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Dynamic analysis and preliminary design of twin-cylinder engines for clean propulsion systems

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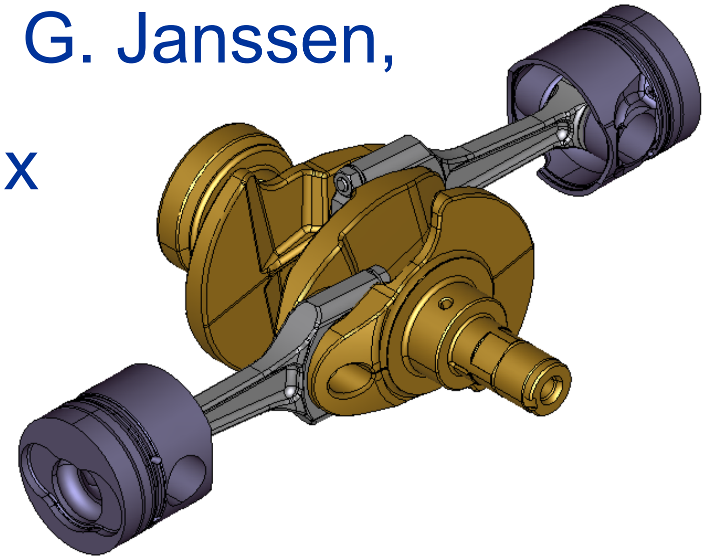

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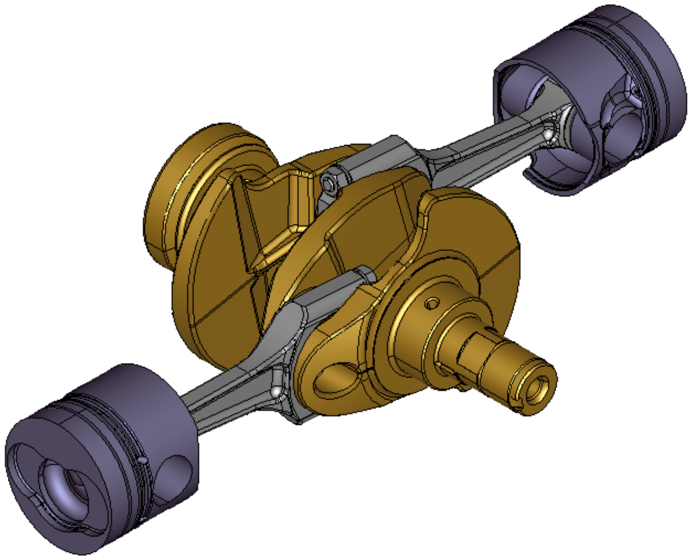
Introduction



Project background

- Growing industrial interest for small internal combustion engine (ICE) for urban or hybrid vehicles
- Support to the prototyping of a twin-cylinder diesel engine by BTD
- Research efforts in non-accurate methods for the design of unusual engine configurations
  - Preliminary design tools
  - Calculation based on multibody systems simulation

Topics of the study

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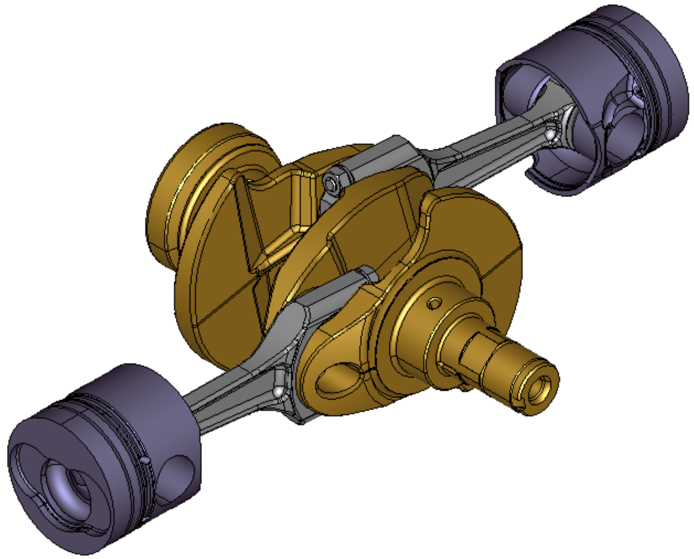
- Developing several models of twin-cylinder engine (from analytical models to flexible multibody simulations)
- Computing inertia forces and moments in the engine
- Balancing the engine (counterweight or balance shafts)
- Comparing different engine configurations
- Taking care of the gas pressure effect on the component’s strains and stresses (crankshaft)

Engines modeling



Engine configurations

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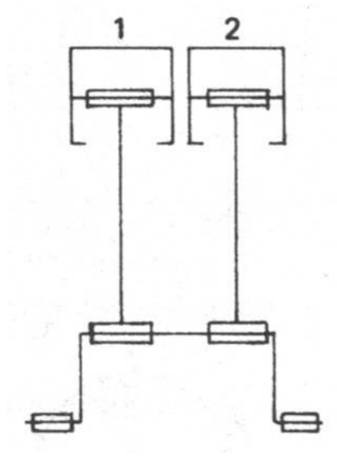
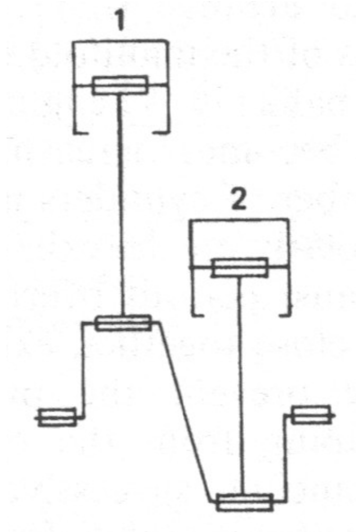
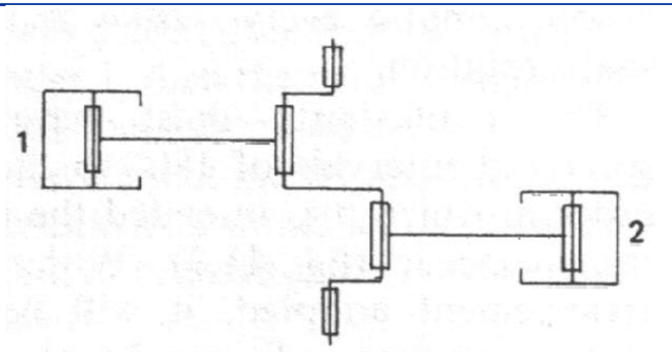
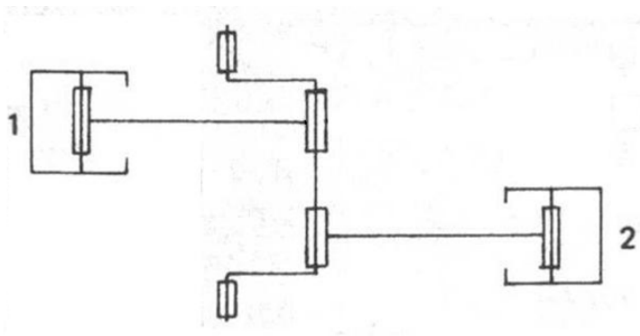
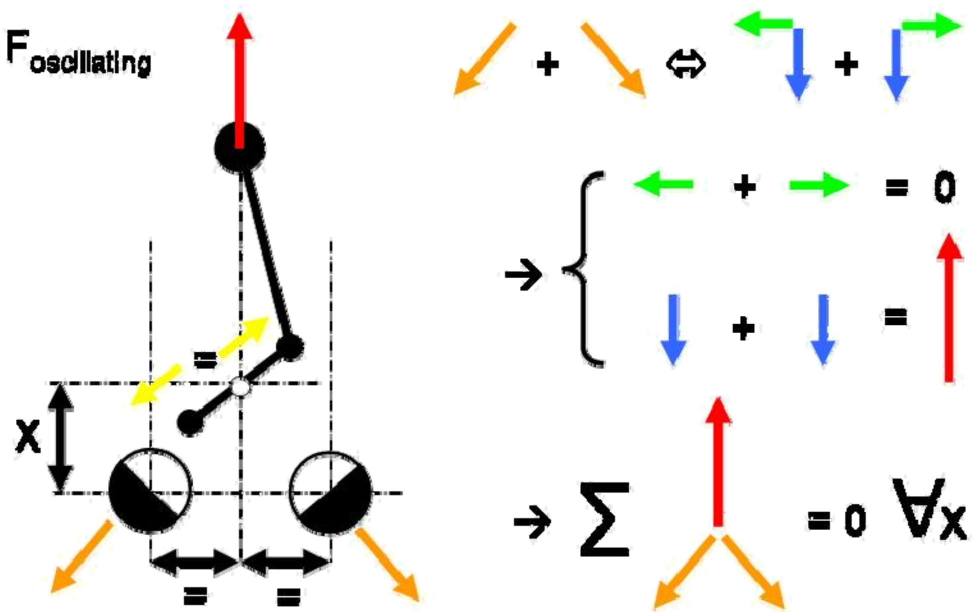
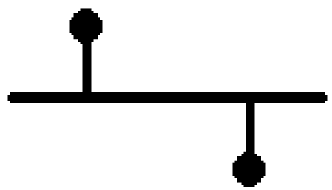
	In-phase	Out-of-phase
In-line		
Boxer		

Balancing systems

- Optimization of the crankshaft counterweights
- Addition of first or second order balance shafts



Normal balance shaft (inertia forces)



Double balance shaft (inertia moments)

Analytical model

- Calculation of inertia forces produced by pistons motion

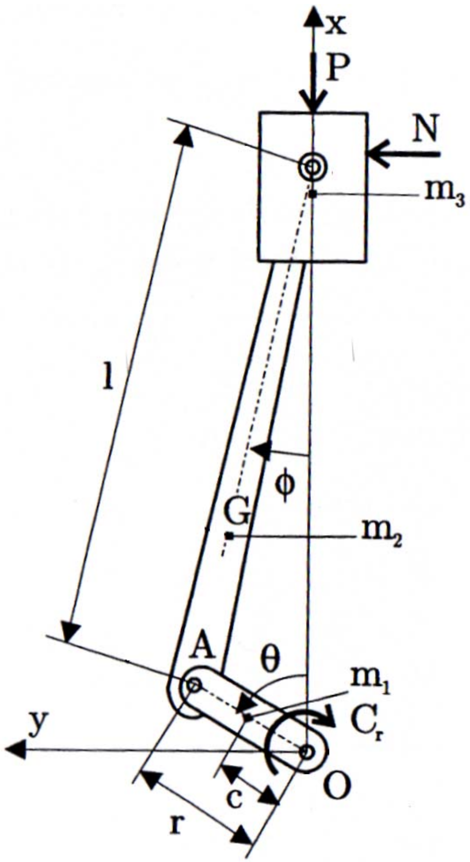
$$F_x = r \cdot \omega^2 \cdot [m_r \cdot \cos\theta + m_o \cdot (\cos\theta + A_2 \cdot \cos 2\theta + A_4 \cdot \cos 4\theta + A_6 \cdot \cos 6\theta + ...)]$$

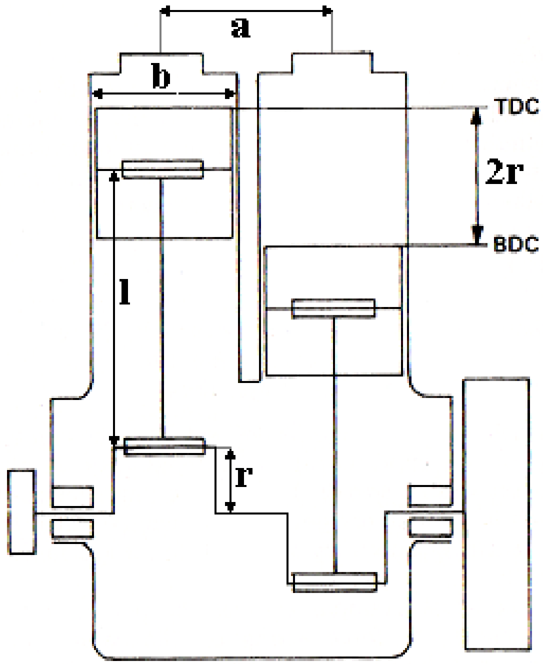
$$F_y = r \cdot \omega^2 \cdot m_r \cdot \sin\theta$$

$$m_r = m_1 + \frac{2}{3} \cdot m_2$$

$$m_o = m_3 + \frac{1}{3} \cdot m_2$$

$$F_{res} = \sqrt{F_x^2 + F_y^2}$$





Rigid multibody model

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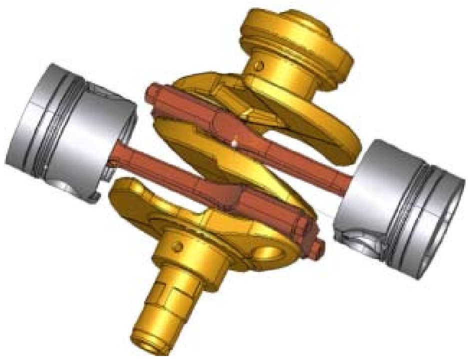
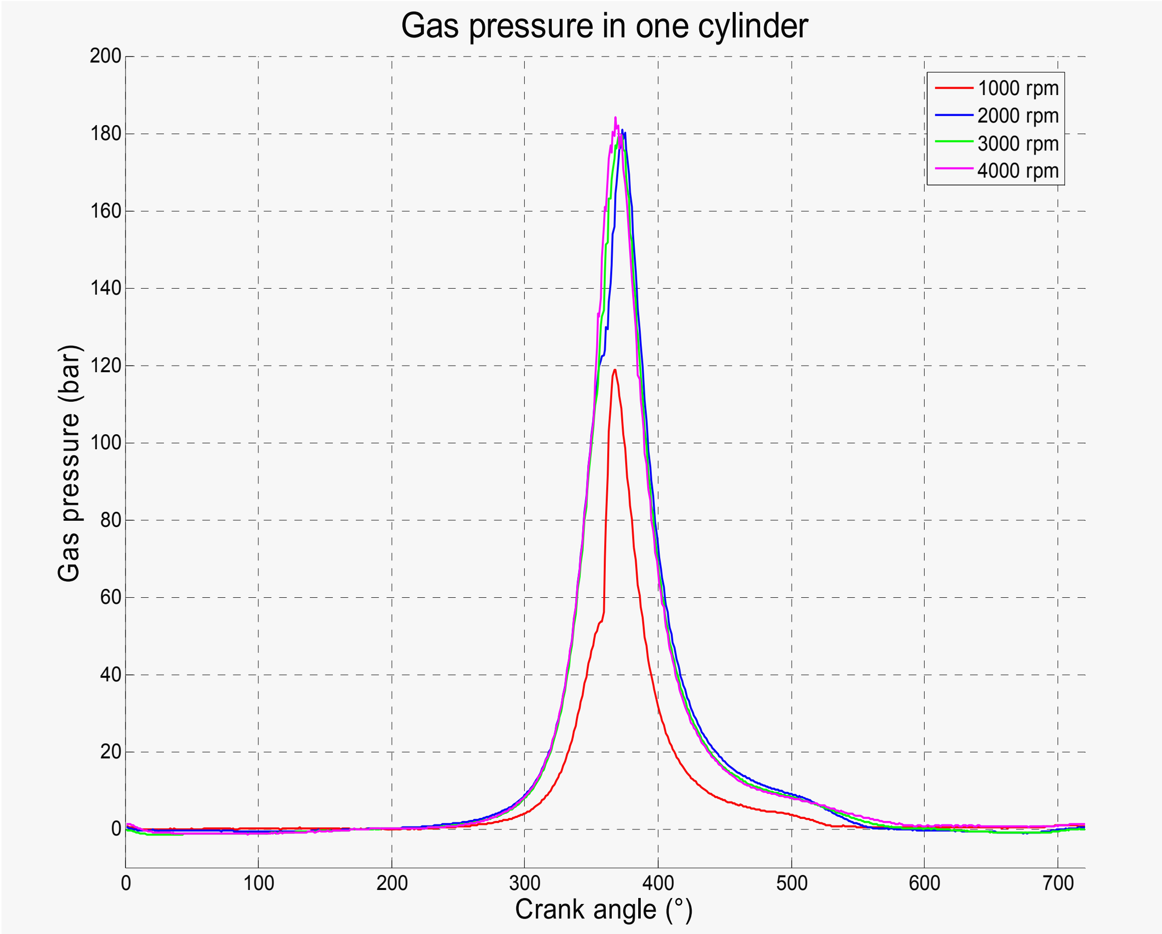
- Rigid multibody model using finite element approach (with ***SamcefField Mecano*** software)
- Real engine parts geometry from CAD models
- Two simulations
  - Kinematic simulation with imposed crankshaft rotation speed => position, speed & acceleration (inertia force)
  - Dynamic simulation with gas pressure effect => total forces acting on each part of the engine



Gas pressure model

- Gas pressure inside one cylinder (experimental data)



Flexible multibody models

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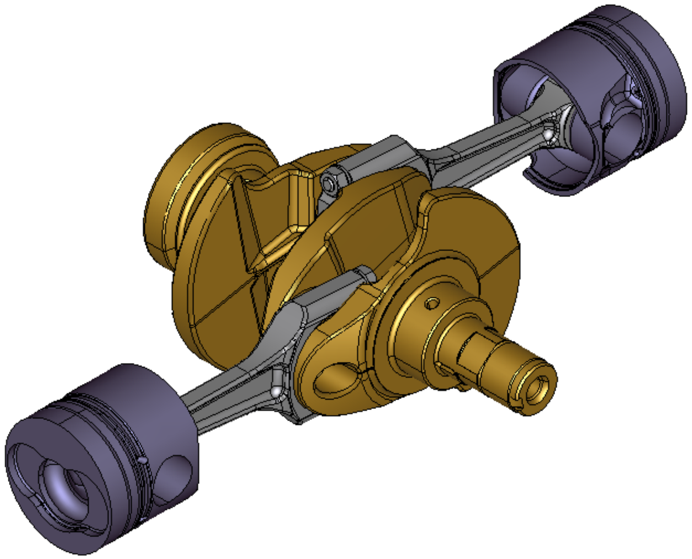
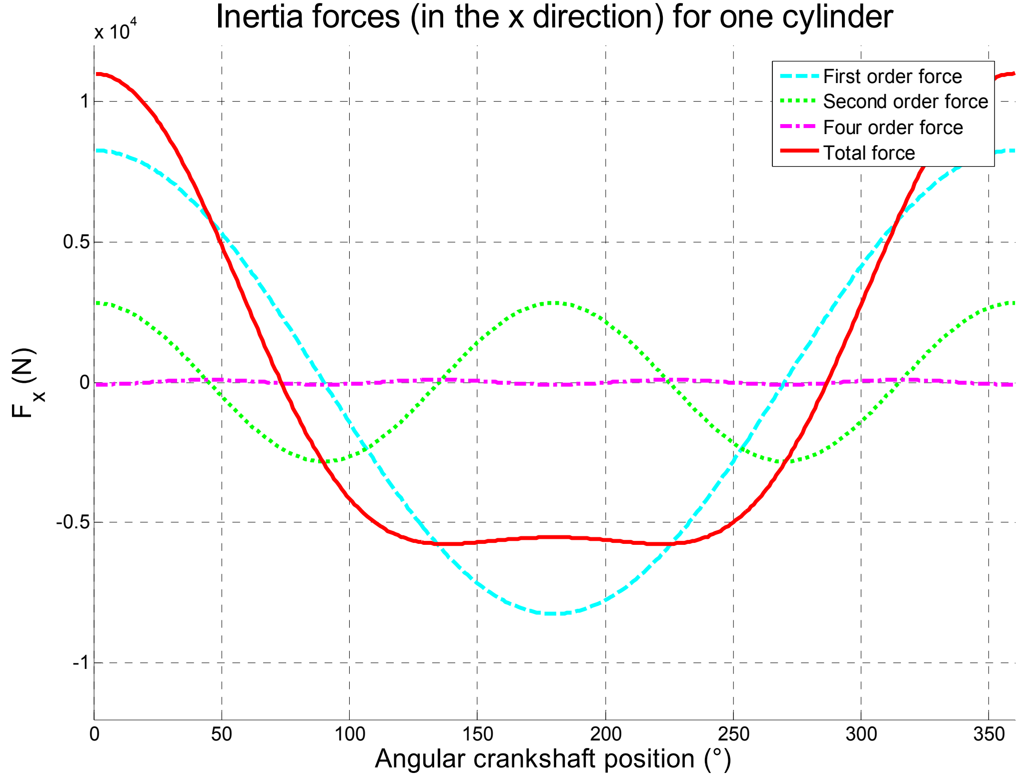
- Simulation of flexible model thanks to the finite element approach
- Two types of simulation are carried out to determine **crankshaft** strains and stresses
  - Static simulations of the crankshaft using forces calculated in the rigid multibody simulation (critical load cases)
  - Dynamic multibody simulation with pistons and connecting rods considered as rigid bodies and crankshaft meshed with flexible finite elements (several models of bearing surface are compared)

Results and discussion



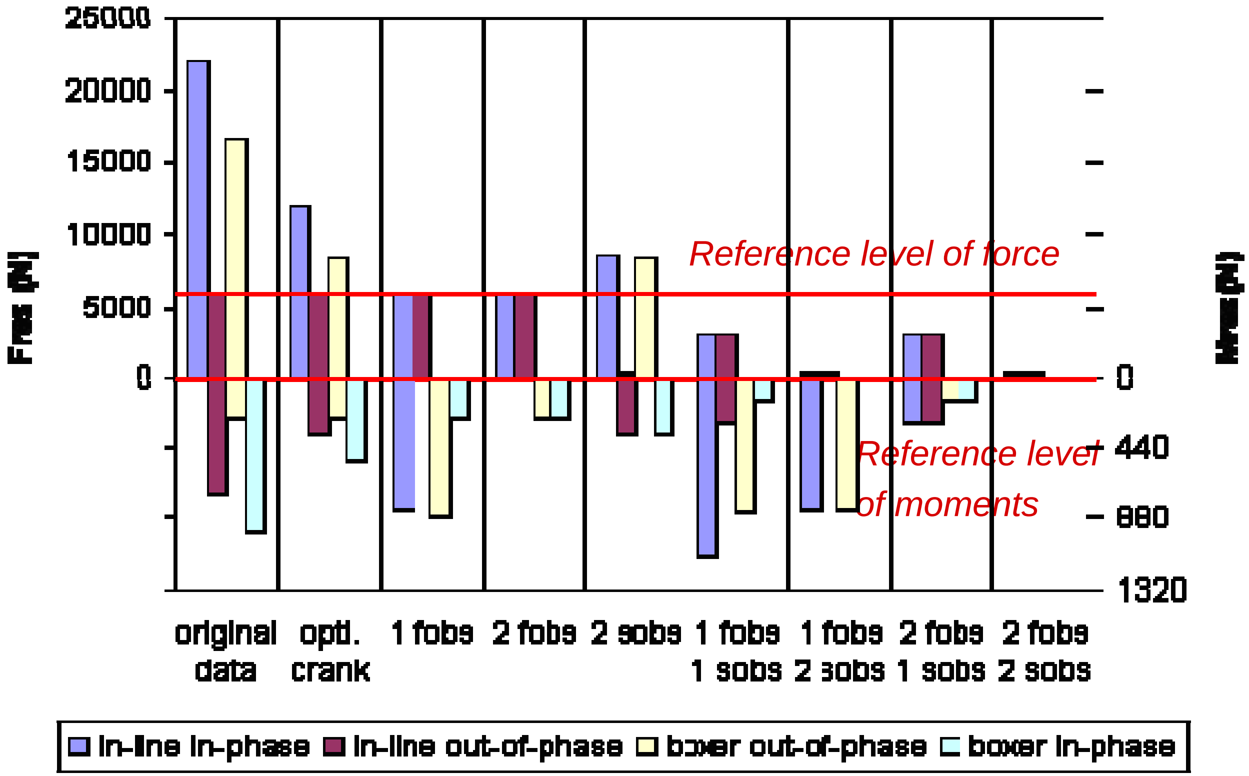
Analytical model

- Calculation of inertia forces generated by **one cylinder**
- Maximum value ≈ 11000 N => balancing system needed



Engines comparison

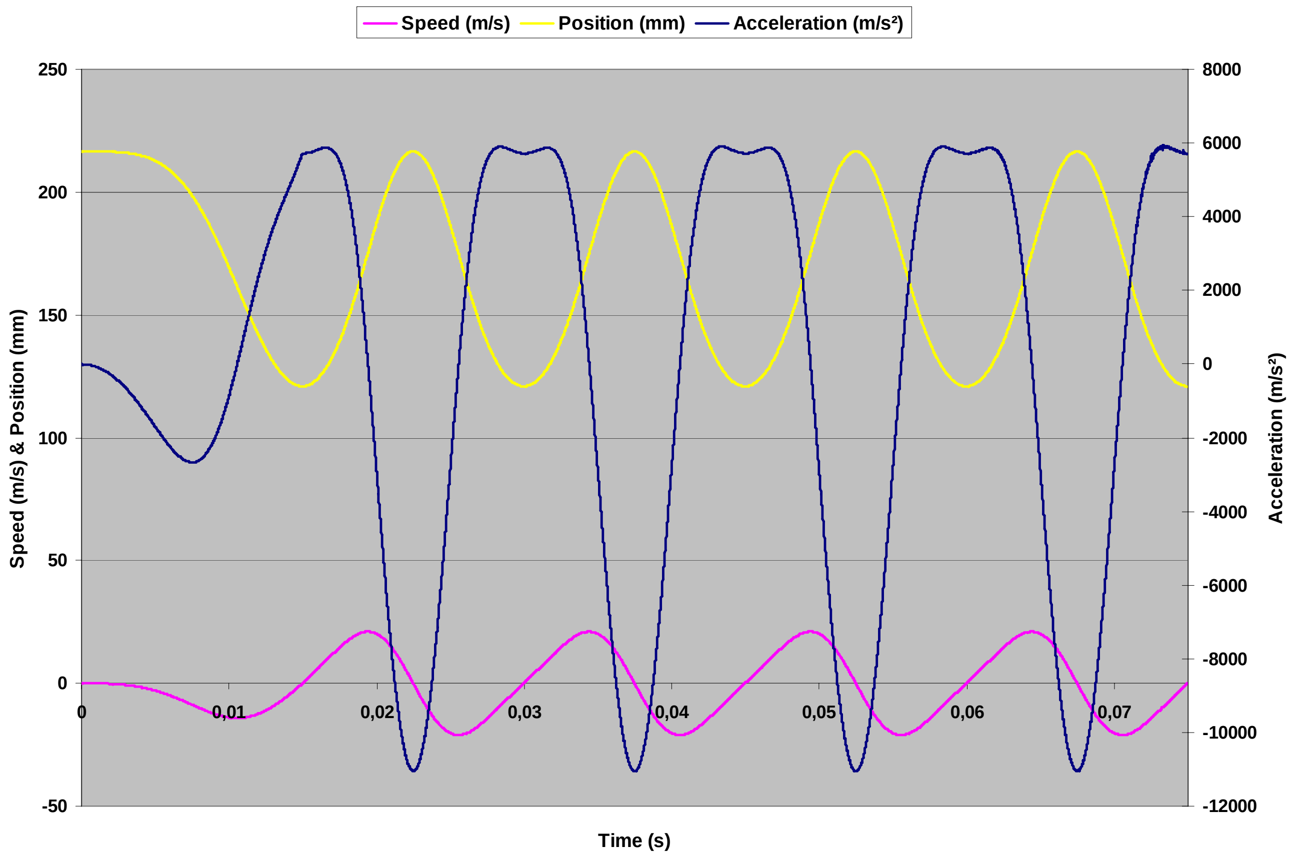
- Forces and moments depending of the ICE configuration
- They can be highly reduced by appropriate balancing systems at the price of a higher complexity (compromise)



- **fobs**: first order balance shaft(s) (rotating at the crankshaft speed)
- **sobs**: second order balance shaft(s) (rotating at twice the crankshaft speed)

Rigid multibody model

- Kinematic simulation with imposed crankshaft speed (varies from 0 to 4000 rpm in 0,015 s then constant)



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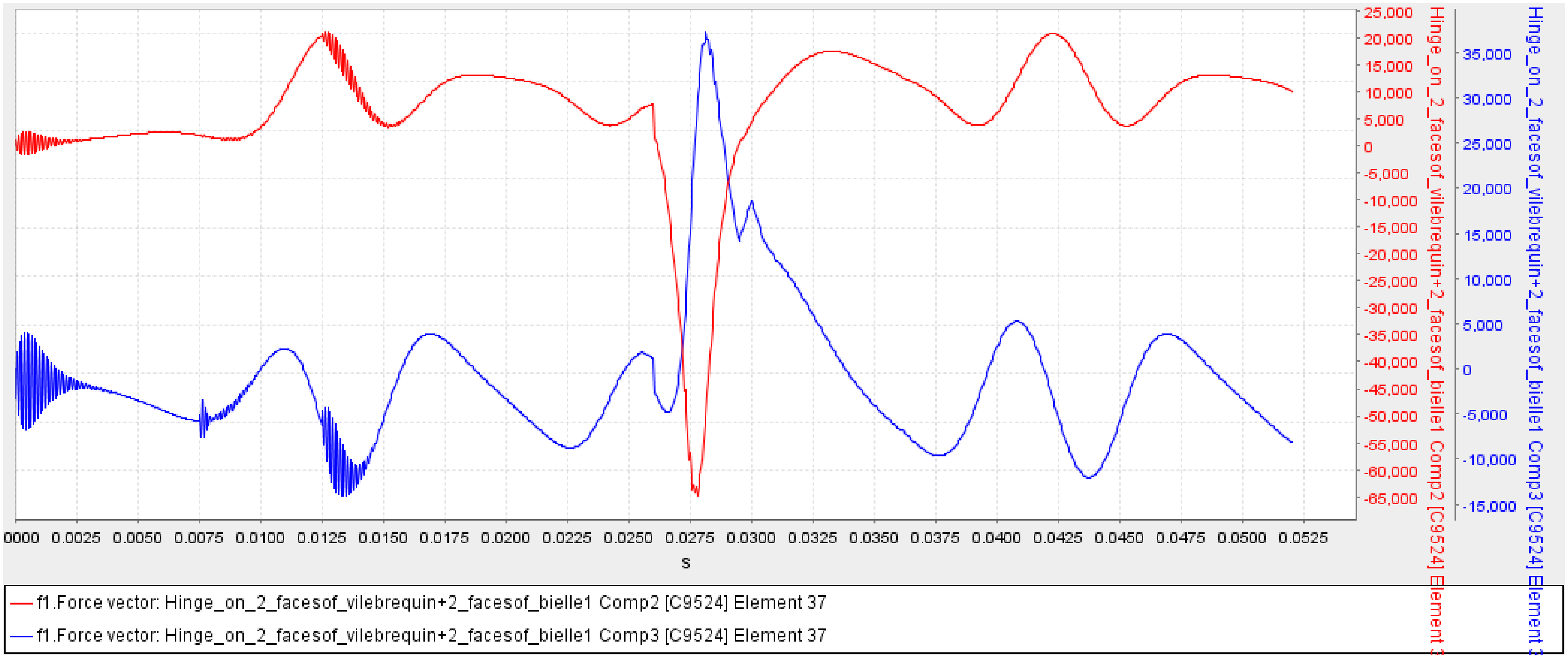
Rigid multibody model

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



Rigid multibody model

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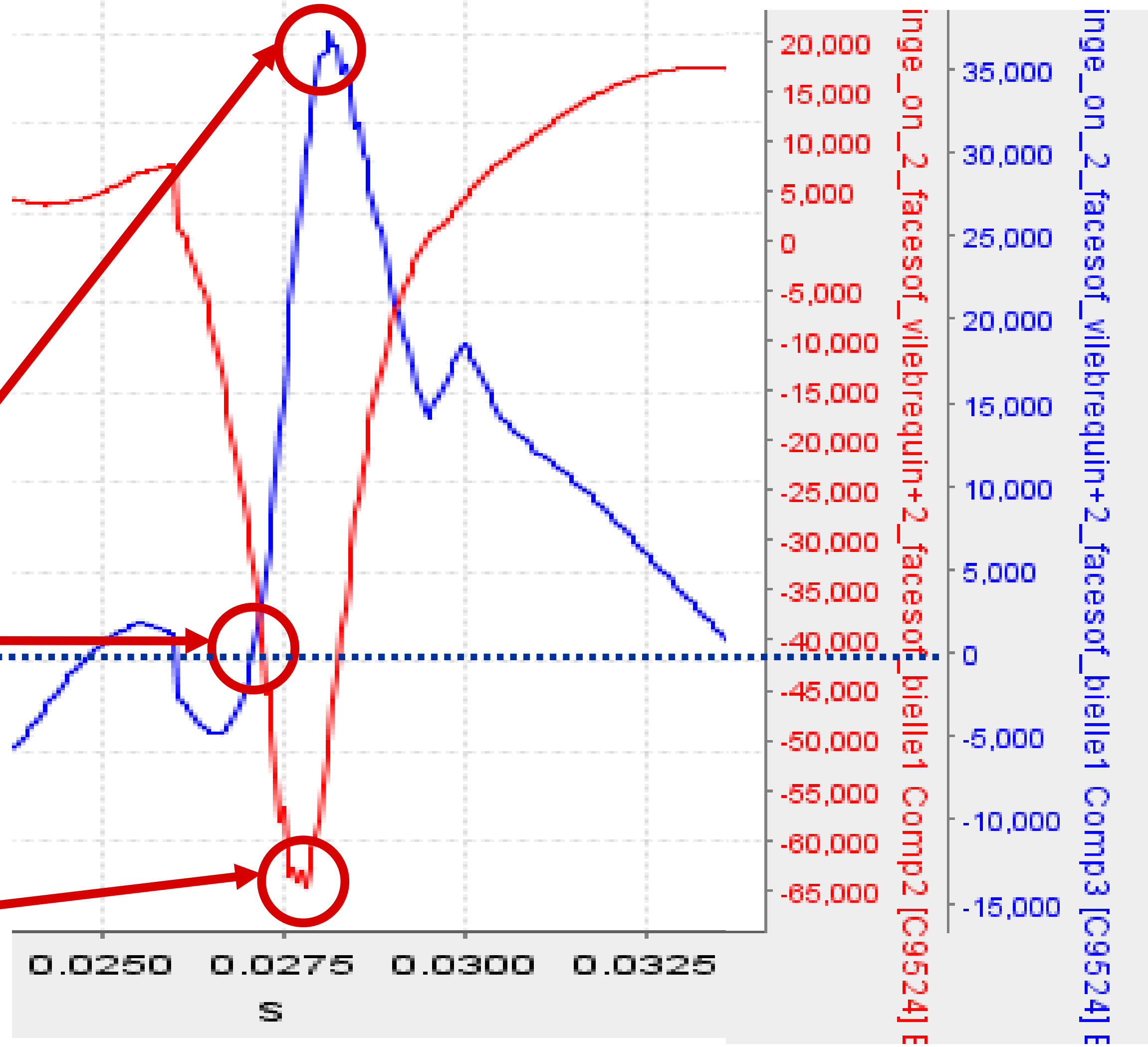
- Load cases for the strain and stress analysis
  - "Maximal tangential force" load case
  - "Top dead center" load case
  - "Maximal radial force" load case



Flexible multibody model

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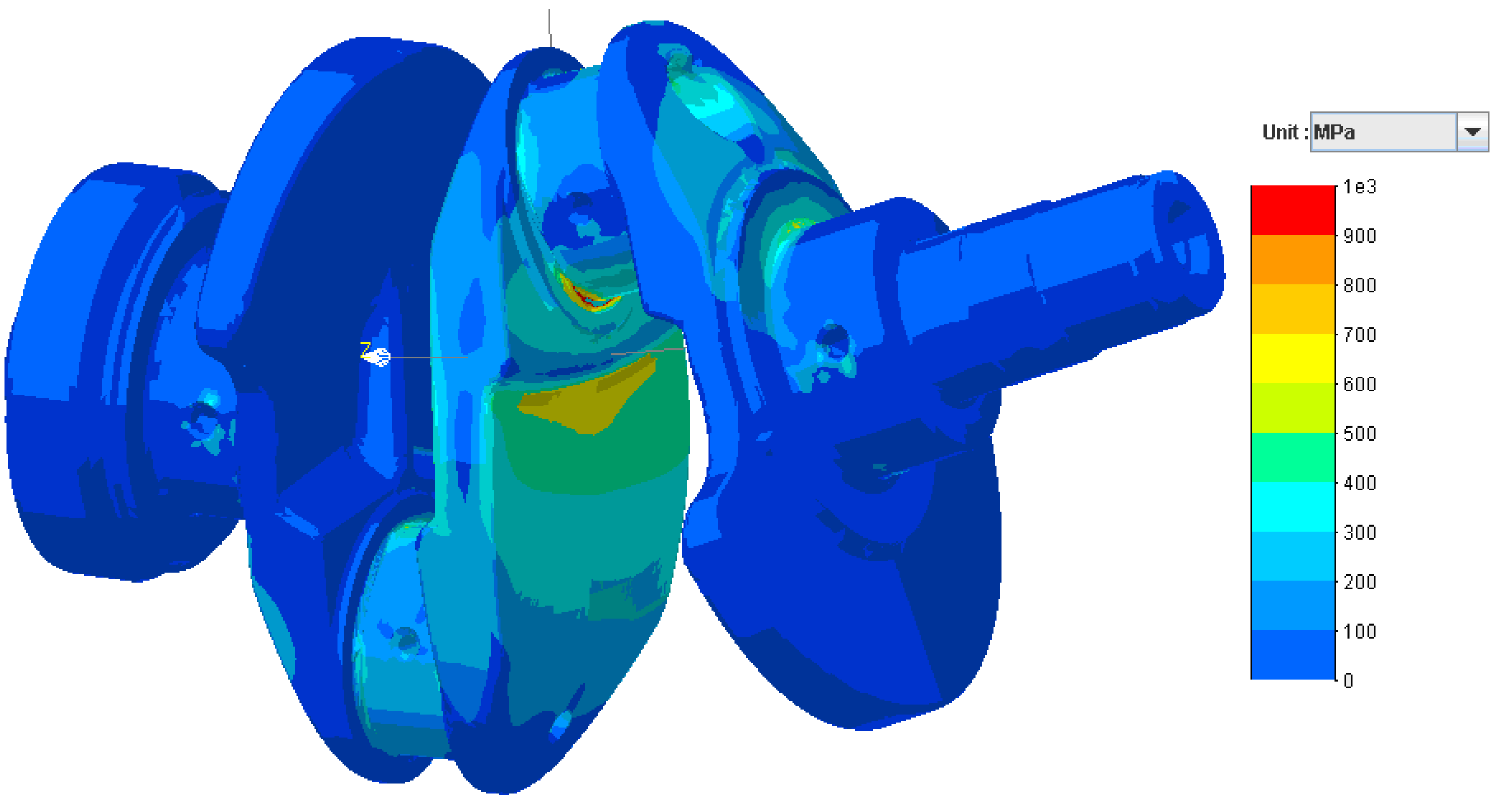
- Static simulations are performed to evaluate crankshaft maximal strains and stresses
  - Critical load cases are deduced from the rigid simulation
  - Crankshaft is meshed with 4 mm second order tetrahedral elements
  - Forces and boundary conditions are applied on the crankshaft by means of flexible rings added on the bearing surfaces to avoid overstress problems

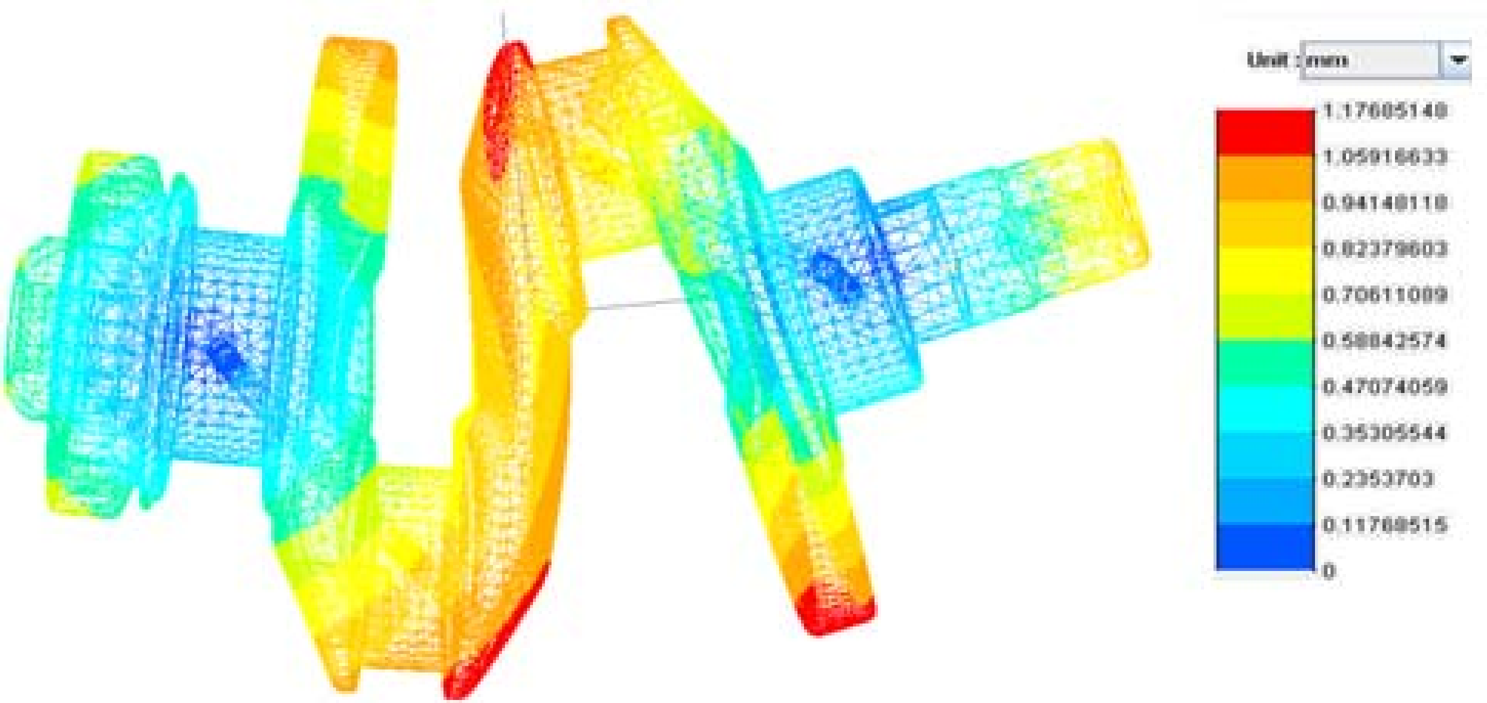
Flexible multibody model

- Crankshaft stresses for the "maximal radial force" load case



Flexible multibody model

– Crankshaft displacements for the “maximal radial force” load case



Flexible multibody model

- Dynamic simulation of the engine
  - Crankshaft strains and stresses are calculated for the complete cycle
  - Different models of bearing surfaces are simulated
  - Crankshaft is meshed with 8 mm first order tetrahedral elements
  - Results are first given for the top dead center position of the piston ("top dead center" load case) and then some results are given for the most critical load case

Flexible multibody model

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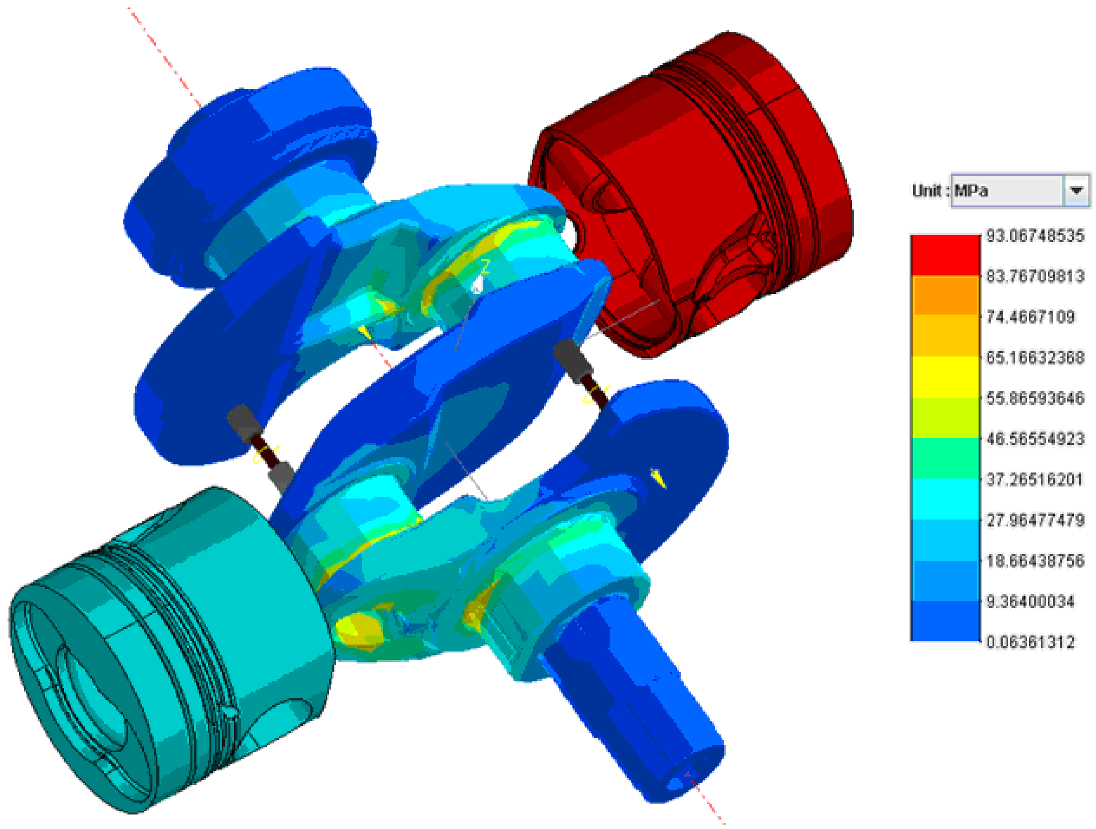
– "Rigid hinge" bearing model



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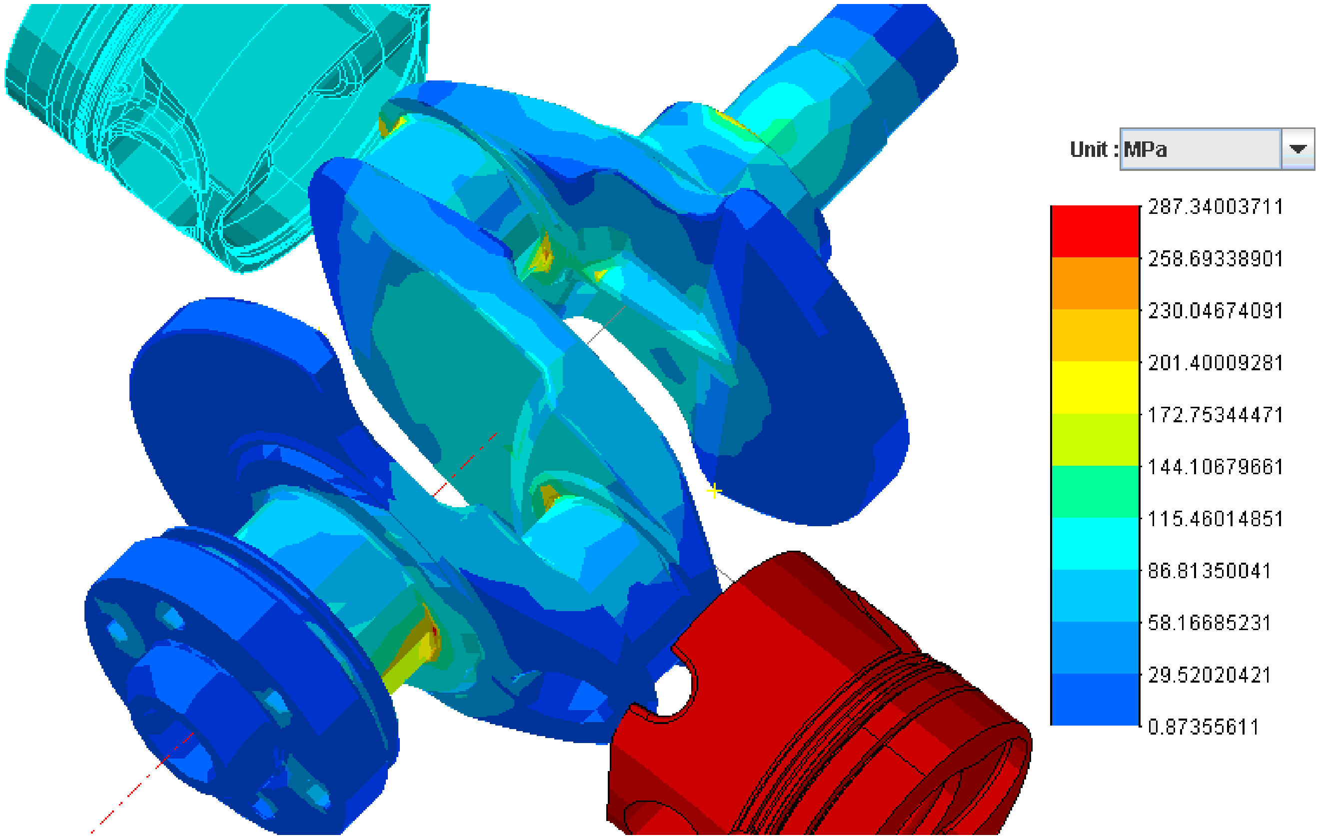
– “Flexible-rigid contact” bearing model with a clearance of 50 µm



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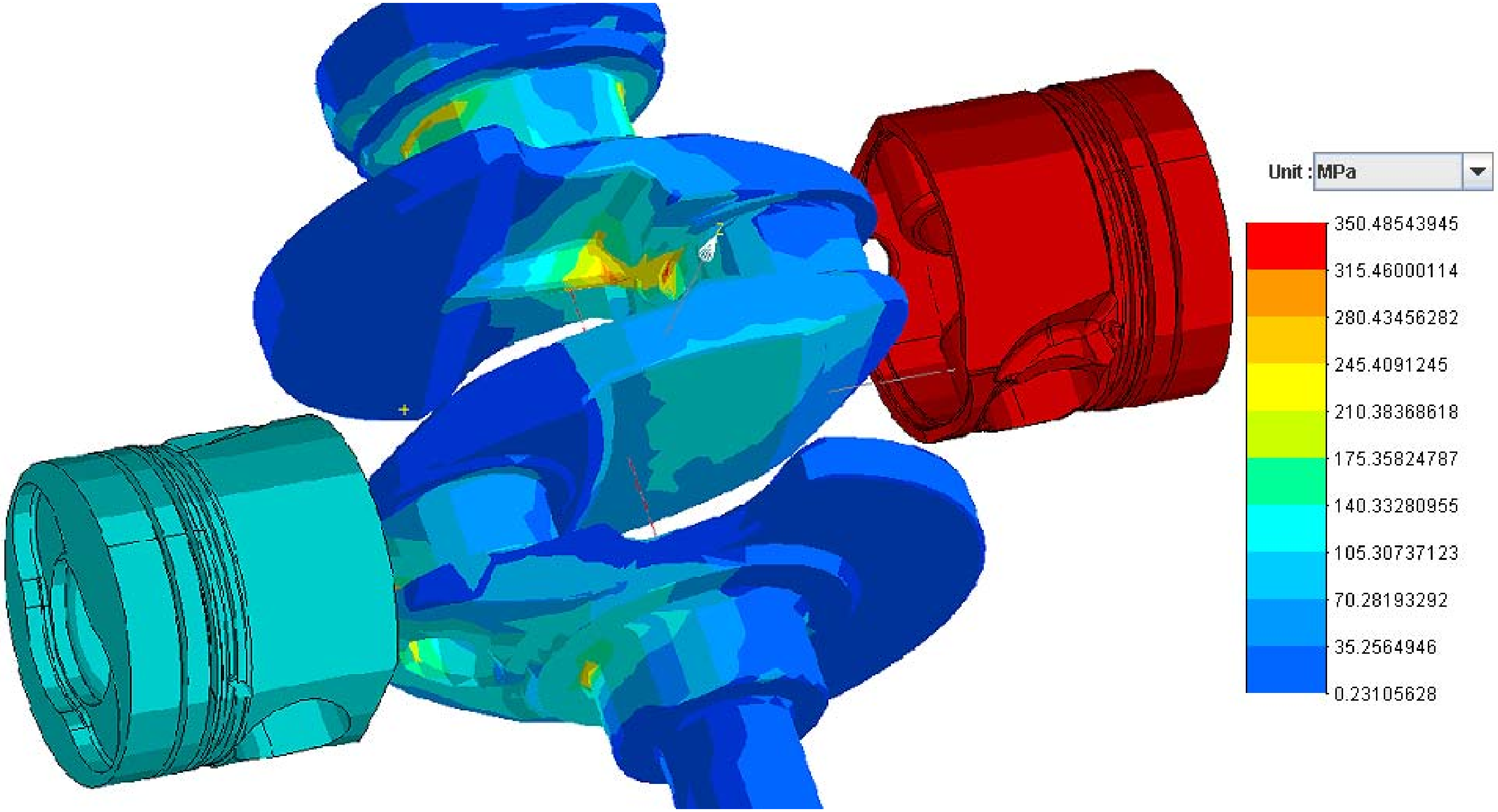
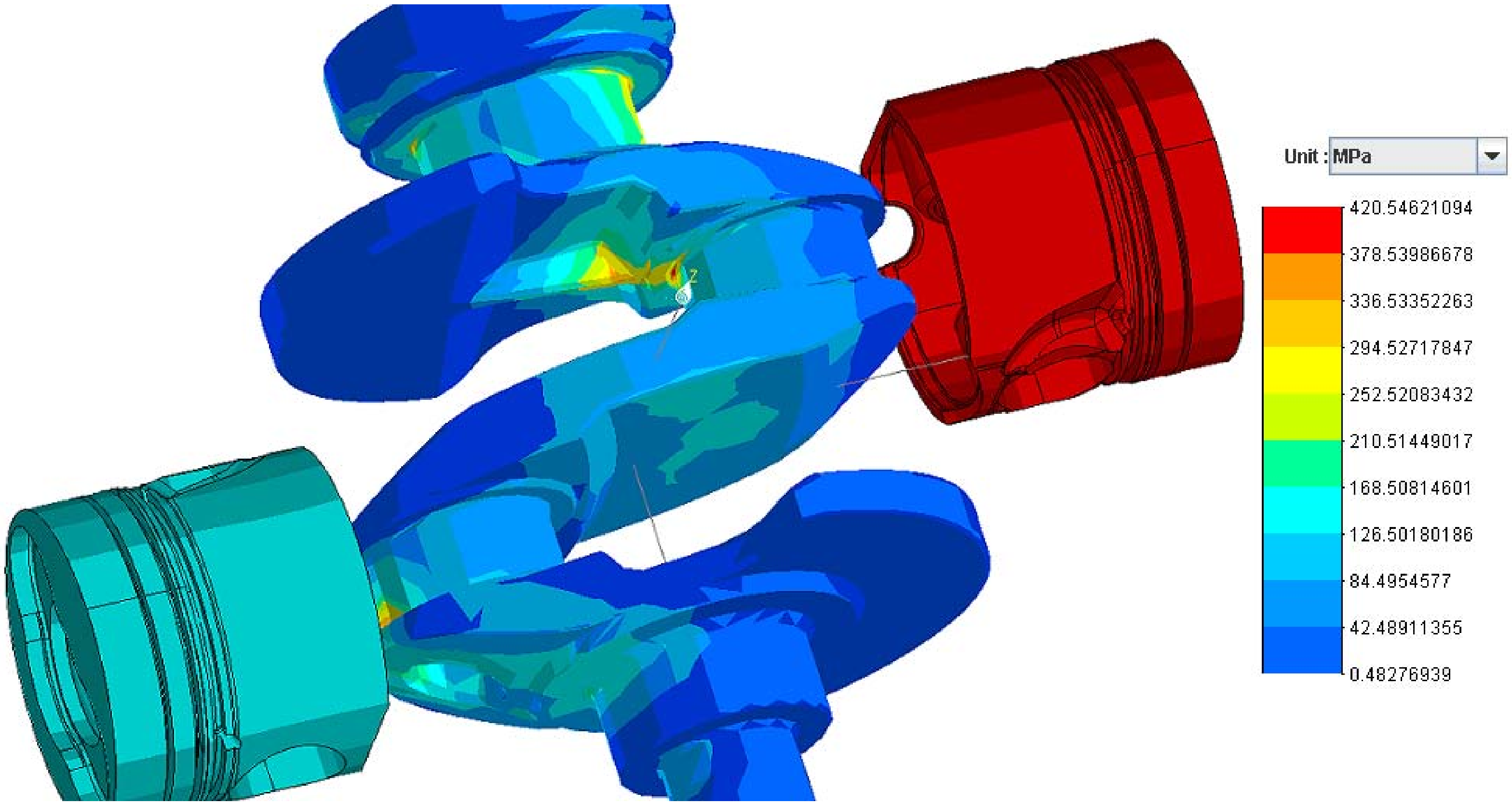
– “Radial bushing” bearing model (stiffness equal to $2*10^6$ N/m)



Flexible multibody model

– "Hydrodynamic bearing" model (viscosity equal to 0,01 Pa*s)



Flexible multibody model

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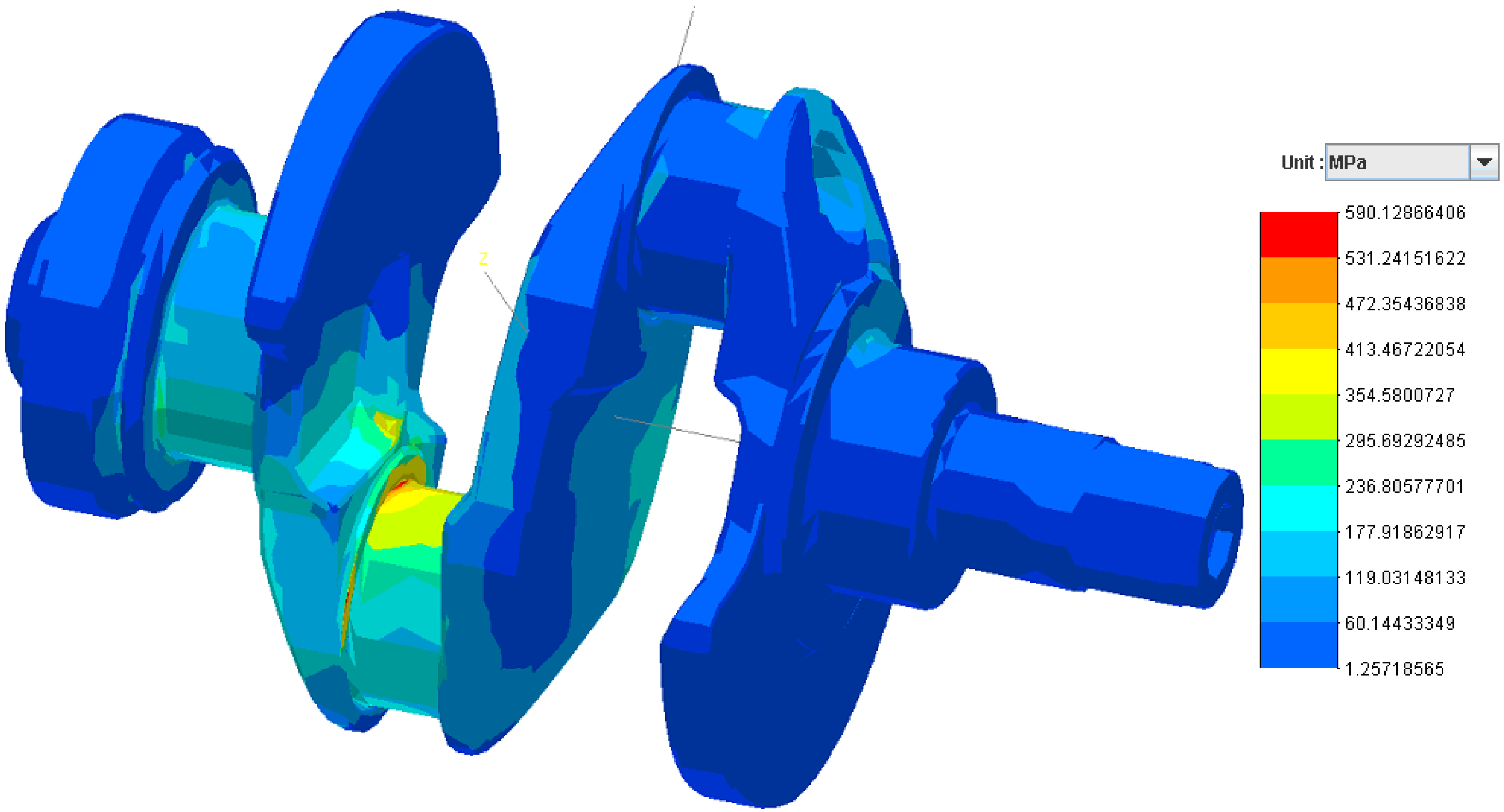
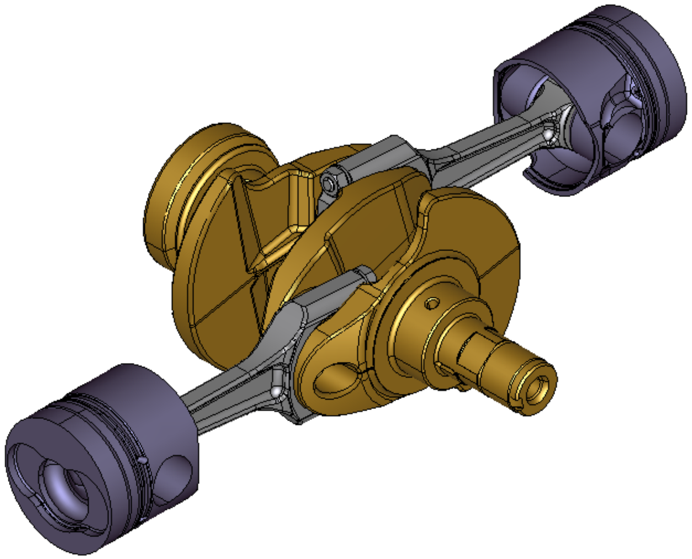
- “Maximal tangential force” load case (critical)
  - “Hydrodynamic bearing” model (viscosity equal to 0,01 Pa*s)



Conclusion



Conclusion

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- Each configuration of engine has its own characteristics in term of inertia forces and moments, which can be reduced by addition of counterweights or balance shafts

	First order forces	High order forces	First order moments	High order moments
In-line, in-phase	Yes	Yes	No	No
In-line, out-of-phase	No	Yes	Yes	No
Boxer, in-phase	No	No	Yes	Yes
Boxer, out-of-phase	Yes	No	No	Yes

Conclusion

- Multibody simulations offer interesting prospects for engine design:
  - Calculations of inertia forces and moments (rigid body simulation)
  - Fast (a few minutes) evaluation of crankshaft maximal strains and stresses thanks to static simulations
  - Flexible body dynamic simulation allows making more precise strain and stress analysis for all crankshaft positions
- Main difficulty is to make correct bearing surfaces models

Perspectives

- Creating multibody models of other twin-cylinder engine configurations
- Comparison of engines based on crankshaft strains and stresses
- Stress analysis of other engine parts (pistons and connecting rods)

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Thank you for your attention