CO_2 Reduction

Comparison of Belt and Chain Front End Drive for a Passenger Car High Pressure Pump

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Germany, 5 - 6 April 2016

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High Pressure Pump Drive

- Fuel Economy – Direct contribution
  - Parasitic losses
    - Friction and Damping losses
    - Hub loads and bearing losses

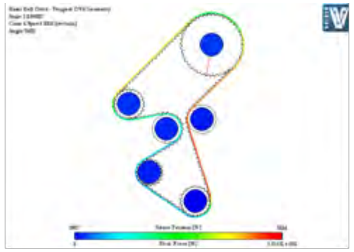
- Fuel Economy – Indirect contribution
  - Injection Dynamics
    - Torque oscillation
    - Drive elongation
    - Damping of C/S torsional vibrations
    - Pressure build-up rate in common rail

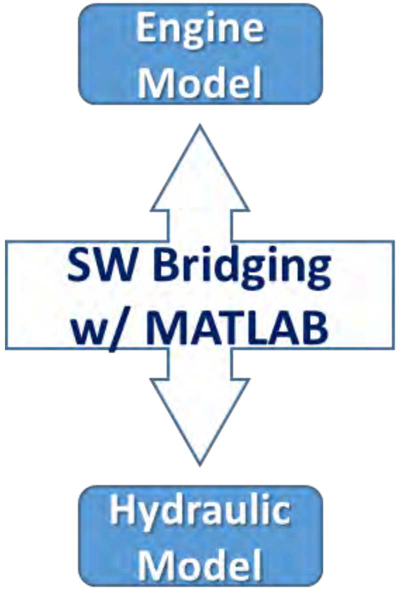
Hydraulics & Mechanics

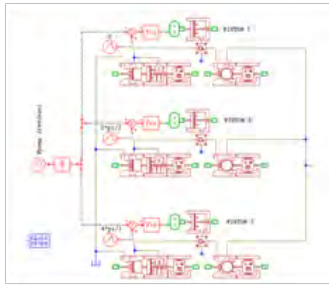
- **Conventional simulation**
  - Mechanic model excited by imposed delivery pressure profile on plunger or torque measured data
  - Hydraulic simulation with imposed rigid motion of plunger or pulley
- **Integrated model**
  - Hydraulic and Mechanic co-simulation
  - Pressure build-up function of computed elastic motion of plunger
  - Mechanical model excitation through simulated pressure at plunger
  - Interaction allowed
  - Imposed crankshaft motion, including torsional vibrations

Simulation Methodology

- Mechanical Model – VALDYN
  - Detailed pump dynamic model
  - Used worldwide since decades for belt and chain drive modeling
- Hydraulic model - AMESim
  - Developed by Bosch
  - Modified to be integrated into a co-simulation;
- Parent Model – Simulink
  - Monitors passage of results between models
  - Coordinates computation time
  - Uses co-simulation libraries available in both environments

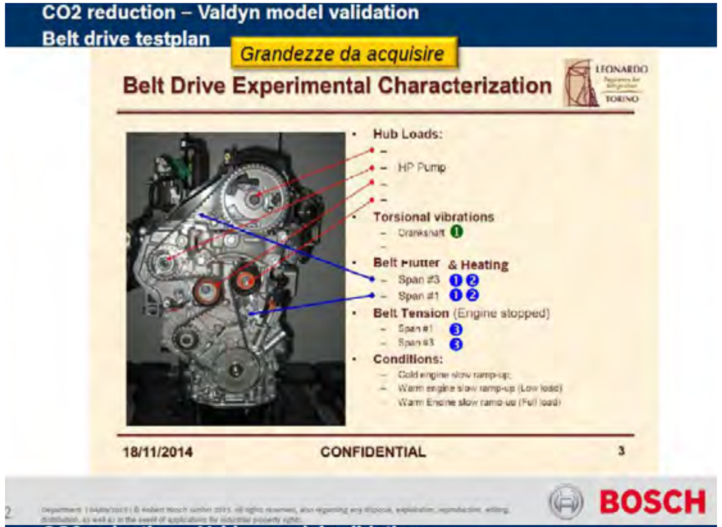


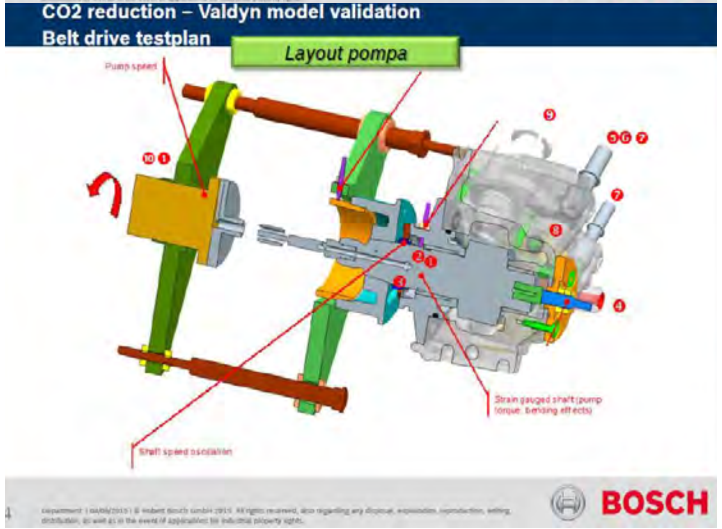




Validation methodology

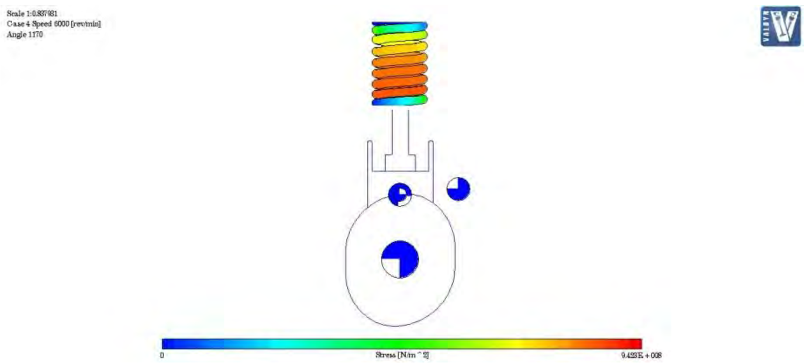
- **Three sources of experimental data (belt)**
  - HPP torque measurement @ test rig;
  - Instrumented HPP on engine @ OEM production plant;
  - Specific engine test at Bosch CVIT
- **Specific instrumentation for:**
  - Belt slap
  - HPP hub load and torque
  - HPP housing vibration
  - Injection system characterization (low and high pressure circuits)

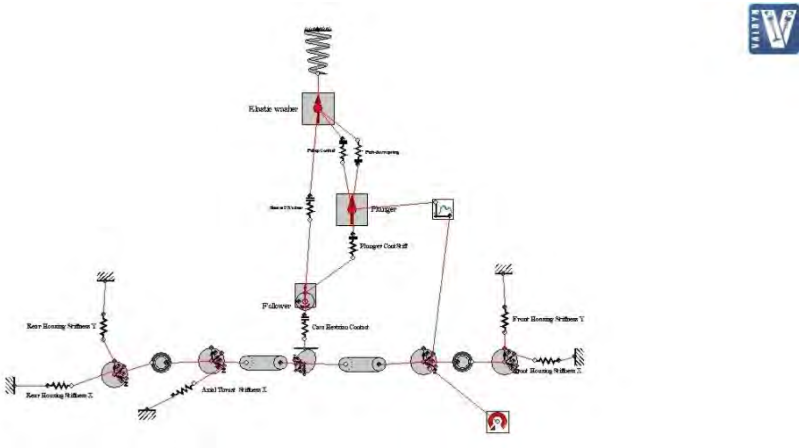




Pump Model

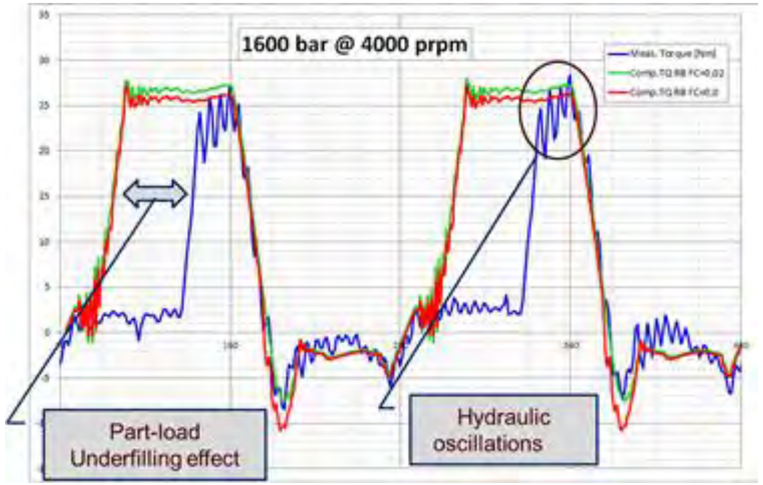
- **Cam – Roller contact**
  - EHD Theory for oil film thickness and friction coefficient assessment
  - Fuel piezo-viscosity parameters
  - Statistic asperity contact model to define friction torque (GWT model)
  - Retainer spring modeled
- **Spring**
  - Multi-mass model (10 segments per coil)
  - Coil contacts and coil surge modeled
- **Shaft**
  - Two flexible elements
  - Two pivot bearing with constant friction coefficient;
  - In the complete model with belt, an additional front cantilever part and toothed pulley are included

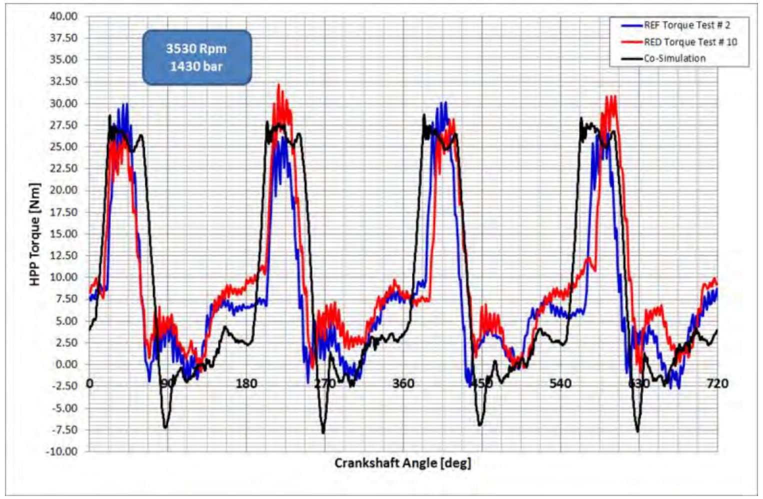




Pump Model Validation

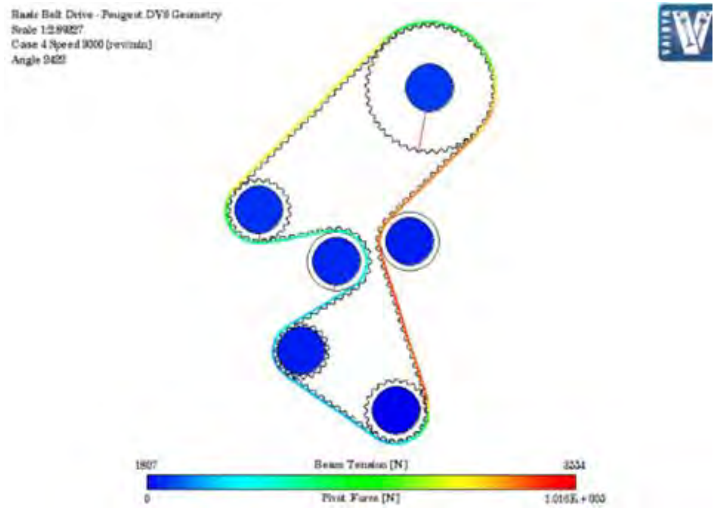
- **Two Phases**
  - Preliminary
    - Stand-alone model, imposed pressure profile from previous injection system simulation;
    - Compared with available pump test rig data;
    - Use to validate torque and friction behavior
  - Final
    - Complete model with belt drive
    - Integration with hydraulic model
    - Compared with engine *ad-hoc* measurements
- **Model evolution**
    - @ part load the throttling of the pump by the Metering Unit can be predicted only with the integrated model

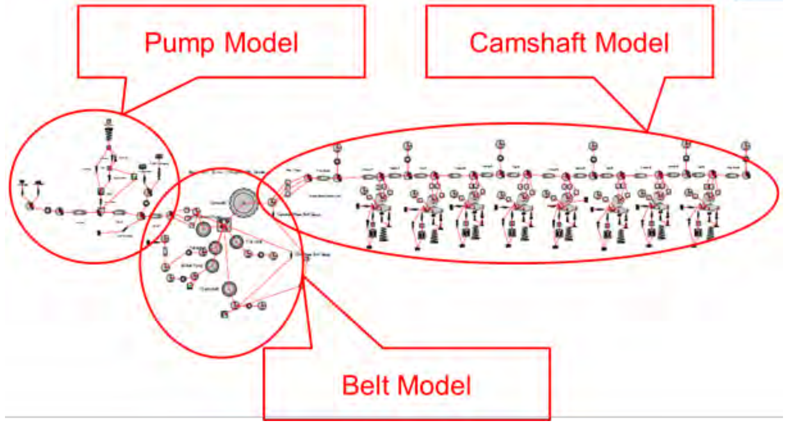




Belt Model

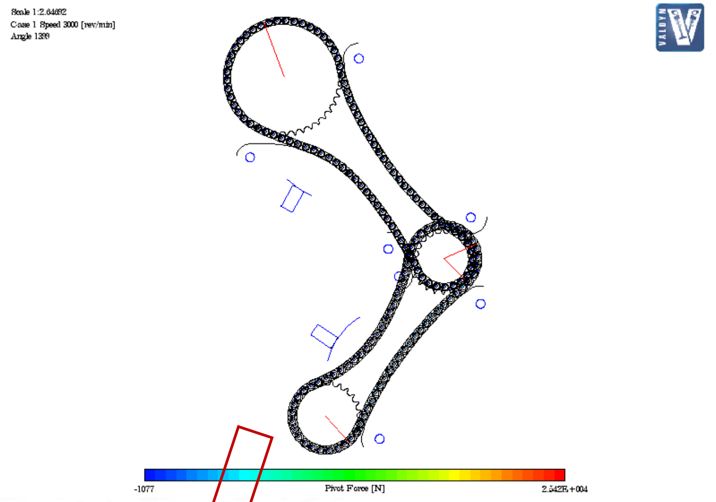
- **Model**
  - Succession of beams with profiles entering the grooves of the pulleys
  - Both contact friction and internal damping modeled
  - Automatic pivoting tensioner
- **Layout**
  - Corresponding to an engine available for tests and on which past engineering experience was available
- **Components**
  - Direct information from suppliers was not available
  - Information derived from purchased spare parts
  - Single camshaft and valve drive included
  - Belt lay-out specific and derived from existing lay-outs
  - Information collected either from spare parts and experimental results

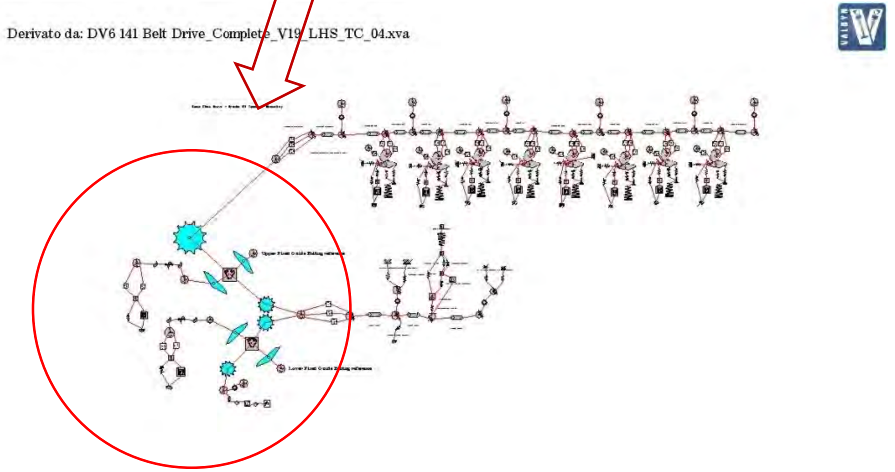




Chain Model

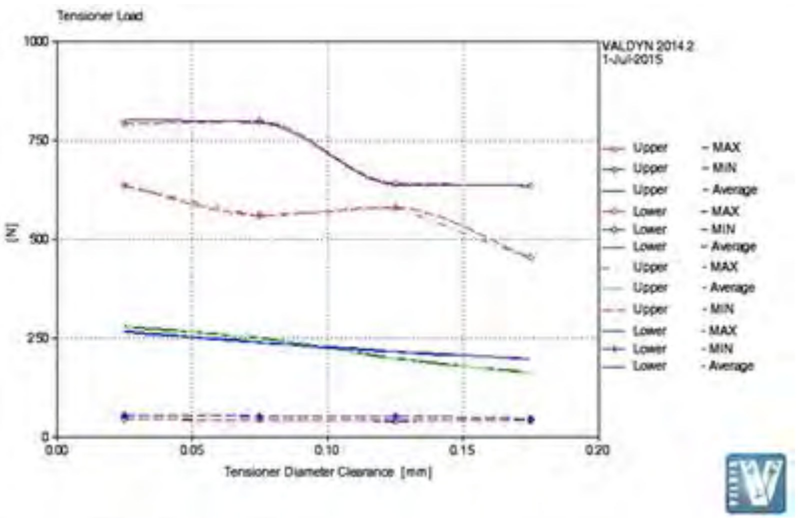
- **Model**
  - Series of partially elastic links with both friction and damping at elements' interface
- **Lay-out**
  - Designed from scratch
  - Concept derived from an existing engine
- **Lower Chain**
  - Step 9,525 mm
  - 72 links
  - 25 teeth sprockets
  - Specs: IWIS G68 HR-4
- **Upper Chain**
  - Step 9,525 mm
  - 90 links
  - 21/42 teeth sprockets
  - Specs: IWIS G67 HR-6
- **Camshaft**
  - Model with one single camshaft to allow for direct comparison with belt drive

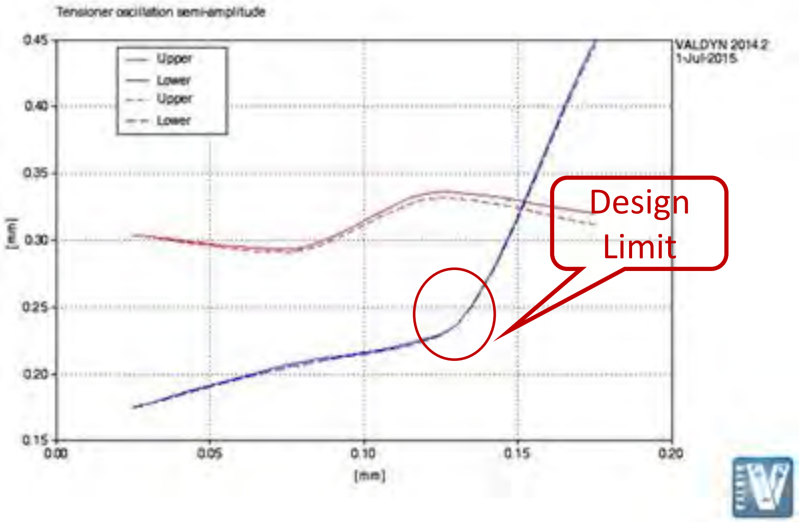




Chain Model Optimization

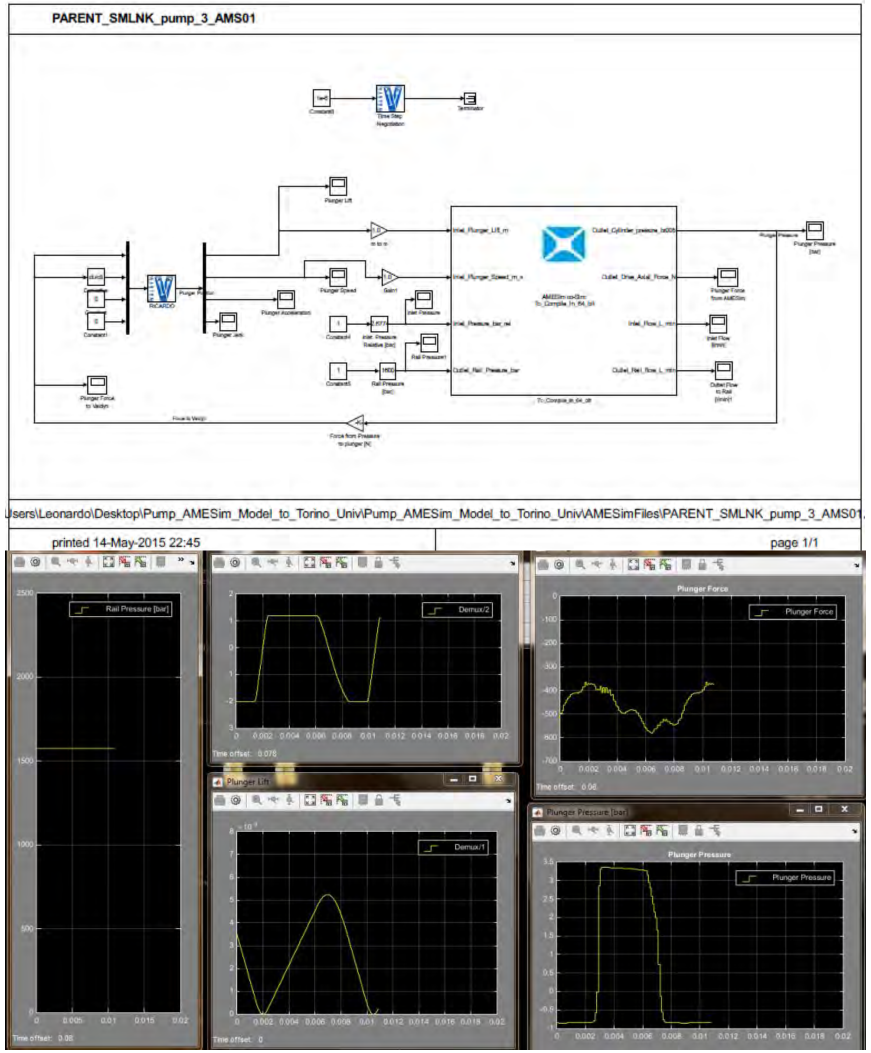
- **Parameters**
  - Tensioners preload
  - Tensioners leakage
  - Guide friction
- **Criteria**
  - Minimum friction in dynamically stable conditions
  - Minimum attainable friction coefficient for guides





Hydraulic Model Integration

- **Hierarchy**
  - Simulink model is parent to both VALDYN and AMESim models
  - S/link coordinates both time step definition and synchronization
- **Visualization**
  - Simulink terminals allow for constant monitoring of the run
- **Simulation time**
  - Approx. 5 engine cycles to achieve convergence
  - Elapsed time: 6h to 8h



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Belt Model Validation

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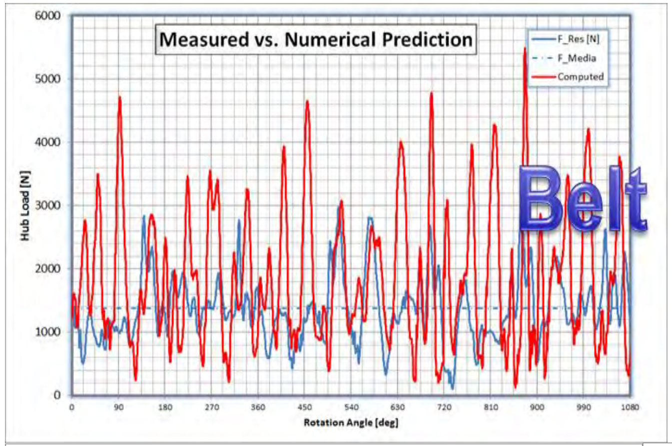
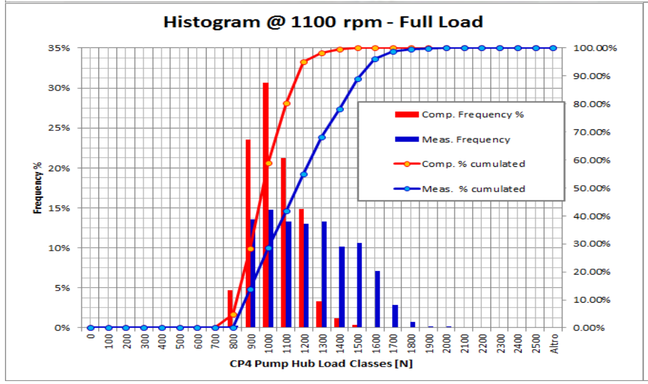
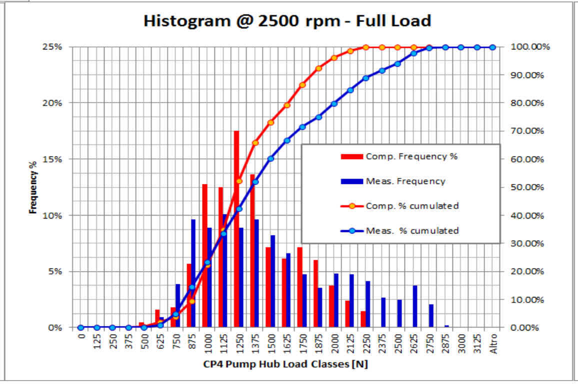
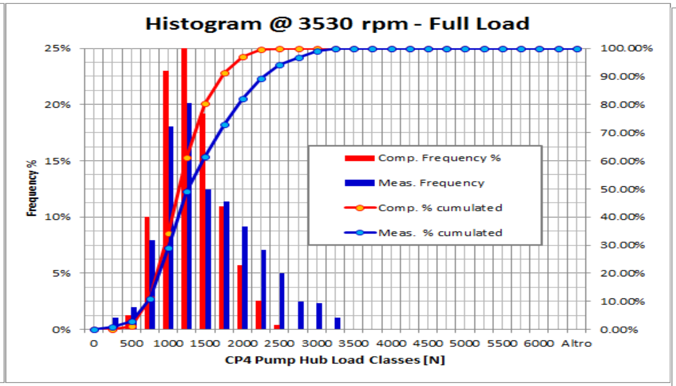
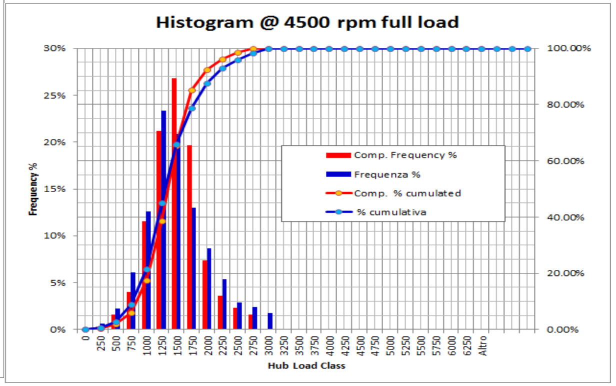


- **Hub Load Comparison**
  - Very dispersed results both in numerical and experimental results, no cyclic repetition;
  - Comparison of frequency distribution curve is used;
  - Very good matching at various speed is obtained after tuning of tensioner characteristics;



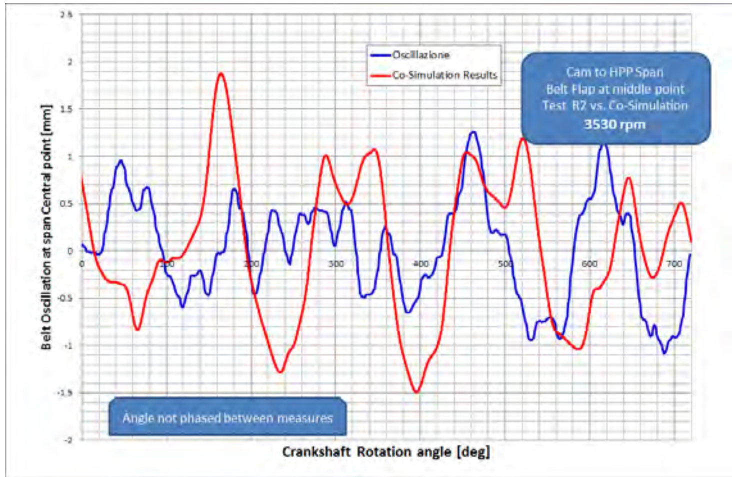


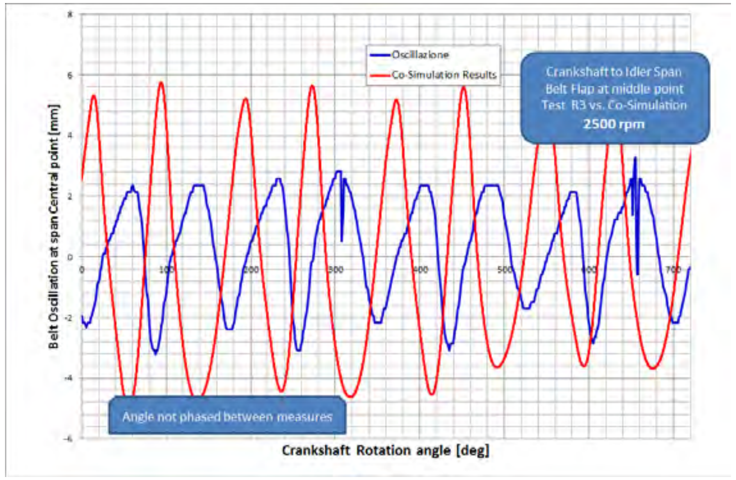


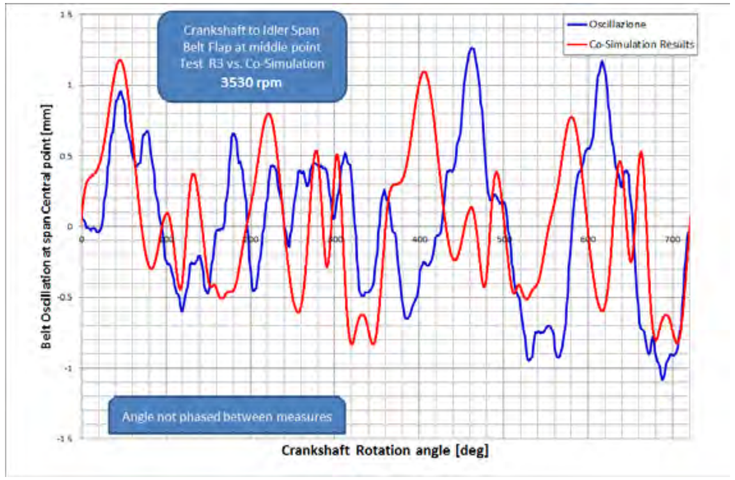


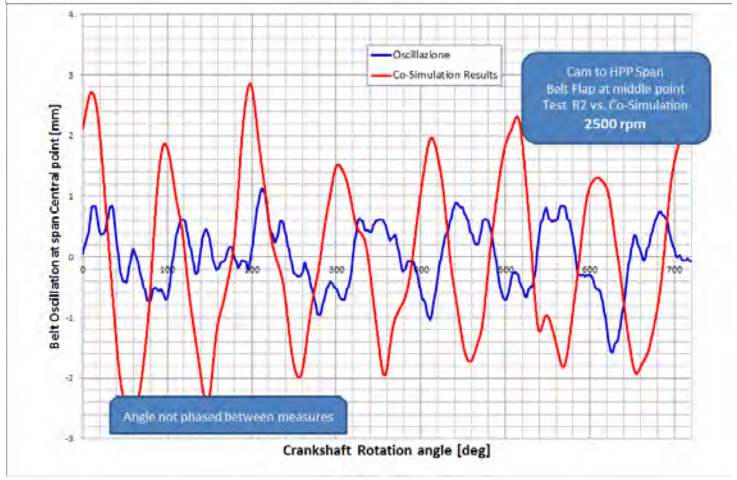
Belt Model Validation

- **Belt flap Comparison**
  - Simulation results matched HSC measurements in a fair good fashion by different speeds;
  - Computed amplitudes generally exceeded measured ones, showing a lower damping than real;
  - Finer definition of belt characteristic for future simulation can be envisaged;









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Simulation Results

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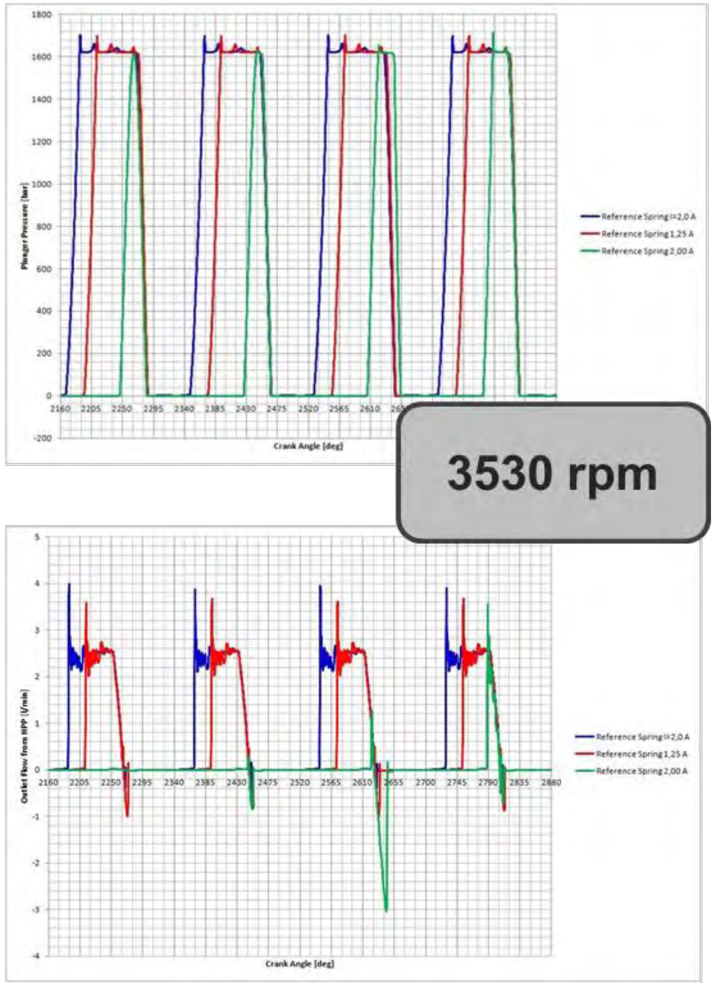
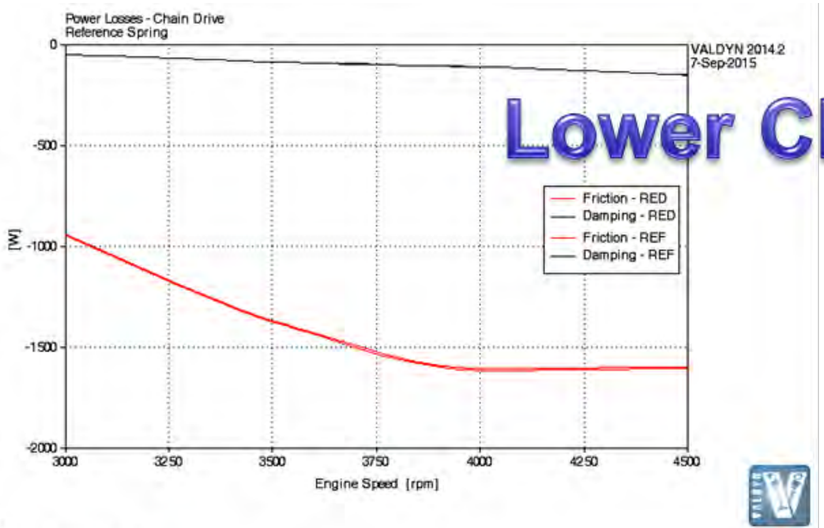
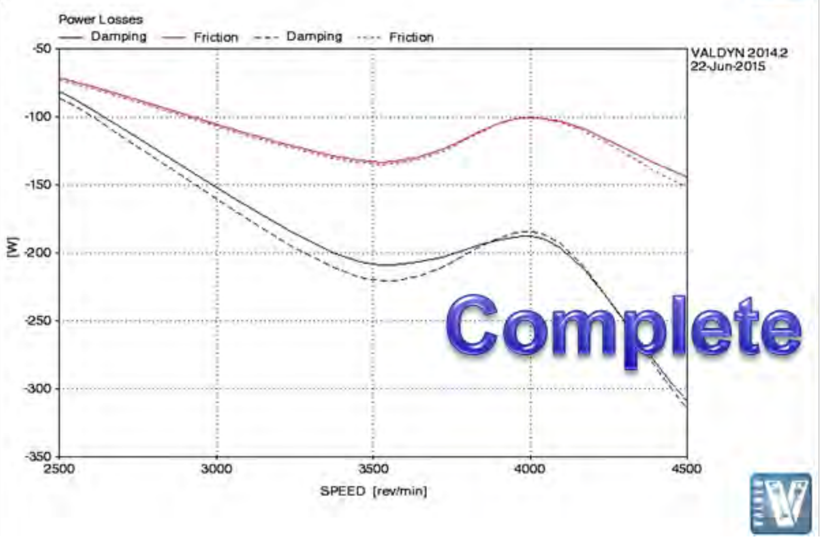
- **Part Load operation**
  - Changes at Metering Unit current correctly result in a lower filling quote of the delivery plunger;
  - This effect can be seen both on the plunger pressure curves and in the flow out of the delivery valve
  - Note zero delivery situation at high throttling;



Simulation Results

- **Parasitic Losses**
  - Power absorption higher for chain drive
  - Optimization could reduce difference but not reverse the result;
  - Belt Losses mainly from internal damping, increase with speed and affected by resonances
  - Chain drive main contribution from friction
  - High speed gasoline engine may experience opposite results;





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Simulation Results

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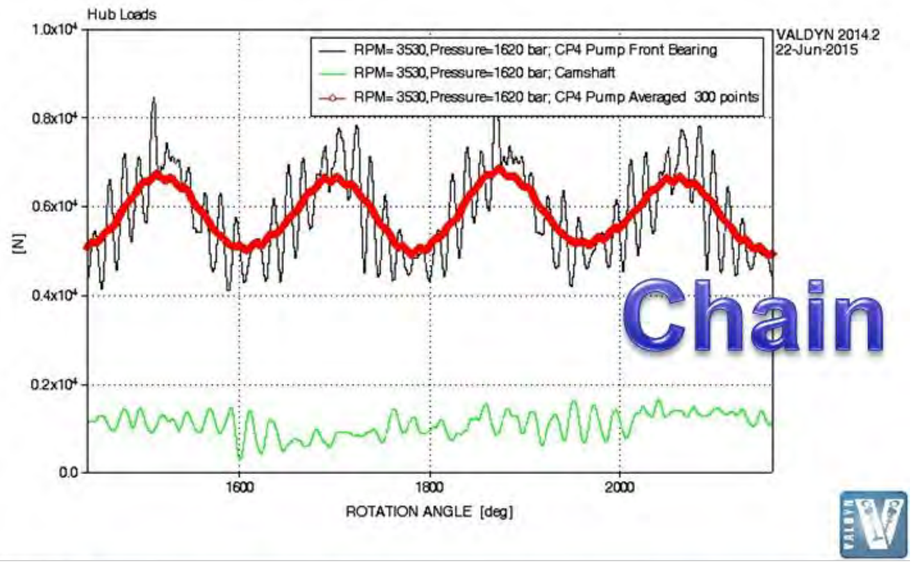
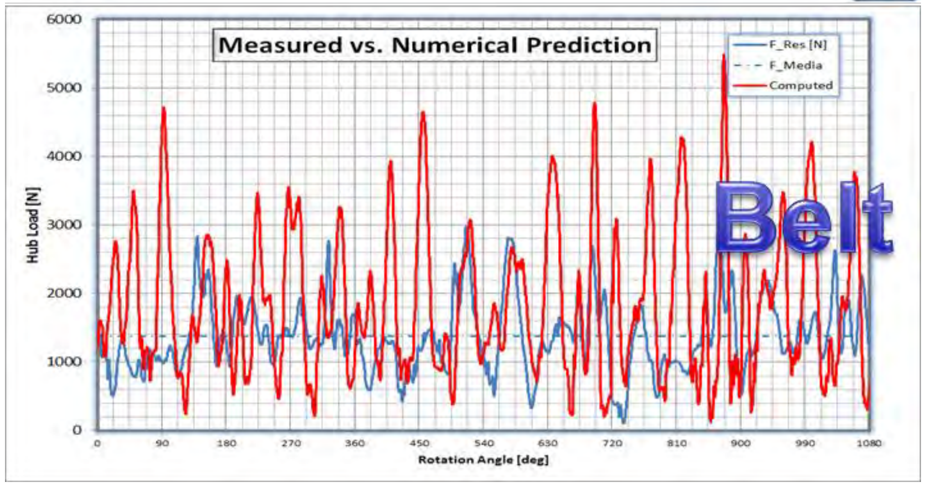
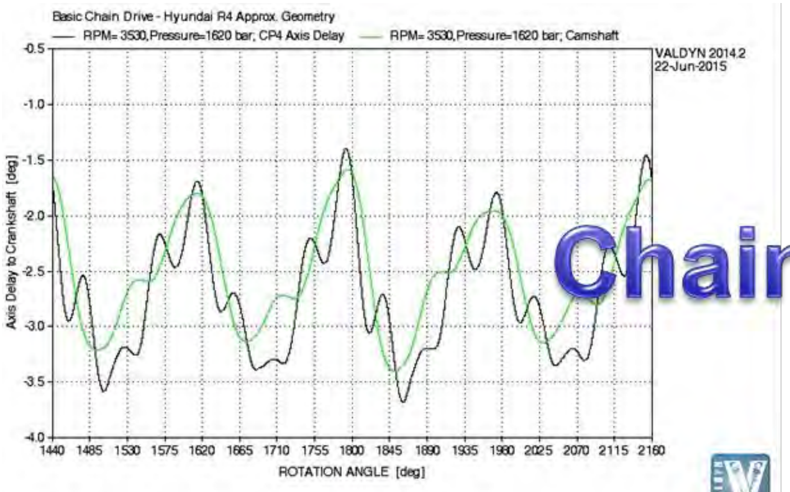
- Dynamic Behavior
  - Belt:
    - Mainly stochastic behavior, oscillation overwhelms cyclic load
  - Chain:
    - Clearly cyclic repeatable oscillation
    - Two predominant frequency:
      - High frequency teeth meshing
      - Low frequency energy bouncing due to elastic behavior of the drive

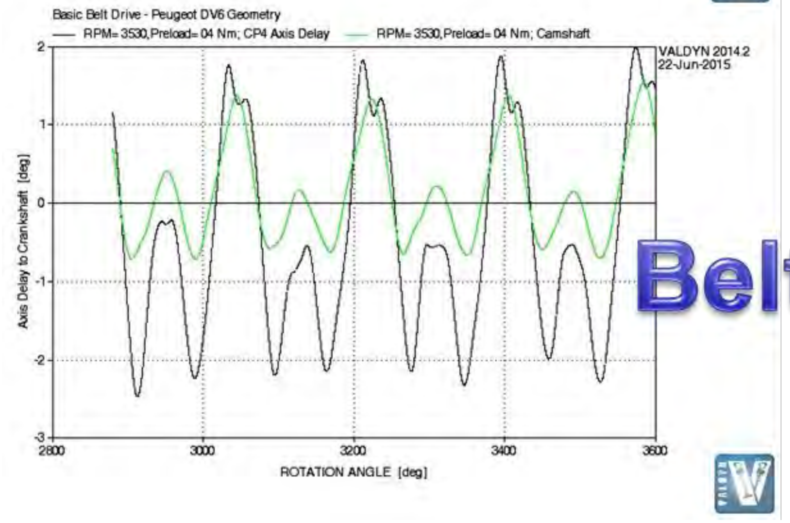




Pump Dynamics

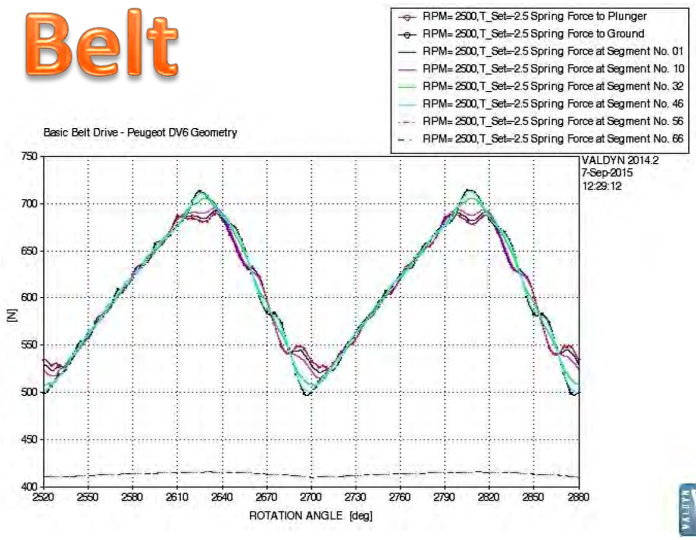
- **Phase shift**
  - Higher belt deformation lead to higher phase shifts
  - HPP pump torque oscillation is the driving force
  - Such phase shift appears to have no significant influence on injections parameters in a HPCR Systems

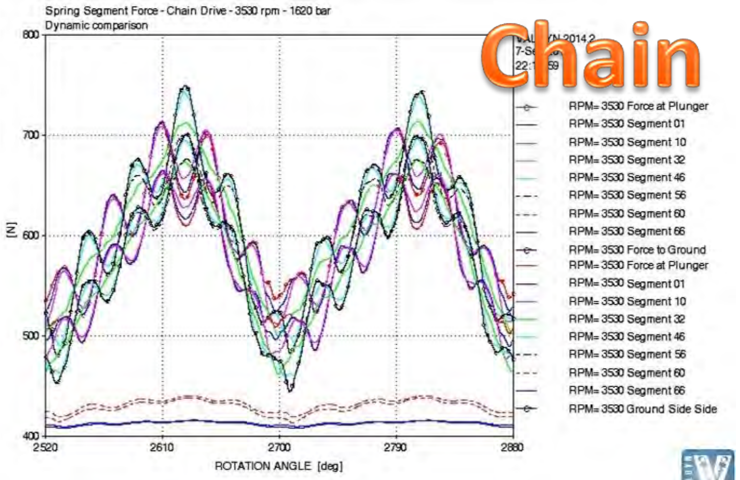




Main pump spring surge

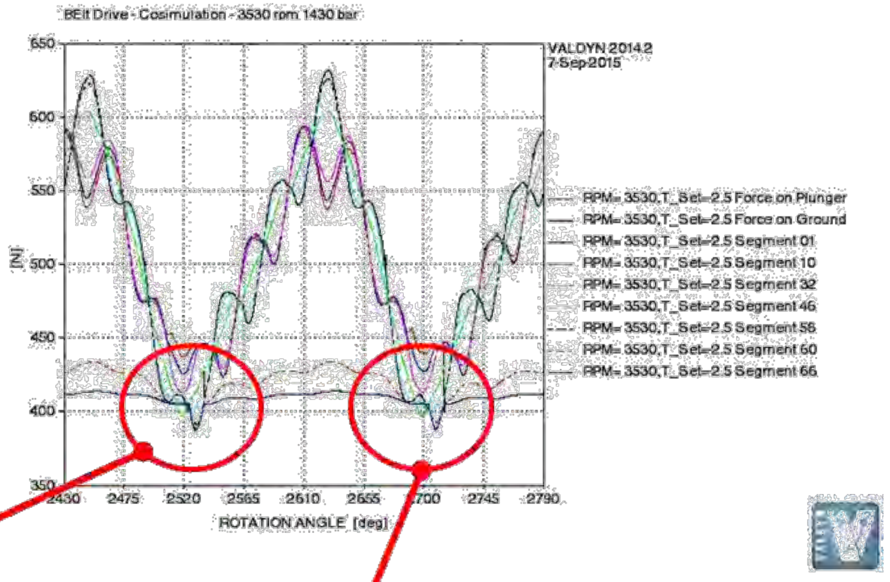
- **Spring dynamics**
  - Forces at different portions of spring coils have been analyzed
  - Oscillation around static force is a consequence of the excitation of spring modal frequencies
  - The repeatable chain meshing frequency excites spring surge at certain speeds
  - Belt drive influence on spring dynamics is negligible

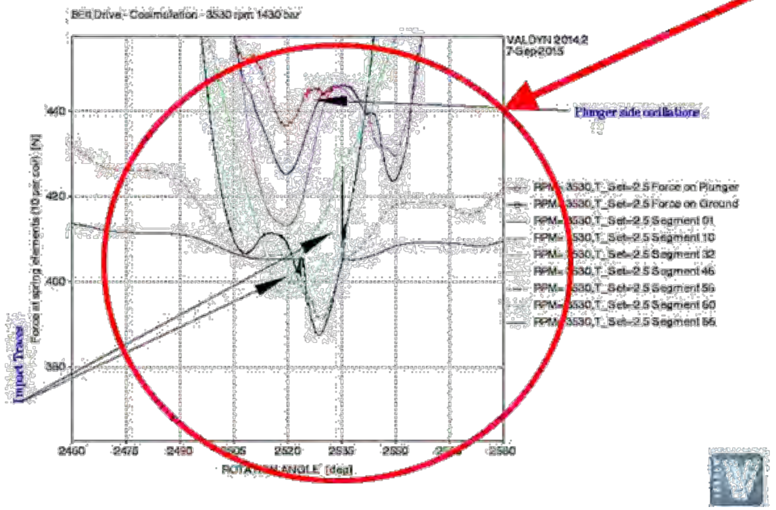


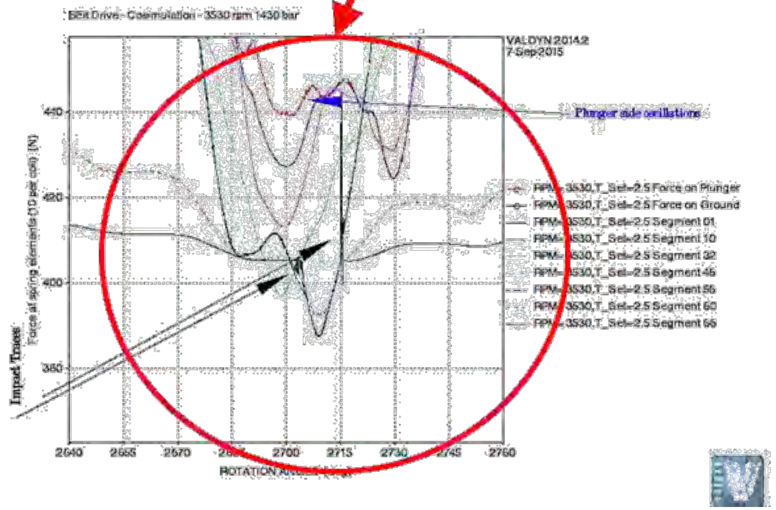


Main pump spring surge

- **Spring surge (Chain Drive)**
  - Spring coil oscillation near spring basis lead to impingements of the first coil with dead ones
  - Such impingement might result into higher vibration level of the HPP housing, hence structure borne noise and delivery pressure oscillation.







Summary and Conclusions

- **Simulation**
  - Use of different codes co-simulation can efficiently deepen the analysis into the dynamics of injection system unveiling interaction between mechanical and hydraulic engineering aspects;
- **Chain vs. Belt Front End drive**
  - For high speed diesel engines for passenger car, a belt drive shows marginal advantages in friction reduction;
  - Chain dynamics may have an impact on secondary dynamics of HPP components, in particular on the return spring dynamics

Q & A session

Q & A

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Thank you

- For any further information:
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