Maha Fluid Power

RESEARCH CENTER

PURDUE UNIVERSITY

# 2015 Annual Report

## Dr. Andrea Vacca's team

Volume II

Lafayette, January 2016

# Preface

The 2015 Maha Fluid Power Research Center Annual Report is split into two volumes this year so that more emphasis can be given to the two research teams' growing contributions to research at Purdue University. Volume II is dedicated entirely to activities performed by Dr. Vacca's team.

The Research Center's vision is a world where fluid power machines are more controllable, energy efficient, and silent; the mission of Dr. Vacca's team specifically is to advance current technology by proposing new concepts for components and systems. The research focuses on developing novel component designs, control architectures, and system layouts that industry can use to develop the next generation of machines for both traditional fluid power fields as well as other fluid transport systems.

Dr. Vacca's current research team features expertise in the following areas:

- Modeling and the formulation of novel design solutions for gear machines, especially external gear machines and gerotor-type units
- Modeling and study of new solutions for radial piston units
- Study of fluid cavitation in fluid power systems and components
- Performance analysis of positive displacement units working with non-Newtonian fluids
- Analysis of novel architectures to achieve vibration attenuation in fluid power machines
- Detailed analysis of operation valve-controlled systems
- Analysis of noise generation and proposal of techniques to reduce noise emissions in fluid power components

During the year 2015, 27 researchers, including PhD and MS students, graduate visiting scholars, and undergraduate students, performed research under Dr. Vacca's supervision in topics mentioned above. The results of these efforts can be summarized by 7 journal papers, 4 conference papers, and one patent application.

Three PhD students, Ram S. Devendran, Tim Opperwall, and Guido F. Ritelli, and two MS students, Pulkit Agarwal and Sidhant Gulati, gave their final defense during 2015, and all have already obtained important positions in recognized fluid power companies. Dr. Vacca's research team has continued to grow in 2015, and he has hired 4 PhD and 2 MS students.

Several improvements have been made to Dr. Vacca's experimental research capabilities during 2015. A new 15-ton wheel loader was made available by CNH Industrial to Dr. Vacca's team at Maha for conducting research in different system aspects of off-road machinery. Other improvements of Dr. Vacca's experimental facilities included a state-of-the-art independent metering system installed on the hydraulic crane test rig and additional functionalities implemented in the multi-functional test rig. These improvements were made possible also though the contributions of Parker Hannifin, Casappa, Walvoil and Hydraforce.

During 2015, Dr. Vacca's team members presented technical papers at several international events. The conferences included the 14th Scandinavian International Conference on Fluid Power, May 20-22, 2015, Tampere, Finland; the SAE 2015 Commercial Vehicle Engineering Congress (COMVEC), Oct 6-8 2015, Rosemont, IL, USA; and the ASME/Bath 2015 Symposium on Fluid Power and Motion Control, Oct 12-14, 2015, Chicago, IL, USA. Dr. Andrea Vacca was also invited to give research presentations at the University of Napoli Federico II, Italy (March 2015), the South China University of Technology, China (August 2015), and the 2015 Esteco North America User Meetings.

Dr. Vacca's team at Maha also promoted educational activities and events in 2015:

- Dr. Vacca coordinated the Center for Compact and Efficient Fluid Power Summer Bootcamp for REUs (May 2015), where about 20 undergraduate students doing their summer research in several university fluid power labs in the nation came to Purdue to learn the basics of fluid power.
- Dr. Vacca's team developed an educational test station to permit experiments in both pre-compensated and post-compensated load sensing systems architectures. This test station developed at Maha is now available for teaching lab experiences in the Purdue Department of Agricultural and Biological Engineering. This test rig was made possible through the sponsorship of the National Fluid Power Association, Hydraforce, and Concentric.
- Dr. Vacca taught the ABE 435 (Hydraulic Control Systems) class for Purdue senior engineering students and added novel components to the curriculum.
- Dr. Vacca led the Purdue team participating in the Parker Chainless Challenge competition. The Purdue team received several awards, including the award for 1st place in Innovation for the original design of the recumbent hydraulic-hybrid bike presented at the competition.

All these achievements were possible though the hard work and dedication of all the students in Dr. Vacca's team, the vital contribution of the Lab Manager, Anthony Franklin, and the Maha staff Susan Gauger and Connie McMindes.

Dr. Andrea Vacca

# Contents

# 1 Research Activities

The main objective of Dr. Vacca's team at Maha Fluid Power Research Center of Purdue University is to advance fluid power discipline, through new discoveries and innovative research approaches. Fluid Power is a consolidated technology for transmitting mechanical power with high power to weight ratios. It is widely used in many engineering fields such as agriculture, construction, transportation, aerospace, marine, manufacturing and entertainment industries, although this technology often suffers the limits of low efficiency, high noise emissions and sometimes of poor controllability. Dr. Vacca's effort aims at overcoming these limits, to permit a better use of the fluid power technology and possibly extend its application to other engineering fields. This goal can be achieved through a deep understanding of the fundamental phenomena in the fluid, thermal and mechanical domains characterizing the functioning of fluid power components and systems that can drive the development of novel solutions.

With a team of 14 researchers (a peak number of 19 was reached in summer 2015, see section 10), Dr. Vacca's research embraces crucial aspects of fluid power. In particular, his team studies:

a) ***New components***: novel design solutions for fluid power components, with particular reference to external gear pumps and motors, gerotors, radial piston machines and hydraulic valves. These new solutions permit additional functionality (an example is the new variable delivery external gear machine studied at Maha), or the reduction of energy losses (like the new solutions proposed to reduce shear losses in external gear pumps), or the reduction of noise emissions. To accomplish the goals of this research, unique approaches for fluid power components with unique features to model power losses and noise generation have been developed. An example is the simulation tool HYGESim (HYdraulic GEar machines Simulator) developed for the simulation of external gear pumps and motors or the novel GESIT (GErotor Simulator) for GEROTORs.

b) ***New systems and controls***: new architectures and control strategies for hydraulic drives in fluid power machines. In this area, Dr. Vacca's team participates in activities aimed at designing novel system solutions characterized by superior energy efficiency (an example is the compact electro-hydraulic actuator proposed in 2013) or at enhancing the controllability of current fluid power machines, reducing the oscillations of payload and the actuators. The research on this latter topic is particularly aimed at formulating a new control strategy of general applicability, which can be used as an energy efficient alternative to current dissipative solutions for oscillation damping.

c) ***Fluid properties***: the properties of the hydraulic fluid, in particular the effects of gas (air release) and vapor cavitation affect the performance of the entire fluid power system. Cavitation is at the origin of many design limitations or mechanical failures of many hydraulic components and it significantly impacts the energetic performance of fluid power systems. The fundamental understanding of both static and dynamic features of cavitation in hydraulic fluids permits the formulation of design criteria for more efficient and reliable hydraulic machines. A simulation approach capable of predicting the dynamic features of air release/absorption and vapor cavitation was recently formulated by Dr. Vacca's team and introduced in the simulation models for hydraulic pumps. The novelty of the proposed approach consists on its formulation, which is suitable for the lumped parameters modeling approach commonly used in the fluid power research field.
Within the area of fluid properties, Dr. Vacca's team recently tackled the problem of simulating the effects of non-Newtonian fluid properties on the pumping features of gear pumps.

d) ***Water hydraulics***: the formulation of concepts for designing components suitable for high pressure water hydraulics. The use of water as a working fluid instead of traditional oil-based hydraulic fluids represents a viable solution to problems related to leakage and oil-dependency of current fluid power systems. This effort is mainly aimed at solving the challenges related to the use of a low viscous fluid in hydraulic components. For this research topic, recently initiated by Dr. Vacca's team, the advanced simulations tools developed in a) and b) have been used to formulate novel design criteria for water hydraulic components capable of reaching high operating pressures (up to 400 bar) thus permitting the implementation of high efficiency fluid power machines utilizing water as hydraulic fluid. In 2015, a novel mixed lubrication model was developed with the aim of studying the lubricating features in case of absence of full film regime, as it often occurs when a low-viscous fluid such as water is utilized.

All above activities implicate significant effort at both theoretical and numerical level. All modelling assumptions are validated through dedicated experimental activities performed at Maha Fluid Power Research Center or at Sponsors' facilities.

## 1.1 Research Highlights in 2015

- A functional prototype of Variable Displacement Gear Pump was developed and tested in 2015 by R. S. Devendran. The unit implements a manual adjustment system for the control of the outlet flow as well as the possibility of testing the pump equipped with a pressure compensator. The prototype demonstrates the applicability of the low-cost concept based on the external gear design principle to implement variable displacement units. The prototype has pressure compensation and it is suitable for high pressure applications. Current research is focused on conceiving different gear profiles able to increase the range of displacement variation (currently limited to about 60% - 100% of the flow range). Also, a prototype for low pressure applications (< 30 bar) is currently under study.
- A complete acoustic model for external gear pumps was finalized in 2015 by Tim Opperwall. The model permits to utilize HYGESim outputs to study the noise generation of the units. The analysis is performed by coupling the fluid-borne noise domain, the structure borne noise domain and the airborne noise.
- A mixed lubrication model was introduced by Divya Thiagarajan within the lateral lubricating gap model of HYGESim to permit the analysis of insufficient lubrication conditions in gear pumps.
- The radial piston pump model was extended by Gautham Ramchandran to study the effect of different shapes of the pistons. The model was also validated in 2015 with experimental results.
- Relevant progresses were made during in 2015 on the GEROTOR model by Matteo Pellegri. The model has now a complete graphical user interface, a geometric model able to read the CAD drawing of the machine and implement functionalities as concerns the study of the micro-motions of the rotors due to the pressure loading.
- A novel gear generator for external gear machines able to generate gears of various geometries and able to automatically generate inputs to perform simulations in HYGESim was developed by Xinran Zhao.
- A model for non-Newtonian fluids was implemented within HYGESim to simulate the operation of gear pumps with pseudo-plastic fluids.
- A frequency based technique to automatically detect and reduce oscillations in fluid power machines was developed by Riccardo Bianchi and Guido F. Ritelli and tested on the hydraulic crane at Maha. Ongoing research include the application of this technique on a wheel loader.
- Guido F. Ritelli extended the frequency based technique to the case of suspended load, and proved on the hydraulic crane the possibility of reducing payload oscillations by using pressure feedback.

## 1.2. HYGESim (HYdraulic GEar Machines Simulator)

Goal: the HYGESim simulation tool has been developed to support research on external gear pumps and motors. HYGESim provides a detailed analysis of the flow though the unit, with capabilities of studying the effects of different geometrical configurations of the gears, lateral bushings and case accounting for the micro-motions of the gears due to their pressure loading.

Approach: HYGESim consists of different submodules, as shown in Fig. 1. A lumped parameter *fluid dynamic module* which includes an advanced model for the fluid properties that considers dynamic aeration and cavitation (see section 1.2.8); *a mechanical module* for the evaluation of the forces in the radial plane, the torque acting on the gears, the gears motion and the casing wear (considering also the micro motion of the gear axes of rotation), a *geometrical module* for the evaluation of the geometrical features of the unit; and finally a *fluid structure and thermal interaction module* for the study of the lateral lubricating gap and the axial balance of the machine.

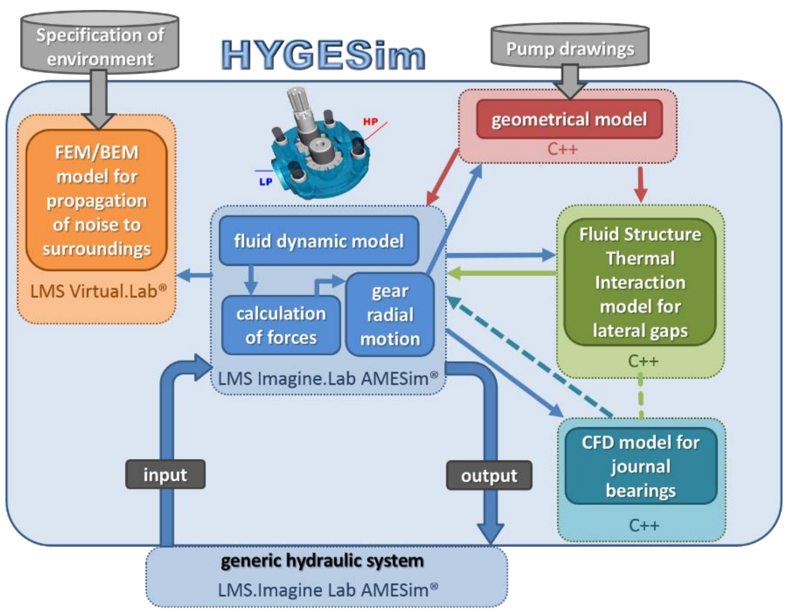



**Figure 1 – Structure of HYGESim**

The first two modules are implemented within the LMS Imagine.Lab AMESim® simulation environment, with sub-models written in C language. This permit the simulation of external pumps or motors in any given hydraulic system implemented in AMESim. The geometrical model is implemented in C++ and accepts the CAD drawings of the unit as inputs. An additional tool has been developed to generate gear profiles (including unconventional cycloidal and asymmetrical profiles) and to generate complex designs for pressure relief grooves in lateral bushings. The Thermal-Fluid-Structure-Interaction module is based on C++ models (using also O-Foam libraries) and it is used to evaluate the flow in the lubricating gap at gears lateral sides considering the material deformation due to pressure and thermal loads. In case of pressure compensated design, this model takes also into account the mechanical balance of the lateral bushings. Recent effort was devoted to the inclusion of the journal bearings effects, with the aim of including effects due to shaft bending and deformation.

HYGESim can be also coupled with an acoustic model for the evaluation of the noise emissions of the unit (see also section 1.5).

Depending on the simulation goal, different versions of HYGESim can be utilized. With HYGESim_F, only the evaluation of the main flow through the unit is evaluated; while with HYGESim_FFI the effect of the radial micro-motion of the gears due to the pressure loading can be considered: the actual location of the gears axis of rotation can be estimated and the wear of the casing can be predicted. With HYGESim_FFIC, the lateral lubricating gap along with the axial balance can be studied, for an accurate determination of the leakages and possible contacts between parts at gears lateral side.

More details on the lateral gap model are given at section 1.4 of this report.

Main Results: The model has been validated through numerous comparisons between experimental results and numerical predictions, with tests performed at Maha or at Sponsors' facilities. Figure 2 shows an example of comparison performed on a prototype pump able to measure both the inter-teeth pressure and the delivery pressure ripple. Figure 3 shows an example of comparison for the volumetric efficiency of a pump, while Fig. 4 displays a comparison of the predicted wear of a pump case after the initial break-in process.

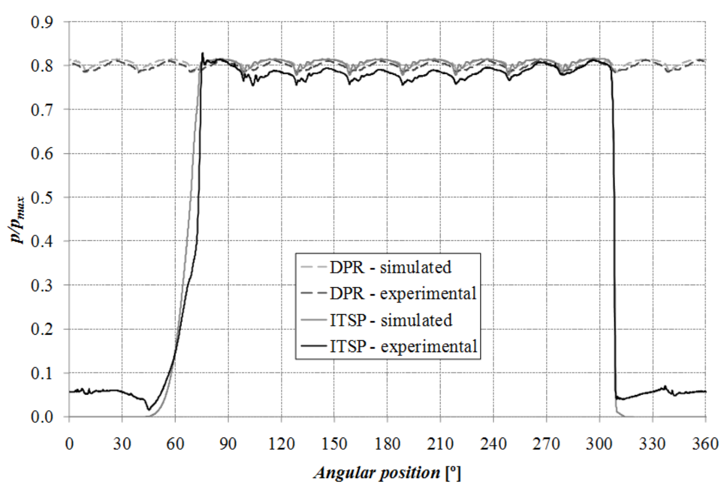



**Figure 2 – Tooth space volume pressure and delivery pressure: measurements vs simulations**

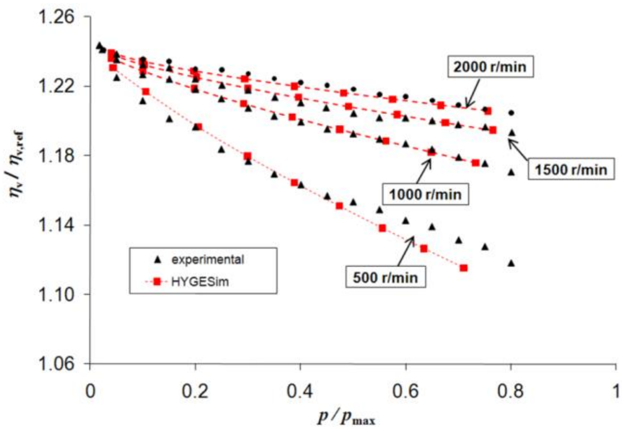



**Figure 3 – normalized volumetric efficiency (simulation vs experiments)**

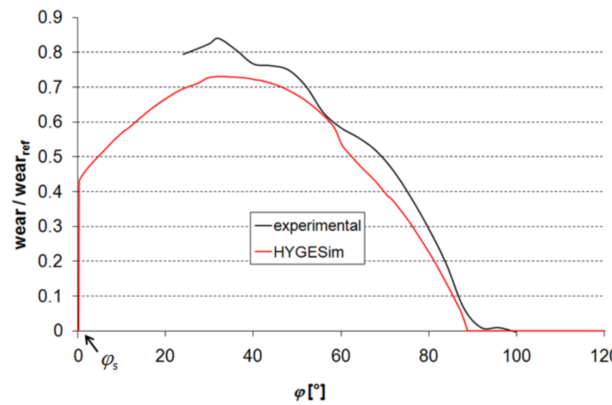



**Figure 4 – Normalized casing wear profile (simulation vs experiments)**

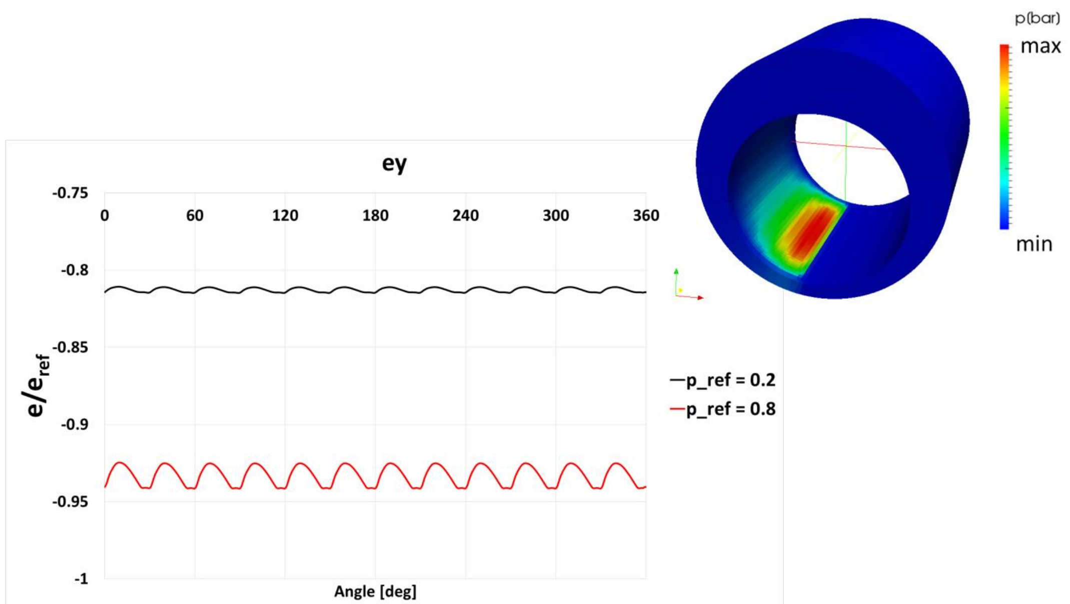



**Figure 5 – Instantaneous shaft eccentricity and pressure field inside the journal bearing provided by HYGESim**

### 1.3. Gear generator for HYGESim

Goal: HYGESim gear generator is separate code package with interactive graphical user interface which can generate various symmetric and asymmetric gear profiles and automatically generate the input necessary to perform simulation with HYGESim. The gear generator also provides the geometry of the rack cutter that has to be used to generate the gears.

Approach/Results: The HYGESim gear generator is implemented in MATLAB, and it has an interactive graphical user interface, as shown in Figure 6 for an involute gear design. The GUI of gear generator allows the users to visualize the design resulting from a certain set of input parameters, and to quickly generate the geometry input files to perform HYGESim simulations.

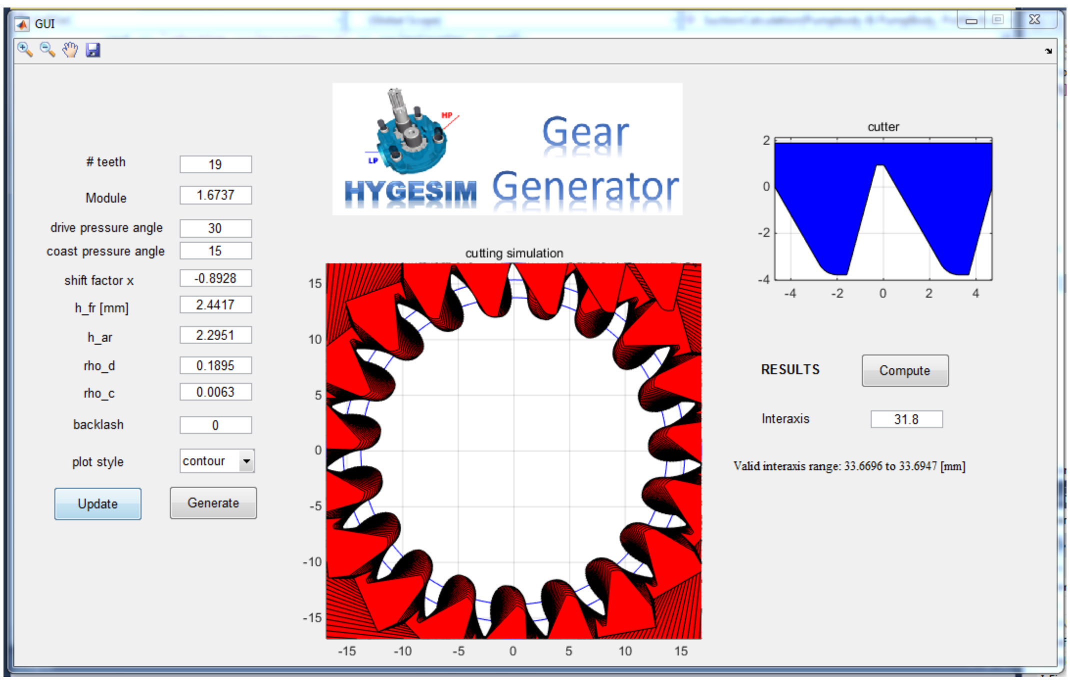



**Figure 6: Graphical User Interface of HYGESim gear generator.**

HYGESim gear generator uses a numerical approach to reproduce the gear cutting process. The first step is to generate the geometry of the rack cutter (Fig. 7). After the cutter geometry is defined, the cutting process is simulated with relative motions of the cutter, as illustrated in Figure 8. This method has the advantage of avoiding approximations usually introduced by analytical expressions to define the root fillet profiles of the gears. The undercutting effect that comes from a certain tip shape can be nicely captured by this gear generator. This can have important effect on the contact ratio parameter, occurrence of interference and on the mechanical strength of the gears.

The generator uses the analytical method to reproduce the portions of tooth profile where exact mathematical description exists, (i.e. involute profile). A proper algorithm is used to switch between the analytical mode and numerical mode, this ensures the accuracy and time-efficiency at the same time.

The gear generator has the capability of generating both symmetric and asymmetric gears, including profiles coming from non-standard, or generalized cutters. Some examples of non-standard, asymmetric involute gears are shown in Figure 9. With this gear generator module as a new component of HYGESim, potentials are enabled for exploring new gear designs particularly suited for hydraulic applications.

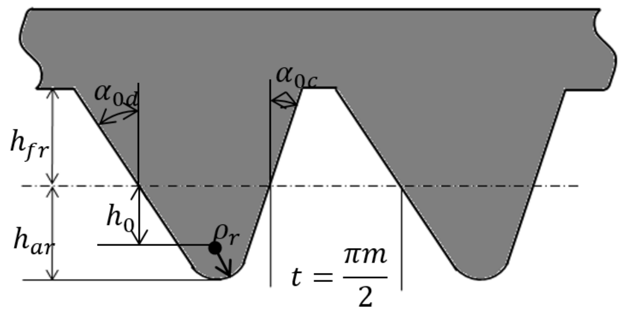



**Figure 7: The geometry and parametrization of a rack cutter of an asymmetric involute gear.**

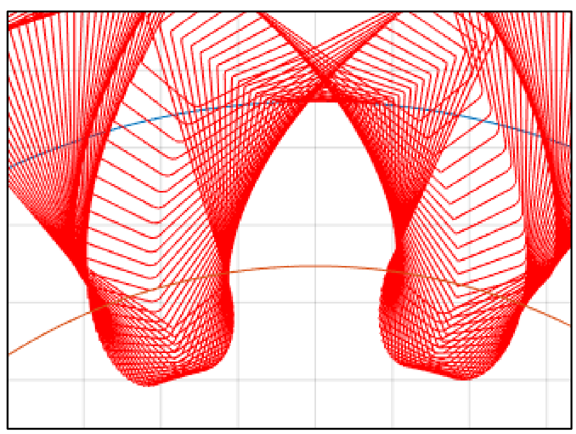


**Figure 8: Virtual “cutting” process during gear generation.**

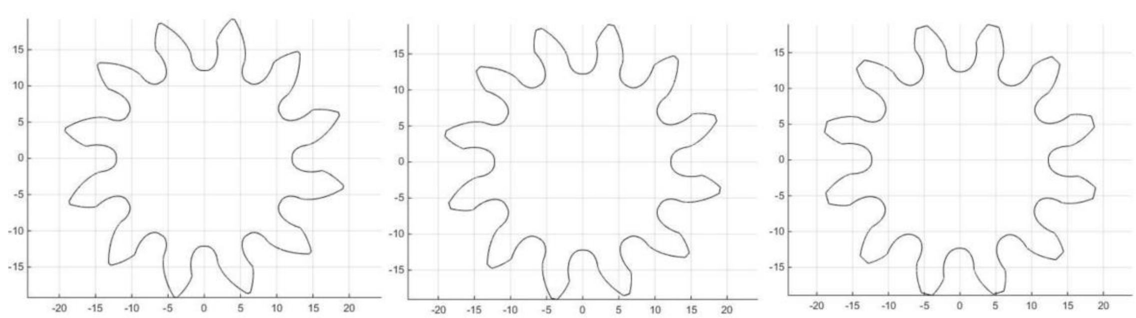


**Figure 9: Examples of non-standard asymmetric gears generated by gear generator**

### 1.4. Variable Delivery External Gear Machine

Goals: In this project, a novel concept for obtaining a variable delivery flow in external gear machines was successfully conceptualized, designed and prototyped. The novel principle stands out from the existing patents and literature available in such a way that the design maintains all the well-known advantages of external gear machines (EGMs) such as low cost, compactness, reasonable operating efficiency and good reliability and still capable of varying the displacement.

Approach: The proposed concept is based on the realization of a variable timing for the connections of the tooth space volumes with the inlet/outlet grooves. The variation in the timing of the connections is achieved by the introduction of a movable element called the "slider" within the lateral bushings of external gear machines as shown in Figure 10(A). The position of the slider determines the amount of flow displaced by the unit per revolution, for both the cases of pumps and motors. The displacing action occurs in the angular interval $\theta$, which defines the meshing region. Between points D and S of the line of action, the TSV is trapped between points of contact, therefore the displacing action is realized by means of the inlet/outlet grooves (a simplified representation of these grooves are indicated in Figure 10B). In standard EGMs, the commutation between inlet and outlet groove is realized when the volume is minimum, so that the maximum volumetric capacity of the pump is utilized as shown in Figure 10B.

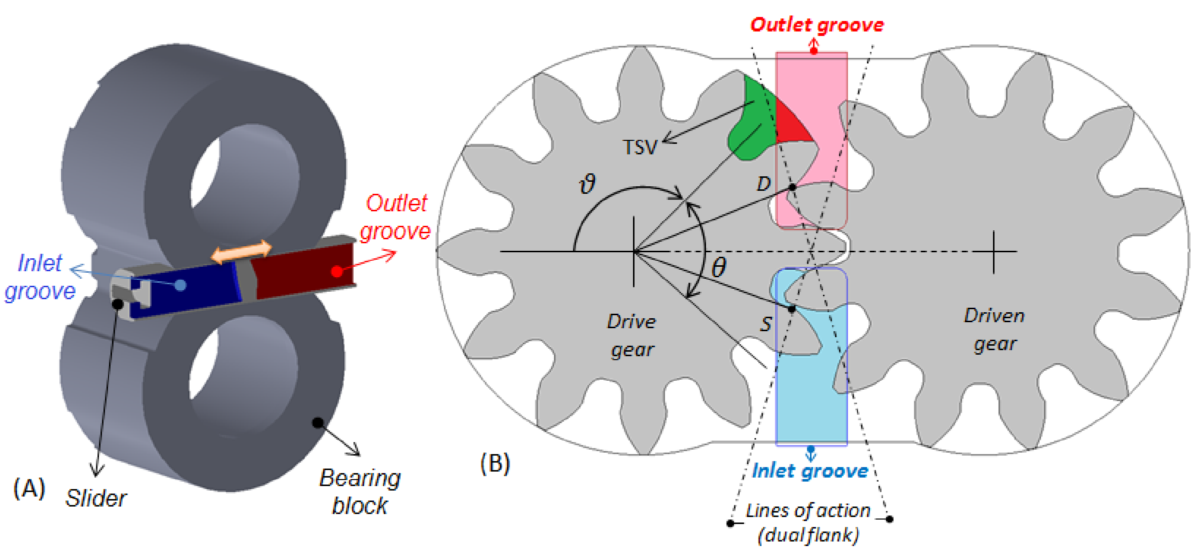



**Figure 10: (A) Slider placed inside the bearing block for achieving variable flow in an external gear machine (B) Generic TSV at angular position ϑ and the angular interval θ in which the meshing process takes place, Groove positions in the slider to achieve max displacement.**

However, a reduced displacement is achieved when the slider is positioned closer to the inlet port (as shown in Fig. 11(A)). This is because each TSV remains connected to the outlet port for a first portion of the filling process (after it reaches the minimum volume point, “M” at 180deg), wherein a part of the fluid already delivered to the outlet is taken back into the TSV which acts as an additional dead volume. Due to this “dead volume”, each TSV is capable of displacing a reduced volume of fluid. Graphically, the principle can be represented in Fig. 11(B): the TSV is connected to the delivery for a larger angular period until “S” and a smaller portion in which the TSV is connected to the inlet after “S”, therefore the delivered volume of fluid is equal to the difference between the max volume and volume at “S”. The additional “dead volume” is equal to the difference between the volumes of points S and M, therefore the effective fluid displaced to the outlet is equal to the difference between the maximum volume and volume at point S.

In the considered design, the slider remains at a fixed position to realize certain unit displacement, and it has to be moved only to realize a different displacement value. Therefore, this implementation does not require fast components, and the flow variation strategy does not necessarily require electronic control (pure hydraulic pressure or flow compensators can be realized with the slider).

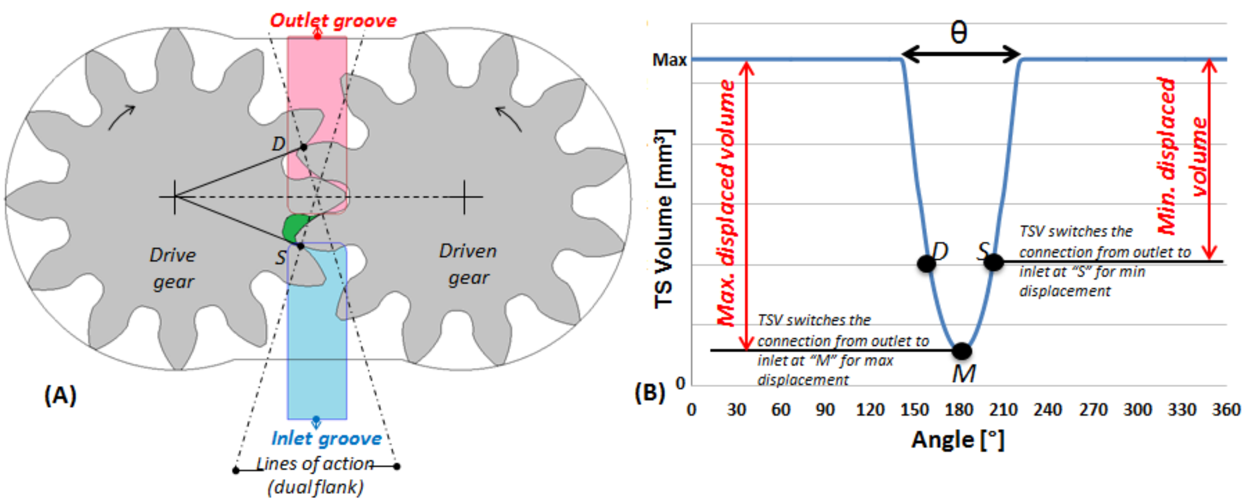



**Figure 11: (A) Position of the grooves to achieve min. displacement. (B) The evolution of TSV with respect to the shaft rotation angle, the switch of the TSVs connection from the outlet to the inlet occurs at “M” for achieving max. displacement and at “S” for achieving min. displacement**

It was identified that gears with symmetric profiles could provide only a very small range of variation of displacement and hence they are not beneficial for obtaining displacement variation. Therefore, gears with asymmetric teeth profile, unconventional for external gear machines were investigated in this work with the particular aim of maximizing the range of displacement variation achievable for the variable displacement external gear machine. A multi-parameter-multi-level-multi-objective genetic algorithm based optimization procedure was developed for determining the optimal design of the gears as well as the grooves in the slider. The performance of the design configuration was based on five different objective functions such as maximization of reduction in displacement, minimization of flow pulsations and features of meshing process such as internal pressure peaks & cavitation and maximization of volumetric efficiency.

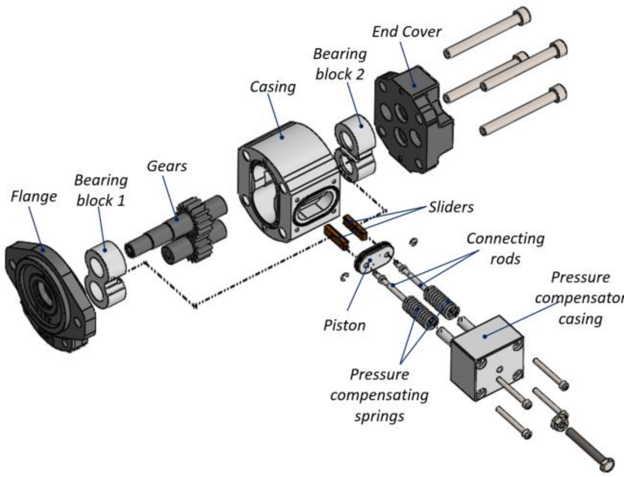



**Figure 12: Exploded view and picture of the VD-EGM prototype realized in 2015**

Main results: Before 2015, a proof of concept prototype was tested and proved to achieve a flow variation from 68-100% of the flow range. In 2015 a fully functional prototype for VD-EGM for high pressure applications was designed, manufactured and tested. The prototype, shown in Fig. 12, permits to test the complete VD-EGM functionality according to: a) a *manual control* for the outlet flow; b) a *pressure compensator* which adjust the output flow to limit the maximum pressure at the delivery.

The VD-EGM of Figure 12 was tested at Maha Fluid Power Research Center at Purdue to obtain a complete steady-state and transient characterization. Figure 13 shows the test set up used for the measurement of shaft torque, outlet flow and pressure, including pressure oscillations.

Experimental results for both the regulating modes of the prototype were collected. Figure 14 shows the case of manual setting of the displacement. It can be seen how the outlet flow is actually regulated by the prototype with a significant torque reduction.

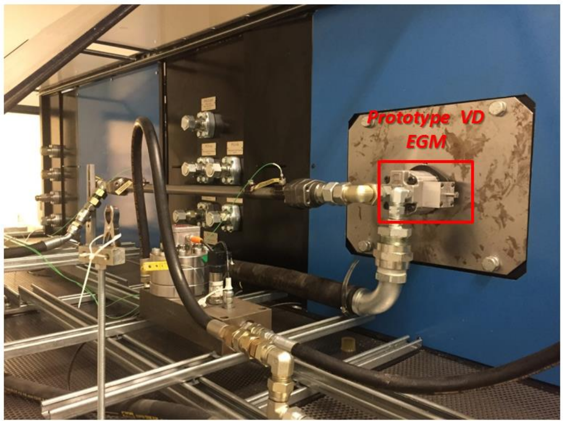



*Figure 13: Test set up for the VD-EGM tests*

Since the gears were not properly treated, the pressure during the tests was limited to 100 bar. Measured data show volumetric efficiencies in about 60% at minimum displacement and 85% at maximum displacement. The reduction of efficiency at maximum displacement is due to the additional leakage path created by the slider at its back side. This could be reduced by a better machining tolerance of the slider, as well as by a different design concept for the slider that introduce proper sealing.

Instead, the further reduction of volumetric efficiency at lower displacement is inevitable, due to the higher weight of the leakages with respect to the outlet flow. This is a common feature for almost all design of VD positive displacement units.

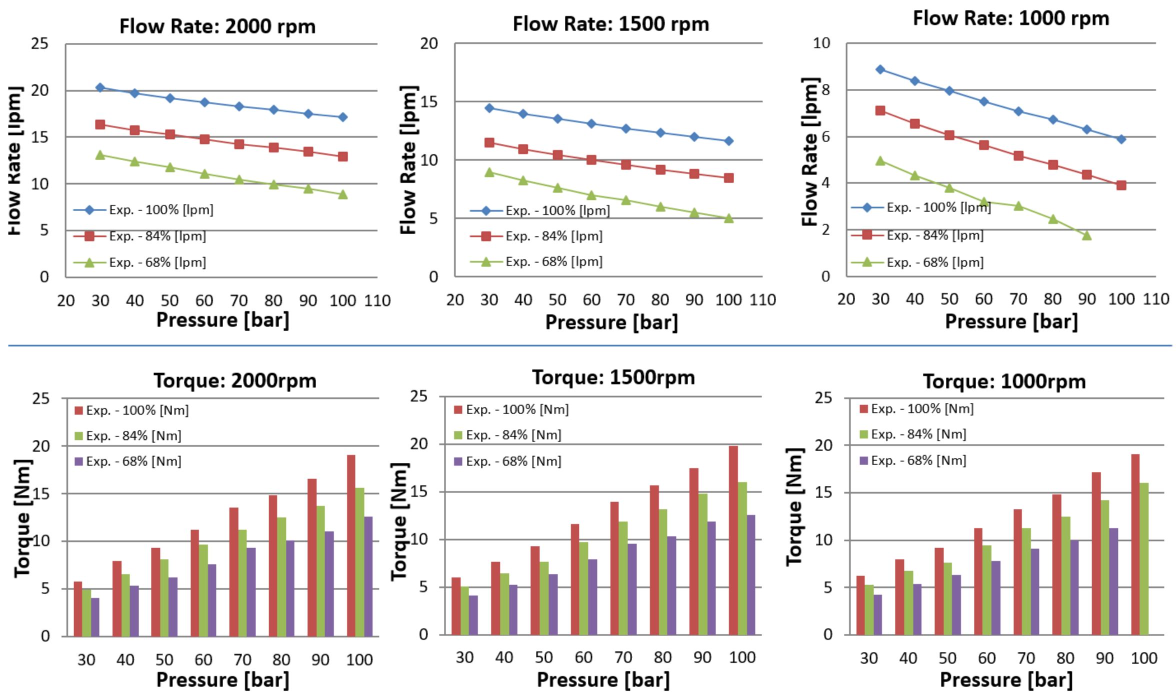



**Figure 14: Test results achieved with the manual setting of delivery flow. Flow variation (upper plots) and torque variation (lower plots for different speeds)**

## 1.5. Modeling of lubricating interfaces in external gear machines

Goals: In high pressure external gear machines (EGMs), the lubricating interfaces between lateral bushings and gears (as shown in Figure 15A) perform important functions of sealing and bearing loads and are the major sources of power losses in these machines. In this research, a numerical model of the lubricating gaps was developed with an aim to gain deeper understanding of the highly coupled fluid, structural and thermal mechanisms at these interfaces. Such an advanced computational model can be used to drive EGM designs with improved efficiency, reliability and operating life. The research presented in this section was developed with the following aims:

- Prediction of the leakage flow, pressure & gap heights in the lateral gap
- Evaluation of effects of material properties and surface features
- Evaluate balancing features of the unit
- Design efficient and novel machine configurations for better performance (improved balancing features, reduction of power losses).

A thermo-elastohydrodynamic (TEHD) model for the lateral gaps was previously developed in Dr. Vacca's research team and was validated during 2014 with capacitive film thickness measurements performed on a prototype EGM. The TEHD model for the gaps was developed with the assumption of full film lubrication at all times during the EGM operation. However, it was observed that for some severe operating conditions involving relatively lower pressures (< 50 bar) or lower speeds ( ~ 500 rpm), areas of mixed lubrication with very low film thickness (as shown in Figure 15B) which are in the order of the surface roughness (~ order of 0.3 µm) of the solid components in the gap are present. This requires that the effect of surface features of both the gears and the lateral bushings need to be taken into account while modelling the lateral gap. For this reason, a mixed lubrication model was added to the existing TEHD to effectively model the regions of low film thickness whenever it is encountered in the EGM operation.

The previously developed numerical optimization procedure to determine the optimal axial balance in a given EGM design can be used in conjunction with the TEHD model to leverage its advantages in achieving efficient and reliable EGM designs with reduced leakages and friction losses along with reduced wear in the gears and the lateral bushes throughout the operating range.

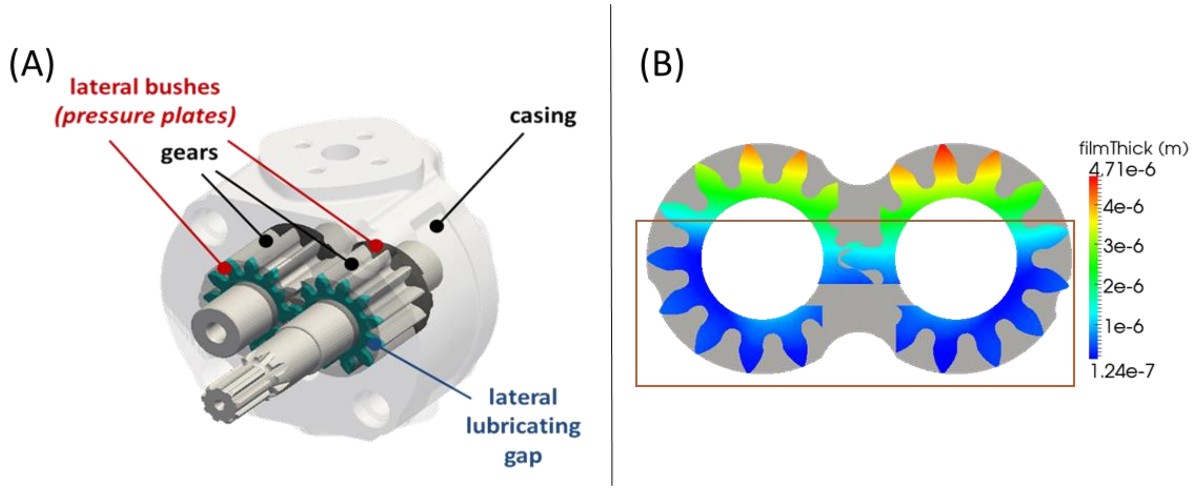



**Figure 15: (A) Representation of the lateral lubricating interface in external gear machines (B) Regions of low film thickness (highlighted in the red box) in certain severe operating conditions of EGMs.**

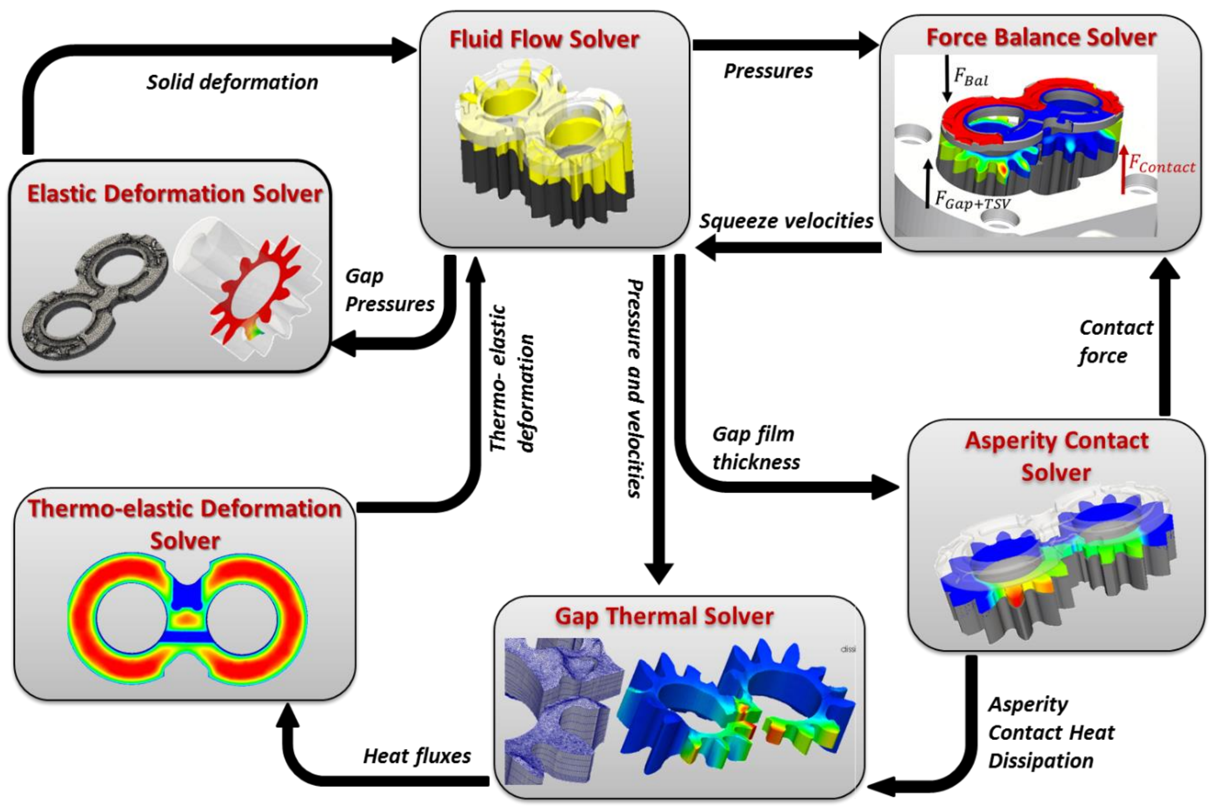



**Figure 16: Schematic representation of the mixed-TEHD model for lateral lubricating interfaces in external gear machines**

Approach: The TEHD model for the lateral lubricating gaps along with the mixed lubrication component has been developed in programming language C ++ using open source libraries such as OpenFOAM, Linux, GSL and gmsh. A broad structure of the numerical model with its several sub-models coupled with each other is shown in **Figure**. As depicted in the figure, a gap flow sub-model calculates the flow and pressure distribution in the lubricating gap which is coupled with structural and thermal sub-models to evaluate the elastic and thermal deformation respectively of the lateral bushings and the gears. A force balance model is also implemented as a sub-model to account for the dynamics and micro-motion of the bushings. An asperity contact sub-model calculates the contact pressure when the film thickness in the gap falls in the order of the surface roughness of the solid components.  All the sub-models are coupled and implemented in an iterative numerical scheme.

Results: The mixed-TEHD model is capable of determining the various numerous parameters associated with the lateral gap such as pressure distribution (as shown in Figure 17A), film thickness, temperature (as shown in Figure 17B) and deformation of the solid components. The recent addition of the mixed lubrication model also facilitates the calculation of contact forces and pressures (as shown in Figure 18A) generated, along with heat dissipation due to the asperity contact, whenever regions of low film thickness (as shown in Figure 18B) occurs.

*Novel EGM designs – Wedge gears.*

Micro surface shaping effects have been found to improve the lubrication performance in the lateral gaps and such effects can be evaluated using the lateral lubricating gap developed in the current research. One particular design solution of adding a linear sloping wedge to either surface of the gear teeth (as shown in Figure 19A) was simulated using the lateral gap model and was found to reduce up to 60 % of the total power losses in the lateral gap (as shown in Figure 19B) due to favorable hydrodynamic effects.

In order to verify the performance of the wedge gears experimentally, a prototype design of the wedge gears with a flat step followed by a linear wedge (in the order of microns), as shown in Figure 19B was manufactured and tested to validate the claims of the lubricating gap model. The measured input torque to the prototype EGM with wedge gears was found to be consistently lower than that of the nominal EGM without the wedge gears. This indicated that there are lesser torque losses in the wedge gears when compared to the nominal EGM design and a sample result from a shaft speed of 1500 rpm across different delivery pressures supporting this claim is shown in Figure 20A. The torque losses measured for the wedge gears were also compared against the corresponding values predicted by the simulations of the gap model and were found to be in good agreement with each other as shown in Figure 20B.

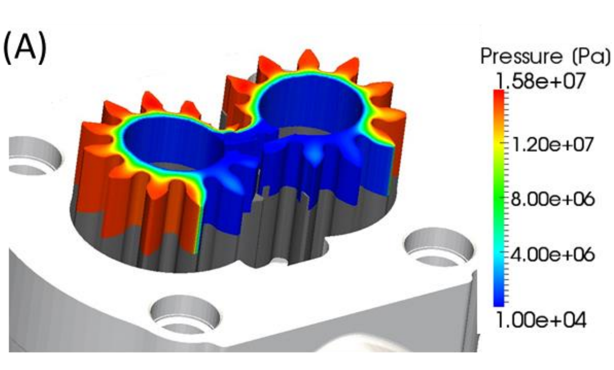



**Figure 17: A) Pressure and lubricant film thickness (B) Bushing temperature and gap film thickness. Film thickness is scaled up by 10000 times for visibility**

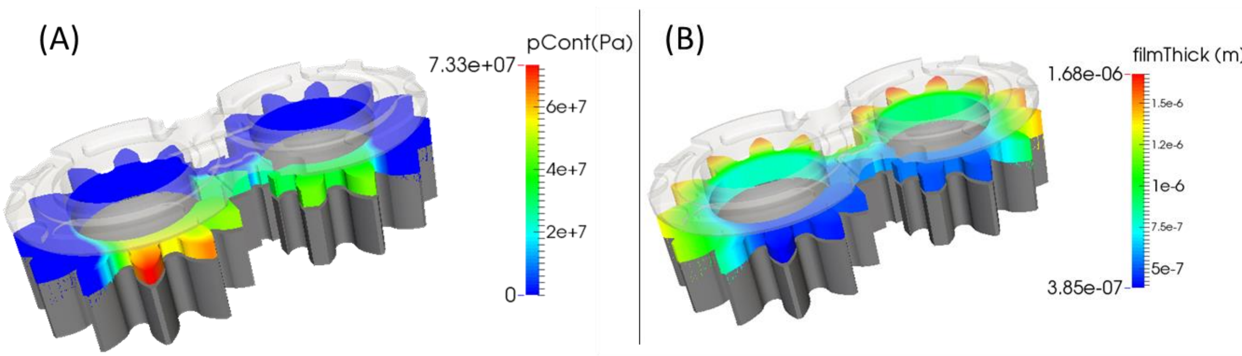



**Figure 18: (A) Contact pressure due to the interaction of the surface asperities as predicted by the mixed lubrication sub-model. (B) Corresponding film thickness plot showing the regions of low film thickness where high contact pressure is predicted.**

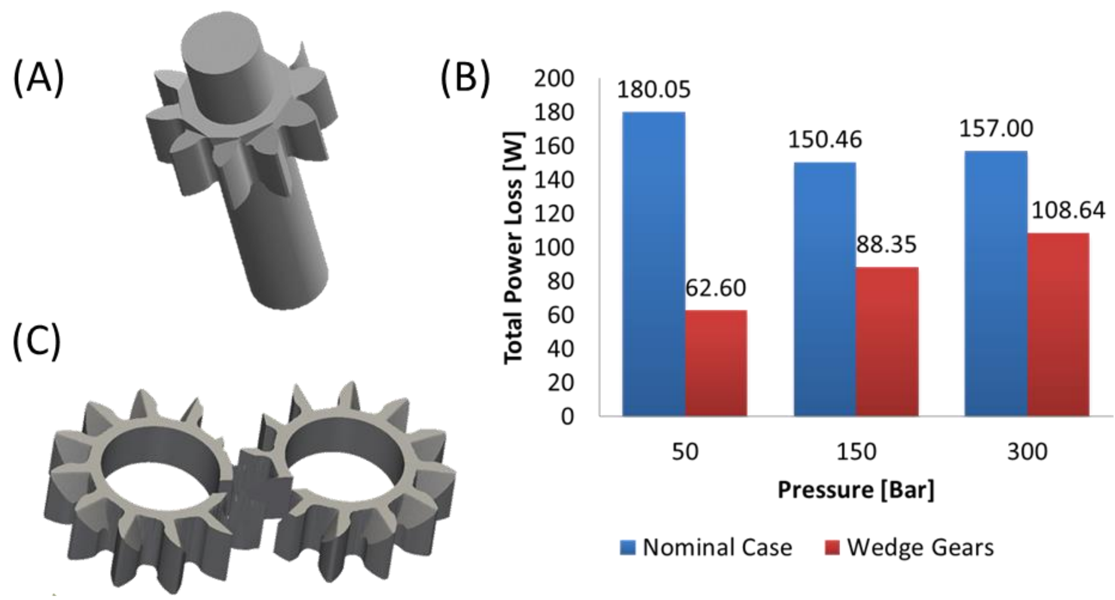



**Figure 19: (A) Linear sloping wedge on each of the gear surface (B) Total power losses predicted by the lateral gap model (C) Modified step and wedge design as represented in the form of the lateral lubricating gap.**

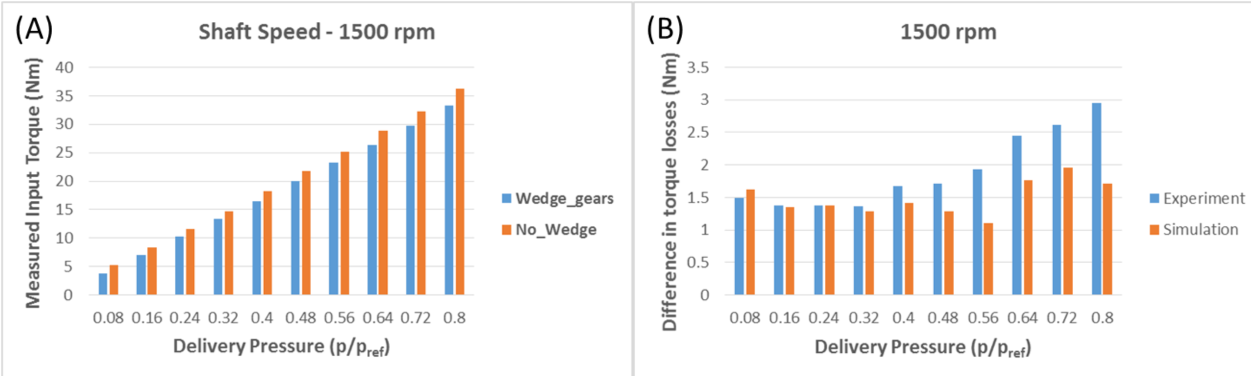



**Figure 20: (A) Comparison of the measured input torque of EGMs with and without wedge gears at a shaft speed of 1500 rpm (B) Comparison of the torque losses predicted for the wedge gears against the corresponding measured values at a shaft speed of 1500 rpm**

The addition of a mixed lubrication model to the existing TEHD lateral lubricating gap model improves the flexibility of the tool which can be used in designing EGMs with a wide range of operating conditions and different fluids such as water where its lower viscosity makes lubrication performance a major challenge for it operation. A combination of the previously developed axial balance optimization procedure along with carefully designed micro surface shaping effects like the wedge gears has the potential to generate novel designs of EGMs with improved lubrication performance which consequently increases the operating efficiency of such units.

### 1.6 Evaluation of noise generation in positive displacement machines

Goals: Currently, oil hydraulics is the best technology for transmitting mechanical power in many engineering applications due to its advantages in power density, ease of control, layout flexibility, and efficiency. Due to these advantages, hydraulic systems are present in many different application including construction, agriculture, aerospace, automotive, forestry, medical, and manufacturing just to name a few. Many of these applications involve the systems in close proximity to human operators and passengers where noise is of the main constraints to the acceptance and spread of this technology.

In order to increase the range of applications where fluid power is advantageous and acceptable, the noise generation must be better understood and ultimately reduced. Besides environmental concerns, decreasing the noise and vibration of hydraulic components has potential additional benefits of improving control stability and increasing machine life and reliability.

Study of the physical phenomena of noise is typically separated into three categories: fluid, structure, and air-borne noise. While many approaches are available to study the air-borne noise (ABN) for general applications, it is difficult to simulate the mechanisms of noise generation in hydrostatic units to predict the fluid-borne noise (FBN) and structure-borne noise (SBN).

The current activity focuses in advance the understanding of the noise generation and propagation in positive displacement machines, taking as reference the particular case of external gear pumps. More specifically, it is to enhance understanding of the phenomena relating the instantaneous pressure and flow fluctuations to the noise radiated by the unit, and to formulate ideas for quieter design of pumps and motors.

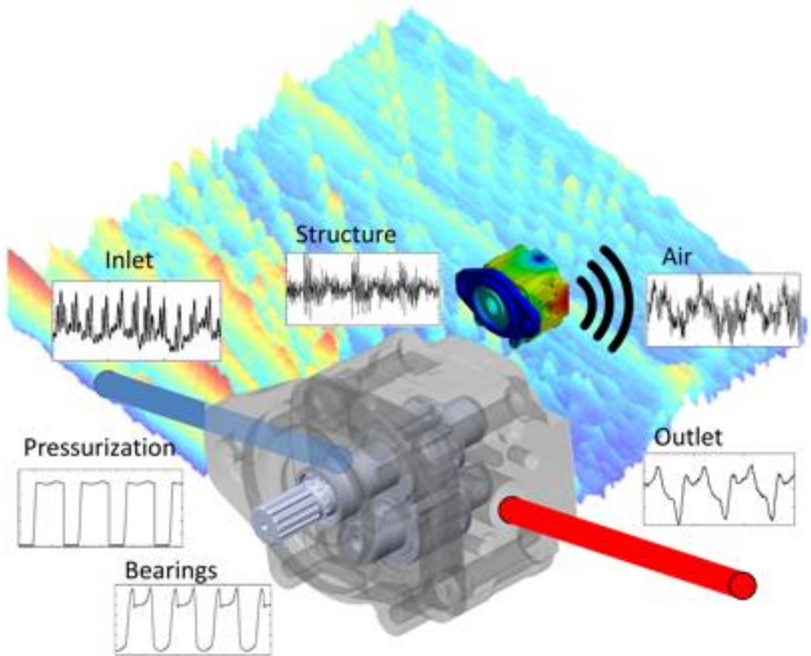



**Figure 21: Approach of study: FBN – SBN – ABN in an external gear machines**

Approach: The case of external gear pumps is taken as reference for a new model suitable to study the generation and transmission of noise from the sources out to the environment (Figure 21). The lumped parameter model HYGESim (Hydraulic Gear machine Simulator) is adapted to provide the loading pressure functions and to predict interactions with the attached system. The different loading functions are then applied to vibro-acoustic models for evaluation of noise transmission. Vibration and sound radiation can be predicted using a combined finite element and boundary element vibro-acoustic model as well as additional models of system components to better understand the essential problems of noise generation. The main structure of the model is shown in Figure 22.

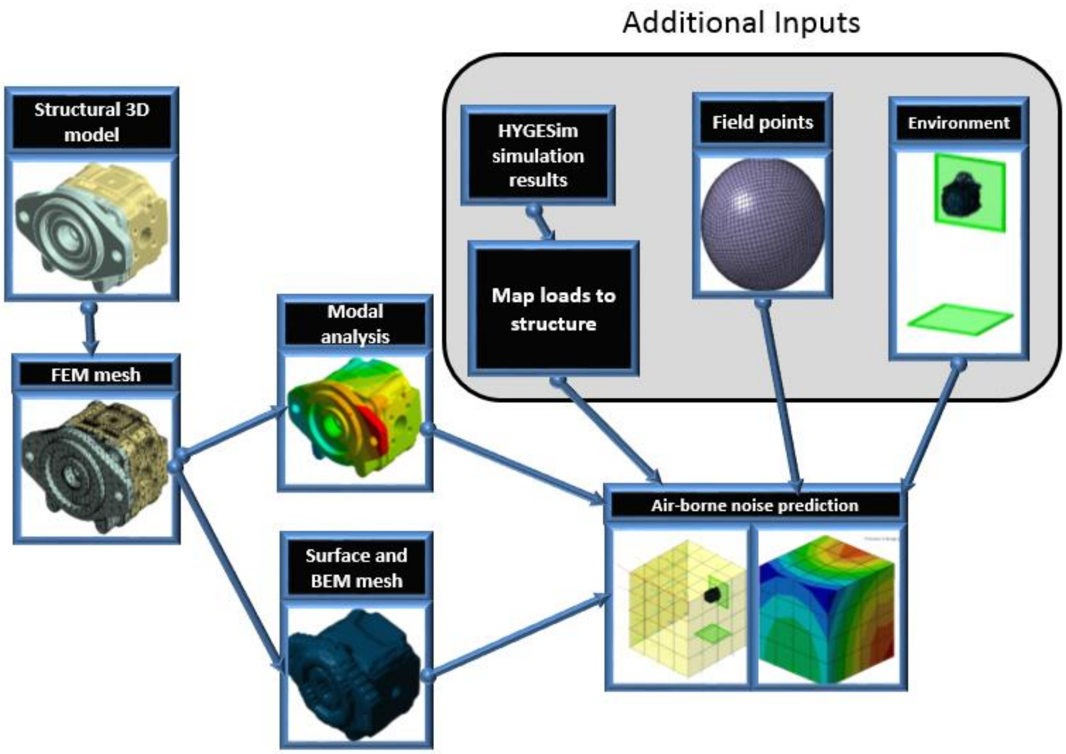



**Figure 22: Structure of the model developed to predict the generation and propagation of noise in external gear pumps**

Several experimental studies were also completed which accomplished key tasks related to the research goals. In particular, the pump model in terms of FBN – SBN – ABN predictions was validated through comparison to experimentally measured results for prototype pumps designed for different levels of outlet flow fluctuations (Figure 23). Subsequently, the study focused on the air-borne noise through sound pressure and intensity measurements on reference and prototype pumps at steady-state operating conditions. Measurements were performed at the semi-anechoic chamber of the Maha Fluid Power Research Center. An additional study was completed to explore the noise transfer path from the fluid to the structure and to the air impact of operating conditions and system design to greater detail through measuring noise and vibration in the working fluid, the system structures, and the air (Figure 23). This permitted to isolate the contribution of the fluid, of the structure to the noise emission map.

An additional study was also performed to evaluate the effect of aeration on airborne noise. For this study a prototype pump designed for inducing high aeration was designed and tested.

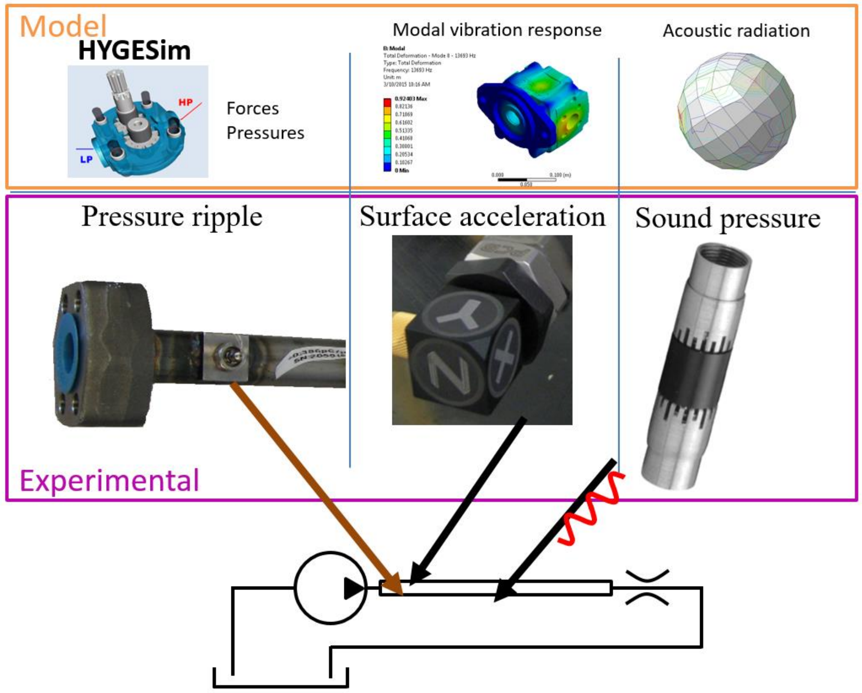



**Figure 23: Validation of the acoustic model at all the different domains**

Results: For the reference external gear pumps, the radiated noise prediction is acting nearly as a pure impedance to the FBN load as shown in the Figure 24. This is evidenced by the presence of frequencies in the air-borne noise that are directly correlated to the pressure loads inside the pump. This is also confirmed by modal analysis of the various pump and system components which shows that the pump body has very high resonant frequencies that mainly do not interact with the pump harmonic excitation.

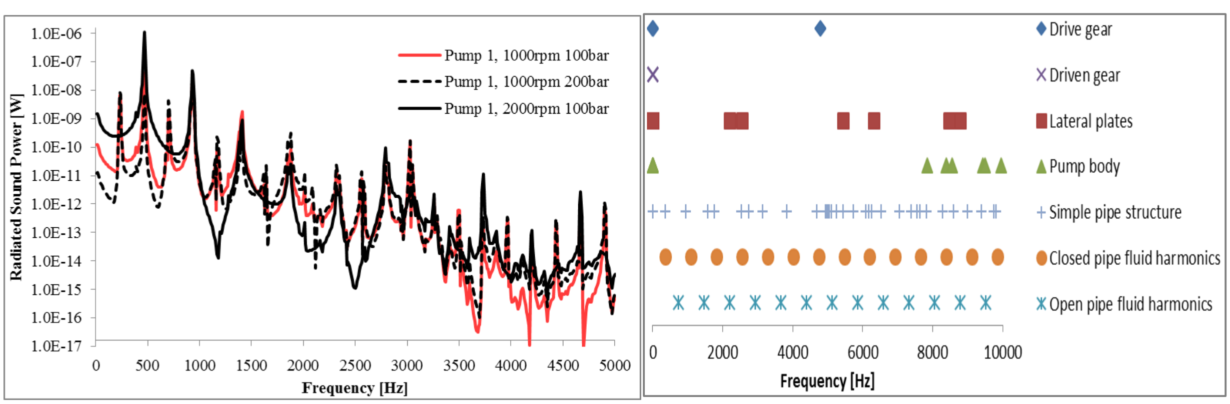



**Figure 24 - (left) Model results for noise radiation. (right) resonant frequencies of the pump and system components**

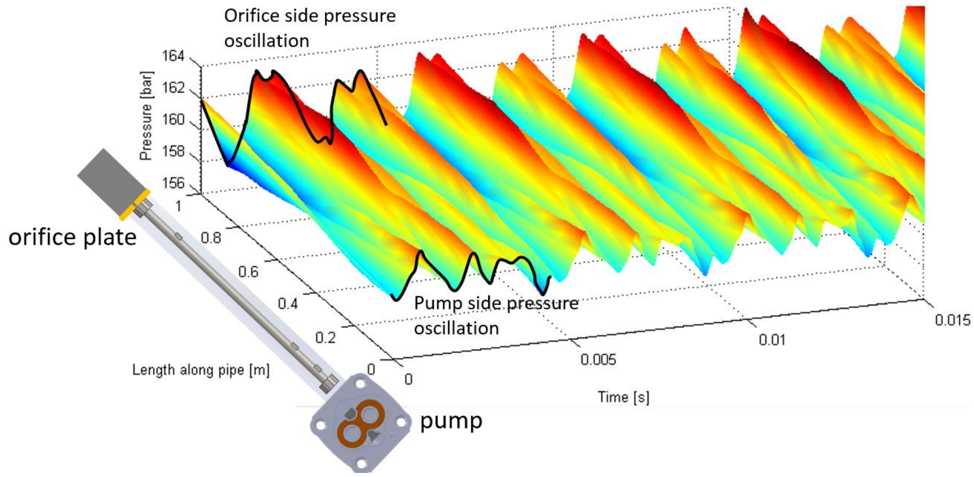



**Figure 25 – Pressure waves propagation in the pump delivery line**

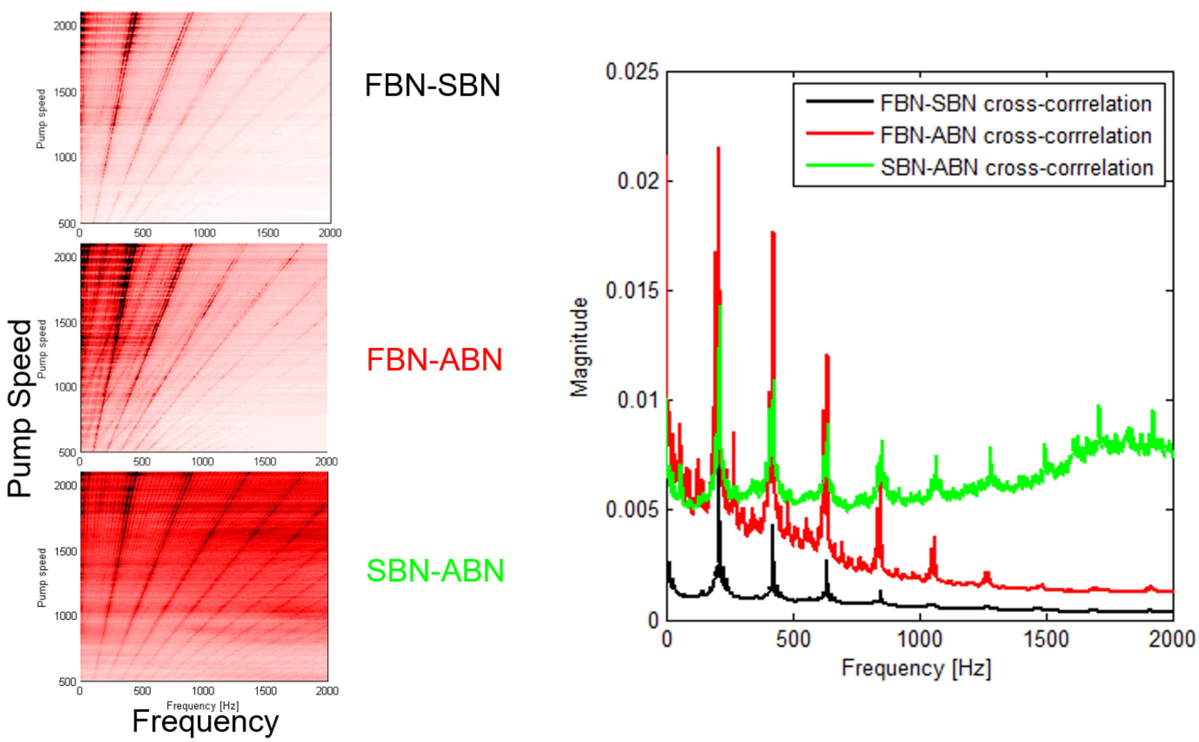



**Figure 26 – Cross correlation of FBN SBN and ABN to understand noise propagation in the pump**

An additional study shows that components of the system including the attached lines and the oil inside them have strong potential to show resonant coupling with the pump frequencies (Fig. 25). Vibration in the steel pipe utilized in the experiments as delivery apparatus to characterize the FBN according to the ISO standard are influenced by resonances of both the fluid inside the pipe and the pipe structure.

In order to quantify the noise transmission through the different domains above, a particular method of post-processing the experimental data was developed. Figure 26 shows the cross correlation of different domains highlighting the effect of the internal FBN to the ABN.

Measuring the surface vibration of the pump and lines sheds light on the influence structural and system considerations have on the pump operation and radiated noise, and allows for smarter optimization and design of new quieter pumping units. Measuring the radiated sound pressure is used to validate noise models and determine if design changes accomplished the desired goals of quieter systems.

The key potential future applications of this methodology is to improve system designs through structural modifications or targeted operating ranges. It also allows for new more efficient and accurate modeling techniques that would be not be possible without the complementary experimental technique.

### 1.7 Modeling of external gear pumps operating with non-Newtonian fluids

Goals: The goal of this project is to develop capability to simulate gear pumps working with non-Newtonian fluids and use it to characterize such pumps and study their behavior in extreme operating conditions.

Approach: HYGESim is a lumped parameter based tool that has been successful in accurately simulating pumps that work with Newtonian fluid. It uses pressure build up equation to calculate pressure in different chambers, turbulent orifice equation to calculate the flow through orifices and laminar flow equation to calculate flow rate through leakages. The latter two of these equations are modified for non-Newtonian fluids. The leakage flow in the external gear pump is modelled as flow through parallel plates with one of the plates moving. The analytical relation for such kind of flow for power law fluids is used to substitute the Newtonian equation.

For determining the accurate orifice flow equation, orifices of various contraction ratios are modelled and flow through them are simulated in Polyflow (figure 27). The fluid is modelled using Phan-Thien-Tanner viscoelastic model. The pressure-flow rate data is then recorded and are found to be matching with the experimental results using same fluid and geometry configurations. Performing regression on the data, a new orifice equation is developed that relates pressure drop and contraction ratio of the orifice to the flow rate through the orifice.

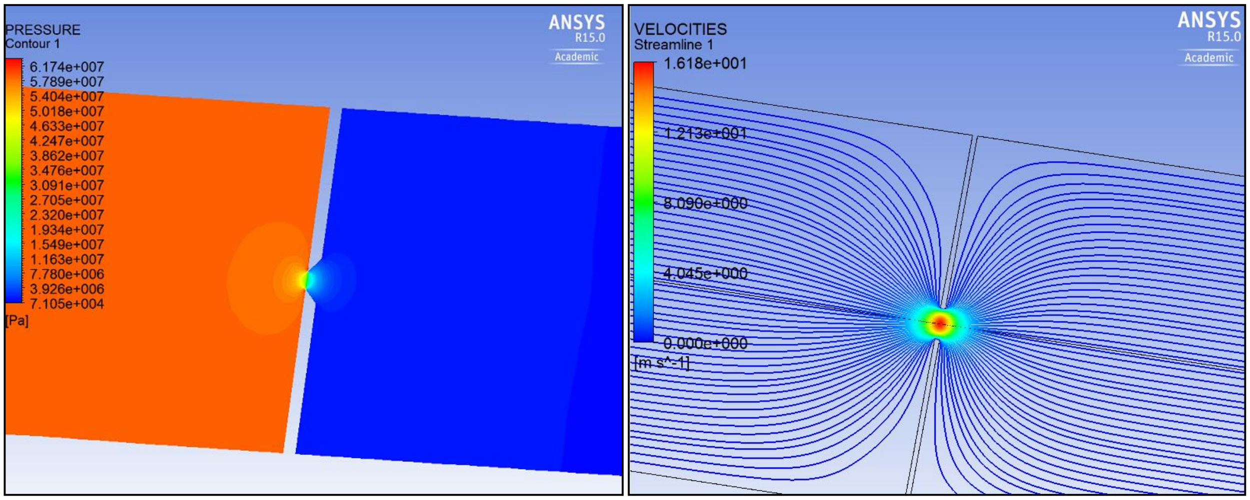



**Figure 27: Polyflow simulation results: (a) Pressure contours of flow through an orifice. (b)Streamlines**

Main results: The non-Newtonian HYGESim tool hence developed predicts the behavior of pump with reasonable accuracy. Figure 28 shows the variation of pressure in a tooth space volume with angle as it starts moving from the meshing zone and rotates in a way that it faces the suction side of the of the gear pump followed by casing, delivery side and back to meshing zone. The TSV pressure increases gradually through the casing zone since the gears are assumed to be concentric with casing with constant radial gap.

Future work includes modification of the model allowing radial micro-motion of the gears. This will be followed by the study of full range of the pump characteristics using our model and study of its performance at extreme operating conditions.

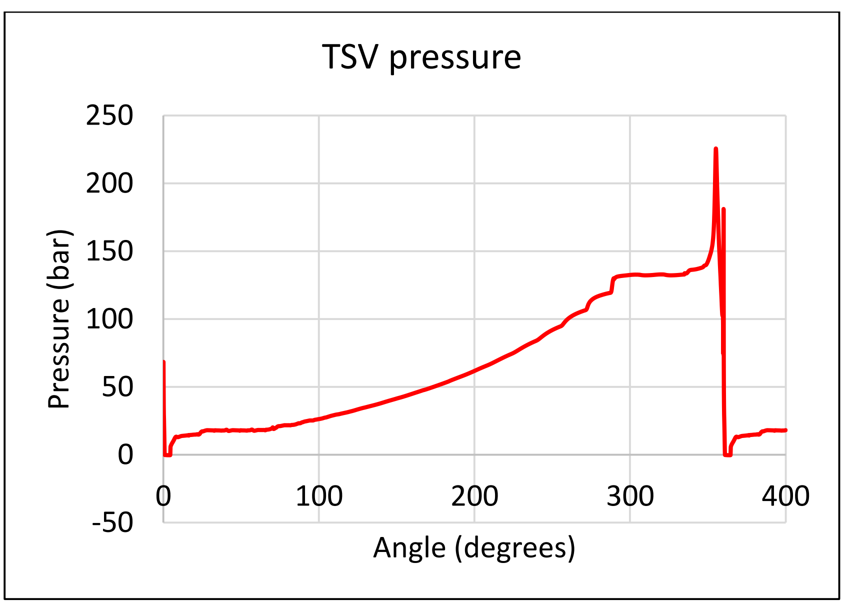



**Figure 28: The variation of pressure in a tooth space volume with angle**

### 1.8 Modeling of Gerotor units

Goal: This research focuses on the development of a simulation model that can be used to study the operation of Gerotor pumps and as a design tool for investigating new solutions. The model takes into account for the main fluid dynamics of the displacing process realized by the machine, considering also the mechanical interaction of the components, particularly as concerns the micro-motions of the rotors. The developed tool is capable of generating the geometry profiles or start from an existing CAD design of the rotors and simulate its operation within AMESim, predicting main features of the operation such as delivery pressure ripples, internal pressure peaks, rotor radial movements and torque losses.

Approach: The model is based on a multi domain simulation approach comprising sub-models for parametric geometry generation, numerical calculation of characteristic geometry data, fluid dynamic model and mechanical model (Figure 29).

A geometric generator of rotors based on the circular arc profile for the outer rotor was also created (Figure 30). The simulation model, however, accepts any profile for the rotors.

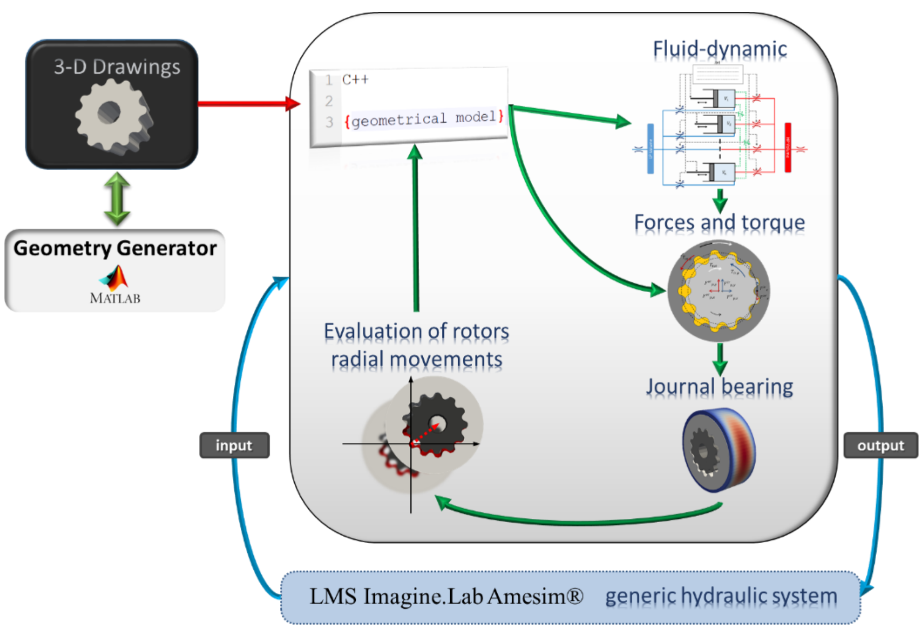



**Figure 29 – Structure of the Gerotor Simulation Tool: Interaction between the internal modules and an external hydraulic system**

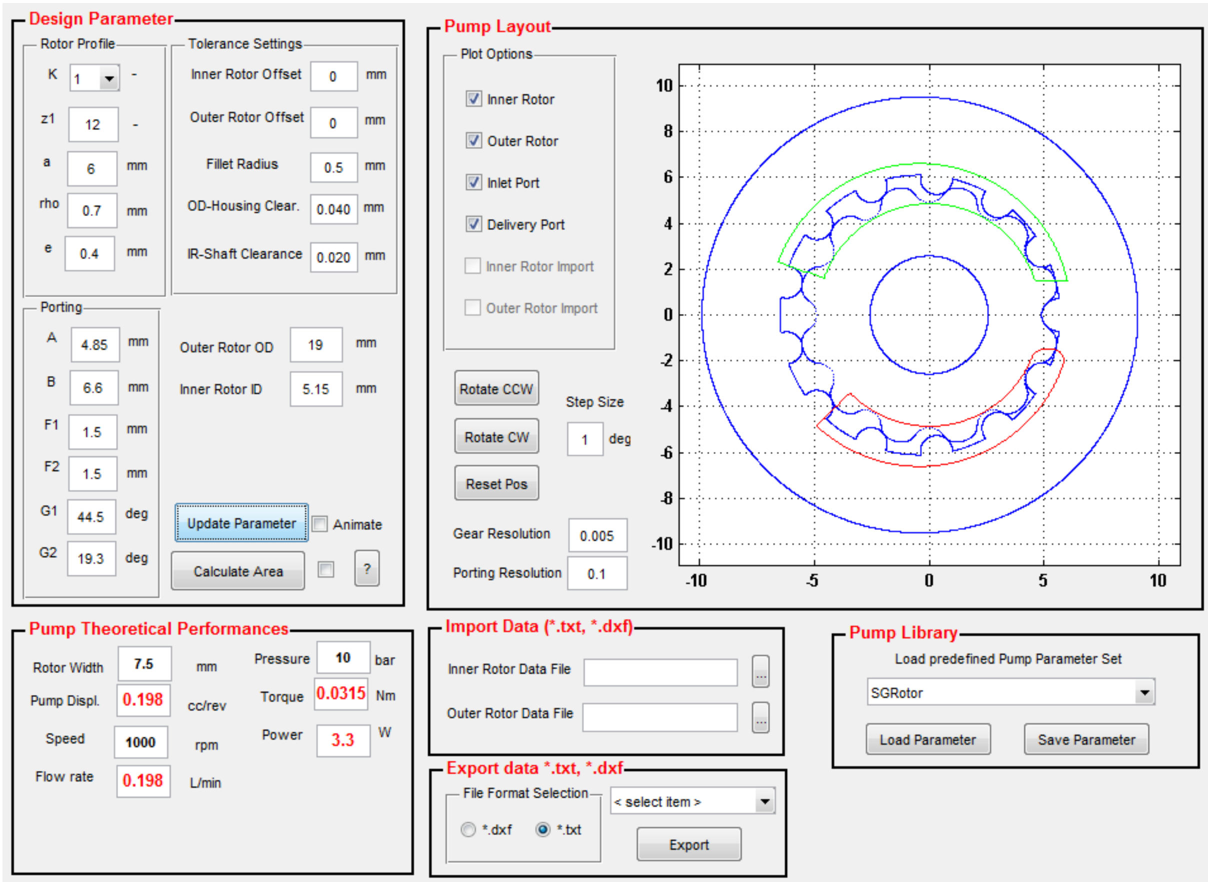



**Figure 30 – Graphical user interface for the GEROTOR profile generator**

Once the geometry of the rotors has been defined, using the in-house Geometry Generator or a predefined profile are carried out, the C/C++ code evaluates the geometrical features of the pump. In particular, it evaluates the Displacement Chambers Volumes (DCV), the inlet and outlet areas (intersection between the DCV and the grooves as depicted in Figure 31 and Figure 32A/B ) and the radial gap between the teeth of the inner and outer rotor along with the length of the gap (Figure 30C).

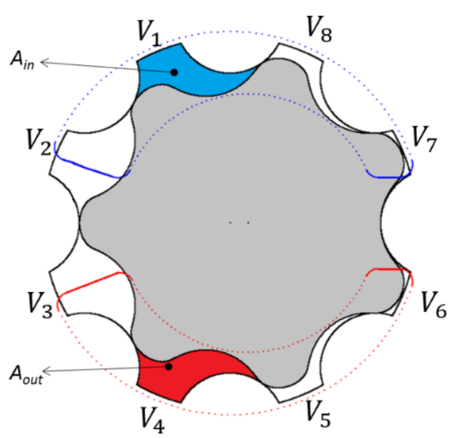



**Figure 31 – Control Volumes and Intersection with Delivery (red) and Suction(blue) Ports**

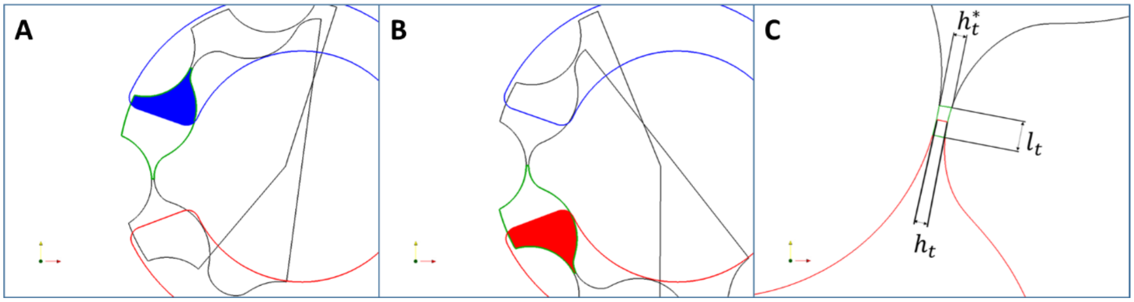



**Figure 32 – (A/B) Area Used by the Equivalent Orifice; (C) Tip Clearance and Equivalent Gap Length**

The fluid dynamic model evaluates the flow through the unit and it is the central part of the developed simulation procedure. In fact, the modeling equations and the assumptions made in it directly affect the implementation of the other sub-models, used to provide input data (Figure 29) to the fluid dynamic model. The approach followed for this model is lumped parameters: the fluid domain is divided in control volumes in which fluid properties are assumed to be uniform. This approach is commonly used for studying the main flow features of hydrostatic units. In particular, each displacement chamber (Vi in Figure 31), is considered as a separate control volume and its pressure is evaluated on the basis of the net flow entering or leaving it. The flow terms are evaluated with the turbulent orifice equation, to evaluate the flow between the DCVs and the suction and delivery ports, while the tooth tip leakages between adjacent DCVs have been accounted using laminar flow equations.

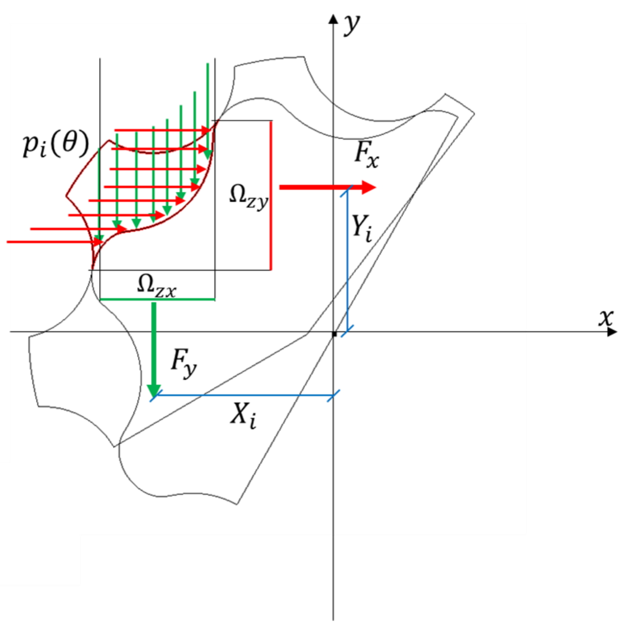



**Figure 33 – Projected DCV Areas for the Evaluation of Pressure Forces**

The simulation model also evaluates the pressure forces acting on each rotor. This is done by evaluating the single force components in each DCV in x and y axes. Thus, the surface corresponding to each tooth profile is projected on a plane perpendicular to the direction of the force, as shown in Figure 33. The total force is then utilized in a journal bearing model to evaluate the actual position of the two rotors. This last information is used to carefully determine geometric parameters such as DCV volume, throat areas and the radial gaps. The micro motion evaluation plays a fundamental role on not only the prediction of the fluid dynamic features but also on the mechanical interaction between the rotors of the unit. The coupling of the mechanical module and the geometrical module of the current simulation model can be used as a valuable tool to estimate the correlation between the rotors profile geometry and factors responsible for the wear of the components namely contact pressure, sliding velocity and curvature of the profile putting the accent on the actual regions where contact occurs.

The model is equipped also with a user-friendly post processing interface in which fluid properties inside of each control volume such as pressure, mass fraction of gas, and mechanical properties like tip clearance at the minimum distance between the rotors can be represented (Figure 34).

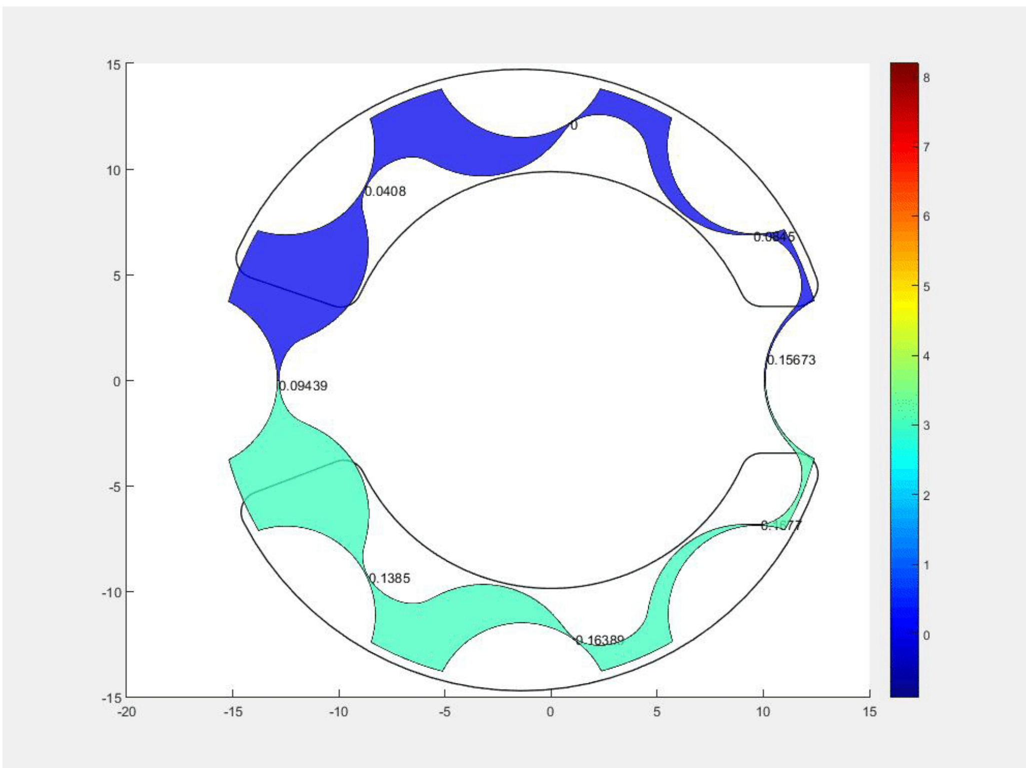
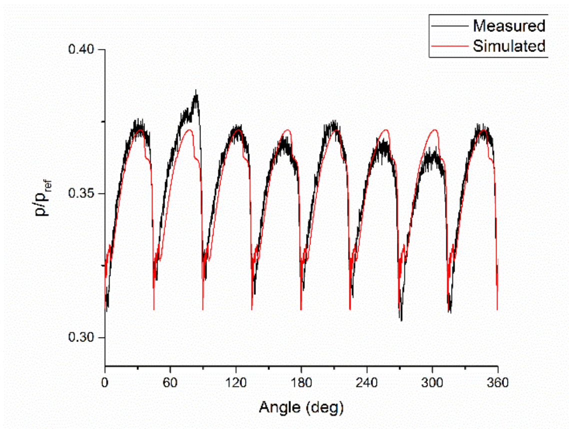



**Figure 34 – Post Processing Add-in Interface**

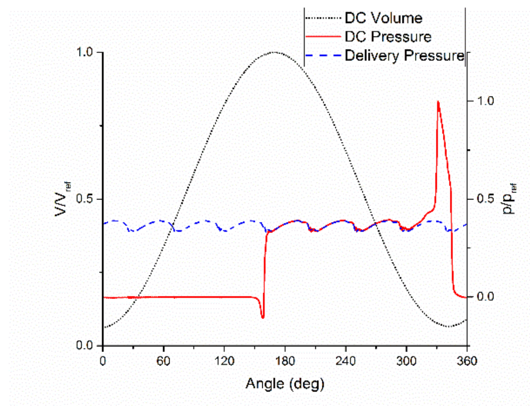
Main results: The model has been validated as concerns the prediction of the instantaneous flow oscillations (pressure ripple) and volumetric efficiency, and measurements were found to be in good accordance with the numerical predictions. At current stage, the model is capable of determining the influence of different designs of the gears or of the input/output port of the unit. Details on the internal flows as well as the instantaneous pressure inside the DCV can also be studied (Figure 35).

The model is also capable of automatically identify the effect of geometrical tolerances and the region of contact resulting from the micro-motions of the two rotors (Figure 36).

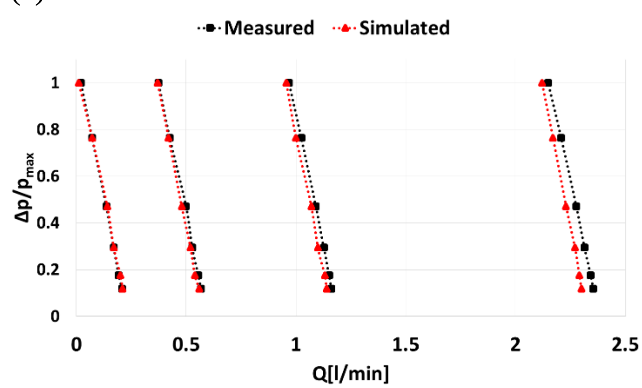
This omni-comprehensive model together with a computational efficient numerical approach, such as the lumped parameter, make the Gerotor simulation tool ideal for characterization and optimization of existing designs and for the study of new ones.




(a)




(b)




(c)

**Figure 35 – (A) Comparison Between Measured and Simulated Delivery Pressure Ripple; (B) DCV Pressure Over One Revolution of the Outer Rotor; (C) Comparison Between Experimental and Simulated Characteristic Curves**

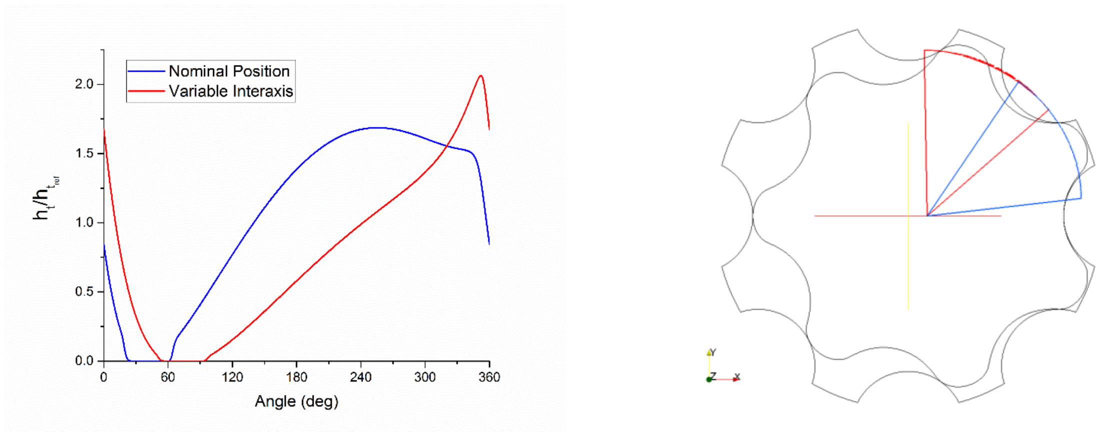



**Figure 36 – Example of numerical results from the simulation model (A) Tip Clearance Variation Over 1 Revolution of the outer rotor; (B) Arc of Contact for Two Different Interaxis Positions**

## 1.9 Modeling and Validation of Lubricating Interfaces in Radial Piston Pumps

Goal: In this research, the capabilities of the multi-domain simulation tool for investigating the operation of radial piston machines – particularly the modules for the lubrication interfaces' performance - have been enhanced. Radial piston machines are widely used positive displacement machines for high pressure applications and offer benefits of high efficiency along with a capability of withstanding very high loads at low speeds.

The focus of the current research is to validate the numerical model developed to predict the friction acting at the cam-piston interface. Also, the capabilities of the piston-cylinder interface model have been enhanced through the implementation of the additional feature of observing the impact of circumferential piston grooves in the design of the pistons.

The reference machine analyzed in this study is a radial piston pump of rotating cam type design as shown in Fig. 37 which is used for high pressure applications.

Approach: Figure 38 shows the fully coupled numerical solver that has been developed to capture fluid-structure interaction phenomena in the piston/cylinder interface at isothermal fluid conditions. This model considers the piston micro-motion during one complete cycle of pump operation. This interface, operating in the elastohydrodynamic lubrication (EHL) regime, represents one of the main sources of power loss due to viscous friction and leakage flow. It performs the functions of a hydrodynamic bearing by supporting the radial loads acting on the piston, seals the high pressure fluid in the displacement chamber and reduces friction between the moving parts.

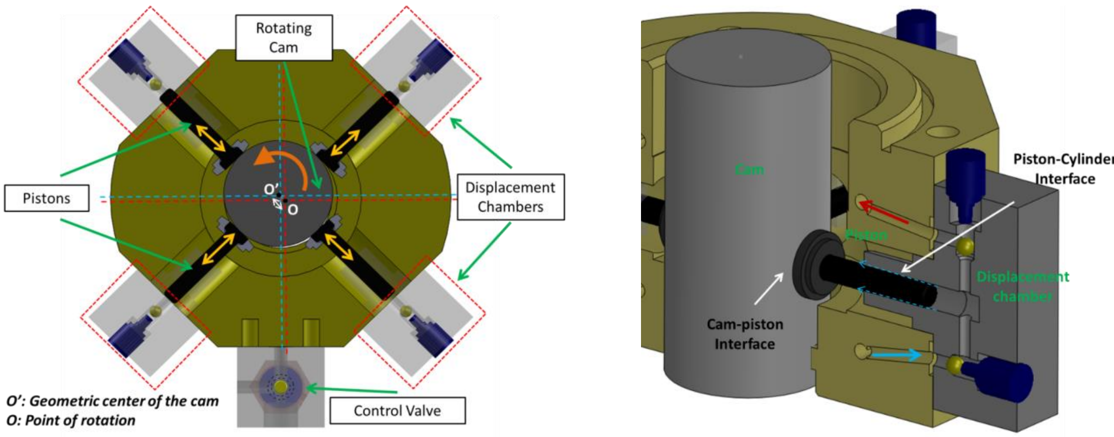



**Figure 37 - (Left) Radial piston pump design used in the present study; (right) Lubricating gaps in a typical rotating cam type radial piston pump**

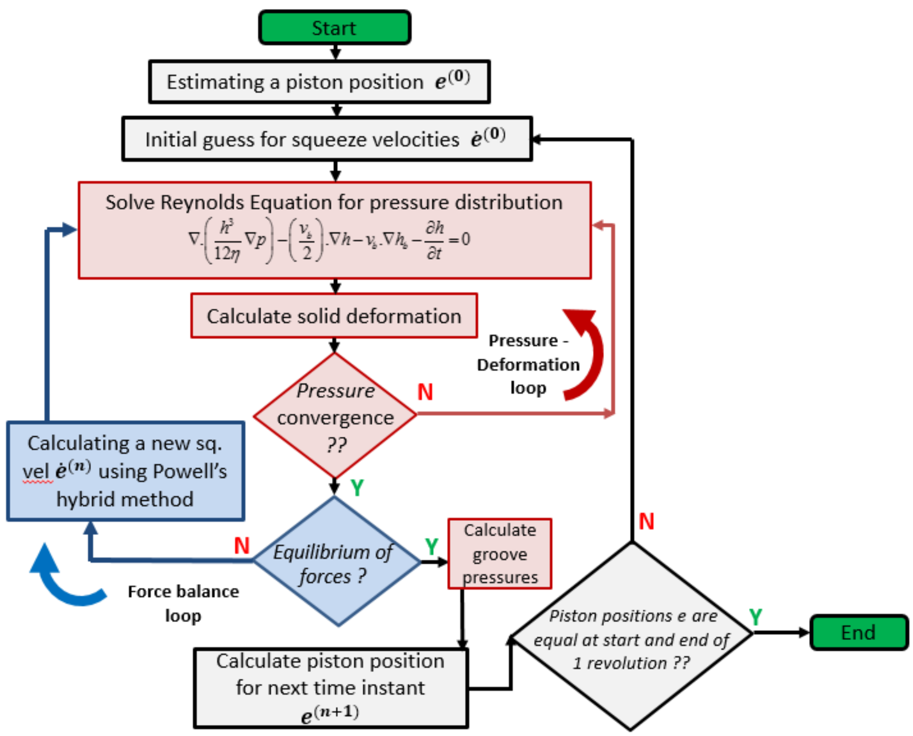



**Figure 38 - Algorithm for the FSI coupled force balance model**

The overall solver evaluates the micro-motion of the piston during each instant of the shaft's rotation by assuming a quasi-steady state behavior wherein the forces acting on the piston at each instant are balanced. This allows for the evaluation of the squeeze motion of the piston which ultimately decides its micro-motion behavior. The effects of EHL are considered while evaluating the pressure profile in the gap. A new feature has been incorporated in the solver developed for the piston/cylinder interface which now considers the effect of introducing a number of circumferential piston grooves at various locations along the length of each piston. One such design is shown in Fig. 39. The groove creates a region of constant pressure for the lubricant during the pumping cycle and this effect is modeled through a lumped parameter approach by using the pressure build-up equation to calculate the pressure within the groove at each instant of the operation of the pump. The locations and number of grooves influence the balance of the piston, as illustrated in Fig. 39.

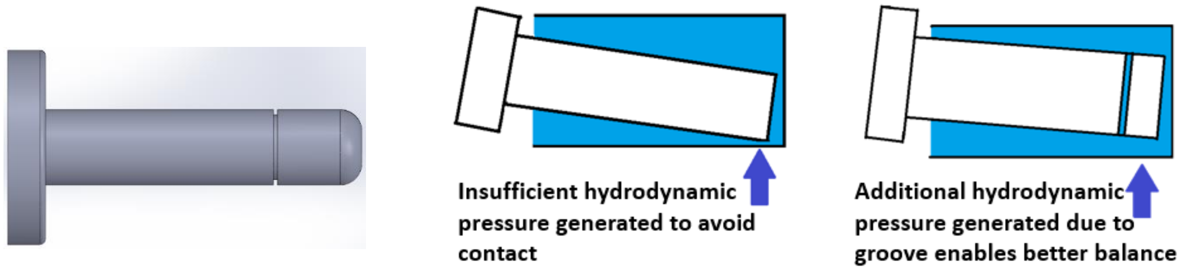



**Figure 39: (Left) Circumferential piston grooves introduced in order to study new interface designs; (Right) Illustration of the effect of piston grooves on the balance of the piston**

The radial loads acting on the piston have a significant influence on piston micro-motion and hence, the power losses in piston-cylinder interface. These loads are caused majorly by the friction forces existing between the cam and piston. A more accurate evaluation of performance parameters in the piston-cylinder interface can be achieved by calculating the instantaneous friction acting between the cam and piston under lubricating conditions. For this purpose, a line contact EHL model was developed that can predict viscous friction forces generated between the cam and piston at changing surface velocities and contact loads. The results obtained from this model have been validated through a combination of experimental and empirical approaches.

Main Results: The validation methodology and results from the numerically predicted behavior of the piston grooves are highlighted in Figs. 40-42. This research takes a step further in evaluating novel radial piston machine designs at low costs through digital prototyping.

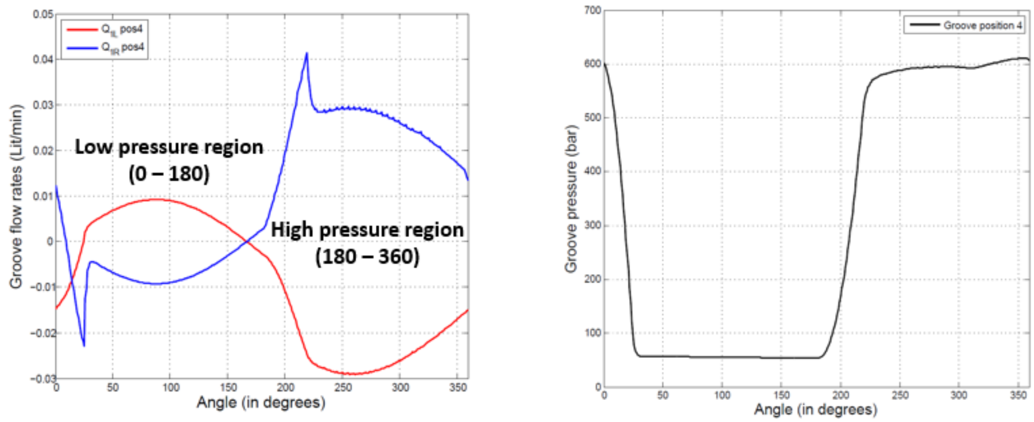



**Figure 40: (Left) Flow rates entering the groove from its either side during one shaft revolution; (Right) Pressure within the groove as a function of shaft angle. Operating condition: Outlet pressure=700 bar, Shaft speed=1800 rpm.**

At present, work is on-going on the evaluation of the effect of mixed lubrication within the piston/cylinder interface and the effect of grooves under such lubricating conditions. Future work includes the incorporation of thermal effects in evaluating lubricating gap flows to realize a more accurate model of radial piston pumps.

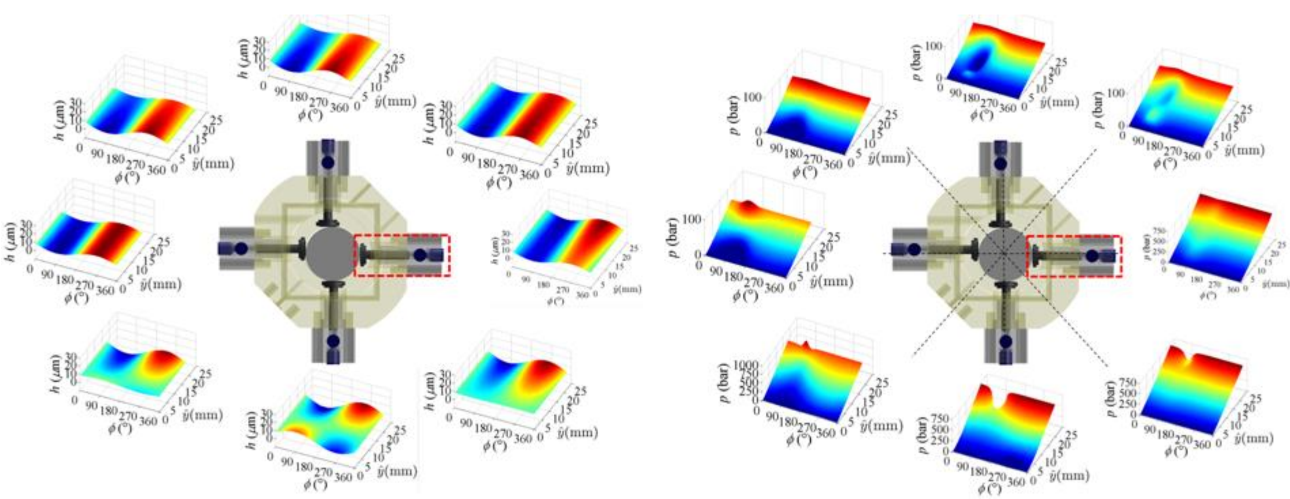
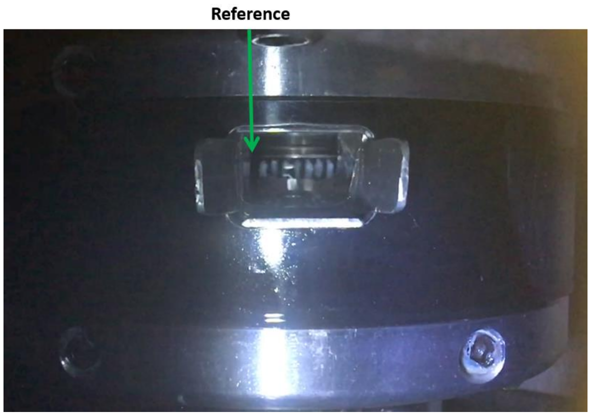


**Figure 41: (Left) Instantaneous film thicknesses and (Right) Pressure profile in the lubricating gap domain over one shaft revolution using FSI model. Operating condition: Outlet pressure=700 bar, Shaft speed=1800 rpm.**



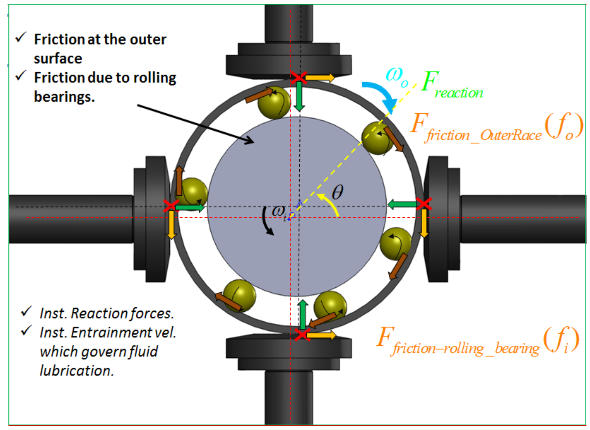



**Figure 42: (Left) Experimental measurement of the angular velocity of the cam to serve as an accurate input to the numerical model; (Right) Force balance of the cam to validate friction coefficient results**

## 1.10 Modeling and Simulation of Cavitation in Fluid Power systems

Goal: This research focuses on modeling and simulation of cavitation in hydraulic systems. Cavitation is traditionally known to cause damage to fluid machinery and is a bottleneck for fluid power applications that involve dealing with high gas content in fluids or high shear stresses during operation. This is true for most of the pumps connected to open reservoirs; therefore in all open loop hydraulic circuits and at the inlet of charge pumps closed loops circuits. Also in other elements of closed loop system, cavitation can limit the performance of the hydraulic components, create damages or produce noise. Therefore, it is imperative to model such effects, in order to improve the energetic performance of fluid power systems. This research entails implementation of effects of cavitation using the popular Lumped Parameter Modeling approach.

Approach: During the past research effort at Dr. Vacca's team, an approach for the prediction of air release and absorption in hydraulic oils was formulated. The proposed approach is derived from the Rayleigh Plesset Equation used to describe bubble dynamics in fluids. With a few additional assumptions, a lumped parameter model was derived to accounts for the effects of the dynamic features of air release and absorption. This modeling approach is unique in the aspects of capturing the dynamic evolution of gas and vapor phases in hydraulic oils. This has been achieved by analyzing the effects of compressibility in lumped parameter models used to describe hydraulic systems.

$$Q = C_q v \text{sign}(P_a - P_b)$$

$$v = \sqrt{2\int_{Pd}^{Pu} \frac{dp}{\rho}}$$

The effects of compressibility have been observed in the form of reduced overall stiffness of the system as well as reduced volumetric flow rate across orifices. The widely used Orifice and Pressure built up equations alone are insufficient for modeling such flows. Our methodology involves devising equations capable of including effects of cavitation.

$$\frac{dP}{dt} = \frac{E}{V}\left(Q_{in} - Q_{out} - \frac{dV}{dt}\right)$$

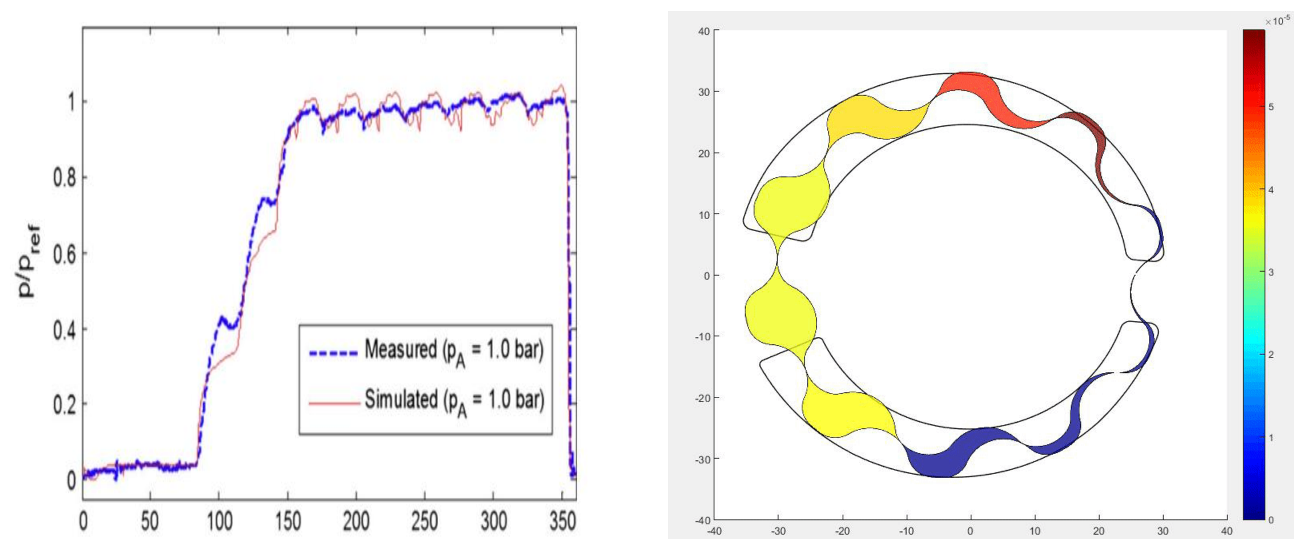
$$E = \left(f_g \frac{\alpha_g \rho}{\lambda P \rho_g} + f_v \frac{\alpha_v \rho}{\lambda P \rho_v} + \frac{1 - \alpha_g - \alpha_v}{E_0}\right)^{-1}$$

$$\frac{df_v}{dt} = \begin{cases} \frac{k_{11}}{\tau}(1 - f_{g0} - f_v)\sqrt{\mid p - p_v \mid} & (p \le p_v) \\ -\frac{k_{12}}{\tau} f_v \sqrt{\mid p - p_v \mid} & (p > p_v) \end{cases}$$

$$\frac{df_g}{dt} = \begin{cases} \frac{k_{21}}{\tau}(f_{gH} - f_g)\sqrt{\mid p_0 - p \mid} & (f_g \le f_{gH}) \\ -\frac{k_{22}}{\tau} f_g \sqrt{\mid p - p_0 \mid} & (f_g > f_{gH}) \end{cases}$$

$$f_{gH} = \begin{cases} f_{g0} & (p \le p_v) \\ f_{g0}\left(1 - \frac{p - p_v}{p_0 - p_v}\right) & (p_v < p \le p_0) \\ 0 & (p > p_0) \end{cases}$$

Implementation of these equations poses several difficulties due to the non-linear nature of the coupled differential algebraic equations. These equations are have been implemented as a sequence of different sub-models in AMESim written using C. This allows for the flexibility of using the cavitation model in most of the simulation environments in AMESim. The model so developed can be calibrated using a MATLAB® script depending on the test conditions to produce results close to the experimental observations.




(a) (b)

**Figure 43 - (a) Experimental Validation of the cavitation model; (b) Colormap of the Gas void fraction in TSVs of a gerotor pump.**

Results: The model has been shown to predict effects of vaporous and gaseous cavitation in External Gear pumps with a good accuracy (Figure 43a).

In 2015 the cavitation model was added into the Gerotor pump model. An example of results related to the instantaneous undissolved air is in the color map shown in Figure 43b, which describes the gas void fractions in Tooth Space Volumes as the pressure inside each TSV transitions from the suction pressure to delivery pressure. The implementation of cavitation model accounts for the generation of air and vapor inside each TSV as well as the transfer between them and across the orifices connected to the pump. The model is being put to test for a variety of cases, which would give us further insights into dynamics of flows inside fluid power systems.

### 1.11 Oscillation Damping in Mobile Machines

Goals: The goal of this project is to develop a novel energy-efficient control methodology to reduce vibrations in hydraulic machines. The proposed control strategies have the potential to replace or limit costly and energy dissipative methods currently utilized to achieve acceptable dynamical behavior in mobile fluid power (FP) applications. The two proposed control strategies directed to structural oscillations and payload oscillations can achieve a reduction of oscillations by up to 70%. These solutions match also a good improvement in the energy consumption of the hydraulic machine.

Applying techniques, like PID controllers and Fourier transformation, at the signal coming from the pressure sensors of the machine, enables these methodologies for heavy equipment, where the necessity to use sensors in well protected locations of the machine is needed, in order to not be damaged from the working environment.

Approach: In order to reduce oscillations in hydraulic machines, an electronic controller is used to detect the oscillations, process the information and generate the control signal sent to the machine actuation (typically hydraulic valves). The addition of sensors in the machine is required, in order to acquire the signal to process; although this will increase the production cost, the number of sensors needed for the controller is limited without introducing a significant cost increase. The control parameters need a continuous tuning, and this is achieved by an adaptive scheme using the Extremum Seeking algorithm. These algorithm is suitable for non-model based strategies, like the two proposed, where the model of the machine is unknown in order to reduce the production cost of the machine. The scheme of the two controllers is represented in Figure 44, where the controller dedicated at structure oscillations is governed by a PID controller which feedback is the pressure signal at the valve work port, instead the controller dedicated to payload oscillations uses the Fast Fourier Transform (FFT) algorithm in order to detect the hidden oscillation in the pressure signal.

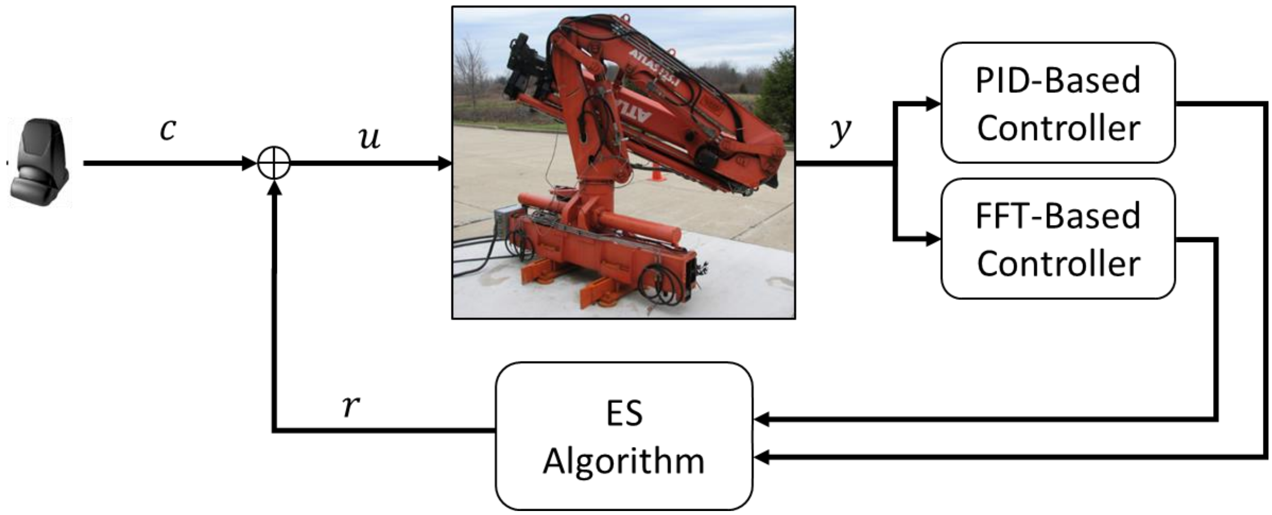
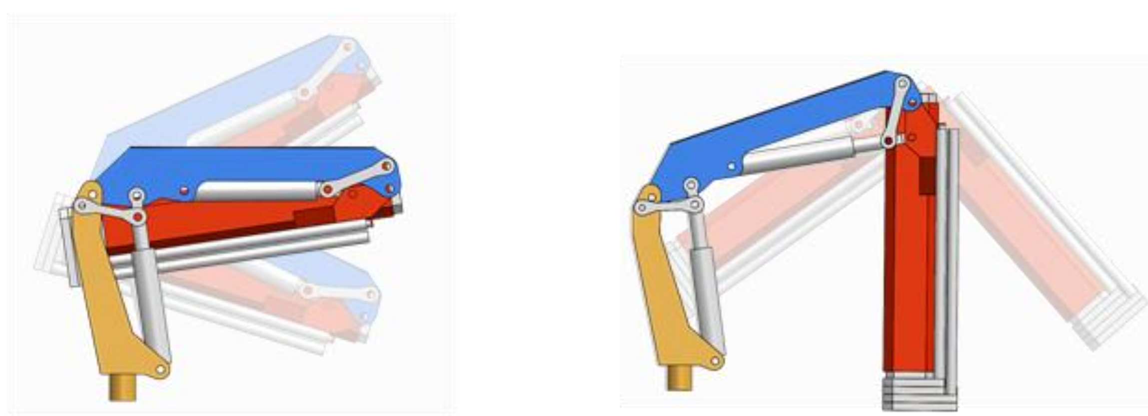



**Figure 44 – Proposed Methodologies**

<u>Main Results:</u>

<u>Control strategy achievements</u>: The first application on which this control scheme was used was a hydraulic crane. A first off-line version of the control algorithm was implemented and tested on the reference machine (for different operating conditions, as shown in Fig. 45). The controller was based on a proportional-derivative (PD) controller with gain scheduler based on the operator signal and on the pressure feedback. For the optimization, a simplified AMESim simulation model for the entire system was implemented.



a) ***Operating condition 1*** b) ***Operating condition 2***

**Figure 45 – Different operating conditions considered for the case of the hydraulic crane**

The controller parameters obtained by this simulation procedure were then tested on the actual experimental crane equipped with accelerometers on the end of its mechanical arm. The measurements reported in Figure 46 show a significant improvement in the machine dynamics (about 30% settling time and overshoot reduction). This is a remarkable result, considering that the crane was in a standard, energy-inefficient configuration. An even more significant result was obtained when the counterbalance valve (CBV) was put on a more energy-efficient setting, which had a higher tendency for oscillation.

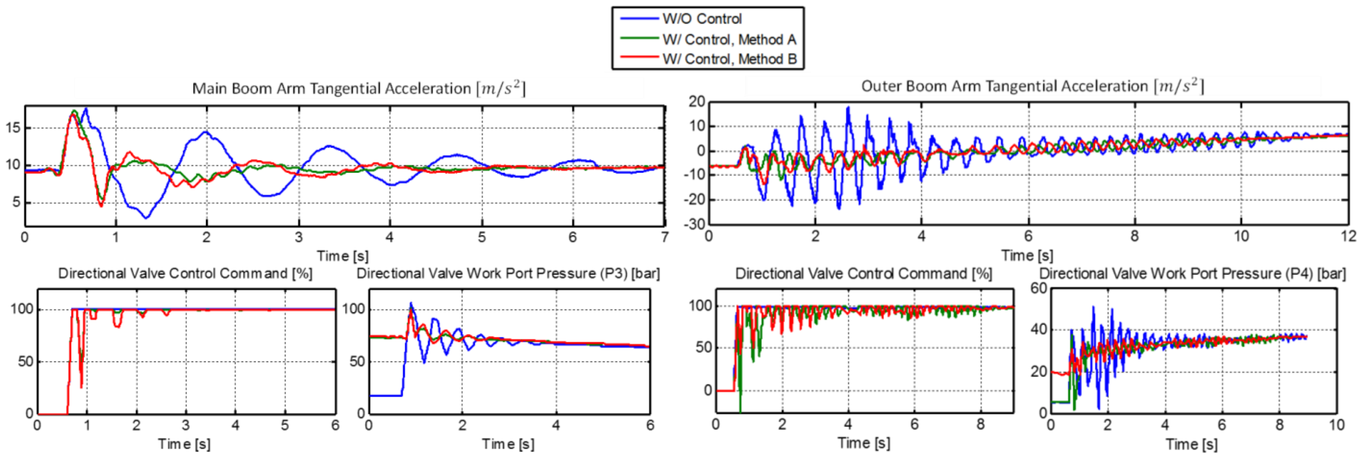



**Figure 46: Experimental results from reference crane**

<u>Energy consumption estimation:</u> In order to perform an estimation of the energy consumption and its possible improvement, a study was conducted on the reference machine by changing the settings of the CBV. Two typical operating cycles were considered for the study, in order to investigate the overall operation of the machine (lifting/lowering, with/without load). A detailed AMESim model, created to model the behavior of the valve, supported this activity. After extensive testing, it was found that the energy consumption on the crane was indeed significantly reduced by the inclusion of the control structure.

***Table 1: Impact of CBV settings on the global energy efficiency of the reference machine.***

| ***CBV SETTINGS*** | | ***CYCLE 1*** | | ***CYCLE 2*** | |
|---|---|---|---|---|---|
| *$p_s$ [bar]* | *α [-]* | *Energy consumption [kJ]* | *Biggest energy difference* | *Energy consumption [kJ]* | *Biggest energy difference* |
| 350 | 8 | 535.2 | 25.6% | 697.2 | 24.5% |
| 350 | 4 | 719.8 | - | 923 | - |
| 275 | 8 | 475 | 34% | 636.8 | 31% |
| 275 | 4 | 647.6 | 10% | 814.5 | 11.7% |

Payload oscillation damping

To design the payload oscillation damping controller, an AMESim model has been developed and validated in order to show the possible effectiveness of the controller. Then, the control strategy applied to the specific machine showed an oscillation reduction of 60% (Figure 46). The simulated load was 1 ton barrel, capable to transmit oscillations at the machine, which has been detected successfully from the controller. The proposed controller, due to a proper combination of filtering and FFT, is able to control the oscillations. These tests have shown indications that the control strategy is also capable of damping structure vibrations and payload oscillations in mobile hydraulic applications, with the addition of not expensive components.

## 1.12. Evaluation of the performance of Counterbalance Valves

Goals: An activity aimed at characterizing the functioning of Counterbalance valves (CBV) was performed by Dr. Vacca's team during 2015. CBVs are hydraulic control valves widely used in machines handling suspended gravitational loads and in load holding applications. CBVs have a double functionality: firstly, the permit the load holding when the system is not operated; secondly, they allow for an easy control of the load in overrunning (or load assistive) conditions. Usually tight tolerances and internal sealing features complicate CBVs realization, and inconsistencies can be found among valves of the same production lot. An extensive method to characterize CBVs with different tests designed to verify steady and unsteady features was performed on samples of CBVs with similar setting from different manufacturers.

Approach: Counterbalance valves (CBV's) are widely used in the fluid power field as safety component on actuators controlling gravitation or overrunning loads. They are three-port metering elements connected to the actuator ports that combine three typical valve functions in a single component, Fig. 47. The main stage acts as a pilot operated pressure relief valve for the return flow from the actuator port (port 1). The pilot pressure (at the pilot port 3) reduces the pressure at port 1 at which the relief valve opens. A check valve permits the flow to bypass the main stage, when flow is provided to the load. While Fig. 47a provides the ISO representation of the CBV.

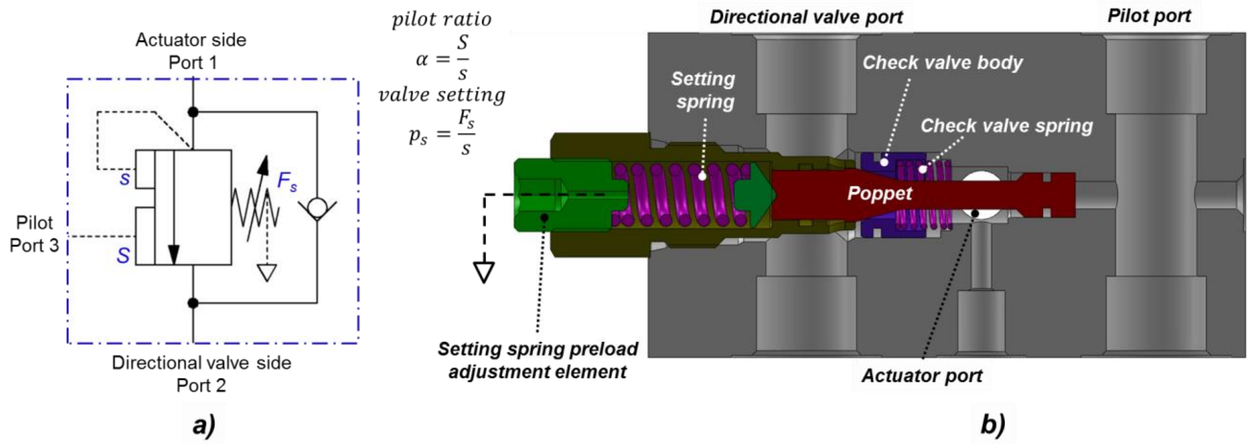



**Figure 47 - CBV symbol (a) and typical CBV cross section (b)**

The present study contributes in the field of experimental characterization of CBVs, considering the considerations made above about the necessity to test both steady-state and transient characteristics as well as verifying consistency from different samples. Two similar CBVs, but from different manufacturers were considered for the experimental study, and tests were performed on three samples for each valve type.

Figure 48 shows the example on an unsteady test performed with a cylinder without cushioning used to generate an abrupt pressure rise at the CBV workport. Figure 49 shows a simplified hydraulic schematic for this circuit.

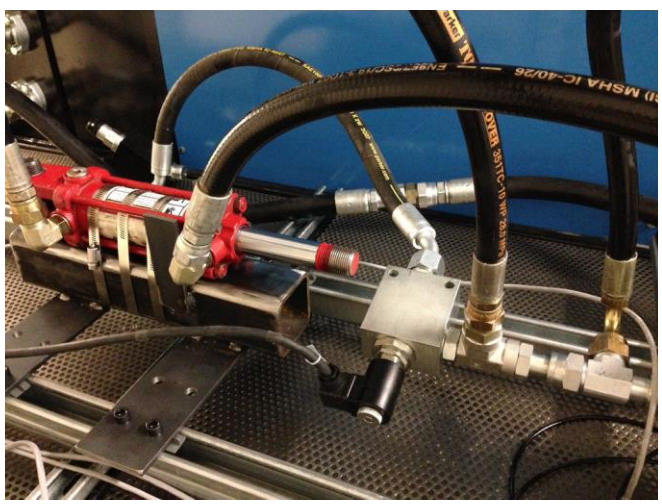


**Figure 48 - Experimental setup for testing the valve response time.**

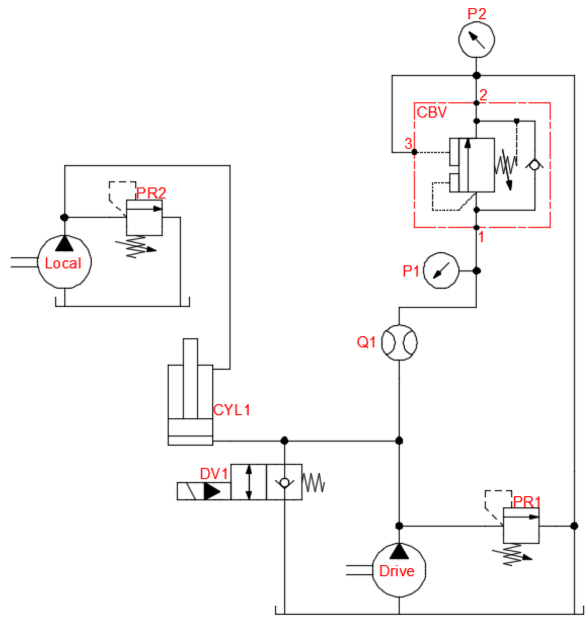



**Figure 49 – hydraulic schematic for the valve response time test.**

Eight different tests were performed to verify the steady state pressure drop curve, the hysteresis features, the response time, the CBV operation as relief; as check and under piloting conditions.

Results: Results were obtained considering valves with similar specifications but from two different manufacturers. To check the quality of the valve in terms of consistency and repeatability, the tests involved 3 samples for each valve. Figure 50 shows an example of measured valve response. Considerations about the equivalent transfer function of the valve were made. Moreover, a numerical model previously developed at Maha by Dr. Vacca's team was validated on the basis of the experimental campaign made on the two reference valves.

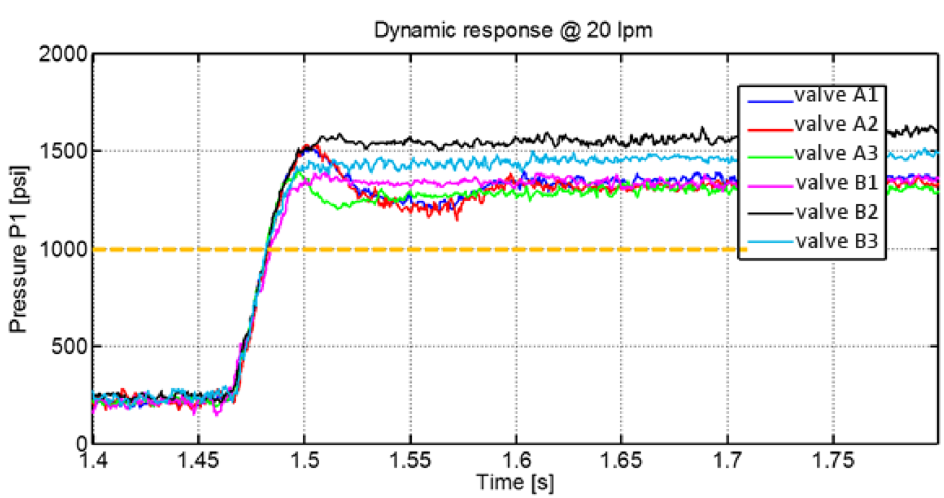


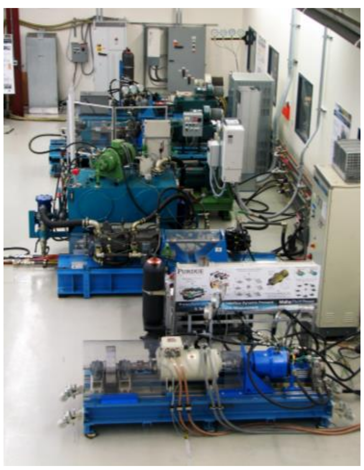

**Figure 50 – example of measured valve response.**

# 2 Research Facilities


Lab Space and Test Rigs at Maha

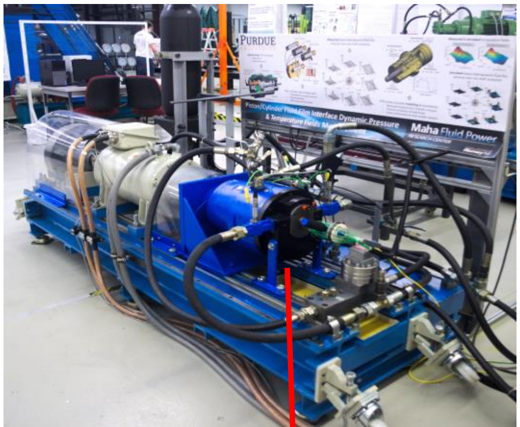
The lab currently houses ten test rigs designed to support our research.

Test beds for technological demonstration (Left)



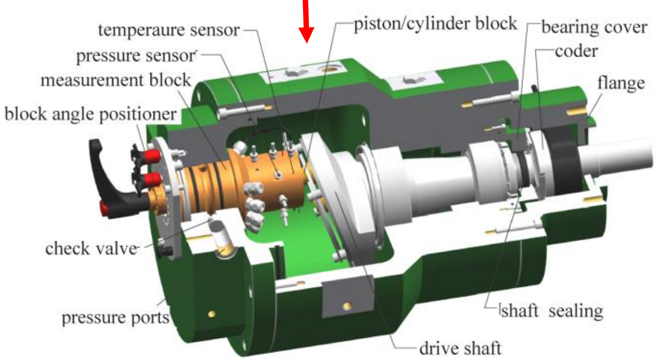

Test rigs and car lift (Above)

and new lab space (Left)

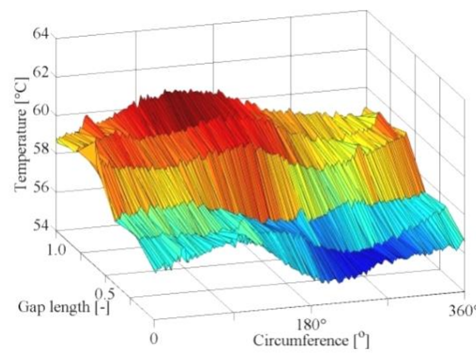


## EHD Test Rig

The EHD test rig is designed to measure the dynamic pressure field in the gap between piston and cylinder and the surface temperature distribution in the cylinder of a swash plate axial piston pump. A special test pump with a single piston cylinder assembly has been designed for this test rig.



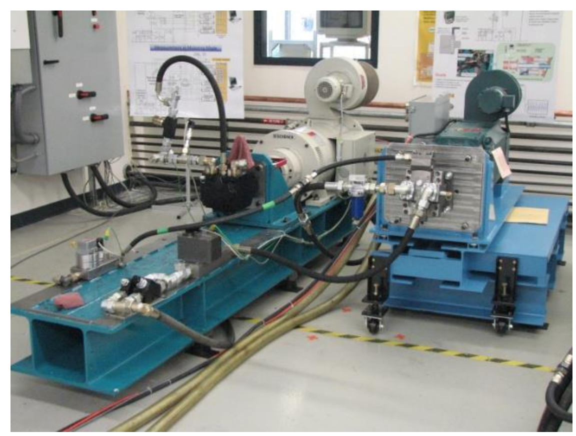

EHD Pump



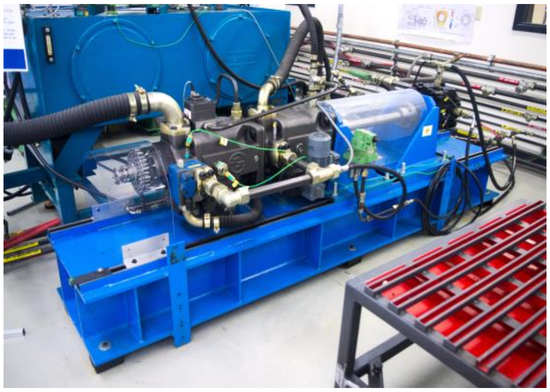

Measured Temperature Field in the Piston/Cylinder Gap

## Test Rigs for Steady State Measurements

Two electric motor driven test rigs have been designed to measure steady state and dynamic characteristics for different pump and motor types including 1 rpm tests. The test rigs are equipped with temperature and pressure sensors as well as speed, flow and torque meters.

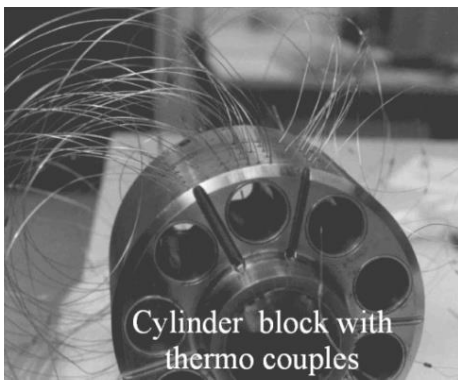


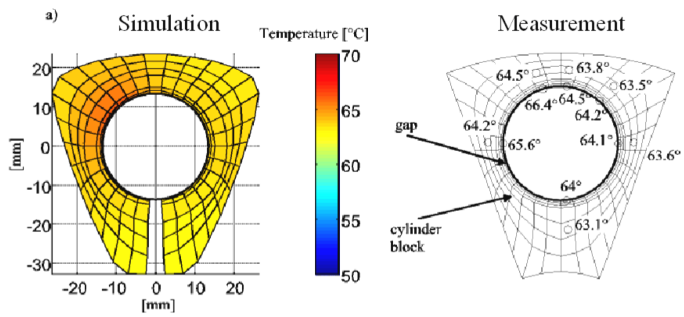
*Performance Characteristics*
Max. installed electric power: 2 x 120 kW
Max. speed: n1 = 7000 rpm/n2 = 3000 rpm
Max. pressure: 450 bar
Max. torque: M1 = 300 Nm/ M2 = 500 Nm



## OLEMS Test Rig

This rig is designed to investigate the temperature behavior in swash plate axial piston pumps. Sixty thermocouples are mounted around a single cylinder to measure the temperature field during operation of the pump. Telemetry is used for data transfer from the rotating cylinder block to the data acquisition board. The measured results are used for the development of a more precise method to calculate the non-isothermal gap flow between piston and cylinder in swash plate type axial piston machines.



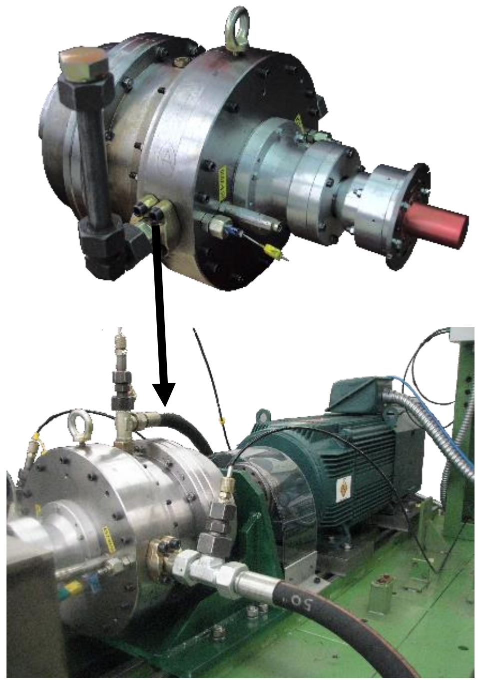



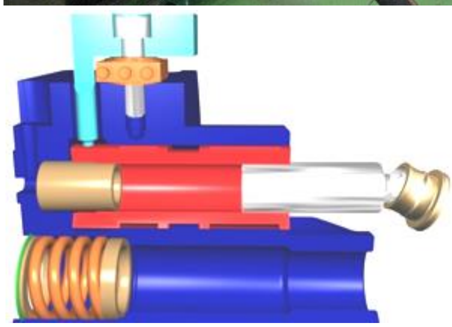

Temperature distribution in the assembly near the slipper slide

## Test Rig to Study Active Vibration Damping of the Swash Plate

A 75cc pump is modified to implement active vibration control using the swash plate. One tri-axial acceleration sensor and one angle sensor is installed on the swash plate and a high speed servovalve is attached on the back of the pump case. The higher harmonic least mean square algorithm gives signal to the servovalve to generate destructive interference force for the swash plate moment. An experimetal test is conducted using Labview FPGA interface via cRIO to investigate the performance of active vibration control.

## Tribo Test Rig





The Tribo pump (left top and middle), is designed to measure the dynamic axial and circumferential friction forces between the piston and cylinder. Data is transmitted wirelessly from the rotating kit to a data acquisition via a telemetry system. The Tribo pump can be operated in either pumping or motoring mode at speeds up to 1800 rpm. Measurements can be taken during steady state conditions at different oil viscosities.

The experimental bushing and piston pair in the Tribo test rig can be readily replaced (left bottom). This provides the capability to examine the impact of novel materials and surface micro-geometry on the behavior of this important lubricating interface.

The past year has been an exciting one for the Tribo Test Rig. The force sensor and data acquisition system were recalibrated using an impact hammer, improving the accuracy of test results. With this recalibration completed the test rig was used to make measurements at several pumping conditions. These measurements and those to come will continue to be helpful guides as we further refine our piston-cylinder models.

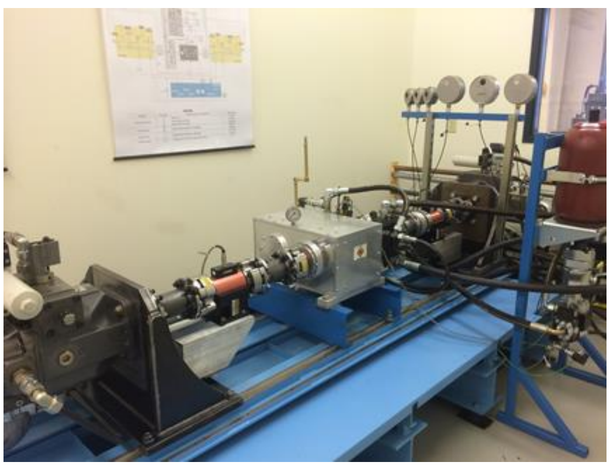
**Light Duty Powertrain Hardware-in-the-Loop Transmission Dynamometer**

One of two HIL transmission dynamometers located at the Maha lab, this test rig is used to investigate powertrain architectures and controls for light duty vehicles. Two electric motor/generators are used to accurately mimic the engine and vehicle dynamics of a simulated vehicle. In this manner the transmission on the test rig can be run through dynamic driving cycles just as if it were in a real vehicle. In its current configuration, the transmission can be easily switched between a series hybrid and the novel blended hybrid architecture.

*Performance Characteristics*

Engine simulator: 300 Nm @ 4000 rpm

Load simulator: 500 Nm @ 3600 rpm



*Performance Characteristics*

Engine simulator: 900 Nm @ 1800 rpm

Load simulator: 900 Nm @ 1800 rpm

**Heavy Duty Powertrain Hardware-in-the-Loop Transmission Dynamometer**

This second HIL transmission dynamometer is used to evaluate heavy duty powertrain architectures and controls. Two secondary controlled hydraulic units function as engine and load simulators enabling the dynamic evaluation of transmissions sized for vehicles up to a class 6 truck. Currently a much smaller hydraulic hybrid power split transmission, intended for use in a Toyota Prius, is installed on the test rig. Current work is ongoing to update the control and data acquisition for more advanced control development.

## JIRA Test Rig

The joint integrated rotary actuator test rig (JIRA) was originally built for the experimental investigation of displacement controlled rotary actuators. The ideas and technologies developed for and implemented in this test rig have been utilized as end effector drives in mobile robots and large manipulators as well as for applications such as stabilizers in cars or ships.

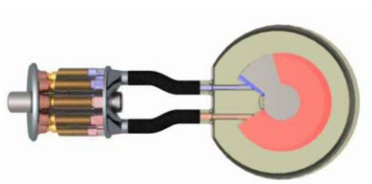
Recent improvements on the test rig have allowed for the demonstration of pump switching for the sequential operation of multiple actuators. New control concepts focused on actuator operability have been developed and demonstrated that DC actuation can be utilized for precise motion actuation. Finally, research is in progress to investigate the application of high-frequency DC actuation to be utilized on railway vibrators.

*Performance Characteristics*

Max. Torque: 30000 Nm

Max. Pressure: 350 bar

Max. Power: 30 kW



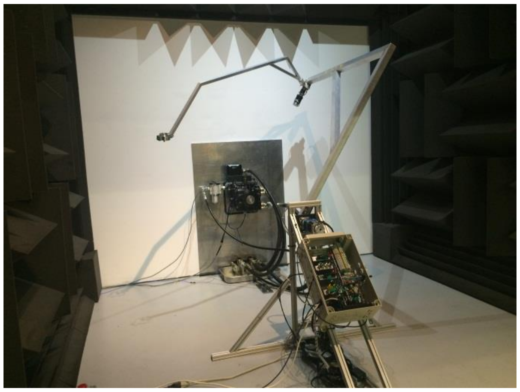
*Rotary Actuator*

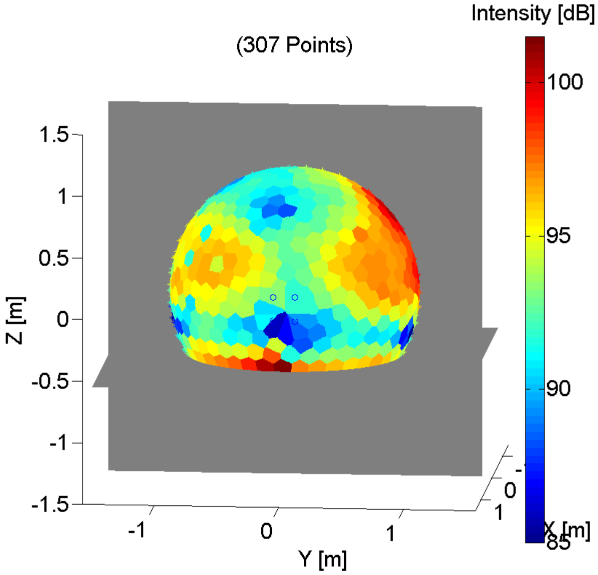
## Cavitation/PIV test rig

This test rig was designed to visualize and conduct Particle Image Velocimetry (PIV) analysis of cavitation in hydraulic oil. This test rig was designed in support of CCEFP project 3C and will support the computational studies in modeling cavitation in hydraulic components.

## Semi-Anechoic Chamber

The semi-anechoic chamber was designed and built with the objectives of (1) fulfilling requirements specified by ISO 16902-1 (2003) for measuring sound intensity, thus, deriving sound power of a pump/motor and (2) creating an environment capable of performing sound power measurements of various hydraulic circuits including complete transmissions. A major improvement to the chamber in 2015 was the addition of a robot able to automate the sound intensity and sound power measurements.






## Multi-functional test rig for hydraulic components

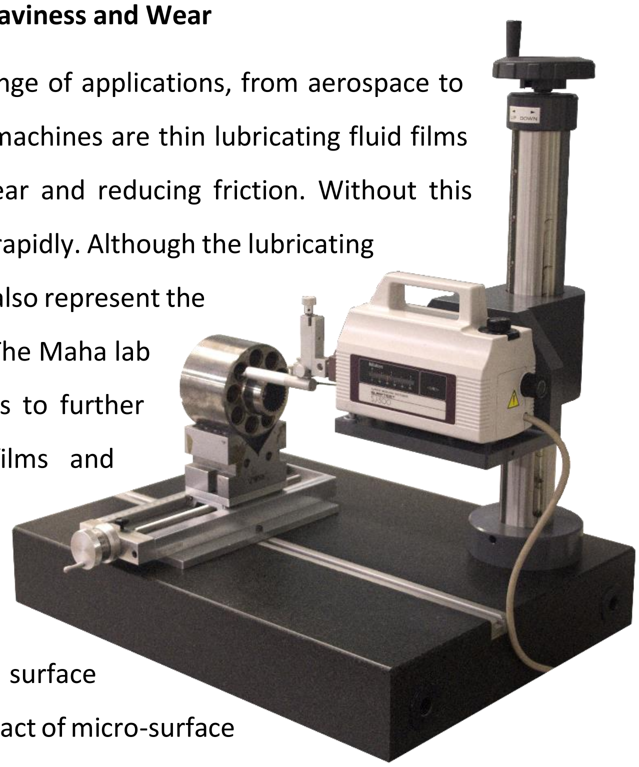
A stand-alone test rig for the steady state and transient characterization of hydraulic components was recently developed at Maha. The test rig has local hydraulic power supply (installed power 240 kW) with high potentials for controlling input flow rate. The test station is specifically developed to test pumps and motors up to 100 kW. With a local temperature control on a relatively small tank (about 400 L), the test rig allows for an accurate test under controlled temperature. Also, the test rig has high flexibility as concerns working fluid (easy replaceable) and test set up (a proper work area, with recirculation of leakages allows to rapidly set up the circuit of test).

## Hydraulic Power Supply

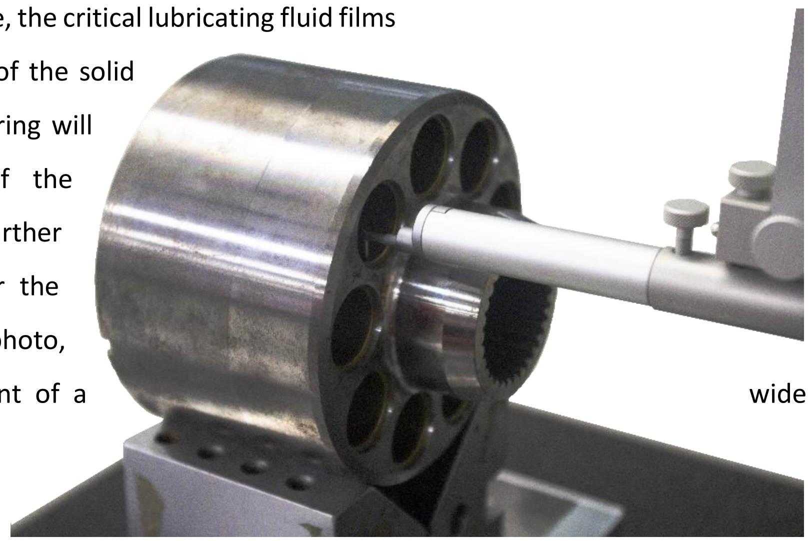
The above test rigs are powered by a 320 kW central hydraulic power supply unit with a 2000 liter tank, a water cooler and heating elements with five individually controlled pressure compensated pumps, 350 bar and 450 lpm output flow and a 60 l/min low pressure installed in 2005. A second medium pressure 63 kW hydraulic power supply, with a maximum flow rate of 250 l/min and pressure differential of 60 bar, has also been added. This supply is equipped with a 300 liter tank. The central pressure net is mainly used to supply hydraulic load units for the individual test rigs, where the load units are based on secondary control. The total installed electric power amounts to 1200 kW.

**Surface Profilometer for Investigating Micro-surface Waviness and Wear**

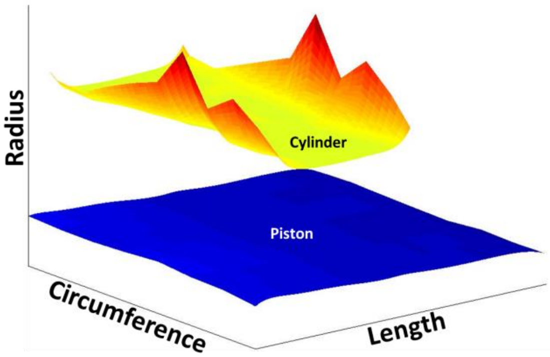
Axial piston pumps and motors are found in a wide range of applications, from aerospace to construction. Key to the successful operation of these machines are thin lubricating fluid films which separate the moving solid parts, preventing wear and reducing friction. Without this proper lubrication, hydraulic pumps and motors will fail rapidly. Although the lubricating films are necessary to prevent catastrophic failure, they also represent the largest source of power loss inside the hydraulic units. The Maha lab has been developing state-of-the-art numerical models to further understand the physics enabling the lubrication films and proposing new design methods to reduce the power loss coming from these fluid gaps.



The Maha lab in 2011 acquired a Mitutoyo stylus surface profilometer to allow for further investigation on the impact of micro-surface shaping and wear inside hydraulic pumps and motors. The profilometer is able to measure the change in height of a specimen with excellent resolution (~0.01 μm) as the stylus slowly traverses in a straight line along the surface. As mentioned above, the critical lubricating fluid films are only microns thick; small deviations of the solid bodies either due to wear or manufacturing will significantly alter the development of the lubrication films. 2012 saw the further acquisition of a measurement stand for the profilometer which can be seen in the photo, allowing for the repeatable measurement of a wide array of part surfaces.

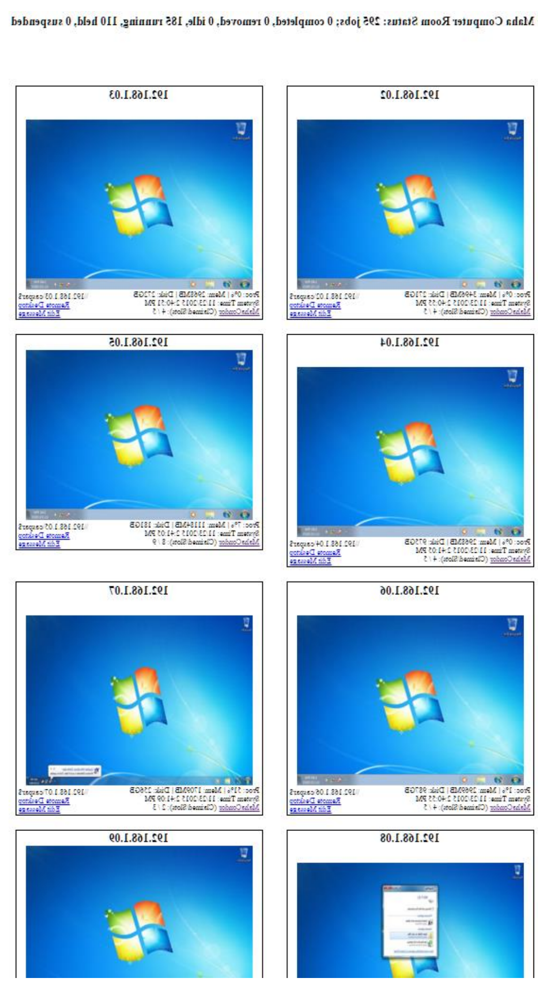


Over the past year the profilometer system has continued to be very useful in determining accurate inputs for our numerical pump modeling efforts. Many lubricating surfaces such as the piston and cylinder shown to the




left have been measured so that the effects of their unique wear profile or manufacturing-based curvature can be investigated. Additionally, several prototype valve plates designed at the Maha lab were measured. Of particular interest was the exact geometry of the relief grooves machined into the valve plate surface. By tracing these grooves with the profilometer stylus we can determine the time-changing area of the connection between the displacement chamber and port. This in turn allows a higher fidelity simulation of displacement chamber pressure throughout a pumping cycle. By ensuring good quality inputs to our models we can use comparison with measurements to validate or further refine our simulations. As we look forward to the next year, the profilometer measurement system is sure to see continued use.

**Maha Computing Cluster**



The focus of many research areas at the Maha lab is shifting from model development to applications in virtual prototyping and design studies. The computational demand has increased accordingly, totaling over 60 years of simulation in the last calendar year. Initially implemented in 2010, the Maha computing cluster now includes 31 computers and 274 computational cores linked with a private 1 Gbps Ethernet network. Most of the computational machines are desktop computers featuring Intel i7 processors and at least 12 GB of RAM running a 64 bit edition of Windows 7. In 2012 a Dell PowerEdge R815 server with Quad AMD Opteron processors and 128 GB ram was installed into the computing cluster. This server allows for large shared-memory parallel simulations to be run on a single machine. When there are no large parallel jobs, the server is automatically allocated to several smaller jobs.

All job scheduling and resource allocation is handled automatically by the HTCondor (http://research.cs.wisc.edu/htcondor/) software suite running on a Debian Linux job scheduling server. Users log in to the job scheduling server to submit simulations to the cluster. Once submitted, a job is assigned to a computer that has enough available processor cores and memory to accommodate the job's requirements. A single computer may simultaneously run multiple jobs. Once a job is complete, it's output and log files are returned to the job scheduling server where the user can retrieve them.

Certain jobs require user interaction during the course of the simulation. To accommodate these jobs, a user may submit an interactive use reservation job through the HTCondor scheduler. Once a computer has been allocated to the interactive use job, the user may establish a Remote Desktop connection with the computer. The user can then transfer files directly and run any Windows compatible program.

## Test Vehicles and Machines

In addition to the stationary test rigs, the Maha Fluid Power Research Center also houses several vehicles that either have been used or are being used currently as platforms for demonstrating and/or investigating new fluid power systems concepts.

### Hydraulic Hybrid Demonstration Vehicle

A new addition for the Maha lab in 2015, this hydraulic hybrid demonstration vehicle enables real world testing of hybrid architectures and control strategies. Especially valuable is the ability to explore drivability and driver perception, a topic difficult to investigate through either simulation or HIL testing. Currently the demonstration vehicle can be operated as either a conventional series hybrid, or the novel blended hybrid, depending on a researcher's needs.

*Performance Characteristics*

Engine: 142 kW gasoline

Unit 1: 100 cc/rev     Units 2,3: 75 cc/rev

High pressure accumulator: 32 l

Maximum system pressure: 450 bar

## Wheel Loaders

Displacement control, the concept of controlling hydraulic actuators with variable displacement pumps instead of throttling valves, was first tested and demonstrated on the boom and bucket functions of this 25-ton front wheel loader.



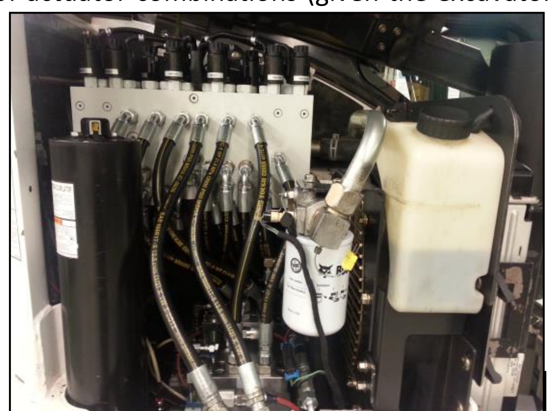
The smaller 5-ton wheel loader originally served as a platform for diagnostics and prognostics on hydraulic systems. In 2013, it was overhauled to implement a displacement controlled (DC) steer-by-wire (SbW) system. The loader served as a prototype test vehicle for investigating and validating adaptive steering control algorithms, virtual yaw rate sensing, yaw stability control via active steering, and for measuring the fuel savings offered by the new DC SbW technology.


The Case 721F is a 14-ton wheel loader which was provided to Maha by CNH Industrial in May 2015. It is being used for research into valve-controlled hydraulic systems with such objectives as better control and behavior, lower oscillations, and higher efficiency.

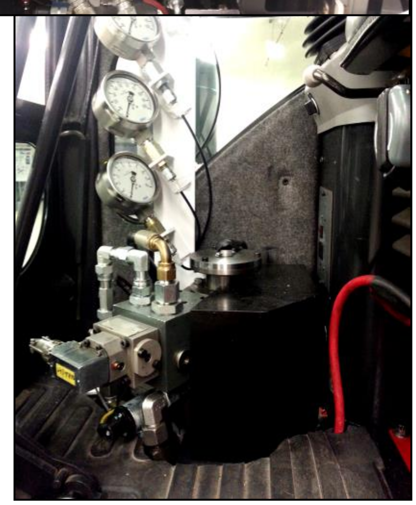
**Highly Efficient DC Hydraulic Hybrid Excavator Prototype**

In 2015, efforts toward the advancement of the fluid power technologies in the hydraulic hybrid excavator focused on the development of supervisory-level algorithms. Two main objectives were posed: 1) managing the newly implemented hydraulics with pump switching and 2) managing the hybrid architecture energy flows.

Pump switching is a novel idea that employs on/off valves (referred to a switching valves) to minimize the installed pump power in displacement-controlled (DC) multi-actuator machines. This task is achieved through the sequential use of actuators, which retains the inherent savings of DC actuation and maximizes operability and performance. To manage DC actuation with pump switching, a supervisory controller that makes use of operator commands and the total number of actuator combinations (given the excavator architecture) was developed. A search algorithm is employed to index a combination matrix containing the commanded actuators and transmit these to the corresponding switching valves and hydraulic units. Ultimately, the combination of pump switching actuator and supervisory-level control algorithms has led to more efficient, reliable and better performing multi-actuator systems with greatly improved operability.



Hydraulic hybrid architectures have increasingly gained recognition as a highly efficient form of power transmission. For the excavator prototype, the swing drive was equipped with a high pressure accumulator and a swash-plate type over-center pump/motor connected to the excavator ring gear. With the demonstration of conventional drive operability, the task for 2015 was to efficiently manage the power flows to demonstrate the possibility of engine downsizing, thereby demonstrating further energy and fuel savings. This task was accomplished and measurements on the excavator prototype showed that the engine could be reduced by up to 45%. The algorithm, an energy-based feed-forward instantaneous optimization, takes



into account the amount of energy demanded by the DC actuators, the amount of energy provided by the prime mover and the amount of energy stored, recovered or demanded by the hydraulic hybrid swing drive, to minimize engine speed, maximize the hydraulic units' displacements and efficiently utilize the energy from the high pressure accumulator.


**Skid-Steer Loader**

Pump-controlled technology has been demonstrated on compact machinery at the Maha Fluid Power Research Center. For the purpose of demonstrating different controls for the next generation of skid steer loaders through displacement control, a Bobcat skid-steer loader was modified. To improve the ride comfort and machine performance, advanced control strategies are currently being researched to improve our already existent active vibration damping algorithms. Along with vibration damping, a robust path planning algorithm for forklift function is being designed which will ensure that the bucket remains in horizontal position at every boom position so that it does not spill its contents. In addition to this, control algorithms are also being developed to achieve smooth speed shift between the two displacement modes of the drive motors. The skid-steer loader has been equipped with new electronics to add data acquisition and control capabilities.

**Hydraulic Crane**

Maha is also equipped with a mid-size hydraulic crane (max extension: about 20m), currently used to test new control strategies and new system configurations for valve-controlled hydraulic systems. Novel oscillation damping techniques are tested on this apparatus, installed outdoor the Lab building.

# 3 Research Grants

## Total annual budget in 2014: $ 924,049

Federal sponsors:

Engineering Research Center – Center for Compact and Efficient Fluid Power.

Project 1F.1 (Variable Displacement Gear Machines): $109,504

USDA – AFRI (Agriculture and Food Research Initiative Competitive Grants Program) - New generation of green, high efficient agricultural machines powered by high-pressure water hydraulic technology: $125,000

NSF – Accelerating Innovation Research

Project title: Novel Concept for Variable Delivery Flow Units for Fluid Power Applications $ 101,000

Purdue Maha Research funds: $45,000

Industry Sponsors: total $ 537,520

Other Sponsors:

Chainless Challenge (Parker Hannifin): $ 6,025

# 4 Publications, Invited Lectures, Patents, and Reports

## Journal Articles

Pan J., Cheng Y., Vacca A., Yang J., 2015, Effect of Temperature on Grease Flow Properties in Pipes, Tribology Transactions, DOI: 10.1080/10402004.2015.1093205

Opperwall, T., Vacca, A., 2015, Modeling Noise Sources and Propagation in Displacement Machines and Hydraulic Lines, JFPS International Journal of Fluid Power System, Vol. 8 (2015) No. 1, pp. 30-37, selected for journal publication from the 9th JFPS International Symposium on Fluid Power, Oct. 28-31, 2014, Matsue, Japan

Altare, G., Vacca, A., 2015, A Design Solution for Efficient and Compact Electro-Hydraulic Actuators, Procedia Engineering 106 ( 2015 ), 8 – 16

Cristofori D., Vacca A., 2015, Modeling Hydraulic Actuator Mechanical Dynamics from Pressure Measured at Control Valve Ports, Journal of Systems and Control Engineering, July 2015, vol 229 n. 6.

Tang Q. , Chen J., Vacca A., 2015, Tribological Behaviors of Carbon Fiber Reinforced PEEK Sliding on Ion Nitrided 2Cr13 Steel Lubricated with Tap Water, Tribology Transactions, Vol. 58, Issue 4, 2015

Thiagarajan D., Dhar S., Vacca A., 2015, A Novel Fluid Structure Interaction-EHD Model and Optimization Procedure for an Asymmetrical Axially Balanced External Gear Machine, Tribology Transactions, vol. 58, issue 2, 2015

Dhar S., Vacca A., 2015, A Novel FSI-Thermal Coupled TEHD Model and Experimental Validation through Indirect Film Thickness Measurements for the Lubricating Interface in External Gear Machines, Tribology International, vol. 82 Part A, February 2015, pp. 162-175

Journal papers under review (at Dec. 2015): 4.

## Conference Proceedings

Pellegri M., Vacca A., 2015, A CFD-Radial Motion Coupled Model for the Evaluation of the Features of Journal Bearings in External Gear Machines, ASME/Bath 2015 Symposium on Fluid Power and Motion Control, Oct 12-14, 2015, Chicago, IL, USA

Bianchi R., Ritelli G.F., Vacca A., Ruggeri M., 2015, A Frequency-Based Methodology for the Reduction of Payload Oscillations in Hydraulic Load Handling Machines, ASME/Bath 2015 Symposium on Fluid Power and Motion Control, Oct 12-14, 2015, Chicago, IL, USA

Opperwall T., Vacca A., 2015, A Transfer Path Approach for Experimentally Determining the Noise Impact of Hydraulic Components, SAE 2015 Commercial Vehicle Engineering Congress (COMVEC), Oct 6-8 2015, Rosemont, IL, USA. SAE paper 2015-01-2854

Devendran R.S., Vacca, A., 2015, A Novel Concept for a Variable Delivery External Gear Machine, SICFP2015 14th Scandinavian International Conference on Fluid Power, May 20-22, 2015, Tampere, Finland

## Invited Talks/Lectures

Invited talk – Dr. Vacca - “Modeling and Optimization of Positive Displacement Pumps for High Pressure Fluid Power Applications”, ModeFrontier North America Users Meeting, 5$^{th}$ Nov 2015, Novi, MI

Invited seminar - Dr. Vacca - on “Understanding the key of positive displacement machines: the internal lubricating gaps”, Dipartimento di Ingegneria Industriale, University of Napoli “Federico II” March 19, 2015

Invited lectures – Dr. Vacca - (4 hrs) on “Pumps and Motors for Fluid Power Applications” to mechanical engineering student (master level), University of Napoli “Federico II”, March 23-25, 2015

## Patents Filed

Vacca, A. and Devendran, R.S., Purdue Research Foundation. 2015. Variable Displacement External Gear Machine. 2014-VACC-66716

# 5 Theses Completed In 2015

## PhD Theses

**Ram Sudarsan Devendran** 2015. An Innovative Working Concept for Variable Delivery Flow External Gear Machine. PhD thesis, Purdue University.

**Timothy Opperwall** 2015. Numerical Modeling and Experimental Investigation of Noise Generation in External Gear Pumps. PhD thesis, Purdue University.

## Master's Theses

**Sidhant Gulati** 2015. A Generic Design Procedure to Determine the Optimal Profile of Porting Grooves in External Gear Machines. Master's thesis, Purdue University.

# 6 Educational Activities

## 6.1 Courses Taught at Purdue

Andrea Vacca is instructor of following courses at Purdue:

- ABE 210 – Thermodynamic Principles of Engineering and Biological Systems
- ME 309 – Fluid Mechanics
- ME 435 – Hydraulic Control Systems

### ABE 210 – Thermodynamic Principles of Engineering and Biological Systems

**Brief Course Description:**
1 Semester, 2 Lectures/week, 3 Credits

The objective of this course is to provide students background on the application of thermodynamic principles in the design and operation of biological and engineering systems. Specifically the course will focus on the first and second laws of thermodynamics and on the applications of these laws to biological and mechanical/agricultural engineering systems.

Specific systems include power cycles, refrigeration cycles, and energy conservation systems.

Emphasis will be placed on developing a mastery of the basic concepts and problem solving skills.

The successful completion of the course will enable the student to:

1. understand basic principles of material, energy, and entropy balances;
2. understand applications of energy and entropy balances to power, refrigeration, and biological systems;
3. apply basic thermodynamic concepts/functions to the design of systems.

**Textbook:** *Thermodynamics: an engineering approach* ($7^{th}$ ed.) by Y.A. Cengel and M.A. Boles. McGraw-Hill (2010).

**Course notes:** All lecture notes are available through Purdue Blackboard Learn

**Lab:** Four lab experiences on $1^{st}$ and $2^{nd}$ Laws of Thermodynamics as well as on power cycles were developed by Dr. Vacca

**Exams/Final project:** two midterm exams and a final exam

## ME 309 – Fluid Mechanics

**Brief Course Description:**

1 Semester, 3 Lectures/week, 4 Credits

Course objectives:

1. Develop the ability to identify and classify the various types of flows one may encounter.
2. Develop (from first principles) the control volume formulation of the basic laws with emphasis on conservation of mass and Newton's 2nd law.
3. Apply the control volume formulation of the basic laws to model physical systems.
4. Conduct simple experiments and analyze data.
5. Enhance systematic problem solving skills and sharpen written communication skills through short technical laboratory reports.

**Textbook:** *Pritchard, P.J, Fox and McDonald's Introduction to Fluid Mechanics, 8th ed., Wiley & Sons*

**Course notes:** All lecture notes are available through Purdue Blackboard Learn

**Lab:** Eight labs on basic equations of fluid mechanics

**Exams/Final project:** two midterm exams and a final exam

## ABE 435 – Hydraulic Control Systems

**Brief Course Description:**

1 Semester, 2 Lectures/week, 4 Credits

**Course Objectives**

This class provides the student with the basics of fluid power technology. After introducing the standard of representation of hydraulic systems and components, in the first part of the class the operation of basic components such as pumps, motors, cylinders, hydraulic control valves, filters and accumulators will be detailed.

The second part of the class provides the basics for analyzing and designing completer hydraulic control systems for both the case of single and multiple user. A particular emphasis will be given to the challenges of meeting functional requirements minimizing both cost and fuel consumption. Starting from basilar circuits, the lectures and labs will cover current state of art systems for mobile applications.

The course is divided into class lectures and labs. During the lab experiences, the students will learn how to assemble and troubleshoot hydraulic circuits and how to simulate the operation of a hydraulic system. The numerical modeling of hydraulic systems will be performed with the commercial software AMESim.

After completion of the course, the student will be capable of:

1. Understanding and design hydraulic systems according to ISO standard
2. Understand the principle of operation of basic hydraulic components such as pumps, motors, hydraulic control valves, pipes, linear actuators (cylinders)
3. Design basic hydraulic control circuits with the components specified above.
4. Analyze the operation of a hydraulic circuit through both analytical and numerical approaches.
5. Test the functioning of hydraulic components and systems.
6. Troubleshoot hydraulic mobile equipment malfunctions.
7. Understand and design the hydraulic systems of mobile machinery, including hydrostatic transmissions, load sensing and power steering systems.

**Textbook:** *N/A*

**Course notes:** All lecture notes are available through Purdue Blackboard Learn

**Lab:** Ten labs on numerical simulation (AMESim) and on basic hydraulic control systems

**Exams/Final project:** two midterm exams and a final project on a complete hydraulic system

## 6.2 CCEFP REU Bootcamp

As faculty member of the CCEFP (Center for Compact and Efficient Fluid Power), Andrea Vacca volunteered for organizing the 2015 edition of the CCEFP Bootocamp at the Maha Fluid Power Research Center, an outreach activity of CCEFP. The 2015 CCEFP Fluid Power REU Bootcamp, was held at Purdue University on May 26-29, 2015. The NSF's Research Experiences for Undergraduates (REU) program is designed to encourage STEM students to continue their learning in graduate school settings by providing opportunities for summer experience in a university research lab. The CCEFP is actively involved in this program and hosted nearly 20 REU students from its 7 member universities (Georgia Tech, University of Illinois in Urbana-Champaign, University of Minnesota, Milwaukee School of Engineering, North Carolina A&T State University, Purdue University, and Vanderbilt University) in a boot camp style introduction to fluid power topics.

This year's boot camp was a two day introduction to the principles of fluid power technology through various lectures, hands-on activities, and tours of some of Purdue University's research laboratories. The students were welcomed by Prof. Monika Ivantysynova followed by an introduction lecture on fluid power by Prof. Andrea Vacca. The students then attended the following lectures / demonstrations:

- "Water Hydraulic Test Rig" prepared by Guido Francesco Ritelli
- "Hydraulic Circuit Construction and Debugging" prepared by Tim Opperwall
- "Pump Displacement Controlled Actuation Technology" prepared by Enrique Busquets
- "Hydraulic Pumps and Motors" prepared by Ashley Wondergem and Lizhi Shang

The boot camp was also a great networking opportunity for the participants to meet other students and faculty members in the Center.

**Pictures from the 2015 Fluid Power Bootcamp**

## More About CCEFP

The Center for Compact and Efficient Fluid Power (CCEFP) is a network of researchers, educators, students and industry working together to transform the fluid power industry—how it is researched, applied and studied. Center research is creating hydraulic and pneumatic technology that is compact, efficient, and effective. The CCEFP's education and outreach program is designed to transfer this knowledge to diverse audiences—students of all ages, users of fluid power and the general public.

The CCEFP is a National Science Foundation Engineering Research Center, established in June 2006. In addition to its grant from NSF, the Center is supported by its seven participating universities and more than 50 industrial partners.

Purdue University is one of the seven universities represented in the CCEFP. The other participating universities are the Georgia Institute of Technology, the University of Illinois at Urbana-Champaign, the University of Minnesota, Milwaukee School of Engineering, North Carolina A&T State University, and Vanderbilt University. More information about the activities of CCEFP are online (www.ccefp.org)

Dr. Andrea Vacca lead the two projects: Project 1F.1: Variable Displacement External Gear Machine; and Project 3B.3 Oscillation Damping in Hydraulic Machines.

## 6.3 Chainless Challenge

This project is aimed to formulate a viable and economically feasible solution for the next generation of human powered green energy vehicles. In particular, the study explores technologies for hydrostatic transmissions which can be used in place of the typical chain system used for power transmission in common bicycles. Although its lower energy transmission efficiency, compared to the pure mechanical chain, the use of a hydraulic system offers opportunities for energy management for more comfortable pedaling as well as for energy recovery in passive phases, such as braking.

Within this project, every year a team of Purdue students supervised by Dr. Vacca design and realize an hydraulic vehicle to compete to the Parker Chainless Challenge. Several US universities (Univ. of Minnesota, Univ. of Illinois at Urbana Champaign, California Polytechnic State Univ., Western Michigan Univ, etc.) take part to this event, presenting every year innovative solutions in accordance to the rules of the competition, established by the main Sponsor (Parker Hannifin).

The final competition, usually held in California during April, is based on different challenges between participants which include a sprint test of 400 m, an efficiency test (performance of the vehicle without human power input), a time trial test (12 miles). The winning team is also determined by other parameters, such as quality of the report and presentation, final design, manufacturability.

Monetary support for the project as well for the trip to the final event is provided by the main sponsor of the competition, but also by other companies identified by the team members. The budget level for the project usually ranges between $8000-$12000.

After participating to the competition in 2012, 2013, 2014, a Purdue team lead by Dr. Vacca competed also in the 2015 event with the HydraTryke.

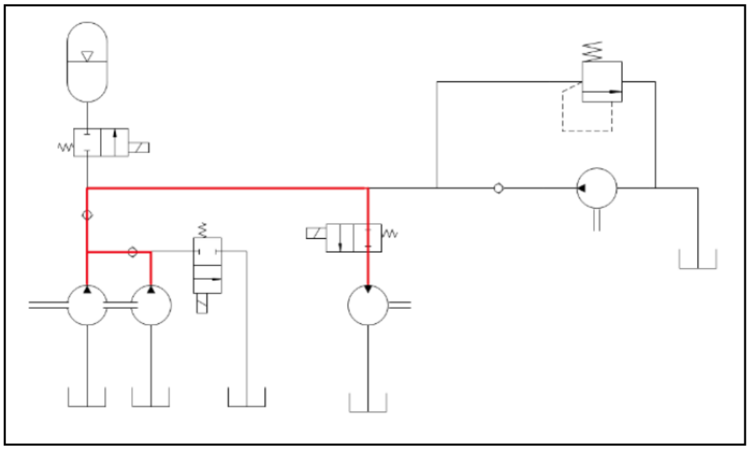
**The Purdue HydraTryke for the 2015 Chainless Challenge**

The HydraTryke is a recumbent bike with following features implemented in it:

- Open circuit series hydrostatic transmission based on gear pumps and gear motors
- Hybrid transmission which permit to charge an accumulator while braking or directly by pedaling
- Electronic control for the modes of operation (pedaling, accumulator charging, accumulator boost, regeneration)
- Monitor display that visualize operating conditions and efficiency values

- Integration with a heart-bit rate sensor to monitor driver's status

The hydraulic circuit of the bike is schematized below.



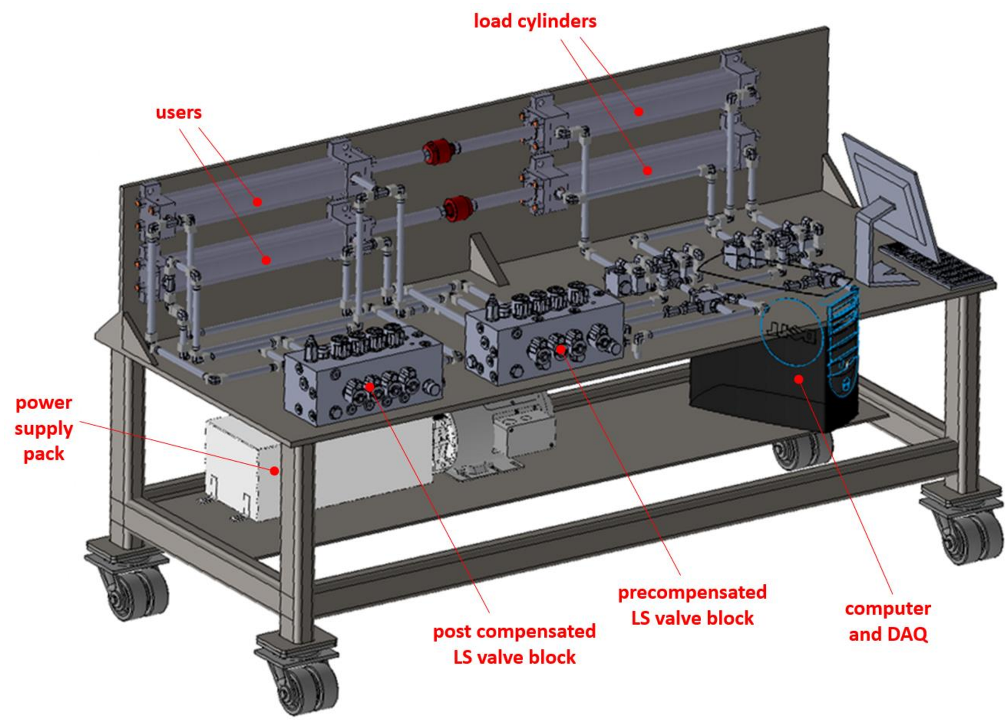
**The hydraulic circuit of the Purdue HydraTryke**

At the final event (April 2015 at Irvine, CA), the bike experienced a failure of the hydraulic motor. Despite this inconvenience, the team received the 1st award for Uniqueness of Design/Originality and the 2nd award for Manufacturability/Workmanship.

## 6.4 Test stands for education in Fluid Power

Dr. Vacca's commitment into education of fluid power technology also involves the creation of original ways to demonstrate basic concepts of fluid power. Within this effort, in 2015 his team created an original test apparatus suitable to demonstrate the features of modern Load Sensing (LS) architectures for hydraulic machines. Load Sensing systems are in use in several applications, especially in the mobile fluid power field. However, basic tests demonstrator suitable for student lab experiences are usually not available in academic fluid power labs. The apparatus designed and developed at the Maha permits to fill the typical gap of both introductory and advances fluid power classes, which usually cover theory of LS systems but very seldom with practical demonstration through hands-on experiences, in which the controllability and energy features of the systems can be quantified.

After its conception and initial tests at Maha, the apparatus was installed in the Fluid Power Lab of the Agricultural and Biological Engineering Dept. of Purdue University, and it has been used for lab experiences within educational courses starting from Fall 2015 (ABE435 – Hydraulic Control Systems).




**CAD drawing of the LS test-stand**

With the layout shown in the figure above, the system permits the students to:

a) Learn the basic principle of operation of load sensing systems;

b) Learn the concept of control of hydraulic actuators through independent metering;

c) Understand the concepts behind pre-compensated and post-compensated LS system architectures;

d) Be able to quantify the energy consumption of the system as a function of the load unbalance of the different users;

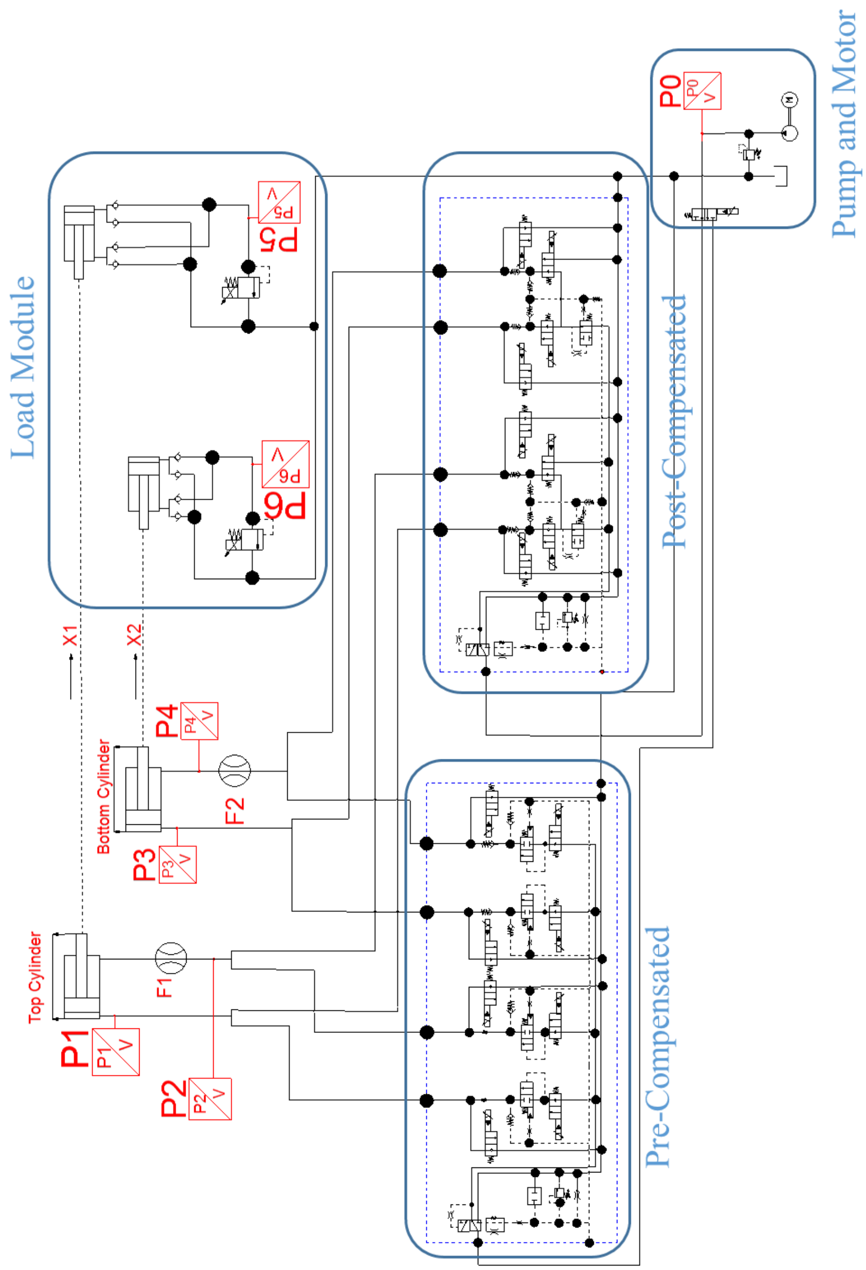
e) Quantify the energy consumption of the system and the system efficiency for steady operating conditions and for specific drive cycles;

f) Understand the concept of flow saturation and pressure saturation;

g) Understand the strategies for realizing flow sharing under flow saturation conditions;

As it can be noticed from the Figure below, the system consists of two hydraulic cylinders (users) connected to the hydraulic power supply by means of a LS hydraulic valve block. For the valve block, two options will be available: a pre-compensated and a post compensated valve block. It is important to notice how both valve blocks implements the *independent metering* control strategy. In this way, the apparatus will permit to show not only the typical features of a LS system, but also those of the emergent independent metering control.

In order to control the load (pressure) of each user, two load modules controlled by proportional relief valves are used. The system will include the necessary sensors to monitor the instantaneous working conditions: flow sensors, pressure sensors and cylinder position sensors as highlighted in the figure above. A DAQ and a LabView software will permit to control and display the main features, highlighting system controllability and energy consumption.




**Hydraulic schematic of the system. The main parts of the circuit are highlighted**

During 2015, three undergraduate students and two graduate students under Dr. Vacca's supervision contributed to the design of the system. It is expected that the system will be used for educational purposes by more than 50 students per year.

The NFPA (National Fluid Power Association – Technology foundation) contribution, through the project "Educational Test Station for Multi-Users Load-Sensing System Architectures", was instrumental for the realization of the apparatus, in particular as concerns the physical structure, the sensors, tubing and fittings.

Instrumental was the contribution of following industrial sponsors:

- Hydraforce: donation of all valves, including the independent metering LS valve blocks;
- Concentric: donation of the hydraulic power pack;
- Parker Hannifin: donation of the pressure sensors

Purdue Agricultural and Biological Engineering Dept also contributed to this project, providing funding specifically dedicated to the improvement of educational labs at Purdue.

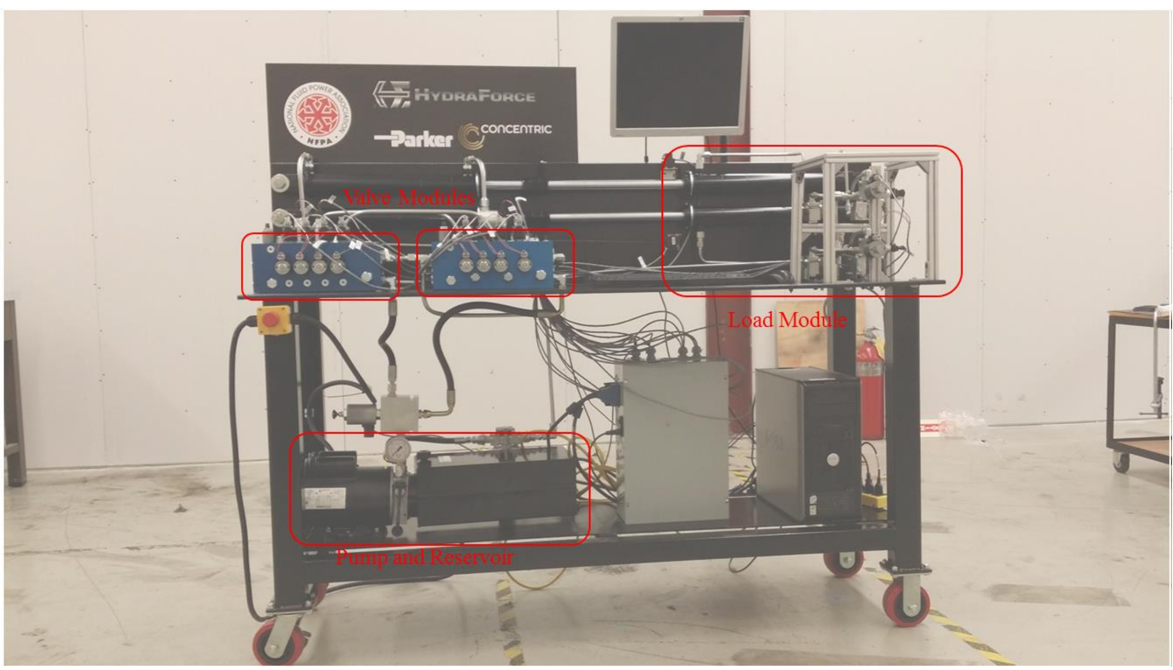



**Image of the test stand for experiments and demonstration on Load Sensing Systems**

# 7 International and National Conferences Attended

### The 14th Scandinavian International Conference on Fluid Power (SICFP2015)

May 20-22, 2015. Tampere Finland.

Attendees:

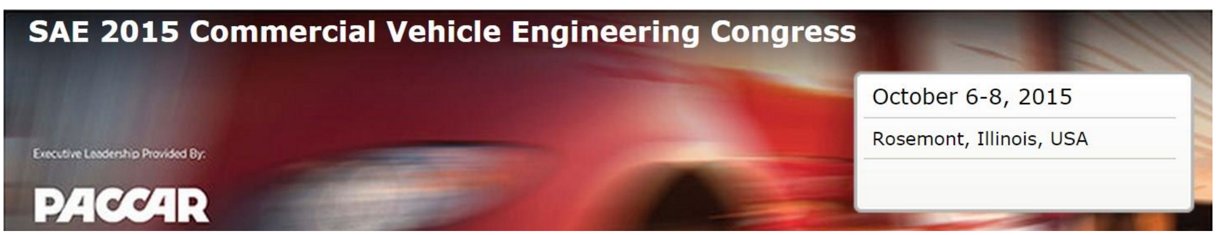
Andrea Vacca (session chair; paper presentation)

### SAE 2015 Commercial Vehicle Engineering Congress (ComVec)

October 6-8, 2015. Rosemont, IL, USA.

Attendees:

Timothy Opperwall (paper Presentation)




### ASME/BATH 2015 Symposium on Fluid Power & Motion Control (FPMC15)

October 12-14, 2015. Chicago, IL, USA.

Attendees:

Andrea Vacca (member of the organizing committee; editorial and publication co-chair)

Matteo Pellegri (Paper Presentation)

Riccardo Bianchi (Paper Presentation)


### Fluid Power Innovation & Research Conference 2015 (FPIRC 15)

October 13-16, 2015. Chicago, IL, USA.

Attendees:

Andrea Vacca (Session chair; Paper presentation)

Divya Thiagarajan (Paper Presentation)

Timothy Opperwall (Paper Presentation)

Gautham Ramchandran (Paper Presentation)

### Esteco ModeFrontier North America User Meeting 2015 (UM 15)

November 4-5, 2015. Novi, MI, USA.

Attendees:

Andrea Vacca (Invited presentation)

# 8 Maha Hosted & Organized Events

## 2015 CCEFP IEC Summit

The Center for Compact and Efficient Fluid Power (CCEFP) held the 2015 Industry Engagement Committee (IEC) Summit meeting at Purdue University on June 3-5 2015. More than 60 representatives from 33 companies and more than 30 researchers from CCEFP member universities attended the event. The summit's theme was "High Power and Mobile Applications" and many of the CCEFP research projects and testbeds were presented for the industry supporters who attended. The CCEFP referred to this event as "the best vehicle for driving a close working relationship between US academic fluid power research and industry."

As part of the summit meeting, Maha hosted a wonderful dinner for the attendees after they spent the afternoon touring the Maha lab. During the tour, both Dr. Ivantysynova’s and and Dr. Vacca’s showcased their research. All the team members were involved in short talks and demonstration. In particular Dr. Vacca’s team shows the novel variable displacement gear pump prototype, the recent advancements in the multi-functional test rig, and the oscillation damping strategies ongoing on the hydraulic crane. The lab tour was also the first occasion to showcase the new wheel loader that Dr. Vacca’s team initiated to use for experimental research in 2015.

**Lab Tour & Machine Demonstration**

# 9 Maha Social Events

Life in the Maha lab is not always about work. Occasionally we are able to get together and enjoy each other's company. Below are some highlights of the past year.

## Summer party at Susan's house

## Andrea's house parties

## Celebrating successful PhD defenses


**Ram's defense**


**Tim's defense**


**Guido’s defense**

# 10 Maha Team in 2015

## Maha Faculty

Dr. **Andrea Vacca**

Associate Professor
Joint Appointment in ABE/ME
avacca@purdue.edu
Phone: (765) 430-0081
Origin: Italy
March 2010-present

**Andrea Vacca – Short Bio**

In 1999 Andrea Vacca earned his Master's degree - with honors - in Mechanical Engineering from the University of Parma (Italy) and his doctorate in Energy Systems from the University of Florence (Italy) in 2005. For both degrees he presented theses in the field of Heat Transfer and Gas Turbine Blade Cooling Technology. Before joining Purdue University as Assistant Professor in 2010, Prof. Vacca was Assistant Professor of Fluid Machinery at the University of Parma (Italy).

In 2014, he was promoted to the role of Associate Professor, with joint appointment between Purdue Agricultural and Biological Engineering and Purdue Mechanical Engineering.

Prior to his arrival to Purdue, Prof. Vacca participated in various research activities related to the fields of internal combustion engines, food technology and hydraulic systems.

Fluid power technology has been Prof. Vacca's major research interest since 2002. Particular goals of his research are the improvement of energy efficiency and controllability of fluid power systems and the reduction of noise emissions of fluid power components. To accomplish the goals of his research, his research team has developed original numerical and experimental techniques to simulate fluid power systems and components, especially for gear machines and hydraulic control valves. Prof. Vacca's interests also include the modeling of the properties of hydraulic fluids, with particular focus to the effects of aeration and cavitation, as well as the use of low viscous fluids (such as water) in fluid power systems.

Prof. Vacca is the author of more about 100 papers, most of them published in international journals or conferences. He is also active in the fluid power research community. He is a faculty member of the Center for Compact and Efficient Fluid Power (CCEFP), a ASME Executive member, and Treasurer and Secretary of the Board of the Fluid Power Net International (FPNI). Prof. Vacca is also a former chair of the SAE Fluid Power division . He is also Associate Editor of the International Journal of Fluid Power.

## Maha Staff

**Anthony Franklin**

Lab Manager
Phone: (765) 448-1587
Origin: Kokomo, IN
November 2008-present

**Susan Gauger**

Maha Secretary/ Assistant
Phone: (765) 448-1587
Origin: Lafayette, IN, USA
June 2011 - present

**Connie McMindes**

Inventory Control Clerk
Phone: (765) 448-1587
Origin: Lafayette, IN
October 2012-present

# Maha Graduate Students

**Yash Shah**
*Masters Student*
phone: (765) 448-1945
BT: IIT Ropar, India
Origin: India
August 2015 - present
Research Topic: Modeling and simulation of cavitation in hydraulic systems.

**Srinath Tankasala**
*Masters Student*
phone: (765) 448-1945
BT: IIT Madras, India
Origin: India
August 2015 - present
Research Topic: Modeling of flow for variable displacement in external gear machines.

**Riccardo Bianchi**
*Ph.D. Student*
phone: (765) 448-1945
BS, MS: University of Ferrara, Italy
Origin: Italy
September 2014 - present
Research Topic: Vibration damping in hydraulic machinery.

**Gautham Ramchandran**
*Masters Student*
phone: (765) 448-1945
BS: VIT University, India
Origin: India
January 2015 - present
Research Topic: Modeling of high pressure radial piston pumps.

**Addison Alexander**
*Ph.D. Student (Direct Ph.D.)*
phone: (765) 448-1945
BS: University of Kentucky
Origin: Kentucky, USA
August 2013 - present
Research Topics: Active vibration damping and traction control development for mobile hydraulic machines.

**Andrew Robison**
*Ph.D. Student (Direct Ph.D.)*
phone: (765) 448-1945
BS, BA: South Dakota State University
Origin: Minnesota, USA
August 2015 - present
Research Topic: Noise emissions of geroter pumps.

**Rituraj**
*Ph.D. Student (Direct Ph.D.)*
phone: (765) 448-1945
BT: IIT Guwahati, India
Origin: India
August 2015 - present
Research Topic: Modeling of external gear machines to handle non-newtonian fluids.

**Xinran Zhao**
*Ph.D. Student*
phone: (765) 448-1945
BS: Shanghai Jiao Tong University, China
MS: Carnegie Mellon University
Origin: China
June 2015 - present
Research Topic: Modeling of gear pumps.

**Matteo Pellegri**
*Ph.D. Student*
phone: (765) 448-1945
BS, MS: University of Parma, Italy
Origin: Italy
August 2014 - present
Research Topic: Investigation of the effects of journal bearings on the operation of external gear machines.

**Divya Thiagarajan**
*Ph.D. Student*
phone: (765) 448-1945
BS: Anna University, India
MS: Purdue University
Origin: India
October 2012 - present
Research Topics: Investigating the possibilities of using low viscosity fluids (with a focus on water) in hydraulic applications.

**Guido Francesco Ritelli**
*Ph.D. Student*
BS, MS: Politecnico of Turin, Italy
Origin: Italy
February 2012 - January 2016
Research Topics: Development of an adaptive, real-time and non-model based control strategy in mobile hydraulic machinery for oscillation dampening and energy saving. Counterbalance and directional valves modeling.

**Sidhant Gulati**
*Master's Student*
BS: VIT University, India
Origin: India
January 2014 - August 2015
Research Topics: Formulation of a novel design methodology for external gear machines.

**Timothy Opperwall**
*Ph.D. Student*
BS: Calvin College
MS: Purdue University
Origin: Michigan, USA
August 2010 - December 2015
Research Topics: Development of a noise emission model for external gear machine; Optimization of the external gear machines design for noise emission reduction.

**Ram Sudarsan Devendran**
*Ph.D. Student*
BS: BITS Pilani, India; MS: Purdue University
Origin: India
September 2010 - June 2015
Research Topics: Formulation of design principles for variable displacement external gear machines; Proposal of innovative design methodology for external gear machines.

# Visiting Scholars

**Kelong Wang**
*Visiting Student from Harbin Institute of Technology, China*
BS, MS: Harbin Institute of Technology, China
Origin: China
October 2013 - February 2015
Research Topic: Modeling and simulation of radial piston pumps.

**Matteo Foà**
*Visiting Scholar from the University of Naples Federico II, Italy*
Email Matteo; phone: (765) 448-1945
BS: University of Naples Federico II, Italy
Origin: Italy
November 2015 - present
Research Topic: Development of a novel hydrostatic transmission system for human-powered vehicles.

**Wencheng Guo**
*Visiting Scholar from Wuhan University, China*
Email Wencheng; phone: (765) 448-1945
BE, ME: Wuhan University, China
Origin: China
August 2015 - present
Research Topic: Vibration damping of fluid power systems.

**Matteo Fergnani**
*Visiting Scholar from the University of Ferrara, Italy*
BS: University of Ferrara, Italy
Origin: Italy
June 2015 - December 2015
Research Topic: New control schemes for detecting the traction state of offroad machines.

**Francesco Napolitano**
*Visiting Scholar from the University of Naples Federico II, Italy*
Email Francesco; phone: (765) 448-1945
BS: University of Naples Federico II, Italy
Origin: Italy
November 2015 - present
Research Topic: Noise emission of external gear pumps.

**Fabio Linzitto**
*Visiting Scholar from the University of Ferrara, Italy*
Email Fabio; phone: (765) 448-1945
BS: University of Ferrara, Italy
Origin: Italy
September 2015 - present
Research Topic: Modeling of external gear pumps using CFD approaches to handle non-Newtonian fluids.

**Jesper Sørensen**
*Visiting Scholar from University of Agder, Norway*
BS, MS: Aalborg University, Denmark
Origin: Denmark
January 2015 - May 2015
Research Topic: Reduction of oscillations in hydraulically-actuated knuckle boom cranes.

## Undergraduate students

**Josias Cruz Gomez**
*Visiting Scholar from the Technological Institute of Toluca, Mexico*
Origin: Mexico
June 2015 - August 2015
Research Topic: Load-sensing test rig.

**Cristina Perez Garcia**
*Visiting Scholar from the Technological University of Queretaro, Mexico*
Origin: Mexico
July 2015 - November 2015
Research Topic: Modeling of external gear pumps using CFD approaches.

**Francisco Arellano**
*Visiting Scholar from Technological University of Queretaro, Mexico*
Origin: Mexico
February 2015 - June 2015
Research Topic: Modeling, implementation, and realization of a load sensing educational test rig.

**Julio Gachuzo**
*Visiting Scholar from Technological Institute of Queretaro, Mexico*
Origin: Mexico
February 2015 - June 2015
Research Topic: Modeling, implementation, and realization of a load sensing educational test rig.

**Karina Bjorklund**
*SURF program 2015 (Summer Undergraduate Research Fellowship)*
Origin: Illinois, USA
May 2015 - August 2015
Research Topic: Experimental characterization and modeling of energy efficient fluid supply systems.