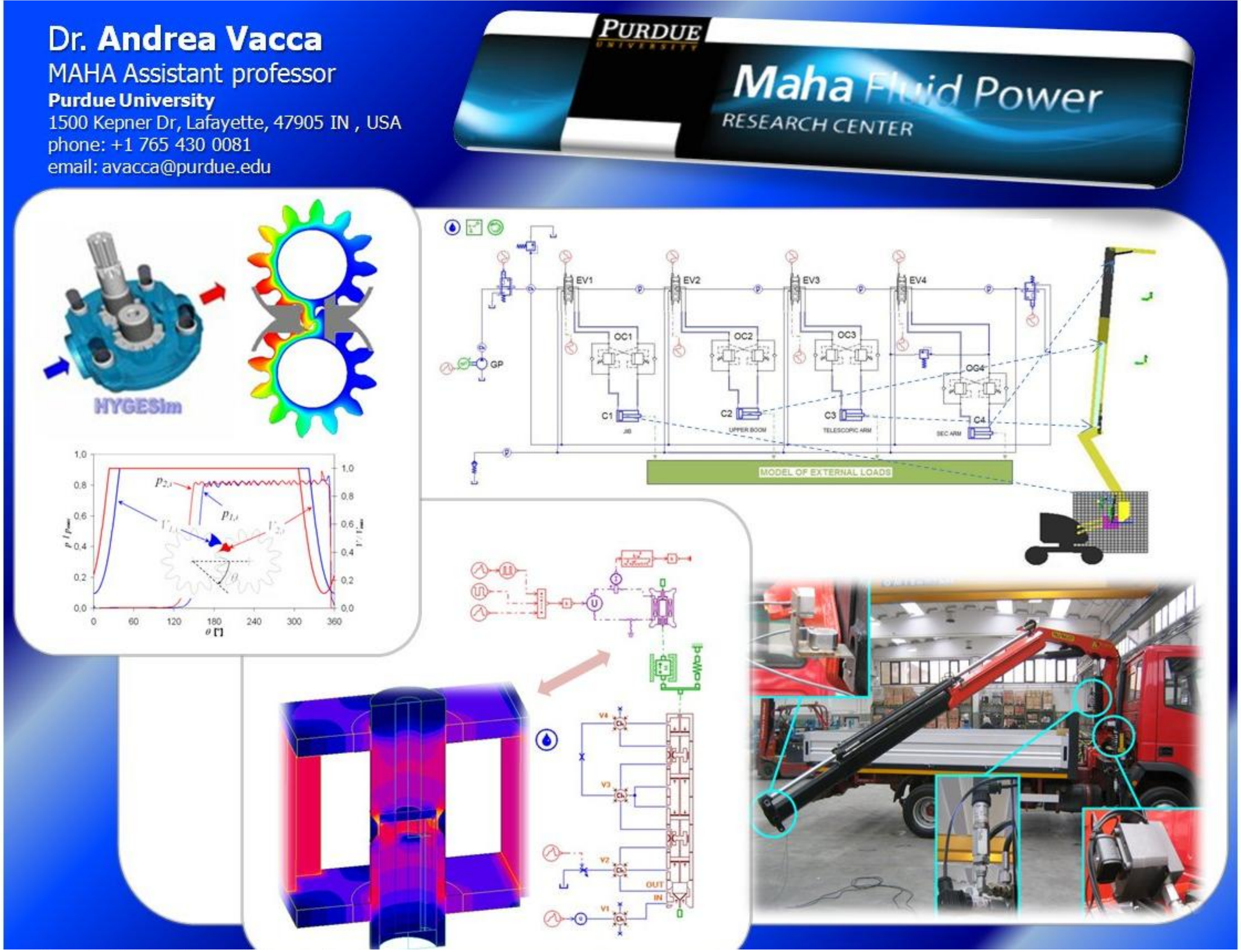


research activities on Systems/Components
- Highlights -

Projects List:

Systems

1. Complete analysis of an aerial platform (articulated boom lift) and its hybridization

2. Analysis of a tractor rear hitch control for agricultural tractor

3. Analysis of a of Diesel/CVT power split transmission

Systems - Components

4. Analysis, design and optimization of power supply systems

    discrete flow rate supply system

    electro-hydraulic system for the displacement control in axial piston pumps

5. Design of a LS flow divider valve for an hydraulic steering system

New research project

6. Adaptive control strategies for the cancellation of low frequency disturbances

Project 1: Articulated aerial boom lift platform (a)

Goals

- Analysis of the hydrostatic transmission and optimization of its operation
- Analysis and design of the hydraulic system for the boom lift
- Design and control optimization of the hydr. system for a Diesel-electro-hydraulic hybrid solution

Fig 1a – prototype of the articulated boom lift

Analysis of the HT

Fig 1b – Schematic of the HT

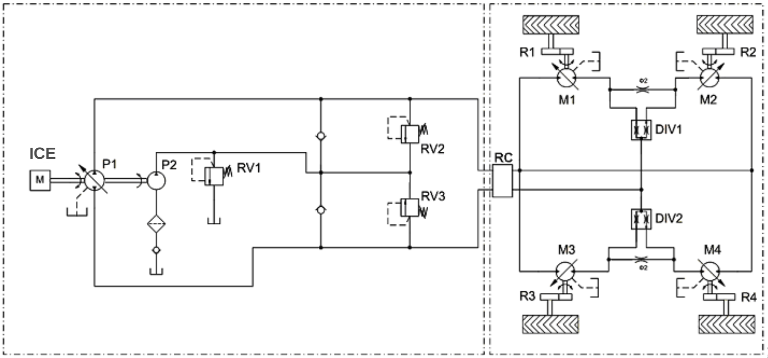
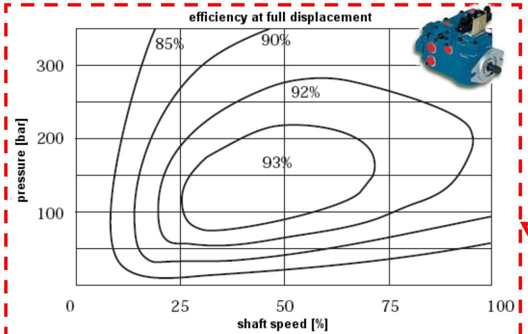
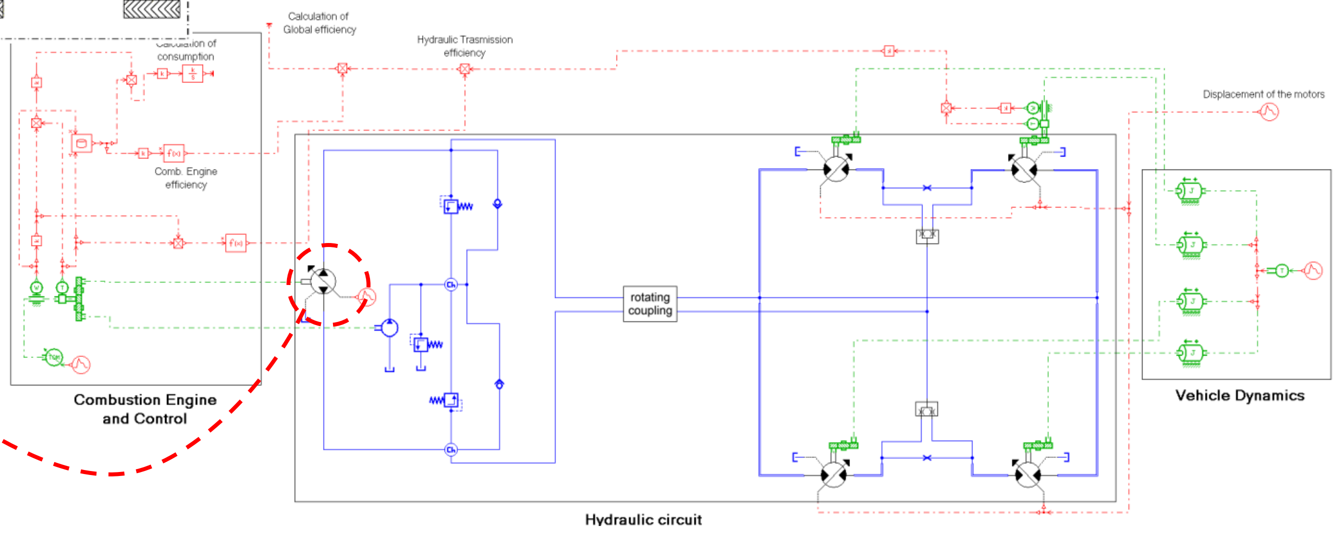


Fig 1c – AMESim model of the HT





Project 1: Articulated aerial boom lift platform (b)

Analysis of the HT (cont)

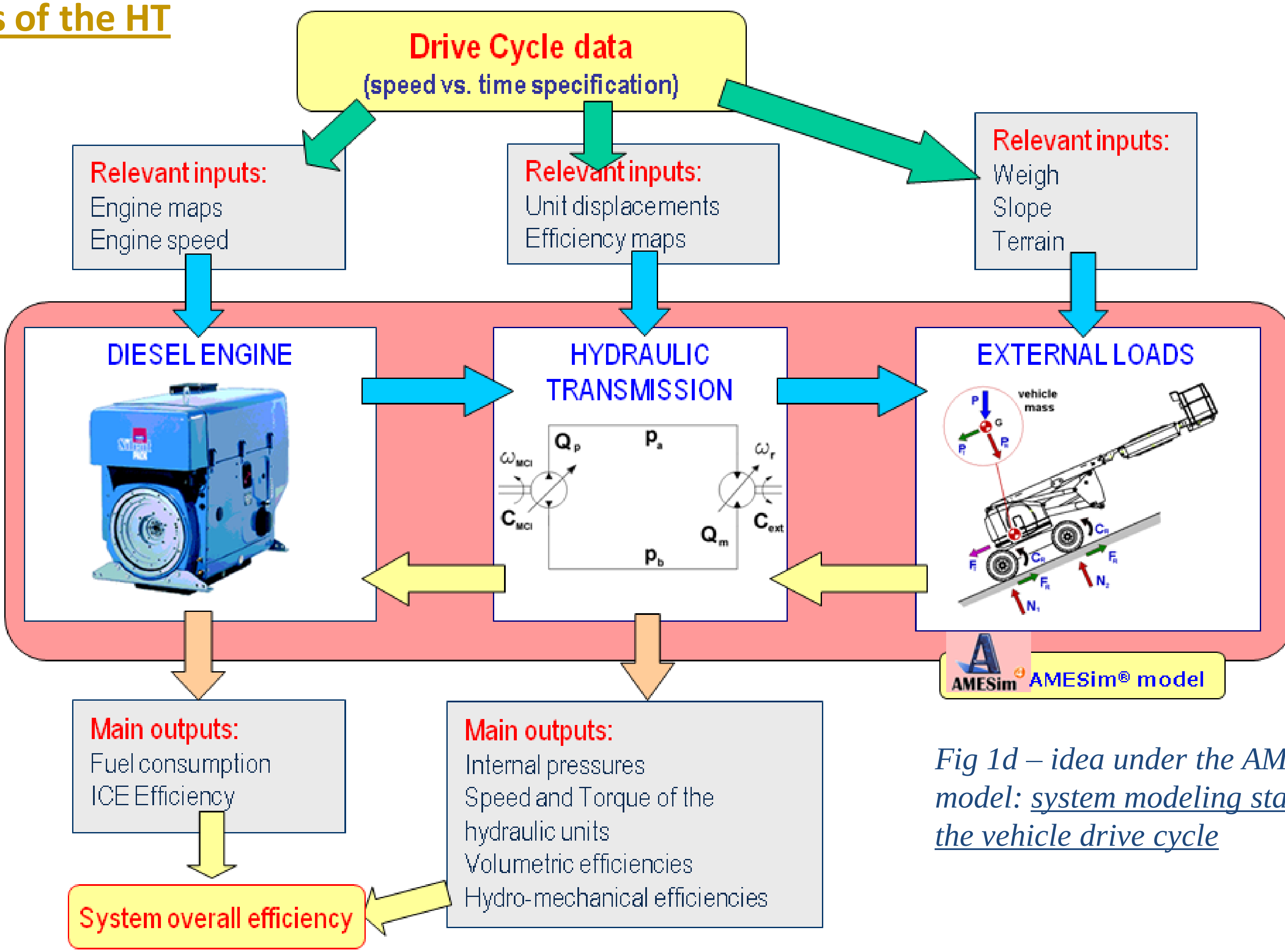
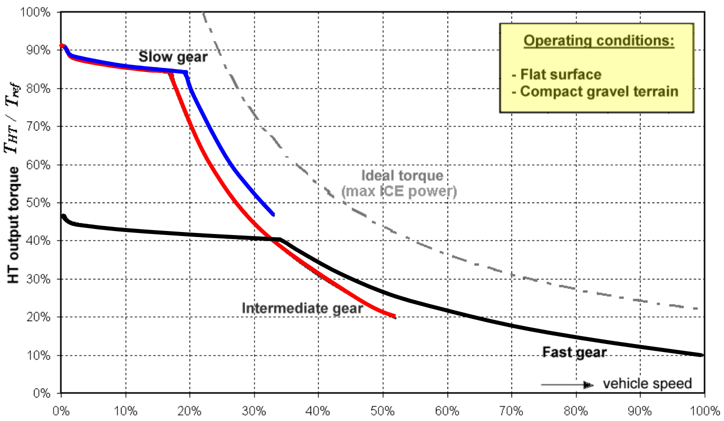


Fig 1d – idea under the AMESim model: system modeling starting from the vehicle drive cycle

Project 1: Articulated aerial boom lift platform (c)

Analysis and design of the HT



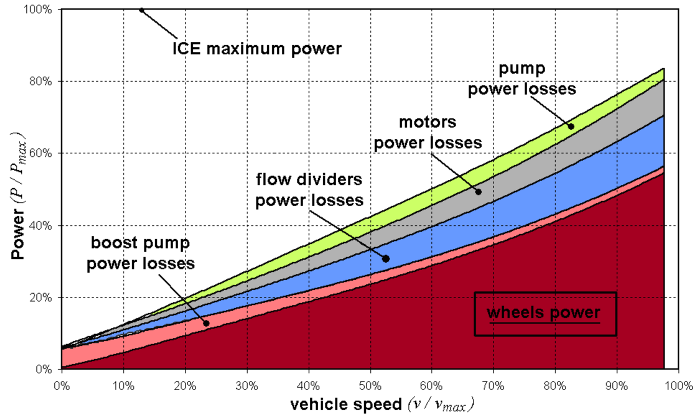
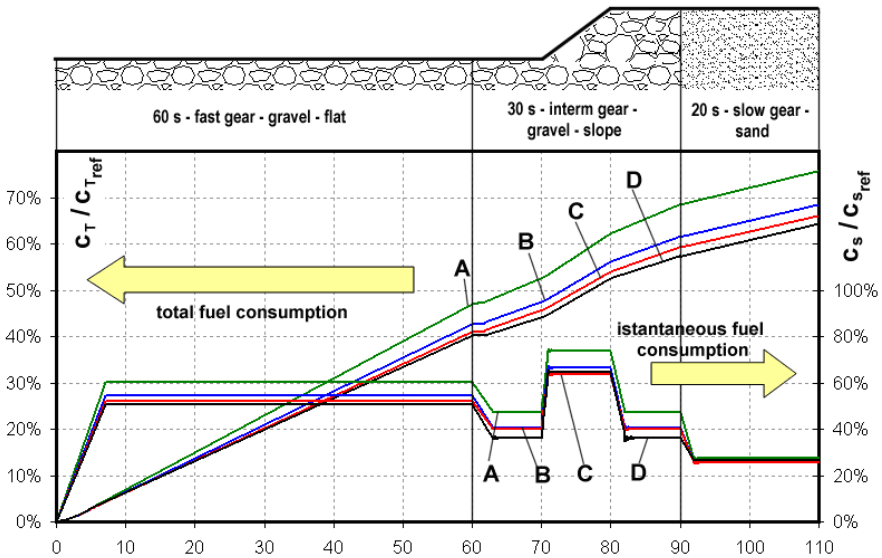


Fig 1d – Example of HT predicted performance: output torque and power losses of the hydraulic system



Reduction of fuel consumption of about 15% respect to the traditional HT system

Fig 1e – Example of HT predicted performance: fuel consumption over a selected drive cycle (A,B,C,D: different designs of the HT)

Project 1: Articulated aerial boom lift platform (c)

Analysis of the hydraulic system for the boom lift

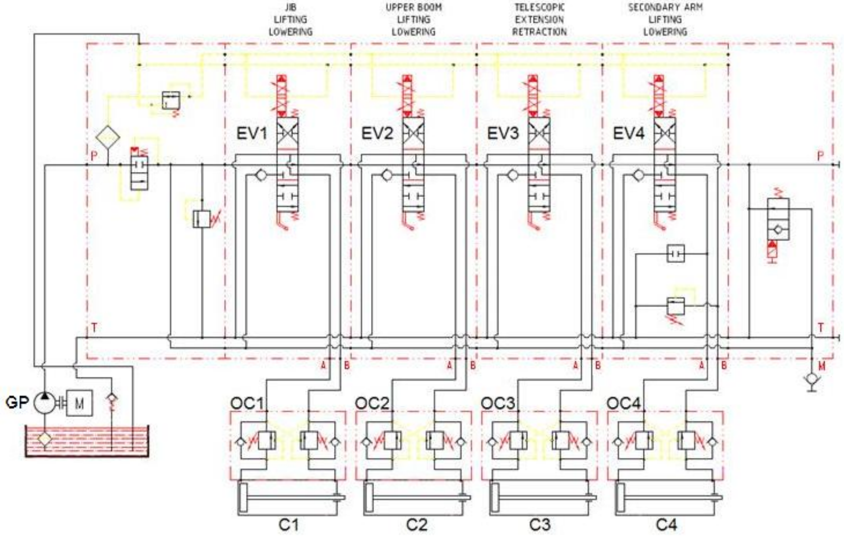
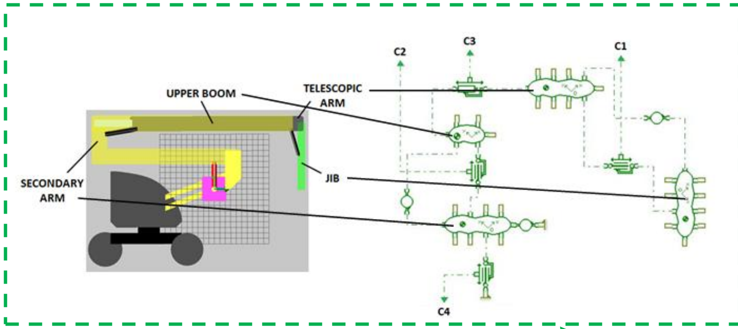


Fig 1f – Schematic of the hydraulic system



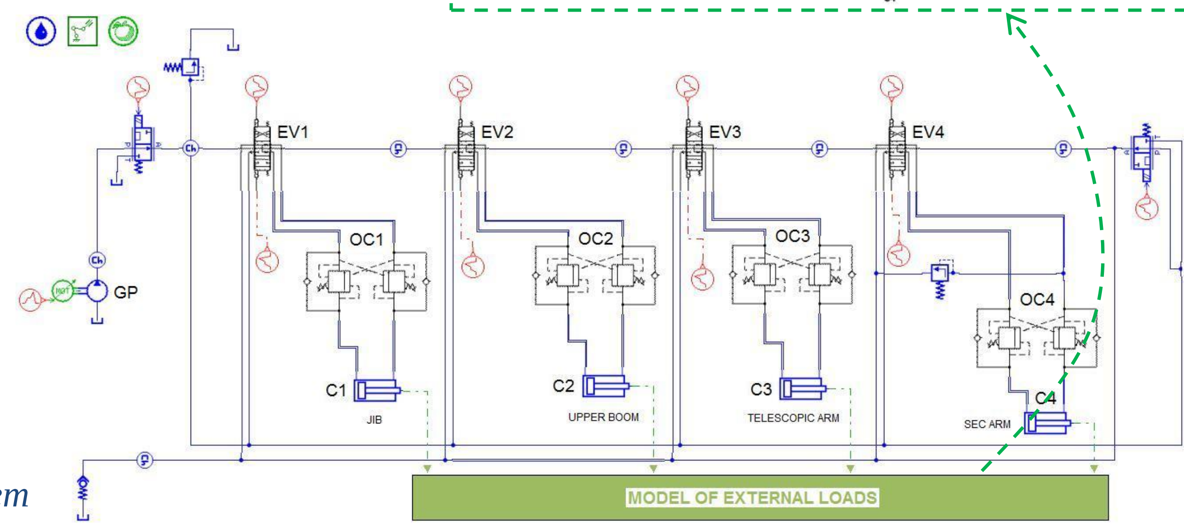


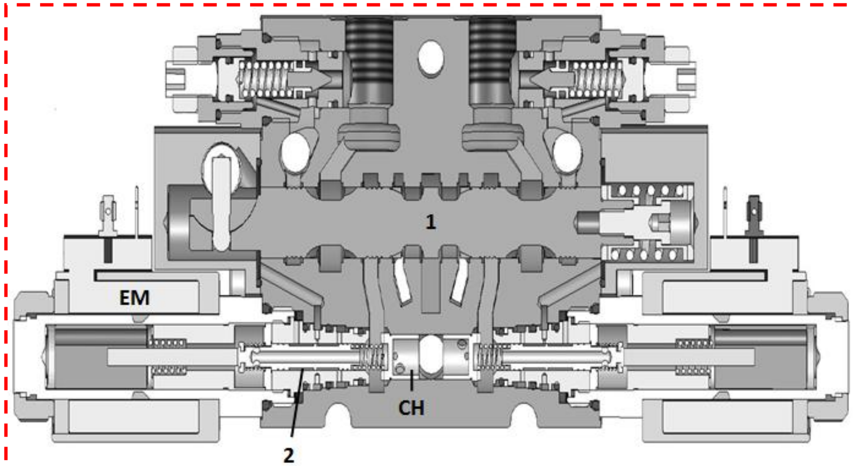
Fig 1g – The AMESim model of the system

Project 1: Articulated aerial boom lift platform (d)

Analysis of the hydraulic system for the boom lift

A patented flow control valve is used into the system,
The valve permits a good flow regulation in each actuator without the use of external LS signal lines

Fig 1h – patented flow control valve



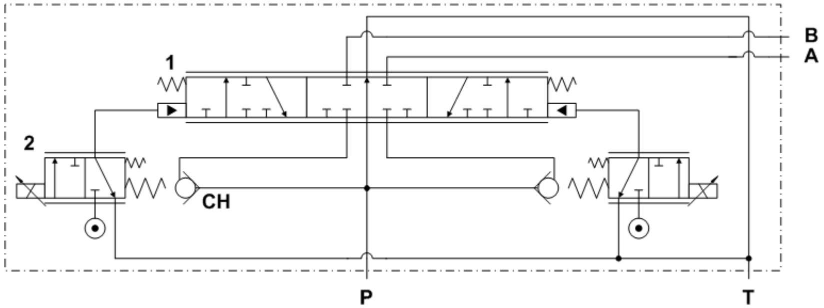


Fig 1i – Simplified scheme of the valve

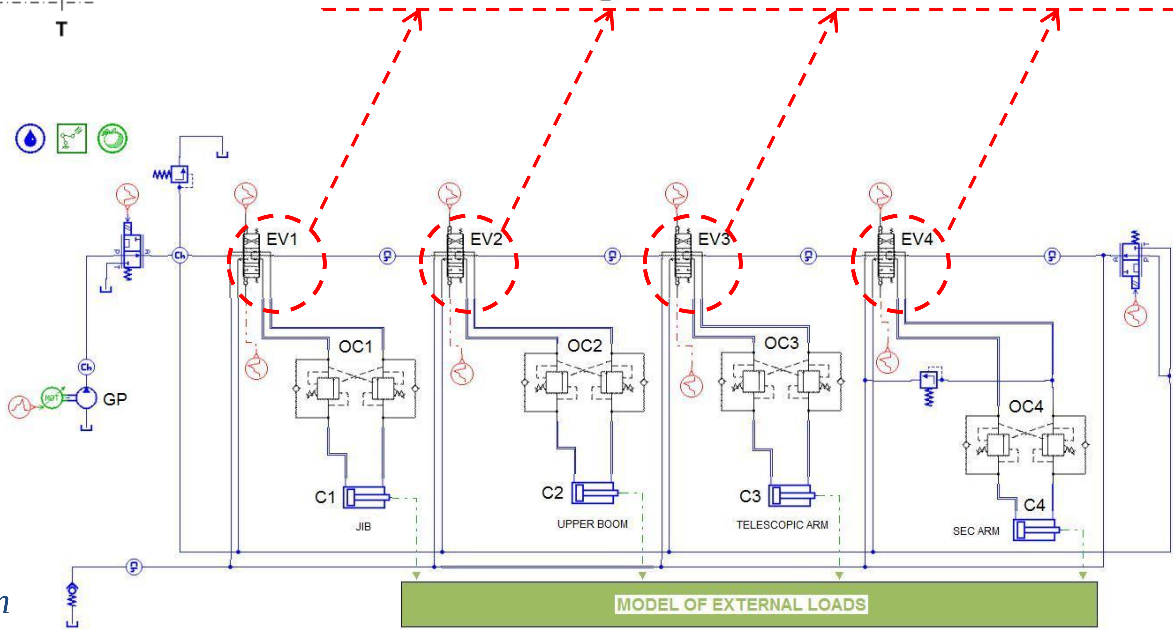


Fig 1j – The AMESim model of the system

Project 1: Articulated aerial boom lift platform (e)

Analysis of the hydraulic system for the boom lift

The flow control valve required the development of a detailed simulation model (AMESim®). Tests were performed with the purpose of model validation

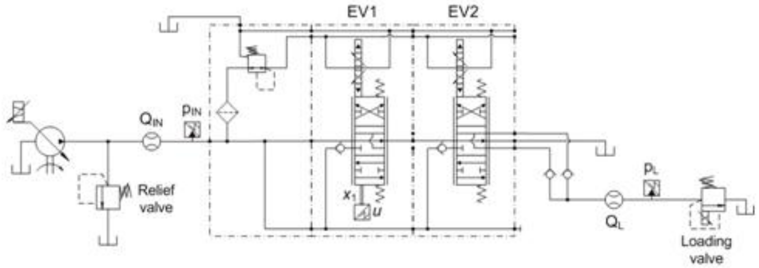
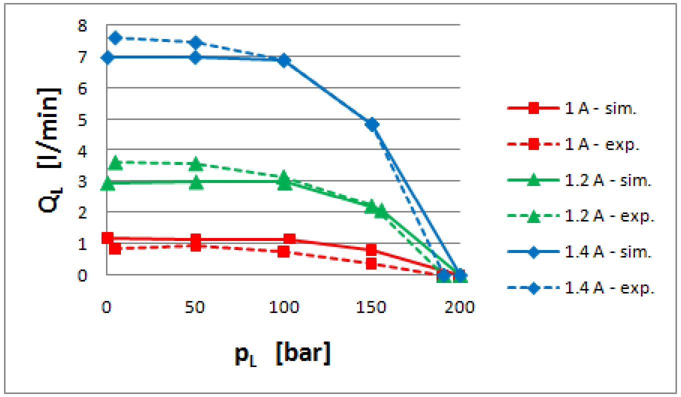
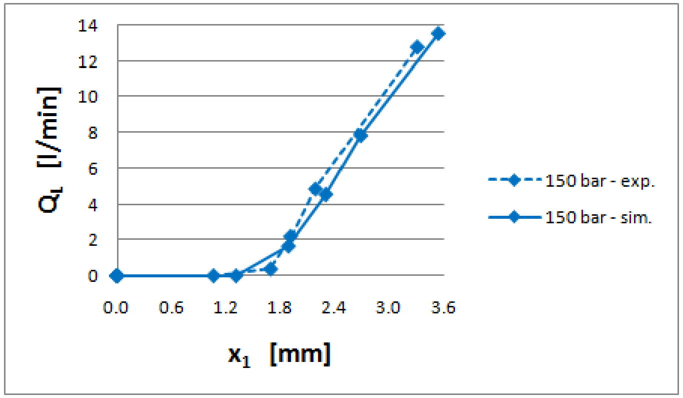


Fig 1k – Valve verification tests





Project 1: Articulated aerial boom lift platform (f)

Analysis of the hydraulic system for the boom lift

Once the model has been validated (using also on field measurements on a machine prototype) the best control strategy has been defined.

The new control strategy considers a variable pump speed, achievable by means of the overall hybridization of the machine.

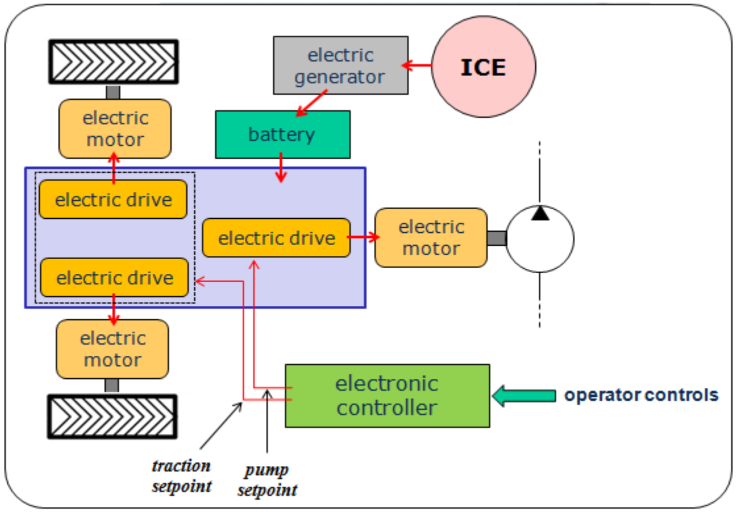


Fig 1l – Principle of hybridization

Energy saving of about 50% respect to the traditional hydraulic system

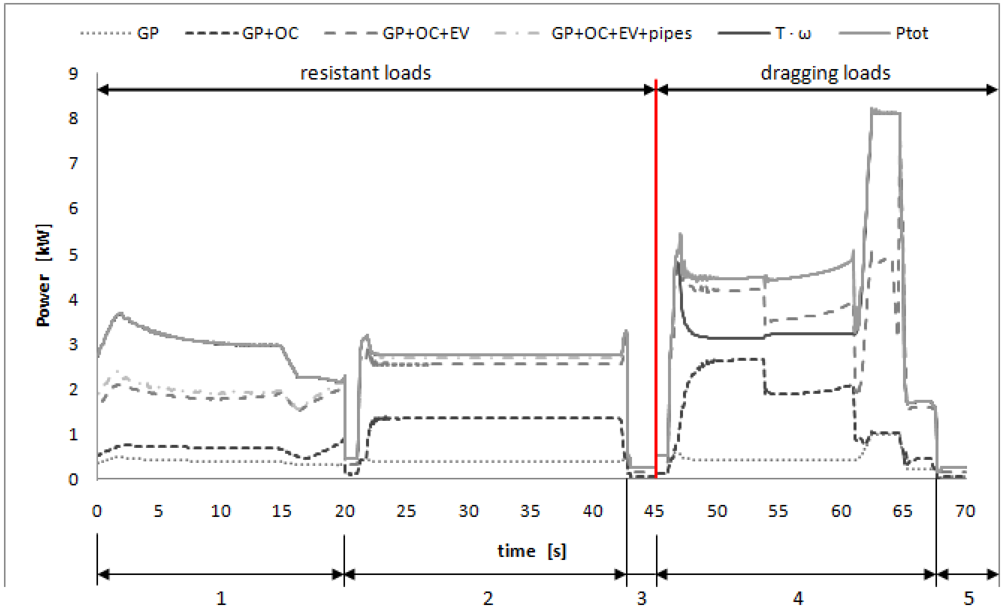


Fig 1m – Estimated power request for the optimal control solution for the reference drive cycle

Project 1: Articulated aerial boom lift platform (g)

Conclusion – final remarks

•The research permitted to optimize the HT and the whole hydraulic system of the machine.
•The integration with the electric hybrid system is under development

For more details..

- write to mahaav@ecn.purdue.edu
- see published papers:

- Vacca, A., Franzoni, G., Bonati, F., 2008, *An Inclusive, System-Oriented Approach for the Study and the Design of Hydrostatic Transmissions: The Case of an Articulated Boom Lift*, **SAE Int. Journal of Commercial Vehicles vol. 1,** April 2009 pp. 488-494.

- Bonati, F., Franzoni, G., Vacca, A., 2007, *Trasmissioni Idrostatiche per Piattaforme Aeree Articolate* (in italian), Oleodinamica-Pneumatica – Tecniche Nuove, Milano. N. 11 Dicembre 2007. Pubblished also in Fluid – Trasmissioni di Potenza n. 3 Maggio 2008.

-Campanella G., Vacca A., 2010, *Modeling and optimization of the control strategy for the hydraulic system of an articulated boom lift* , 2010 SAE Commercial Vehicle Engineering Congress and Exhibition, October 5-6, *2010*. Rosemont, Illinois, USA.

Project 2: Tractor rear hitch control for agricultural tractors (a)

a project completely performed at the University of Parma, Italy

Goals

This research is part of a project (supported by the Italian government; CNH as industrial partner): aimed to develop a parametric numerical model for the simulation of the dynamics of a small tractor. Parts considered: ICE & transmission system, auxiliaries; rear hitch.

Particular goals:

- analysis of the hydraulic system (rear hitch)
- individuation of power losses and formulation of possible improvements
- dynamic analysis and definition of possible improvement of control strategy

The system

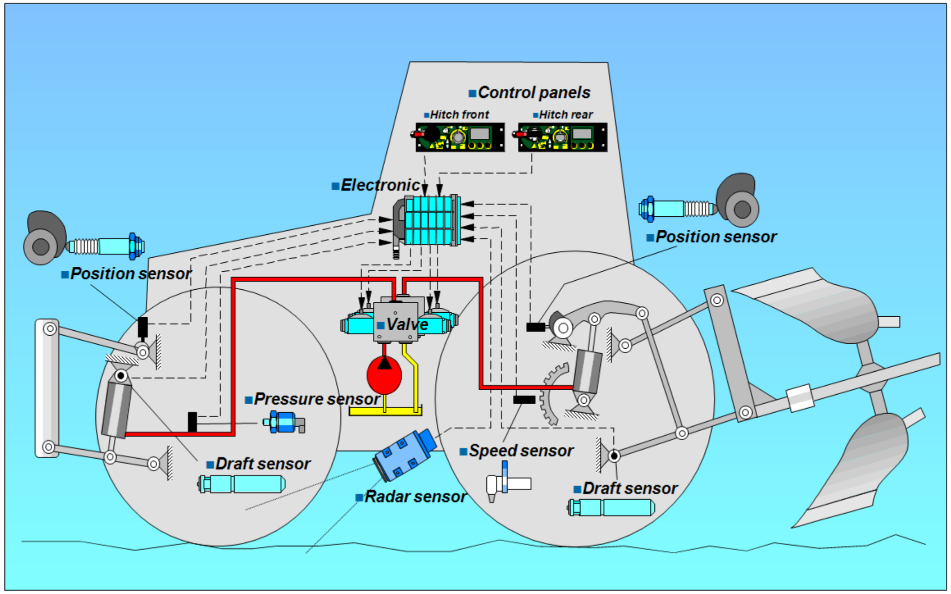


Fig 2a – The hitch control system (source: Bosh Rexroth)

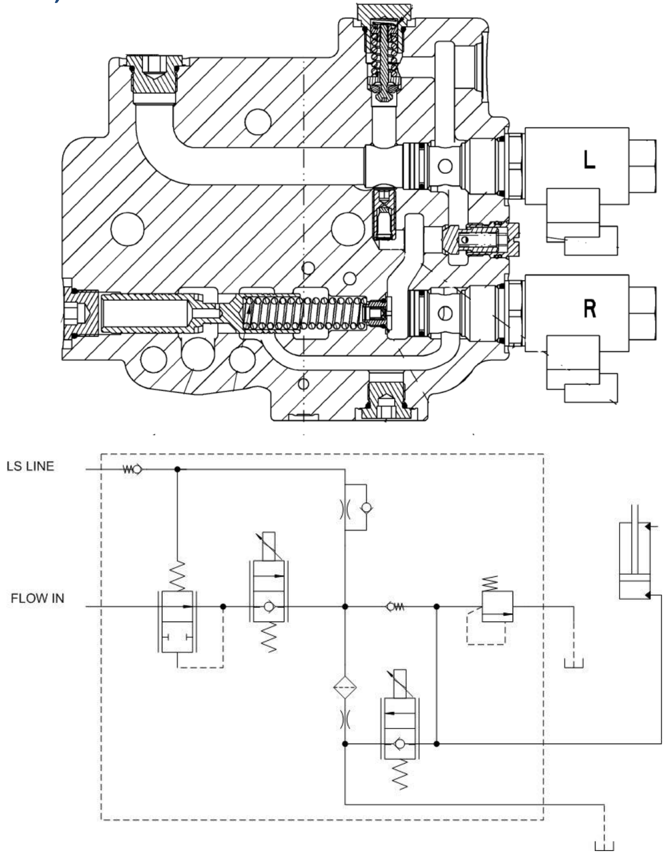


Fig 2b – The hydraulic system and the control valve used in the CNH system

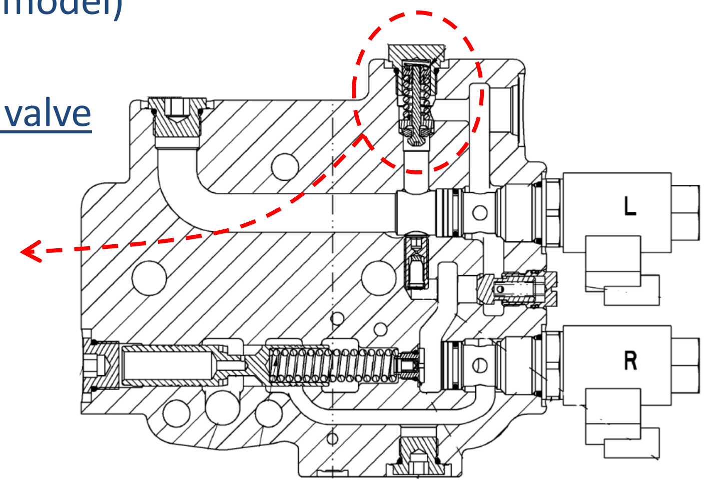
Project 2: Tractor rear hitch control for agricultural tractors (b)

a project completely performed at the University of Parma, Italy

The approach

Detailed simulation of each element of the main valve (AMESim® model)

Anti-shock and anti-cavitation relief valve



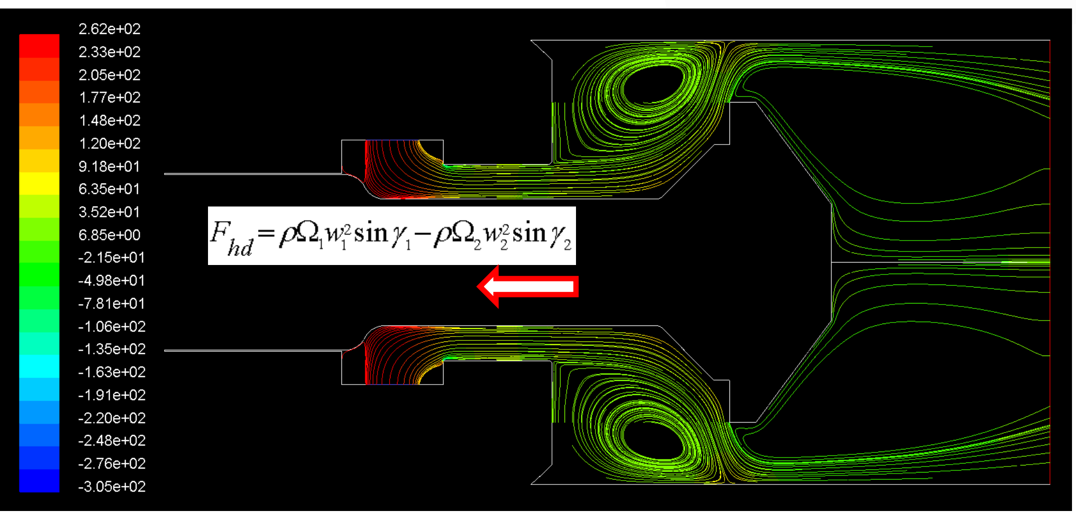


Fig 2c – CFD simulation for the verification of flow forces and throat areas used in the lumped parameters model

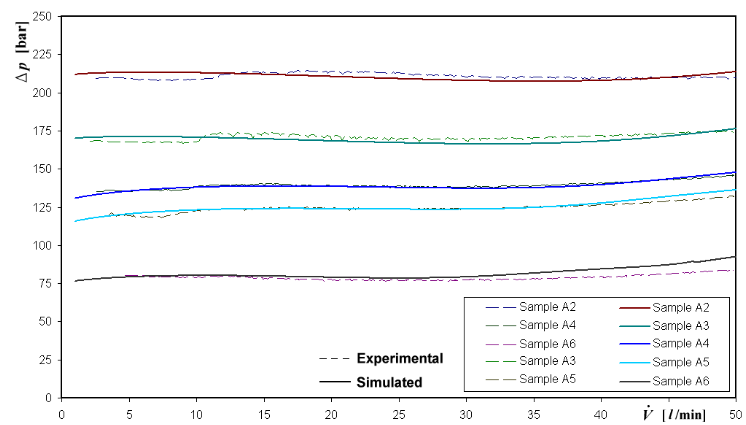


Fig 2d – Predicted vs measured characteristic of the valve

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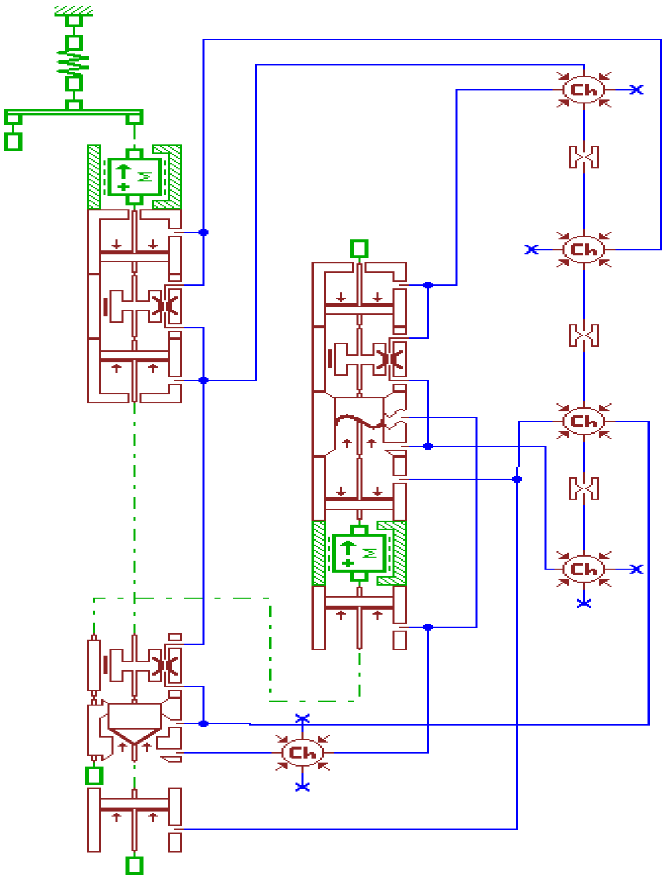
Project 2: Tractor rear hitch control for agricultural tractors (c)

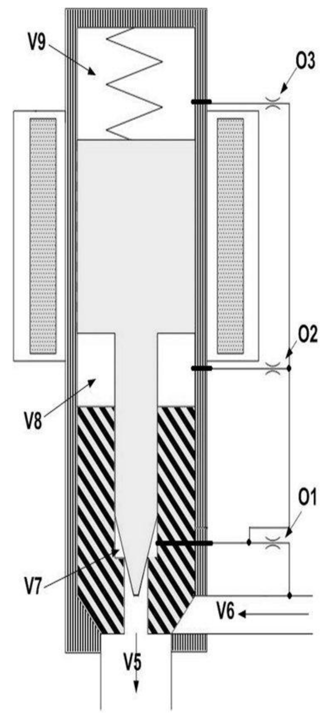
a project completely performed at the University of Parma, Italy

The approach

Detailed simulation of each element of the main valve (AMESim® model)

electro-hydraulic pilot operated flow control valve





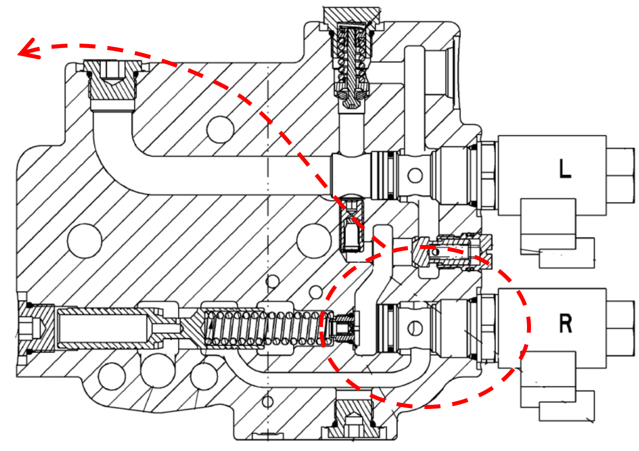


Fig 2e – Simplified scheme of the flow control valve
And detailed AMESim sketch

Project 2: Tractor rear hitch control for agricultural tractors (d)

The approach

The complete model (AMESim®)

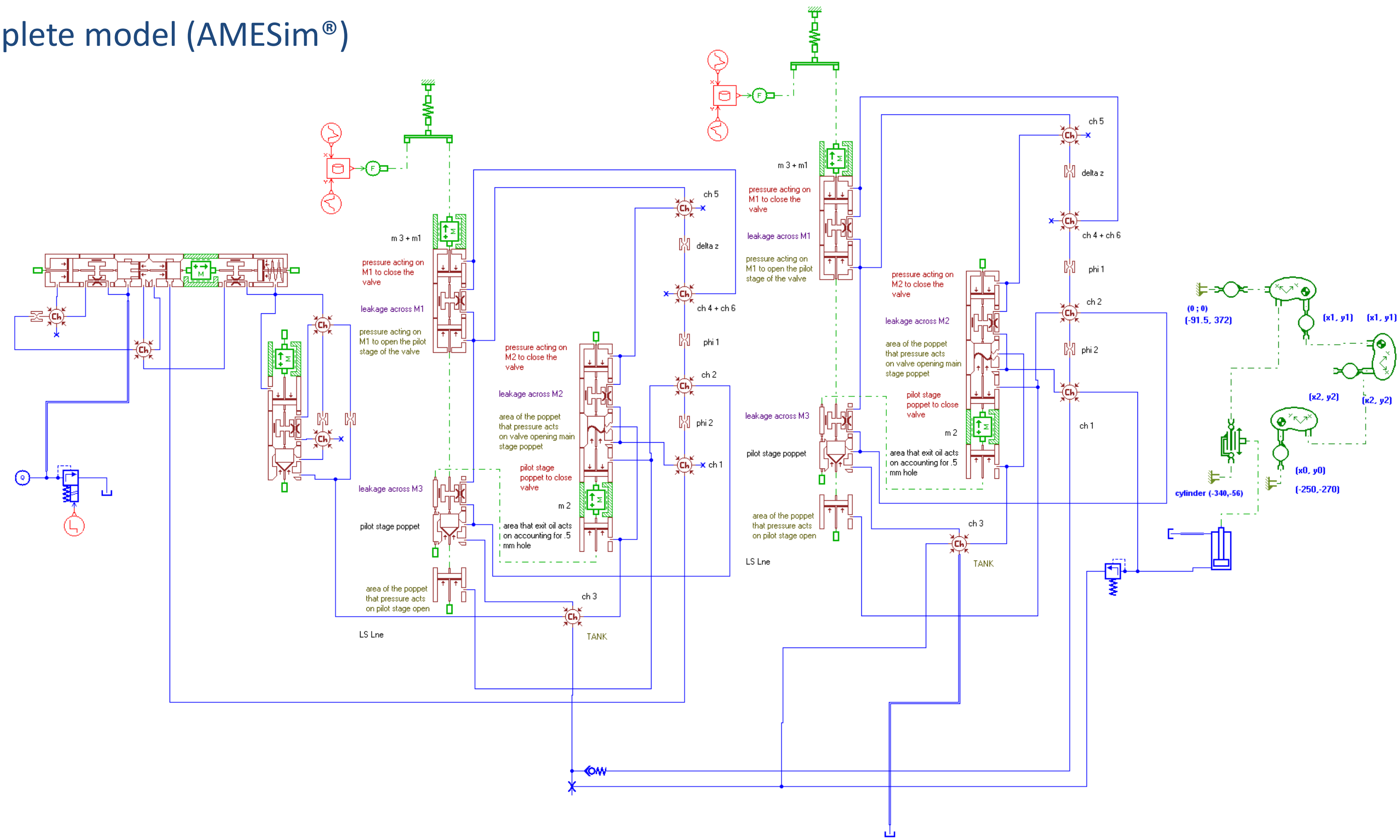


Fig 2f –AMESim® sketch of the complete model

Project 2: Tractor rear hitch control for agricultural tractors (d)

a project completely performed at the University of Parma, Italy

Model verification

Verification of the model on the basis of experimental results

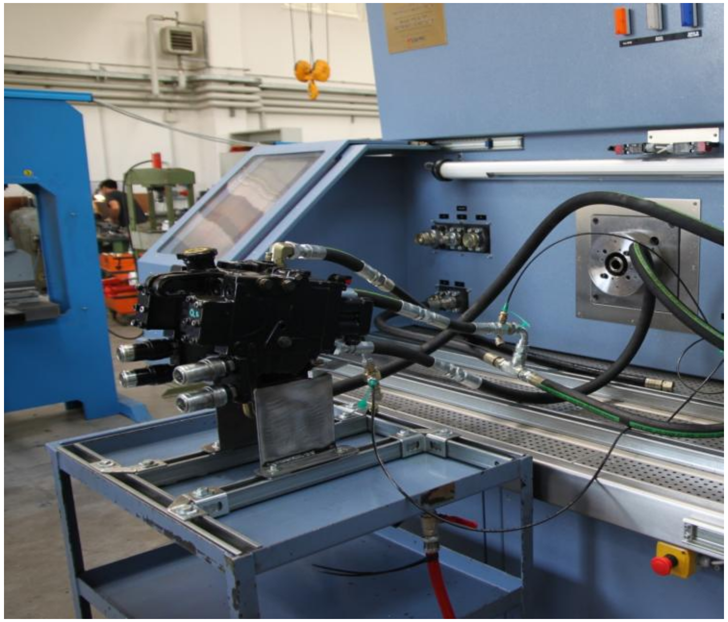
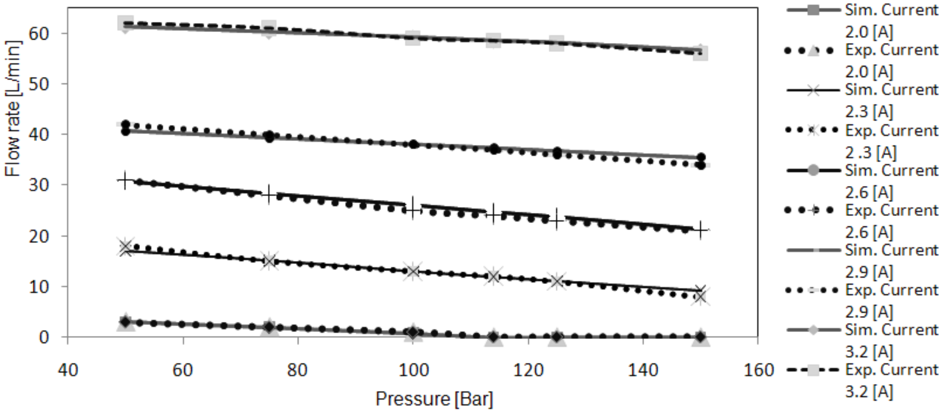


Fig 2g – Test performed on the valve

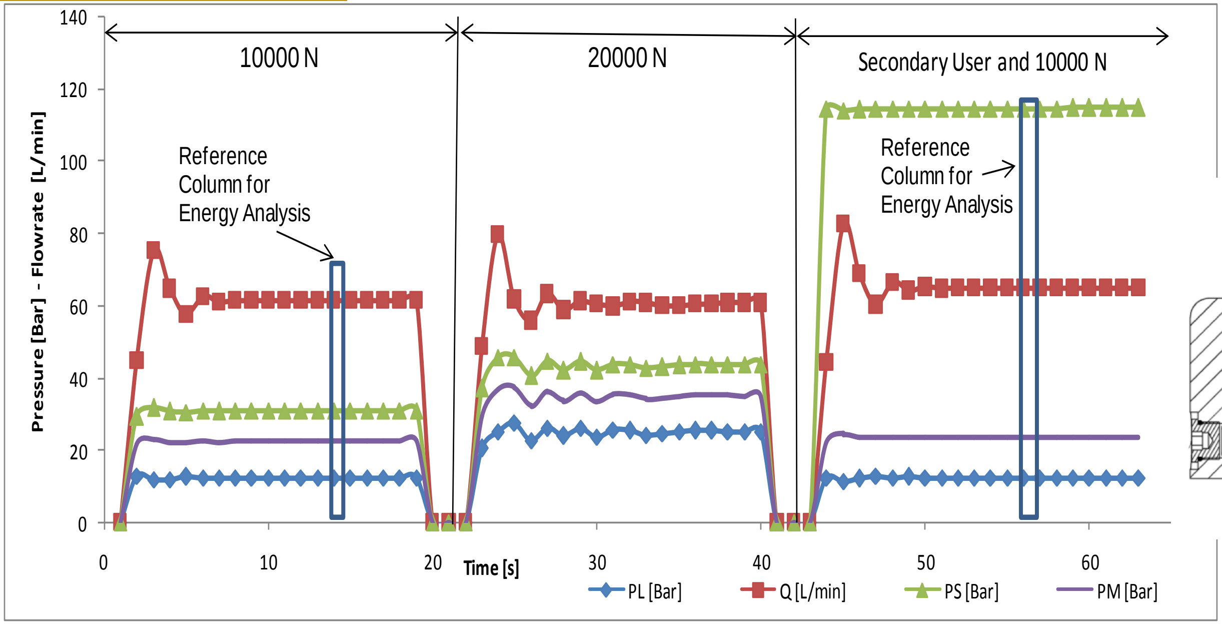
Fig 2h – Simulation results vs. experimental data



Project 2: Tractor rear hitch control for agricultural tractors (e)

a project completely performed at the University of Parma, Italy

Simulation results



Simulation of generic driving cycles

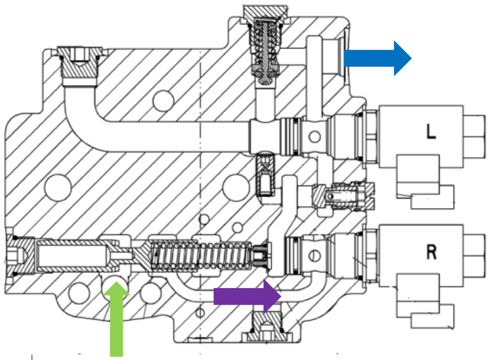
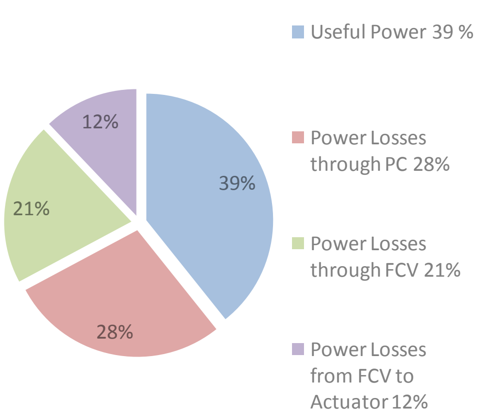


Fig 2i – Simulation of a driving cycle



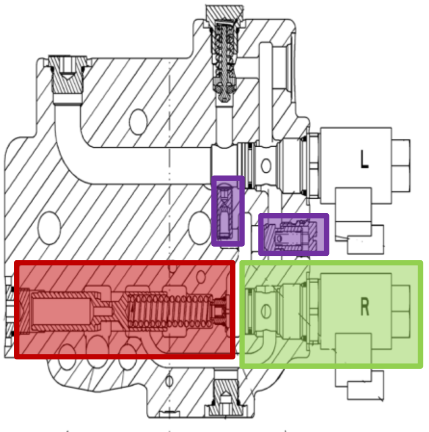


Fig 2j – Power dissipation

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Project 2: Tractor rear hitch control in agricultural tractors (f)

a project completely performed at the University of Parma, Italy

Dynamic analysis

Derivation of a linearized model

$$M_{pc}\Delta\ddot{x}_{pc} + \left\{B_{pc} + \rho L K_{qpc} + A_{pcs}^2 (R_J - R_J)\right\}\Delta\dot{x}_{pc} - \left\{K_{pc} + K_{ff}\cdot\frac{dA_{pc}}{dx_{pc}}(x_{pc0})\cdot(P_s - P_{m0})\right\}\Delta x_{pc} - \left\{K_{ff}\cdot A_{pc}(x_{pc0}) - A_{pcs}\right\}\Delta P_m = A_{pcs}\Delta P_L - K_{ff}\cdot A_{pc}(x_{pc0})\cdot\Delta P_s$$

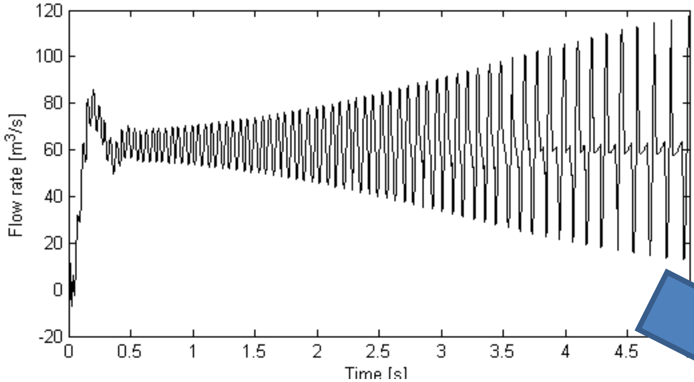


Fig 2k – Flow at load original system

Frequency analysis

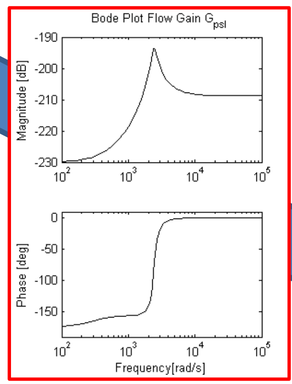
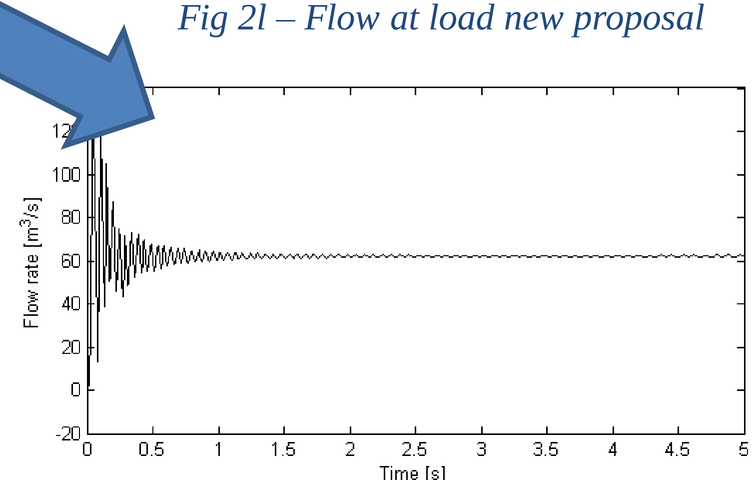


Fig 2l – Flow at load new proposal



Project 2: Tractor rear hitch control in agricultural tractors (g)

a project completely performed at the University of Parma, Italy

Conclusion – final remarks

•The research permitted to realize a complete model of the system, useful for design purposes
•The integration with the electronic controller is under development

For more details..

- write to mahaav@ecn.purdue.edu; paolo.casoli@unipr.it
- see published papers:

-Vacca, A., Franzoni, G., Casoli, P., 2004, *Experimental investigation on a hydraulic special pressure control valve*, 3rd Fluid Power Net International PhD Symposium, Technical University of Catalonia, Terrassa – Spain, 30th June – 2nd July 2004
-Casoli, P., Vacca, A., 2007, *Design Optimization of a Special Relief Valve with Response Surface Methodology*, PTMC 2007, Bath Symposium on Power Transmission & Motion Control, September 12-14, 2007, Bath, UK
- Casoli P., Vacca A., Anthony A., Berta G.L., 2010, *Numerical and Experimental Analysis of the Hydraulic Circuit for the Rear Hitch Control in Agricultural Tractors*, 7IFK International Fluid Power Conference, 22-24 March 2010, Aachen, Germany.
-Anthony A., Casoli P., Vacca A., 2010, *Analysis of a Tractor Rear Hitch Control System*, 6th FPNI *PhD Symposium* June 15-19, *2010* , West Lafayette IN, USA.

Project 3: Analysis of a Diesel/CVT Power split transmission (a)

a project completely performed at the University of Parma, Italy

Goals

- Development of a simulation model for a input couplet power split transmission
- Prediction of fuel consumption
- Individuation of the optimal operating point

The simulation model

- Developed in Simulink, includes:
  - model for speed calculation
  - model for torque calculation
  - calculation of powertrain efficiency
  - evaluation of total transmission efficiency

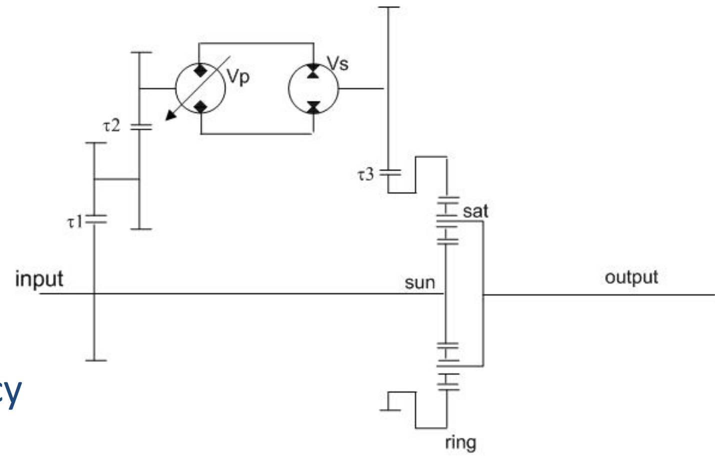


Fig 3a – Simplified scheme of the input couple transmission (CNH is partner of this research project)

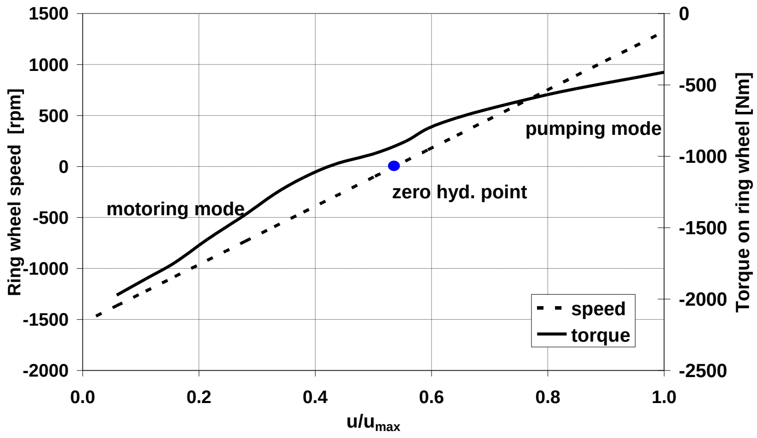


Fig 3b – Results for torques vs speed

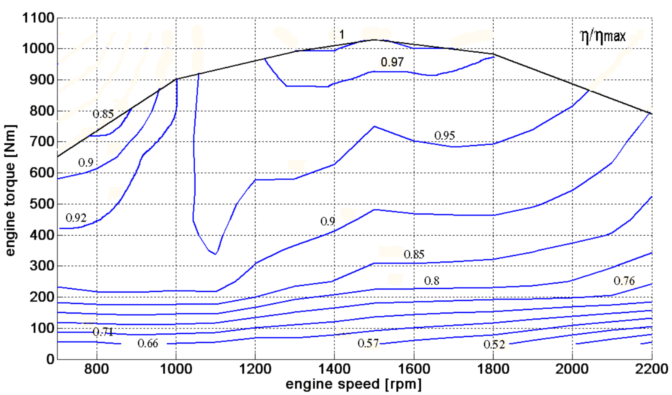
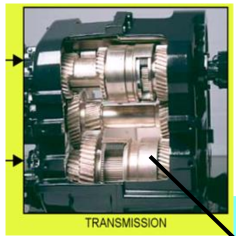


Fig 3c – Map of engine efficiency

Project 3: Analysis of a Diesel/CVT Power split transmission (b)

a project completely performed at the University of Parma, Italy

The simulation model



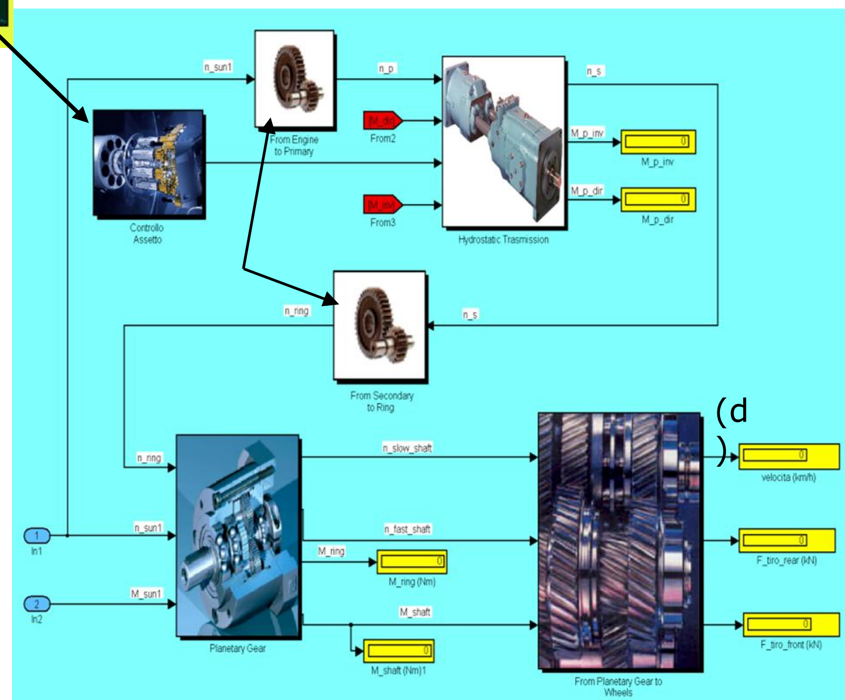


Fig 3d – Detail of the Simulink model representation (the transmission)

Project 3: Analysis of a Diesel/CVT Power split transmission (c)

a project completely performed at the University of Parma, Italy

Some results

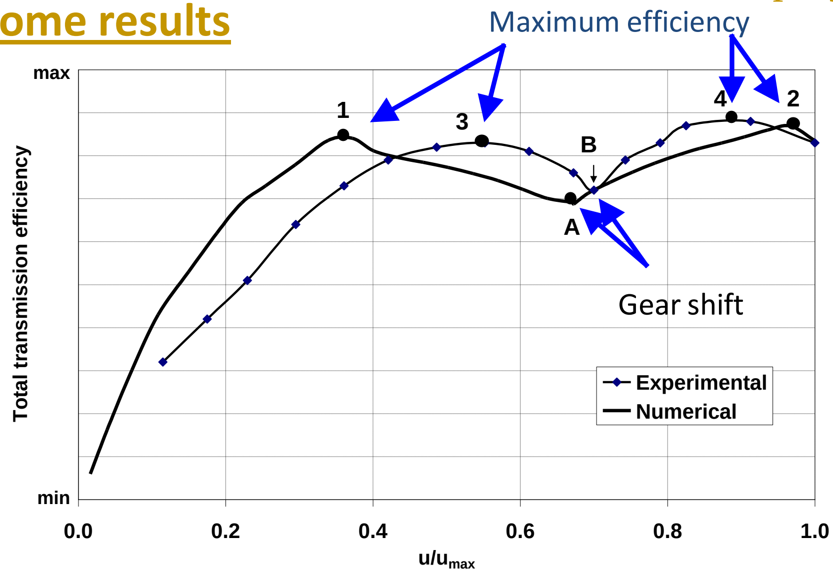
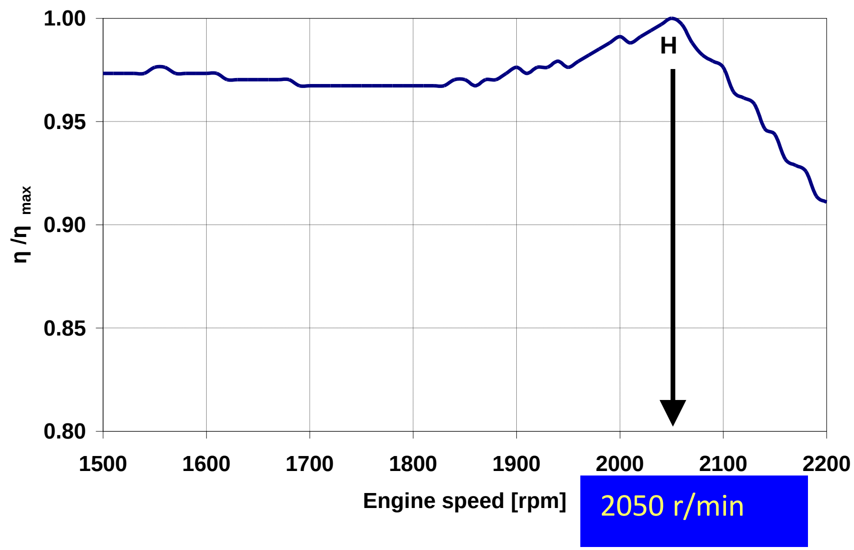


Fig. 3e – Predicted and measured total transmission efficiency vs tractor speed (in first and second gear)

Fig. 3f – Individuation of the optimal operating point



Final remarks

•The model utilizes a significant amount of experimental data for simulating the real performance of both the hydrostatic units and the Diesel engine.

•The optimum operating point (minimum fuel consumption) can be predicted for different duties

For more details..

• write to paolo.casoli@unipr.it; mahaav@ecn.purdue.edu

• see published papers:

- Casoli, P., Vacca, A., Berta, G.L., Meleti, S., Vescovini, M., 2007, *A Numerical Model for the Simulation of Diesel/CVT Power Split Transmission*, ICE2007 – 8th SAE Int. Conf. on Engines for Automobile, September 16-20, Capri (NA), Italy.

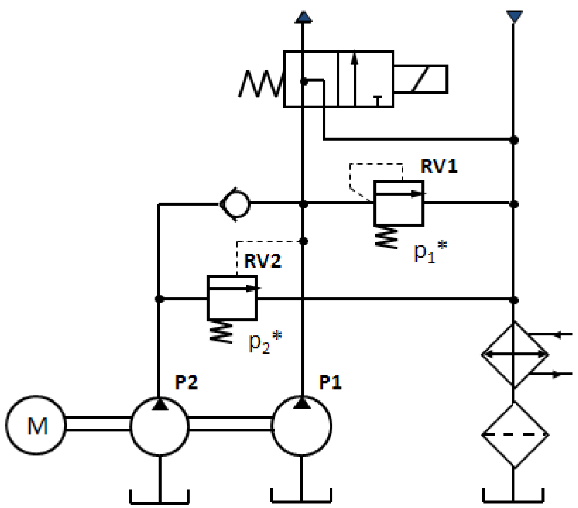
Project 4: Analysis, design, optimization of power supply systems (a)

a project completely performed at the University of Parma, Italy

Project 4.1: discrete variable flow rate supply group

Goals

- Study and improvement of system controllability
- Improvement of system efficiency
- Analysis of new ideas (electro-hydraulic control of RV2)



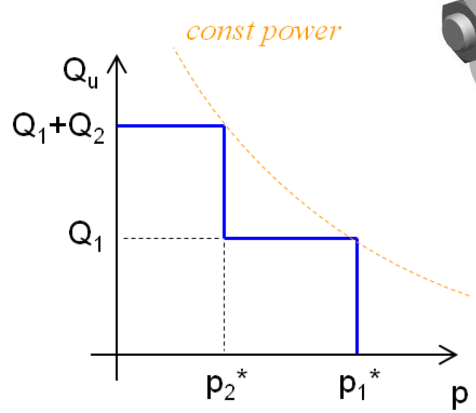


Fig 4a – Schematic of a non optimized variable displacement (2 level) supply group

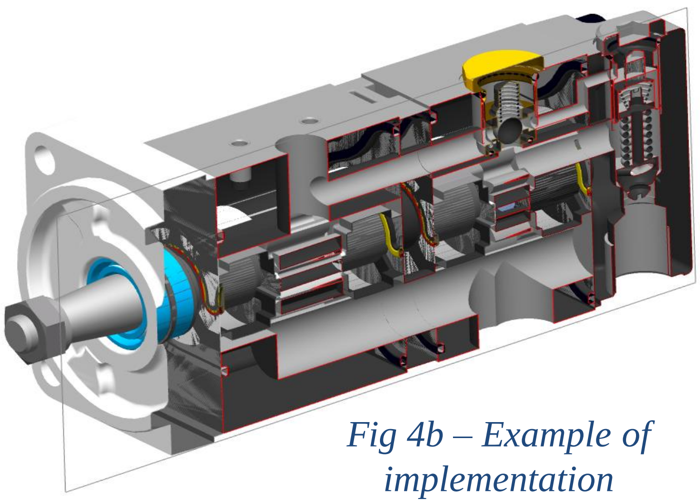


Fig 4b – Example of implementation

Dr. **Andrea Vacca**
MAHA Assistant professor
Purdue University

Project 4: Analysis, design, optimization of power supply systems (b)

a project completely performed at the University of Parma, Italy

Project 4.1: discrete variable flow rate supply group

Approach of analysis

- Detailed simulation model of the each element of the system

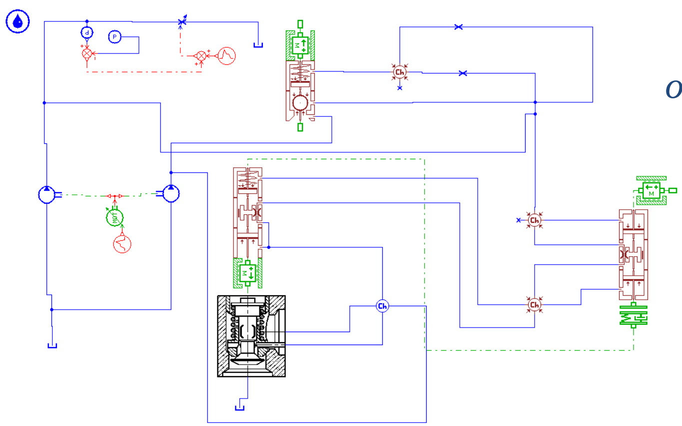
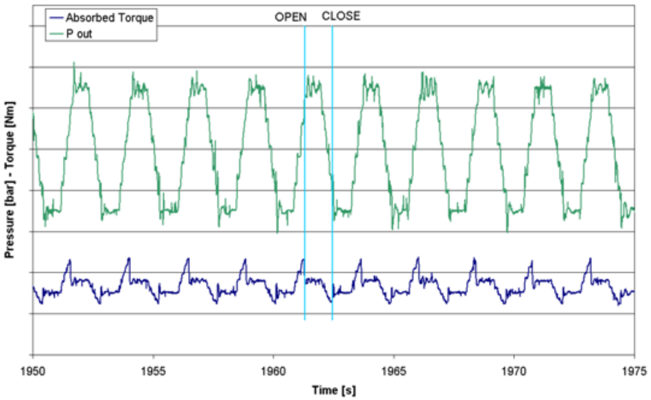


Fig 4c – The AMESim model of one of the considered alternatives

- Model validation



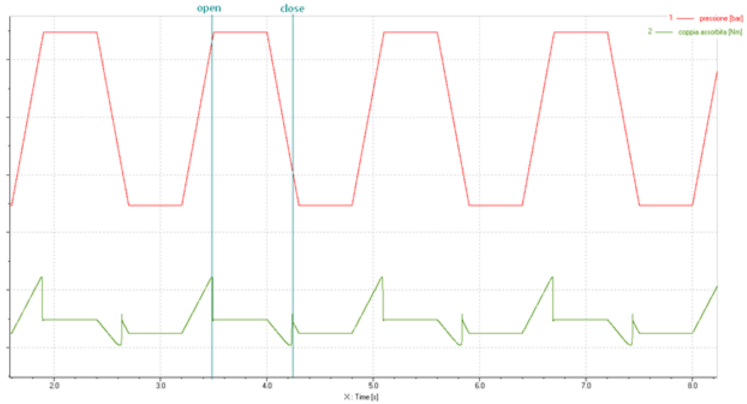


Fig 4d – Comparison between simulation results and experimental data

Project 4: Analysis, design, optimization of power supply systems (c)

a project completely performed at the University of Parma, Italy

Project 4.1: discrete variable flow rate supply group

Final remarks

- Work in progress. High potentials of improvement of system behavior
- Simulation model already utilized to dimension the internal components

For more details..

write to mahaav@ecn.purdue.edu

Project 4: Analysis, design, optimization of power supply systems (d)

Project 4.2: electro-hydraulic system for the displacement control

Goals
- Accurate simulation of the interaction between the hydraulic system and the electronic controller
- Optimization of the components
- Development of a toll for the control design

The analized system

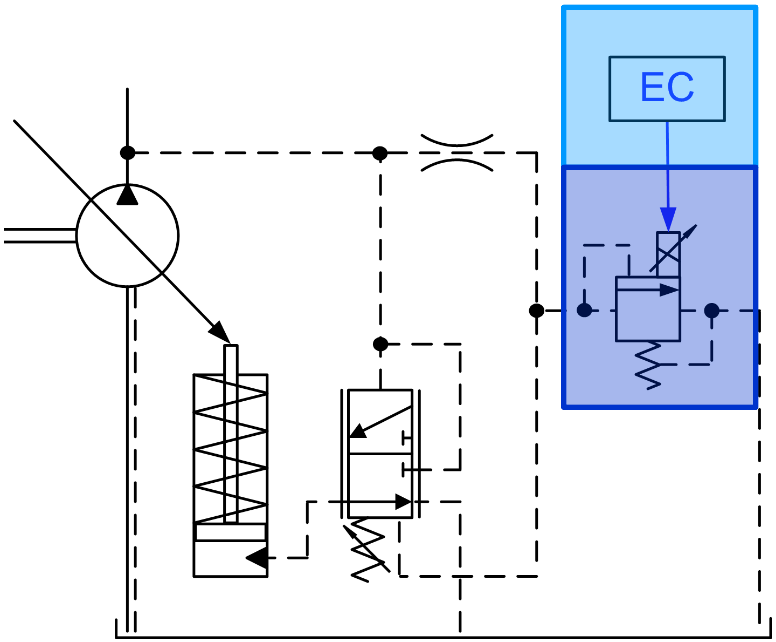


Fig 4e – The system under study: the electro-hydraulic LS

Fig 4f – The proportional valve actuated by the electronic controller to change the pump displacement

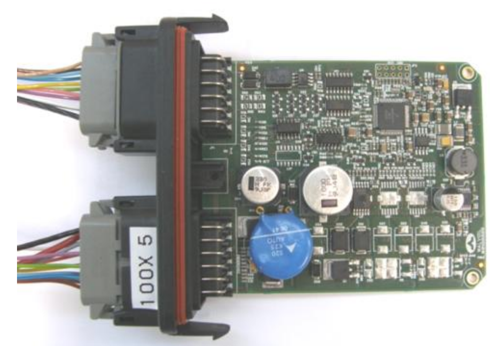


Fig 4g – The electronic controller developed by the company partner of the research

Project 4: Analysis, design, optimization of power supply systems (e)

Project 4.2: electro-hydraulic system for the displacement control

The simulation approach

AMESim — Co-Simulation — MATLAB SIMULINK

Fig 4h – Valve model

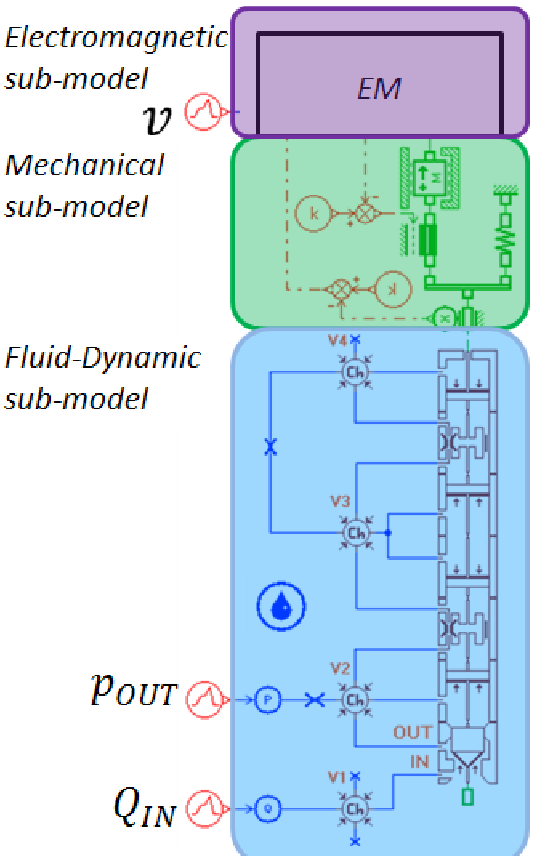
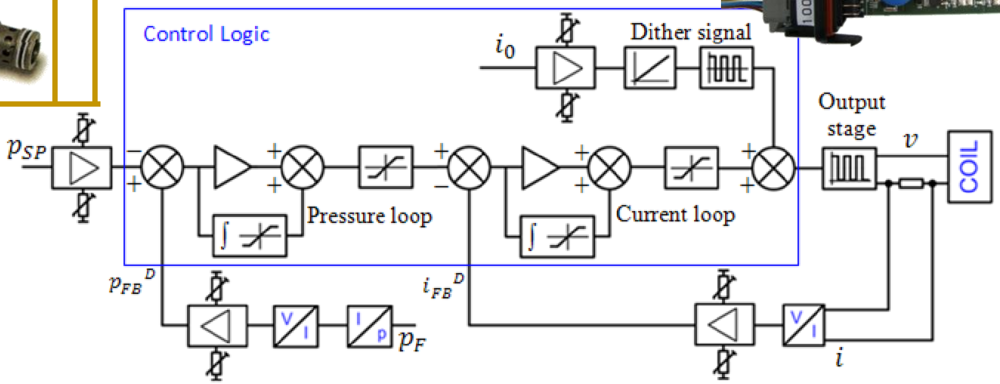


Fig 4i – Controller model



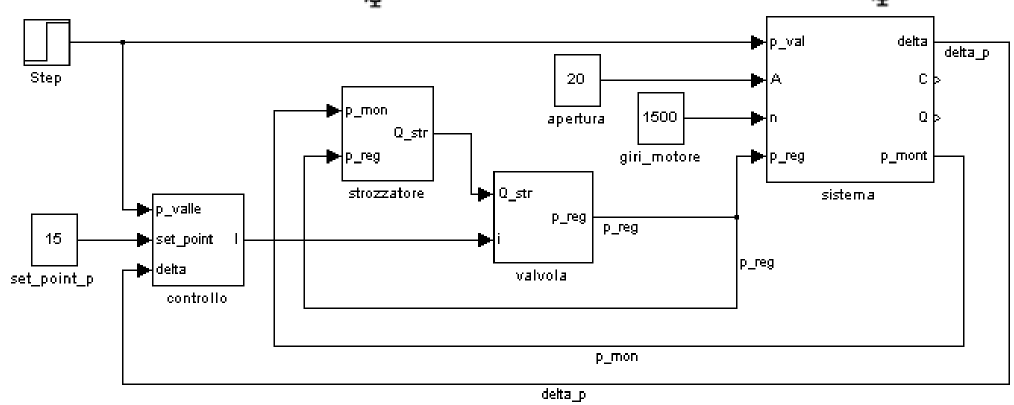


Fig 4j – Controller and Valve interface

Project 4: Analysis, design, optimization of power supply systems (e)

Project 4.2: electro-hydraulic system for the displacement control

The simulation approach

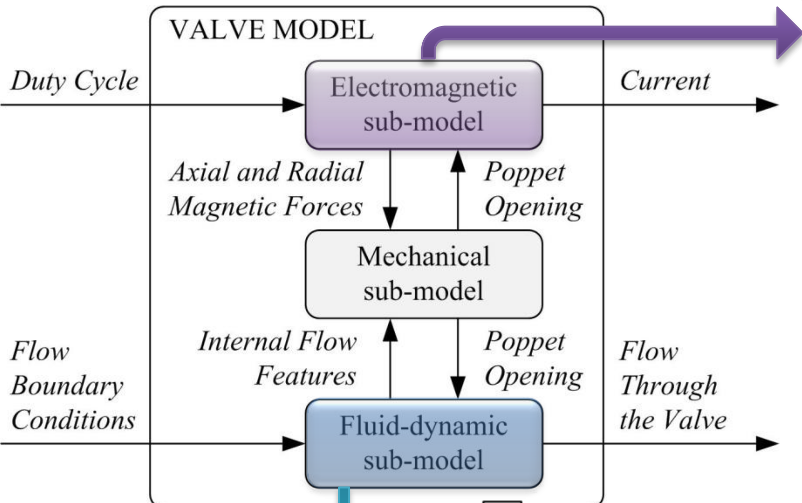


Fig 4k – The model of proportional valve

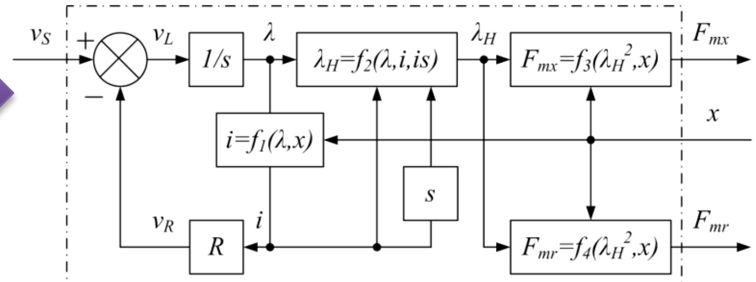


Fig 4m – Electromagnetic submodel, accounting for transient effects (accounting hysteresis, eddy currents)

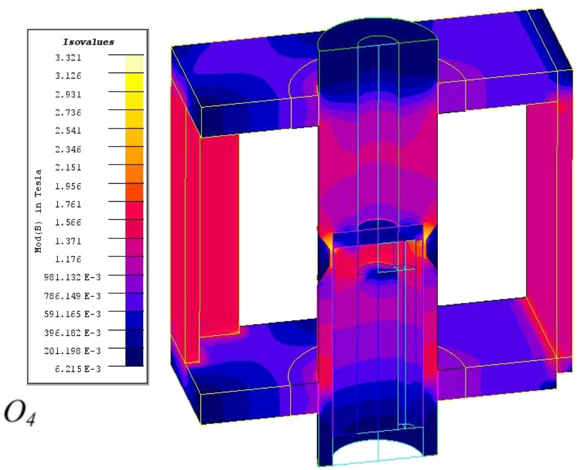


Fig 4n – Magnetic flux resulting from the FEEM 3D simulation model (CEDRAT FLUX 3D)

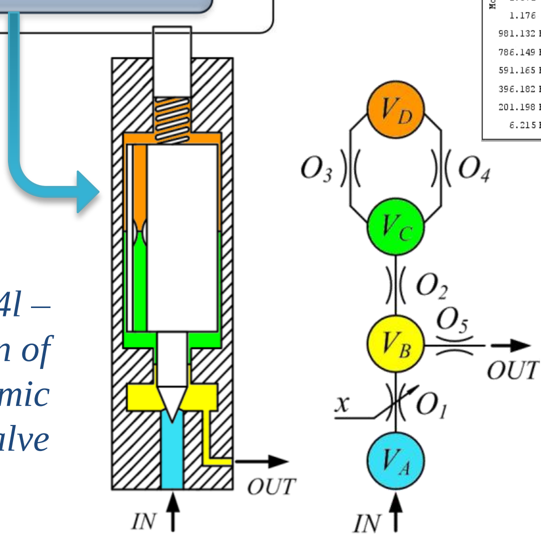


Fig 4l – Representation of the fluid dynamic model of the valve

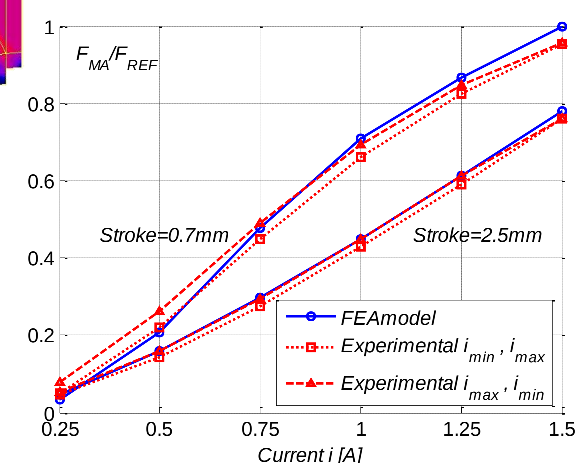


Fig 4o – Experimental validation of Magnetic force calculated by the FEEM 3D simulation model

Project 4: Analysis, design, optimization of power supply systems (g)

Project 4.2: electro-hydraulic system for the displacement control

The simulation approach (cont.)

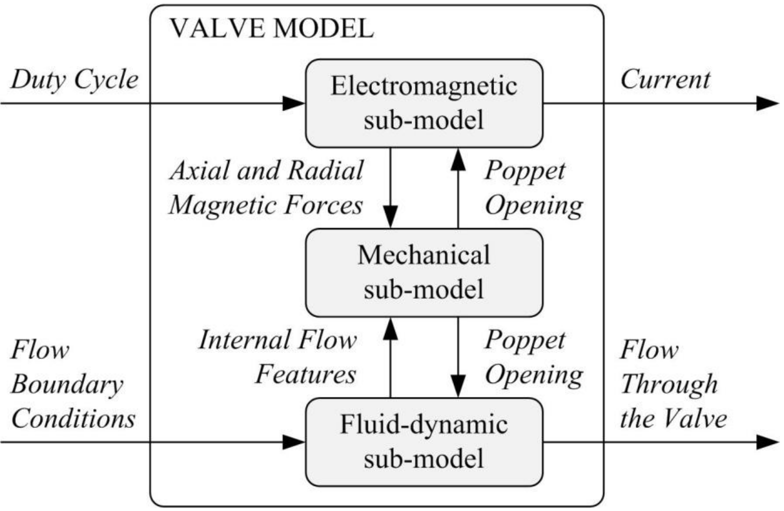


Fig 4p – The model of proportional valve

Linearization → Frequency Analysis

- Design of the control strategy
- Influence of nonlinearities

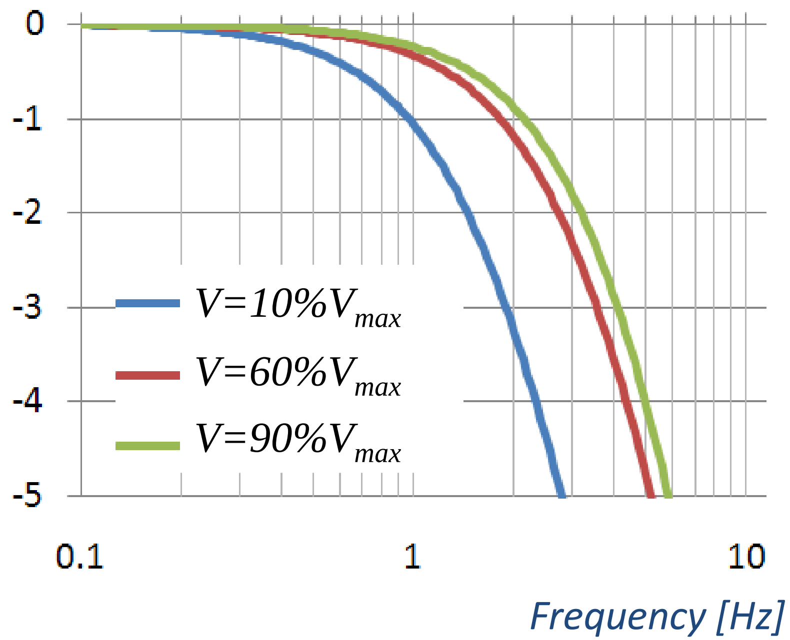
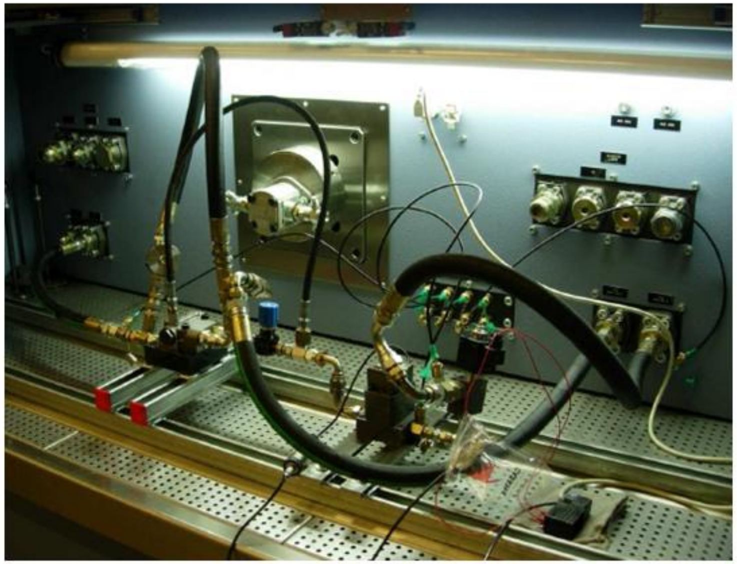


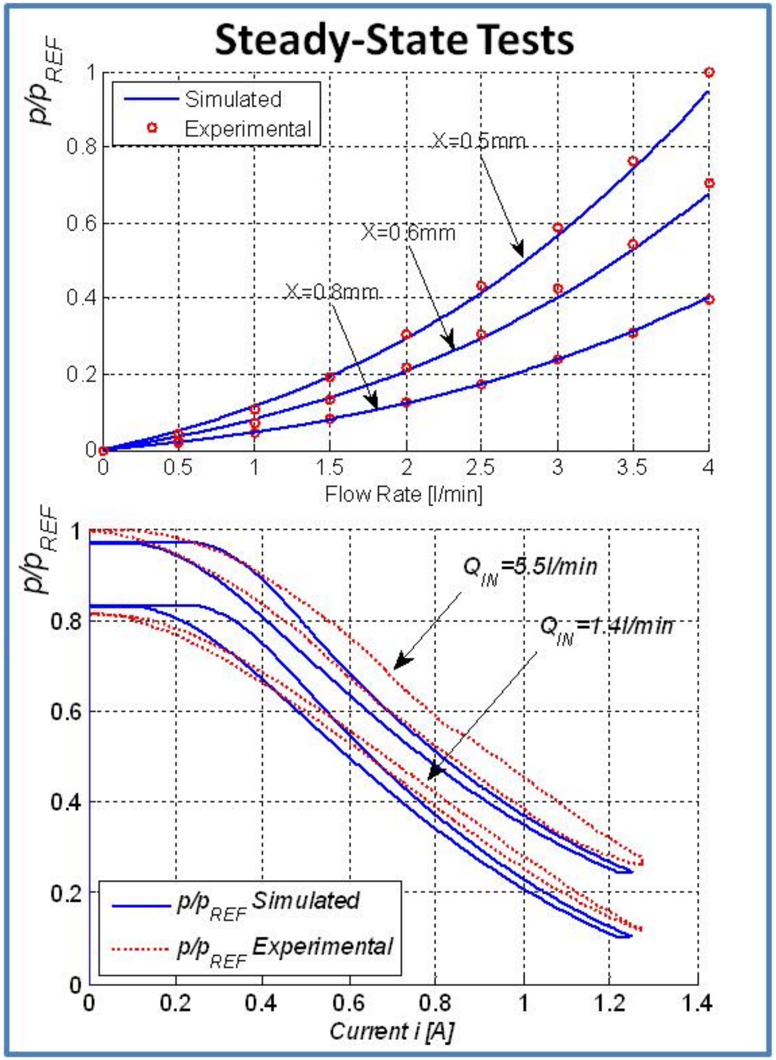
Fig 4q – Example of Bode plot obtained by model linearization.

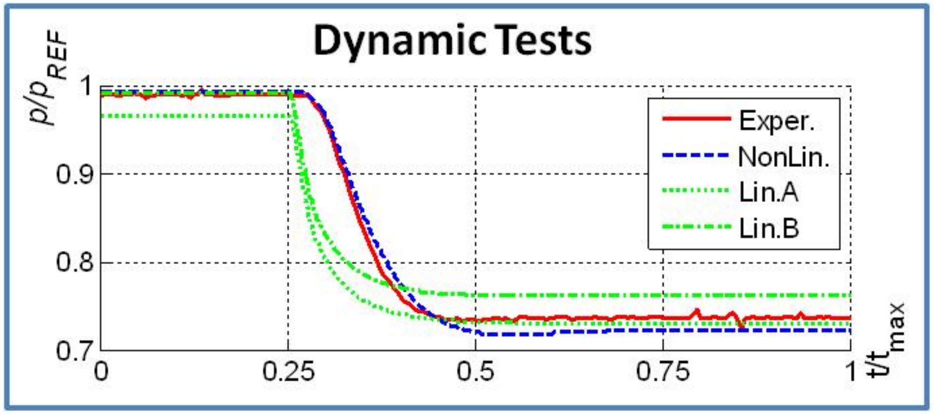
Project 4: Analysis, design, optimization of power supply systems (h)

Project 4.2: electro-hydraulic system for the displacement control

Experimental validation of the valve model







Project 4: Analysis, design, optimization of power supply systems (h)

Project 4.2: electro-hydraulic system for the displacement control

Experimental validation of the valve model

Fig 4r – Circuit taken as reference to test the effect of different control strategies

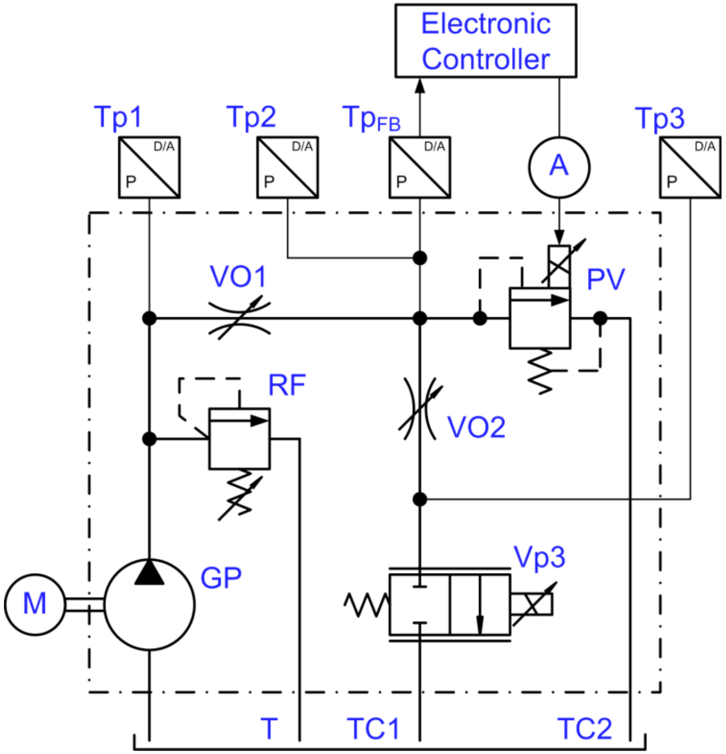
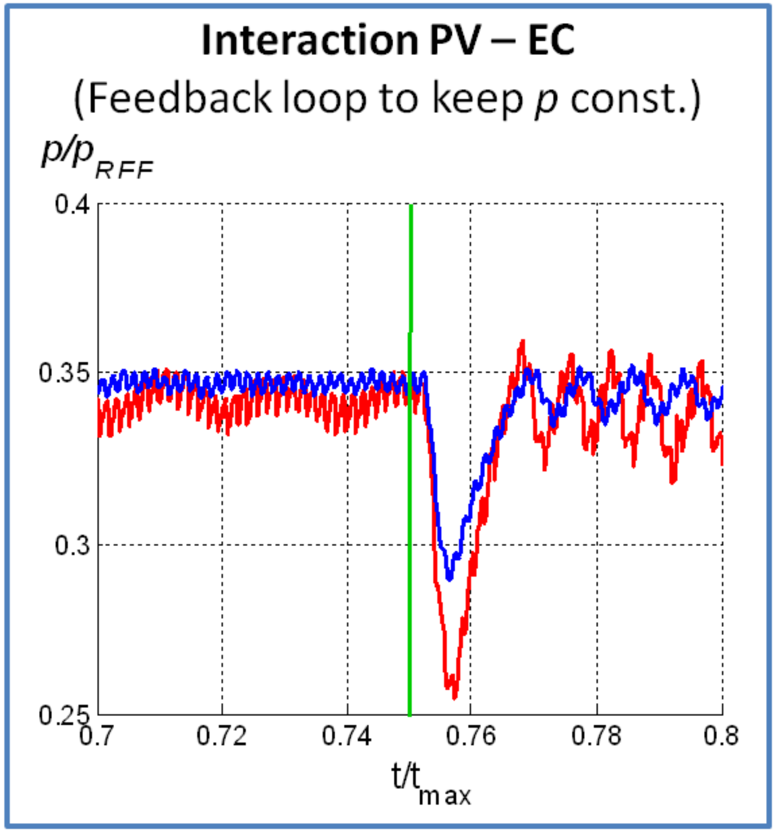


Fig 4s – Details of effects (time domain) of a selected control strategy



Project 4: Analysis, design, optimization of power supply systems (I)

Project 4.2: electro-hydraulic system for the displacement control

Conclusions – Final Remarks

- A very accurate non-linear simulation model for the proportional valve has been developed
- The integration between the non linear hydraulic system – electronic controller permits to investigate the effects of different control strategies

For more details..

- write to mahaav@ecn.purdue.edu
- see published papers:

- Cristofori D., Vacca A., 2010, Analysis of the Dynamics of a Proportional Valve operated by an Electronic Controller, 6th FPNI *PhD Symposium* June 15-19, *2010* , West Lafayette IN, USA.
- Vacca A., Cristofori D., 2010, *The Modelling of Electro-Hydraulic Proportional Valves*, submitted to Int. Journal for Fluid Power.

Dr. Andrea Vacca
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Project 5: Design of a LS flow divider valve (a)

a project completely performed at the University of Parma, Italy

Goals

- Development of an accurate model for a flow divider valve utilized in hydraulic power steering system power steering
- Reduction of losses and of interdependence between the primary port and secondary port

Typical example of application

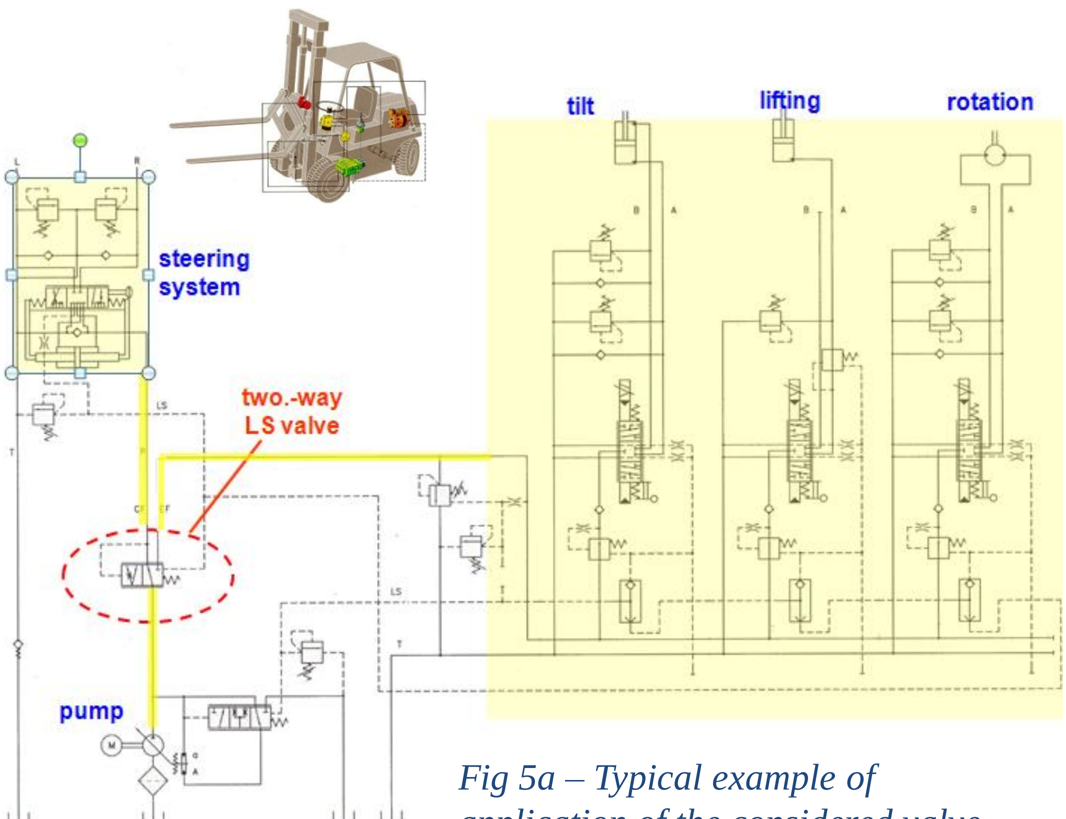


Fig 5a – Typical example of application of the considered valve

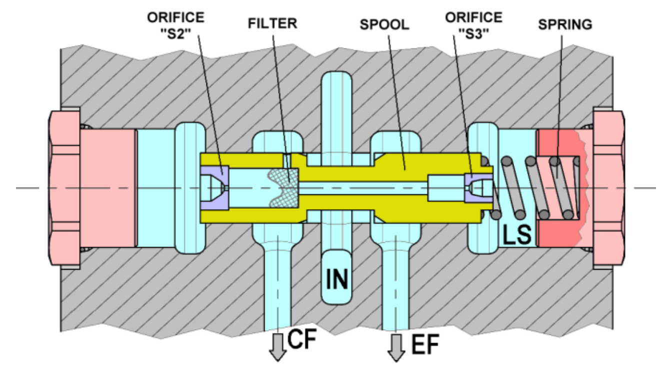


Fig 5b – The valve

IN: input
CF: primary outlet port
EF: secondary outlet port
LS: load sensing signal

Project 5: Design of a LS flow divider valve (b)

a project completely performed at the University of Parma, Italy

Valve modeling

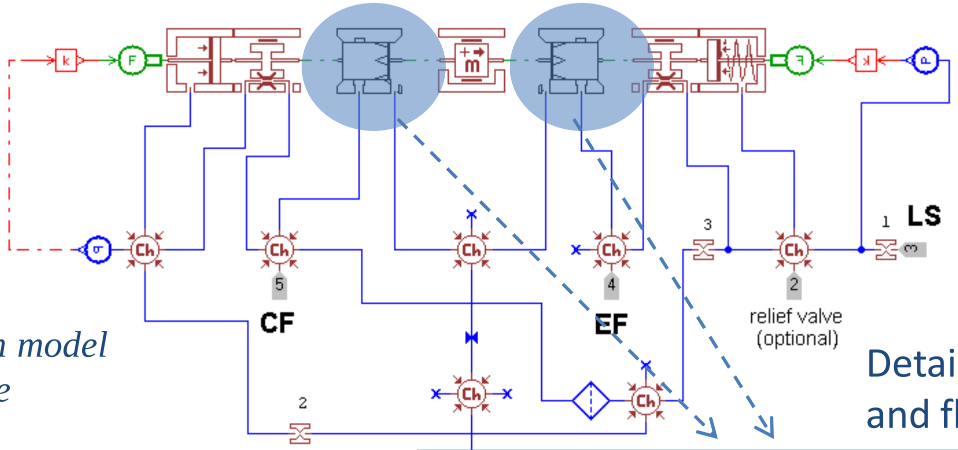


Fig 5c – AMESim model of the valve

Detailed evaluation of flow forces and flow area (considering notches)

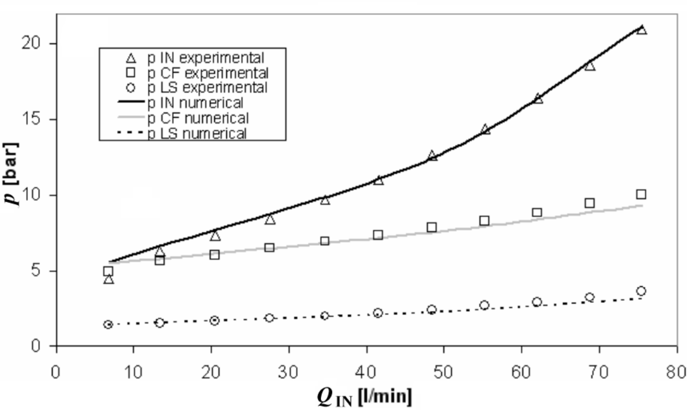


Fig 5e – Model validation

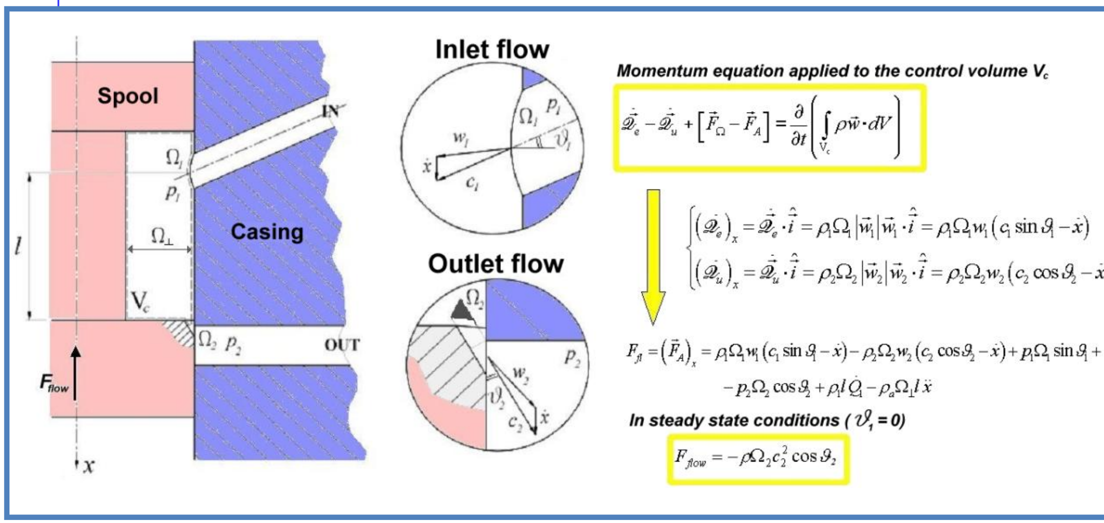


Fig 5d – Reference scheme for the calculation of flow forces

Project 5: Design of a LS flow divider valve (c)

a project completely performed at the University of Parma, Italy

Design optimization

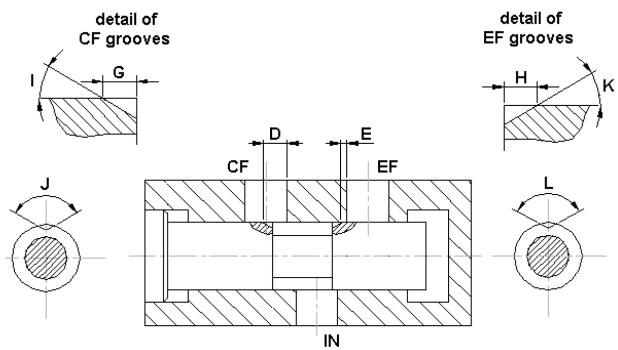
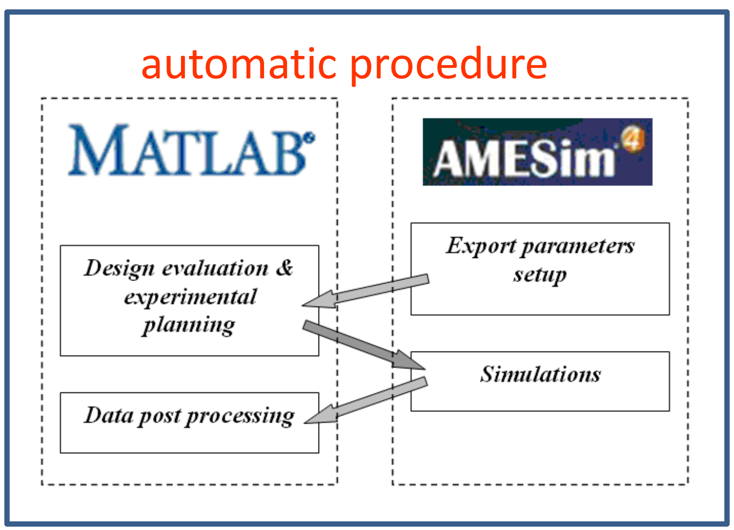


Fig 5f – Parameters considered

Objective functions:

1. Flow rate on primary port independent from load, Q_{IN}
2. Power losses through secondary port
3. Independence of pressure peaks during transients

Investigation procedure by means of Design of Experiments (DOE)



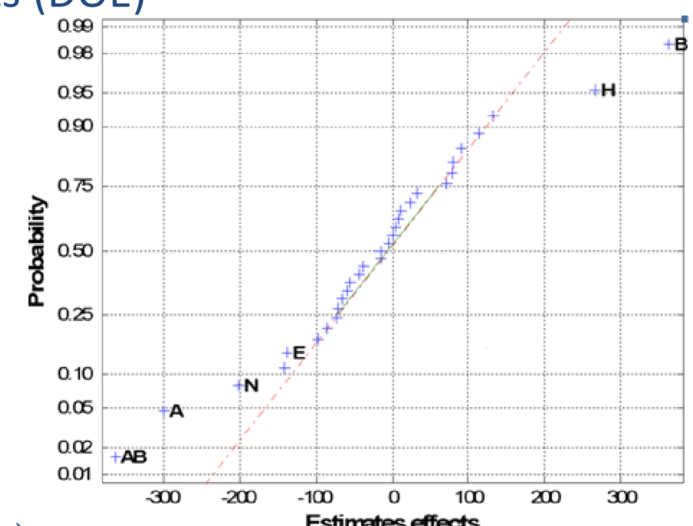


Fig 5g – Parameters affecting one of the objective functions (normal probability plot)

Project 5: Design of a LS flow divider valve (d)

a project completely performed at the University of Parma, Italy

Design optimization

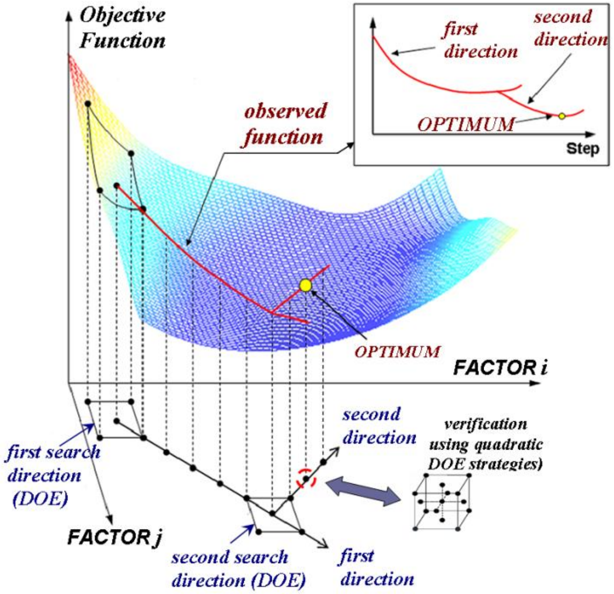


Fig 5h – The combined DOE-RSM algorithm

Optimization through Response surface Methodology (RSM)

Fig 5i – The optimized spool design

Results of the optimization

All targets improved with respect to the initial, standard design. Improvement of controllability and improvement of pressure losses up to 40%

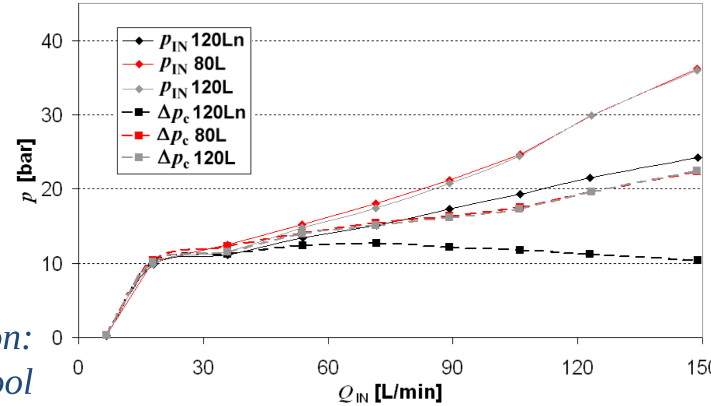


Fig 5j – Experimental comparison: new spool vs. old spool

Project 5: Design of a LS flow divider valve (e)

a project completely performed at the University of Parma, Italy

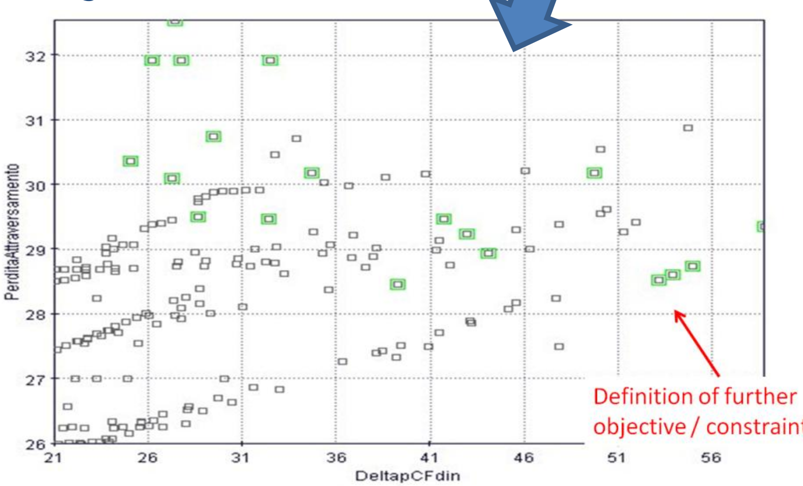
Design optimization

Recent application of a optimization procedure specifically multi-objective

modeFRONTIER
multi-objective optimization and design environment

Initial DOE created by SOBOL method
Optimization by MOGA II algorithm
Evaluation of 1280 designs

Fig 5l – pareto frontier for design selection



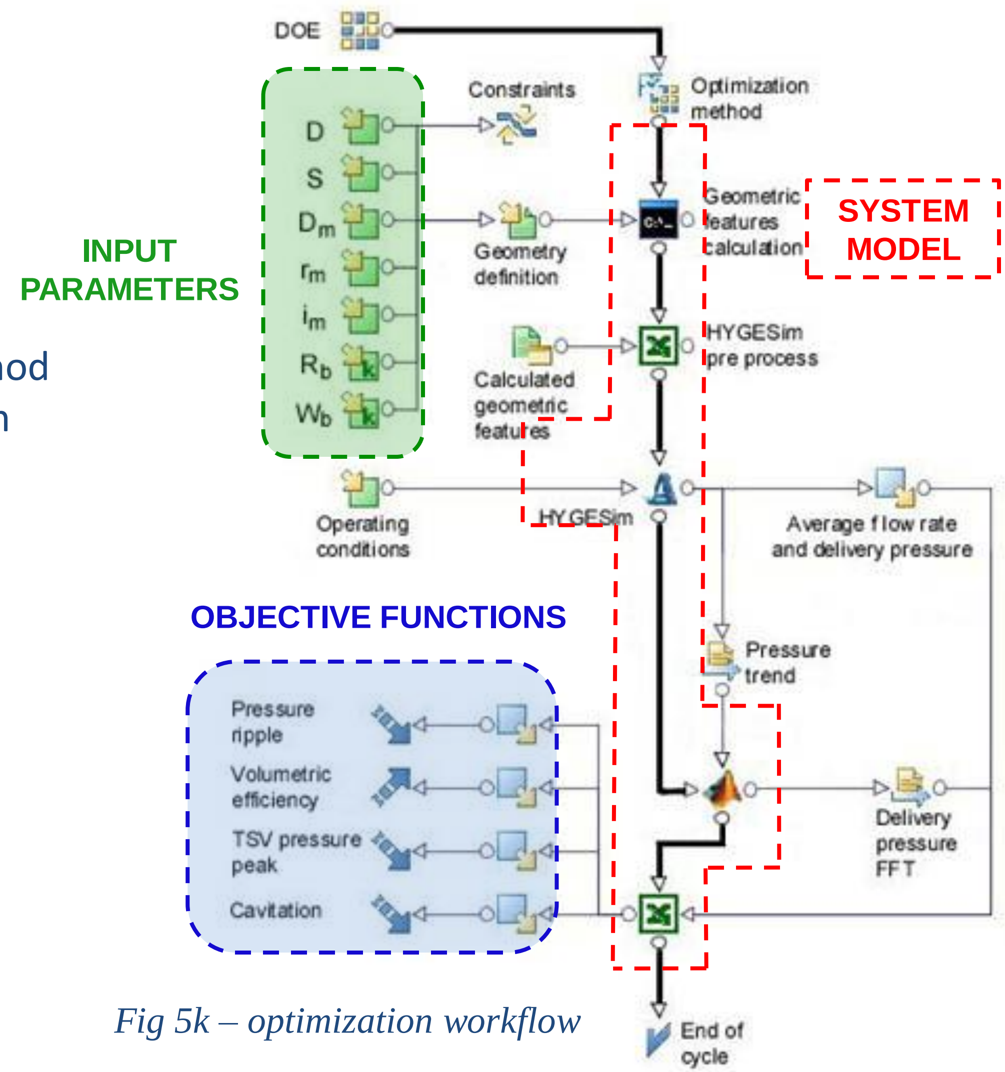


Fig 5k – optimization workflow

Project 5: Design of a LS flow divider valve (f)

a project completely performed at the University of Parma, Italy

Valve testing

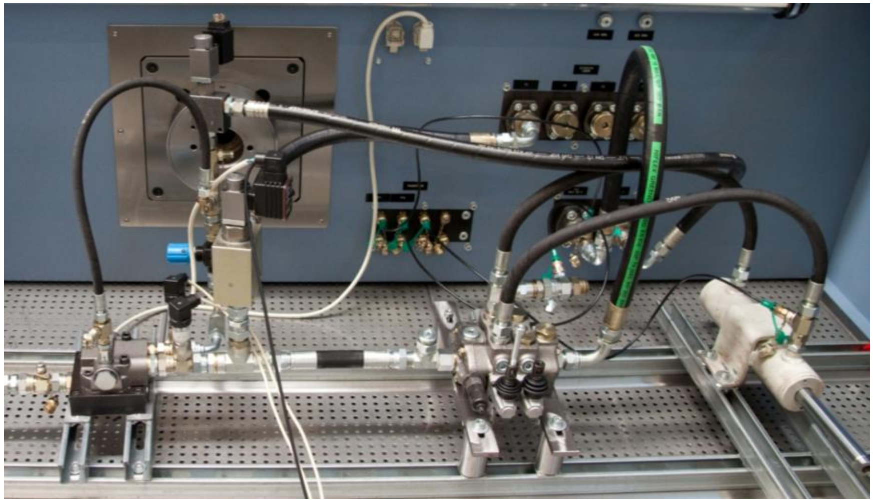


Fig 5m – Apparatus for dynamic test on the valve (reproduction of sudden pressure peaks)

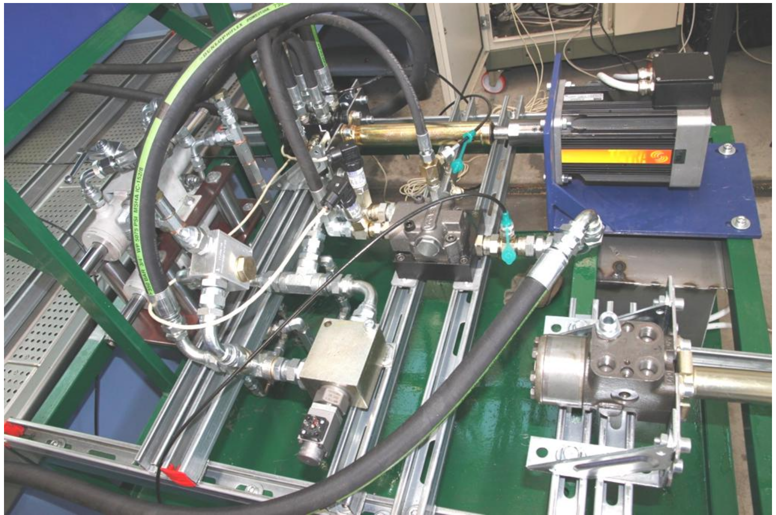


Fig 5n – Reproduction of a complete power steering system for repetitive measurements

Project 5: Design of a LS flow divider valve (g)

a project completely performed at the University of Parma, Italy

Conclusions – Final Remarks

- Detailed simulation model: evaluation of flow forces in spool valves
- Valve optimization: development of an automatic algorithm that minimize the simulation time by means of a combined RSM-DOE procedure
- Advance valve testing for steady state and transient (realistic) conditions

For more details..

- write to mahaav@ecn.purdue.edu
- see published papers:

- Casoli, P., Vacca, A., Franzoni, G., 2003, *A numerical model for simulation of "load sensing" spool valves,* The 18th International Conference on Hydraulics and Pneumatics, Prague, Czech Republic, September 30 – October 1, 2003
-Vacca, A. 2006, Proposal of a Load Sensing Two-Way Valve Model, Applying "Design Of Experiments" Techniques to Simulations, IMECE2006, 2006 ASME International Mechanical Engineering Congress and Exposition, November 2006, Chicago, Illinois, USA
-Vacca, A., Cerutti, M., 2007, Analysis and Optimization of a Two-Way Valve Using Response Surface Methodology, International Journal of Fluid Power, Vol. 8, N. 3, November 2007, pp. 43-59

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Project 6:
Innovative Oscillations Damping in Valve Controlled Systems (b)

Goals

Definition of an adaptive control strategy for the reduction of oscillations in generic valve controlled systems

Motivations

Frequent problem in many applications (like garbage trucks, hydr. cranes, etc.):

- controllability
- safety
- Productivity, …

Sources of oscillations

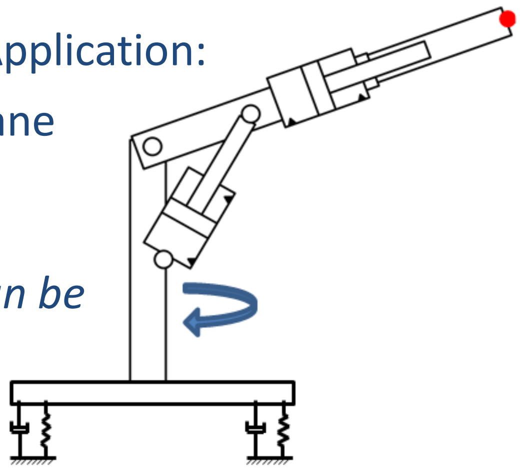
- Hydraulic system
  - Load holding valves (Over center)
  - Hydraulic lines
  - LS System, …
- Oscillations of the external load (3D)
- Oscillations due to chassis (shock abs.)
- Natural frequencies of the structure

Project 6:
Innovative Oscillations Damping in Valve Controlled Systems (b)

Our Idea

Example of Application:

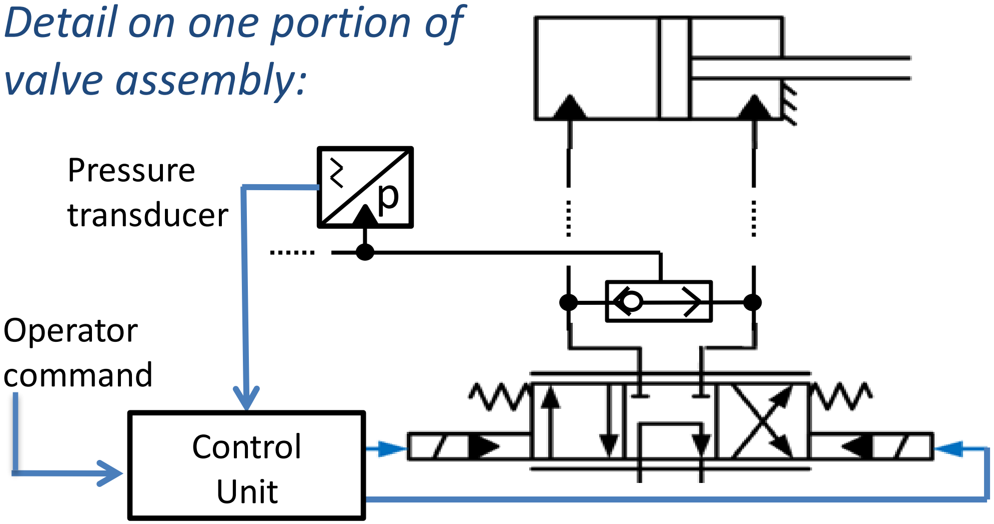
Hydraulic Crane
(All possible sources of oscillation can be highlighted)



Potential Advantages of Our Solution

- Effective reduction of the oscillations
- Simplification of the hydraulic system, respect to the traditional hydraulic solutions used to damp the oscillations
- Reduction of time required by the tuning process
- Applicability to every hydraulic layout/mech. system

Detail on one portion of valve assembly:



The control unit evaluates the command to the electro-hydraulic valves on the basis of the pressure transducer (placed close to valve ports) signal.

The new control strategy can be used as option (enable/disable).

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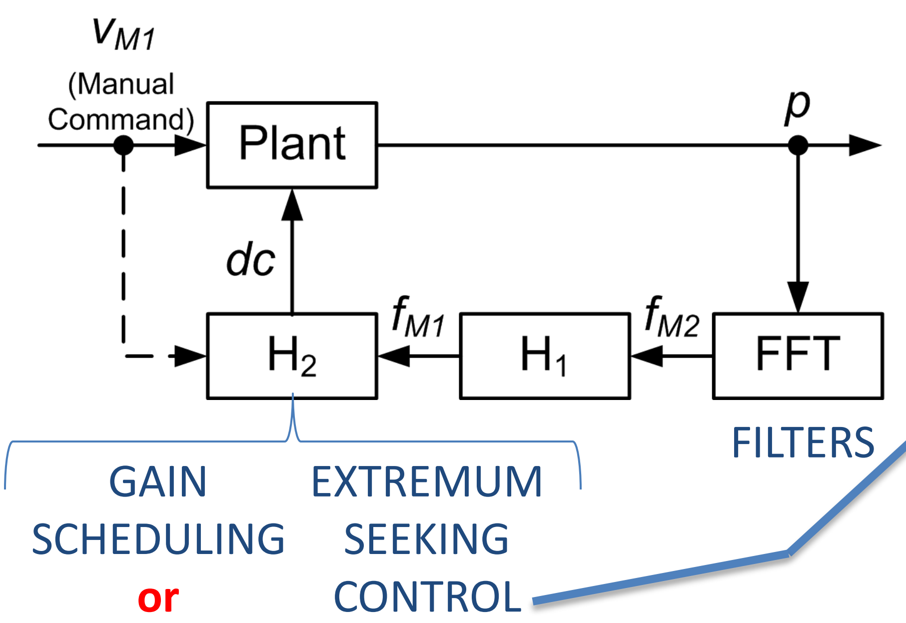
MAHA Assistant professor
Purdue University

Project 6:
Innovative Oscillations Damping in Valve Controlled Systems (b)

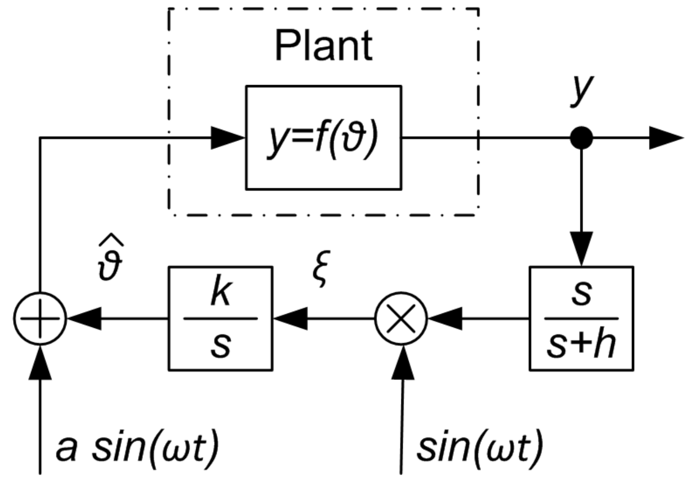
Our Idea

The control strategy

Simplified sketch of the control strategy



Extremum Seeking Control (ESC)



Example of ESC for one-variable system

What's New?

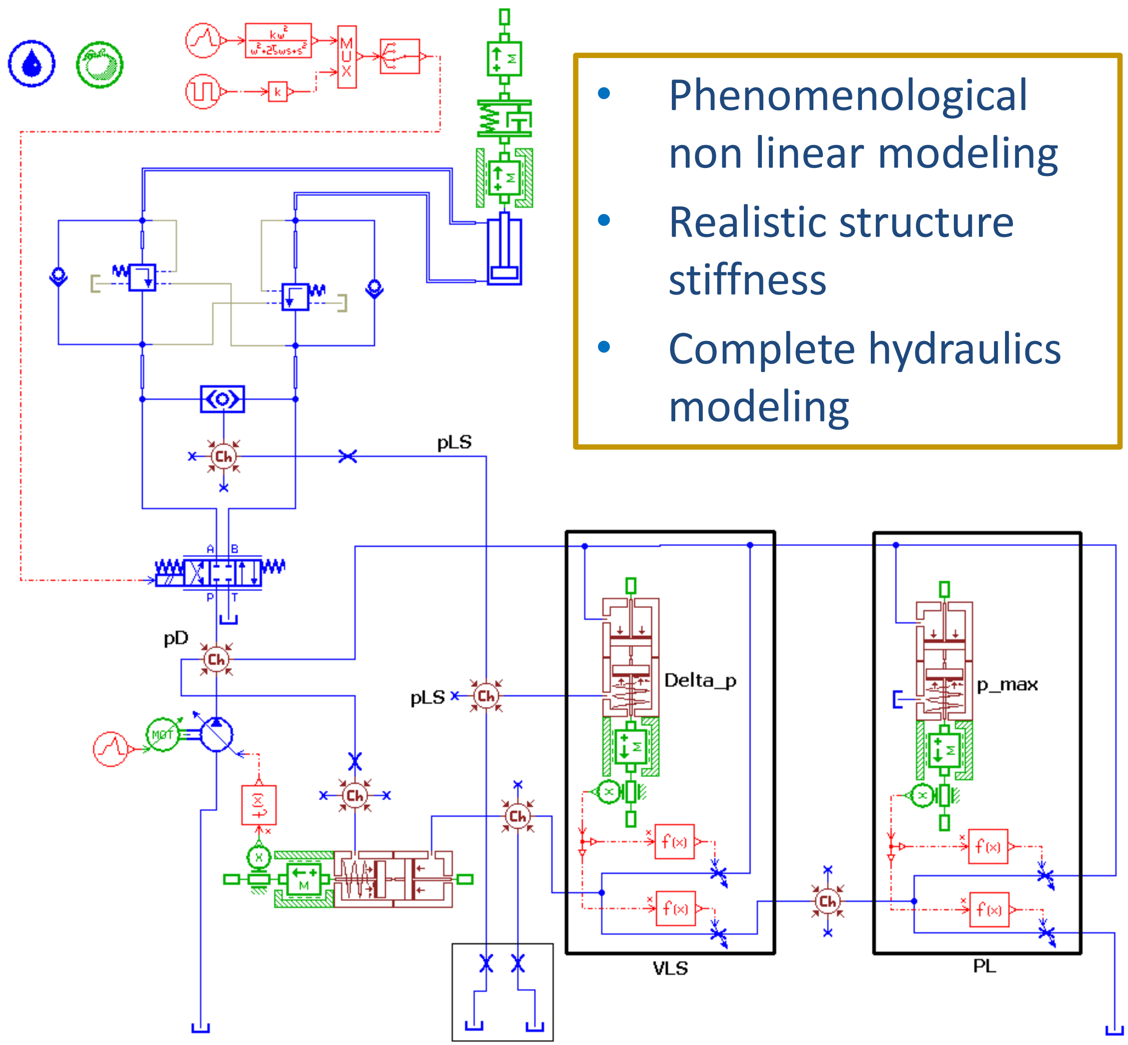
- **Adaptive control strategy**, to allow the use of the solution to generic cases
- Solution suitable for standard hydraulic layouts and advanced **independent metering** system as well

Project 6:
Adaptive control for the cancellation of low freq. disturbances (c)

Modelling approach

AMESim **Co-Simulation** MATLAB SIMULINK

- Simulation model representative of a real system
- Reference machine: hydraulic crane for trucks
- The plant model (AMESim®) includes the hydr. system, the mech. system and is targeted to describe all possible sources of load oscillation
- The controller model (Simulink®) runs in co-simulation with the plant model



- Phenomenological non linear modeling
- Realistic structure stiffness
- Complete hydraulics modeling

Project 6:
Adaptive control for the cancellation of low freq. disturbances (d)

Summary

- *Definition of the reference system*: Hydraulic crane
  - Mechanical Structure: chassis with shock absorbers
  - Hydraulic System:
    - Standard (LS)
    - Independent metering
- *Definition of the control strategy*:
  Extremum Seeking vs. Gain Scheduling
- *System modeling*:
  AMESim® - Simulink® co-simulation
- *System testing*:
  Installation of the crane at MAHA (Purdue University)

Under development

- numerical model completion
- evaluation of the alternatives control strategies
- building a test rig for experimental confirmation

For more details..

- write to mahaav@ecn.purdue.edu