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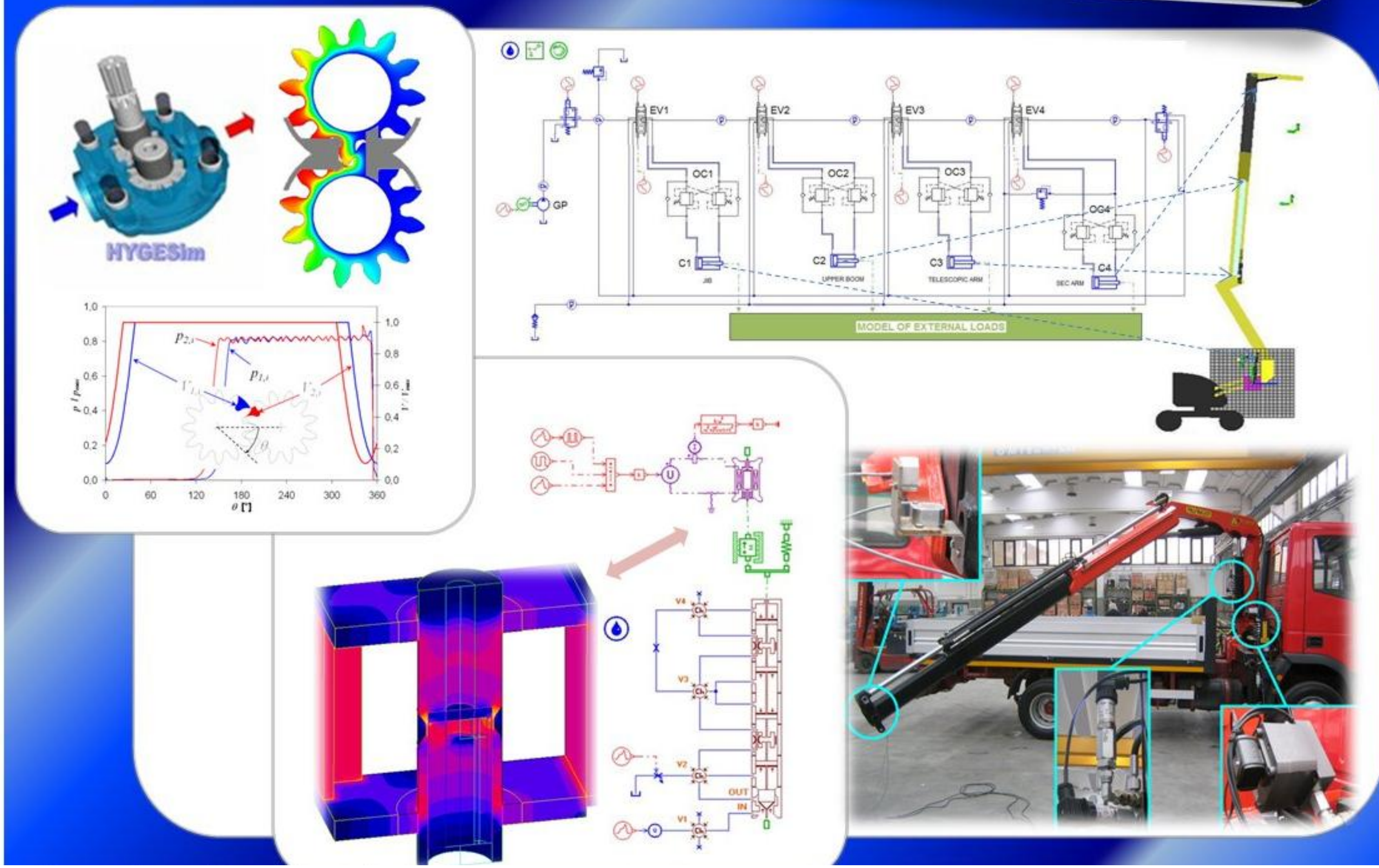



# research activities on Gear Pumps/Motors
# - Highlights -

# Projects List:

1. Modeling: the simulation tool HYGESim (*HYdraulic GEar machines Simulator*)
2. Pump / motor testing
3. Optimization of standard designs
4. Proposal, analysis and optimization of new designs
5. Analysis of solutions for variable displacement units

# Project 1: The simulation tool HYGESim (a)

**Goals**
- Entire simulation of external gear machines (pumps/motors) considering main physical phenomena
- Tool versatile, useful for verification/design purposes

## Main features of the HYGESim (HYdraulic GEar machines Simulator)

- detailed geometrical model
- developed within AMESim®
- detailed model for fluid properties
- simulation of the complete inlet/outlet hydr. systems
- evaluation of flow delivery features
- evaluation of internal pressure peaks
- calculation of gears' axes of rotation micro-motion
- evaluation of casing wear

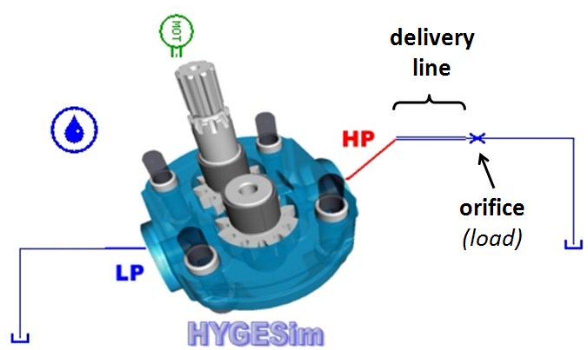



*Fig 1a - HYGESim icon within AMESim simulation environment*

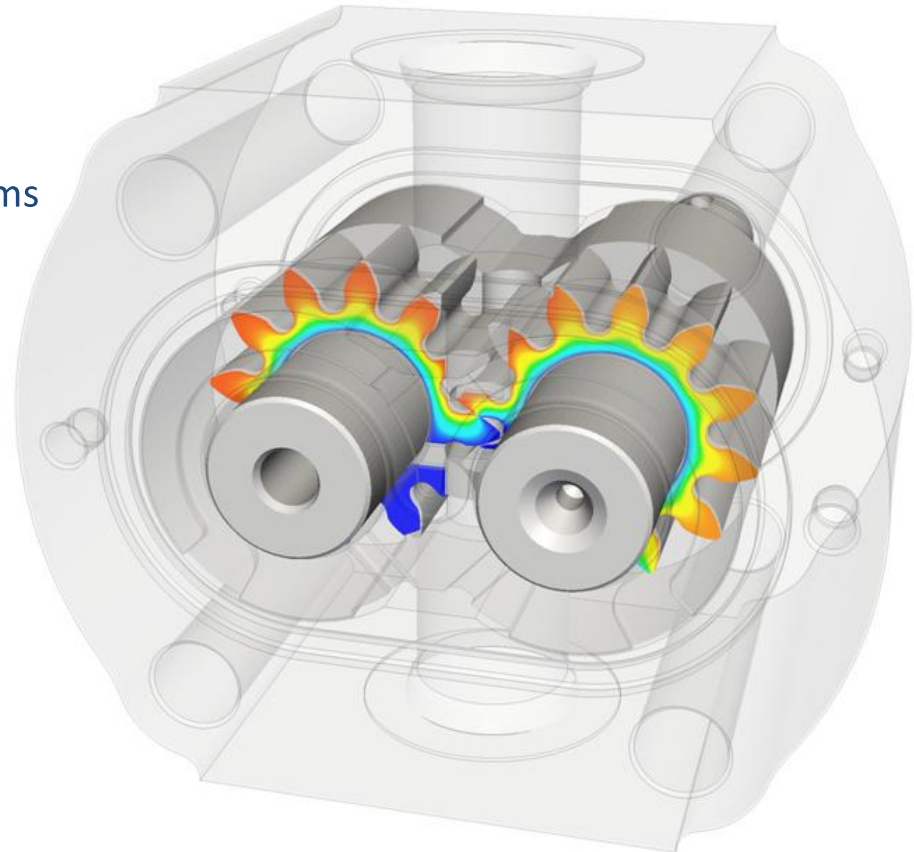


*Fig 1b – hydrodynamic pressure in the gap between gears and bushings evaluated by HYGESim CFD module*

# Project 1: The simulation tool HYGESim (b)

## Structure of the model

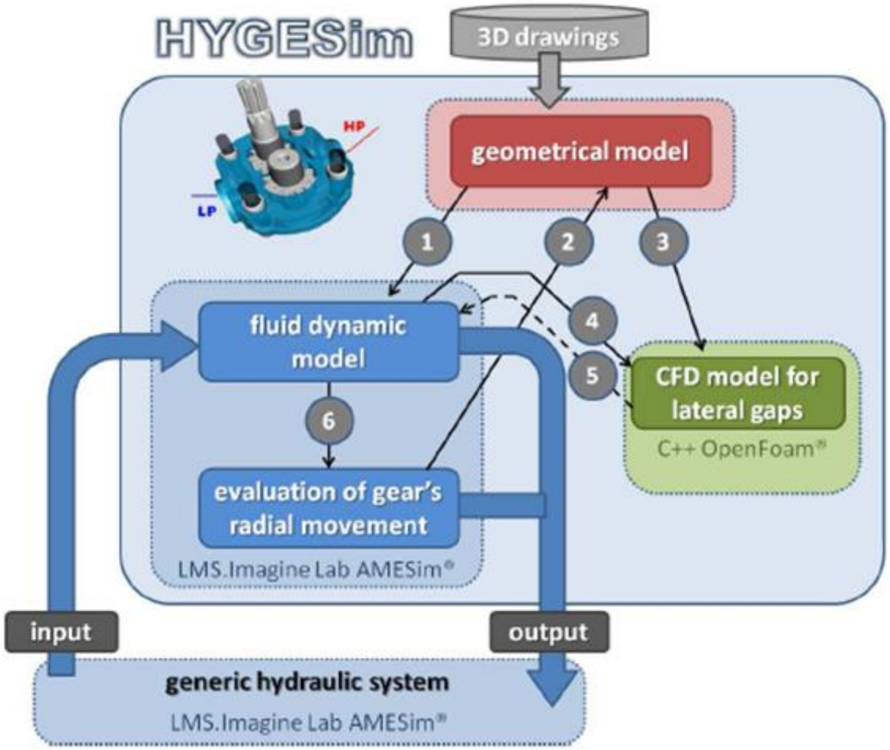



*Fig 1c - HYGESim structure*

Different versions of HYGESim are available, as a function of the level of details considered in the simulation

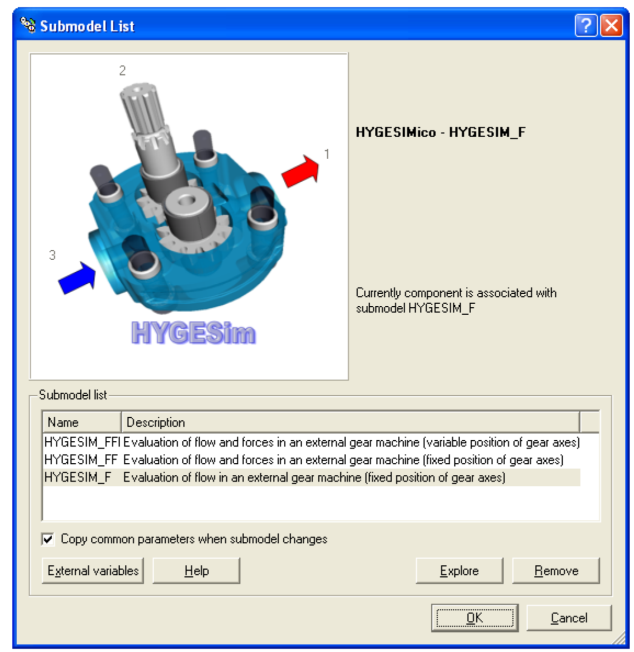



*Fig 1d – different HYGESim submodels*

# Project 1: Simulation tool HYGESim (c)

## Modeling insights

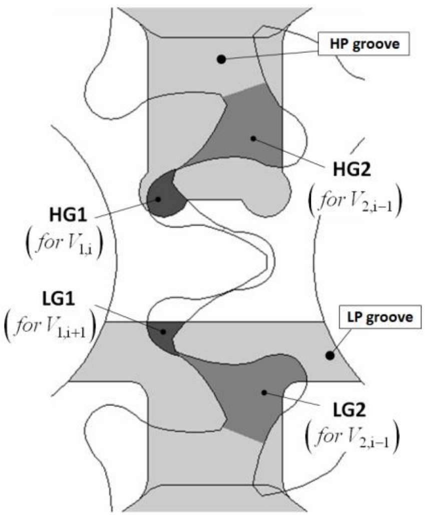



*Fig 1e – detailed evaluation of all internal geometrical features*

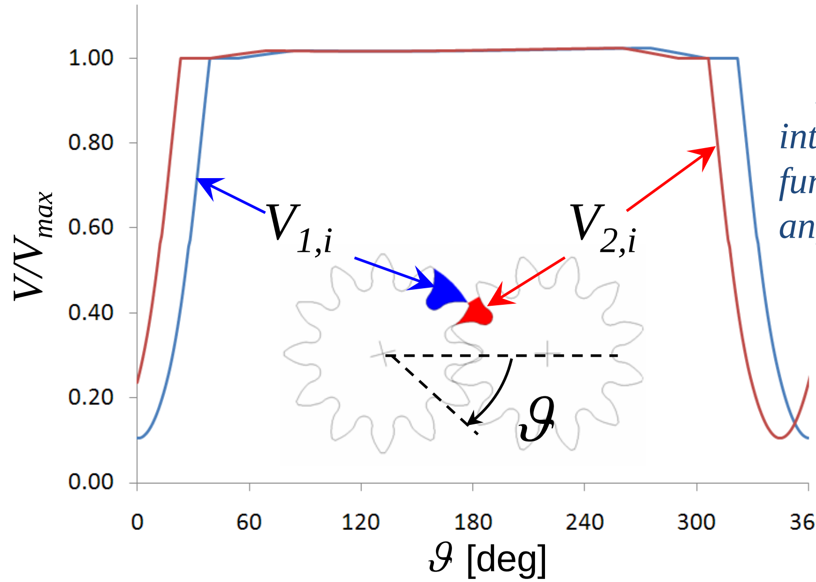
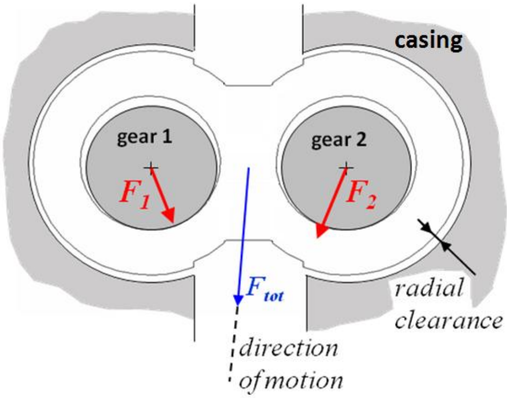



*Fig 1f – evaluation of internal control volumes as a function of gears (centers and angular) position*



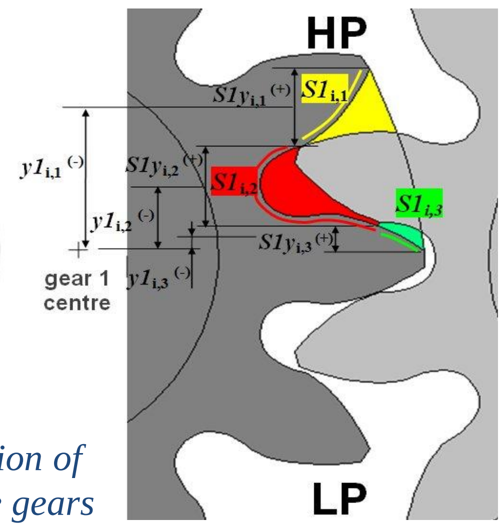




*Fig 1g – accurate evaluation of pressure forces acting on the gears*

# Project 1: Simulation tool HYGESim (d)

## Modeling insights

**CFD module implemented in O-Foam**

- evaluation of leakage flow in the lubricating gap at gears' lateral sides
- calculation of thrust forces
- possibility of simulating a tilt angle (no-flat gap)

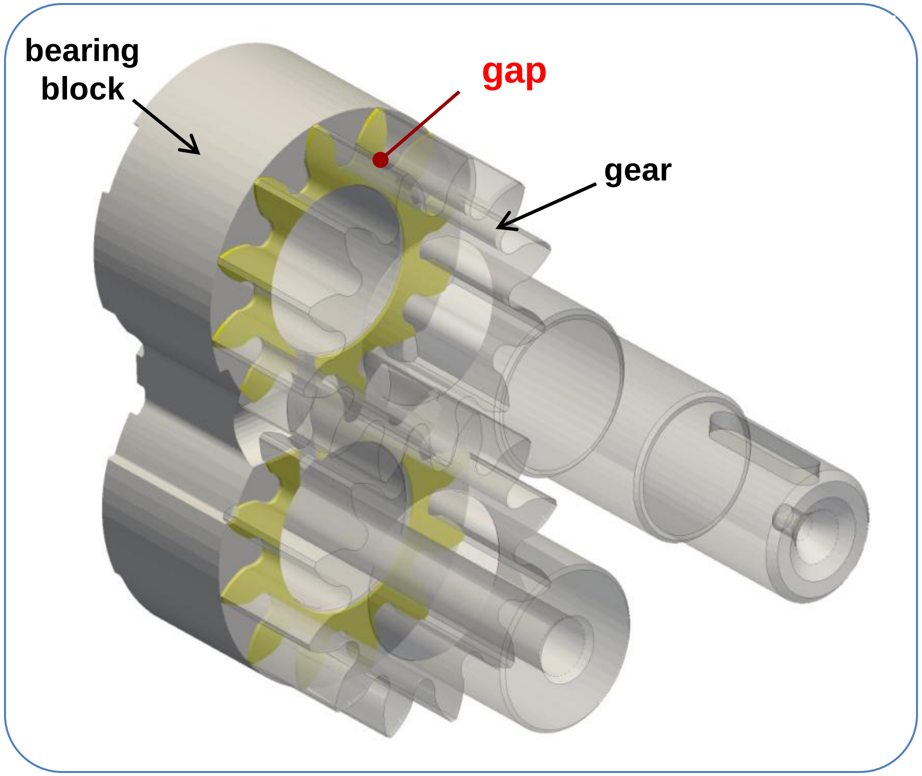




*Fig 1h – the lubricating gap considered by the CFD module*

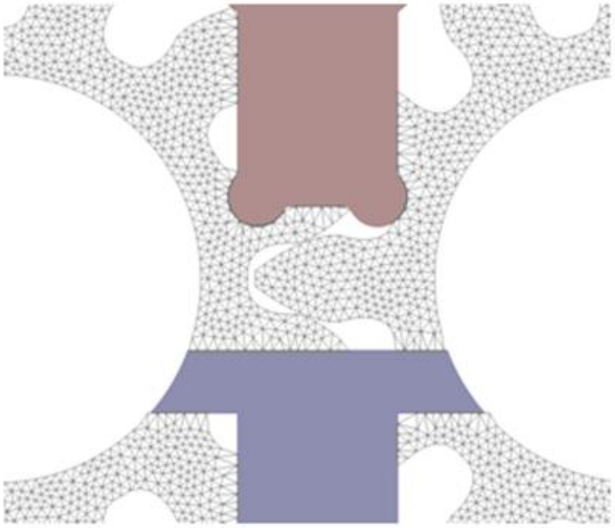


*Fig 1i – Automatic meshing during gear revolution considering the presence of grooves*

# Project 1: Simulation tool HYGESim (e)

## Typical results

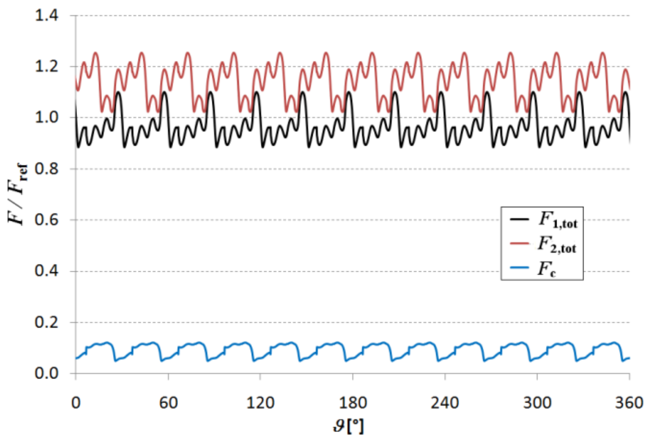



*Fig 1j – forces acting on the gears and contact force*

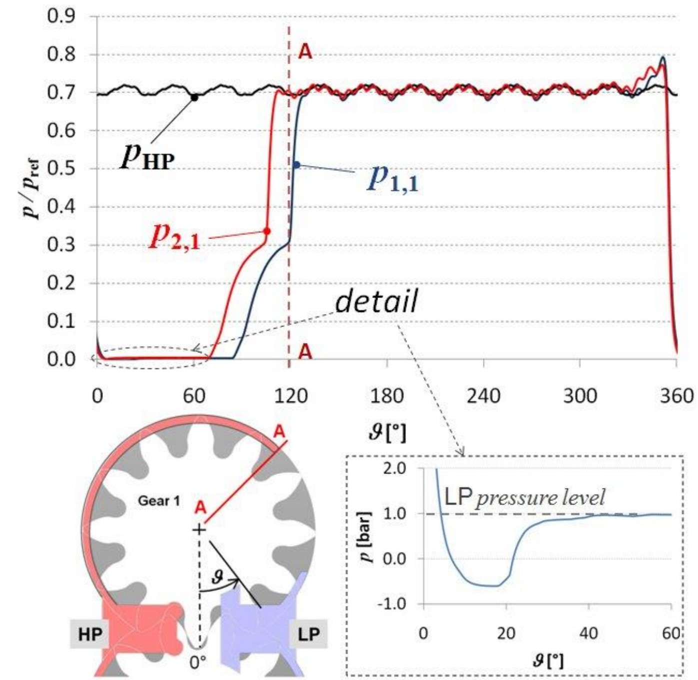



*Fig 1k – pressure in a tooth space volume and detection of cavitation*

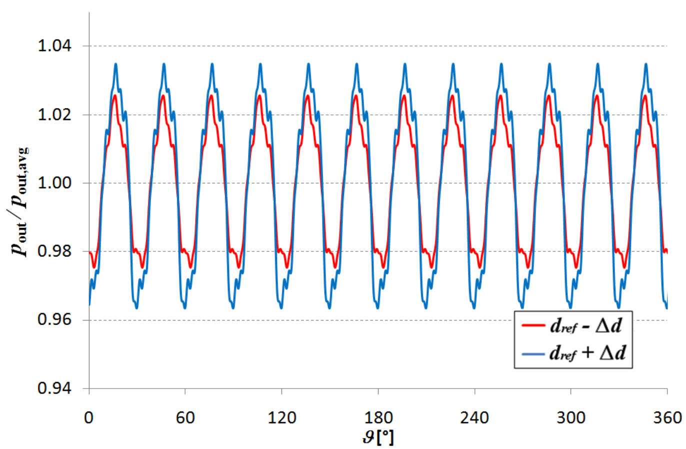



*Fig 1l – evaluation of outlet flow pulsation*

# Project 1: Simulation tool HYGESim (f)

## Typical results

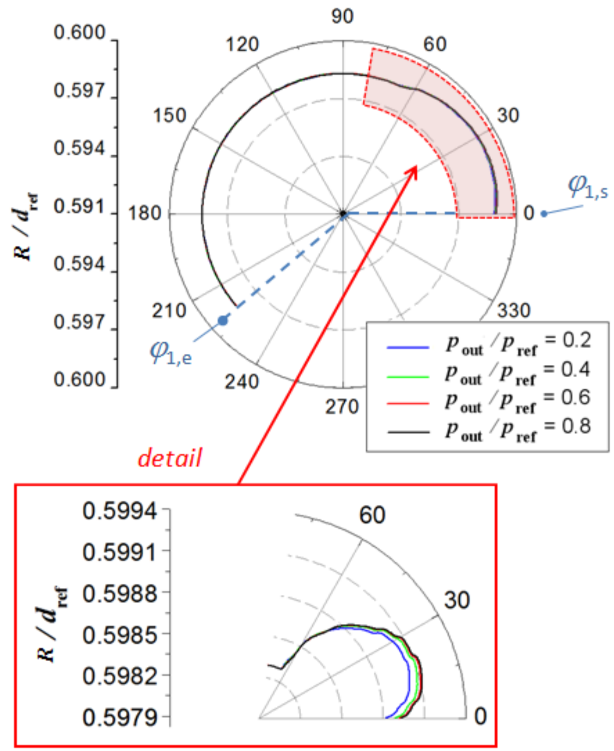



*Fig 1m – radius of the casing after the operation*

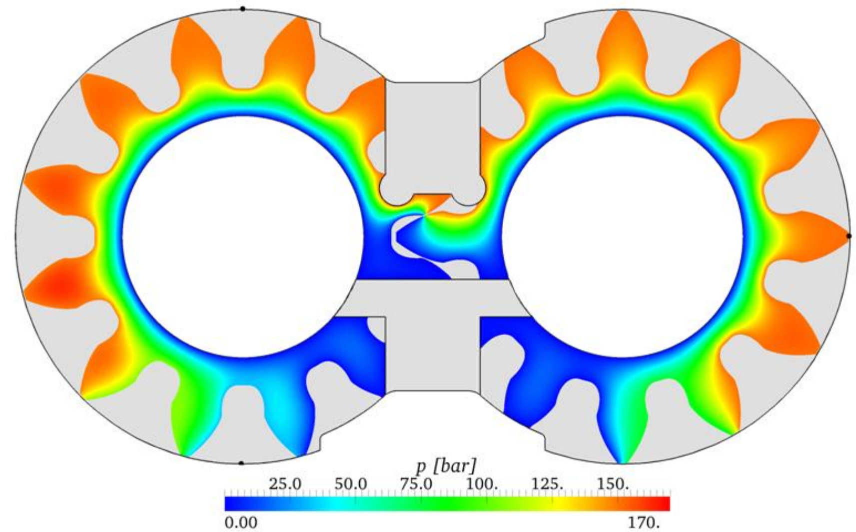



*Fig 1n – example of pressure distribution on gear lateral surface (flat gap)*

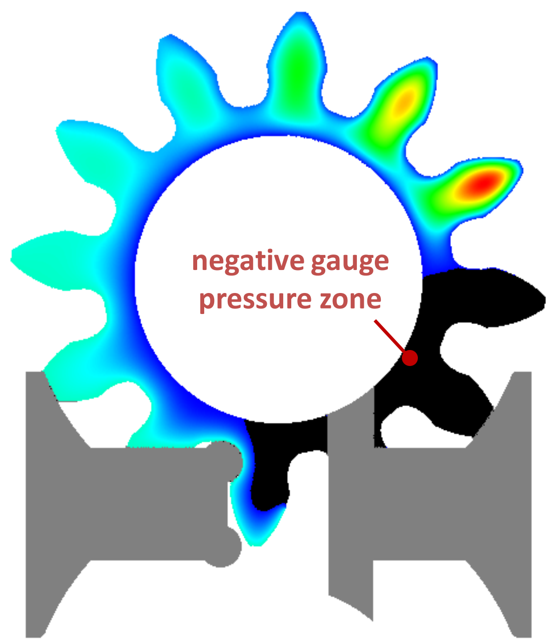



*Fig 1o – pressure distribution on gear lateral surface (tilted gap)*

# Project 1: Simulation tool HYGESim (g)

## Typical results

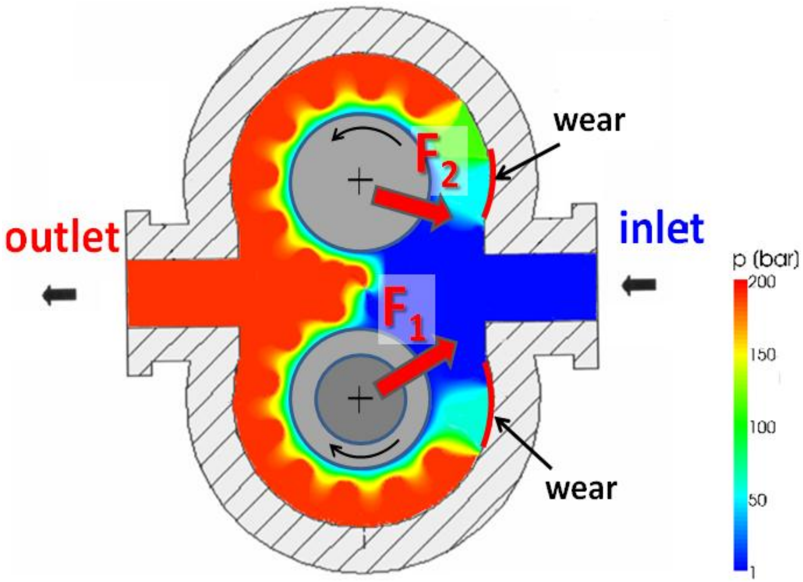



*Fig 1p – evaluation of radial forces and of pressure distribution on lateral bushings*

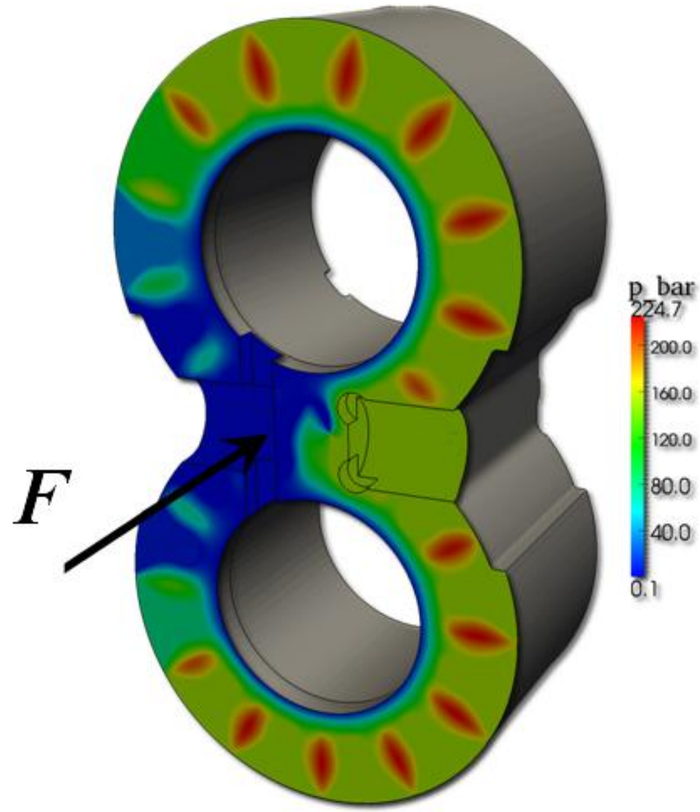



*Fig 1q – calculation of axial force on bushings or sliding bearing blocks*

# Project 1: Simulation tool HYGESim (h)

## Model validation

HYGESim predictions have been successfully validated on the basis of various comparisons between simulation results and experimental data. See project 2 for more details about the experimental apparatus

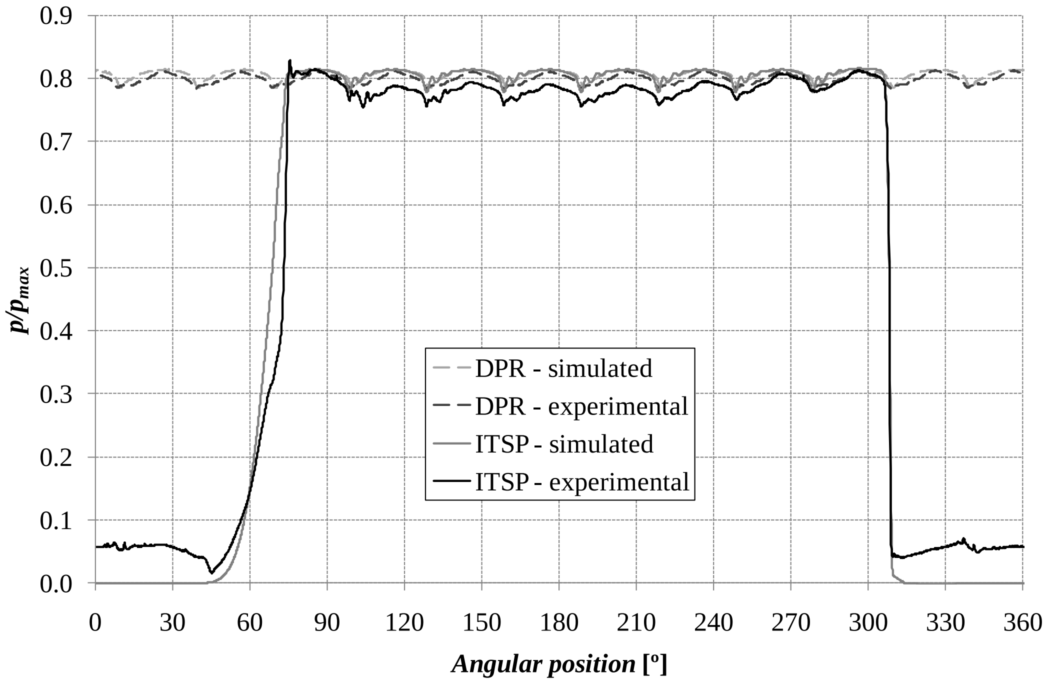



*Fig 1s – measured vs. compared pressure ripple and tooth space pressure (pump)*

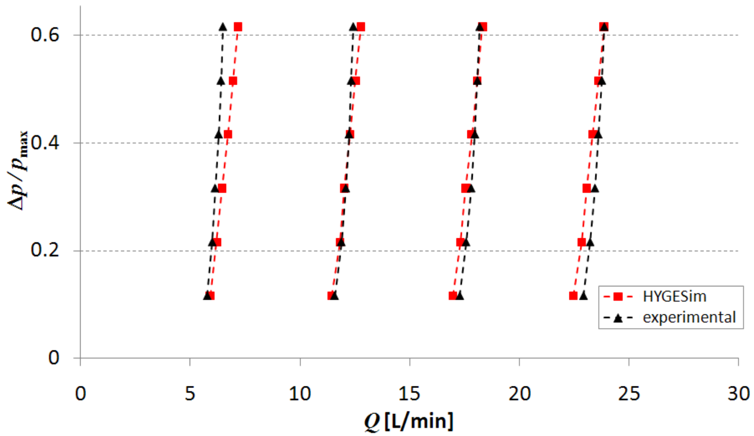
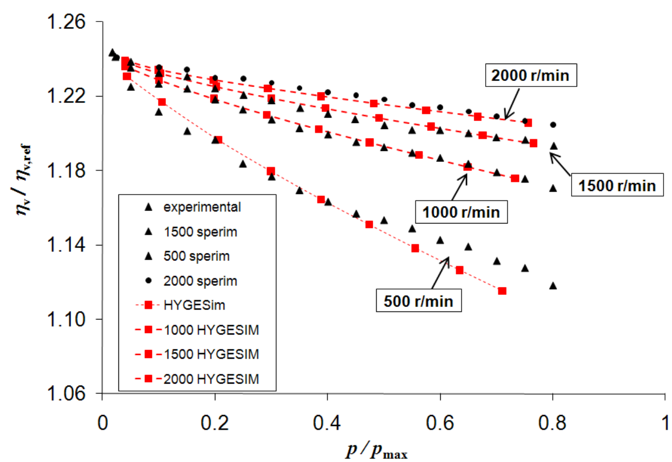



*Fig 1r – measured vs. compared steady state characteristics (pump)*



# Project 1: Simulation tool HYGESim (i)

## Model validation

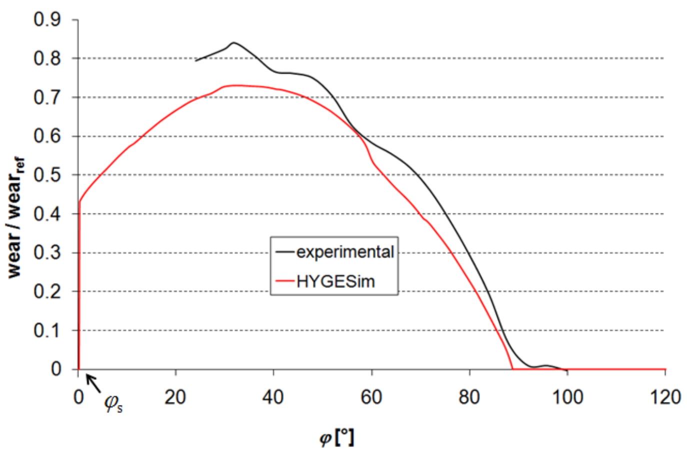



*Fig 1t – measured vs. compared casing wear (pump, driven gear side)*

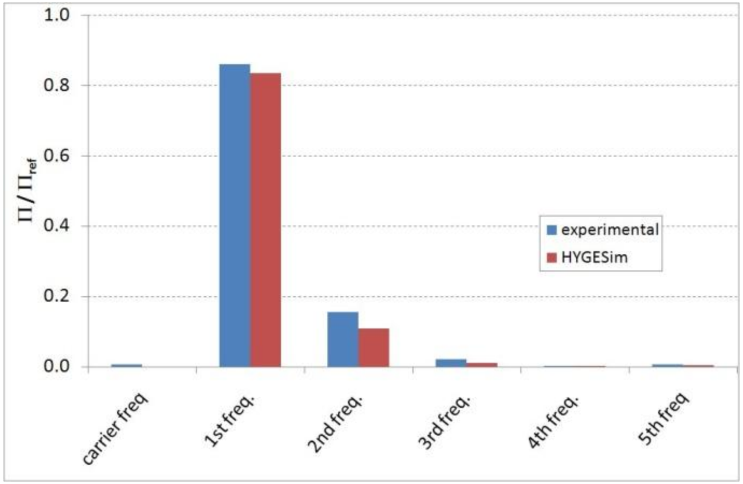



*Fig 1u – Energy of fundamental frequency terms in delivery pressure ripple (pump)*

## Conclusions – Final remarks of Project 1

- HYGESim is an advanced and unique tool for the analysis of main aspects related to the operation of external gear machines
- HYGESim can be utilized for design purposes. Source of losses, noise emissions can be investigated using HYGESim. HYGESim can also be utilized for the analysis of new design solutions (see also following projects)

# Project 1: Simulation tool HYGESim (j)

## For more details..

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

- Vacca A., Guidetti M., 2010, *HYGESim: A Simulation Model for External Gear Machines part 1: Numerical Approach*, submitted to International Journal of Fluid Power.
- Vacca A., Lettini A., Casoli P., 2010, *HYGESim: A Simulation model for external gear machines. part 2: Comparison with Experimental Results*, submitted to International Journal of Fluid Power.
-Casoli,P., Vacca, A., Franzoni, G., 2005, *A numerical model for the simulation of external gear pumps*, JFPS2005, The Sixth JFPS International Symphosium on Fluid Power Tsukuba 2005, Novembre 7-10, Tsukuba, Japan.
- Casoli, P., Vacca, A., Berta, G.L., 2006, *A Numerical Model for the Simulation of Flow in Hydraulic External Gear Machines*, PTMC2006 Power Transmission and Motion Control, 13-15 September 2006, University of Bath (GB).
- Casoli, P., Vacca, A., Berta, G.L., 2007, *Potentials of a Numerical Tool for the Simulation of Flow in External Gear Machines*, SICFP07, The Tenth Scandinavian International Conference on Fluid Power, May 21-23, 2007, Tampere, Finland.
- Vacca, A., Franzoni, G., Casoli,P., 2007, *On the Analysis of Experimental Data for External Gear Machines and their Comparison with Simulation Results*, IMECE2007, 2007 ASME Int. Mech. Engineering Congress and Exposition, November 11-15, 2007, Seattle, (WA), USA.
- Casoli, P., Vacca, A., Franzoni, G., Guidetti, M., 2008, *Effects of Some Relevant Design Parameters on External Gear Pumps Operating: Numerical Predictions and Experimental Investigations*, 6IFK Int. Fluidtechnisches Kolloquium, 31 March – 2 April 2008, Dreden (Germany).
-Casoli, P., Vacca, A., Berta, G.L., Zecchi, M., 2009, *A CFD Analysis of the Flow Field in the Lateral Clearance of External Gear Pumps*. The 11th Scandinavian Int. Conference on Fluid Power, SICFP'09, June 2-4, 2009, Linköping, Sweden
- Zecchi M., Vacca A., Casoli P., 2010, *Numerical analysis of the lubricating gap at bushes lateral sides in external spur gear machines*, submitted to PTMC2010 Symposium on Fluid Power & Motion Control (FPMC *2010*). 15-17 September *2010*, Bath. *UK*.

# Project 2: Pump/Motor testing (a)

## Goals

- Development of a innovative measurements techniques for external gear machines
- Deep understanding of operating phenomena
- Verification of HYGESim predictions

## Performed tests

- Steady state measurements

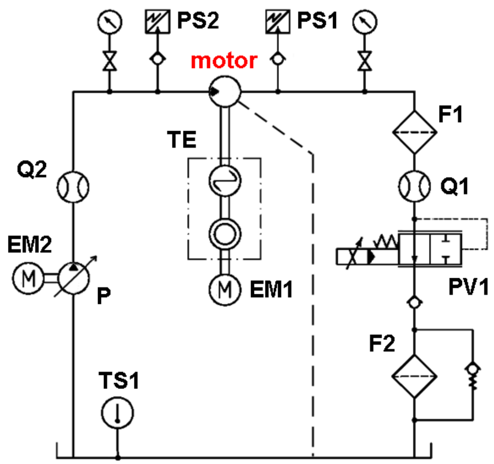



*Fig 2a – Example of system used for the steady state characterization (motor)*

- Pressure ripple measurements (pumps)

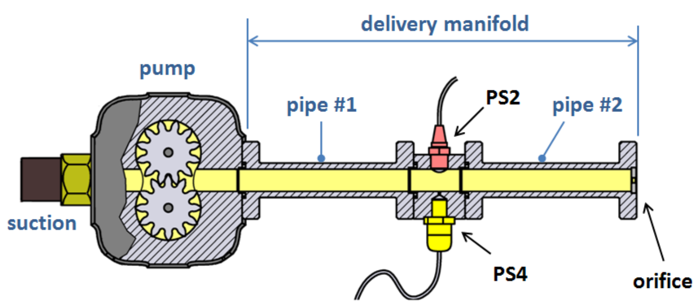



*Fig 2b – Schematic of the experimental apparatus to permit an easy comparison with HYGESim predictions*

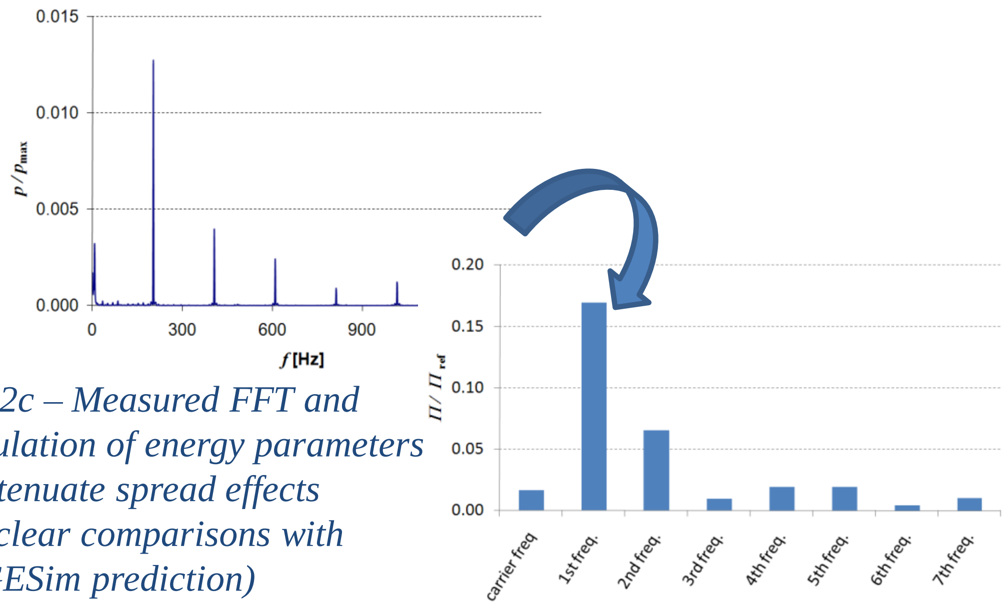



*Fig. 2c – Measured FFT and calculation of energy parameters to attenuate spread effects (for clear comparisons with HYGESim prediction)*

Dr. Andrea Vacca
MAHA Assistant professor
Purdue University



# Project 2: Pump/Motor testing (b)

## Performed tests

- Wear measurements

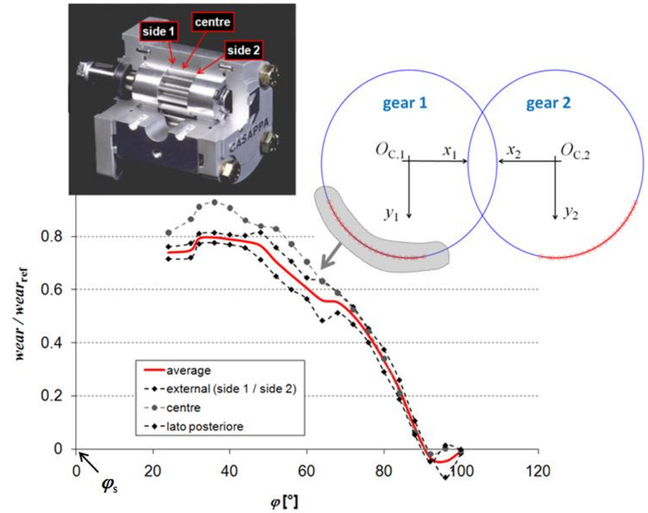



*Fig 2d – Measurement of the casing wear at different axial position*

- Internal tooth space pressure measurements

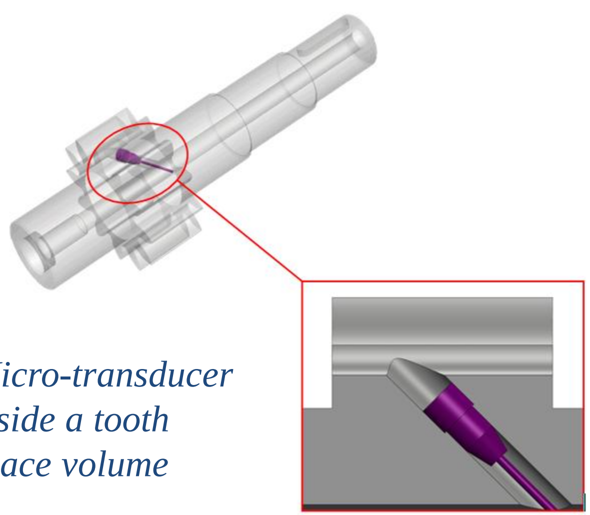


*Fig 2e – Micro-transducer inside a tooth space volume*

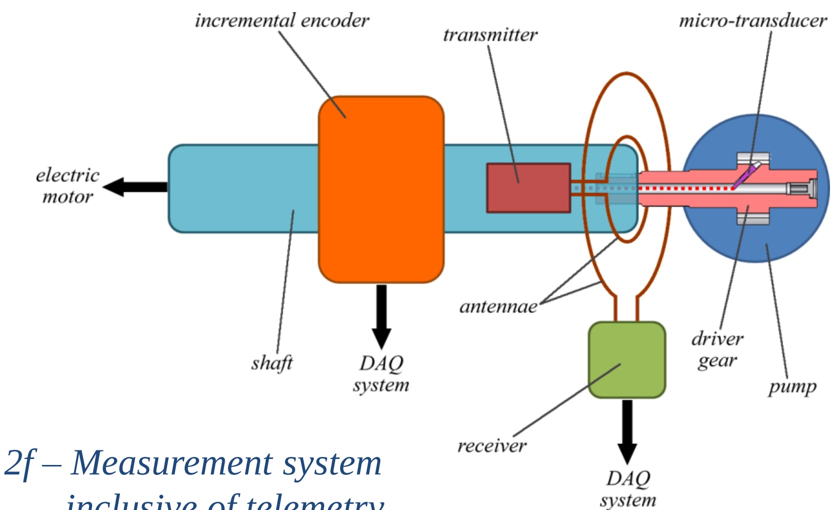



*Fig 2f – Measurement system inclusive of telemetry*

# Project 2: Pump/Motor testing (c)

## Performed tests

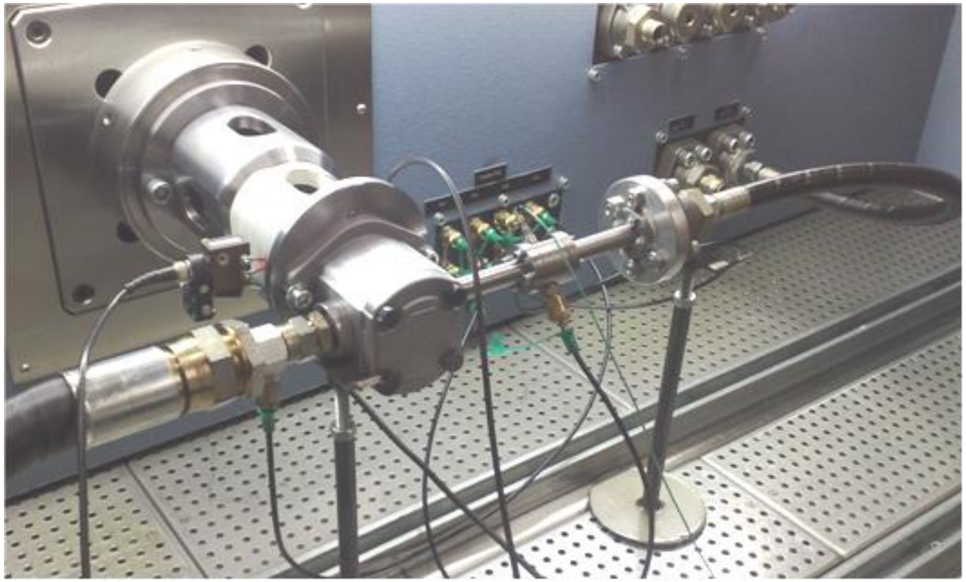


*Fig 2g – Apparatus inclusive of telemetry system and pressure ripple measurements*

## Conclusions – Final remarks of Project 2

- Experimental apparatus have been conceived for specific and precise tests on external gear machines
- Performed tests have permitted a clear understanding of the main features related to the operation of pumps and motors
- Particular attention has been made on developing procedure for testing and data post-processing suitable for the comparisons with numerical results

# Project 2: Pump/Motor testing (d)

## For more details..

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

- Vacca A., Lettini A., Casoli P., 2010, *HYGESim: A Simulation model for external gear machines. part 2: Comparison with Experimental Results*, submitted to International Journal of Fluid Power.
-Casoli, P., Vacca, A., Berta, G.L., 2007, *Potentials of a Numerical Tool for the Simulation of Flow in External Gear Machines*, SICFP07, The Tenth Scandinavian International Conference on Fluid Power, May 21-23, 2007, Tampere, Finland.
- Vacca, A., Franzoni, G., Casoli,P., 2007, *On the Analysis of Experimental Data for External Gear Machines and their Comparison with Simulation Results*, IMECE2007, 2007 ASME Int. Mech. Engineering Congress and Exposition, November 11-15, 2007, Seattle, (WA), USA.
- Casoli, P., Vacca, A., Franzoni, G., Guidetti, M., 2008, *Effects of Some Relevant Design Parameters on External Gear Pumps Operating: Numerical Predictions and Experimental Investigations*, 6IFK Int. Fluidtechnisches Kolloquium, 31 March – 2 April 2008, Dreden (Germany).
-Vacca, A., Casoli, P., Greco, M., 2009, *Experimental Analysis of Flow through External Gear Machines. ICFP 2009 Seventh Int. Conference on Fluid Power Transmission and Control*, April 7-10, 2009 Hangzhou, China.

# Project 3: Optimization of Standard Designs(a)

## Goals

- Proposal of new designs characterized by improved performance
- Targets considered for the definition of the optimization problem: efficiency
  noise emissions
  internal pressure peaks
  gross or local cavitation

## The approach

Stochastic optimization based on HYGESim simulation results

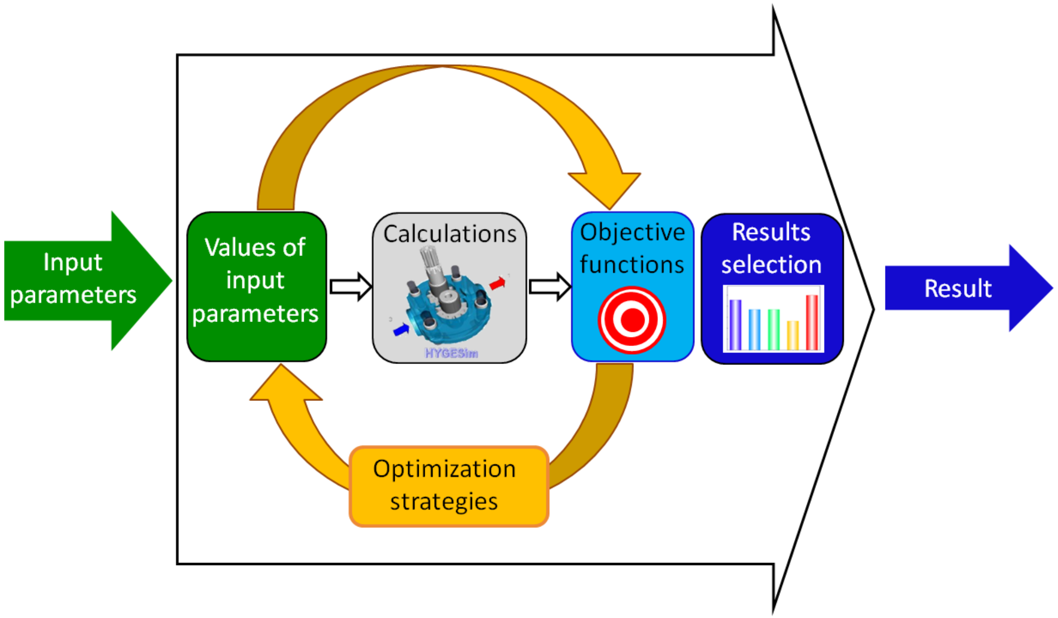



*Fig 3a – Scheme of the optimization approach based on HYGESim results*

**Main features of the algorithm:**

- valid for generic cases *(depending on selected input parameters and objective functions)*
- multi-objective optimization features *(deep analysis of possible optimal alternatives)*
- analysis of single/mutual influence of input factors on objective functions
- procedure completely automated

# Project 3: Optimization of Standard Designs(b)

## Implementation of the optimization procedure

Selected optimization environment: modeFrontier®

modeFRONTIER multi-objective optimization and design environment

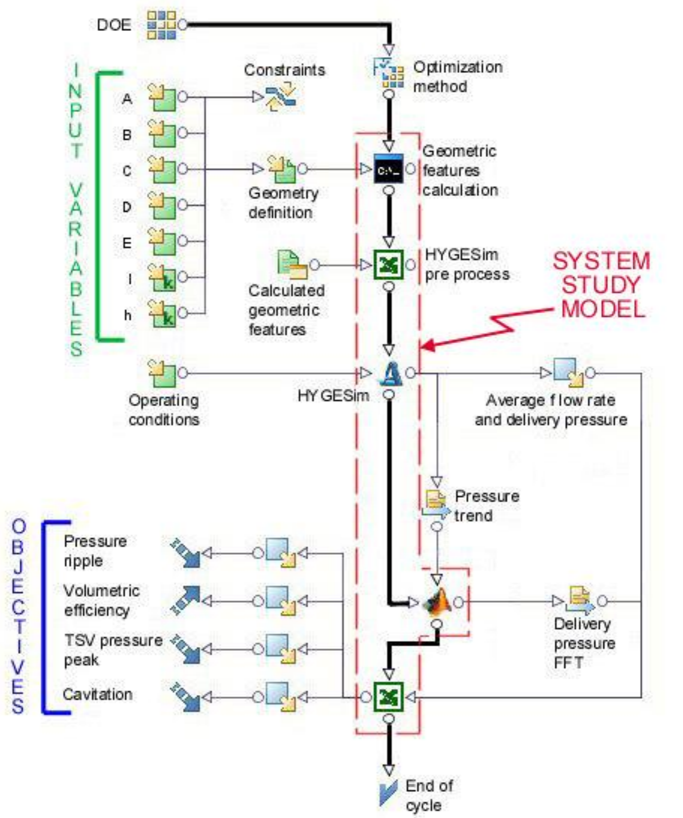



*Fig 3b – Simplified representation of the optimization workflow. Black icons are representative of simulation tools executed by the procedure automatically*

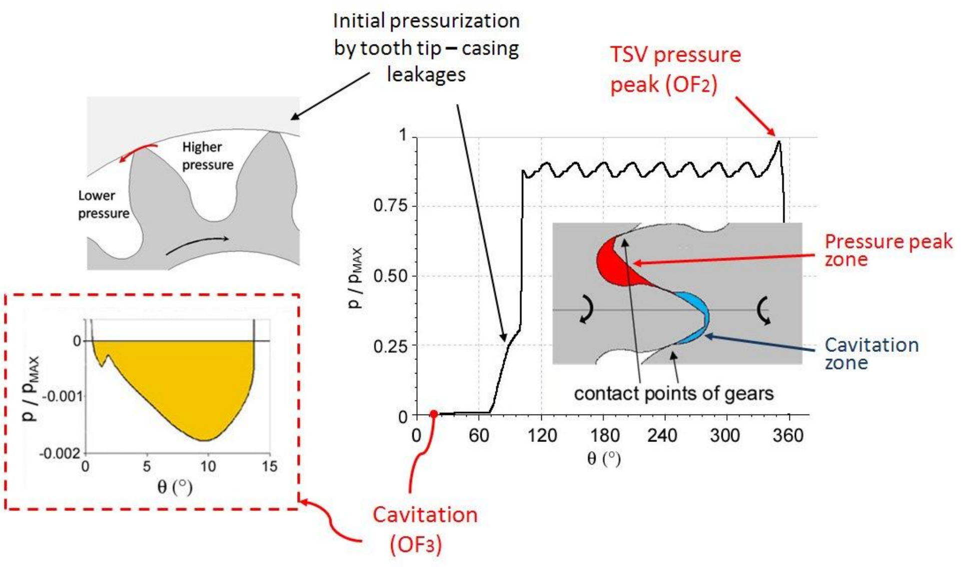



*Fig 3c – Definition of some considered objective functions*

# Project 3: Optimization of Standard Designs(c)

## Example of optimization

### Selected input parameters

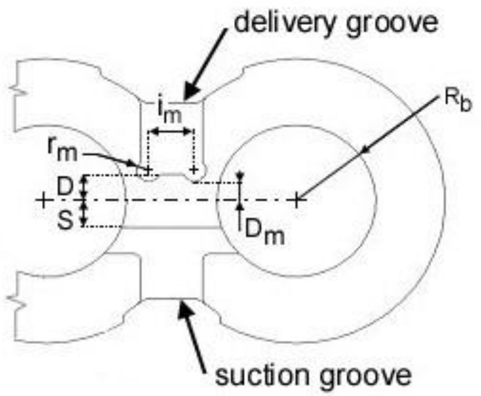



*Fig 3d – Shape of recesses machined on the sliding bearing blocks*

### Results

Obtained after more than 400 configurations considered by the optimization algorithm

| OBJECTIVES | $OF_1$ Pressure ripple [Δ%] | $OF_4$ Volumetric efficiency [Δ%] | $OF_2$ TSV pressure peak [Δ%] | $OF_3$ Cavitation [Δ%] |
|---|---|---|---|---|
| TARGET | minimize | maximize | minimize | minimize |
| C1 configuration | +3.5 | +1.5 | +18.8 | +1.3 |
| C2 configuration | -8.47 | +0.4 | -4.7 | +1.4 |

two proposed configurations

*experimental comparison*
*(configuration C1 – standard)*

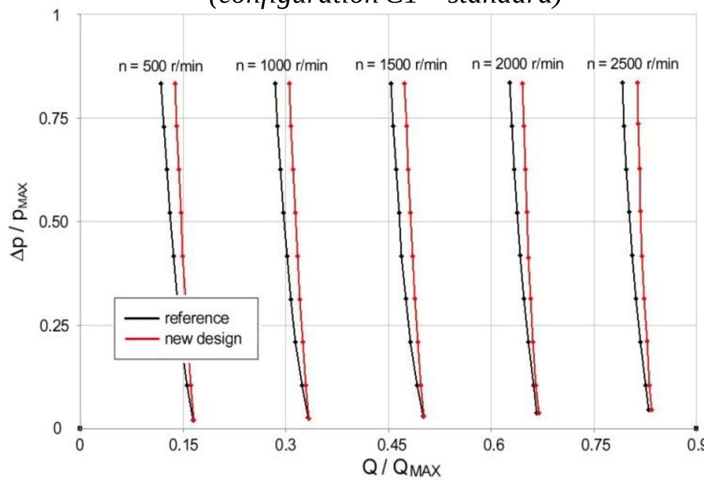



*Fig 3e – Measured steady-state characteristics (improvements achieved by C1 are evident)*

C1: *better on volumetric efficiency*

C2: *lower noise emissions*

# Project 3: Optimization of Standard Designs(d)

## Conclusions – Final remarks of Project 3

- The developed optimization procedure is general. It can be used to optimize other design parameters using the same workflow and same formulation for the objective functions
- Other optimization targets can be easily included in the procedure as additional objective functions

## For more details..

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

- Casoli, P., Vacca, A., Berta, G.L., 2008, *Optimization of Relevant Design Parameters of External Gear Pumps, The Seventh JFPS International Symposium on Fluid Power*, September 15-18, 2008, Toyama, Japan.
- Vassena A., Vacca A., 2010, *Design optimization of the sliding elements of external gear machines,* 6th FPNI *PhD Symposium* June 15-19, *2010* , West Lafayette IN, USA.

# Project 4: Proposal, analysis and optimization of new solutions

## Goals

- Proposal of innovative, high efficient designs for external gear machines
- Targets considered for the definition of the optimization problem: efficiency, noise emissions, internal pressure peaks, gross or local cavitation *(same as project 3)*

## Considered ideas

1. Uses of internal pre-compression volumes opportunely connected to tooth space volumes
   Target achieved: reduction of flow pulsation
2. Uses of intermediate volumes connected to delivery and meshing zone
   Target achieved: reduction of flow pulsation; increment of efficiency

Schematic drawings
not reported
(not yet published!)

## Approach of analyis

- Extensive use of the simulation tool HYGESim for the understanding of the phenomena involved in the new solution
- Adoption of the optimization procedure described in Project 3

## Conclusions – Final remarks of Project 4

- The potentials of the new ideas and of the optimization procedure (project 2) is highlighted by numerical results and preliminary tests
- The design of other possible new ideas can be defined using the same optimization procedure

## For more details..

write to mahaav@ecn.purdue.edu

# Project 5: Analysis of solutions to realize variable displacement units

## Goals

•Proposal of innovative designs characterized by the possibility of realizing variable displacement without a significant increment of costs

## Considered ideas

1. Variable displacement obtained changing the distance between gears
   Target: analysis of maximum displacement range
   design of the solution
2. Variable displacement obtained varying the length of the active contact between the gears
   Target design of the solution
3. Variable displacement obtained varying the timing of the connections in the meshing zone (low cost solution)
   Target: analysis of maximum displacement range
   design of the solution
   *(schematic drawing not reported, not yet published)*

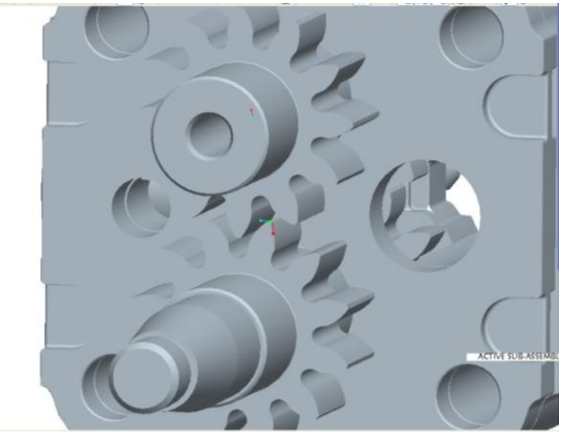


*Fig 5a – idea 1: increased distance between gears*

## Approach of analyis

•Extensive use of the simulation tool HYGESim for the understanding of the phenomena involved in the proposed design
•Use of simulation tool modeFrontier to optimize the parameters

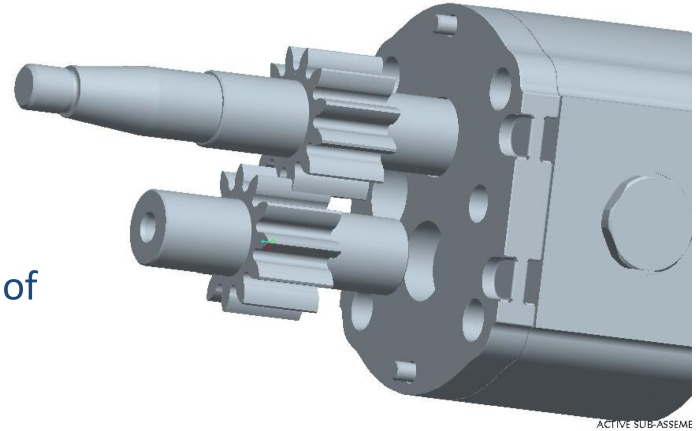


*Fig 5b – idea 2: reduction of the lenght of contact between gears*

## For more details..

write to mahaav@ecn.purdue.edu