Maha Fluid Power
RESEARCH CENTER
PURDUE UNIVERSITY

2014 Annual Report

Lafayette, January 2015

Preface

The Maha Fluid Power Research Center celebrated its 10th anniversary on October 1st through 3rd. The guest list included colleagues and friends, Maha alumni, past visiting researchers and industrial partners. The celebration included a comprehensive lab tour and presentation of current research activities. One of the highlights was a machine demonstration where guests were invited to try the Maha displacement controlled hybrid excavator and the newest addition to Maha's prototype machines – the world's first wheel loader with a displacement controlled steer by-wire steering system. This new steering system improves machine efficiency through fuel-savings and increased steering productivity while introducing variable steering ratio, variable steering effort, and active safety. This machine also demonstrated capabilities of remote and autonomous machine operation. Certainly the 10th anniversary was a landmark event in Maha lab history, but there were many other impressive highlights last year.

Another highlight was certainly the visit of Purdue's president Mitch Daniels to Maha on November 8. It was his first visit and he left impressed by the power and achievements of the Maha research team. Also this last May, Maha again organized and hosted the REU Bootcamp of the NSF Center for Compact Efficient Fluid Power (CCEFP) providing a crash course in fluid power for undergraduate students from various US universities.

I am very proud to announce that this annual report first time covers the activities and achievements of both Maha research teams, my own team and the research team lead by Andrea Vacca.

Major breakthroughs and discoveries in 2014 include the successful demonstration of the novel displacement controlled steer by wire system in Maha's wheel loader, the first implementation and test of the novel blended hydraulic hybrid transmission at Maha's hardware-in-the-loop transmission test rig, the successful test of the novel pump switching concept for displacement controlled actuation in Maha's hydraulic hybrid excavator, first time successful direct measurements of fluid film thickness of the slipper /swash plate interface conducted on a stock machine under real operating conditions. The measurements confirm the presence of dynamic surface deformations of the slipper and swash plate due to pressure and thermal loading. These measurements verify that squeeze effects due to transient surface pressure deformation need to be considered in order to reproduce fluid film behavior in simulation. This represents a very important discovery in understanding the main physical effects in pump and motor tribological interfaces.

In December 2014, Andrea's team also tested a novel concept for external gear pumps that implements variable delivery flow features. This novel design permits the flow rate to vary in a certain range (about 35%, in the tested prototype), maintaining energy efficiency levels comparable to other variable displacement units. Entirely conceived at Maha, this design preserves the typical advantages (cost, reliability, flexible configurations) of external gear machines and has potential to lower energy consumption of many machines currently based on fixed displacement units.

Maha researchers presented their findings at key international fluid power conferences. We traveled to Aachen, Germany, where Andrew Schenk, Mike Sprengel, Naseem Daher, Guido Ritelli and Sujan Dhar each presented a paper about their recent research results. One of the highlights of this, with more than 800 participants making the largest fluid power international conference, is the ceremonial Aachen HP Award given to persons who have distinguished themselves by outstanding studies in the field of Fluid Power. I am extremely proud to report that Davide Cristofori received the HP Award for his PhD dissertation "*Advanced Control Strategies for Mobile Hydraulic Applications*" during the conference this last March in Aachen. In June 2014 seven Maha PhD students presented their research progress at the 8th FPNI PhD Symposium in Lappeenranta, Finland. Mike Sprengel won the prestigious Backe medal for the best paper presentation, which is the fifth time in the 15 year history of the FPNI PhD Symposium that one of the Maha reseachers has won this medal. The FPNI PhD Symposium included a debate on "*Hydraulic vs Electric Drives*" to which I was invited as one of the keynote speakers. I received another invitation from ExxonMobile to give a lecture entitled "*Optimized fluid films essential for displacement control & hydraulic hybrid systems"* to their R&D team. In September Enrique and I attended the ASME/Bath workshop in Bath, UK and Enrique presented our paper. Mike Sprengel, Andrea and I presented papers at the SAE 2014 Commercial Vehicle Congress in Chicago. This last October, Enrique Busquets and Tim Opperwall traveled to Matsue, Japan to present their work at the 9th JFPS International Conference. I am very proud that Enrique received the best paper award from Japanese Fluid Power Society for our paper on "*The World's First Displacement Controlled Excavator Prototype with Pump Switching - A Study of the Architecture and Control"*. Finally, Andrea attended with three of his researchers the conference held at the International Fluid Power Expo in Las Vegas.

The Maha team published its research finding in 19 journal papers this last year, which is a record in terms of journal publication. Maha received more than 2.6 million US$ of new research funding in 2014 the highest funding in the history of Maha. In addition to the research funding, the Maha team continued receiving major donations from industrial partners, which helped us to create important new test rigs and prototype machines. My special thanks go to Danfoss, Sun Hydraulics, Parker Hannifin, Moog, Bobcat, Hydac, Bosch

Rexroth and Casappa for donating major equipment and components to the Maha lab. My special thanks additionally go to Ken and Susan Warren who continued their support of Maha also this past year.

Four of our PhD students defended their thesis in 2014 and left Maha. Sujan Dhar defended his PhD thesis in March 2014 and left to work for Simerics. Rohit Hippalgaonkar completed his PhD studies in April and went to work for Ford. Naseem Daher defended his thesis in August and I am very proud to share that he is my first PhD student who started a faculty career. He joined the American University of Beirut as an assistant professor this past September. Finally, Andrew Schenk who has been one of the key contributors to pump research defended his PhD thesis in December 2014. Andrew left Maha to work for Mathworks. We wish all of them a great start in their new jobs and hope to get some exciting new collaborations started soon.

Our research team did grow again and reached with 52 graduate students and visiting researchers its largest size. In August 2014, we welcomed seven new graduate students: Ryan Jenkins, Jeremy Beale, Liu Ning, Mrudula Orpe, Colleen Reidy, Riccardo Bianchi and Matteo Pellegri. Maha also welcomed Nils Trochelmann and Anna Garcia Teruel as new IEASTE exchange students from Germany. And, during summer 2014, we hosted two SURF students: Andrew Adelsberger and Andy Wang.

I would like to thank all team members for their outstanding contributions in 2014. It is a great pleasure to present the following survey of our activities and achievements during this past year. I am confident that we will continue our exciting and successful research. I wish all the members of our team much success during 2015.

Dr. Monika Ivantysynova
Maha Professor Fluid Power Systems
Director Maha Fluid Power Research Center

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1 Research Activities

1.1 Research activities – Dr. Ivantysynova's research team

Our research efforts on revolutionizing fluid power technology with complete new system architectures, controls and component design methods continued in 2014 leading to several breakthroughs, which will be described in this section. We are very proud to report that the Dr. Ivantysynova's team was able to double the number of journal publications and received two very prestige best paper awards for papers presented on international conferences in 2014. Our research funding remained with nearly 2Million dollar on a high level even when the ERC funding for our team dropped by 75% in year nine of the center. Our team did grow again this last year by adding five new graduate students and several visiting scholars. Our research activities can be broadly divided into two main areas:

1) **Research into efficient hydraulic actuation and drive systems,** which includes displacement controlled (DC) systems, novel hydraulic power trains (hybrid and non-hybrid), power management and control, active vibration damping and machine diagnostics.
2) **Research into design and optimization of piston pumps and motors,** which includes modeling, control, experimental investigations and testing. Current main focus is on modeling of fluid structure interaction phenomena, thermal behavior and noise generation and propagation in order to gain a better understanding of physical phenomena influencing pump performance. Long term goal is to provide methods and tools for computational design and digital prototyping of pumps and motors.

In general the research activities involve extensive computational, experimental and theoretical work. During the last sixteen years a comprehensive fluid power research laboratory has been built and equipped with pump and motor test rigs, actuator test rigs, drive-line control and transmission test rigs including test machines as well as several specialized test rigs for investigation of tribological systems of displacement machines.

1.1.1 Research Highlights in 2014

- The Maha team under the leadership of Nassem Daher built and successfully tested the world's first displacement controlled steer by wire system for a wheel loader. The system not only reduces fuel consumption and increases machine steering productivity but also improves machine safety and driver comfort. 40% productivity improvement for vehicle steering has been measured on the prototype wheel loader.

- Andrew Schenk first time conducted fluid film thickness measurements below the slippers on a stock axial piston machine under real operating conditions. The measurements confirm the presence of dynamic surface deformations of the slipper and swash plate due to pressure and thermal loading. These measurements confirm that squeeze effects due to transient surface pressure deformation need to be considered in order to reproduce fluid film behavior. This represents a very important discovery in understanding the main physical effects in pump and motor tribological interfaces.
- Mike Sprengel first time successfully tested the blended hydraulic hybrid trasmisision concept on Maha's dynamometer test rig. The blended hybrid uses a combination of hybrid and hydrostatic operation in a new circuit solution. Mike received the prestigious Backe Medal 2014 for his paper on "*Hardware-in-the-Loop Testing of a Novel Blended Hydraulic Hybrid Transmission*" published in Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland.
- The novel pump switching concept for displacement controlled (DC) actuation has been successfully implemented and tested by Enrique Busquet in Maha's hydraulic hybrid excavator with DC actuation systems for boom, bucket and arm, which forms also test bed #1 of the NSF funded ERC for Compact and effcient Fluid Power (CCEFP).
- The Maha team continued its efforts in investigating the potential for major reduction in energy dissipation while improving load carrying ability for the piston cylinder interface of swash plate type axial piston pumps. Ashley Wondergem presented her newest research results with the paper "*The Impact of the Surface Shape of the Piston on Power Losses"* at the 8th FPNI PhD Symposium, in Lappeenranta, Finland. Meike Ernst continued her piston/cylinder shaping research study to enable the operation of piston machines for water hydraulics utilizing high pressure. Her recent results show very promising results for the piston/cylinder interface for pressures up to 400 bar.
- Maha's sound chamber was equipped with a new robot enabling automatic sound intensity measurements.

Our research activities are focused in five main areas:

1) Advanced energy saving hydraulic actuators, new system architecture and controls
2) Advanced hydraulic hybrid power trains and control
3) Fluid Structure Interaction in critical piston pump/motor interfaces
4) New computational design methods for piston pumps and motors
5) Investigation of pump and transmission noise sources

Research is supported by government agencies like NSF, DOE and USDA with 2/3 of funding coming from industry.

1.1.2 Research into Efficient Hydraulic Actuation and Drive Systems

Advanced Energy-Saving Circuits for Hydraulic Actuation

This research area involves the development of novel throttle-less hydraulic actuation architectures together with necessary motion control concepts, to improve system efficiency while maintaining or improving productivity. A closed-circuit throttle-less solution, called displacement controlled (DC) actuation, was first developed and successfully tested in Professor Ivantysynova's lab in 1998 at Duisburg University in Germany. Since then much research effort has been directed toward introduction of this concept into mobile machines such as wheel loaders, excavators and skid-steer loaders and for the purpose of throttle-less actuation of working hydraulics and auxiliary functions, as well as active vibration damping.

In August 2010, a prototype 5-ton DC excavator built at Maha, using pump-controlled actuation (PCA) for all functions showed 40% fuel savings in side-by-side measurements against a standard 5-ton excavator using load-sensing architecture. These measurements were made after detailed modeling of the PCA and LS architectures in 2008 and 2009, using a co-simulation model that captured the dynamics as well as the mechanics of both systems and predicted these savings.

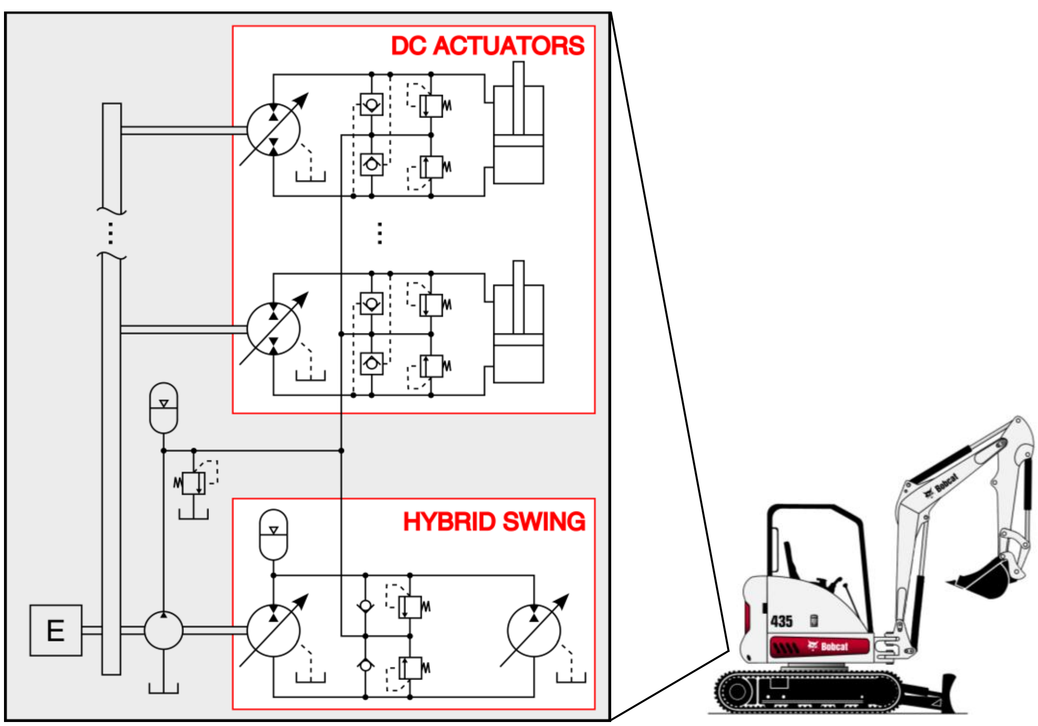


Fig. 1: Series-Parallel (S-P) Hybrid Pump-Controlled Excavator Architecture

A novel hydraulic hybrid excavator architecture (Fig. 1) was proposed by Zimmerman and Ivantysynova (SICFP, 2011), which retained PCA for the boom, stick and bucket functions while employing a series-hybrid hydraulic swing drive. The architecture enabled 50% engine downsizing (which was first predicted in simulation by Zimmerman), while meeting aggressive digging cycles (representing peak power demands from the excavators). Using a conservative power management scheme ('single-point strategy'), the architecture also enabled fuel savings in excess of 52% over the standard, valve-controlled 5-t excavator (and 20% fuel savings over the non-hybrid PCA architecture).

In 2013, this architecture was implemented on a mini-excavator, together with implementation of energy management algorithms that limited engine power to 50% while meeting digging cycles. Fig. 2 shows the results of implementation of the 'single-point' strategy, wherein the engine speed was operated at its maximum governed speed and maintained at a constant torque (near the maximum torque of an engine with 50% reduced power) through appropriate control of the primary unit.

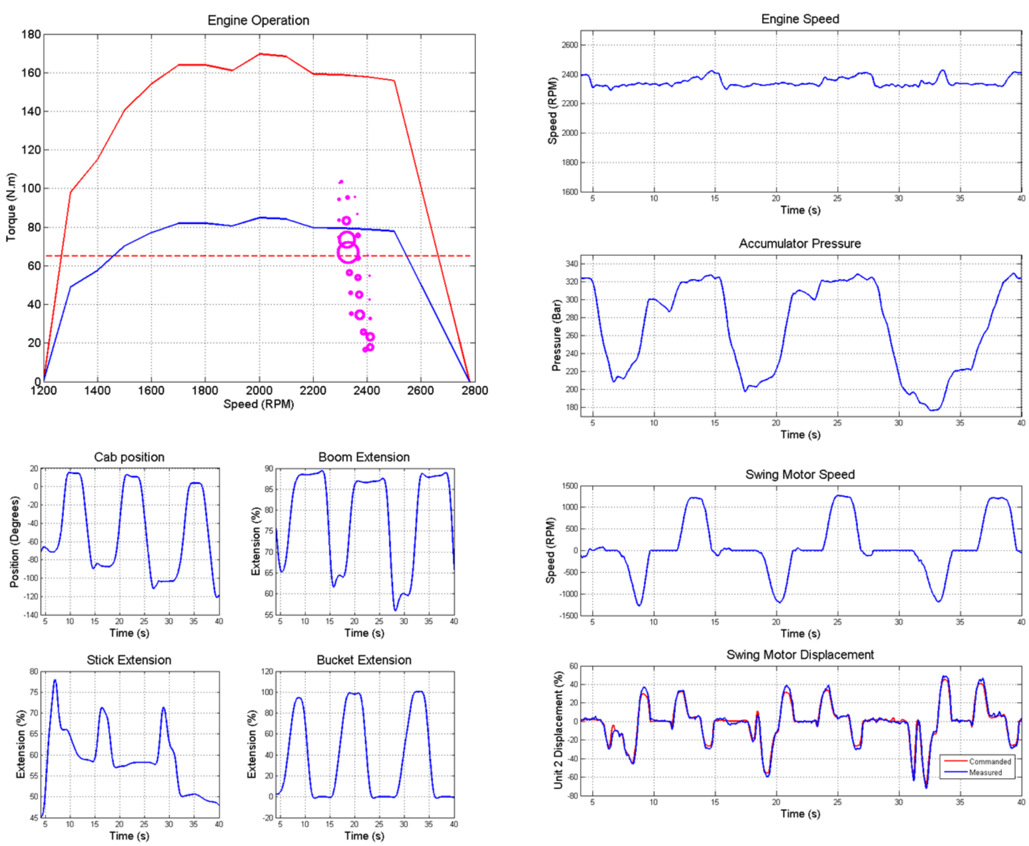


Fig. 2: Measurement Results with the Single-Point Power Management Strategy (Digging Cycle)

Another strategy, called the minimum-speed strategy (Hippalgaonkar, Ivantysynova & Zimmerman (IFK, 2012)), that exploited all degrees of freedom of the hydraulic hybrid architecture was also implemented on the excavator. In simulation, this strategy showed higher efficiency than the single-point strategy and allowed replication of optimal control results obtained from dynamic programming (Zimmerman, Ivantysynova and Hippalgaonkar (ASME-Bath, 2012)), for the series-parallel hybrid hydraulic architecture with a 50% downsized engine. In implementation of this strategy, the engine power (the engine was not actually downsized on the mini-excavator at Maha) was limited to be below 25 kW (slightly above 20.5 kW, which is 50% of the maximum engine power), while exploiting engine speed variation (Fig. 3).

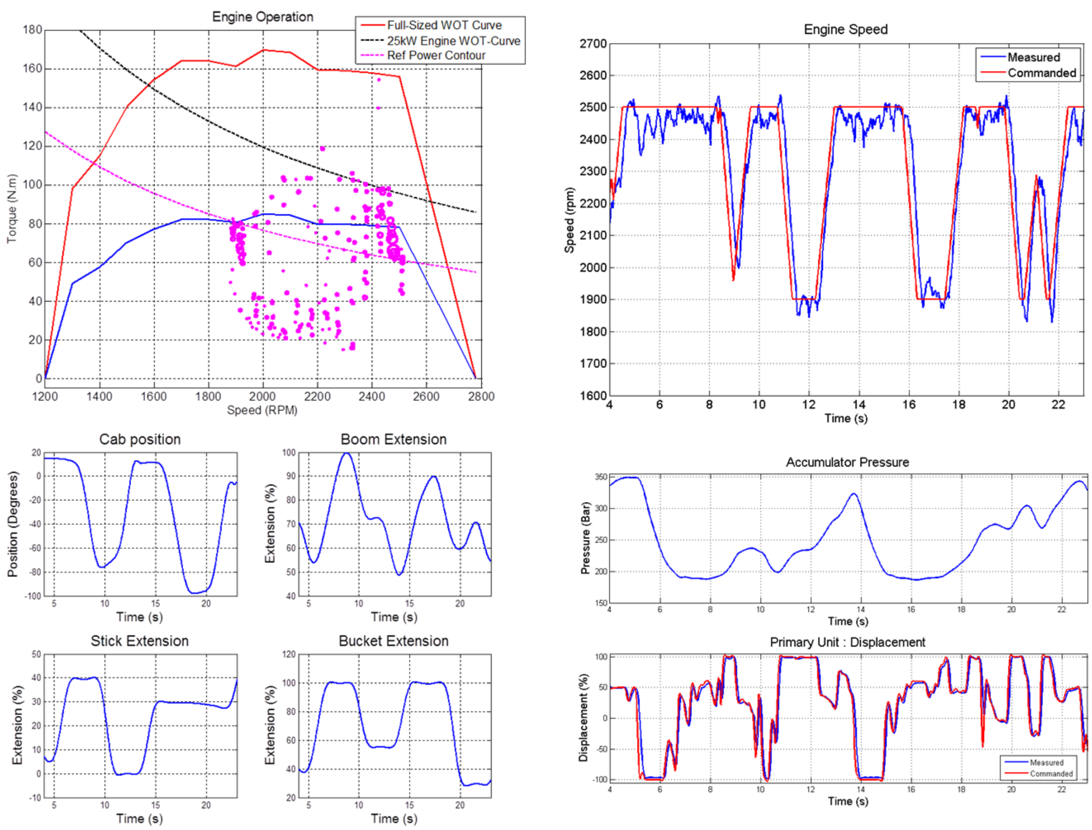


Fig. 3: Measurement Results with the Single-Point Power Management Strategy (Digging Cycle)

This strategy also showed higher efficiency over the single-point strategy for the parallel-hybrid hydraulic excavator architecture (Hippalgaonkar, Zimmerman & Ivantysynova, SAE Comvec-2011)), with a 50% downsized engine. Details of the closed-loop speed control strategy employed for the swing drive are outlined in Hippalgaonkar & Ivantysynova (SICFP, 2013).

In addition to the investigation of the hydraulic hybrid swing drive, the investigation of DC actuation with pump switching was conducted at Maha. This concept was born from one of the major obstacles for DC multi-actuator machines: the increased production costs due to the one-pump-per-actuator requirement. Up to 2011, research in DC technology at Maha mainly focused on architectures with one pump per actuator. This certainly increases machine production costs especially for large machines where for traditional DC operation the required pump sizes or number are very large. The concept of pump switching was simulated and implemented on a test rig validating its benefits and allowing to create control concepts to mitigate its challenges. With this in mind, a hydraulic architecture was proposed for the mini excavator prototype. The hydraulic circuit of the proposed idea is shown in Fig. 4.

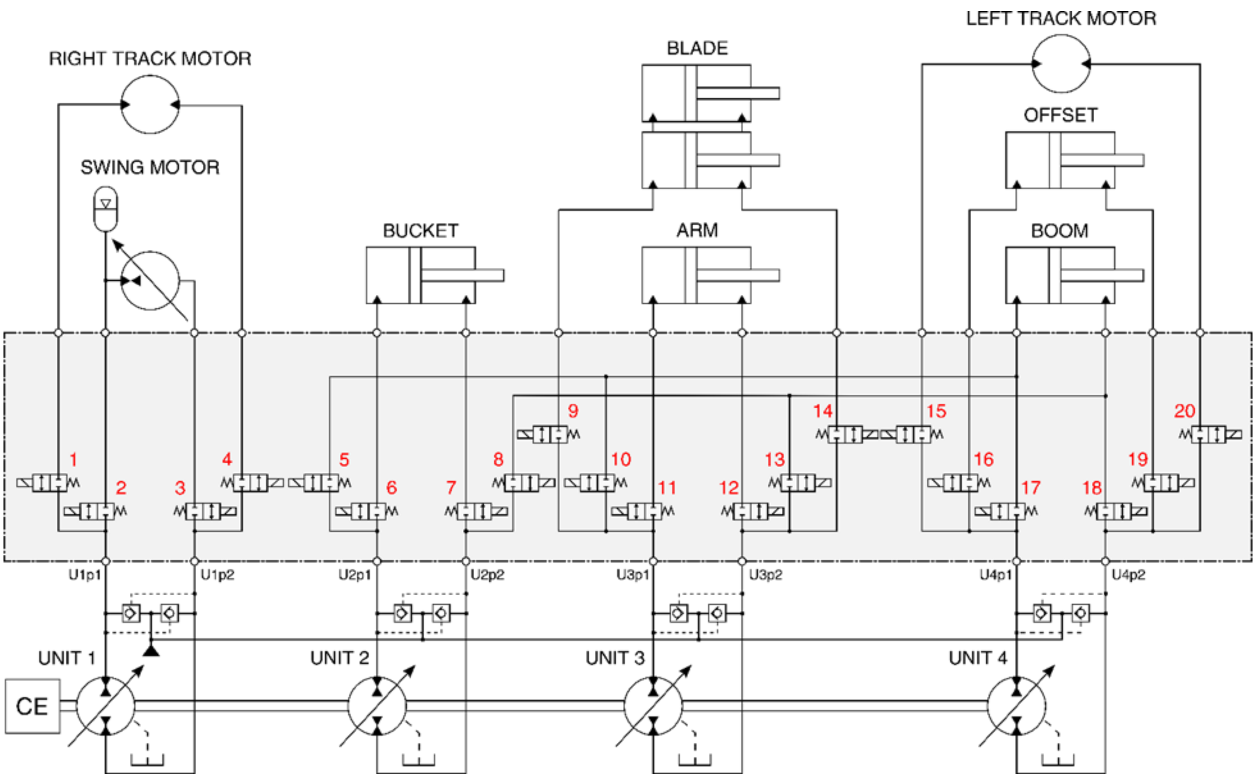


Fig. 4: Hydraulic Hybrid Excavator Prototype Hydraulic Circuit

To demonstrate the pump switching concept, the excavator prototype was studied and a hydraulic architecture was proposed and implemented, Fig. 5 shows the system architecture and shows the machine working hydraulics.

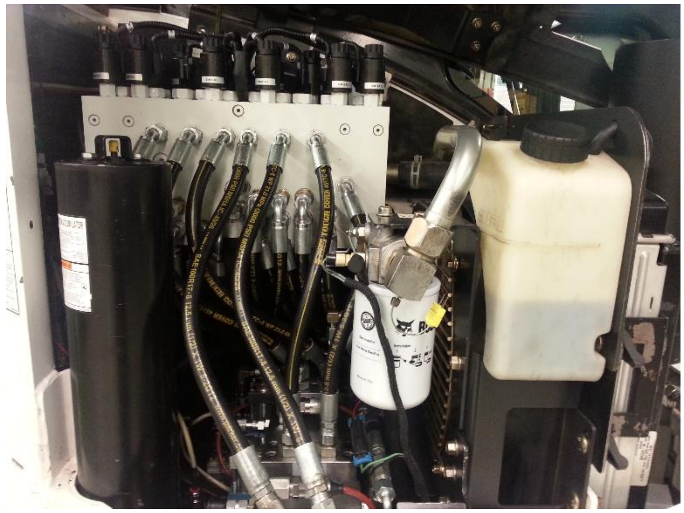


Fig. 5: Machine Working Hydraulics

Measurements of the proposed controller show that the concept is achievable on the actuator level. This is evident by the pressure and actuator position transients observed in Fig. 6 a), where no controls were applied, and the complete mitigation off the effects of pump switching shown in Fig. 6 b), where proper controls have been implemented.

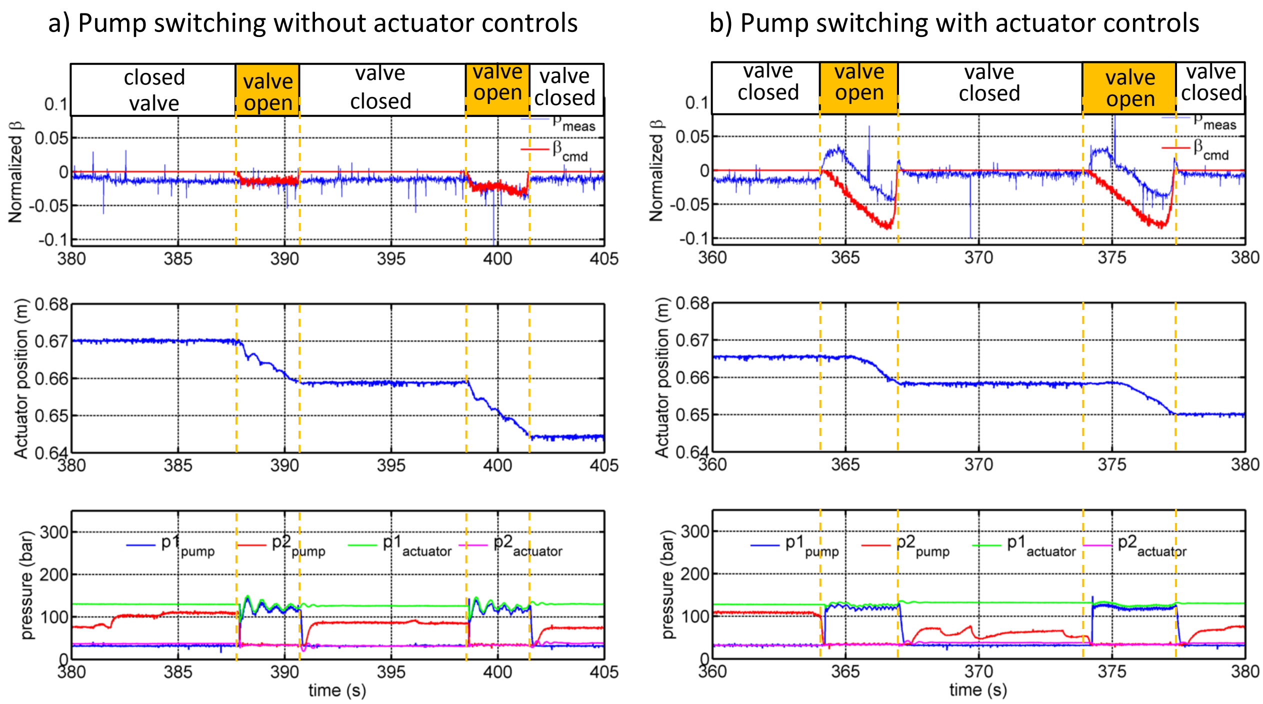


Fig. 6: Measurements of the Actuator Level Control Pump Switching Concept under a Moderate Load

Novel Energy-Saving Electrohydraulic Steer-by-Wire System via Pump Displacement Control Actuation

Pump displacement control (DC) is an energy-efficient alternative to traditional valve control. A novel steer-by-wire (SBW) technology based on DC actuation is under current research and development. A hydraulic schematic of the proposed system is shown in Fig. 7 below. The actuator (8) velocity is controlled by adjusting the pump (2) speed, displacement, or both. The differential fluid flow between the single-rod actuator's uneven sides is overcome by means of pilot-operated check valves (6). The low pressure system has its own fixed displacement charge pump (4) that provides continuous flow to the cylinder's low pressure side. The low pressure level setting is controlled via a pressure relief valve (5). The system is protected against over-pressurization by means of high pressure relief valves (7). The pump control system (3) consists of a proportional control valve that meters flow to a double rod actuator that is mechanically coupled to the pump swash plate.

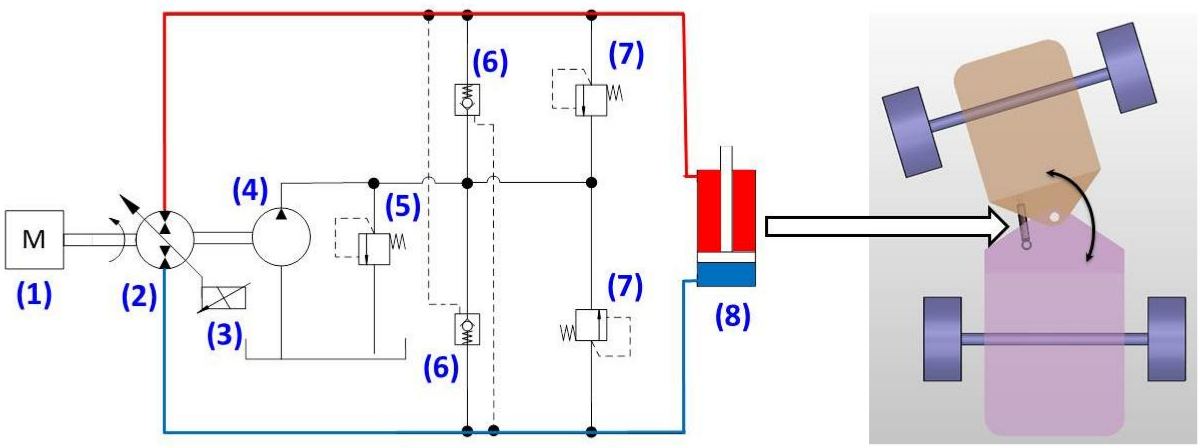


Fig. 7: DC Electro-hydraulic Steering System – Hydraulic Schematic

Two main components are required by the DC steering system: a dedicated variable displacement pump and a tactile feedback device to control the steering wheel torque level. The two subsystems are controlled by an on-board electronic control unit (ECU) and vary based on vehicle speed, articulation angle, and steering wheel velocity as depicted in Fig. 8.

A high-fidelity nonlinear dynamic model is generated for the entire vehicle system, which includes a hydraulics module and a mechanics model as shown in Fig. 9. The hydraulics subsystem is modeled in MATLAB Simulink® environment, while the mechanics subsystem is modeled in MSC Adams software. Linear models are derived for each of the hydraulics and the mechanics subsystems, and the two models are coupled at the steering actuator interface. The mechanics subsystem is based on a multi degrees-of-freedom vehicle dynamics model based on Lagrangian mechanics principles. The hydraulics subsystem includes the pressure build-up equations of the steering actuator chambers. The obtained model is a linear time-invariant (LTI) single-input single-output (SISO) system with pump displacement as its input and articulation angle as its output.

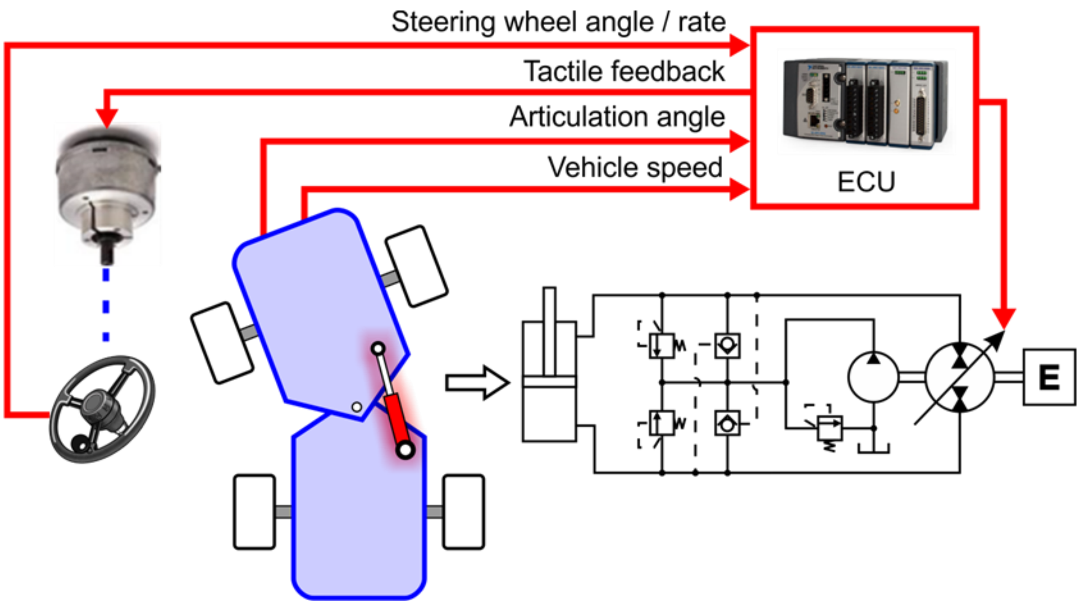


Fig. 8: DC Steering System Depiction

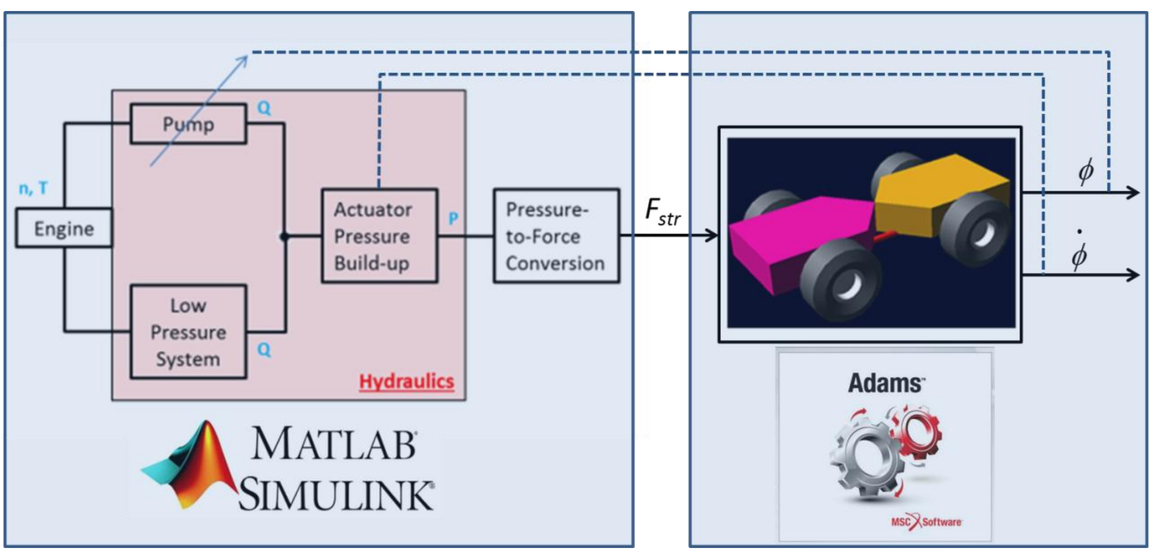


Fig. 9: Block Diagram of Steering System Dynamic Model

A linear control law that includes feedforward and feedback is designed as shown in Fig. 10.

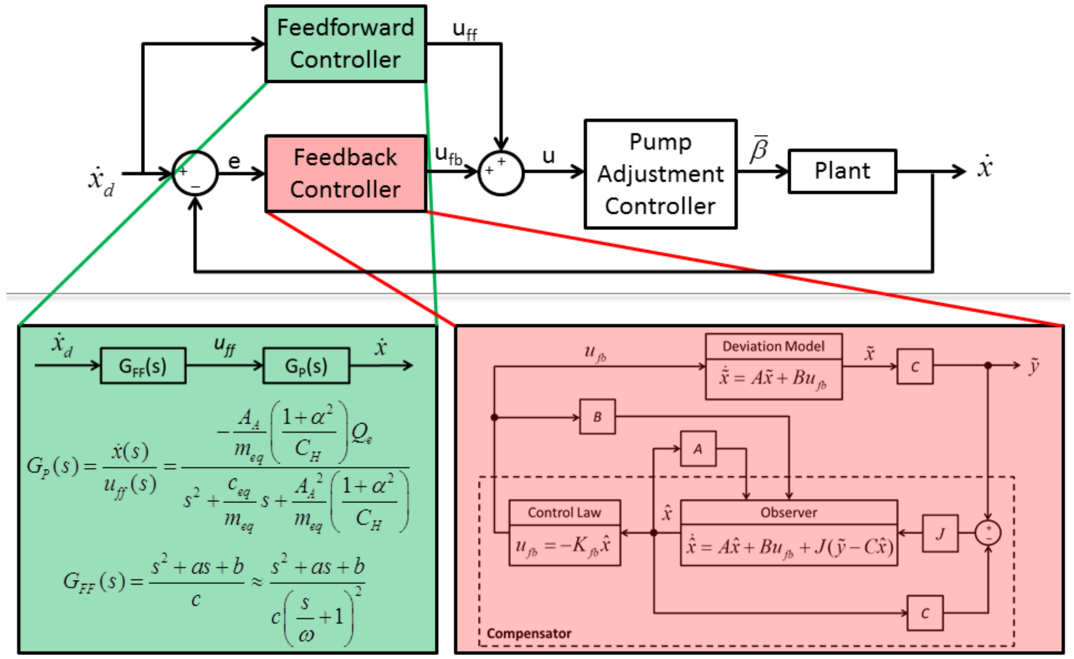


Fig. 10: DC Steering System Controller Structure

A designated prototype test vehicle, a compact 5-ton wheel loader, is overhauled to retrofit a DC steering system, which includes the following main hardware components as shown in Fig. 11: a variable displacement axial piston pump (dashed red) dedicated to the steering actuator, a proportional control valve (dashed green) to adjust the swash plate angle, a gear type charge pump (dashed blue) to supply flow to the low pressure source, and a tactile feedback device (dashed orange) to provide torque feedback at the steering wheel. For research and algorithm development purposes, a load-cell torque sensor (dashed yellow) is installed to measure driver effort, and a slip ring (dashed purple) is used for cable management (infinite no. of rotations).

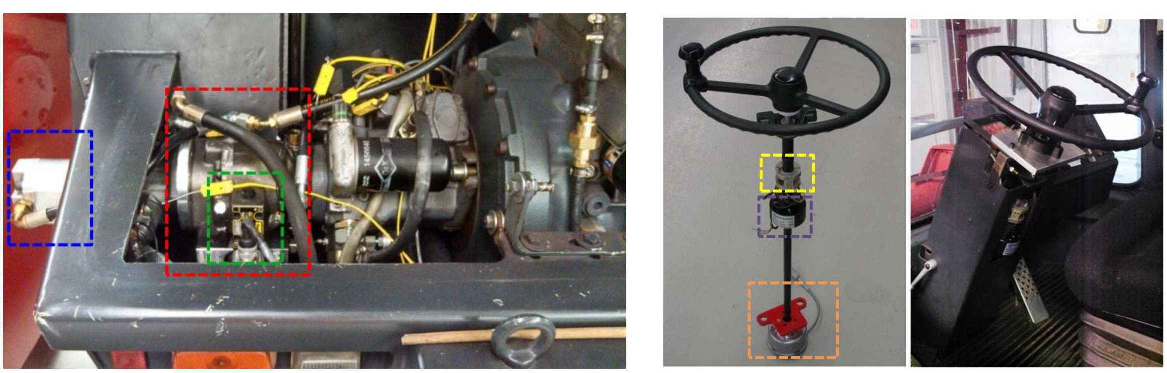


Fig. 11: New DC Steering System Hardware Components

The prototype wheel loader was baseline tested according to a steering-only cycle during which all other hydraulic functions are inactive, in order to characterize the steering system contribution to the energy losses incurred during the event. The stock machine had a valve controlled (hydrostatic) steering system, for which the valve alone is responsible for 61% (2.14MJ), which is more than the entire energy losses incurred with the DC steering system (1.52MJ).

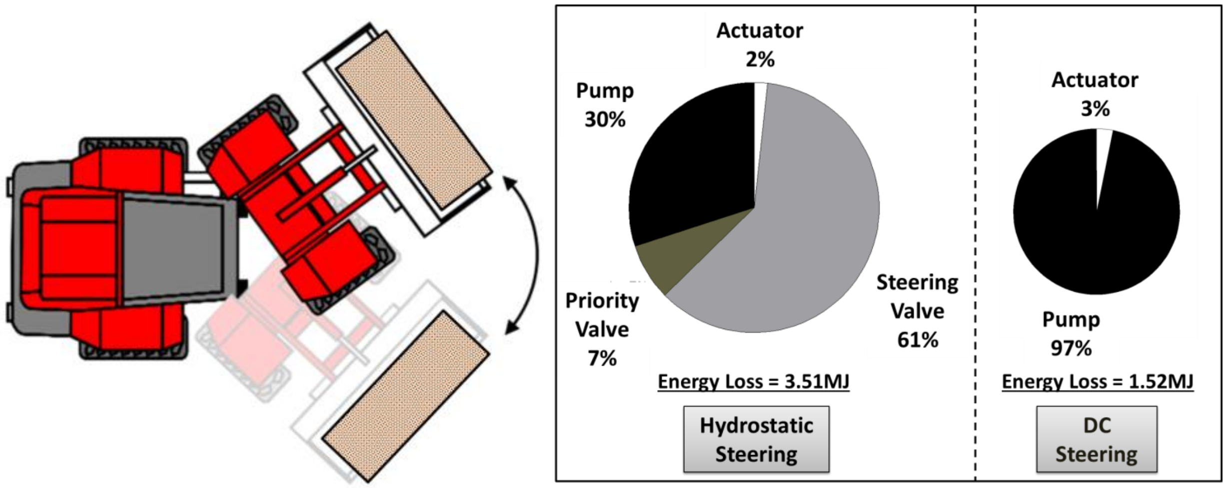


Fig. 12: Steering-only Cycle (left) and Energy Losses Comparison (right)

The reduced energy losses of the DC steering system translate into 14.5% fuel-savings, 22.6% increased productivity, for an overall fuel usage efficiency boost of 43.5% as shown in Table 1. Fuel consumption is measured by weighing the mass of an auxiliary fuel tank pre- and post-testing. Steering work is computed by integrating the product of steering torque and articulation velocity over the event time. Fuel efficiency is determined by taking the ratio of steering work done per fuel mass consumed.

Table 1: Systems Fuel Consumption, Productivity, and Efficiency Comparison

	Fuel Consumption [kg]	Total Steering Work Done by Machine [MJ]	Steering Work per Fuel Mass [MJ/kg]
Conventional Valve Controlled Steering	0.291	0.639	2.232
New DC Steering	0.249	0.784	3.203
Difference	-14.5%	22.6%	43.5%

Stability control systems geared towards wheel-steered passenger vehicles and articulated heavy commercial vehicles have seen steady progress and have been under rigorous research and development for the past few decades. On the other hand, the off-highway machinery sector has lagged behind in this area and very few publications that deal with this topic are found in literature. The purpose of an active steering controller is to provide corrective action by adjusting the steering angle to follow the path as intended by the driver. Hence, the aggregate articulation angle is a combination of the driver input to follow a certain path and the automatic controller command to attenuate the disturbances.

A standard dynamic maneuver, J-Turn, was utilized to evaluate the effectiveness of the stability control algorithm. To induce lateral instability at low-to-moderate speeds that off-highway vehicles typically travel at, a low friction surface was modeled. As depicted in Fig. 13, the purpose of the stability controller is to get the vehicle to follow the desired path by the operator, up to the allowable adhesion limits of the road surface. When the yaw stability control system is inactive, the vehicle skids sideways and tracks a larger curvature path, or in some instances loses control and spinout.

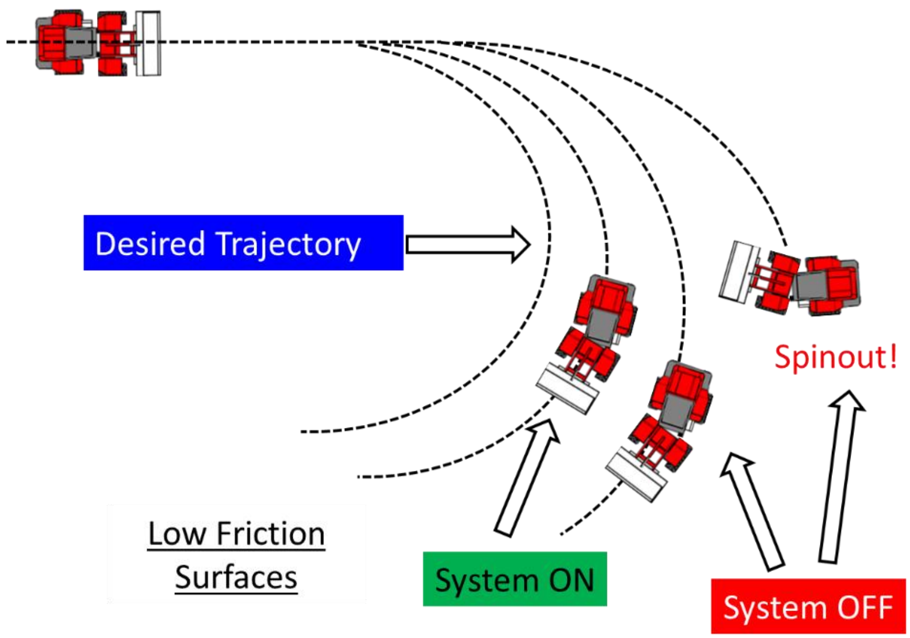


Fig. 13: J-Turn Maneuver on Low Friction Surfaces.

A suitable test track was selected to have the appropriate size and surface conditions that allow for conducting dynamic maneuvers at appropriate speeds in a controlled manner. The prototype test vehicle has a maximum speed of 20km/h. Therefore, in order to induce lateral instabilities in the prototype vehicle, a low friction surface is required. The selected test track is paved with gravel, thus the road surface is composed of snow-covered gravel as shown in Fig. 14. Several J-Turn maneuvers are conducted at 20 km/h with the stability control system turned on and off. The results are shown in Fig. 15.

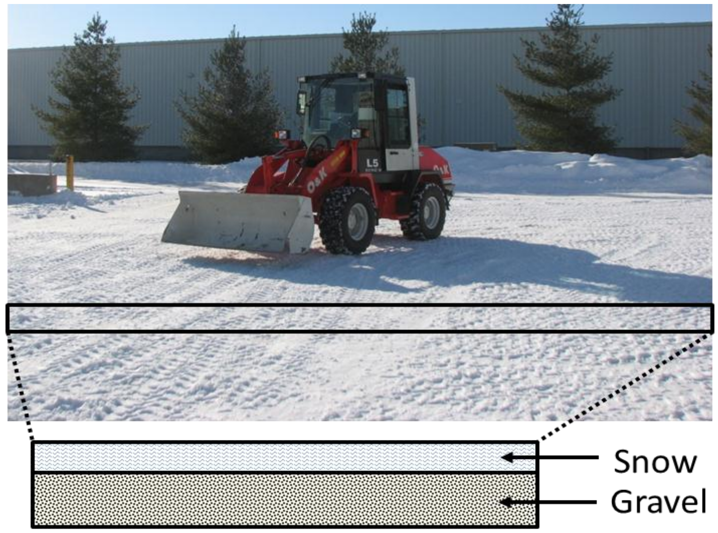


Fig. 14: Low-friction Surface Composition.

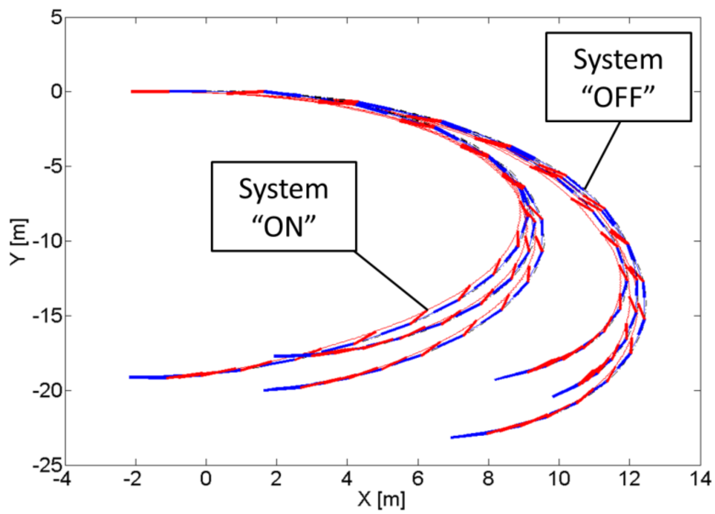


Fig. 15: J-Turn Maneuver Experimental Results.

Given that in most real-world applications not all of the system states can be measured, for various considerations, the concept of virtual sensing gains favorability for its effectiveness and convenience in providing critical information that would otherwise be hard or costly to retrieve. In this case, a virtual sensor that estimates an articulated frame steering vehicle's front frame yaw angle rate is investigated for its application in the vehicle active yaw stability. Fig. 16 shows the block diagram of the designed observer structure.

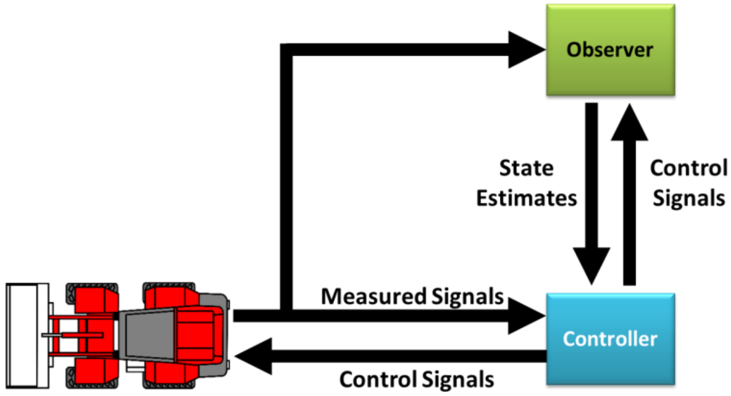


Fig. 16: State Observer Block Diagram.

To permit executing numerical simulations and conducting measurements on the prototype test vehicle, a controller was first designed to meet specified performance criteria relative to command tracking, response, and stability. An LQE observer design is selected for implementation on the test vehicle, and the results for the comparison between the yaw rate virtual sensor and the measured yaw rate are shown in Fig. 17.

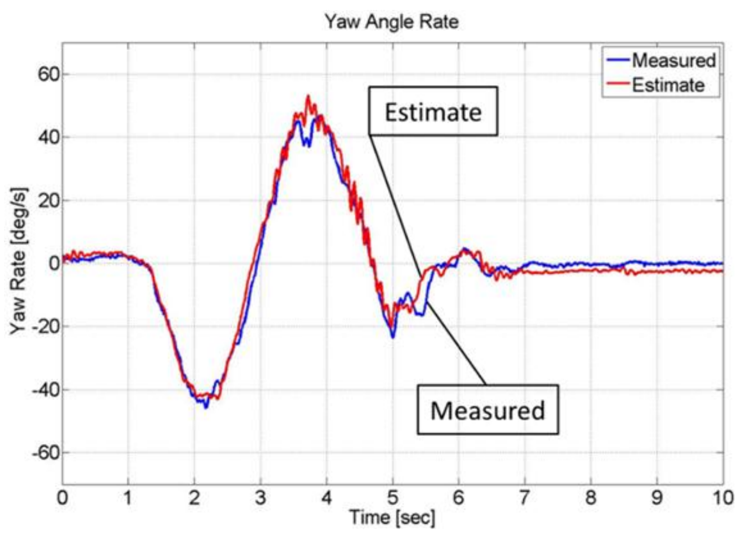


Fig. 17: Yaw rate measured and estimated quantities for a lane changing maneuver.

In the realm of automotive, agricultural, construction, and earth-moving equipment industries, an additional highly desired feature that has been steadily trending is the capability to offer remote and autonomous operation. One scenario for implementing remote operation, which has gained favorability in the past decade, is by having a central command station where one or more expert human operators can deploy, monitor, and control multiple machines to perform a certain task or set of tasks. At the same time, machines that are equipped with appropriate sensors can be programmed to perform certain tasks without real-time control by a human operator. In the case where machines are required to perform precise motion maneuvers, a global position system (GPS) sensor can be utilized to accurately guide the machine with a precision that can be superior to that of an expert human operator. The new DC steering technology was retrofitted for this purpose. For this work, XBee Series 1 modules are selected given their signal reliability, relative ease of programming and setup, adequate operating range, and reasonable cost given the application on hand. The new system setup is shown in Fig. 18.

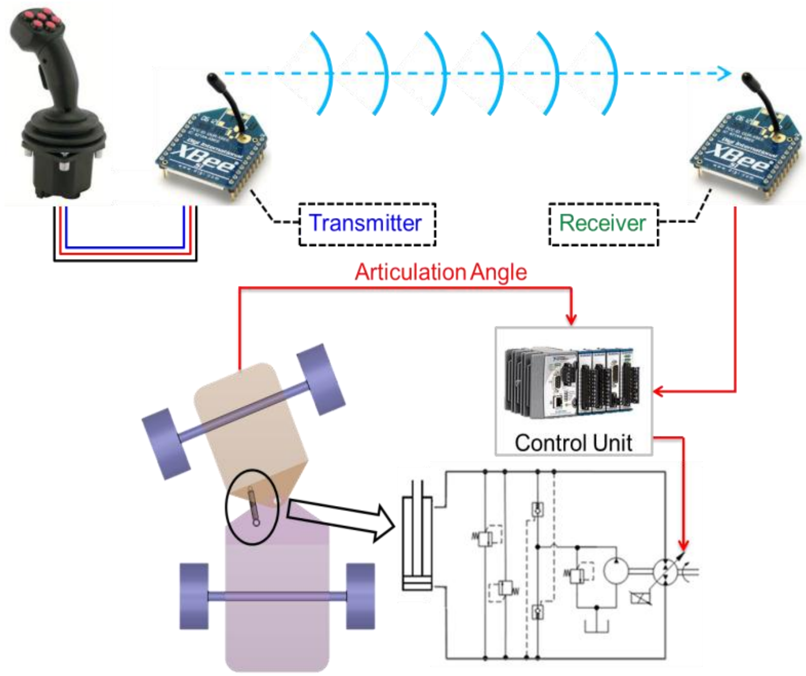


Fig. 18: Wireless Remote Control of DC Steering System

Advanced Energy-Saving Hybrid Power Trains

Research in this area focuses on investigating the feasibility and performance of alternative drive line technologies for different types of vehicles. The aim is to develop system concepts for minimizing fuel consumption and exhaust emissions without limiting the vehicle's driving power. A special software tool called PSDD (Power Split Drive Design) has been developed to support virtual prototyping of power split drives, multi-motor hydrostatic transmissions and hydraulic hybrid power train configurations. The research activities are supported by performance measurements using pump and motor test rigs and a hardware-in-the-loop power train test rigs based on hydrostatic dynamometers. Current areas of research include:

- Investigating power split hydraulic transmission for heavy on-road and off-highway applications
- Virtual prototyping of power split drives and hydraulic hybrid power trains
- Optimal control of hybrid transmissions to aid in vehicle baselining and optimal sizing

Novel Blended Hybrid Architecture

During 2014 research continued on a novel transmission architecture for on-road and off-highway vehicles. This so call "Blended Hydraulic Hybrid" architecture was originally proposed by Sprengel and Ivantysynova in 2012 (Fig. 19) and has several advantages over existing hydraulic hybrid transmission configurations. At its core the blended hybrid combines a hydrostatic transmission with a uniquely connected high pressure accumulator. This partial separation of power transmission from energy storage enables the blended hybrid to maximize efficiency through an optimal combination of system pressure and unit displacements. In contrast conventional series hydraulic hybrids require the transmission to function at the current accumulator pressure often resulting in inefficient operation at high pressures and low unit displacements. The hydrostatic path also enables the blended hybrid to rapidly increase pressure to meet the driver's demand yielding a powerful and responsive transmission. This is counter to series hybrids which due to the compliance inherent in their high pressure accumulators permit only a relatively slow change in system pressure. The inability of series hybrids to rapidly change pressure may result in sluggish response and poor driver feel if the current system pressure is insufficient to meet the driver's demand, a deficiency which is solved with the blended hybrid architecture. Finally the blended hybrid removes the need for over center units connected to the wheels which may have benefits in certain applications.

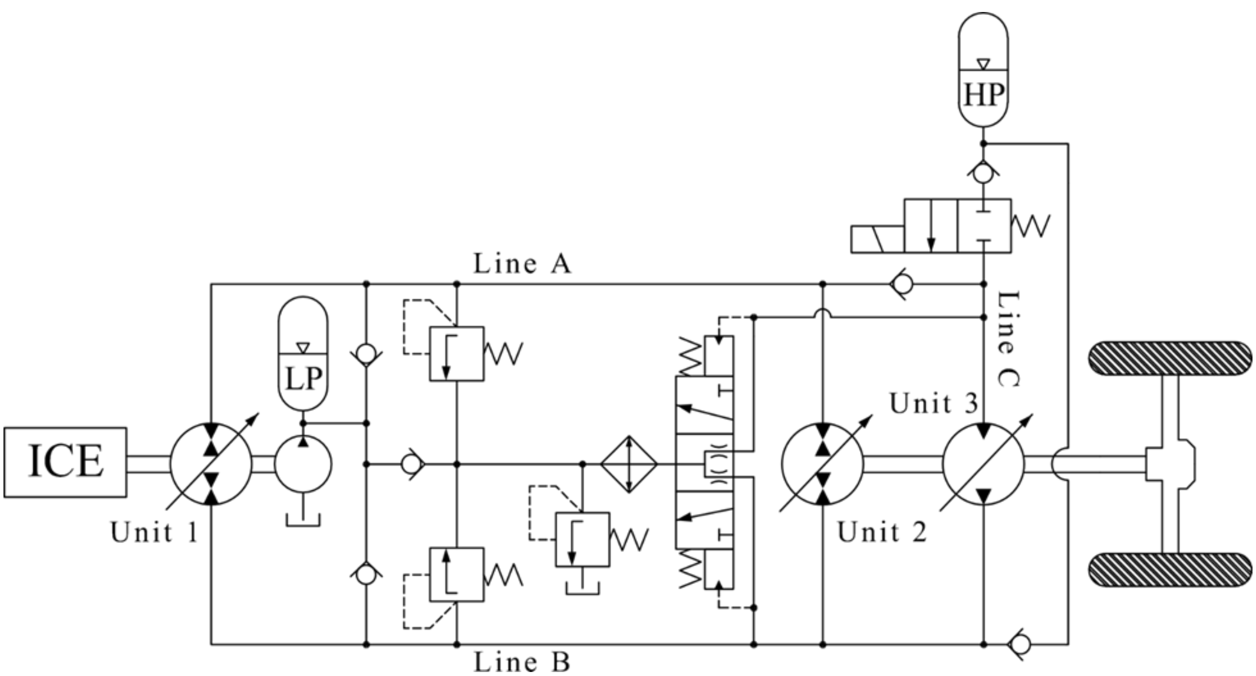


Fig. 19: Blended Hybrid Architecture

During 2014 three research papers were published investigating the blended hybrid. In the first paper Sprengel and Ivantysynova proposed replacing the hydraulic path in a conventional series hybrid power split transmission (PST) with a blended hybrid transmission yielding a novel blended hybrid PST. Power split transmissions are an advanced system architecture which use a planetary gear train to merge power between an efficient mechanical path and a flexible hybrid path. The resulting blended hybrid PST retains the response and performance of the base blended hybrid transmission while further increasing its efficiency. In a second paper Sprengel and Ivantysynova compared the novel blended hybrid and blended hybrid PST transmissions with baseline manual and automatic transmissions and conventional series hydraulic hybrid and series hydraulic hybrid PSTs. To ensure a fair comparison and remove any designer bias all six transmissions were optimally controlled by means of dynamic programming over a standard drive cycle. This investigation showed that both blended hybrid architectures yielded superior fuel economy over the baseline transmissions as well as their respective conventional hydraulic hybrid transmissions. In a final paper Sprengel and Ivantysynova detailed work on a new blended hybrid hardware-in-the-loop (HIL) test rig which was constructed in the Maha lab (Fig. 20). This work demonstrated the blended hybrid's feasibility by evaluating and validating the transmission under the same dynamic conditions present in a real vehicle.

Fig. 20: Blended hybrid hardware-in-the-loop test rig

Presented in this third paper were measurement results (Fig. 21) from the HIL test rig which demonstrate the blended hybrid's distinct modes of operation. First in section A the transmission operates in a pure hydrostatic mode, in section B the transmission switches to a combined hydrostatic and hybrid mode, section C demonstrates pure hybrid driving, while second D highlights regenerative braking.

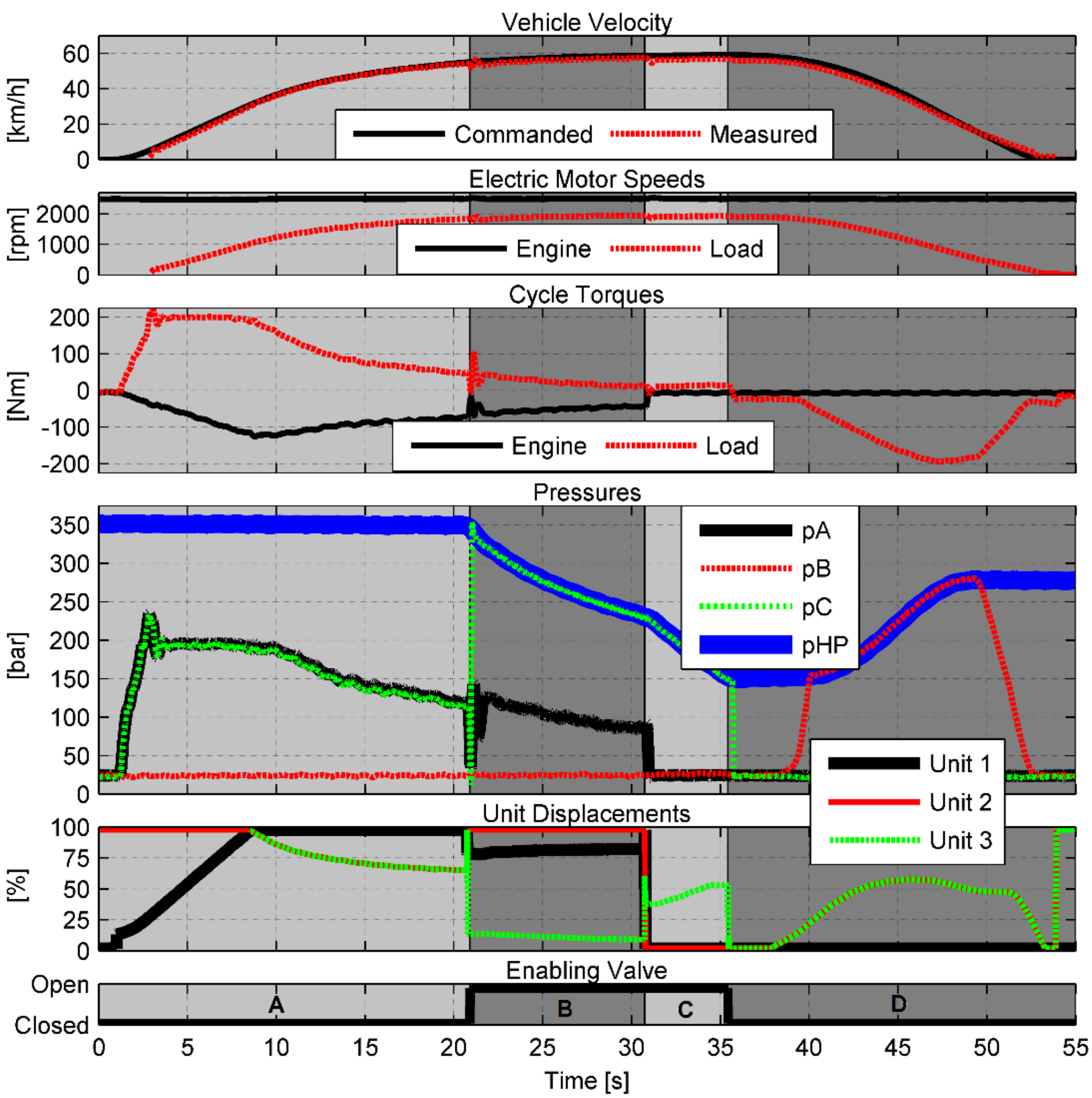


Fig. 21: Blended hybrid HIL measurements

Optimal Control

It is well know that how a vehicle is controlled has a major impact on fuel economy, this influence is especially pronounced in hybrid powertrains where multiple power sources must be balanced. In fact the influence of powertrain control is so significant that it often obscures which base system architecture is fundamentally superior for a given application. To address this issue researches at the Maha lab use dynamic programming (DP) to optimally control various powertrain and machine architectures thereby eliminating all influences of control on system performance and efficiency. While DP is a powerful tool capable of furthering the fundamental understanding of many systems it is also computationally demanding commonly requiring the execution of billions of dynamic simulations. Over the course of the preceding two years researchers at the Maha lab have addressed this inherent computational burden by developing improved methods of implementing DP which yielded a 2+ order of magnitude reduction in runtime. Simultaneously dynamic programming fidelity has significantly improved with the technique now being implemented directly on high fidelity MATLAB Simulink models rather than the simplified plant models used in years past. These tools enable researchers at the lab further the fundamental knowledge of system design while also developing novel control strategies which may not be intuitive but are nevertheless highly effective.

PSDD - Power Split Drive Design Simulation

One of the principle drivers for using hydraulic hybrid transmissions in many applications are the advantages gained by combining an infinitely variable transmissions with energy recovery and storage. However in order to fully and accurately model these systems the highly non-linear loss behaviors of all powertrain components must be fully considered. In fact these non-linear losses are often such that analytical models are insufficient accurately describe their behavior. In these cases detailed empirical model are essential for generating high fidelity system models. While empirical models for both engine and vehicle operation are often obtained from outside sources the Maha lab has made detailed loss measurements on a wide range of hydraulic units which enable very high fidelity transmission modeling. Over the years researchers at the Maha lab have compiled and validated a set of component models in MATLAB Simulink (often referred to as Power Split Drive Design (PSDD)) which enables various powertrain configurations to be rapidly constructed and evaluated. An example of PSDD in use can be seen in Fig. 22. This tool enables researchers at the lab to rapidly change system architectures and predict with a high degree of accuracy how a given system will perform. These component libraries can also be optimally controlled with a new dynamic programming algorithm develop within the Maha lab further increasing the range of discoveries now possible.

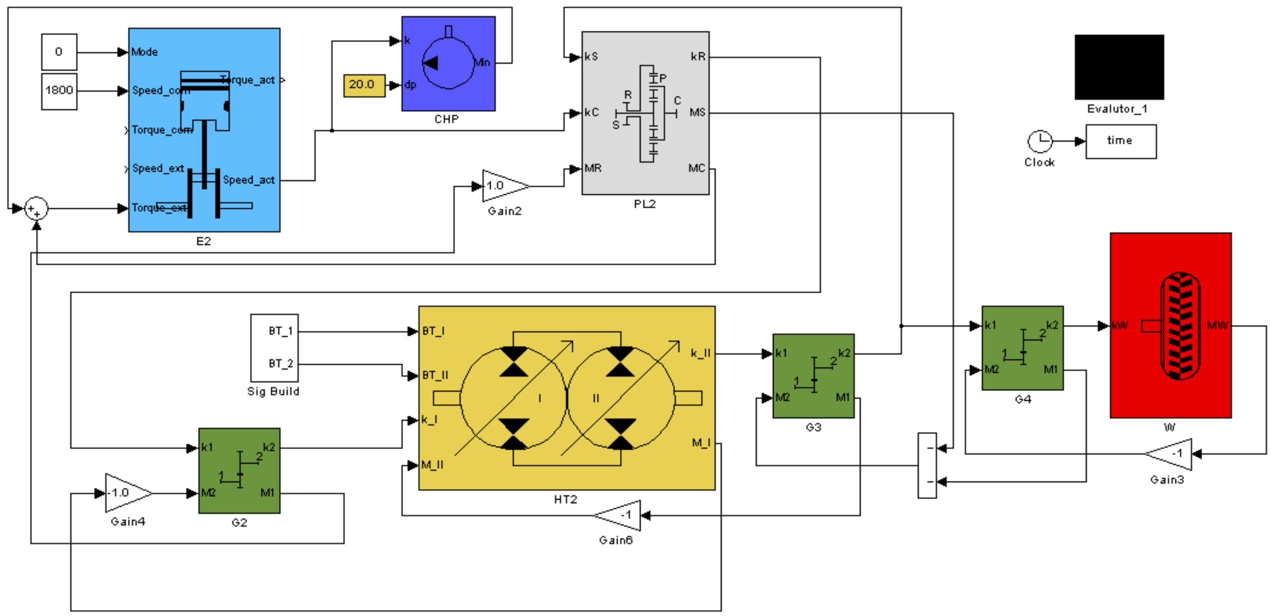


Fig. 22: PSDD Simulation Model

1.1.3 Research into Design and Optimization of Piston Pumps and Motors

Advances in Modeling, Fundamental Understanding, and Optimization of Axial Piston Pumps

Maha researchers have combined experimental research with advanced multi-domain modeling to discover the secrets of the fluid film in the important swashplate type aixal piston pump interfaces as a product of more than 15 years of experience and research by numerious individuals. A major breakthrough was the discovery of the fundamental importance of elasto-hydrodynamic and thermal effects on film generation and film stability. Recent research results have proven that these phenomena are responsible for substantial modification of the fluid film thickness and need to be considered in addition to micro and macro motion effects to correctly predict fluid film behavior. The inclusion of these additional effects however, increases enormously the complexity of the simulation model and has required tailoring numerical techniques and the modeling approach to the specific needs of each interface. The researchers created the world's first fully-coupled fluid-structure interaction and multi-body dynamics simulation model that also considers thermal deformation of main interfaces and their influence on fluid film behavior.

The model simulates the full fluid film lubrication performance between the three primary sliding interfaces of a swash plate type axial piston pump or motor (Fig. 23):

- Piston/cylinder block bore interface
- Cylinder block/valve plate interface
- Slipper/swashplate interface

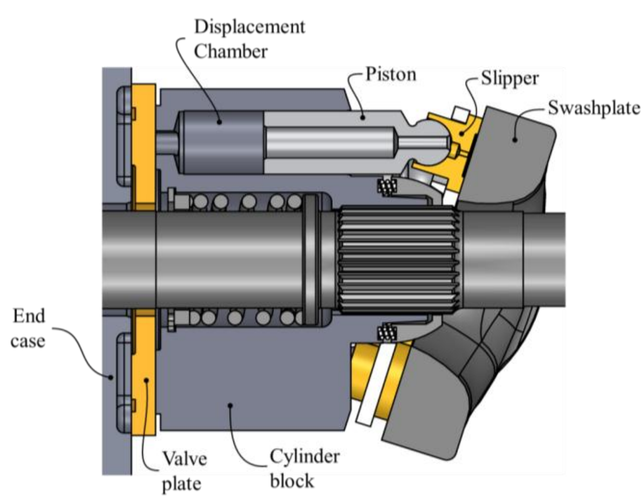


Fig. 23: Swash-Plate Type Axial Piston Machine Cross Section

The primary function of these lubricating fluid films is to transmit large compressive loads across the sliding interfaces as well as limit the leakage of fluid from the displacement chamber into the pump or motor housing.

Each lubricating interface model allows capturing the complex fluid-structure interaction and thermal phenomena affecting the non-isothermal fluid film conditions. In particular, the model considers the change in fluid film thickness and squeeze film effect due to the component micro-motion as well as the solid boundaries elastic deformations. The elastic deformation of the surfaces is related to the fluid film pressure and thermal stresses.

The model couples iteratively different numerical domains and solution schemes, as depicted for the case of the piston/cylinder by Fig. 24 and Fig. 25 for the slipper/swashplate interface. Different numerical methods, discretization schemes and solvers are necessary in order to solve all different physical problems/domains. The communication and coupling is allowed through advanced interpolation methods based on nearest neighbors searching. The three main numerical modules are briefly described as follows:

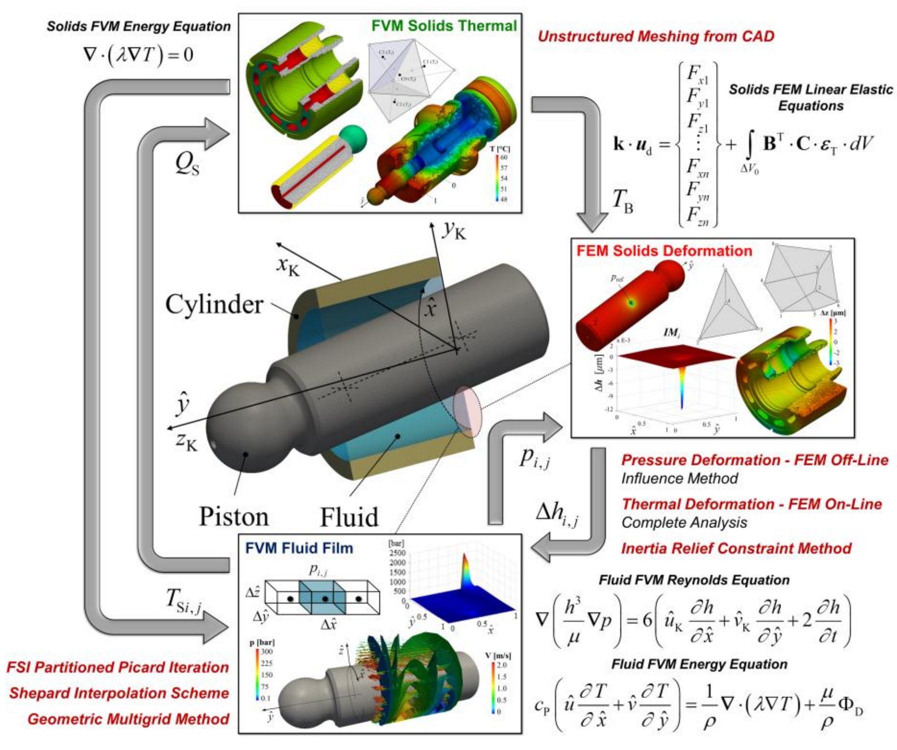


Fig. 24: Fluid Structure Interaction and Thermal Model

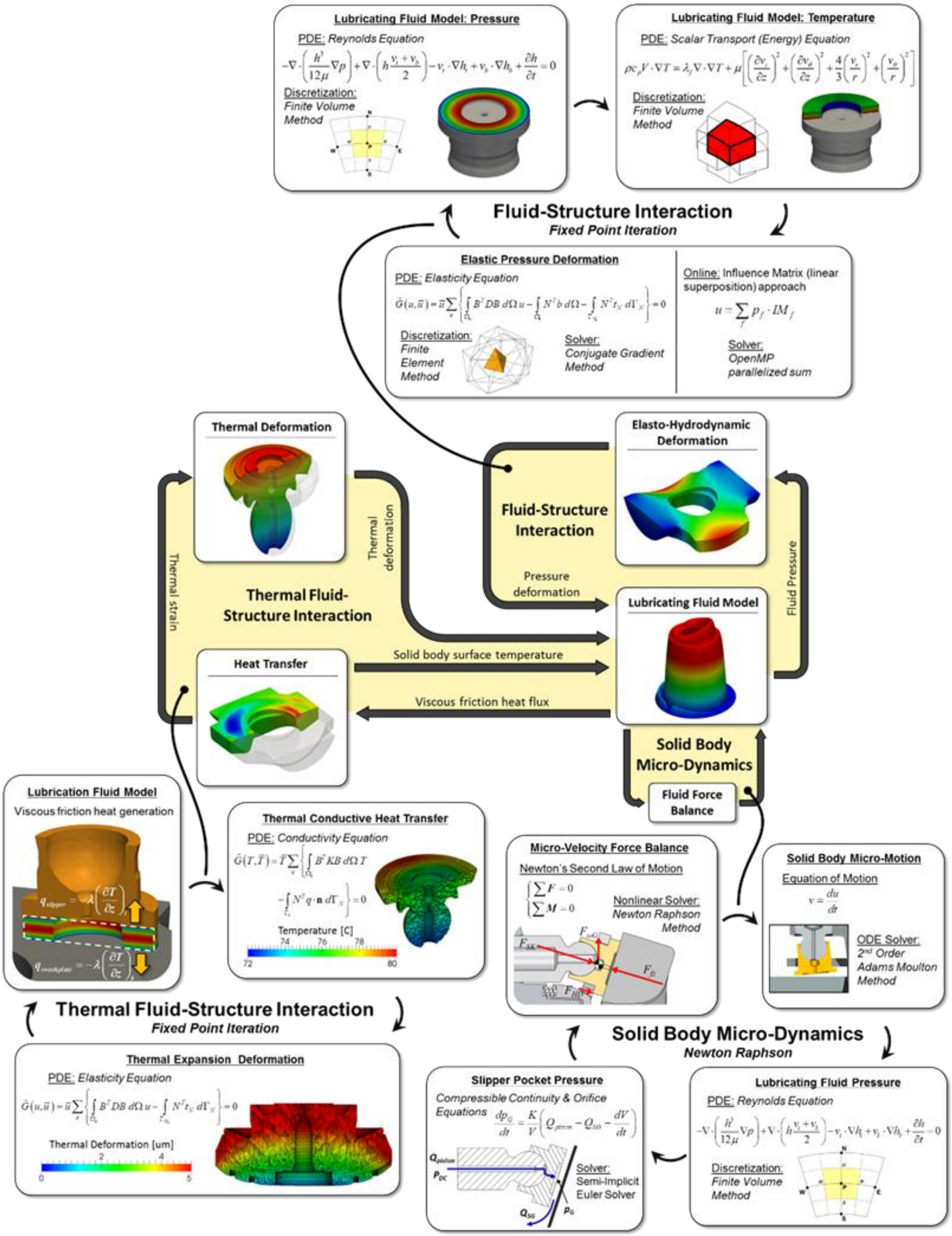


Fig. 25: Slipper/Swashplate Fluid-Structure-Thermal Interaction Model

1) **Fluid Film Finite Volume Non-Isothermal Flow Model:** this module predicts the instantaneous pressure distribution and temperature distribution in the lubricating interface fluid film. The solution of Reynolds and energy equations is obtained simultaneously. The change in fluid properties due to pressure field, p, and temperature field, T, is considered. The non-linearity introduced by the change in fluid film due to pressure surface elastic deformation, Δh, is coupled with the non-isothermal fluid film model via a partitioned fluid-structure interaction analysis, based on an outer fixed-point iteration scheme. The Reynolds equation is solved using a **Geometric Multigrid** algorithm to improve accuracy and performance.
2) **Solids Finite Element Heat Transfer Model:** this module calculates the solid bodies' temperature distributions. The conductive form of the energy equation is solved. Based on the heat fluxes due to viscous dissipation, Q_S, the temperature distribution of the solid parts, T_B, is predicted. The temperature distribution is used as more accurate surface temperature boundary, T_S, for the fluid film and to determine the thermal stress condition for the solid parts. High geometrical accuracy for the solid bodies is allowed through the **unstructured** discretization, which allows generating solid geometries directly from CAD software.
3) **Solids Finite Element Elastic Deformation Model:** this module allows determining the elastic deformation of the solid bodies due to external fluid film pressure and internal thermal loading. Two different methods are used according to the type of load. The solution of pressure surface elastic deformation is obtained using an influence method, running complete FEM analysis off-line. The solution of the thermal deformation is achieved running complete FEM analysis at run-time. The ultimate information provided by this numerical model is the total deflection of the bounding surface, Δh. FEM analysis based on CAD solid models coupled with the inclusion of advanced constraints methods, such as **Inertia Relief**, allows a very accurate prediction of the fluid film boundaries surface elastic deformations.

The model, validated through the comparison with several measurements, is used by Maha researchers to discover lubricating interface physical behavior and to study the energy dissipation through viscous friction and leakage flow.

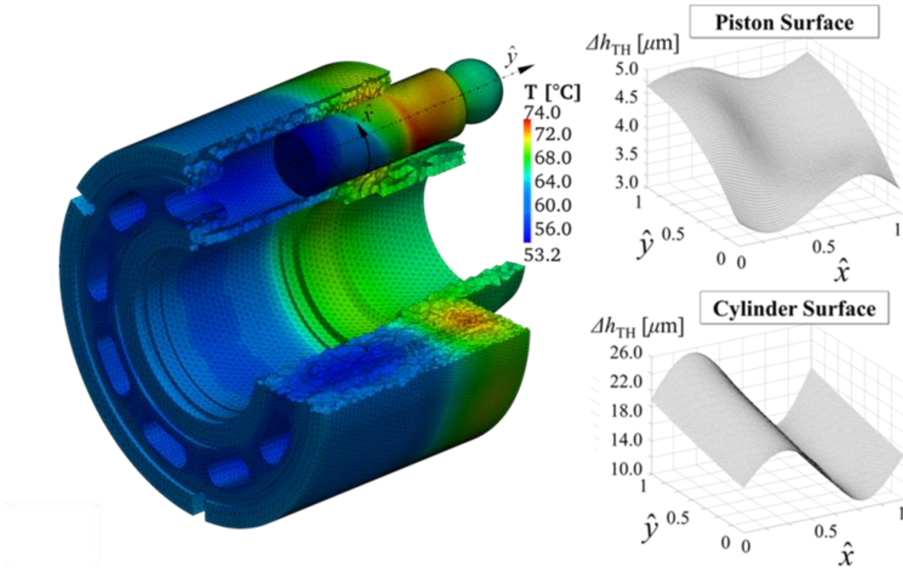


Fig. 26: Axial Piston Machine Piston/Cylinder Block Temperature Distribution (Left) and Surface Thermal Deformations for a High Load Operating Condition (Right)

Thermal expansion due to energy dissipation in the fluid film can lead to major changes of the fluid film thickness and shape. For pumps using a brass bushing pressed into the cylinder made from steel, these thermal expansions introduce a wavy surface shape that helps to improve the load carrying ability of the fluid film, as shown by Fig. 26. This explains why all pumps and motors working at extreme high pressures have to have a brass bushing in order to achieve a reliable operation and acceptable efficiency values.

This discovery together with the developed multi-physics model forms the starting point for a new computational based design approach. The model will be used to investigate better interface designs, including novel material combinations and shaped surfaces. These innovative interface designs will lead to better machine performance and increased efficiency over a wider range of operating conditions.

The slipper swashplate interface model incorporates the effects of both pressure and thermal deformations. These deformations affect both the slipper and the swashplate running surfaces. Fig. **25** illustrates how the multiple non-linear physical effects interactions are numerically modeled to enable successful prediction of slipper and swashplate lubrication performance.

Another important factor affecting the performance of all three lubricating interfaces is surface shaping occurring during the pump wear-in process. Slipper designs which exhibited frequent low fluid film thicknesses were prone to having microns of wear during the initial pump run-in process. These microns of wear on the inner or outer sealing land edges enable steady state full film lubrication. The stylus profilometer detailed in its respective section of this report has proven extremely valuable to validating the simulation results and actual lubricating surface wear.

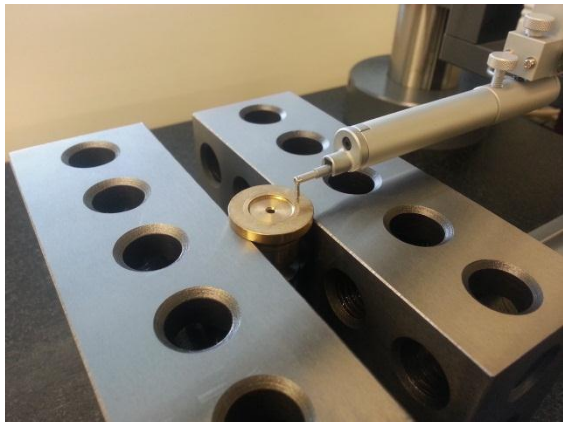


Fig. 27: Measuring Slipper Wear Using the Mitutoyo Stylus Profilometer

A specially modified piston pump was constructed to allow for the insertion of six high-speed eddy current displacement transducers to be mounted inside of the swashplate. As the rotating slippers passed over the stationary sensor face, the specially calibrated sensors would measure the dynamic film thickness between the swashplate and slipper allowing for a direct comparison to simulation results. A diagram of pump modifications to incorporate the sensors is shown in Fig. 28.

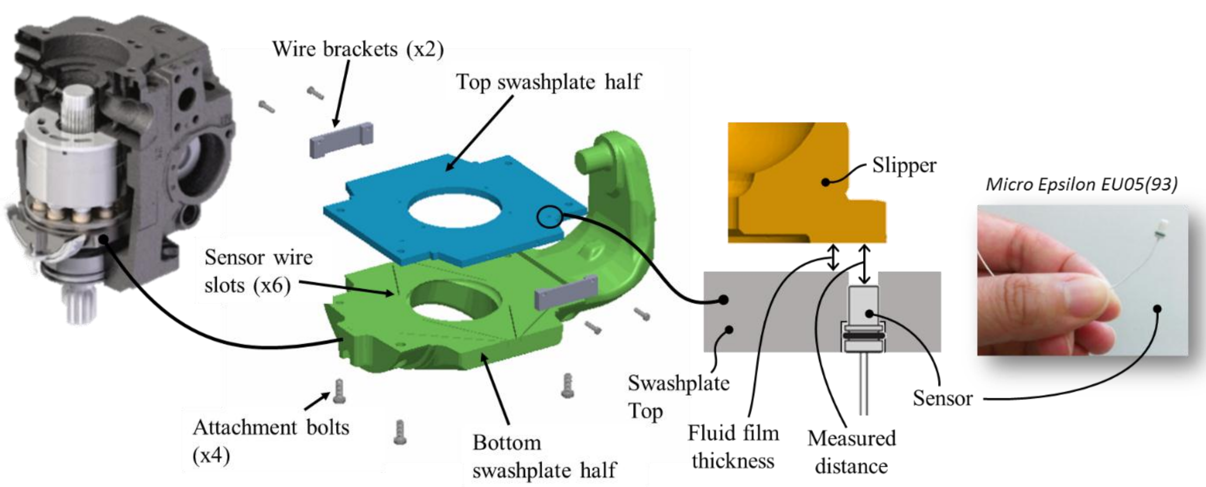


Fig. 28: Modified Pump Incorporating Sensors

The slipper test rig was used to investigate the impact of slipper wear on fluid film thickness. Fig. **29** (left) shows the measured film thickness at each of the six sensor locations with a diagram of the sensor location number at the bottom. The film thicknesses for each of the nine slippers in the rotating kit during initial operation are plotted with a thin line, and after the run-in wear period, the film thicknesses are plotted with a thick line. It is clear that especially during the high pressure stroke, the slipper wear has a significant impact on changing the lubrication operation. Simulations for the same operating condition both considering the nominal (un-worn) slipper design as well as including the run-in wear profile are presented in Fig. 29 (right). Similar changes in film thickness and tilting behavior between the nominal and worn slipper designs are predicted.

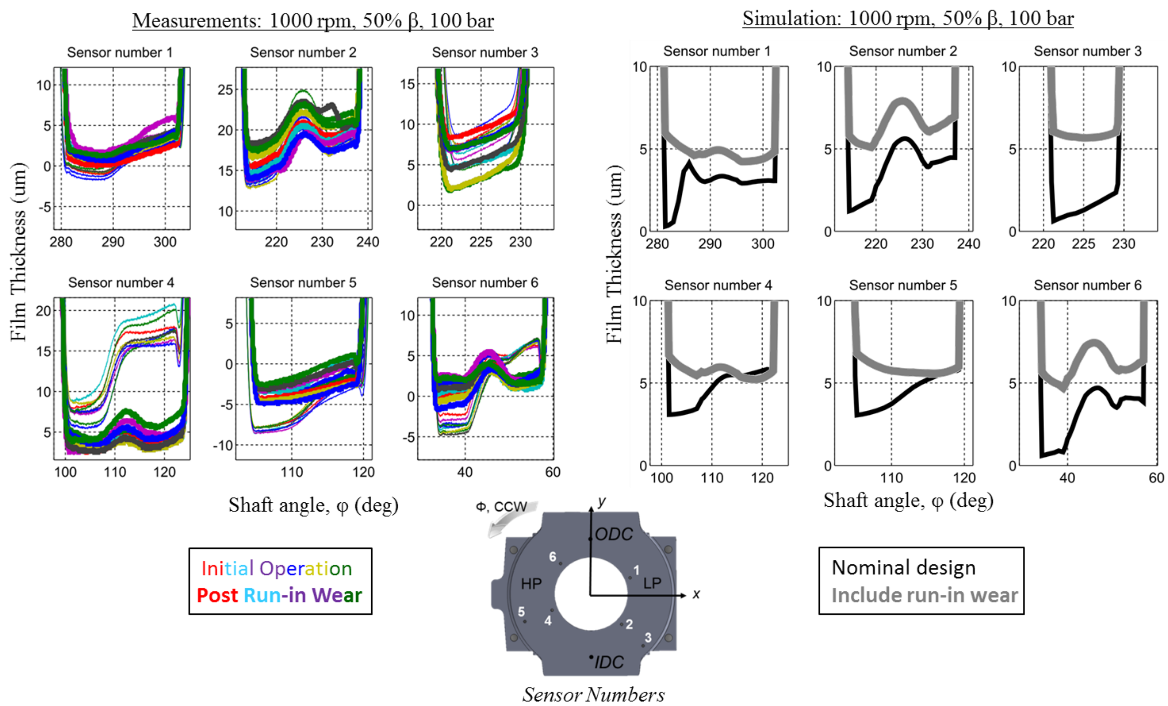


Fig. 29: Measured and Simulated Slipper Fluid Film Thickness

The cylinder block/valve plate interface was validated against test data this year. A pump was specially fitted with thermocouples arranged near the valve plate surface. Fig. 30 compares the predicted temperatures for these locations based on simulation and the measured values. The level of agreement between the two temperature fields speaks to the validity of the modelling approach considering thermal and pressure deformation of the solid parts.

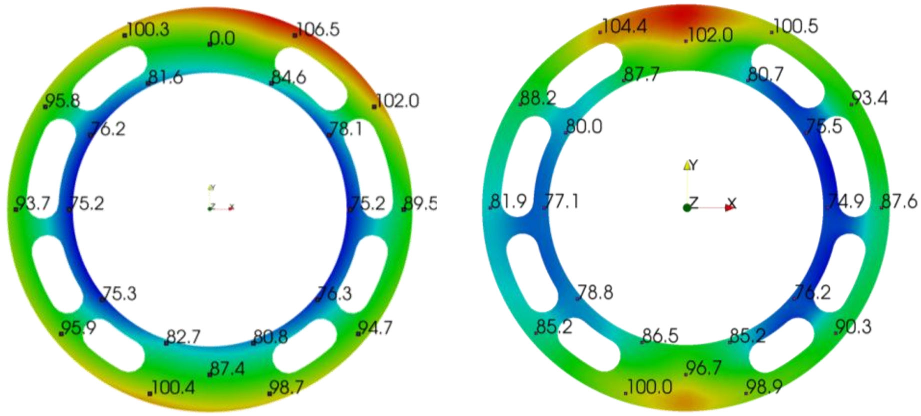


Fig. 30: Comparison of Measured (Left) and Simulated (Right) Temperature Distribution of the Valve Plate at 2000 rpm, 200 bar, and 50% Displacement.

Advanced Port and Case Flow Temperature Prediction for Axial Piston Machines

The solids finite element heat transfer model included in the Fluid-Structure-Thermal Interaction model requires inlet port temperature, outlet port temperature and case flow temperature as thermal boundary conditions. When the Fluid-Structure-Thermal Interaction model is used to analyze or optimize an existing pump or motor, the required boundary temperatures can be taken from steady state measurement conducted on the pump or motor of interest. However, when the model is used to support the design of new pumps and motors, the measurement data are not available. Therefore a port and case flow temperature prediction model was proposed to predict the unknown outlet port and case flow temperature for a chosen inlet temperature based on known fluid properties and calculated energy dissipation in the rotating group of an axial piston pump. This temperature prediction model also considers the temperature change due to fluid compression/expansion and estimated churning losses for a given axial piston machine.

As shown in Fig. 31, the red dashed line connects the inlet and outlet state in the enthalpy entropy diagram of the hydraulic fluid based on the measured pressure and temperature. Due to the heat transfer, the real compression process does not follow a vertical line. Since in a real axial piston machine, the fluid pressure changes only over a very short time period and the heat transfer occurs under constant pressure mostly, the real compression process has been divided into two vectors as shown in Fig. 31. The vertical black vector represents an adiabatic compression and the green vector represents the temperature variation due to the heat transfer at constant pressure. This allows separate study on the temperature variation due to the pressure change and due to the heat transfer.

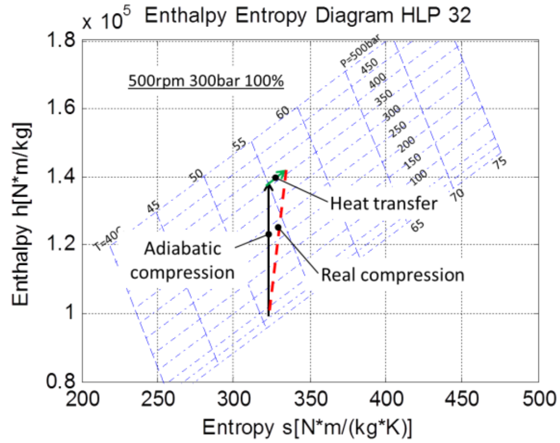


Fig. 31: Enthalpy Entropy Diagram of the Hydraulic Fluid

The case temperature variation can also be divided into the adiabatic compression or expansion and the heat transfer.

Therefore the proposed pump outlet port and case flow temperatures prediction model includes two separated modules, the thermodynamic module, and the heat transfer module, considering the temperature variation due to the pressure change.

- The thermodynamic module predicts the temperature variation due to the pressure changes assuming adiabatic compression and expansion. The enthalpy and entropy of the compressible fluid need to be solved as a necessary step.
- The heat transfer module corrects the result of thermodynamic module using heat transfer calculation.

In order to use the port and case flow temperature prediction model coupled with the fluid structure and thermal interaction model to support design new pumps and motors, the simulation need to start with given pump design, given inlet port temperature, given fluid properties and estimated outlet port and case flow temperatures. In a second step the pump outlet port and case flow temperature prediction model is used to calculate the outlet port temperature and the case flow temperature based on the power loss and the outlet and case flow rate from the fluid structure and thermal interaction model. In a third step the obtained outlet port and case flow temperature will be used to rerun the fluid structure and thermal interaction model to update the power loss and the outlet and case flow rate. The described iteration cycle between the two models will be repeated until the outlet and case flow temperature converge as shown in Fig. 32.

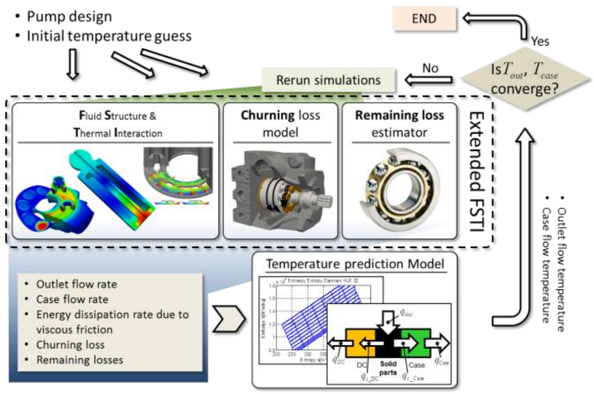


Fig. 32: Iteration Cycle Between the Two Models

New Micro-Surface Shapes Study

One of the main activities of the center towards the improvement of current swash plate type axial piston machines is the investigation of micro-surface shaping and novel material combination in relation to the performance of the three main lubricating interfaces. The main goal is to achieve higher efficiency and increase load carrying capacity especially at low displacement and low pressure.

In 2008 the center had worked on the study of barrel and waved barrel like micro-surface shaping on the pistons surface. Also, in 2009 a wave like micro-surface shape was introduced on the piston's surface (Filed patent: 61/165, 661). In these cases, simulations had shown a potential improvement of up to 60% in total power loss. Most recently, the center has been investigating the impact of micro-surface shaping on the piston surface, shown in Fig. 33, along with varying gap heights on the overall performance of the machine through a fully coupled fluid structure interaction model in which thermal deformation and elastic deformation is considered that was developed in the center. From this model that is able to provide much more accurate predictions along with a combination of various micro-surface shapes and a decrease in the clearance between the piston and cylinder, simulations have shown potential improvements of overall power loss up to 30% at full displacement and 45% at partial displacements as shown in Fig. 34. Also, critical fluid film thicknesses and areas of friction are being investigated to better understand what is occurring between the piston and cylinder allowing to even better improve the overall operation of the machine as the clearance is reduced between the piston and the cylinder; the hydrodynamic pressure build up in the fluid allowing for this as a surface profile is added to the piston. Design studies are being conducted on the existing surface profiles to better understand the effect that the design parameters have on the results. Future plans include and optimization study extended to include the consideration of polynomial surfaces. Once these numerical studies are concluded, modern manufacturing will be utilized to produce prototypes and testing will be done on both the Tribo and EHD test rigs to verify the simulation results. These results represent a major breakthrough in this research direction and suggest an even deeper study of the possible new technology.

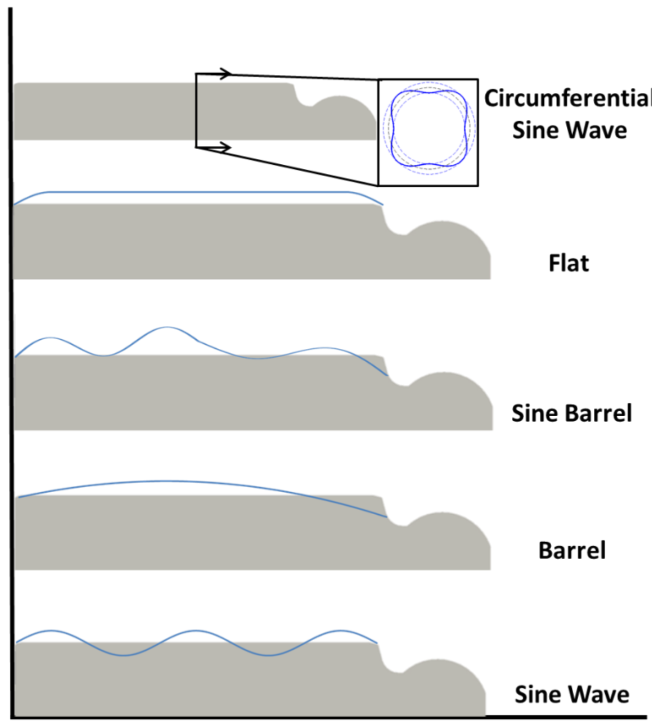


Fig. 33: Various Micro-Surface Shapes on the Piston Surface

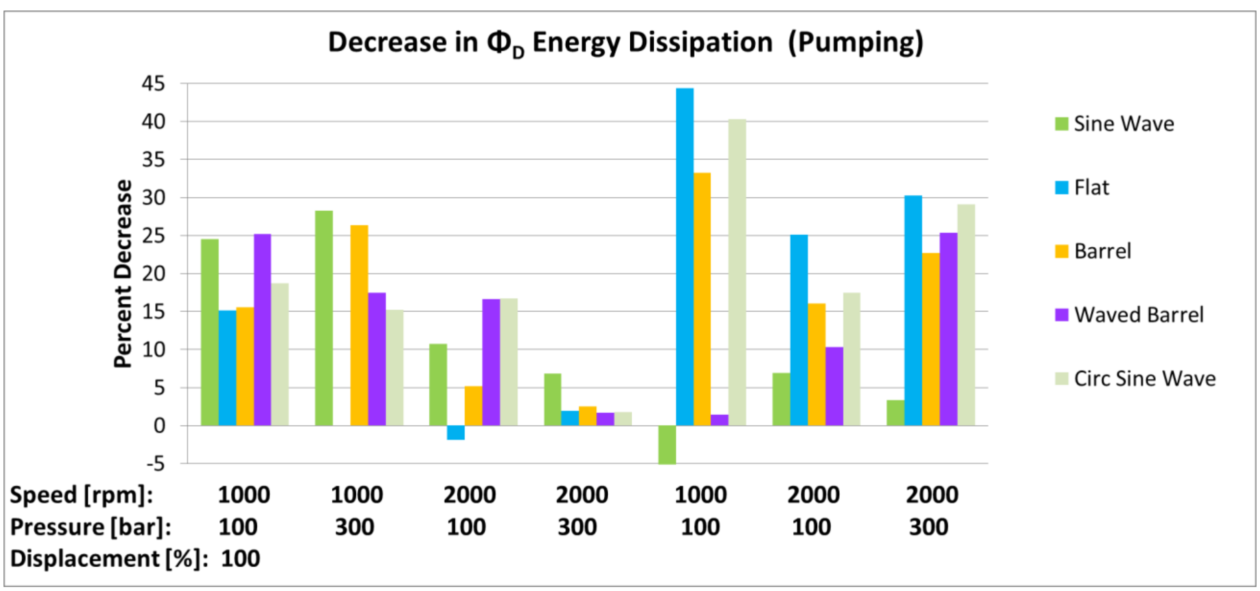


Fig. 34: Reduction in Energy Dissipation due to Micro-Surface Shaping of the Piston

Water Hydraulics

In 1905, Janney and Williams' use of mineral oil in their hydrostatic transmission triggered a large-scale replacement of water with oil as the working fluid in hydraulic systems (A Brief Hydraulics Encyclopaedia 2011). Today, however, water as a working fluid is an idea that is coming back into vogue due to the numerous advantages it offers: water is environmentally friendly (cheaper disposal than for oil) and nonflammable (safer), it has a higher thermal conductivity than oil (easier to cool the system), it has a higher bulk modulus (allows for more precise machine motion), and it has a lower viscosity (smaller line losses) (Krutz, & Chua 2004). That last property, viscosity, while advantageous in terms of reducing line losses, is actually the key obstacle in the implementation of "water hydraulics." This is because the viscosity of water is roughly 1/30th that of oil, which results in a low load-carrying capacity.

A low load-carrying capacity is detrimental to the operation of piston machines, which form the centerpiece of many hydraulic circuits, especially the highly efficient displacement-controlled circuits that are subject to detailed and continual investigation at the Maha Fluid Power Research Center. The higher the pressure difference across these machines, the more difficult it is to balance the pressure-dependent forces— e.g. the side load acting on a piston— using a low-viscosity fluid such as water. For this reason, the Center is currently working to find solutions that will aid water's load carrying ability in the lubricating interfaces of piston machines operating at high pressures, for example through clever micro-surface shaping at the piston-cylinder lubrication interface (the most critical lubrication interface in these machines; note: the height of the gap between piston and cylinder is on the order of microns).

To do this, the axial piston machine is used as a testing ground for novel design modifications aimed at improving the load-carrying ability of water, and the performance of these ideas is evaluated by simulating the behavior of the piston-cylinder lubrication interface over the course of one shaft revolution. The simulations are conducted using FSTI, the highly advanced non-isothermal "**F**luid **S**tructure **I**nteraction **M**odel" developed at Maha. FSTI calculates the leakage and power loss, as well as pressure buildup and lubricating gap heights associated with a given design over one shaft revolution, thus revealing the merits/demerits of that design, and allowing for comparison between different design modifications. Axial piston pumps were chosen as a testing ground for such design modifications because the pistons of this type of pump are subjected to an exceptionally large side load when running at high pressures, making this one of the most challenging scenarios water hydraulics will encounter.

One of the design modifications studied in detail in 2014 is an axial sine wave micro-surface shape on the piston, shown in Fig. 35. This shape has been studied by Monika's research team since 2012 for applications using oil as a working fluid under a variety of operating conditions by multiple researchers. Ashley Wondergem published her findings as part of the proceedings of the 8th FPNI Ph.D. Symposium on Fluid Power in Lappeenranta, Finland under the title "The Impact of the Surface Shape of the Piston on Power Losses" as well as in her master's thesis entitled "Piston/Cylinder Interface of Axial Piston Machines— Effect of Piston Micro-Surface Shaping."

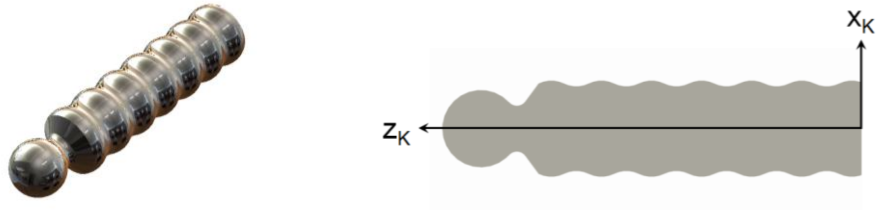


Fig. 35: Piston with an Axial Sine Wave Micro-Surface Shape (Left), Profile of the Same Piston in the x_K-z_K Plane (Right)

In terms of water hydraulics, the effects of the wave amplitude of this surface shaping on the pressure buildup in the piston-cylinder lubricating interface of a 75 cc unit were examined this past year. Near the end of the lubricating interface closest to the displacement chamber of the pump (the "DC End"), higher amplitudes— e.g. 12 μm— have shown favorable results, whereas near the other end of the lubricating interface (the "Case End"), the opposite is true and lower wave amplitudes— e.g. 4 μm— yield better pressure buildup. The point of having "proper" pressure buildup in the lubricating gap is to avoid mixed friction or even contact between the piston and the cylinder bore in which it sits, and so to understand why different wave amplitudes result in "favorable" pressure buildup near one end of the lubricating interface vs. the other, the two mechanisms by which piston-cylinder contact can occur in the lubricating interface must be understood.

Such insight lays the foundation on which new, better surface shape designs can be built. Water-lubricated piston machines will only function at high pressures if substantial friction/contact between piston and cylinder bore can be prevented, and the prevention of contact requires the manipulation of pressure buildup. With regards to this point, the 2014 investigation of the sine wave piston profile in a water-lubricated piston machine has been the step that must precede the leap toward a fully functioning design.

Noise Control and Acoustics

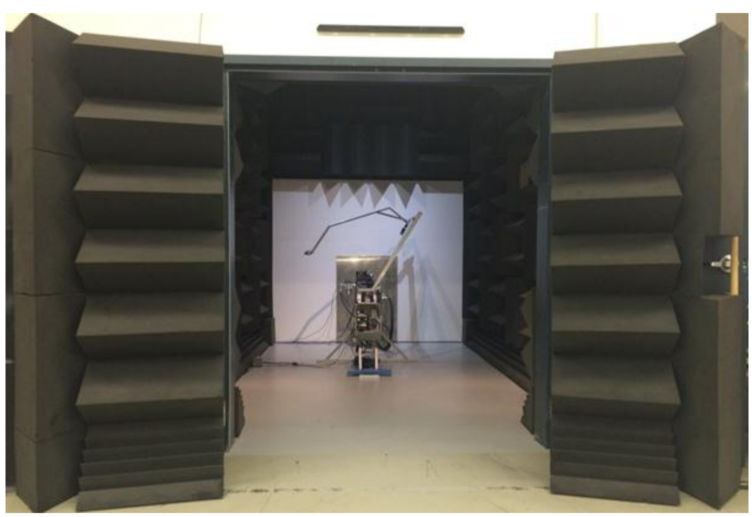


Fig. 36: Maha's Semi-Anechoic Chamber

The goal for this area of research is to understand the sources of noise within hydraulic systems. A fundamental understanding of noise generation for hydraulic systems will enable design of hydraulic components and systems. The use of complex hydraulic systems has led to the demand for a more comprehensive understanding of audible noise. The widespread use of axial-piston based hydraulic systems, within multiple industries, has motivated our research to center on the design of a pump/motor system.

The acoustic energy (Airborne Noise, ABN) emitted from the hydraulic system can be attributed to two main sources, namely, Fluid Borne Noise Sources (FBNS) and Structure Borne Noise Sources (SBNS). It is important that all projects consider both sources of noise.

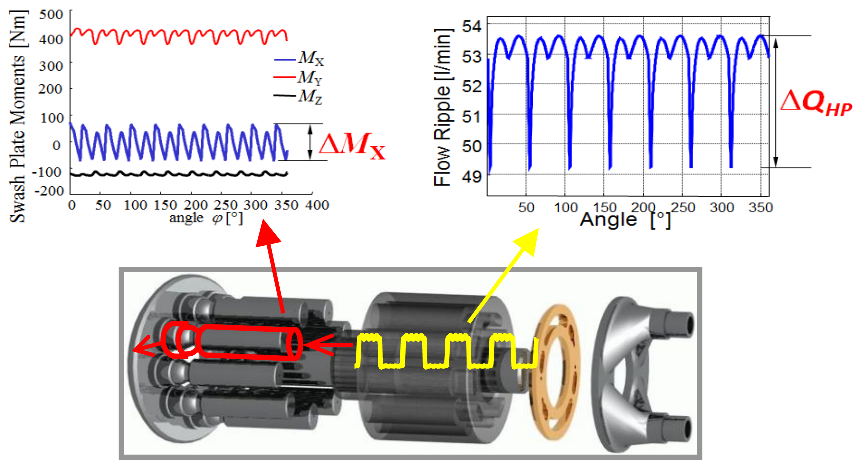


Fig. 37: Axial Piston Pump Showing the Fluid Borne and Structure Borne Noise Sources

VpOptim

The first approach aims to reduce noise generated by pumps and motors at the source level (FBNS and SBNS). Both Fluid Borne Noise Sources (FBNS) and Structure Borne Noise Sources (SBNS) are generated from the pressure changes in the displacement chambers. The most effective modification to a pump, in order to reduce noise sources, is a well-designed valve plate. VpOptim receives its name from optimizing the valve plate of a pump.

Designing a valve plate requires the designer to optimize multiple sources of noise simultaneously through the selection of several design input variables. VpOptim is therefore a multi-parameter multi-objective optimization procedure developed to reduce sources (FBNS and SBNS) of noises from pumps and motors which operate in a wide range of operating conditions.

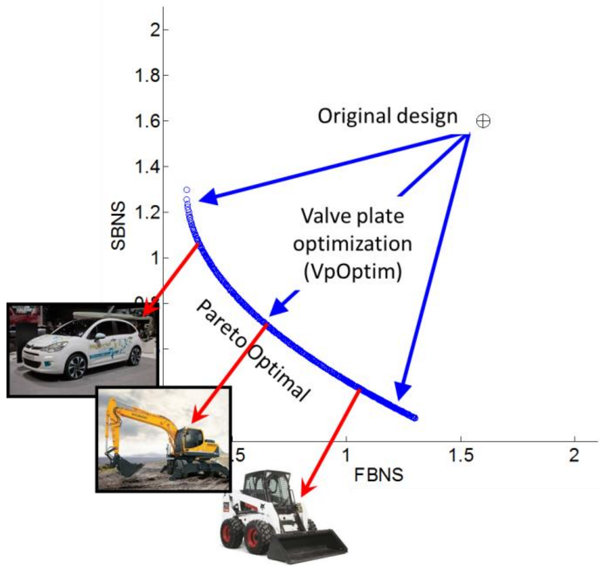


Fig. 38: Schematic of the Process Flow inside VpOptim

VpOptim enables a designer to optimize, independently, the relief grooves and pre/post compression filter volumes. The relief groove reduction technique is characterized by multiple design variables which influence the area between displacement chamber and the pump's external ports. This more precisely controls the change in pressure inside the displacement chamber. The pre-compression filter volume and post-compression filter volumes describe a volume of fluid attached to the displacement chamber to reduce noise. Both reduction techniques are inputs to VpOptim's Multi Objective Optimization algorithm to select a Pareto optimum set of relief grooves and/or Compression filter volumes which will have the minimum possible FBNS and SBNS over the selected range of operating conditions.

The valve plate design methodology was completely redesigned in 2014. The complexity of the valve plate designs was increased yet again to allow 25 design variables as compared to 12 in 2013. The computation speed was also increased an additional 25 times as compared with VpOptim in 2013. This creates a 25,000 times speed up as compared with 2012 VpOptim. This enabled a much faster (Wall-clock time) design process.

The Optimization algorithm was also redesigned to utilize population based metaheuristic search algorithms (which include the popular Genetic algorithms). Using population based algorithms enables the use of non-dominating sorting algorithms, which allows the valve plate designer to choice the best valve plate for their application post-facto to the optimization procedure. This allows the optimization algorithm to be only run once, as compared to many times in a trial and error approach in 2013 and previously. This has reduced the valve plate design process by a factor of months.

TransModel

The second approach aims to reduce the noise generation at the system level. The system chosen here is a hydrostatic transmission which employs pumps and motors usually running at varying displacements, speeds and pressure levels. Simulation software (TransModel) has been developed which includes a time-domain model of the transmission coupling the pump and the motor using a line. In particular, a time domain line model is necessary to couple time domain dynamic pump and motor models. TransModel has the capabilities to investigate different factors such as rotating group design and hose dimensions which have an effect on the overall noise of the system.

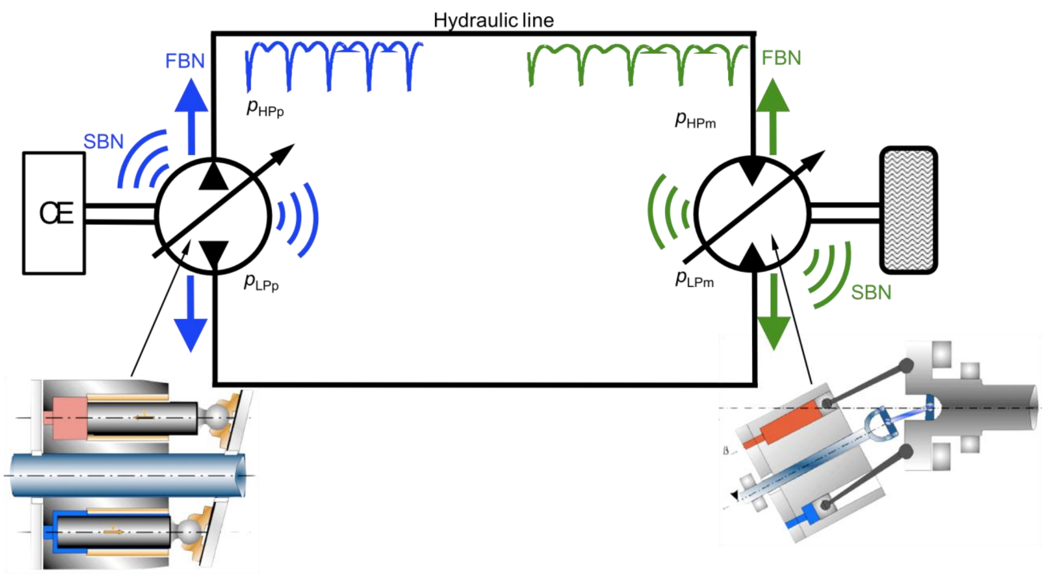


Fig. 39: Schematic of hydrostatic transmission implemented in TransModel

The line model chosen solves the continuity and momentum equations based on the partial differential equation technique, method of characteristics. This approach is selected because superimposed pressure and flow pulsations can be predicted and both noise sources (FBNS and SBNS) are quantified. Fluid borne noise source (FBNS) is quantified by calculating instantaneous pressure and flow ripples throughout the HP line between the pump and motor. Structure borne noise source (SBNS) is characterized by calculating instantaneous swash plate moments in all directions, for both units.

1.2 Research activities – Dr. Vacca's research team

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. While Fluid Power is a consolidated technology for transmitting mechanical power in agriculture, construction, transportation, aerospace, marine, manufacturing and entertainment industries, there still are tremendous opportunities to improve the efficiency and reduce energy demands of fluid power machines. This can be done by investigating the fundamental fluid-mechanical relationships in fluid power components and developing new fluid power solutions. Another challenge with fluid power technology is its low acceptance level in applications that require quiet actuation, zero leakage, and no risk of fire or explosion. In nearly all existing systems, the hydraulic fluid is mineral oil based, leading to environmental concerns, and the high noise emissions of hydraulic components limit use in sensitive applications. These factors, along with concerns for human health, the need for environmental protection and conservation of energy resources, are incentives for improving – or innovating - current fluid power machines.

With a team of 12 researchers (a peak number of 14 was reached in summer 2014, see section 14.2), 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 which 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.

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 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 hydraulic fluids, in particular the effects of gas (air release) and vapor cavitation on 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 new simulation approach capable of predicting the dynamic features of air release/absorption and vapor cavitation was recently formulated by Dr. Vacca's team. 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.

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.

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.

1.2.1 Research Highlights in 2014

- After a proof of concept test performed at Maha in 2013, in December 2014 the first prototype of Variable Delivery External Gear Machine (VD-EGM) was built and tested by Ram S. Devendran and G. Altare. First experimental results in pump mode show the possibility of realizing flow regulation in the 32% range (from 68% to 100% of full flow) maintaining high values of both torque and volumetric efficiencies. Further testing activities on this new design concept, including the use of a pressure compensator integrated within the pump will be performed during 2015.

This design solutions is particularly promising for application which require inexpensive units, such as EGMs, in which a partial flow regulation would directly permit substantial energy savings. Examples are hydraulic fan drives, charge pumps for hydrostatic transmissions and some fuel injection systems.

- A novel experimental approach to study noise generation and transmission in positive displacement machines has been developed by Tim Opperwall. This approach permits to isolate different sources and contributions within Fluid Borne Noise, Structure Borne Noise and Airborne noise. This technique is used to drive improvements in external gear machines towards the design of quieter solutions.
- An optimization procedure to optimize the axial balance for external gear machines has been created by Divya Thiagarajan. The procedure automatically identifies the balance areas necessary to minimize the losses due to volumetric leakages and fluid shear, and it is based on the use of the Fluid Structure Interaction model of the HYGESim software developed at Maha for the simulation of EGMs.
- A novel model for gerotor pumps was developed by Dr. Gabriele Altare during 2014. The model revisited a previous simulation tool developed by Wolfgang Schweiger et al. and introduced additional features as concerns both the geometrical model and the lumped parameter fluid dynamic model.
- Sujar Dhar completed his capacitive measurements of the internal lateral lubricating gap in a prototype of an external gear pump, and he was able to find very good agreement between the predictions of the Thermal Fluid Structure Interaction model he developed and the experimental measurements. This result prove the ability of the HYGESim simulation tool to predict the features of the axial balance in external gear machines.
- A numerical model for the simulation of radial piston pumps for high pressure application has been developed by Pulkit Agarwal and Kelong Wang. The model includes the evaluation of the cam-piston cylinder interface (through EHL modelling) and of the piston-cylinder interface, and it is used to evaluate possible design solutions for ultra-high pressure pumps (up to 2500 bar).
- Preliminary results of a novel non-model based technique to reduce oscillation in mobile machines were obtained by Guido Ritelli on the hydraulic crane installed at Maha. The novel technique is frequency based, automatically detects the nature of the oscillations and have capability of induce flow variations for their reduction.

1.2.2 HYGESim (HYdraulic GEar Machines Simulator)

Goal: 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 geometry configurations of the gears, lateral bushings and case.

Approach: HYGESim consists of different submodules, as shown in Fig. 40. 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.

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 the external pump or motor in any given AMESim circuit. The geometrical model is implemented in C++ and he can read the drawings of the unit generated by its CAD model. 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 Fluid Structure and Thermal 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 pressure and thermal deformation. In case of pressure compensated design, this model takes also into account the balance of the different parts.

Recently, the effort is also put on the model for the journal bearings, with the aim of including effects of 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 1.2.4).

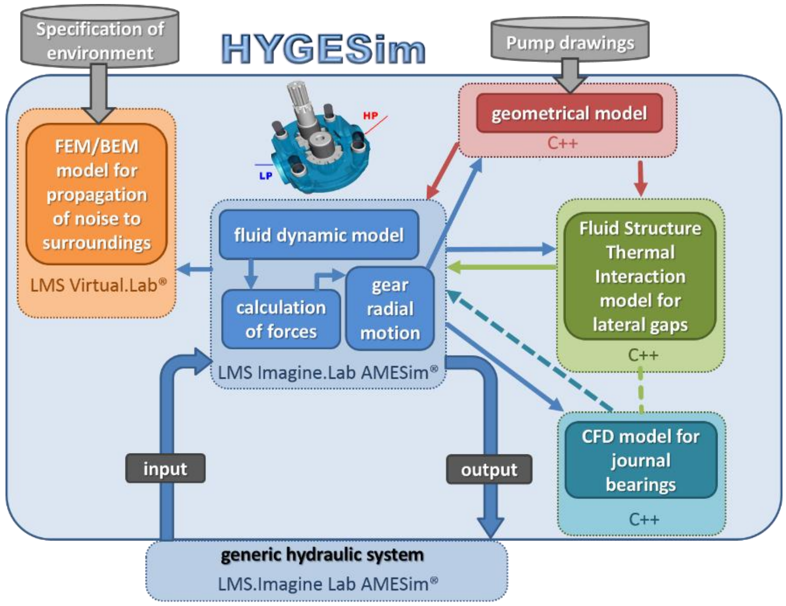


Figure 40 – Structure of HYGESim

Depending on the simulation goal, different versions of HYGESim can be utilized. In HYGESim_F, only the evaluation of the main flow through the unit is evaluated; in HYGESim_FFI, also the radial micro-motion of the gears are 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 1.2.5 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 41 shows an example of comparison performed on a prototype pump able to measure both the inter-teeth pressure and the delivery pressure ripple.

Figure 42 shows an example of comparison for the volumetric efficiency of a pump, while Fig. 43 displays a comparison of the predicted wear of a pump case after the initial break-in process.

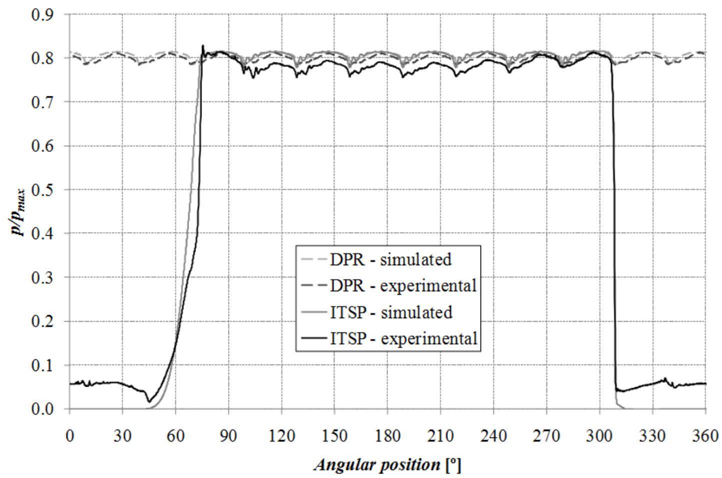


Figure 41 – Tooth space volume pressure and delivery pressure: measurements vs simulations

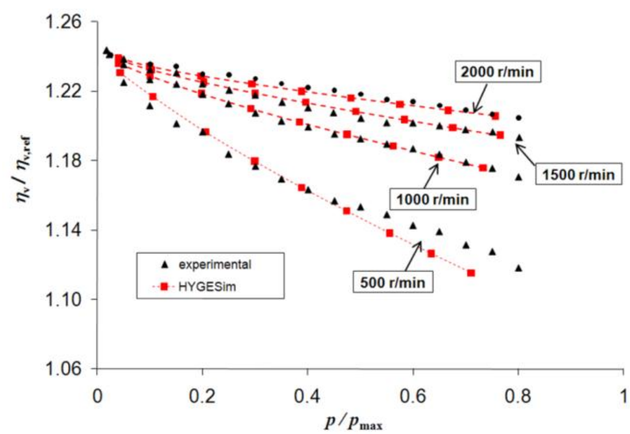


Figure 42 – normalized volumetric efficiency (simulation vs experiments)

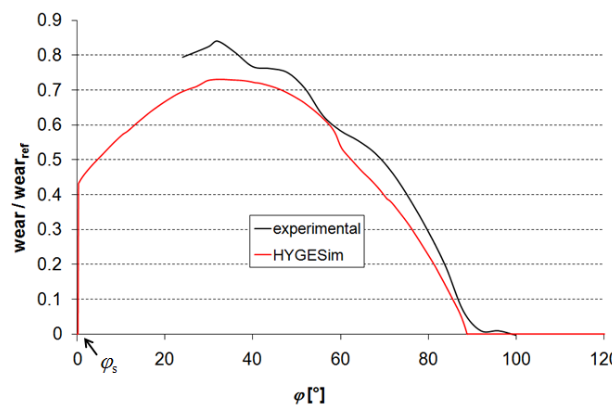


Figure 43 – Normalized casing wear profile (simulation vs experiments)

1.2.3 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 44(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 θ, 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 44(B)). 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 44(B).

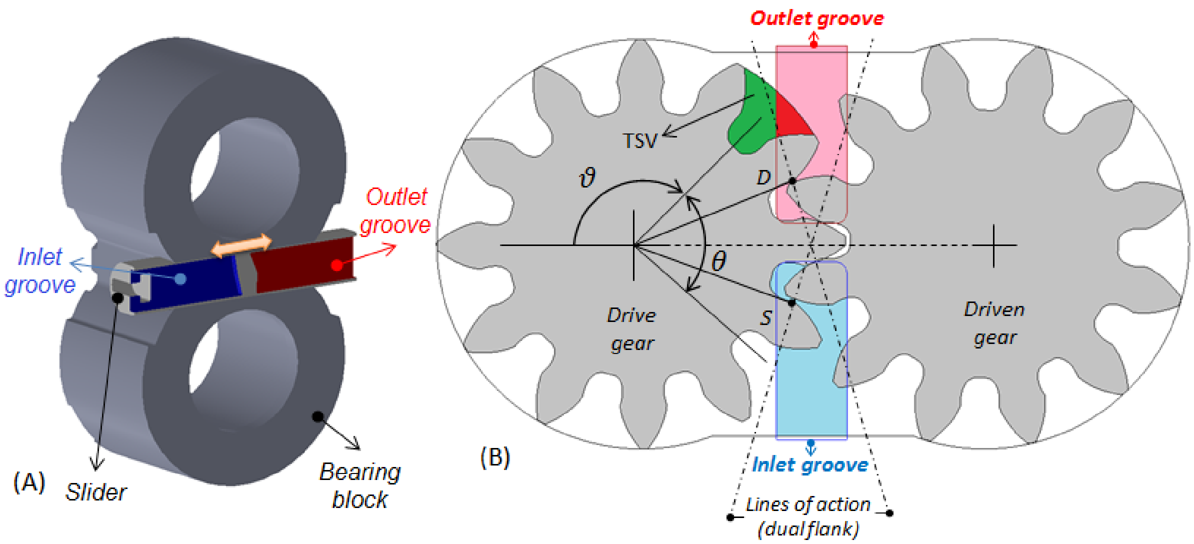


Figure 44: (A) Slider placed inside the bearing block for achieving variable flow in an external gear machine (B) Generic TSV at angular position ϑ and the angular interval θ in which the meshing process takes place, Groove positions in the slider to achieve max displacement.

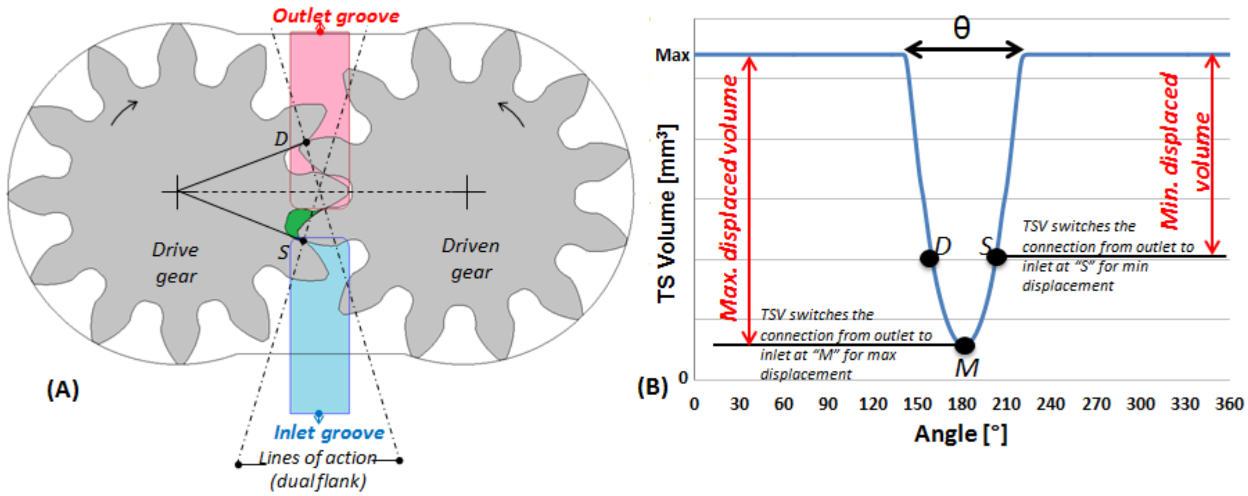
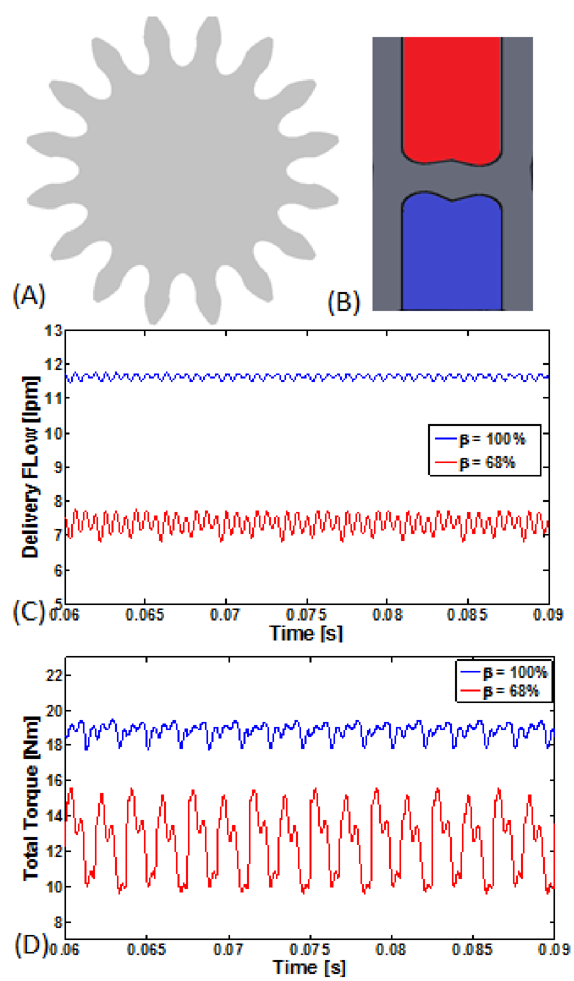


Figure 45: (A) Position of the grooves to achieve min. displacement. (B) The evolution of TSV with respect to the shaft rotation angle, the switch of the TSVs connection from the outlet to the inlet occurs at "M" for achieving max. displacement and at "S" for achieving min. displacement

However, a reduced displacement is achieved when the slider is positioned closer to the inlet port (as shown in Fig. 45(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 the fluid "virtual 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 FigureFig. 45(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).

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 deign 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.

<u>Main Results:</u>

The optimal design of the gears and the grooves in the slider which offered a remarkable variation in displacement from 100% to 68% is shown in Figure 46Figure 46(A) and (B) respectively. The performance of the design was analyzed using HYGESIM as shown in Fig. 46(C), it can be seen that that the delivery flow at min displacement is 68% of that provided at 100% displacement, hence, proving the concept for variable delivery EGMs. The predictions of torque are shown in Fig. 46(D), it can be seen that the required torque at min displacement is about 68% of that provided at 100% displacement, due to the lower total force acting on the gear as explained previously. The lower input shaft torque required reflects on the lower energy consumption at min. displacement, thus supporting the viability of a variable displacement type external gear machine.

Figure 46: (A) Optimal design of gears (B) Optimal design of grooves (C) Delivery flow predictions at max and min displacement (D) Delivery flow predictions at max and min displacement

The encouraging performance potentials obtained in simulations for a wide range of operating conditions, provided motivation for designing a proof of concept test, whose primary goal is to prove the principle behind the proposed VD-EGM. The optimal gears were prototyped using electric discharge machining (Wire EDM) and the grooves in the slider were machined using traditional milling process. Steady state measurements were performed on the Maha multi-functional test rig (see section 3) and the results are shown in Figure 47.

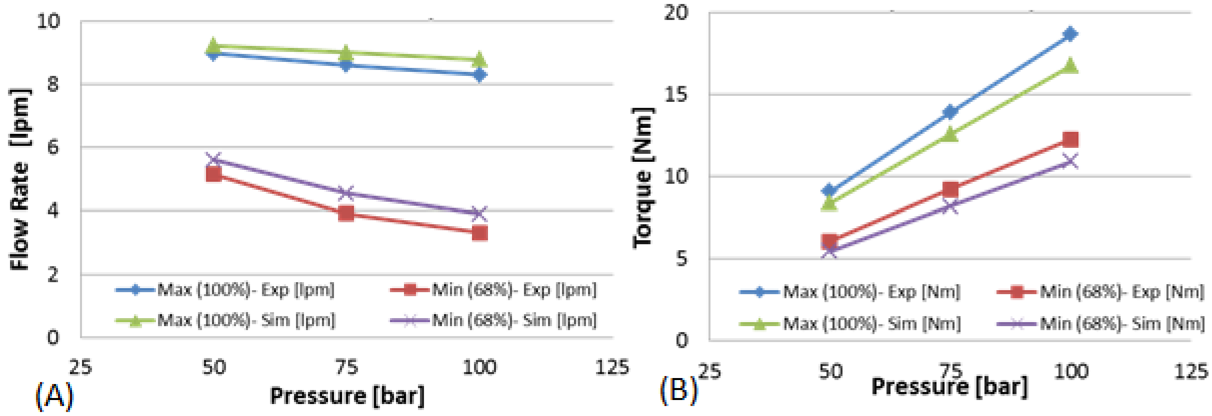


Figure 47: (A) Proof of concept for flow rate at max and min displacement (B) Proof of concept for torque at max and min displacement

It can be seen from Fig. 47(A) that the flow rate proportionally (68%) reduces at min displacement as compared to those at full or max. displacement. Approximately 32% reduction in torque is obtained at all the operating conditions tested for min displacement as shown in Figure(B). A good agreement between simulated data and measurements can be observed from these figures.

The immediate future work of the project is to design and prototype a variable displacement external gear machine with a manual actuation system. Followed by the generation of the prototype an experimental campaign will be conducted to understand the performance of the machine. It is also intended to design and develop a pressure compensated type of actuation for achieving variable displacement. Eventually, it is planned to apply the design in a typical fan drive application available in an excavator.

1.2.4 Evaluation of noise generation in positive displacement machines

Goals: Fluid power applications generally include heavy loads where noise is not a primary requirement and often include large machinery in construction and agriculture. With the increase of environment health and safety standards, the amount of noise generated by hydraulic components has increased in importance. Fluid power is also expanding into new industries with lighter applications such as passenger vehicles. In lighter and quieter machines, the importance of the level of noise transmitting from the hydraulic components to the passengers and environment becomes a primary design concern. In order to increase the range of applications where fluid power is advantageous, the noise generation must be better understood and ultimately reduced. Besides environmental concerns, decreasing the noise generation of hydraulic components has potential additional benefits of smoothing control 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 present activity focuses on noise generation from displacement machines and the attached systems through simulation and experimental techniques and considering all three domains for sound generation and propagation*. The goals are to model the important physical phenomena which relate to noise. Simulations can also be compared to noise measurements taken in the Maha anechoic chamber and on the Multi-Purpose Test Rig. Predicting the changes in noise generation from new designs will all use of simulation techniques to design quieter units and bypass typical trial and error methods.

Approach: The case of external gear pumps is taken as reference for a new model to understand the generation and transmission of noise from the sources out to the environment. 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 Fig. 48.

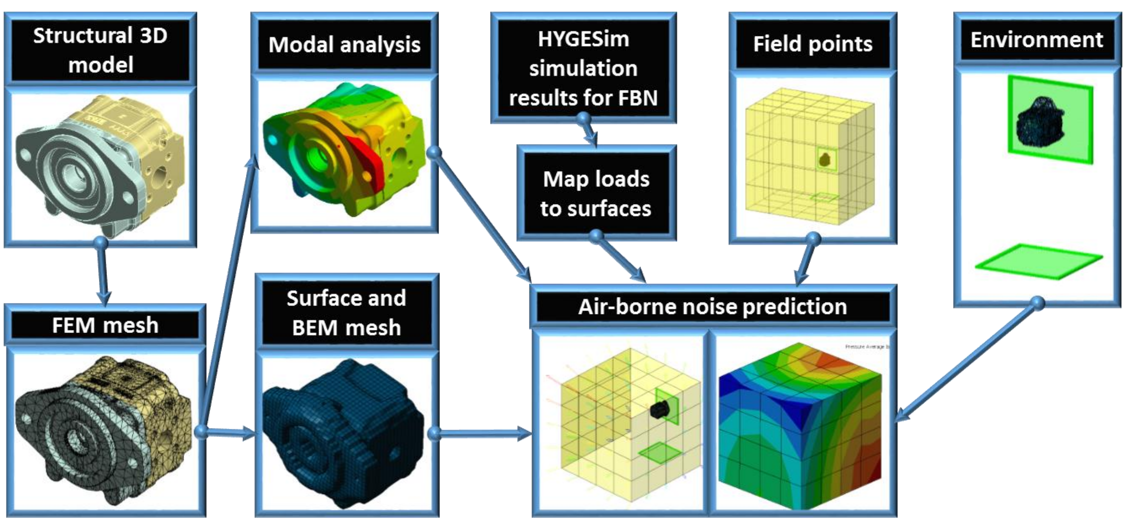


Figure 48 - Vibro-acoustic model layout for predicting radiated sound power from a reference external gear pump

Several experimental studies were also completed which accomplished key tasks related to the research goals. The first study validated the pump model in terms of pressure ripple prediction through comparison to experimentally measured results for the reference pump as well as prototype pumps designed for low outlet pressure ripple. The second study focused on the air-borne noise through sound pressure and intensity measurements on reference and prototype pumps at steady-state operating conditions. A third study over a wide range of operating speeds and pressures was completed to explore the impact of operating condition and system design to greater detail through measuring noise and vibration in the working fluid, the system structures, and the air.

Main Results: The radiated noise prediction is acting nearly as a pure impedance to the FBN load as shown in Fig. 49. 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 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. Furthermore, 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.

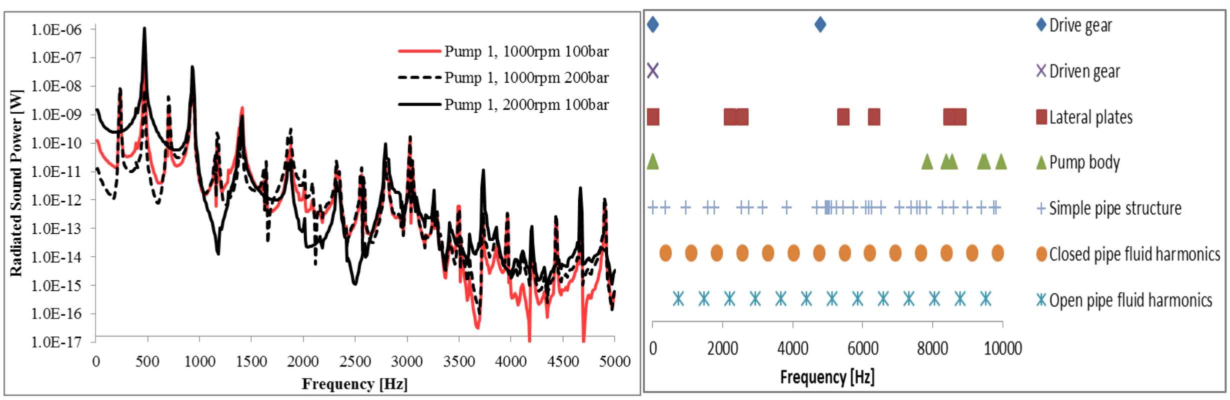


Figure 49 - (left) Model results for noise radiation. (right) resonant frequencies of the pump and system components

The trends from the models correlate well with measurements of the fluid and air-borne noise shown in Fig. 50. The frequencies in the ABN largely correlate with the excitation frequencies in the fluid pressure oscillations measured at the pump outlet. However, there is a greater amount of noise generation and propagation measured at frequencies where there is interaction between the excitation frequencies and the system/structural components.

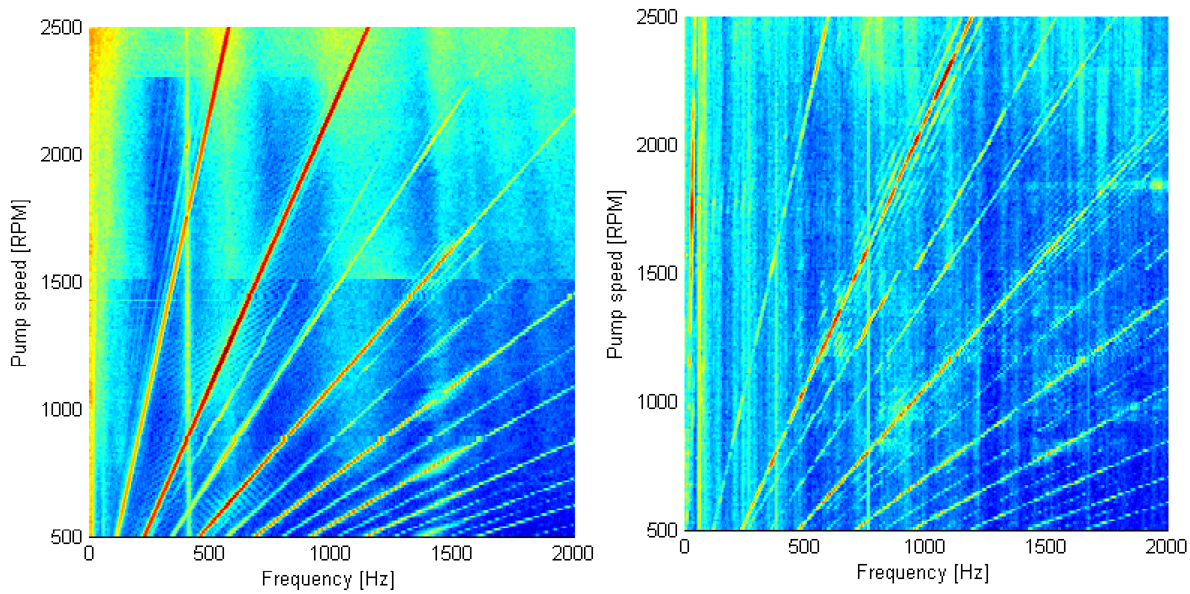


Figure 50 - (left) measured PSD of pump outlet oil pressure. (right) measured PSD of air-borne noise.

The main future work of this research is to improve and extend the numerical noise prediction model to include additional sources of noise and to gain better correlation between experimental and predicted values for radiated sound power. Applying the knowledge gained through experimental and simulation studies has brought new advances in design of quieter hydraulic systems.

1.2.5 Design optimization of External Gear Machines (EGMs)

Optimization of the design of the gears and internal connections

Goals: The performance of an EGM depends greatly on the design of two major components: the gears and lateral bushings. The lack of tools capable of carefully evaluating the impact of design changes in these machines in their performance limited the exploration of new design principles. As in any positive displacement machine, optimal operation of an EGM implies high volumetric and hydro-mechanical efficiency, limited noise emission and high reliability. For EGMs, these goals can be achieved by obtaining an optimal design of the gears with the lateral bushings.

At Maha, a multi-objective optimization tool has been created to optimize the design of EGMs considering all the design requirements of gears and lateral bushes.

Approach: In all the studies done in the past, it is shown how a convenient design of the grooves in a gear pump can permit the reduction of the delivery flow oscillation as well as an increment of the volumetric efficiency. Also, the internal pressure peaks and the local cavitation related to the meshing process can be reduced. The best profile for the grooves depends on the gear profile and on which both the above mentioned aspects has to be considered equally important. This is also reflected by the different designs of the lateral bushings present in the various commercial EGMs commercially available.

A multi-objective two level optimization is set-up to achieve the optimal design of gears in the first level and obtain the optimal groove shape design of the lateral bushings in the second level as shown in Figure 51.

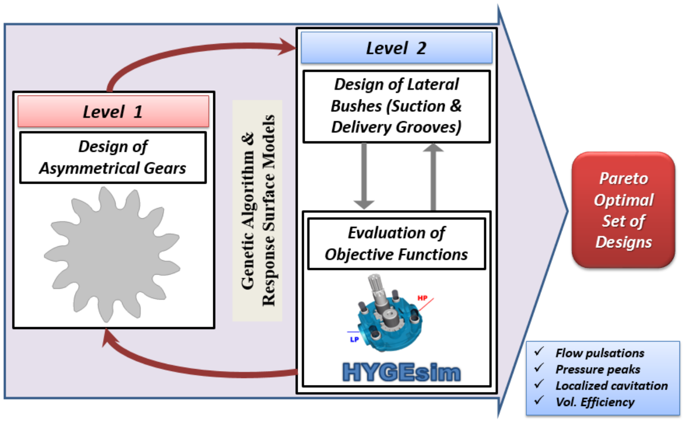


Figure 51 - Two level optimization for the design of EGM

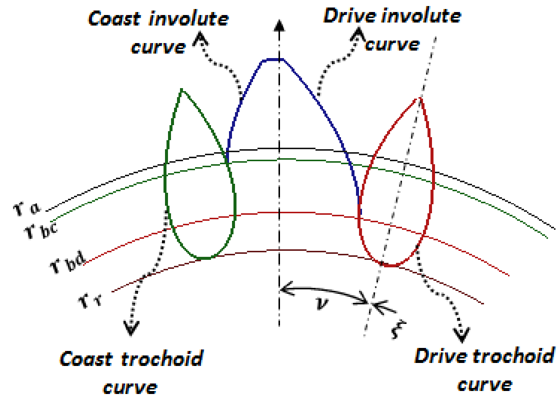


Figure 52 - Generation of drive and coast involute profile

The design of the gears is assumed to be comprised of involute profiles above the base circle of the gears and trochoid profile below it as shown in Figure 52. The optimization procedure can deal with both symmetric and asymmetric profiles for the teeth. In order to accomplish the goal of designing asymmetric teeth, two different pressure angles are considered respectively for the drive and coast side of the tooth. Also the number of teeth per gear could vary depending on the performance of the machine. It is ensured that the asymmetrical teeth gear profile can be physically manufactured using conventional manufacturing processes like hobbing, shaping, rack-cutting etc. An asymmetrical cutter profile is assumed first and the teeth profile is derived based on the parameters that determine the shape of the asymmetric.

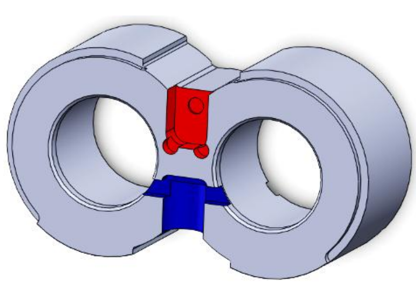
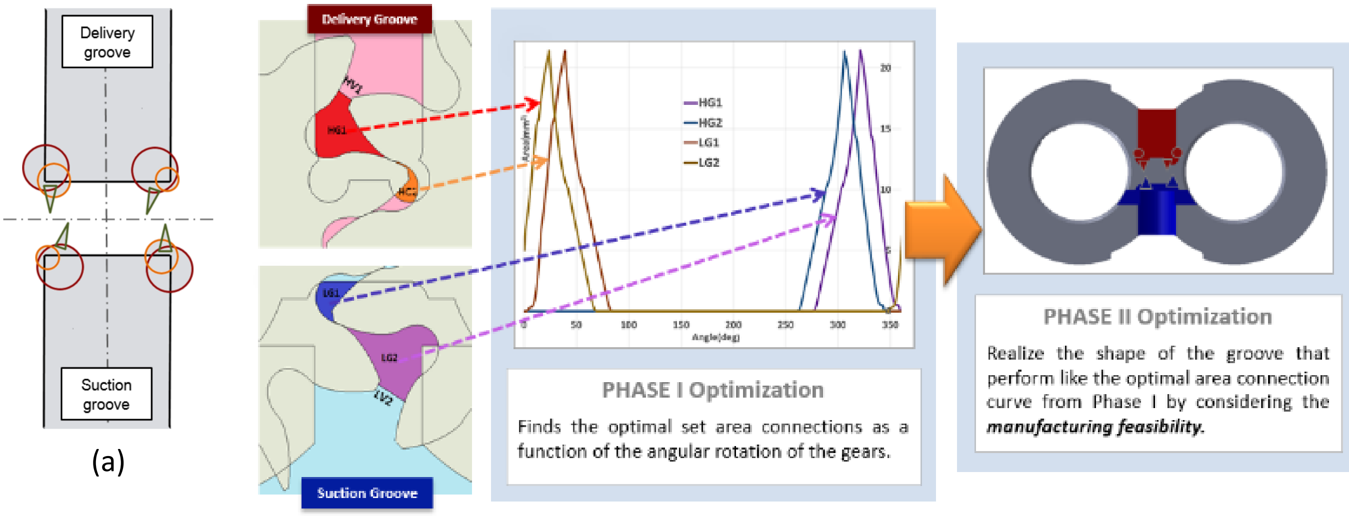


Figure 53 - Groove shape design on Bushing



(a)

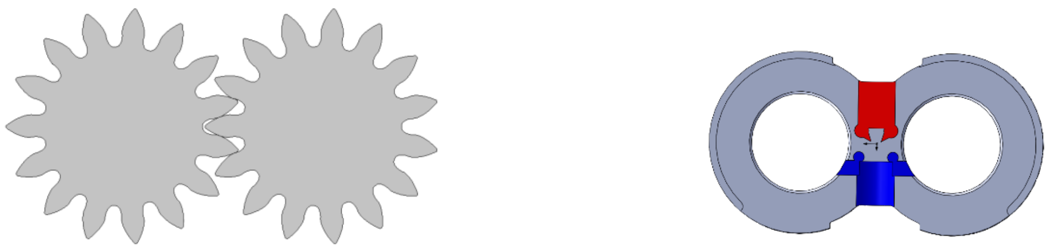
(b)

Figure 54(a) - Groove shape formation methodology. (b) Optimization procedure to realize the ideal geometry of the groove

Shape of the grooves on the lateral bushing as shown in Figure 53 also play an important role in cutting down the pressure peaks and flow ripple which causes instabilities in the operation of EGM. The approach to realize the ideal groove morphology is performed without assuming any specific shape or a template (as shown in Figure 54(a)). In this approach simple geometry features like circles and triangles were taken on a rectangular base and an intersection of all these features gives a groove shape design. This optimization procedure is completed in two phases. Phase I obtains the ideal connection area curve between the gears and the grooves on the lateral bushings as a function of the rotation of the gears considering the optimal performance of the EGM. Phase II realizes the geometrical morphology of the groove taking into account the ideal connection area obtained in the Phase I. In this way, an ideal groove shape geometry is obtained whose performance matches the optimal design obtained in Phase I.

<u>Main results:</u> The two-level optimization automatically produces a set of gears with the matching optimal groove shape on the lateral bushings. An example of optimized set of asymmetric gears are shown in the Figure 55(a) along with the groove shape design shown in Figure 55(b). These designs obtained are unconventional as compared to the designs available in the market. The shape of the gear appear to be different from traditional symmetric gears used in the commercial pumps. The grooves in the lateral bushings have a novel triangular shape which serve as relief to the high pressure peaks in the meshing process. At operating condition of 2000 rpm 200 bar, the flow ripple is reduced by 33% compared to a commercially existing pump. The pressure peaks which occur during the meshing process are completely cut down as can

be seen in the Figure 56(b). The comparison of the performance with respect to the reference can be seen in the Figure 57.



(a) (b)

Figure 55(a) - Optimized Asymmetric gears. (b) Optimized groove shape design

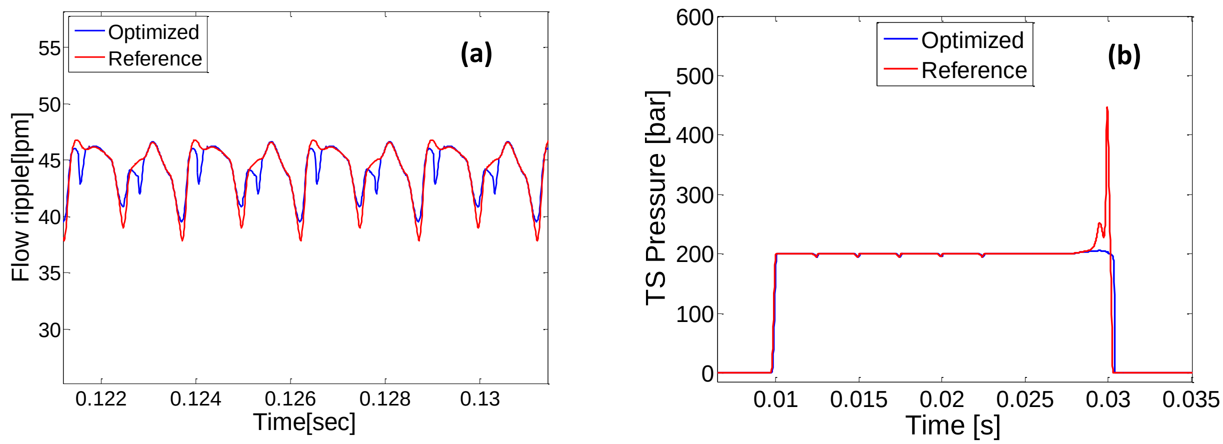
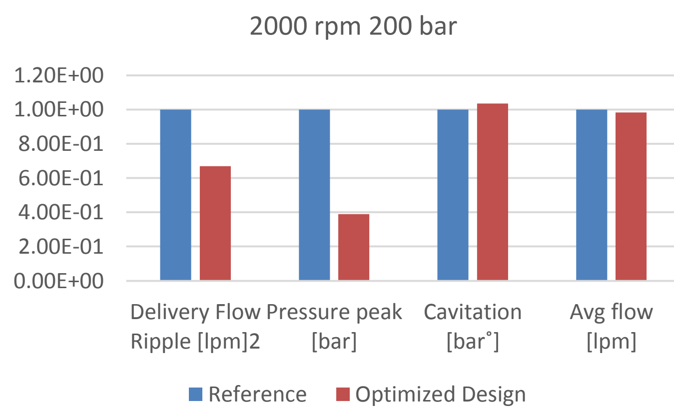


Figure 56(a) - Delivery flow ripple comparison (b) Pressure peak comparison (2000 rpm, 200 bar)

Figure 57 - Comparison between the reference and the optimal design



Modeling and optimization of lubricating interfaces in external gear machines

Goal: In high pressure external gear machines (EGMs), the lubricating interfaces between lateral bushings and gears (as shown in Fig. 58(A)) 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. Consequently, such an advanced computational model can be used to drive external gear machine designs with improved efficiency, reliability and operating life. The thermal-elastohydrodynamic (TEHD) fluid structure model of the lateral lubricating interfaces developed in this research has 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).*

The power losses occurring in the lateral gap can be minimized by determining proper balancing areas on the lateral bushings (as shown in Fig. 58(B)). A fully automatic optimization procedure to design these areas have been developed in conjunction with the lateral gap model with an aim to practically leverage the lubricating gap model to achieve EGM designs with reduced leakages and friction losses along with reduced wear in the gears and the lateral bushes throughout the operating range.

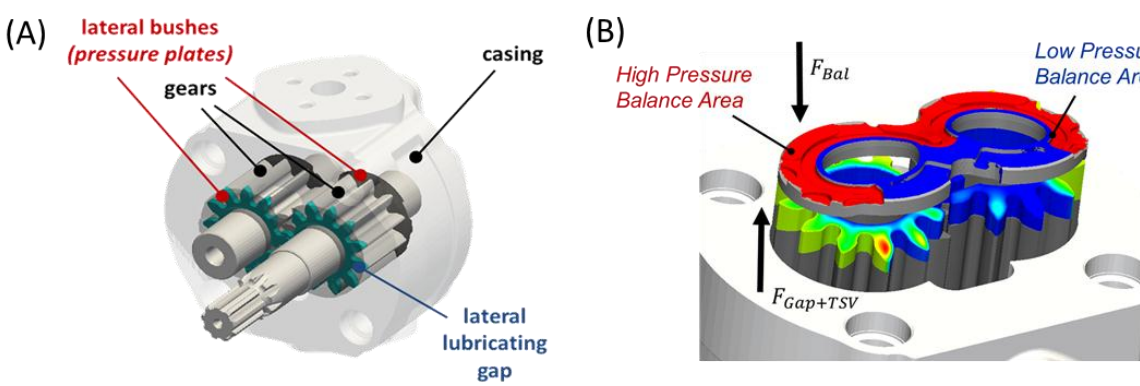


Figure 58 - (A) Lateral lubricating gaps in external gear machines (B) High pressure and low pressure balancing areas on the side of the lateral bushing not facing the gears

Approach: The TEHD model of the lateral lubricating gaps in EGMs 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 FigureFig. 59. 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. All the sub-models are coupled and implemented in an iterative numerical scheme.

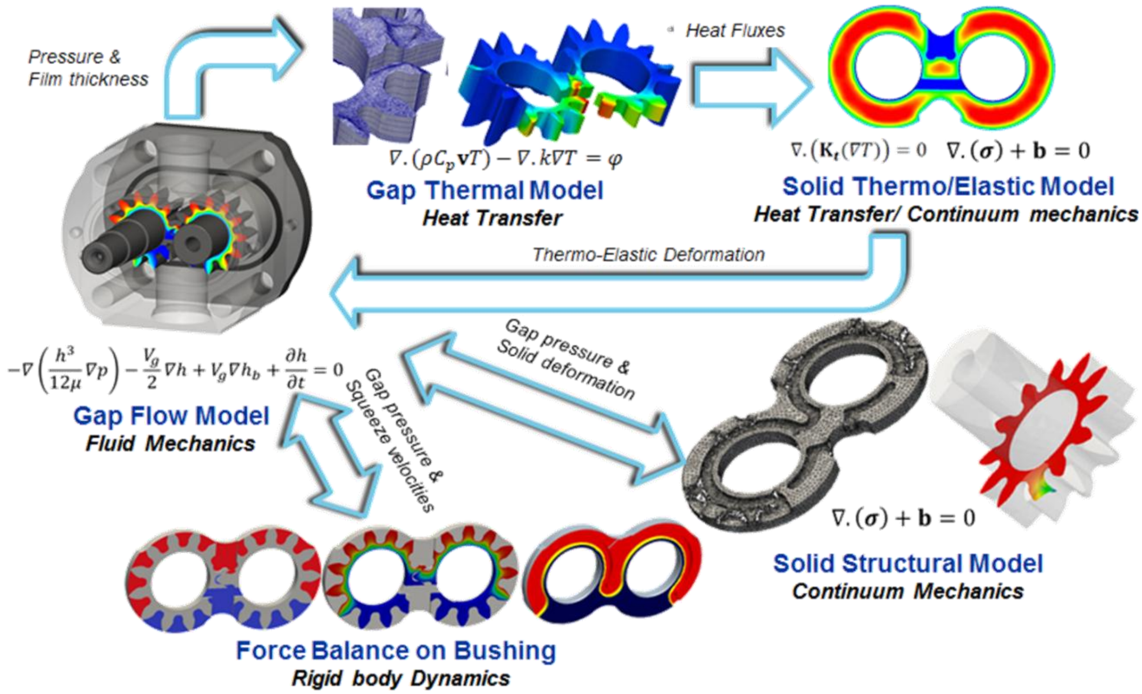


Figure 59 - Structure of the TEHD model for the lateral lubricating gaps in external gear machines

The scheme of the numerical procedure to determine the optimal balance areas which has been coupled to the lateral gap model. The following two objective functions has been formulated for this procedure:

- Minimizing the two opposing sources of power losses due to leakages and viscous friction generated in the lateral gap.
- Minimizing the occurrence of sharp contacts between the gears and the lateral bushes.

The gap model evaluates different designs of the balance area across the input operating conditions and the iterative optimization procedure determines the final design area with the minimum possible objective functions subject to practical realization constraints.

Results:

Results from the TEHD gap model

The TEHD model is capable of determining the various numerous parameters associated with the lateral gap such as pressure distribution (as shown in Fig. 60(A)), film thickness, temperature (as shown in Fig. 60(B)) and deformation of the solid components.

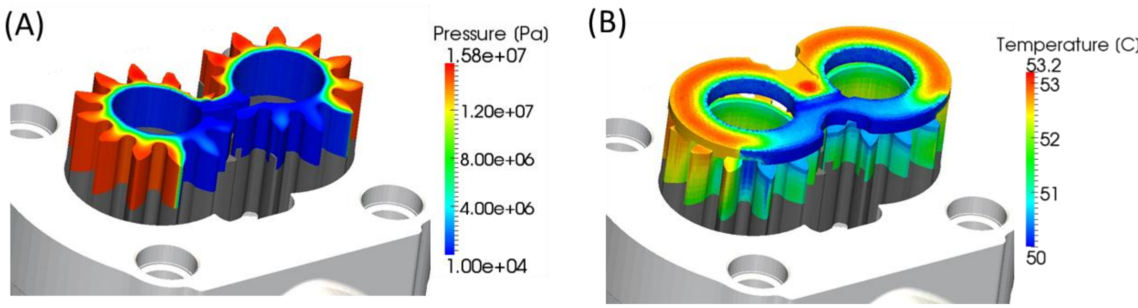


Figure 60 - (A) Pressure and lubricant film thickness (B) Bushing temperature and gap film thickness. Film thickness is scaled up by 10000 times for visibility

Capacitive film thickness measurements were performed in a prototype EGM (as shown in Fig. 61(A) and were found to be in good agreement with those predicted by corresponding simulations using the TEHD model. Comparison for a sample operating condition (200 bar delivery pressure and 2000 rpm shaft speed is shown in Fig. 61(B) and (C).

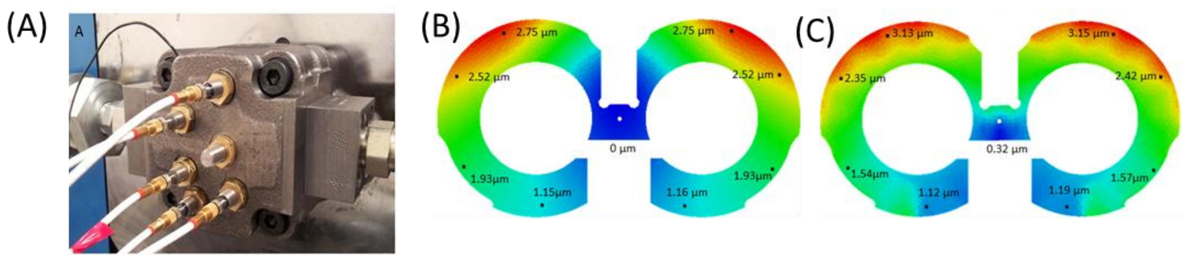


Figure 61 - (A) Capacitive sensors instrumented on a prototype EGM used for the experiment. (B) Measured relative gap height (interpolated) (C) Simulated relative gap height

<u>Results from the optimization procedure</u>

The numerical procedure for determining the optimal balance area can be used for a variety of EGM designs. Optimized results for film thickness in a reference external gear machine is shown in Fig. 62 at a sample operating condition of 80 bar and 1000 rpm. A total of 37 % reduction in the total power losses in the lateral gap was observed in this case.

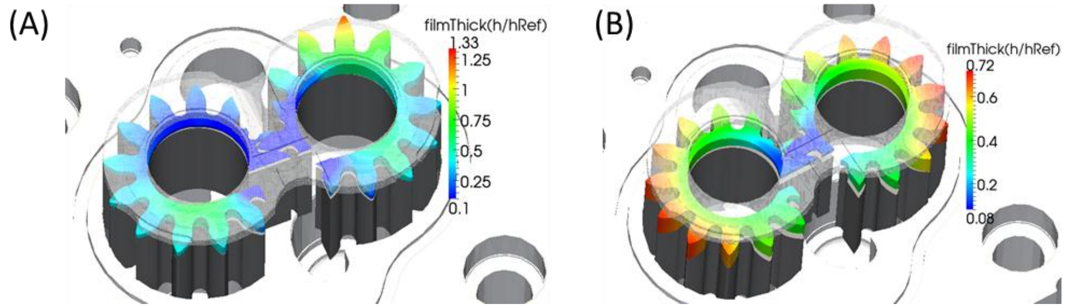


Figure 62 - Gap film thickness plots in the reference EGM with (A) Original balance area (B) Optimized balance area

1.2.6 Modeling of radial piston pumps

Goal: Within this research, a *comprehensive multi-domain simulation tool* for investigating the operation of radial piston machines has been developed. Radial piston machines are widely used positive displacement machines for high pressure applications and offer benefits of high efficiency together with a capability of withstanding very high loads at low speeds. They are characterized by a compact arrangement with high energy conversion efficiency and are widely used in mobile applications, particularly hydrostatic transmission systems as well as in stationary applications such as hydraulic presses.

The simulation tool is capable of analyzing the displacing action of the machine parts as well as the power losses occurring in the lubricating interfaces which makes it useful for supporting the design process of radial piston units. The reference machine analyzed in this study is a radial piston pump of rotating cam type design as shown in Fig. 63 which is used for high pressure applications.

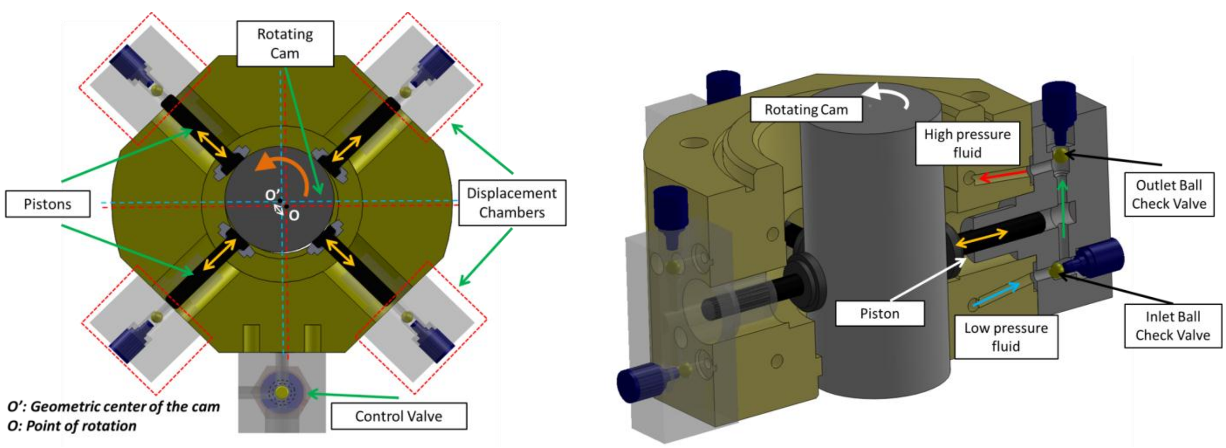


Figure 63 - Radial piston pump design used in the present study

Approach: Fig. 64 shows the schematic of the multi-domain simulation tool that is currently being developed as a part of this research. A lumped parameter based model for complete hydraulic system of the pump has been formulated which can predict the main flow parameters in the pump namely flow rate and pressure at pump outlet. This model can be easily coupled with other hydraulic components present in a circuit to model the systems level performance of the machine. The second part of the simulation tool comprises a lubricating gap model which is essential for accurate prediction of leakage and hence the performance parameters. This module consists of separate sub-modules for *piston-cylinder interface* and *cam-piston interface* whose geometries are depicted in Fig. 65.

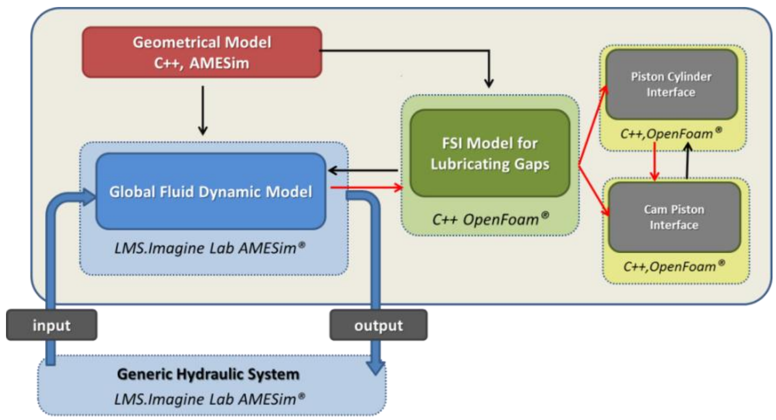


Figure 64 - Schematic of the multi-domain simulation tool for modeling radial piston machines.

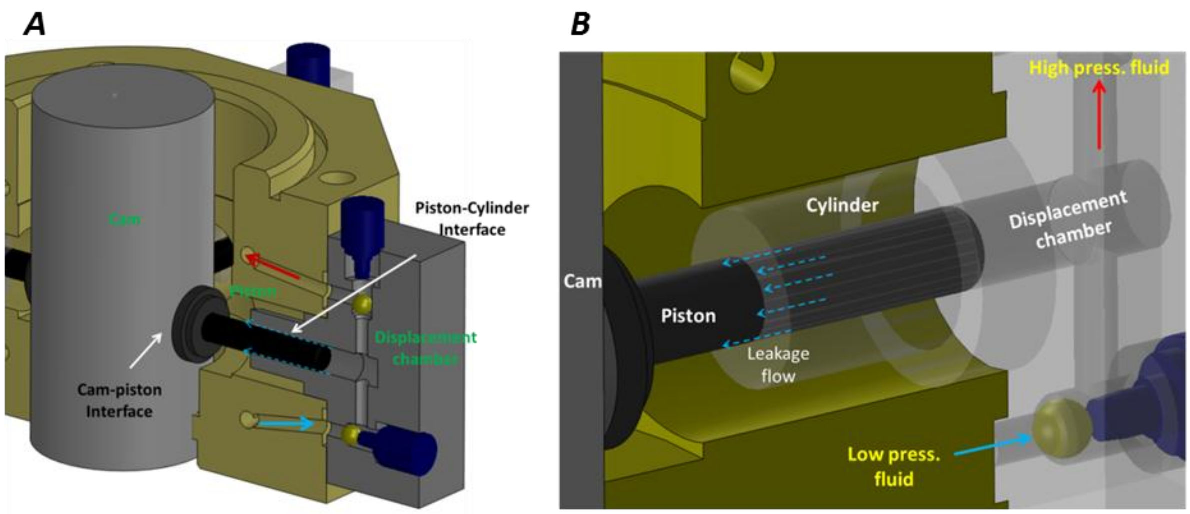


Figure 65 - (A) Lubricating gaps in a rotating cam type radial piston pump. (B) Detailed view of piston-cylinder interface

The piston/cylinder lubricating interface represents one of the most critical design elements of radial piston machines and 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. However, operating in the Elastohydrodyamic Lubrication (EHL) regime, it also represents one of the main sources of power loss due to viscous friction and leakage flow. An accurate prediction of instantaneous film thickness, pressure field, and load carrying ability is necessary to create more efficient interface designs. For this purpose, a fully coupled numerical solver has been developed to capture fluid-structure interaction phenomena in the lubricating interface at isothermal fluid conditions. This model considers the piston micro-motion during one complete cycle of pump operation.

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. Also, instantaneous pressure field and film thickness can be predicted to a reasonable accuracy.

Main Results: The numerical results achieved through this work provide detailed information of the pump performance parameters at different operating conditions thereby confirming the utility of the simulation tool to support the design process of these units and assist in creation of more energy efficient pumps. Figs. 66-68 show the different results obtained using the simulation tool.

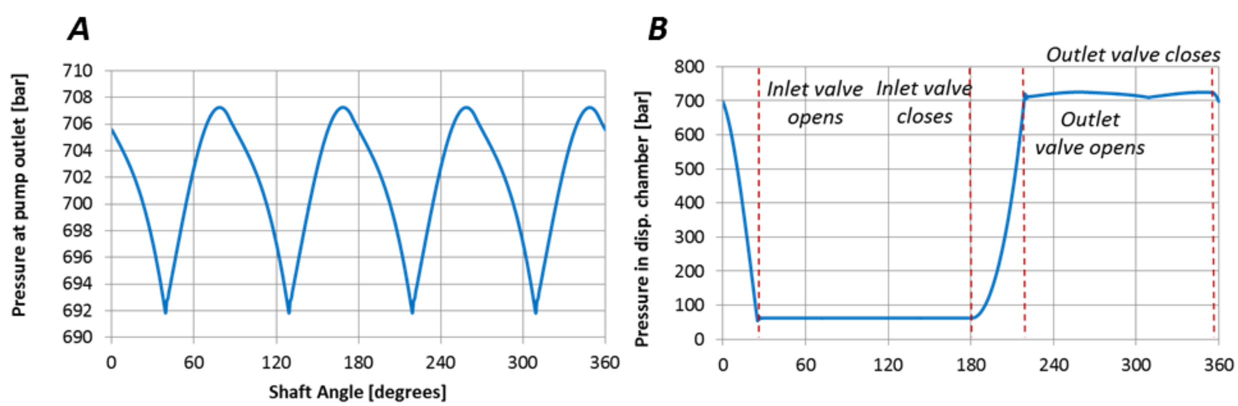


Figure 66 - Pressure at pump outlet (A) and displacement chamber low rate (B) at pump outlet as a function of shaft angle for pump outlet pressure 700 bar and 1800 rpm shaft speed

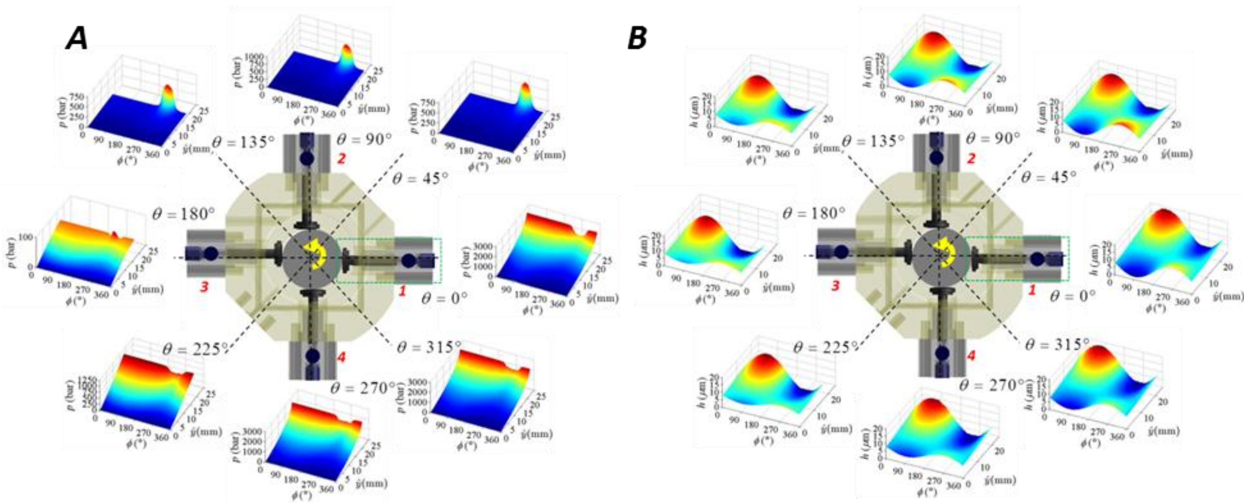


Figure 67 - Pressure distribution (A) and instantaneous film thicknesses (B) in lubricating gap domain over one shaft revolution using the FSI model. Operating condition: Outlet pressure=2500 bar, speed=1800 rpm

Future Work include the incorporation of thermal effects in evaluating lubricating gap flows is the next step in realizing a more accurate model of radial piston pumps. Moreover, further investigation into the motion parameters of cam-piston interface has to be performed to generate accurate input parameters for the cam-piston numerical model. Validation of the simulation tool with experimental results also needs to be conducted in future.

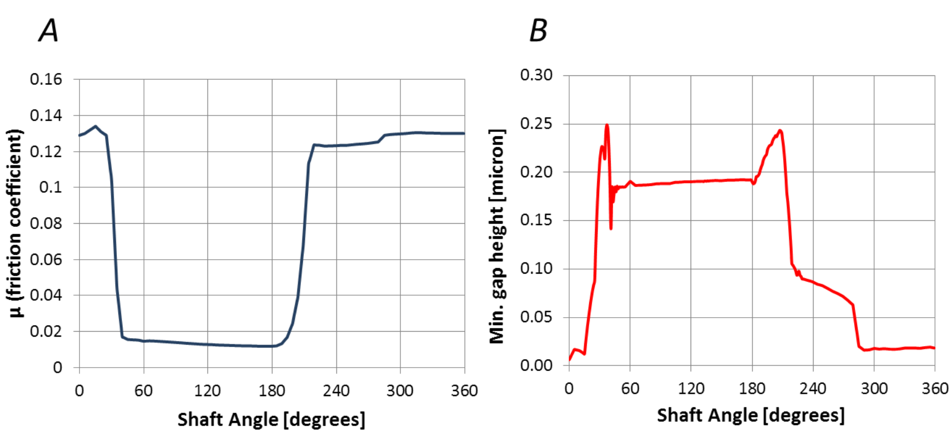


Figure 68 - Results from friction model for Pump outlet pressure: 700 bar, Shaft speed = 1800 rpm. (A) Friction coefficient variation with shaft angle. (B) Minimum film thickness with varying shaft angle.

1.2.7 Modeling of Gerotors

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 solution. The developed tool follows an approach initially developed by Schweiger (2011), and it is capable to generate the geometry profiles of the rotors and simulate its operation within AMESim, predicting main features of the operation such as delivery pressure ripples, internal pressure peaks, etc.

Approach: The model is based on a multi domain simulation approach comprising sub-models for parametric geometry generation, numerical calculation of characteristic geometry data and fluid dynamic model (Fig. 69).

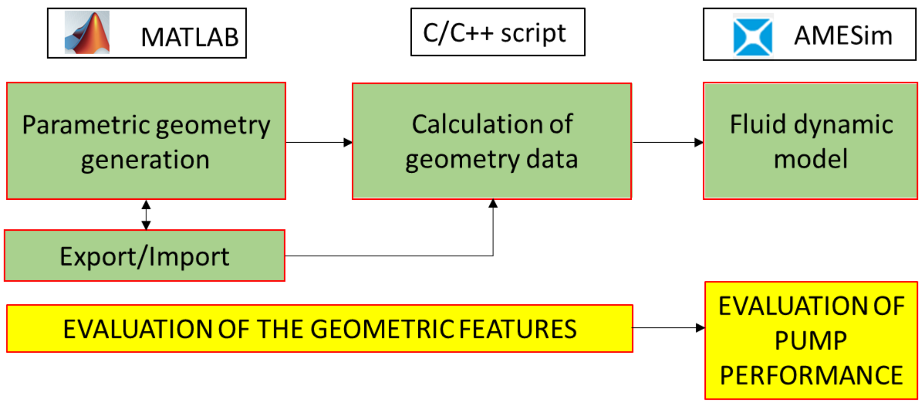


Figure 69 - Structure and interaction of the submodels

The procedure for geometry generation involves the steps as described below:

- Generation of a basis trochoidal curve based on analytical equations
- Determination of the first rotor profile as envelope of the basis trochoidal curve
- Numerically computation of the contact points and the conjugate profile for the second rotor, based on the theory of gearing

Once the geometry is carried out the C/C++ code evaluates the geometrical features of the pump. In particular it evaluates the Tooth Space Volumes (TSV), the inlet and outlet areas (intersection between the TSV and the grooves as depicted in Fig. 70) and the radial gap between the teeth of the inner and outer rotor along with the length of the gap (Fig. 71).

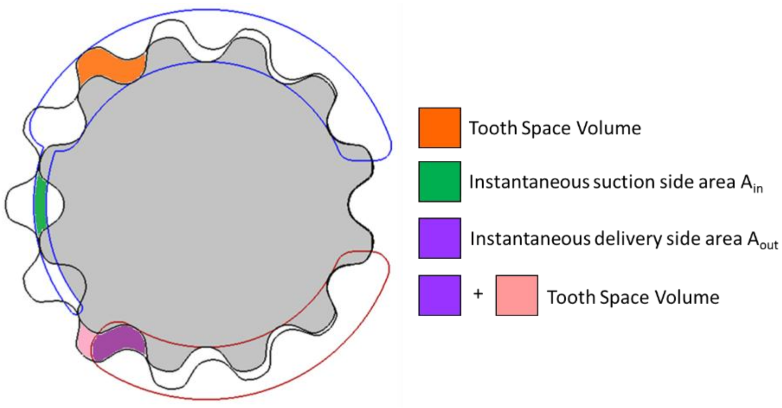


Figure 70: Tooth Space Volume, instantaneous suction and delivery areas

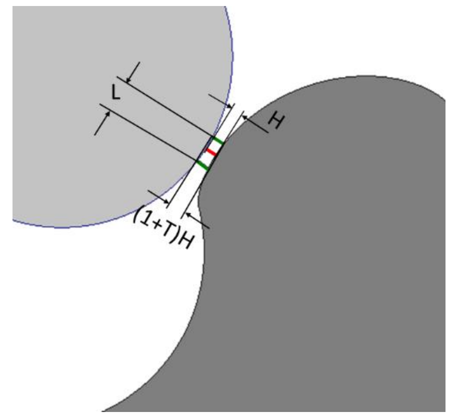


Figure 71: Radial gap evaluation

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 submodels, used to provide input data (Fig. 72) to the fluid dynamic model.

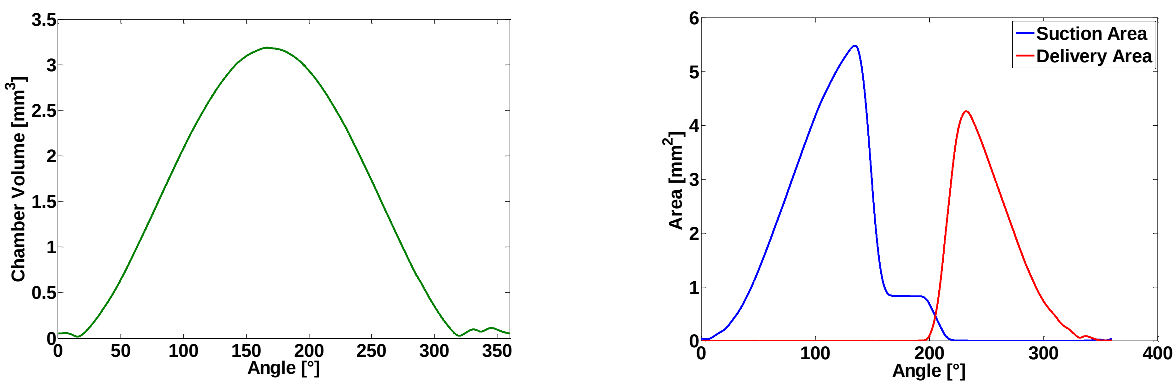


Figure 72: Tooth Space Volume (left), suction and delivery areas (right)

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 utilized for studying the main flow features of hydrostatic units. In particular, each displacement chamber (TSV_i in in Fig. 73a), 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 TSVs and the suction and delivery ports, while the tooth tip leakages between adjacent TSVs have been accounted using laminar flow equations.

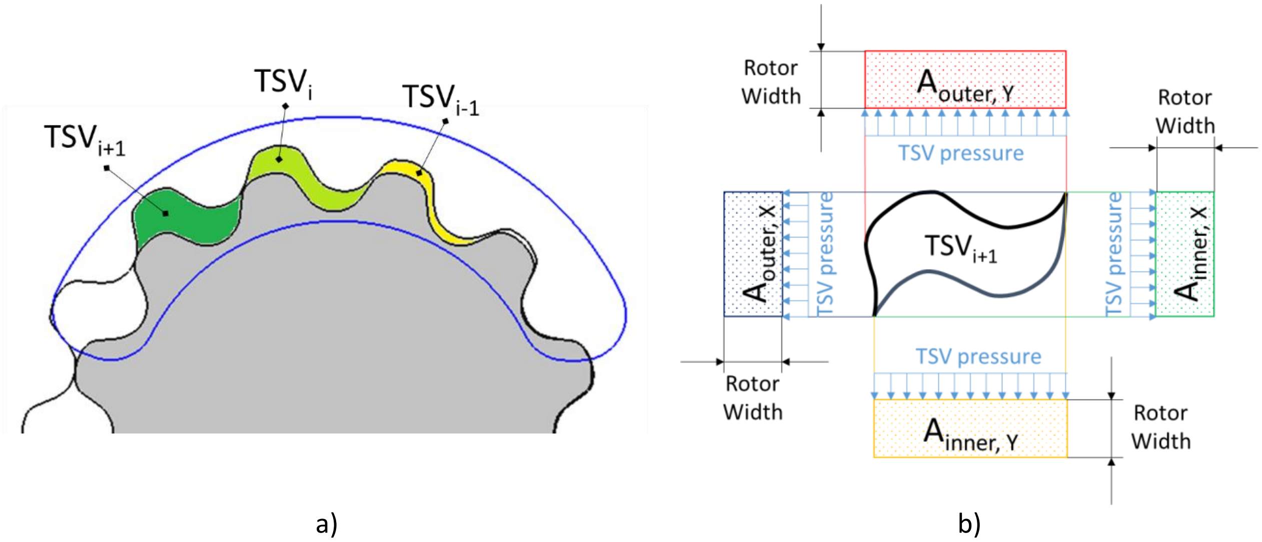


Figure 73 - TSVs (a), areas projection for the force evaluation of a single TSV

The simulation model also evaluates the pressure forces acting on each rotor. This is done by evaluating the single force components in each TSV 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 Fig. 73b. 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 TSV volume, throat areas and the radial gaps.

Main results: The model has been validated (with tests performed at a Sponsor's test lab) as concerns the prediction of the instantaneous flow oscillations (pressure ripple) and volumetric efficiency, and measurements were 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 TSV can also be studied (Fig. 74).

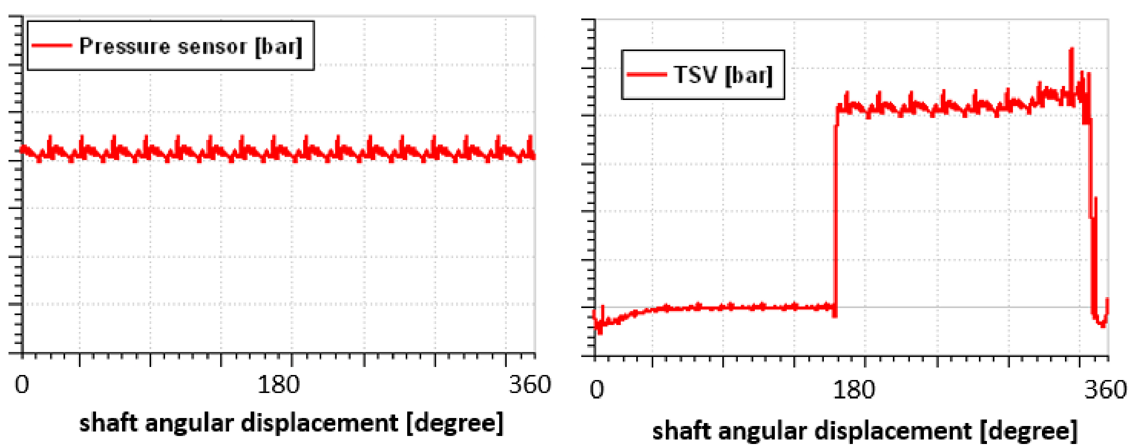


Figure 74: Example of predictions of delivery pressure ripple and TSV pressure for a given pump speed and delivery apparatus

1.2.8 Cavitation modeling for lumped parameter modeling approaches

Goal: The research deals with the formulation of a model suitable to consider aeration and vapor cavitation effects in the analysis of hydraulic systems with lumped parameter approaches.

A new model for the evaluation of fluid properties of hydraulic fluids has been developed accounting for the transient features of cavitation.

Approach: The developed model for fluid properties is able to provide an estimation of the fluid parameters required by lumped approach based on pressure build up or orifice flow equations (Fig. 75). Therefore fluid density, bulk modulus and viscosity (necessary when laminar flow equations are used to evaluate the mass flow rates entering/leaving the volumes) need to be accurately evaluated.

In the evaluation of these properties, additional compressibility effects due to fluid aeration and vaporization cannot be neglected for hydraulic components subjected to work below fluid saturation conditions. Commonly, all open circuit systems suffer of aeration effects due to the air release upstream the suction port of the pump. Typical steady-state approaches for the evaluation of the effective bulk modulus, or for the calculation of the instantaneous air (or vapor) content on the basis of the fluid pressure often fail in predicting the actual flow conditions in hydrostatic units (at it will be shown in the results section). This because of the transient features of cavitation (Fig. 76).

For this reason, an additional equation to evaluate the instantaneous gas content f_g in the control volume (CV) was formulated by Maha's researchers (Fig. 77). This equation is formulated for varying volumes (as in the displacement chambers of positive displacement machines) and it includes the terms given by the air content entering/leaving the chamber, the term related to the volume variation, and the internal air evolution evaluated by a simplified formulation of the Full Cavitation model (Singhal, 2002).

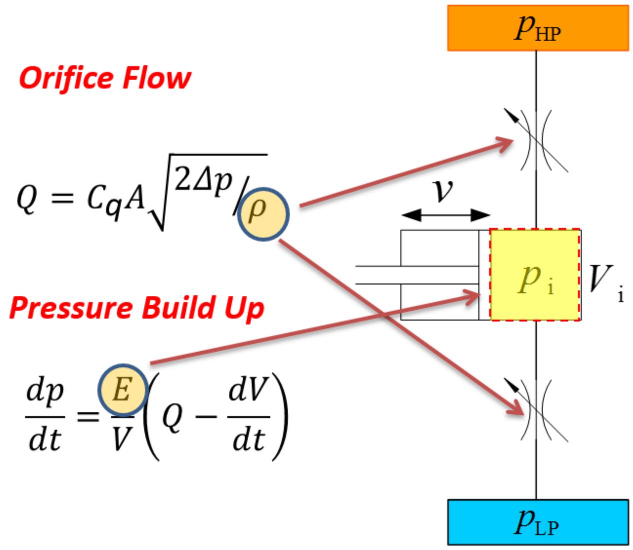


Figure 75 – Main equation used in lumped parameter approaches

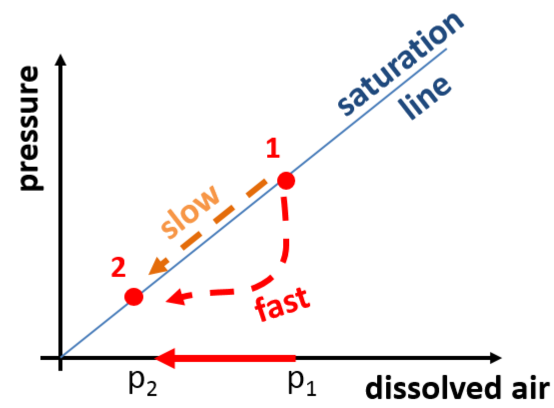


Figure 76 – Qualitative representation of air release process in hydraulic oil. A steady state approach for the evaluation of air content cannot represent fast processes

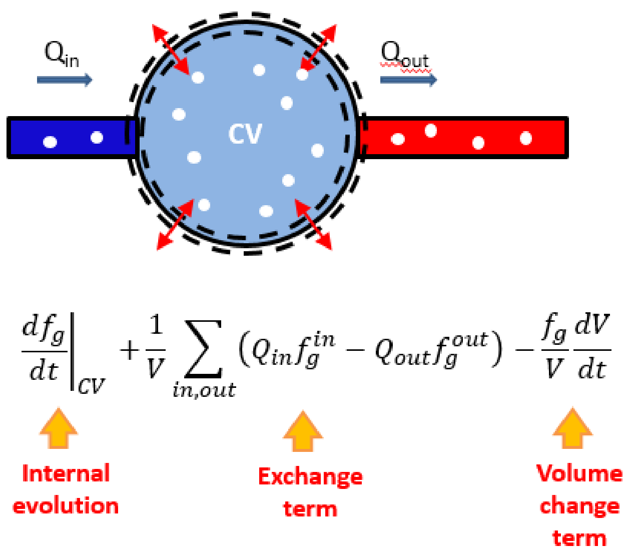
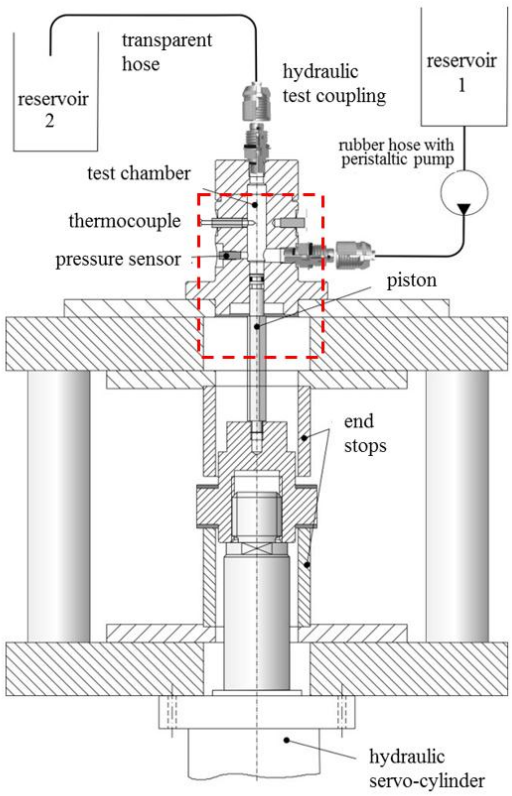


Figure 77 – Evaluation of the instantaneous gas content in a generic control volume

Once the gas content is evaluated, the fluid properties are evaluated by considering the different fractions of liquid, air and vapor, as shown in the following equations for fluid density.

$$\frac{1}{\rho} = \frac{f_v}{\rho_v} + \frac{f_g}{\rho_g} + \frac{1 - f_v - f_g}{\rho_l}$$

Main Results: The novel fluid model has been validated on the basis of experiments made at J. Kepler University of Linz (Austria) on the basis of compression/decompression tests performed on a specifically dedicated piston-cylinder device test rig (Fig. 78).



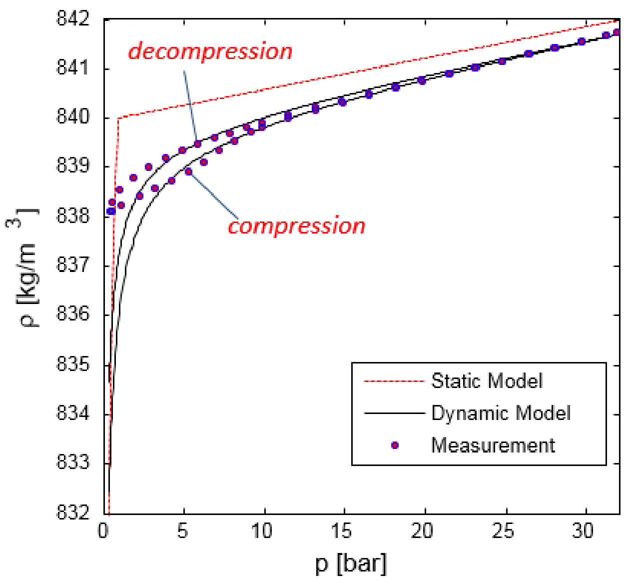
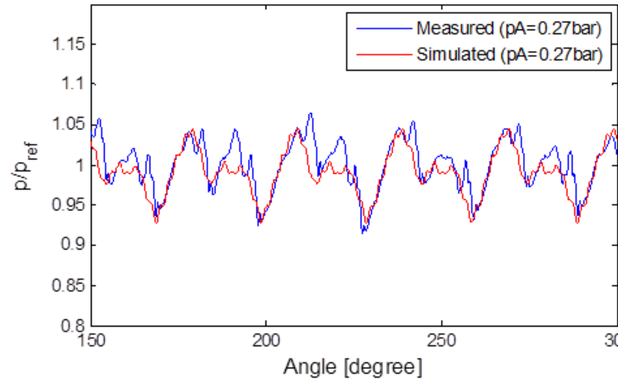
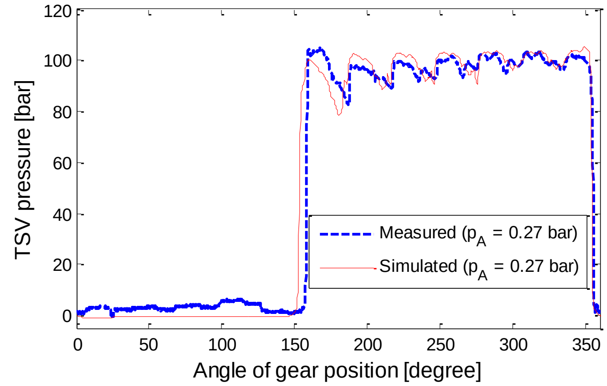


Figure 78 – Experimental apparatus used for the model validation, and example of comparison between simulation results and exp data (the hysteresis on the density is given by air release)

The model was also implemented within HYGESim for the simulation of external gear pumps. Experiments done under significant cavitating conditions showed the capability of the model of predicting flow rate and also variations of the features of delivery pressure ripple induced by presence of air in the oil (Fig. 79).

It is important to notice how for a conventional steady-state model for the evaluation of the gas phase content based on static pressure, HYGESim is not able to provide accurate predictions for strong cavitating conditions (Fig. 80).





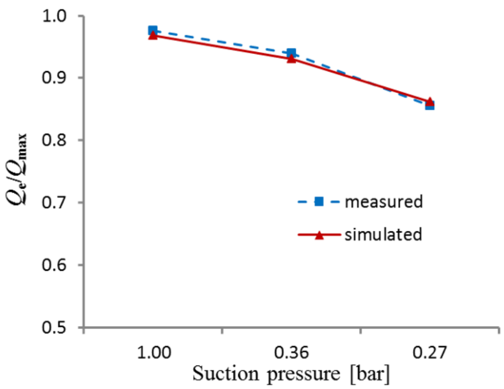


Figure 79 – Predictions vs measurements for an external gear pump under cavitating conditions (delivery pressure ripple and flow rate, pressure inside a tooth space volume)

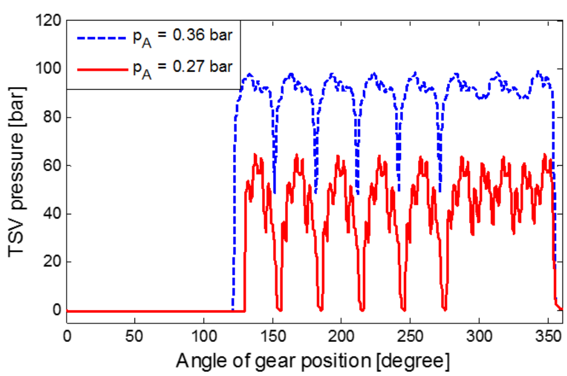


Figure 80 – Predicted tooth space volume pressure in a gear pump for cavitating conditions for a working pressure of 100 bar: for low pressure (0.27 bar absolute), HYGESim does not provide accurate evaluations if a static model for fluid properties is used.

1.2.9 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 strategy has 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 novel solution would allow for a reduction of both amplitude and duration of actuator and machine oscillations by up to 70%. The solution must also offer some margin of energy consumption reduction. Using an adaptive control method based on pressure feedback (using pressure sensors located in well protected locations of the machine), the proposed technique is suitable to all mobile applications without introducing a significant cost increase.

Approach: In order to reduce oscillations in a hydraulic machines, a controller is used to control the input signals of the control elements for the machine actuation (typically hydraulic valves). The input parameters of the controller are signals determined by sensors installed on the given machine, for which the oscillations have to be minimized. These feedback sensors can be either pressure sensors or accelerometers, depending on the application at hand. The tuning of the control parameters is achieved through online or offline optimization methods. This research applies an adaptation/optimization scheme using Extremum Seeking (ES) theory to FP applications. ES is an algorithm structure capable of identifying the set of parameters that can produce the maximum or minimum of a given function. Figure 81 describes the idea under the proposed control approach. A cost function associated to the oscillations is generated using real experiments or computer simulations. The ES algorithm examines the effects of controller parameters on this vibration cost function to achieve minimum oscillations through a fast convergence loop.

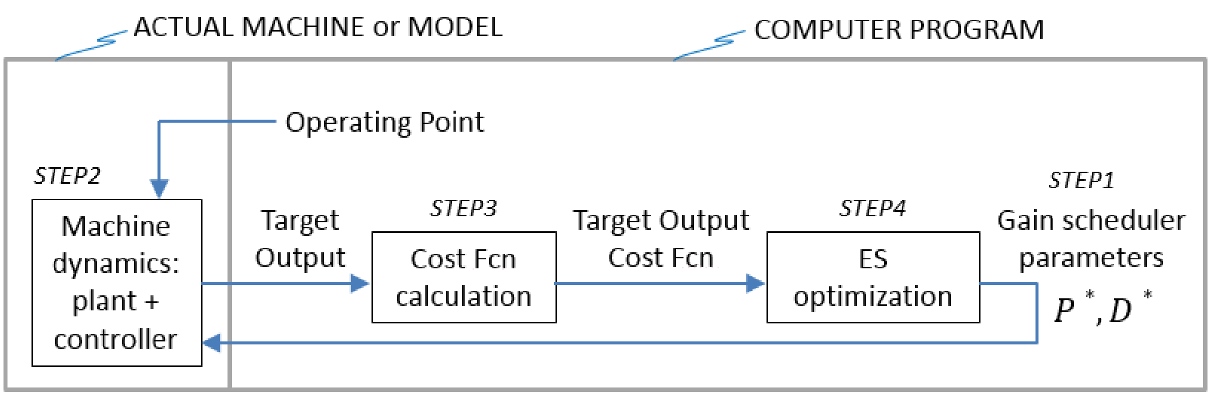


Figure 81 - Controller optimization algorithm

Main Results:

Control strategy achievements

The first application on which this control scheme was used was a hydraulic crane (see research facilities – section 3). 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. 82). The optimization scheme is shown in Figure 1 and 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.

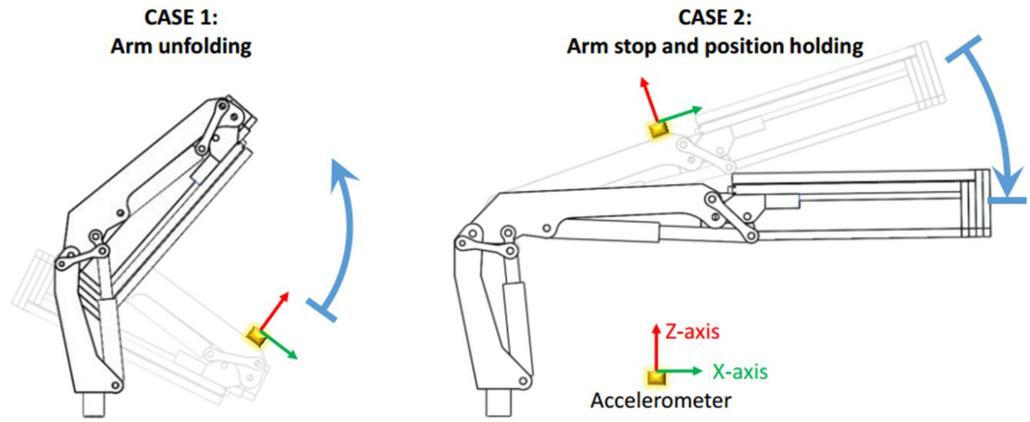


Figure 82 – reference cases on the hydraulic crane

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 83 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.

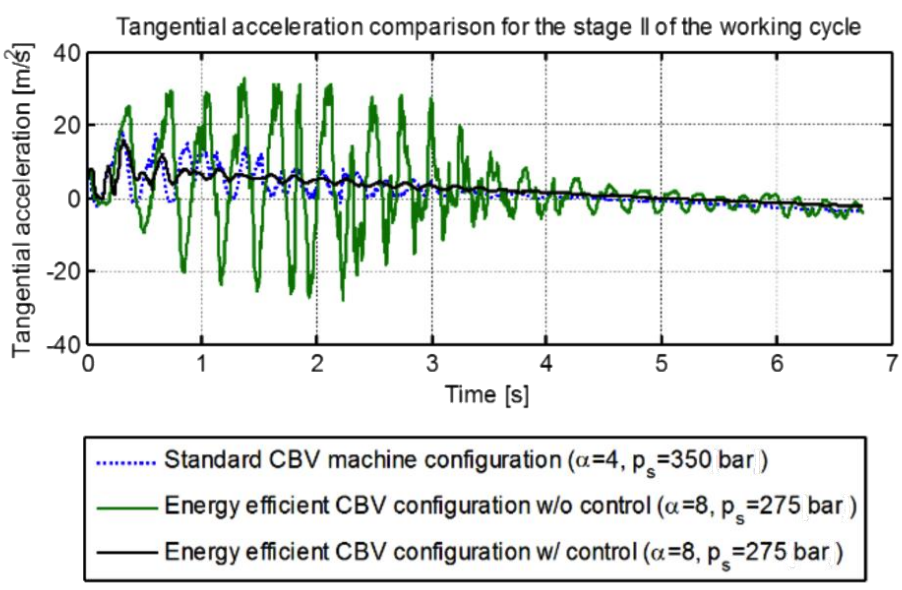


Figure 83: Experimental results from reference crane

Energy consumption estimation

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%

Mobile hydraulic applications

Along with the testing of the control structure for vibration reduction on the hydraulic crane, applications in mobile hydraulic machinery have also been considered. The specific machine which was considered for this implementation is a wheel loader. Much like with the crane, computer simulations were conducted using a model of the wheel loader to determine the viability of using actuator motion to damp system vibrations. After the simulations showed positive results, experimental tests were conducted on a wheel loader. These tests have shown indications that the control strategy is also capable of damping vibrations in mobile hydraulic applications.

1.2.10 Electro-Hydraulic Actuator

Goal: This research focuses on the formulation of novel compact electro hydraulic actuator system architectures.

Although the current trend in many mobile applications is towards the use of Electro Mechanical Solutions (EMAS) instead of Hydraulic Actuation Systems (HAS), HEAs can actually represent the best technological compromise. In fact, EHAs can combine the power to weight ratio advantage of hydraulic technology with the versatility and ease of installation and control of electric technology. Compared to EMAS, which are often equipped with low efficiency load holding mechanisms, EHAs can also offer superior energy efficiency.

Moreover, the EHAs do not suffer of jamming problems, which make them a strong candidate to be employed in harsh environments. Applications of the proposed EHA include aircrafts, cargo and vehicle doors, hatches and landing gears.

Approach: A novel EHA system was proposed in this study. Its ISO schematic is represented in Figure 84, while in Figure 85 shows a 3D representation of its actual implementation. The system includes a brushless, variable speed, electric motor which drives a bi-rotational external gear pump. The pump can therefore send the hydraulic fluid to both the rod and the bore sides of the actuator without the need of a directional flow control valve. A spring loaded accumulator (ACC) serves as pressurized system reservoir and it is connected to the pump by means of a dual pressure valve.

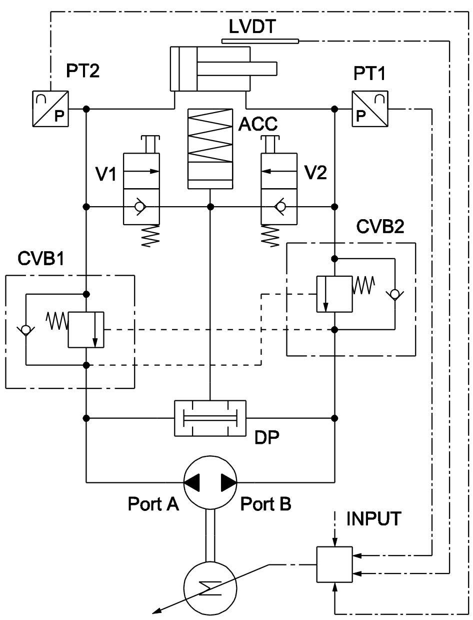


Figure 84 - Proposed EHA circuit layout

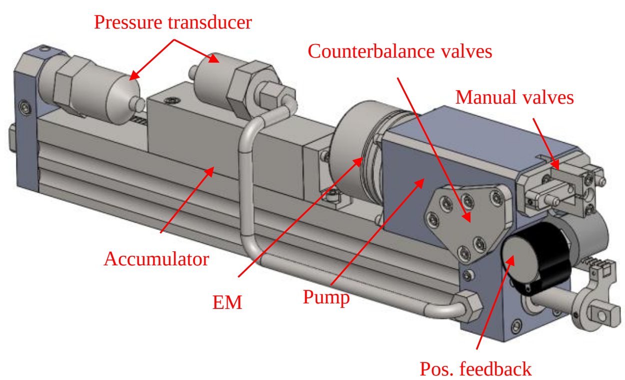


Figure 85 - 3D view of the EHA

The crucial element of the system is represented by the pump, since it directly affects energy efficiency, noise emissions, life and reliability of the system. In EHA systems, the pump design is commonly fixed displacement, being the flow controlled by the electric motor speed with a design suitable for miniaturization and permitting higher shaft speed. From this regard, external gear pumps offer high potential, considering manufacture cost and simplicity. Miniature gear pumps for EHA systems, however, do not offer high performance level, in terms of energy efficiency since they do not usually implement pressure compensation to control the internal lubricating gaps.

For this research, a novel design based on miniature bi-directional gear pump (from 0.13 cc/rev), was specifically proposed to maximize performance in terms of efficiency, noise emissions and durability of the reference EHA application.

This design is visible in Figure 86. The novelty of this design is represented by the lateral bushings along with the pressure compensation system, which are uncommon for miniaturized gear pumps.

For the design of the gears and of the unit, the HYGESim simulation tool was utilized in an optimization process as described in section 1.2.5. HYGESim was used to study and determine the optimal design as concerns following aspects: design of the recesses machined in the lateral bushings, radial balance of gears, axial balance of lateral bushes.

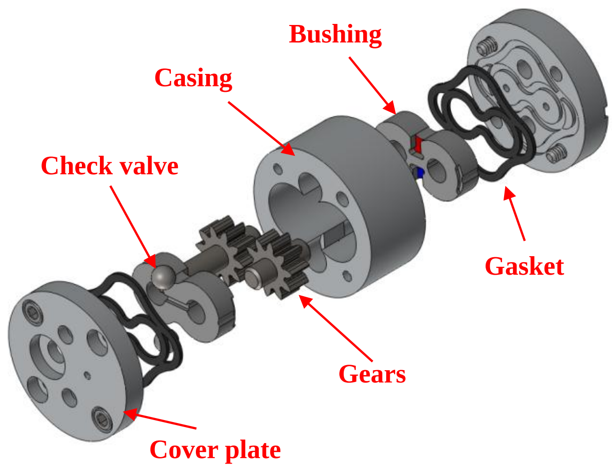


Figure 86 – Exploded view of the pump designed

Main Results:

A picture of a prototype of the EHA system is shown in Fig. 87. The proposed circuit layout is characterized by lower power consumption in all conditions, as confirmed by the power plot of Fig. 88. Only at the end of phase B the power consumption of the proposed circuit is higher with respect to the reference one (standard EHA). This is necessary to permit the full control of the actuator.

For the considered cycle, the overall energy consumption is 717 J for the proposed circuit, and 1685 J for the reference one, thus showing a 57% of reduction offered by the proposed solution.

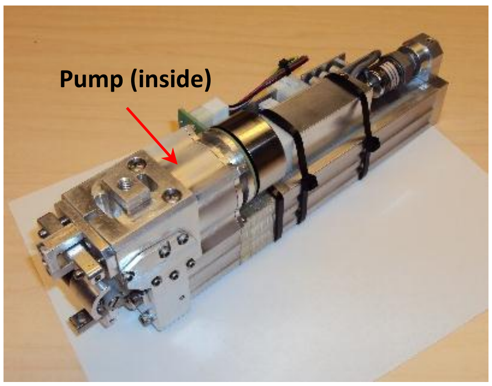


Figure 87. Prototype of EHA

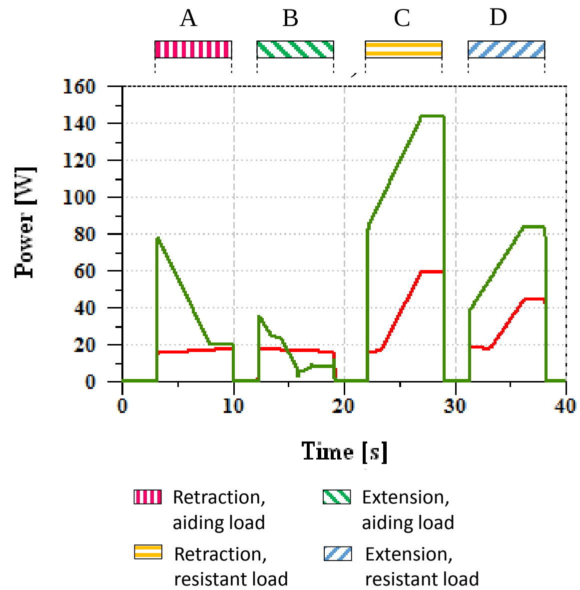


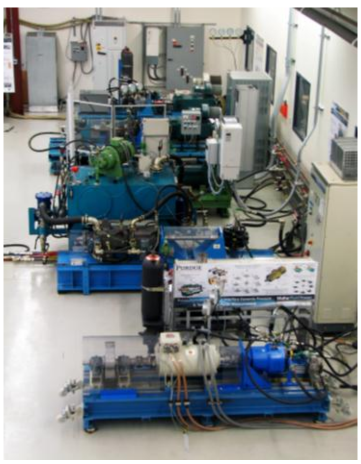
Figure 88. Power consumption comparison between reference circuit (green) and proposed circuit (red)

2 Research Facilities

Lab Space and Test Rigs at Maha

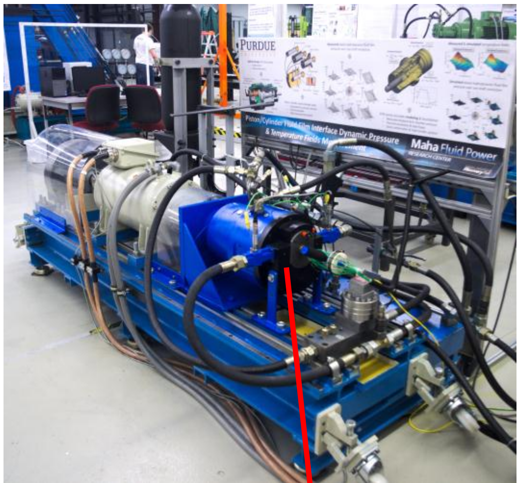
The lab currently houses eleven test rigs designed to support our research.

Test Beds for Technological Demonstration (Left)



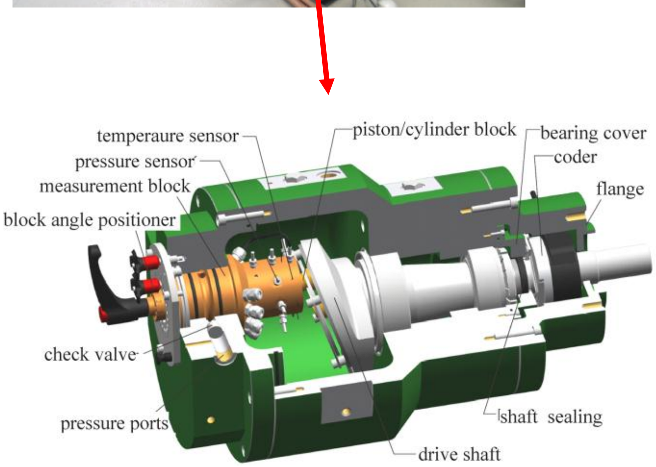
Test Rigs and Car Lift (Above)

and Control Room (Left)

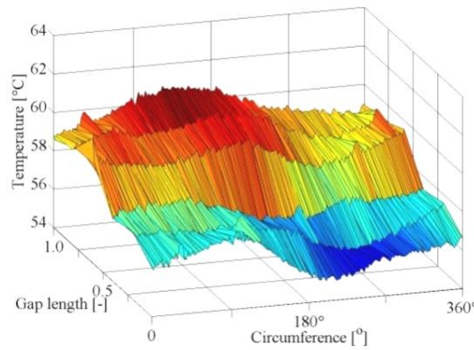


EHD Test Rig

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

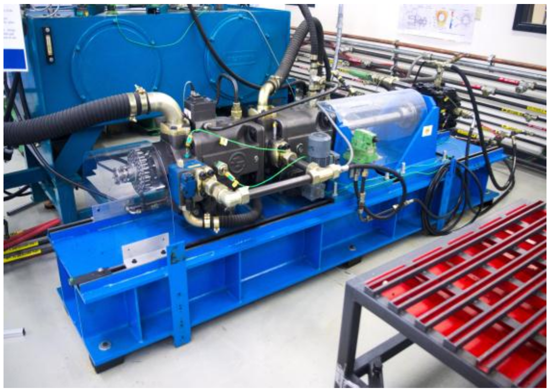


Measured Temperature Field in the Piston/Cylinder Gap

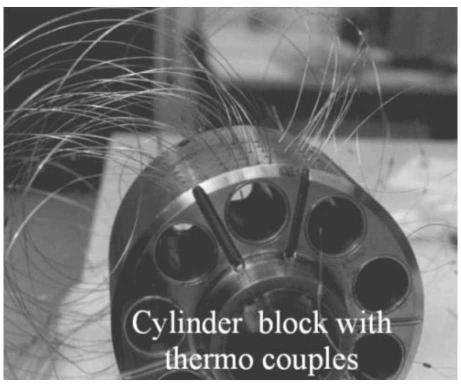
Cavitation/PIV test rig

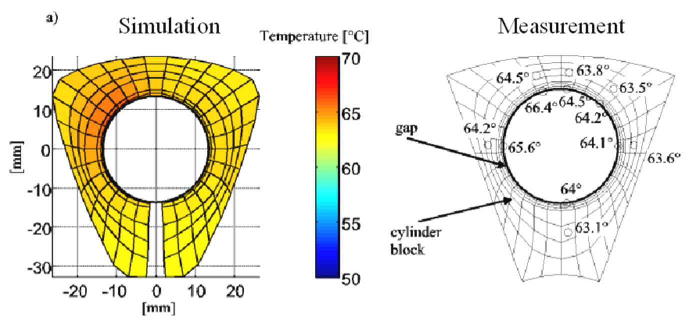
This test rig was designed to visualize and conduct Particle Image Velocimetry (PIV) analysis of cavitation in hydraulic oil. This test rig was designed in support of CCEFP project 3C and will support the computational studies in modeling cavitation in hydraulic components.

OLEMS Test Rig



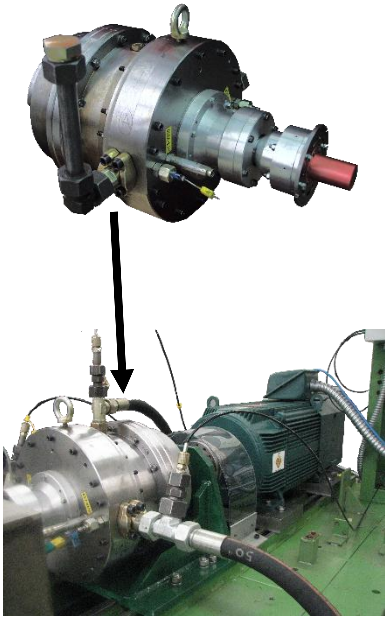
This rig is designed to investigate the temperature behavior in swash plate axial piston pumps. Sixty thermocouples are mounted around a single cylinder to measure the temperature field during operation of the pump. Telemetry is used for data transfer from the rotating cylinder block to the data acquisition 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.





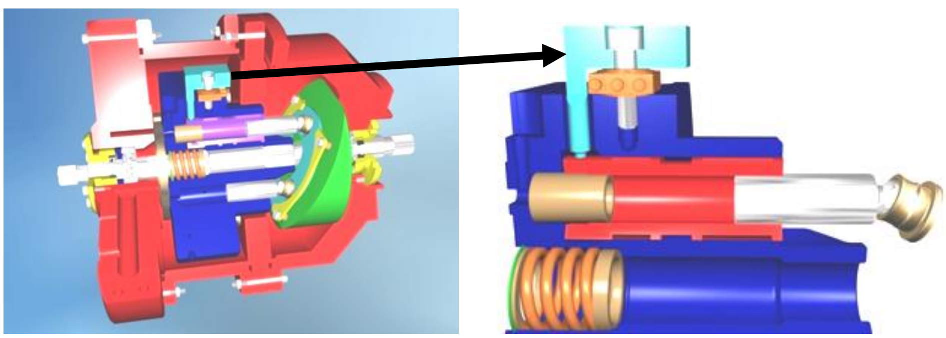
Temperature distribution in the assembly near the slipper slide

Tribo Test Rig



The heart of the test rig, the Tribo pump (below, left), 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. This provides the capability to examine the impact of novel materials and surface micro-geometry on the behavior of this important lubricating interface.



Transmission Test Rig

The test rig is designed to determine the efficiency of a hydrostatic car transmission at different loads and gear ratios. The transmission is driven by a diesel engine and a secondary controlled unit simulates the driving resistance of the vehicle.

Hardware-in-the-Loop Transmission Test Rig

In 2014 one of the two HIL transmission test rigs was upgrade with a larger base plate and a completely revamped data acquisition and control system. This test rig uses two electric motors to replicate engine and vehicle dynamics enabling the transmission to operate under 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 a novel blended hydraulic hybrid transmission.

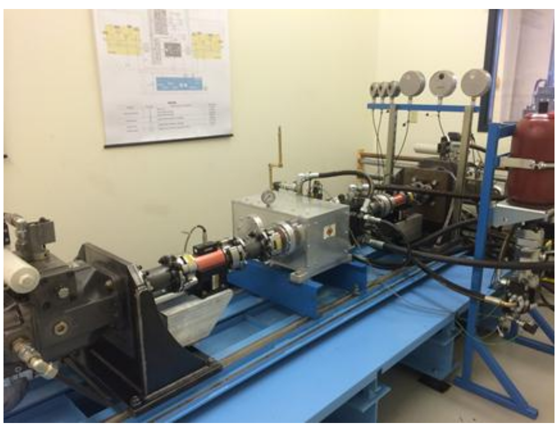
Performance Characteristics

Engine simulator: 300 Nm @ 4000 rpm

Load simulator: 500 Nm @ 3600 rpm

Hardware-in-the-Loop Transmission Test Rig

This is one of two HIL transmission test rigs in the Maha lab which has been designed for the purpose of testing powertrains and powertrain control concepts. This test rig uses two secondary controlled hydraulic units to mimic the engine and road loads enabling dynamic drive cycle testing of transmissions for vehicles up to a class 6 truck in size. Pictured is a series hydraulic hybrid power split transmission intended for use in a Toyota Prius.



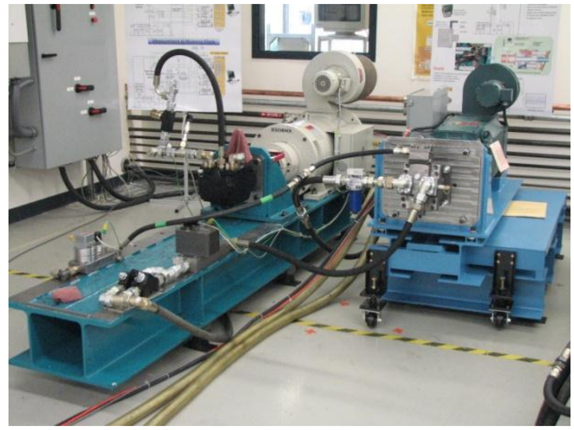
Performance Characteristics

Engine simulator: 900 Nm @ 1800 rpm

Load simulator: 900 Nm @ 1800 rpm

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.



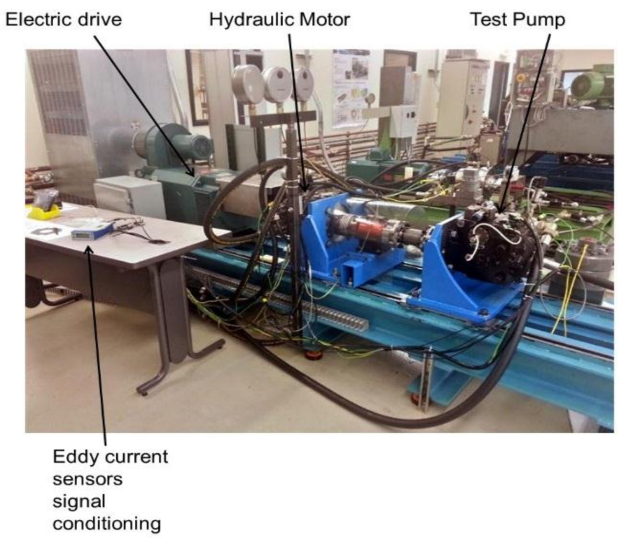
Performance Characteristics

Max. installed electric power: 2 x 120 kW

Max. speed: n1 = 7000 rpm/n2 = 3000 rpm

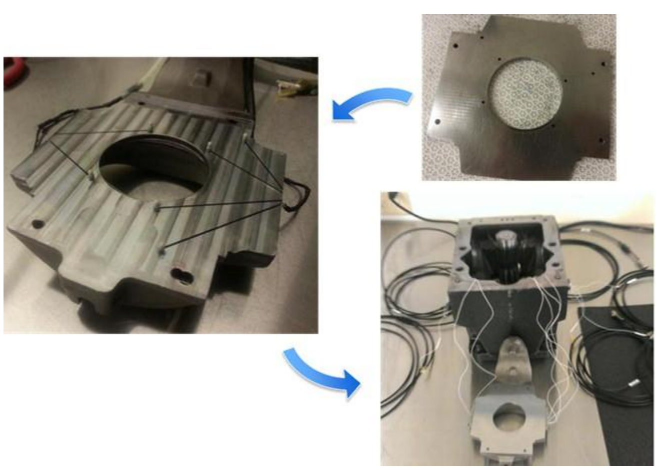
Max. pressure: 450 bar

Max. torque: M1 = 300 Nm/ M2 = 500 Nm



Slipper Film Thickness Pump

A swashplate type piston pump was modified to incorporate six high-speed eddy current displacement transducers into the swashplate running face. These sensors directly measure the transient fluid film thickness between the swashplate and slipper during actual machine operation. The steady state test rig electric motor is used to drive the hydraulic pump with an additional energy recirculating hydraulic motor installed inline, necessary for peak power operating conditions.

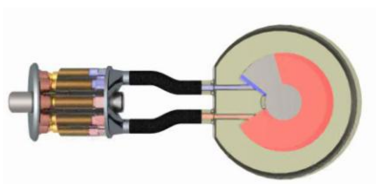


Performance

Max. Torque: 30000 Nm

Max. Pressure: 350 bar

Max. Power: 30 kW



Rotary Actuator

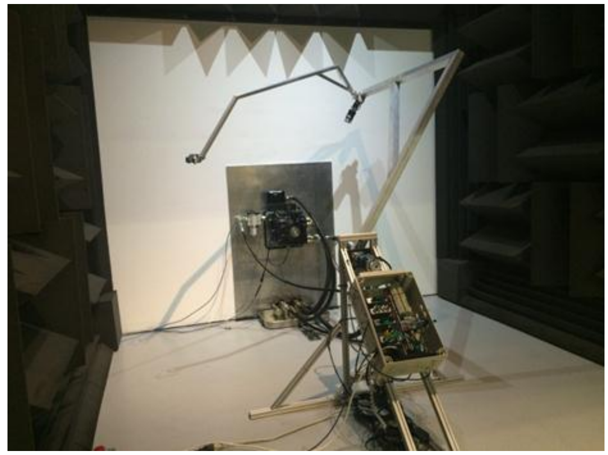
JIRA Test Rig

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. This technology not only reduces the installed pump power but increases overall efficiency by reducing parasitic losses. In addition to the hardware improvements, new control concepts focused on actuator operability have been developed. Research is in progress to investigate the applications and limitations of these new hydraulic architectures and control strategies.

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 2014 was the addition of a robot able to automate the sound intensity measurements.



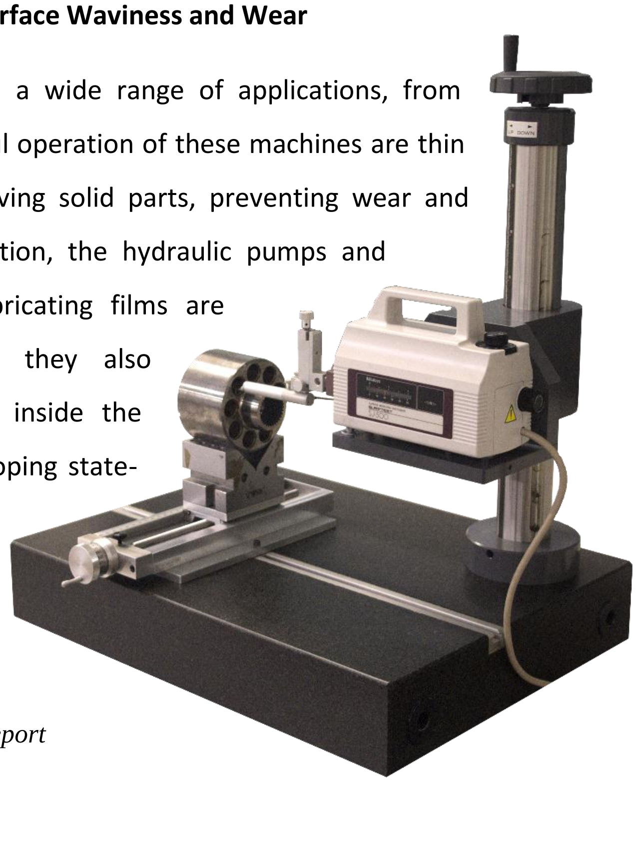
Multi functional test rig for hydraulic components

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 a 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

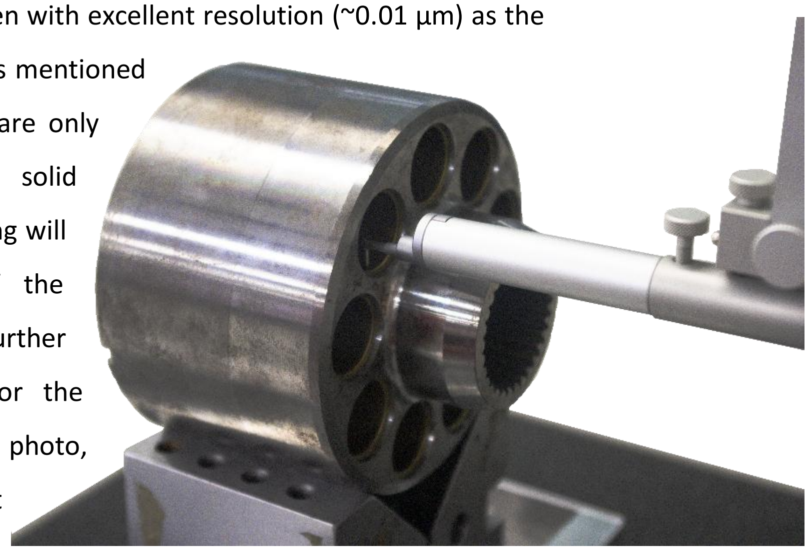
The above test rigs are powered by a 320 kW central hydraulic power supply unit with a 2000 liter tank, a water cooler and heating elements with five individually controlled pressure compensated pumps, 350 bar and 450 lpm output flow and a 60 l/min low pressure installed in 2005. A second medium pressure 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.

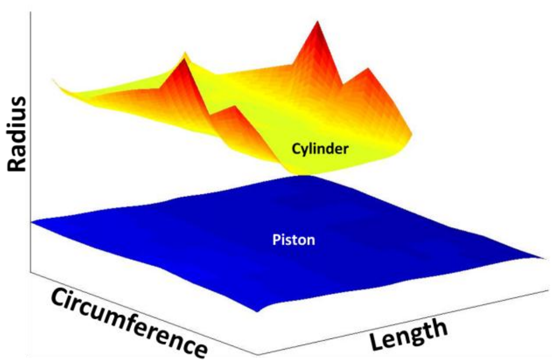
Surface Profilometer for Investigating Micro-surface Waviness and Wear



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, the hydraulic pumps and motors would 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. 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.





The value of the profilometer system was demonstrated on several occasions during the past year. The system has aided in the precision assembly of sensors in a novel slipper – swashplate lubricant fluid film thickness test rig. The profilometer has also aided in surface wear measurements on the piston and cylinder of various machines in order to be used as accurate inputs into the model for establishing a valid baseline and also for conducting a surface wear profile study. The profilometer system continues to be useful not only as a source of simulation inputs, but also as a means of validating simulation outputs. In both ways, it is helping refine the models developed at the Maha lab.

Maha Computing Cluster

As the fidelity and complexity of numeral models developed and used at the Maha lab increase, so do the computational demands. Design of experiment studies compound the problem by requiring a single numerically expensive simulation to be run hundreds or thousands of times over in order to analyze the sensitivity and effect of system architecture or design parameter changes. Some of the studies conducted at Maha over the past year would have required hundreds of weeks of simulation time on the individual's desktop computer – a simply unacceptable burden. To solve this problem a set of new computers exclusively for simulation were purchased in 2010 and then further expanded in 2011 to total 16 machines. The computers feature i7 (4-real, 4-hyperthreaded core) processors, 12 GB ram, and 7200k hard disks with 100 Mbps Ethernet. Windows 7 x64 is installed on all machines which enables interactive use of each machine through Windows remote desktop for GUI only applications. In 2012 a Dell PowerEdge R815 server with Quad AMD Opteron processors and 128 GB ram was installed into the computing cluster. This new machine enables large in-core matrix simulations and 64 core shared-memory parallel simulations when necessary; when the large single machine capabilities are not required, the computer is easily partitioned using the HTCondor software described below. The simulation machines are networked together on a private LAN and can only be accessed remotely through a secure VPN. A custom in-house developed software suite allows monitoring the status and interactive use of each machine by every Maha member quickly through a simple web interface as illustrated below:

Beyond interactive use, HTCondor (http://research.cs.wisc.edu/htcondor/) a job management and scheduling system, is installed on all of the computers. This allows for a large queue (1000's of jobs) of command-line only programs to be submitted and scheduled at a head node. HTCondor handles the burden of input file transfer to each worker node, execution of the program, and the retrieval of simulation output back to the submit node. Using this system, hundreds of simulations can be performed in parallel with maximum throughput requiring little effort from the end user – something unfeasible just using remote desktop. The HTCondor head node in the Maha compute cluster runs Debian Linux which enables simple multi-remote user functionality and also fulfills network router, VPN, file and web server roles.

Test Beds

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.

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.

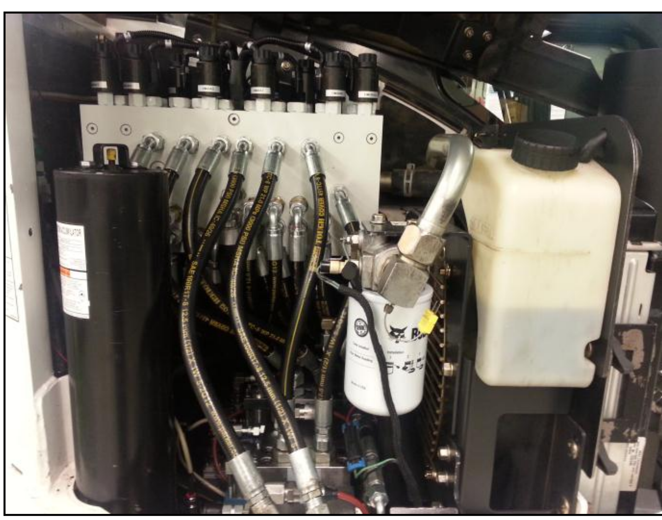
The smaller 5-ton wheel loader originally served as a platform for diagnostics and prognostics on hydraulic systems. In 2013, it was overhauled to implement a displacement controlled (DC) steer-by-wire (SbW) system. The loader served as a prototype test vehicle for investigating and validating adaptive 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.

Mini Excavator

Throughout 2014, the working hydraulics of our DC hydraulic hybrid excavator prototype were entirely overhauled to implement the latest advance in DC actuation: Pump Switching. The concept allows for the minimization of the installed pump power through the use of a distributing manifold and intelligent controls. Both the energy savings demonstrated through the implementation of DC actuation on the working actuators as well as the predicted savings using the hydraulic hybrid swing drive are preserved since the basic architecture concept is conserved. In addition, the hydraulic hybrid swing drive architecture and electrical systems were modified to greatly improve their functionality and reliability.

In addition to the required control strategies for the realization of DC with pump switching, a number of new control concepts have been developed and successfully implemented on the prototype. One example is the development and implementation of control algorithms for improved operability of the secondary controlled hydraulic hybrid swing drive. Another example is the development and demonstration of an observer-based electronic anti-stall controller for the prime mover in the prototype.

More advanced control techniques are currently under study for pump switching and hydraulic hybrid architectures and are planned for implementation in 2015.



Skid-Steer Loader

Pump-controlled technology has been demonstrated on compact machinery at the Maha Fluid Power Research Center. For the purpose of demonstrating active vibration damping through displacement control, a Bobcat skid-steer loader was modified. Previous Maha researchers have implemented active vibration damping using linear control theory. The skid-steer loader has been equipped with new electronics to add data acquisition and control capabilities. In addition, advanced control strategies are currently being researched to improve our already existent active vibration damping algorithms.

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

3.1. Dr. Ivantysynova's Research Grants

Total grants for 2014: $1,877,153

Engineering Research Center for compact and efficient fluid power. **NSF + industry funds, 9th** year funding **$ 676,147.**

Advanced Hydraulic Systems for Next Generation of Skid Steer Loaders. Bosch-Rexroth Corporation. **$427,856.**

Evaluation and Design Study of the Piston/Cylinder Interface of a Swash Plate Type Hydraulic Motor Operating with Jet Fuel. Moog Inc. **$152,846.**

Modelling and analysis of swash plate axial piston pump. Hitachi Ltd. **$230,592.**

Investigation of Alternative Cylinder Block Materials using Fluid Structure Interaction Modeling (FSTI). Parker Hannifin Corp. **$196,161.**

DOE Hosier Center on Heavy Duty Hybrids**. $59,550.**

Maha lab support. Maha funds. **$129,000.**

Research donation, Kalamazoo **$ 6,000**

3.2. Dr. Vacca's Research Grants

Total annual budget (2014): $ 736,084

Federal sponsors:
Engineering Research Center – Center for Compact and Efficient Fluid Power.
Project 1F.1 (Variable Displacement Gear Machines) + Project 3B.3 (Active Vibration Damping for Mobile Machines): $215,251

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

Industry Sponsors: total $ 366,568

Other Sponsors:
Chainless Challenge (Parker Hannifin): $ 8,075
National Fluid Power Association, Education and Technology Foundation, Multi-Users Load-Sensing System Educational Test Station, $ 5,000
Dept. Support (ABE): $ 16,190

4 Publications, Invited Lectures, Patents, and Reports

4.1 Dr. Ivantysynova's team

Journal Articles

Daher, N. and **Ivantysynova, M.** 2014. An Indirect Adaptive Velocity Controller for a Novel Steer-by-Wire System. ASME Journal of Dynamic Systems, Measurement, and Control, Vol. 136, Issue 5, pp. 051012

Daher, N. and **Ivantysynova, M.** 2014. A Virtual Yaw Rate Sensor for Articulated Vehicles Featuring Novel Electro-Hydraulic Steer-by-Wire Technology. Control Engineering Practice, Vol. 30, pp. 45-54

Daher, N. and **Ivantysynova, M.** 2014. Energy Analysis of an Original Steering Technology that Saves Fuel and Boosts Efficiency. Energy Conversion and Management, Vol. 86, pp. 1059-1068

Kim, T., **Kalbfleisch, P.**, and **Ivantysynova, M.** 2014. The effect of cross porting on derived displacement volume. International Journal of Fluid Power, Vol. 15, Issue 2, pp. TBD

Schenk, A. and **Ivantysynova, M.** 2014. A transient thermoelastohydrodynamic lubrication model for the slipper / swashplate in axial piston machines. ASME Journal of Tribology. TBD (In Review)

Busquets, E. and **Ivantysynova, M.** 2014. Discontinuous Projection-Based Adaptive Robust Control for Displacement-Controlled Actuators. ASME Journal of Dynamic Systems. TBD (In Review)

Busquets, E. and **Ivantysynova, M.** 2014. A Multi-Actuator Displacement-Controlled System with Pump Switching – A Study of the Architecture and Actuator-Level Control. Transactions of the Japan Fluid Power System Society. TBD (In Review)

Shang, L. and **Ivantysynova, M.** 2014. Port and Case Flow Temperature Prediction for Axial Piston Machines. International Journal of Fluid Power. (In Review)

Daher, N. and **Ivantysynova, M.** 2014. Yaw Stability Control of Articulated Frame Off-Highway Vehicles via Displacement Controlled Steer-by-Wire. Control Engineering Practice. Manuscript No. CONENGPRAC-D-14-00439 (In Review)

Hippalgaonkar, R. and **Ivantysynova, M.** 2014. Optimal Power Management for DC Hydraulic Hybrid Multi-Actuator Machines – Part 1: Theoretical Studies, Modeling and Simulation. ASME Journal of Dynamic Systems, Measurement and Control. TBD (In Review)

Hippalgaonkar, R. and **Ivantysynova, M.** 2014. Optimal Power Management for DC Hydraulic Hybrid Multi-Actuator Machines – Part 2: Machine Implementation and Measurement. ASME Journal of Dynamic Systems, Measurement and Control. TBD (In Review)

Conference Proceedings

Busquets, E. and **Ivantysynova, M.** 2014. An Adaptive Robust Control for Displacement-controlled End-effectors. Proc. of the 8th FPNI PhD Symposium, Lappeenranta, Finland.

Sprengel, M. and **Ivantysynova, M.** 2014. Hardware-in-the-Loop Testing of a Novel Blended Hydraulic Hybrid Transmission. Proc. of the 8th FPNI PhD Symposium, Lappeenranta, Finland. **- Best Paper Award (Backe Medal).**

Mizell, D. and **Ivantysynova, M.** 2014. Material Combinations for the Piston-Cylinder Interface of Axial Piston Machines: A Simulation Study. Proc. of the 8th FPNI PhD Symposium, Lappeenranta, Finland.

Chacon, R. and **Ivantysynova, M.** 2014. An Investigation of the Impact of Micro Surface Shaping on Cylinder Block/Valve Plate Interface Performance. Proc. of the 8th FPNI PhD Symposium, Lappeenranta, Finland.

Wondergem, A. and **Ivantysynova, M.** 2014. The Impact of the Surface Shape of the Piston on Power Losses. Proc. of the 8th FPNI PhD Symposium, Lappeenranta, Finland.

Padovani, D. and **Ivantysynova, M.** 2014. Energy Efficient Hydraulic Rotary Drive: Analysis and Comparison of Two Different Displacement Controlled Solutions. Proc. of the 8th FPNI PhD Symposium, Lappeenranta, Finland.

Busquets, E. and **Ivantysynova, M.** 2014. A Robust Multi-Input Multi-Output Control Strategy for the Secondary Controlled Hydraulic Hybrid Swing of a Compact Excavator with Variable Accumulator Pressure. Proceedings of the ASME/BATH 2014 Symposium on Fluid Power & Motion Control, September 10-12 2014, Bath, United Kingdom.

Daher, N. and **Ivantysynova, M.** 2014. A Steer-by-wire System that Enables Remote and Autonomous Operation. SAE 2014 Commercial Vehicle Engineering Congress, Oct. 7-9 2014, Rosemont, IL, USA. SAE Technical Paper 2014-01-2404.

Sprengel, M. and **Ivantysynova, M.** 2014. Recent Developments in a Novel Blended Hydraulic Hybrid Transmission. SAE 2014 Commercial Vehicle Engineering Congress, Oct. 7-9 2014, Rosemont, IL, USA. SAE Technical Paper 2014-01-2399.

Busquets, E. and **Ivantysynova, M.** 2014. The World's First Displacement Controlled Excavator Prototype with Pump Switching - A Study of the Architecture and Control. 9th JFPS International Symposium on Fluid Power. Matsue, Japan. pp. 324 - 331. **Best Paper Award.**

Daher, N. and **Ivantysynova, M.** 2014. New Steering Concept for Wheel Loaders. Proceedings of the 9th International Fluid Power Conference (9IFK), Mar. 24-26, 2014. Aachen, Germany, Vol 1. pp.224-235.

Schenk, A. and **Ivantysynova, M.** 2014. A transient fluid structure interaction model for lubrication between the slipper and swashplate in axial piston machines. Proceedings of the 9th International Fluid Power Conference (9IFK), Mar. 24-26, 2014. Aachen, Germany, Vol 1. pp.398-409.

Sprengel, M. and **Ivantysynova, M.** 2014. Investigation and Energetic Analysis of a Novel Blended Hydraulic Hybrid Power Split Transmission. Proceedings of the 9th International Fluid Power Conference (9IFK), Mar. 24-26, 2014. Aachen, Germany, Vol 1. pp.140-151.

Invited Lectures

Ivantysynova, M. 2014. Optimized fluid films essential for displacement control & hydraulic hybrid systems. ExxonMobile, Feb. 2014. Philadelphia PA, USA

Ivantysynova, M. 2014. Debate Hydraulic vs. Electric Drive. The 8th FPNI PhD Symposium, Jun. 12, 2014. Lappeenranta, Finland.

Research Reports

Wondergem, A. and **Ivantysynova, M.** 2014. Piston Surface Shapes and Configurations Investigated. Research Report MAHA01-2014-in

Wondergem, A. and **Ivantysynova, M.** 2014. Piston Surface Shapes and Configurations with Various Code Versions. Research Report MAHA02-2014-in

Kalbfleisch, P. and **Ivantysynova, M.** 2014. Optimization of Valve Plate to Reduce Noise and Maintain Low Control Effort. Research Report MAHA12-2014-ex

Wondergem, A. and **Ivantysynova, M.** 2014. Baseline Code Comparison and Verification. Research Report MAHA04-2014-in

Wondergem, A. and **Ivantysynova, M.** 2014. Tribo Code Comparison and Verification. Research Report MAHA05-2014-in

Wondergem, A., Mizell, D., and Ivantysynova, M. 2014. Code Used for Ashley Wondergem's Master's Thesis. Research Report MAHA06-2014-in

Garcia, A., Mizell, D., and Ivantysynova, M. 2014. The Tribo Telemetry System. Research Report MAHA07-2014-in

Ernst, M. and Ivantysynova, M. 2014. Designing the Piston-Cylinder Interface of High Pressure Water-Lubricated Piston Pumps. Research Report MAHA08-2014-in

Ernst, M. and Ivantysynova, M. 2014. Code Comparison: Linear vs. Iterative Methods of Handling Contact at the Piston-Cylinder Interface for Water Hydraulics. Research Report MAHA09-2014-in

4.1 Dr. Vacca's team

Journal Articles

Altare, G., Vacca, A., 2014, A Design Solution for Efficient and Compact Electro-Hydraulic Actuators, Elsevier Proceedia (in review) TBD

Opperwall T.J., **Vacca A.,** 2014, Modeling Noise Sources and Propagation in Displacement Machines and Hydraulic Lines, Transactions of the Japan Fluid Power System Society (in review) TBD

Cristofori D., Vacca A., 2014, Modeling Hydraulic Actuator Mechanical Dynamics from Pressure Measured at Control Valve Ports, Journal of Systems and Control Engineering (accepted).

Tang Q. , Chen J., Vacca A., 2014, Tribological Behaviors of Carbon Fiber Reinforced PEEK Sliding on Ion Nitrided 2Cr13 Steel Lubricated with Tap Water, Tribology Transaction, available online, DOI: 10.1080/10402004.2014. 990593)

Devendran R.S., Vacca A., 2014, A Novel Design Concept for Variable Delivery Flow External Gear Pumps and Motors, International Journal of Fluid Power, Vol. 15, Issue 3, 2014, pp.121-137

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 Transaction, Vol 58(2) (available online since Oct 2014).

Dhar S., Vacca A., 2014, *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.

Agarwal P., Vacca A., Wang K., Kim K., Kim T., 2014, *An Analysis of Lubricating Gap Flow in Radial Piston Machines*, SAE International Journal of Commercial Vehicles, 7(2): 524-534.

Zhou J., Vacca A., Casoli P., 2014, *A Novel Approach for Predicting the Operation of External Gear Pumps under Cavitating Conditions*, Simulation Modeling Practice and Theory (Elsevier), Vol. 45, pp. 35-49.

Conference Proceedings

Altare G., Vacca A., 2014, *A Design Solution for Efficient and Compact Electro-Hydraulic Actuators*, The Second International Conference on Dynamics and Vibroacoustics of Machines, September 15-17, Samara, Russia.

Thiagarajan D., Vacca A., 2014, *A Numerical Procedure to Design the Optimal Axial Balance of Pressure Compensated Gear Machines*, 8th FPNI Ph.D. Syposium on Fluid Power, June 11-13, Lappenranta, Finland.

Ritelli G.F., Vacca A. 2014, *Experimental-Auto-Tuning Method for Active Vibration Damping Controller. The Case Study of a Hydraulic Crane*, 9th IFK, Int. Fluid Power Conference, March 24-26, Aachen, Germany.

Dhar S., Vacca A., Lettini A., 2014, *An Experimental Investigation of the Lateral Lubricating Gaps in External Gear Machines with Axially Balanced Lateral Bushes*, 9th IFK, Int. Fluid Power Conference, March 24-26, Aachen, Germany.

Devendran R.S., Vacca A., 2014, *Experimental Characterization of External Gear Machines with Asymmetric Teeth Profile*, IFPE 2014, Int. Fluid Power Expo, March 4-8, Las Vegas, USA.

Zhou J., Vacca A., Casoli P., Lettini A., 2014, *Investigation of the impact of Oil Aeration on Outlet Flow Oscillations in External Gear Pumps*, IFPE 2014, Int. Fluid Power Expo, March 4-8, Las Vegas, USA.

Agarwal P., Vacca A., 2014, *A Numerical Model for the Simulation of Flow in Radial Piston Machines*, IFPE 2014, Int. Fluid Power Expo, March 4-8, Las Vegas, USA.

Altare G., Vacca A., Richter C., 2014, *A Novel Pump Design for an Efficient and Compact Electro-Hydraulic Actuator*, 2014 IEEE Aerospace Conference, March 1-8, Big Sky, Montana, USA.

Invited Lectures

Invited talk "Research trends in fluid power", Samara Aerospace University (Russian Federation), Jun 2-6, 2014

5 Theses Completed In 2014

5.1 Under Dr. Ivantysynova's supervision

PhD Theses

Rohit Hippalgaonkar 2014. Power management strategies for hydraulic hybrid multi-actuator mobile machines with DC actuators. PhD thesis, Purdue University.

Naseem Daher 2014. Novel Energy Efficient Electrohydraulic Steer-By-Wire Technology. PhD thesis, Purdue University.

Andrew Schenk 2014. Predicting Lubrication Performance between the Slipper and Swashplate in Axial Piston Hydraulic Machines. PhD thesis, Purdue University.

Master's Theses

Natalie Spencer 2014. Design and Development of a Novel Test Method to Measure the Slipper / Swashplate Interface Fluid Film in a Positive Displacement Machine. Master's thesis, Purdue University.

Rene Chacon 2014. Cylinder Block / Valve Plate Interface Performance Investigation Through the Introduction of Micro-Surface Shaping. Master's thesis, Purdue University.

Ashley Wondergem 2014. Piston / Cylinder Interface of Axial Piston Machines – Effect of Piston Micro-Surface Shaping. Master's thesis, Purdue University.

5.1 Under Dr. Vacca's supervision

PhD Theses

Sujan Dhar 2014. A Study of the Fluid Structure and Thermal Interactions in the Lubricating Interface between Gears and Lateral Bushes in External Gear Machines, PhD thesis, Purdue University.

Master's Theses

Divya Thiagarajan 2014. A Numerical Procedure to Design the Optimal Axial Balance in External Gear Machines and its Potential in Formulating Novel Efficient Design Solutions, Master's thesis, Purdue University.

Pulkit Agarwal, 2014, Modeling of High Pressure Radial Piston Pumps, Master's thesis, Purdue University,.

6 International Co-operation

Every year, the Maha lab is pleased to host international scholars for a period of some months. Our successful international co-operations with fluid power research centers worldwide has been strengthened through our membership in the international network “Fluid Power Net International” (FPNI), which is currently joined by members from 26 countries, refer to http://fluid.power.net

6.1 International students and researchers (Dr. Ivantysynova’s team)

In 2014, the following international students and researchers have worked in our team

Juliane

Xuewen

Zhongsheng

Anna

Nils

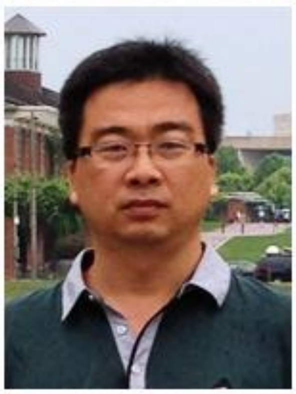
Dongyun

Tong

Juliane Bach	Germany
Dr. Xuewen Du	China
Dr. Zhonghseng Sun	China
Anna Garcia Teruel	Spain
Nils Trochelmann	Germany
Dr. Dongyun Wang	China
Dr Tong Xing	China

6.1 International students and researchers (Dr. Vacca's team)

Qunguo Tang
Visiting Scholar from Huazhong University of Science and Technology, China
Ph.D.: Harbin Institute of Technology, China
Origin: China
January 2014-December 2014
Research Topic: Modelling and simulation of fluid-structure interaction, material screening of water hydraulic external gear pump.



Yanhai Cheng
Ph.D.: Shandong University, China.
Origin: China
July 2013-September 2014
Research Topics: Low temperature grease transporting system modeling; Realization of a centralized greasing units.

Julian Che
Visiting Student from Universidad Tecnologica de Queretaro, Mexico
BS: Universidad Tecnologica de Queretaro, Mexico.
Origin: Mexico
February 2014-June 2014
Research Topic: Realization of a platform capable of producing controlled external disturbances for testing adaptive vibration damping of a hydraulic crane.

Riccardo Bianchi
Visiting Scholar from University of Ferrara, Italy
BS: University of Ferrara, Italy
Origin: Italy
September 2014-present
Research Topic: Vibration damping in hydraulic machinery.

7 International and National Conferences Attended

IFPE2014, International Fluid Power Conference and Exposition

March 4-8, 2014. Las Vegas, USA

Attendees:

Andrea Vacca (Paper Presentation)

Pulkit Agarwal (Paper Presentation)

Ram S. Devendran (Paper Presentation)

9th International Fluid Power Conference (9IFK)

March 24-26, 2014. Aachen, Germany.

Attendees:

Monika Ivantysynova

Naseem Daher (Paper Presentation)

Andrew Schenk (Paper Presentation)

Mike Sprengel (Paper Presentation)

Andrea Vacca (Paper Presentation)

Guido Ritelli (Paper Presentation)

8th FPNI Ph.D Symposium, on Fluid Power

June 11-13, 2014. Lappeenranta, Finland.

Attendees:

Monika Ivantysynova (**Invited Lecture**)

Enrique Busquets (Paper Presentation)

Mike Sprengel (Paper Presentation – **Best Paper Award (Backe Medal)**)

Dan Mizell (Paper Presentation)

Rene Chacon (Paper Presentation)

Ashley Wondergem (Paper Presentation)

Damiano Padovani (Paper Presentation)

Andrea Vacca

Guido Ritelli (Paper Presentation)

Divya Thiagarajan (Paper Presentation)

ASME/BATH 2014 Symposium on Fluid Power & Motion Control

September 10-12, 2014. Bath, United Kingdom.

Attendees:

Monika Ivantysynova

Enrique Busquets (Paper Presentation)

SAE 2014 Commercial Vehicle Engineering Congress

October 7-9, 2014. Rosemont, IL.

Attendees:

Monika Ivantysynova

Naseem Daher (Paper Presentation)

Michael Sprengel (Paper Presentation)

Andrea Vacca

Kelong Wang, Pulkit Agarwal (Paper Presentation)

Fluid Power Innovation & Research Conference 2014 (FPIRC 14)

October 13-16, 2014. Nashville, TN.

Attendees:

Monika Ivantysynova

Enrique Busquets (Paper Presentation)

Andrew Schenk (Paper Presentation)

Lizhi Shang (Poster Presentation)

Andrea Vacca

Ram S. Devendran (Paper Presentation)

Guido F. Ritelli (Paper Presentation)

FLUID POWER FPIRC14 INNOVATION & RESEARCH CONFERENCE 2014

9th JFPS International Symposium on Fluid Power

October 28-31, 2014. Matsue, Japan.

Attendees:

Monika Ivantysynova

Enrique Busquets (Paper Presentation – **Best Paper Award**)

Andrea Vacca

Tim J. Opperwall (Paper Presentation)

8 Maha Hosted & Organized Events

8.1 Maha Hosting the 2014 10th Anniversary Party

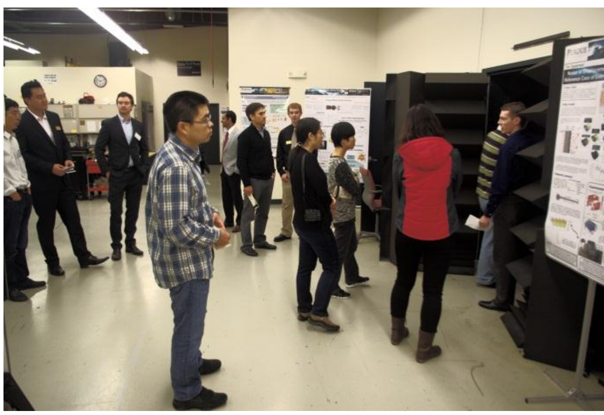
Maha Celebrates 10 Year Anniversary

This year Maha celebrated 10 years since being founded. We invited past and current students and collaborators to share in the celebration during October 1-3, 2014. The guests were greeted on Wednesday night with a welcoming pig roast BBQ dinner. The next day, participants engaged in a lab tour on the topics of displacement actuation, piston pump modeling, gear pump modeling, hybrids, system research, and noise along with machine demonstrations of the excavator and wheel loader. The evening was concluded with a nice banquet party in the lab. The final day of the celebration was complete with more in depth presentations on Blended hydraulic hybrid power trains, the next steps towards virtual prototyping of pumps and motors, advanced modeling of gear pumps, and noise.

This unique opportunity allowed Maha to display the achievements accomplished during 10 years of establishment.

BBQ Dinner

Lab Tour



Machine Demonstration

Banquet in the Maha Lab



Presentations


8.2 Education and Outreach

REU Bootcamp

The Maha lab again organized and hosted the NSF Center for Compact Efficient Fluid Power (CCEFP) REU Bootcamp on May 27-29, 2014. Undergraduate students from various U.S. universities joined the Center's 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) to perform research in fluid power during the summer period.
A crash course was designed to teach the students the fundamental principles of hydraulics and pneumatics. The program started by an opening address by Prof. Monika Ivantysynova about fluid power in general and then a lecture entitled "Introduction to Fluid Power Systems" by Prof. Andrea Vacca. The students attended the following lectures / demonstrations:

- "Water Hydraulic Test Rig" prepared by Guido Francesco Ritelli
- "Hydraulic Circuit Construction and Debugging" prepared by Gabriele Altare
- "Pump Displacement Controlled Actuation Technology" prepared by Naseem Daher and Enrique Busquets
- "Hydraulic Pumps and Motors" prepared by Dan Mizell and Lizhi Shang

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

More About CCEFP

The Center for Compact and Efficient Fluid Power (CCEFP) is an NSF funded Engineering Research Center (ERC) which was established in June 2006. The Center's mission is to transform fluid power technology. 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.
In addition to the NSF funding, 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.

Dr. Monika Ivantysynova is a member of the executive committee of the CCEFP. She is the leader of Thrust Area 1: Efficiency and leader of the Test Bed 1: Mobile Heavy Equipment – High Efficiency Excavator.

The Purdue research team is composed of three Purdue faculty members: Monika Ivantysynova, Andrea Vacca, and John Lumkes and 10 graduate students.

9 Maha in the News

Research at the Maha Fluid Power Research Center has generated some public interest this year. The list below details Maha in the news.

- Recents results about external gear pump research at Dr. Vacca's team were featured on Hydraulics and Pneumatics (*hydraulicspneumatics.com*), January 2014.

Forget what you know about gear pumps

Alan Hitchcox | *Hydraulics & Pneumatics*

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Most of us are well acquainted with gears, especially when it comes to gear pumps. Gear pumps typically use gears with teeth similar in geometry to those used for power transmission: they are symmetrical. Symmetrical teeth are needed because gear sets used in mechanical power transmission often rotate clockwise and counterclockwise.

Gear sets used in hydraulic motors also must allow bidirectional rotation. In fact, that's one of the great advantages of hydraulics: simply shifting a valve reverses rotational direction of a hydraulic motor. It doesn't get much simpler than that.

Gear pumps, on the other hand, pose a different scenario. Most gear pumps (or any hydraulic pump, for that matter) rarely, rotate in two directions. Whether they're driven by an electric motor, internal-combustion engine, or other prime mover, chances are, the direction of rotation will be in only in one direction.

However, most gear pumps have symmetrical teeth — the tooth profile of the leading face is identical to that of the trailing face. This may be one reason why gear pumps tend to be noisy and generate pressure pulsations. So if you were to remove the constraint of designing gear teeth for pumps to be symmetrical, maybe you could reduce noise and pressure pulsations. You might even make the pump operate more efficiently.

RELATED

» Internal-gear pumps
» Gear motor
» Low-noise gear pumps

- "Daniels tours Maha Fluid Power Research Center", *WLFI News 18*, November 2014.

- “Daniels tours Maha Fluid Power Research Center”, *Purdue Today*, November 2014.

10 Awards, Honors, and Recognitions

2014 Aachen HP Award

Davide Cristofori's PhD dissertation "Advanced Control Strategies for Mobile Hydraulic Applications" received the Aachen HP Award during the International Fluid Power Conference IFK2014 (Aachen, Germany, March 24-26, 2014). The Aachen HP Award is awarded to persons who have distinguished themselves by outstanding studies in the field of Fluid Power.

2014 9th JFPS Symposium Best Paper Award

Busquets, E. and Ivantysynova, M. 2014. The World's First Displacement Controlled Excavator Prototype with Pump Switching - A Study of the Architecture and Control. 9th JFPS International Symposium on Fluid Power. Matsue, Japan. pp. 324 - 331.

2014 FPNI Best Paper Award (Backe Medal).

Sprengel, M. and Ivantysynova, M. 2014. Hardware-in-the-Loop Testing of a Novel Blended Hydraulic Hybrid Transmission. Proc. of the 8th FPNI PhD Symposium, Lappeenranta, Finland.

The Backe Medal is given for the best paper presented at each FPNI PhD Symposium. Mike is the fifth recipient of the Maha team to receive this prestigious award since the establishment of the FPNI PhD Symposium in 2000.

Mike (second from right) receiving the Backe Medal along with Honorable Mention award recipient, Roman Ivantysyn (second from left), Conference Chairman, Professor Heikki Handroos (left), and Chairman of FPNI Board, Associate Professor Bernhard Manhartsgruber (right).

SAE Fellow Grade

Prof. Monika Ivantysynova has been awarded the SAE Fellow Grade of Membership, which is SAE's premier membership grade, intended to "honor and recognize important engineering, scientific, and leadership achievements to enhance the status of SAE's contributions to the profession and to society."

The SAE Fellows Committee selected Prof. Ivantysynova for her outstanding achievements in fluid power research, developing energy efficient systems for mobile vehicle applications. Prof. Ivantysynova was honored during the SAE 2014 World Congress and Exhibition held in Detroit, Michigan, U.S.A. during the week of April 6, 2014.

Selected for Purdue Innovator Hall of Fame

Prof. Monika Ivantysynova has been selected for the Purdue Innovator Hall of Fame in recognition of her research and innovation in fluid power. She was specifically recognized for reducing the fuel consumption of heavy construction equipment and for developing a new energy saving hydraulic steer by wire system. Several patents were also cited including US Patent 8474254 “System and method for enabling floating of earthmoving implements," for which Prof. Ivantysynova received a plaque.

11 Educational Activities

Courses Taught at Purdue

Dr. Ivantysynova has taught, developed or been advisor to several courses in her time thus far at Purdue:

- ABE 691 / ME 697 – Hydraulic Power Trains and Hybrid Systems *(Spring 2008, 2009, 2010, 2012, and 2014)*
- ME 597/ABE 591 – Design and Modeling of Fluid Power Systems *(Fall 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, and 2014)*
- ME 463 – Senior Design Project *(Spring 2006, 2007, 2008, 2009, and 2011)*
- ABE 697 – Seminar *(Fall 2009)*

In his time at Purdue (since 2010), Dr. Vacca has had teaching responsibilities for following courses:

- ABE 435 – Hydraulic Control Systems *(Fall 2012, 2013, 2014)*
- ME 309 – Fluid Mechanics *(Fall 2011, Spring 2014)*
- ABE 210 – Thermodynamic Principles of Engineering and Biological Systems (*Spring 2011, 2012, 2013 and 2014*)
- ME 497 – Research Credits "Hydraulic Vehicle Design" and "Modeling of Cavitation" (*Spring & Fall 2012, Spring & Fall 2013, Spring & Fall 2014*)
- ABE 485 Engineering Design (supervision of one team) (*Spring 2012, 2013 and 2014*)

Details on the fluid power courses taught by Drs. Ivantysynova and Vacca are reported in the following part of this section

ABE 691M/ ME 697M – Hydraulic Power Trains and Hybrid Systems

Spring Semester 2014

Course Description:
ABE 691M / ME 697M Hydraulic Power Trains and Hybrid Systems
1 Semester, 3 Lectures/week, 3 Credits
Prerequisite: ME 475 or 575 or ABE 460, ABE 591/ME 597 or ABE 435 or consent of instructor.

This course provides a thorough understanding of continuously variable transmissions and hydraulic hybrid power train systems. It covers the design and modeling techniques for analyzing, predicting, and specifying the performance of continuously variable transmissions, hybrid power trains and complex hydraulic machine systems including transmission and power train controls. It also provides an introductory treatment of vehicle steering, braking and active vibration damping systems based on displacement control. Fundamentals of power train control and machine power management concepts will be discussed.

Course notes: All lecture material can be downloaded from MAHA lab website,
http://cobweb.ecn.purdue.edu/~mahalab/index

References:
J. Ivantysyn and M. Ivantysynova: *Hydrostatic Pumps and Motors Principles, Design, Peformance, Modelling, Analysis, Control and Testing.* Akademia Books International, New Dehli, 2001.
H. E. Merritt: *Hydraulic Control Systems.* John Wiley & Sons, Inc, 1967.
N. Manring: *Hydraulic Control Systems.* John Wiley & Sons, Inc, 2005.

Coordinator:
M. Ivantysynova, Maha Professor Fluid Power Systems, ME and ABE

Goals:
To give graduate students in engineering the ability to design, model and analyze continuously variable transmissions and hybrid power train systems including control concepts. The course is designed to teach students how to apply engineering fundamentals and computer software to develop, simulate and measure advanced CVT systems and power train structures including controls.

Prerequisites by Topic:
1. Design and modeling of Fluid Power Systems
2. Automatic Control
3. Instrumentation and measurement

Topics:
1. Introduction and overview of components, circuits and classification of CVT systems
2. Modeling, control and measurements of hydrostatic transmissions
3. Secondary controlled transmissions and hybrid structures
4. Torque converter based CVT, design principle, performance
5. Power split transmissions, classification, output coupled transmission, sizing, modeling and control
6. Input coupled power split transmissions, sizing, modeling and control

7. Advanced power split drive transmissions, dual stage and compound system structure
8. Hydraulic hybrid systems based on power split technology
9. Power train control, concepts and controller design
10. Hardware in-the-loop power train testing and performance measurements
11. Machine Power management
12. Hydraulic steering, braking and suspension system concepts
13. Vehicle active vibration damping based on displacement control
14. Special system design aspects, transmission noise
15. Fluid and structure borne noise sources, design concepts to reduce transmission noise

Computer Usage:
Matlab experience is required.

Laboratory Projects:
Three

Nature of the Design Content:
The design component of this course will consist of students designing two different continuously variable transmissions (CVT) to meet the required vehicle performance. The students will learn to model different types of CVT using a special simulation software (PSDD) and predict their performance. The results of both transmission design projects including system simulation will be summarized in an engineering design project report. A third project will deal with co-simulation of the hydraulic and mechanical system of a working machine.

ABET category content as estimated by faculty member who prepared the course description:
Engineering Science: 1.5 credits or 50%
Engineering Design: 1.5 credits or 50 %

ME 597 /ABE 591 – Design and Modeling of Fluid Power Systems

Fall Semester 2014

Course Description:

ME 597/ABE 591 Design and Modeling of Fluid Power Systems

1 Semester, 3 Lecture/week, 3 Credits

Prerequisite: ABE 435 or ME 309, ME 375 or consent of instructor.

This course provides an introduction into modeling and design of fluid power components and systems. Modeling techniques based on physical laws and measured performance characteristics will be applied to design and analyze component and system performance. Fundamentals: design principles of displacement machines, flow and pressure control, motion control using resistance control, motion control using displacement controlled actuators, variable speed transmissions, modeling of flow in lubricating gaps, transmission line models, secondary controlled systems, load sensing systems.

References:

J. Ivantysyn and M. Ivantysynova: *Hydrostatic Pumps and Motors Principles, Design, Peformance, Modelling, Analysis, Control and Testing*. Akademia Books International, New Dehli, 2001.

Fitch, E.C. and I.T. Hong: *Hydraulic Component Design and Selection*. BarDyne, Inc. 1998.

H. E. Merritt. *Hydraulic Control Systems*. John Wiley & Sons, Inc.

Coordinator:

M. Ivantysynova, Maha Professor of Fluid Power Systems, ME and ABE

Goals:

To give seniors and graduates students in engineering the ability to design and analyze fluid power systems applying computational methods. The course is designed to teach students how to apply engineering fundamentals to develop mathematical models of fluid power components and systems, so that advanced systems can be developed.

Prerequisites by Topic:

Fluid Mechanics

Modeling and analysis of physical systems

Differential equations and calculus

Topics:

1. Introduction and overview of components, circuit and system design methods
2. Fluid properties, modeling of transmission lines, impedance model of lines
3. Displacement machines design principles
4. Steady state characteristics, measurement methods and modeling
5. Gap flow models
6. Flow and pressure pulsation
7. Resistance control, modeling of steady state and dynamic performance
8. Pressure and flow control valves
9. Servo and proportional valves, nonlinear and linear system models
10. Modeling of valve controlled systems, linear and rotary actuators
11. Modeling of displacement controlled actuators, pump control systems
12. Secondary controlled actuator, modeling and application
13. Special system design aspects, load sensing systems

Computer Usage:

Matlab experience would be helpful but not necessary.

Laboratory Project:

Hardware-in-the-loop test rig of a vehicle drive line

Aim:

To learn to plan, design and operate an experimental test set up for performance testing of a fluid power system. To become familiar with X-PC target software, measurement equipment and data acquisition system used on a hardware in-the-loop test rig of a vehicle drive line. The project should also prove the student's ability to perform a measurement, evaluate test data and write a measurement report in an appropriate form.

Method:

Students will have to form teams of three students. One lecture will be used for introduction into the problem and the existing test rig. Students will then have to learn to operate the test rig and to perform measurement. Each team has to write a measurement report.

Formulation of problem:

Students are requested to perform the following work:

1. Study the test rig structure including the X-PC target system and describe it in the report accordingly.
2. Specify a drive cycle of the vehicle you like to test using the hardware-in-the loop test environment.
3. Perform the measurement of the drive cycle.
4. Evaluate the test results and complete a report.

Nature of the Design Content:

The design component of this course will consist of students designing a fluid power system to meet a particular need and required performance. The students will solve several sub problems of an entire system design as part of the regular course homework.

Engineering project to be completed during the course

Aim:

To demonstrate in form of an engineering project the ability to design fluid power systems, to understand the function of components and how to model their steady state and dynamic behavior to predict the system performance. The project should also prove the student's ability to write an engineering report in an appropriate form.

Method:

Students will solve several sub problems of the entire system design work as part of the regular course homework.

Formulation of problem:

Students are requested to perform the following work:

1. Choose and define your own system design project, i.e. define a hydraulic actuator, drive system or transmission as a part of a machine or vehicle. Describe briefly the machine or vehicle function.

2. Specify the system requirements (work task, operating parameter range, safety issue, energy consumption, type of primary energy source) and conclude the requirements in form of a system specification as the first chapter of your project report.
3. Remember to apply individual course topics to your system
4. During the semester it will be requested that you add a second actuation system to your initial one. This is to ensure that each project has at a minimum one rotary and one linear drive system.
5. It is also necessary that you investigate and compare at least one alternative solution for one of your chosen actuator/drive or transmission solution. The comparison must include energy consumption and a brief statement of other properties (system complexity, costs etc).
6. Define system structure, draw circuit diagram and a scheme showing the interfaces between your fluid power system and the entire machine/vehicle.
7. Select type and size of components
8. Create models to describe the loss behavior, energy consumption
9. Create models to predict system behavior including dynamics (system parameter as function of time)
10. Define measurement methods and test procedure for a selected component and your whole actuation system
11. Write the system development report

ABET category content as estimated by faculty member who prepared the course description:

Engineering Science: 1.5 credits or 50%

Engineering Design: 1.5 credits or 50 %

Grading: 60% engineering project, 30 % written final exam, 10 % measurement report

ABE 435 – Hydraulic Control Systems

Fall Semester 2014

Course Description

Class title: Hydraulic Control Systems

Class period: 1 Semester, 4 credits

Class hours: 4 hrs per week (2 lectures/ 2 labs)

Prerequisites: ME 30900 (Fluid Mechanics) or equivalent class with a minimum grade of D-

Textbook: Lecture notes and supplementary material will be provided prior each lectures.

Readings are also from: "Hydraulics in Industrial and Mobile Applications", by ASSOFLUID
"Hydraulic Control Systems", by H.E. Merritt
"Fluid Power Control" by J.F. Blackburn, G. Reethof, J.L. Shearer
"Fluid Power Circuits and Controls" by D.R. Buckmaster, J.S. Cundiff

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.

Grading policy

Grades will be earned based on a weighted average as follows:

Midterm exams (n. 2) 45 % (20% exam 1; 25% exam 2);

Final Project – 30 %;

Homework & Lab reports – 25 %

Grades and final score may be adjusted (up to ±5%) based on class/lab attendance, attitude, and class participation and overall performance. Class participation will be measured through iClickers questions, which will be given during lectures.

Plagiarism and/or cheating are sufficient for an F. See student handbook for University rules.

Detailed Course Description

Reading Assignments: reading assignments are a very important part of the coursework. Assignments will be announced at the end of each lecture. Students are expected to read the assignment before the class period.

Class attendance and honest policy: Students are expected to attend all class lectures (attendance may be taken in class). Multiple absences will result in a decreased grade (see grading policy). Students will be held responsible for all information from the reading assignments, lectures, e-mail, etc., regardless of attendance. In case of extenuating circumstance, please inform the instructor prior to the absence.

Cheating, plagiarism, and other forms of academic dishonesty will be prosecuted according to Purdue University policy.

Homework: there will be a problem set every week. The problems will be posted on Blackboard Learn normally on Wednesday, to be submitted in class the following Wednesday, unless otherwise specified (the due date will be specified on each homework). Homework must be turned in before the lecture begins on the due date. Homework will not be accepted at the end of the lecture period or in another lecture period. Late homework will not be accepted without an authorized excuse. Homework and solutions will be posted on Blackboard.

Homework format: All solutions turned in must include your name, course number, hmw number and date. Please make sure that handwriting it legible. The procedure, assumptions, schematics followed to obtain the final answers have all be understandable to receive full credit.

Labs: Numerical and hands-on lab experiences will be an essential part of the class. Homework assignments will be often based on material covered during lab. Typical examples includes (but are not limited to): the solution of specific problems through simulation; the use of row data acquired during a lab experience. Missing one Lab without a reasonable justification (communicated to the instructor prior the lab) will result in a 50% grade reduction for the related hmw assignment.

Exams: Exams are designed to provide students with opportunities to give evidence of their ability to analyze and design fluid power systems. There will be two exams during the semester, which are closed notes and closed book. The necessary equations, charts, tables will be provided with each exam.

Final Project: By the date indicated in the class schedule below, each student has to agree with the instructors the topic for the final project. A list of possible topics is provided at the end of the class description. Additional topics might be suggested by the instructors or proposed by the students.

For the topic selected, each student has to work individually to design the system, identify the commercial and custom-made component parts and estimate the overall cost. A project report has to be submitted prior the last week of the course. The report should give and introduction of the system, a clear representation of all main parts, a description of the methodologies used to design it and most significant aspect of its numerical modeling along with significant simulation results. A template of the final report will be provided by the instructor.

The last week of the class is used for the project presentation. Each student has to prepare a 10 min presentation of his project to give to the whole class. Each students has to evaluate three projects presentations, according to a template also provided at the end of this syllabus.

Detailed Project evaluation: 45 % project report; 45 % project presentation; 10 % project peer evaluation.

class schedule (Fall 2014)

Date		Topic	HMW
Wed.	Aug. 27	Introduction to the course, Syllabus, Hydraulic symbols	HM1: Symbols
	Aug. 27	Computer LAB 1 – AMESim. Introduction to the software	
Fri.	Aug. 29	Basic Equations in Fluid Power	
Wed	Sept. 3	Orifice equation	
	Sept. 3	Computed LAB 2 – AMESim. Orifice equation, capacity and lines	HM2: Analytical and numerical modeling of orifices
Fri.	Sept. 5	Valve 1 - Flow Control Valves	
Wed.	Sept. 10	Valve 2 - Pressure Control valves	HM3: Hydraulic control valves 1
	Sept. 10	Computer LAB 3 – AMESim. Hydraulic component library (HCD)	
Fri.	Sept. 12	Valve 3 - Directional Control Valves	
Wed.	Sept. 17	Valve 4 – Directional Control Valves	HM4 – Hydraulic control Valves 2 (Analytical and AMESim HCD valve)
	Sept. 17	Exp LAB 1 – Introduction to hydraulic trainer bench – Valves	
Fri.	Sept. 19	Pump & Motors 1	
Wed.	Sept. 24	Pump & Motors 2	HM5: Pumps/Motors + LAB report + AMESim circuit
	Sept. 24	Exp LAB 2 Regeneration, cushioning, cylinders @ Trainer bench	
Fri.	Sept. 26	Pump & Motors 3	
Wed.	Oct. 1	Hydraulic Fluids	HM6: properties of the fluid + AMESim fluids
	Oct. 1	Exp LAB 3 (on WHTR) Pump characterization	
Fri.	Oct. 3	EXAM 1.	
Wed.	Oct. 8	Controlling loads 1. Meter-in, Meter-out	**PROJECTS ASSIGNMENT**
	Oct. 8	Computer LAB 4 – AMESim. Planar library, Mech. library and crane example	HM7: Controlling loads + LAB report + AMESim circuit
Fri.	Oct. 10	Controlling loads 2. Resistive and assistive loads	
Wed.	Oct. 15	Accumulators	HM8: LS + AMESim (Planar

			libray)
	Oct. 15	Exp LAB 4 – Meter-in, Meter-out, Bleed off @ Trainer bench	
Fri.	Oct. 17	Load Sensing systems 1	
Wed.	Oct. 22	Load Sensing systems 2	HM9: LS (analytical), filters, hoses: + AMESim (double pressure circuit)
	Oct. 22	Exp LAB 5 - Hoses, filters, Sequence	
Fri.	Oct. 24	Hydrostatic transmissions 1	
Wed.	Oct. 29	Hydrostatic transmissions 2	HM10: hydrostatic transmission, accumulators + AMESim circuit hydrostatic transmission
	Oct. 29	Exp LAB 6 (@WHTR) – Hydrostatic Transmissions	
Fri.	Oct. 31	Hydrostatic transmissions 3	
Wed.	Nov. 5	Steering systems 1	HM11: steering systems
	Nov. 5	Exp LAB 7 - Pneumatics	
Fri.	Nov. 7	Steering systems 2	
Wed.	Nov. 12	EXAM 2	
	Nov. 12	PROJECT REVIEW SESSIONS	
Fri.	Nov. 14	Invited lecture (Parker Hannifin)	
Wed.	Nov. 19	FLUID POWER COMPANY VISIT	Case New Holland (CNH)
	Nov. 19	FLUID POWER COMPANY VISIT	Bus tour 8am – 5pm
Fri.	Nov. 21	Invited lecture (pump manufacturer)	
Thanksgiving			
Wed.	Dec. 3	Controls & Stability 1	
	Dec. 3	Exp LAB 8 – Electrohydraulic	
Fri.	Dec. 5	Controls & Stability 2	**PROJECT REPORT DUE**
Wed.	Dec. 10	PROJECTS PRESENTATION	
	Dec. 10	PROJECTS PRESENTATION	
Fri.	Dec. 12	PROJECTS PRESENTATION	

List of Projects

Each student should agree with the instructors a project.

1. Load sensing system (3 users) inclusive of
   a. Variable displacement pump and directional LS valves
   b. Power steering unit

c. Hydrostatic transmission (open circuit)

d. Load module + Linear actuator

2. Hydrostatic transmission for wheel loader (closed circuit)

The aim of the project is to design a hydraulic transmission for a wheel loader

3. Hydrostatic transmission for fan drive system (open circuit)

The aim of the project is to design a hydraulic transmission for a fan drive system used in mobile applications

4. Movable dam

The aim of the project is to design a hydraulic system for moving the dam's gates

5. Hydraulic press

a. 2 cylinders

b. 3 cylinders

6. Car lift

7. Tow truck (winch + lift)

8. Car jack

9. Boatlift

10. Rear hitch – plug

11. Earthquake platform

12. Crane with winch and one extension

13. Labview (WHTR)

ME 309 – Fluid Mechanics

Spring Semester 2014

Class title: Fluid Mechanics

Class period: 1 Semester, 4 credits

Class hours: 4 hrs per week (3 lectures/ 1 labs)

Prerequisites: ME 30900 must be preceded by differential equations, dynamics, and a first course in thermodynamics.

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

Lecture notes and supplementary material will be provided prior each lectures.

Readings are also from:

Munson, B.R., Young, D.F., and Okiishi, T.H., Fundamentals of Fluid Mechanics, Wiley & Sons

Sabersky, R.H., Acosta, A.J., and Hauptmann, E.G., Fluid Flow: A First Course in Fluid Mechanics, Macmillan

Wassgren, C., Notes on Fluid Mechanics and Gas Dynamics

White, F.M., Fluid Mechanics, McGraw-Hill

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.

Computer Usage

Knowledge of word processing and spreadsheet software will be necessary for laboratory report preparation and some homework assignments. Knowledge of a computer programming language may also be helpful for some assignments.

Grading Policy

Final grades will be determined using the following algorithm.

1. All final scores will be normalized (i.e., divided) by, at most, the largest student final score in the class and multiplied by 100. The value of the normalization score may be smaller than the largest student final score,

based on the instructor's discretion and the overall course performance. For example, if the largest final score in the class is a 95, all other scores will be divided by a value ≤ 95.

2. The final grades will be determined using the following table.

97 ≤ score	⇒	A+	93 ≤ score < 97	⇒	A	90 ≤
score < 93	⇒	A-				
87 ≤ score < 90	⇒	B+	83 ≤ score < 87	⇒	B	80 ≤
score < 83	⇒	B-				
77 ≤ score < 80	⇒	C+	73 ≤ score < 77	⇒	C	70 ≤
score < 73	⇒	C-				
67 ≤ score < 70	⇒	D+	63 ≤ score < 67	⇒	D	60 ≤
score < 63	⇒	D-				
score < 60	⇒	F				

5% Homework

a) Homework assignments may be completed in teams of up to, but no more than three students.

All team members must be in the same lecture section and each team member is expected to contribute to each assignment. Team members may change from assignment to assignment, but teams should not split during the course of a single assignment. Each team member's name must appear on each page of the assignment, and all team members will receive the same assignment score.

A subset of the assigned homework problems will be graded. Homework solutions will be posted on Blackboard.

10% Laboratory

Refer to the Laboratory Policy and Procedures handout for details concerning the laboratories.

5% Laboratory Preparation Quizzes

Short quizzes will be given during many of the lab preparation periods and will be based on material covered in previous weeks.

20% Exam 1

20% Exam 2

20% Exam 3

20% Final

a) All exams will be closed notes and closed book unless otherwise indicated. Formula sheets will be provided with the exams. No materials other than the formula sheets are to be used during exams.

b) The only calculating device students are allowed to use on exams is a TI-30XIIS calculator unless otherwise indicated.

2% Bonus, In-class participation i>clicker questions

Short i>clicker question will be given during many of the lectures. The questions will be based on the day's reading assignment and on conceptual questions based on the covered material.

Note: All students are expected to have their i>clicker devices for each lecture. The devices will be register for the class during the first week.

Class schedule and topics

Period	Date			Topic	Read Pages*
01	Mo	Jan	13	Course Introduction, Policies, Concept Inventory	1-16
02	We		15	Flow visualization, Velocity Field, Fundamental Concepts	20-29
03	Fr		17	Viscosity, Flow Classification	29-45; 789-793
	Mo		20	No class	
04	We		22	Density; Pressure; Pressure variation; Manometry	21-23; 55-68
05	Fr		24	Forces on submerged surfaces	69-79
06	Mo		27	Forces on submerged surfaces (cont.); Buoyancy	69-79; 80-82
07	We		29	Basic system laws; Reynolds Transport Theorem; Conservation of mass	96-110
08	Fr		31	Momentum equation – fixed frame of reference	110-121
09	Mo	Feb	03	Momentum equation – fixed frame of reference (cont.)	110-121
10	We		05	**(lecture cancelled)**	
11	Fr		07	Bernoulli's equation	122-125; 244-253
12	Mo		10	Momentum equation – non-accelerating, but translating frame of reference	126-128
13	We		12	Momentum equation – rectilinearly accelerating frame of reference, reading assignment, **conservation of energy**	128-135, and 139-146; 253-257
14	Fr		14	***Review Lectures 01-13***	
	Mo		17	No class	
15	**Mo**		**17**	**EXAM 1; 8:00 – 10:00 P.M.; WTHR 200**	**LECS 01 - 14**
16	We		19	Continuity equation; Acceleration of a fluid particle	171-180; 184-190
17	Fr		21	Navier-Stokes equations	197-207; 332-344
18	Mo		24	Navier-Stokes equations (cont.)	197-207; 332-344
19	We		26	Euler's equations in streamline coordinates	235-241
20	Fr		28	Dimensional analysis	290-305
21	Mo	Mar	03	Similarity and scaling	305-319
22	We		05	Similarity and scaling (cont.)	305-319
23	Fr		07	Introduction to pipe flows	329-332; 344-355
24	Mo		10	Head loss; Fluid machines in the energy equation; Hydraulic diameter	355-369
25	We		12	Pipe flows	369-387
26	Fr		14	Pipe flows (cont.)	369-387
	Mo		17	No class	
	We		19	No class	
	Fr		21	No class	
27	Mo		24	***Review Lectures 15-26***	
	We		26	No class	
28	**Thu**		**27**	**EXAM 2; 8:00-10:00 P.M.; SMTH 108 and LILY G126**	**LECS 01 – 27**
29	Fr		28	Introduction to fluid machinery; Specific speed	492-499; 504-410
30	Mo		31	Performance characteristics; Similarity	516-526
31	We	Apr	02	Net positive suction head; Application to fluid systems	526-541
32	Fr		04	Introduction to boundary layers; Boundary layer thickness	422-428
33	Mo		07	Momentum integral equation; Laminar boundary layer – no pressure gradient	428-438
34	We		09	Turbulent boundary layer – no pressure gradient	439-442
35	Fr		11	Pressure gradient effects; Flow about immersed bodies	442-459
36	Mo		14	Lift and drag	459-474
37	We		16	***Review Lectures 29-36***	
38	**Thu**		**17**	**EXAM 3; 8:00-10:00 P.M.; WTHR 200**	**LECS 01 – 37**
	Fr		18	No class	
39	Mo		21	Introduction to compressible flow; Review of thermodynamics	657-665
40	We		23	Speed of sound; 1D isentropic flow; stagnation and sonic conditions	665-683
41	Fr		25	1D isentropic flow with area change; Flow in a converging-diverging nozzle	689-714
42	Mo		28	***Review Class***	
43	We		30	***Review Class***	
44	Fr	May	02	**Wrap up, Concept Inventory**	
				FINAL EXAM (Time and location to be determined.)	**LECS 01-44**

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

Students should read the assignment before coming to lecture.

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 a 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.

Vehicles prepared by the Purdue team for the 2013 and 2014 competition

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.

Purdue vehicle and team during the 2014 competition (Irvine, CA, April 2014)

For the 2014 edition of the Chainless Competition, the Purdue team (formed by ABE and ME senior students) prepared a three-wheel recumbent bike. The hydraulic system was based on an open circuit hydrostatic transmission with external gear units. A duplex gear pump was utilized to provide optimal utilization of the input human power; in particular, high pressure during charging and high flow during pedaling. The system also equipped a 7 speed mechanical gear shift electronically controlled by a Parker CANbus system (IQAN). A monitor was used to visualize the status of the system but also to actively control the mode of operation of the bike. The chassis and the location of the hydraulic components permitted the maximum weight reduction and the optimal maneuverability of the vehicle.

The 2014 vehicle placed 2nd in the overall ranking of the competition, receiving awards for Innovation (1st place); Manufacturability and Workmanship (3rd place); Best Design Chosen by Peers (1st place); Best Sprint (3rd place); Sprint Team Partner (4th place); Efficiency (4th place); Time Trial (4th place); Best Paper (2nd place).

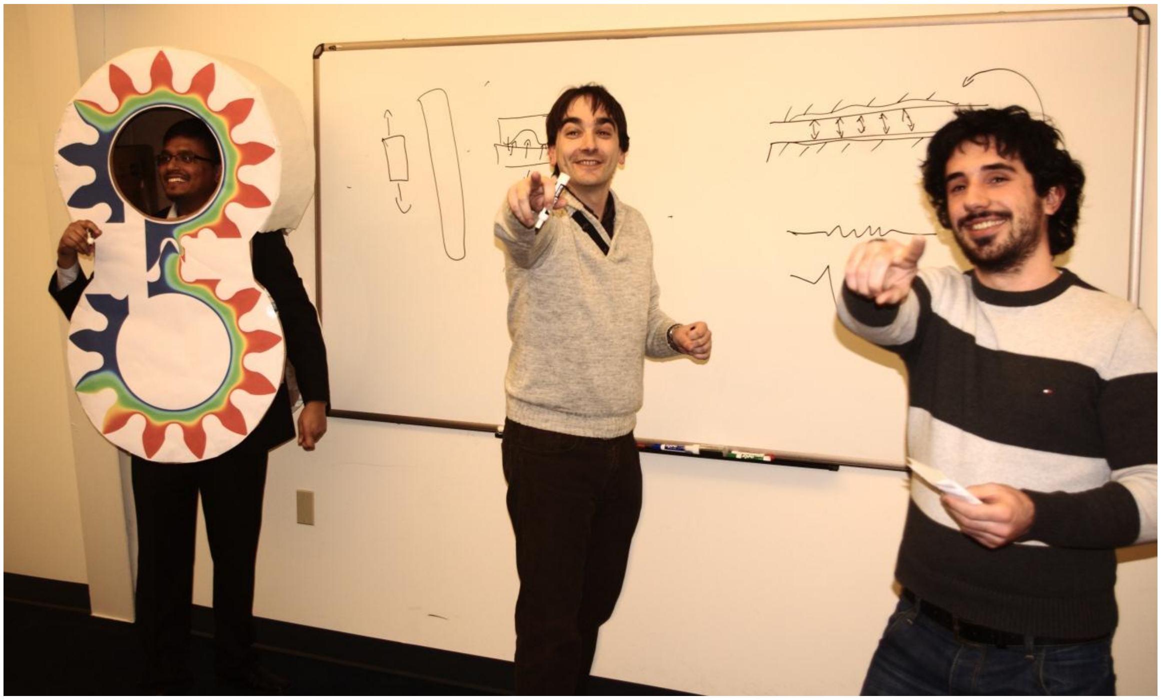
Group picture during Parker Chainless Challenge Final event, Irvine, CA, April 2014

12 Maha Social Events

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

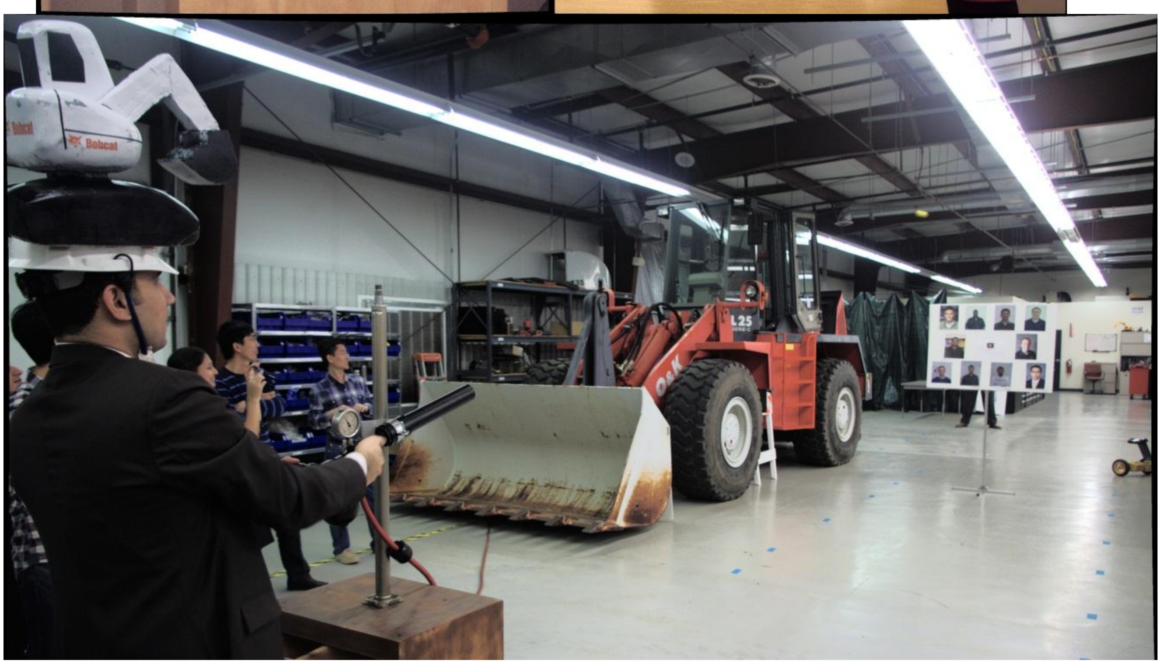
CCEFP Basketball & Pizza

Celebrating Sujan‘s successful PhD defense



Summer party at Susan’s house

Celebrating Rohit's successful PhD defense

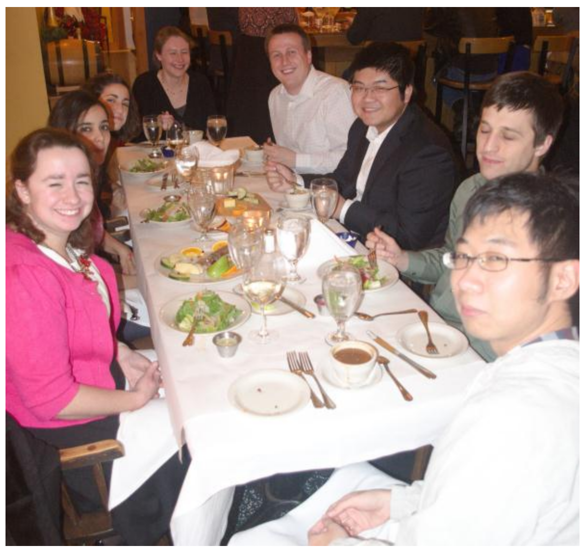


Celebrating Naseem's successful PhD defense

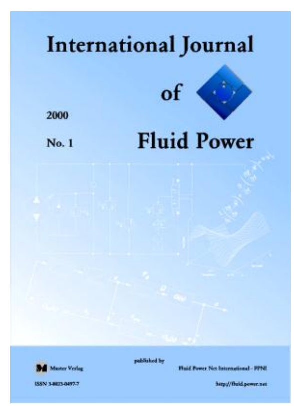
Monika's Summer Party

Celebrating Andrew's successful PhD defense

Christmas / Monika's birthday dinner



13 International Journal of Fluid Power



Dear Associate Editors and Members of Editorial Board,

It's that time of year when we look back on our accomplishments and reflect on the friends and colleagues, whose support makes our work possible. The year 2014 was the first year of the *International Journal of Fluid Power* published by Taylor & Francis. With that the International Journal of Fluid Power has completed its fifteenth year of publication. The third issue of the 15th volume, which is the 45th issue of the Journal was published this past November.

Taylor & Francis brought several new features for our authors, reviewers and readers as well as the editorial team. While the scope, content and layout of the Journal remained unchanged; the switch to the online submission and review tool was a major step towards more visibility and open access. The Journal's new website http://www.tandfonline.com/loi/tjfp20 allows downloading of all past and current issues and lists most cited and most read articles.

Another important new feature of the Journal is that authors are now receiving 50 free electronic offprints of their papers and have perpetual access to their papers within the 'My Authored Works' section of the website.

Let me express my gratitude to all members of the editorial board for their continuous support of the Journal. My special thanks goes to all the associate editors who have done an excellent job in managing the transmission to the new paper submission and review system. Without the tremendous support and voluntary work of all associate editors the journal would not have made it through the past 15 years and the transition to the new publisher this past year.

I would also like to thank all reviewers for their great assistance and hard work. Having such a wonderful and knowledgeable group of reviewers has helped to further ensure the work published in the Journal is only of the highest quality. The list of reviewers will be published again in the first issue of 2015.

This letter cannot be completed without thanking Susan Gauger for all her passion and hard work as the Journal's technical editor. She has done an incredible great job in managing the transition to the new online submission and review system ensuring a smooth and timely review process and the submission of final papers to Taylor & Francis's production team. Please join me in thanking her for her outstanding service and personal care about authors, associate editors, reviewers and readers.

Finally, I want to give recognition to all members of the editorial board for your great assistance and advice.

Let me add some statistical information regarding the Journal's progress this past year. Since the establishment of the Journal in 2000 we have presented 34 different fluid power software tools and introduced 35 fluid power research center spanning 4 different continents. The Journals continues to publish the Fluid Power calendar and abstracts of recently published books and completed PhD theses. There have been authors from 36 different countries that have submitted papers to the International Journal of Fluid Power during the last fifteen years. In order to ensure that the review process is fair and the Journal's final publication is of the highest quality all papers are reviewed by at least two experts. Accepted papers require two positive reviews. The rate of successfully approved papers in the past year was 48%.

The Journal's re-evaluation by the Scientific Citation index is still in process. I hope that we will be successful this time and I am certain that the change of publisher with all the new features for indexing and citation will help the Journal to achieve this breakthrough.

I wish you and your families my warmest wishes for an enjoyable holiday season, a happy New Year, and all the best for 2015 and sincerest gratitude for your friendship, loyalty and continuous support.

Best regards,

14 Maha Team in 2014

Maha Faculty

Dr. **Monika Ivantysynova**

Maha Professor of Fluid Power Systems
Joint Appointment in ABE/ME
Director of the Maha Fluid Power Research and Education Center
mivantys@purdue.edu
Phone: (765) 447-1609
Origin: Germany
August 2004-present

Dr. **Andrea Vacca**

Associate Professor
Joint Appointment in ABE/ME
Maha Fluid Power Research and Education Center
avacca@purdue.edu
Phone: (765) 430-0081
Origin: Italy
March 2010-present

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

14.1 Dr. Ivantysynova's team

Graduate Students

Jeremy Beale
Master's Student
BS: University of Kentucky
Origin: North Carolina, USA
July 2014-present

Tyler Bleazard
Master's Student
BS: Brigham Young University
Origin: Illinois, USA
July 2013-present

Enrique Busquets
PhD Student
BS: U. of Texas at El Paso
MS: Purdue University
Origin: Mexico
July 2011-present

Rene Chacon Portillo
PhD Student
BS: U. of Texas at El Paso
MS: Purdue University
Origin: Mexico
July 2012-present

Meike Ernst
Master's Student
BS: Case Western Reserve University
Origin: Stuttgart, Germany
July 2013-present

Ryan Jenkins
PhD Student
BS: Brigham Young University
Origin: Utah, USA
July 2014-present

Mrudula Orpe
Master’s Student
BS: University of Pune
Origin: India
August 2014-present

Paul Kalbfleisch
PhD Student
BS: Purdue University
Origin: Kentucky, USA
Oct 2011-present

Taeho Kim
PhD Student
BS: Ajou University, South Korea
MS: KAIST, South Korea
MS: University of Florida
Origin: S. Korea
Aug 2012-present

Ning Liu
PhD Student
BS: Hunan University
MS: Hunan University
Origin: China
August 2014-present

Dan Mizell
PhD Student
BS: Michigan Technological University
Origin: Michigan, USA
July 2011-present

Amine Nhila
PhD Student
BS: UC Berkeley
MS: U of Illinois at Urbana Champaign
Origin: Casablanca, Morocco
August 2013-present

Damiano Padovani
PhD Student
BS, MS: Polytechnic University of Turin
Origin: Italy
August 2012-present

Colleen Reidy
PhD Student
BS: University of Notre Dame
Origin: New York, USA
August 2014-present

Andrew Schenk
PhD Student
BS: Kettering University
Origin: Michigan, USA
July 2009-present

Lizhi Shang
PhD Student
BS: Huazhong University of Science and Technology
MS: New Jersey Institute of Technology
Origin: China
January 2013 - Present

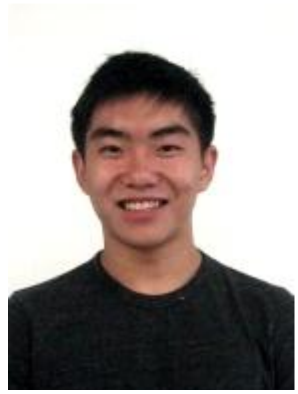
Michael Sprengel
PhD Student
BS: Missouri S&T
Origin: Missouri, USA
August 2010-present

Kyle Williams
PhD Student
MS: Purdue University
Origin: USA
July 2013-present

Ashley Wondergem
PhD Student
BS: Saginaw Valley State University
MS: Purdue University
Origin: Michigan, USA
August 2012-present

Summer Undergraduate Students

Andrew Adelsperger
Undergraduate
Researcher
SURF 2014
BS: Purdue University
Origin: Peru, Indiana
May 2014-August 2014



Andy Yang
Undergraduate
Researcher
BS: Columbia University
Origin: Carmel, Indiana
June 2014-August 2014

14.2 Dr. Vacca's team

Post Doc Students

Gabriele Altare
Post doc
BS,MS,PhD: Technical University of Turin, Italy
Origin: Italy
Jan 2013 – Dec 2014

Graduate Students

Divya Thiagarajan
PhD student
MS: Purdue University
BS: Anna University, India
Origin: India
Oct 2012 – present

Timothy Opperwall
PhD student
MS: Purdue University
BS: Calvin College, US
Origin: Michigan, US
Aug 2010 – present

Ram S. Devendran
PhD student
MS: Purdue University
BS: BITS Pilani, India
Origin: India
Sep 2010 – present

Matteo Pellegri
PhD student
MS, BS: Univ. of Parma, Italy
Origin: Italy
Aug 2013 – present

Guido F. Ritelli
PhD student
MS, BS: Technical Univ. of Turin, Italy
Origin: Italy
Feb 2012 – present

Addison Alexander
PhD student
BS: Univ. of Kentucky Lexington
Origin: Kentucky, US
Aug 2013 – present

Sidhant Gulati
Master student
BS: VIT Univ., India
Origin: India
Jan 2014 – present

Pulkit Agarwal
Master student
BS: BITS Pilani, India
Origin: India
Jan 2013 – present

Kelong Wang
PhD student
BS,MS: Harbin Inst. Of Technology, China
Origin: China
Oct 2013 – present

Sujan Dhar
PhD student
MS: Suny at Buffalo, US
BS: BITS Pilani, India
Origin: India
Aug 2010 – Feb 2014

UnderGraduate Students

Marlon Baez
Undergraduate researcher
BS: University of Rochester, NY
Origin: NY, US
June 2014 – Aug 2014

15 Donors, Sponsors, Partners, & Guests

Generous donors, Mr. Ken Warren and his kind wife Susan, support Maha research with $5,000 this year!

Mr. Ken Warren and his wife Mrs. Susan Warren have decided to support Maha research activities with $5,000 this year.

Ken has been in fluid power industry for decades and is currently working for Parker Aerospace. We are very proud and pleased to receive this generous personal gift from Ken and Susan and thank them for their support of our fluid power research at Maha. Below is a photo of Ken and Susan.

Industrial Sponsors & Partners

We are proud of and grateful for our list of partners/sponsors. We would like to thank all our partners for their fruitful co-operation and support of our research:

Actia, Toulouse, France

Airbus Deutschland GmbH, Hamburg, Germany

AM General, South Bend, USA

Bobcat, West Fargo, USA

Bosch-Rexroth AG, Elchingen, Germany

Bosch-Rexroth Corporation, Sturtevant, USA

B+V (Blohm+Voss) Industrietechnik, Hamburg, Germany

Borg Warner, Inc., Auburn Hills, Minnesota, USA

Casappa, Italy

Case New Holland, Burr Ridge, Chicago, USA

Caterpillar Inc., Peoria, USA

Centro Ricerche Fiat, Orbassano, Italy

Claas Industrietechnik GmbH, Paderborn, Germany

Cummins Inc., Columbus, USA

Dae Jin – TECPOS, South Korea

Doosan Infracore, Seoul, South Korea

Deltrol Fluid Power, Milwaukee, USA

Evonik Industries, Germany

Ford Motor Company, Detroit, Michigan, USA

John Deere Product Engineering Center, Waterloo, USA

K. & H. Eppensteiner GmbH & Co. KG, Ketsch, Germany

Eaton Corporation, Eden Prairie, USA

Fairfield Manufacturing, Lafayette, USA

Gates Corporation, Denver, USA

Harsco Rail, South Carolina, USA

Hägglunds Drives Inc., Columbus, USA

Hyundai Heavy Industries Co., Korea

Honeywell Aerospace, South Bend, USA

HYDAC International GmbH, Sulzbach/Saar, Germany

INNAS, Breda, Netherlands

Jungheinrich AG, Norderstedt, Germany

Komatsu Ltd., Tokyo, Japan

Liebherr, USA

Linde AG, Aschaffenburg, Germany

Linde Hydraulics Corp, Canfield, USA

Mecalac, Annecy-le-Vieux, France

MGI Coutier, France

Moog GmbH, Böblingen, Germany

Moog Inc., East Aurora, USA

National Fluid Power Association (NFPA)

Adam Opel AG, Rüsselsheim, Germany

Oilgear Towler GmbH, Hattersheim, Germany

Orenstein & Koppel AG O&K, Berlin, Germany

Parker Hannifin GmbH, Kaarst, Germany

Parker Hannifin Corp., Cleveland, USA

Quality Control Corporation, Chicago, USA

ROSS Controls, Troy, USA

Sauer-Danfoss, Neumünster, Germany

Sauer-Danfoss, Aimes, Iowa, USA

Sun Hydraulics, Sarasota, USA

Thomas Magnete GmbH, Germany

Triumph Group, Inc., Pensylvania, USA

TRW Automotive, Lafayette, USA

Walvoil, Italy

Hense Systems, Bochum, Germany

Hitachi Construction Machinery Co., Ltd, Japan

Honda R&D Americas Inc., Raymond, USA

WIKA Instruments Corporation, Lawrencewille, USA

ZF Luftfahrttechnik, Kassel, Germany

Visitors & Guests

Johnathan Roehrl - Bobcat

Eric Zabel - Bobcat

Rob Bettcher – Braun Corporation

Ron Goodrich – Braun Corporation

John Hayes – Braun Corporation

Aaron Kiser – Braun Corporation

Jan Amrhein – Bosch Rexroth

Jan Amrhein - Bosch Rexroth

Uwe Neuman - Bosch Rexroth

Marco Guidetti – Casappa

Antonio Lettini – Casappa

Chris Beaudin – Caterpillar, Inc.

Hongliu Du – Caterpillar, Inc.

Bill Durr – Caterpillar Inc.

Aleks Egelja – Caterpillar Inc.

Randy Peterson – Caterpillar Inc.

Ed Mate - Caterpillar Inc.

Phil McCluskey – Caterpillar Inc.

Gary Schwartzkopf – Caterpillar Inc.

Kail Weiss – Caterpillar Inc.

Christopher Williamson – Caterpillar Inc.

Josh Zimmerman – CNH

Navneet Gulati – CNH

Stephanie Severance – Cummins Inc.

Raymond Shute – Cummins Inc.

Joan Wills – Cummins Inc.

Marco Zecchi – Danfoss Power Solutions

Mario Antonio Morselli – Danfoss Power Solutions

Mike Froehlich - Eaton Corporate Research and Technology

Steven Herzog – Evonik Industries

Donald J. Smolenski – Evonik Industries

Steve Frait - Ford Motor Company

Chip Hartinger - Ford Motor Company

Jeff Knutson - Ford Motor Company

Rohit Hippalgaonkar – Ford Motor Company

Steve Cragg – GKN Walterscheid

Reinhard Reinartz – GKN Walterscheid

John Zubik – GKN Walterscheid

Marc Davidson – Halliburton

Enrique Reyes – Halliburton

ShashiTalya – Halliburton

John Wisinger – Halliburton

Makoto Henmi - Hitachi

Kenji Hiraku – Hitachi

Takashi Niidome – Hitachi

Morio Ooshina – Hitachi

Shigeyuki Sajurai - Hitachi

Nikhil Seera – Hitachi

Kenta Suzuki – Hitachi

Motoshi Suzuki – Hitachi

Masakazu Takahashi – Hitachi

David Dornbach – Hydraforce

Jim Draffkorn – Hydraforce

Seung-Ok Ahn – Hyundai Heavy Industries Co. Ltd.

Byung-Woon Choi – Hyundai Heavy Industries Co. Ltd.

Ho-Byung Jeon – Hyundai Heavy Industries Co. Ltd.

Jae-Koo Shim – Hyundai Heavy Industries Co. Ltd.

Alice Popescu-Gatlan – John Deere Technology & Innovation Center

Mark Chaney - John Deere Company

Dan Corbett - John Deere Company

Bryan Dugas - John Deere Company

Brian Gilmore – John Deere Company

Mark Louviere - John Deere Company

Paul Marvin - John Deere Company

Jeff Wigand - John Deere Company

Dr. Ranga Pitchumani – Kenninger Professorship Candidate

Yun-Joo Nam - Korea Institute of Industrial Technology

Naok Dae-Young Shin – Korea Institute of Industrial Technology

Kwang Sun Kim – Korea University of Technology and Education

Sugano - Kobelco Corporation Japan

Ja-Ho Seo – Korean Institue for Machinery and Metals

Sung-Dong Kim – Kumoh National Institute of Technology

Justin Doughery – Oerlikon Fairfield

Scott Martin - Oerlikon Fairfield

Bill Schrader - Oerlikon Fairfield

Dean Elmore – Oerlikon Fairfield

Matt Richards – Oerlikon Fairfield

Lee Bangs – Parker Hannifin Corporation

Ray Collett – Parker Hannifin Corporation

Jeff Cullman – Parker Hannifin Corporation

Art Donaldson – Parker Hannifin Corporation

Germano Franzoni – Parker Hannifin Corporation

Edward Harley – Parker Hannifin Corporation

Richard Friedman – Parker Hannifin Corporation

Adel Mansour – Parker Hannifin Corporation

James Chu – Parker Hannifin Corporation

Rick Klop – Parker Hannifin Corporation

Craig Maxwell – Parker Hannifin Corporation

Matthew Owen – Purdue Applications

Jay Akridge – Purdue University ABE

Scott Bravel - Purdue University

Mitch Daniels – Purdue University

Bernard Engel – Purdue University ABE

Pan Hancock - Purdue University

Pam Hardebech - Purdue University

Leah Jamieson - Purdue University

Gary Krutz - Purdue University

Jon Lumkes - Purdue University

Becky Peer - Purdue University

Robert Stwalley – Purdue University

Carol Weaver - Purdue University

John Weaver - Purdue University

Ganesh Seeniraj – Siemens

Sujan Dhar - Simerics

Akashi – Sumitomo Heavy Industries, Ltd.

Kawashima - Sumitomo Heavy Industries, Ltd.

Makino - Sumitomo Heavy Industries, Ltd.

Matsuzaki - Sumitomo Heavy Industries, Ltd.

Steve Weber – SUN Hydraulics

Etienne Dautry – Thomas Magnete GmbH

Benjamin Ginsberg – Thomas Magnete GmbH

Winston Cheng – TRW

Anderson St. Hilaire - TRW

Tim Strieh – TRW

Juergen Weber – TU Dresden

Michael Hansen – University of Adger, Norway

Pal Grandal – University of Adger, Norway

Knut Brautaset - University of Adger, Norway

Guofang Gong – Zhejiang University

Xiaoping Ouyang – Zhejiang University

ME Prospective Students

Engineering Explorer Post Students