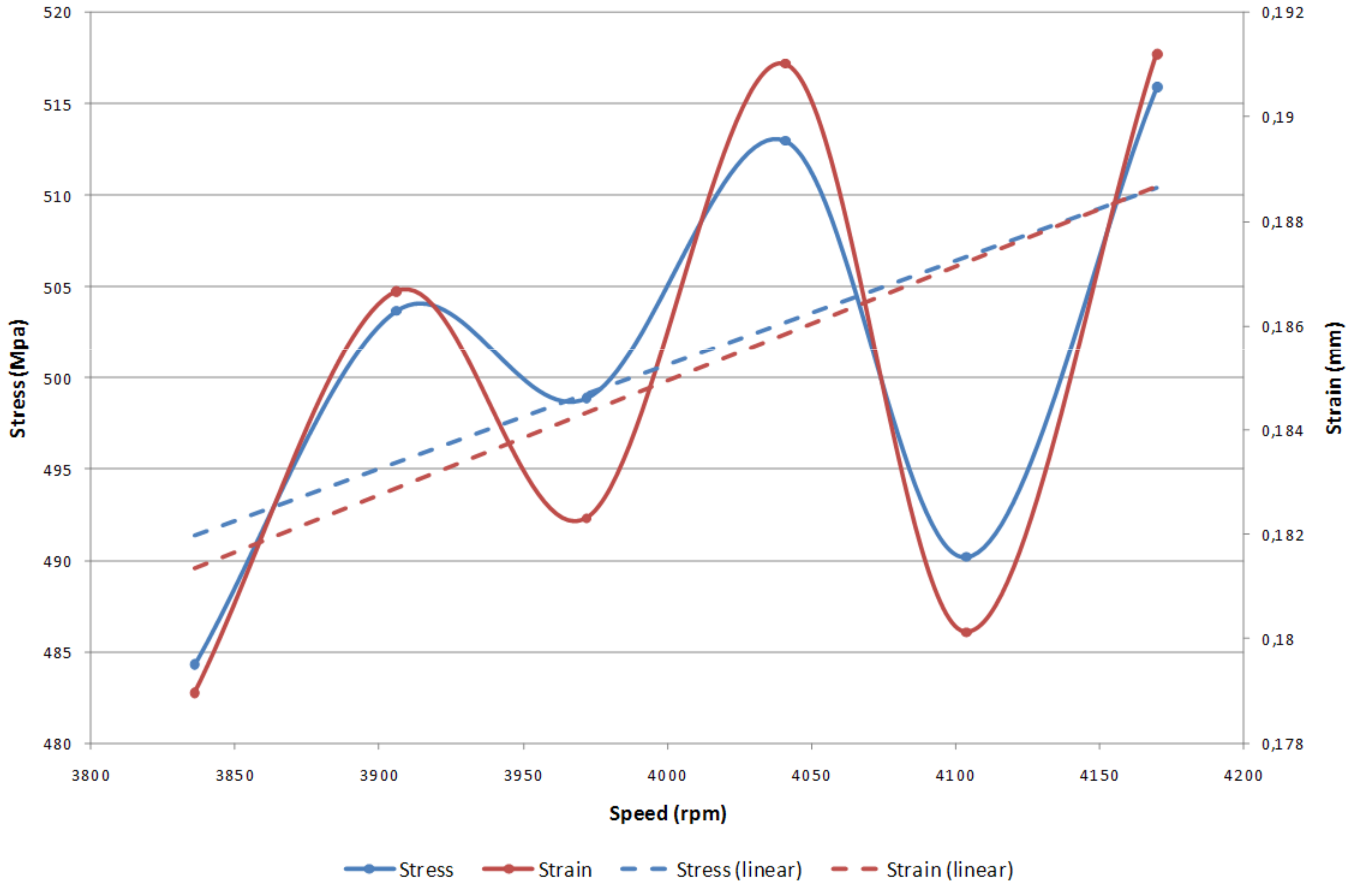

Conclusions

- Multibody simulations offer interesting prospects for engine design:
  - Easy calculations of inertia forces and moments (rigid body simulation)
  - Calculations of the exact forces acting on each engine parts
  - Flexible body dynamic simulation allows strain and stress analysis for all crankshaft positions but require lots of computing resources and time => need for **simplified models**

Conclusions

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- Super element method allows to:
  - Perform faster simulations
  - Isolate the displacement coming from the deformation and from the rotation

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Thank you for your attention