CO$_2$ Reduction
Comparison of Belt and Chain Front End Drive for a Passenger Car High Pressure Pump

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• 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
Belt Model Validation

• 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;
Simulation Results

• 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;
• 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;
**Simulation Results**

- **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
Thank you

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