Advanced modeling of automotive variable displacement vane oil pumps

Italia GT-SUITE Conference 2017 – Torino, 10 May 2017

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The modeling & simulation department gives advise on a wide range of products, whenever physical aspects need to be clarified. It gives support at different stages of product development. While its routine job is the prediction of performances and the interpretation of experimental data, it also has a valuable role in proposing innovative solutions and design guidelines.
Activities on variable displacement vane oil pumps

The simulations should focus on the most relevant aspects of the physical processes, in order to maximize the benefit/cost ratio of the computations.

Tools of varying complexity are used for different levels of detail and different purposes.

1D tools are fit for the analysis of complex system when many low-level details can be simplified. These models are validated by other analyses, experiments, and past experience.
Variable Displacement Vane Oil Pump

Variable displacement vane oil pumps are used in lubrication circuits of automotive combustion engines.

They are driven by the crankshaft, so the speed is imposed and cannot be regulated to satisfy the requested performances.

The displacement depends on the eccentricity between rotor and stator. The eccentricity is varied by a movement of the control ring, either translating or rotating around a pivot.

The variable displacement allows to regulate the oil flow rate provided by the pump, with valuable advantages in power consumption and ultimately CO₂ emissions.

The position of the control ring is controlled by the pressure difference between two control chambers. The control chambers are inserted in a hydraulic control circuit. Several types of control circuits are possible.
Example of GT-ISE model

- Suction duct
- Inlet volumes
- Rotor chambers
- Outlet volumes
- Delivery duct
- Spring chamber
- Pilot chamber
- Feedback channels (external to the pump)
- Feedback channel (internal to the pump)
- Solenoid valve
- Spool valve
- Bypass valve
- Rotor
- Control ring
1D analyses for variable displacement VOPs

1D models are used mainly for the following purposes:

- **Sweep speed curves**
- Pump performance maps
- Cavitation curves
- Cold start behavior
- Stability analysis
- Spectral analysis

Each type of analysis has its own peculiarities and the model must be tailored to suite them.
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Sweep speed curves

Sweep speed curves are used to check that the pump regulates as intended. The pump is tested at steady state at several speeds, and the values of quantities of interest are retrieved, e.g. the delivery pressure.

For each working point, the relevant quantities are **averages** in a cycle.

**Sweep speed curves depend on the impedance of the circuit**, that must be known, at least approximately.
Sweep speed curves – convergence

The assumption of stable behavior can be used to reduce simulation time.

Low frequency resonances of the system in some cases fade out very slowly. Attaining convergence would be computationally demanding.

However, there is no need to attain convergence.

Taking the average over many cycles gives a reasonable prediction of the asymptotic behavior when the signal oscillates symmetrically.
Pump performance maps

The pump performance maps are one of the most complete descriptions of the behavior of a pump.

In the case of VOPs, a relatively small amount of working points is necessary to draw the curves. Below the regulated pressure the pump works at maximum eccentricity, so it has constant displacement and the performance curves are evenly spaced straight lines.

However, at high speed the phenomenon of cavitation takes place and the flow rate reaches a maximum.
Cavitation curves

The effects of cavitation are best seen through cavitation tests.

The pump is tested at fixed eccentricity and fixed delivery pressure at increasing pump speeds.

The information from a cavitation curve – experimental or simulated – can be used to construct the pump maps at high speed.

The greatest difficulty in predicting cavitation is the determination of the path of the fluid through the inlet ports.

In 1D simulations the effective cross section of the inlet ports must be corrected by a factor that can be calibrated via experimental or 3D CFD data.
Cold start behavior

At very low temperatures (~-30°C) the time to fill the pump volumes with oil and reach a steady state can be long. The pump initially processes air and oil vapor and gradually fills itself, the control volumes, and the oil circuit.

This type of simulation requires an accurate representation of the volumes, not only of the pump but of the whole circuit.

Some relevant information is usually unavailable, such as the impedance of the circuit at low temperature and only partially filled with oil.

In spite of its limitations, the model can predict possible undesired behaviors due to the partially filled control volumes.
Cold start behavior

Examples of 3D and 1D simulated cold start.

Volume fraction

Pressure @ Feedback Pressure Sensor = f(t) [bar]

Pump Delivery Flow Rate = f(t) [L/min]
Stability analysis – standard model

The oil circuit is a feedback system that can become unstable. Generally speaking, a feedback system becomes unstable when it reacts to the feedback signal too late and too strongly. For example, a long and narrow feedback pipe favors instability.

Typical unstable frequencies are below 50 Hz.

The low frequency instabilities of variable displacement VOPs can be studied with a simplified model, where an ideal pump is substituted for the real one.

The ideal pump does not model leakages and has constant flow rate, as opposed to the real one where the instantaneous theoretical flow rate oscillates.

The oscillations of flow rate and the related oscillations of the delivery pressure are driven oscillations (as opposed to natural ones) and are at higher frequencies than those characteristic of instability. Their effect on instability is negligible.

Care must be placed in the modeling of feedback pipe, spool valve and springs.
Stability analysis

To help in the design process, the response to a speed ramp is simulated for two (or more) design parameters.

- Delivery pressure \( p \) [bar]
- Feedback pressure \( p_{\text{speed}} \) [bar]

Simulated design

Pilot chamber width [mm]
Spring chamber width [mm]

\( n \) [rpm]

Power/frequency (dB/Hz)

Frequency [Hz]

Pump speed \( n \) [rpm]

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Spectral analysis

The pump stability can be studied with a complete 1D-model, with higher computational costs, to take into account additional physical details, as aeration and internal pump forces. The same model is also useful to evaluate the relative strength of the pump orders (oscillations driven by pump revolution) as a guide to noise reduction.
Conclusions

- Our department has developed 1D models for all the products on which it gives support.
- During this presentation we have seen the 1D models most often used by our department for the analysis of Variable Displacement VOPs.
- With 1D models we are able to reproduce the most used performance indicators: performance maps and sweep speed curves. We are also able to reproduce many important physical phenomena: cavitation, cold start priming, system instabilities.
- We have shown only examples of GT models, both because this is a user conference and because GT-Suite is at the moment the tool we use the most for VOP analysis. However, our department has long been aware of the 1D approach using and integrating other tools.
- Effective and reliable 1D-models can only be made when there is a clear understanding of the physical and technical aspects of the problem at hand. Our department has accumulated a fair amount of knowledge and expertise by a continue effort to improve its methodologies.
- Of great importance have also been academic collaborations. We want here to recall the long collaboration with Politecnico di Torino, of which we are grateful, started in 2000.

Thank you

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