Maha Fluid Power
RESEARCH CENTER
PURDUE UNIVERSITY

2012 Annual Report

Monika Ivantysynova

Maha Professor of Fluid Power Systems

Lafayette, January 2013

Preface

After the successful presentation of our pump controlled mini-excavator at the CONEXPO trade show in Las Vegas in 2011 and the filing of a patent for the series-parallel hydraulic hybrid system for displacement controlled multi-actuator machines we started building the first hydraulic hybrid displacement controlled excavator. After nearly a year of hard work the first technology demonstrator is ready for testing. The hybrid displacement controlled mini-excavator, which forms the test bed #1 of the National Science Foundation sponsored Engineering Research Center (ERC) for Compact and Efficient Fluid Power (CCEFP), will be demonstrated to the public next April during the CCEFP site visit. The machine allows for a 50% downsizing of the engine while saving more than 50% of fuel compared to the current state of the art. While the research work on the hybrid displacement controlled excavator is part of our fundamental research on energy efficient hydraulic systems and controls we are excited to report that the Maha team was asked to build a large displacement controlled excavator. The excavator was finished late November and successfully tested during the last weeks of 2012. In a comparison test 33% fuel savings were measured for standard truck loading cycles. This means a huge success for our displacement controlled actuation technology. We hope that the technology will be on the market and form the new technical standard in few years from now.

The Maha team presented its recent research results at major international conferences in 2012. We traveled to Dresden Germany, where Marco and Rohit presented a paper about their recent research results. I was invited to present a keynote lecture on milestones of discovery in tribological pump interfaces at the 8th IFK International Conference on Fluid Power in Dresden, Germany. I also gave keynote lecture about hydraulic hybrid technology at the 2012 SAE International Commercial Vehicle Engineering Congress & Exhibition in Chicago. The National Fluid Power Association invited me to present a keynote lecture on Future Technology Focus – Displacement Controlled Actuation at the Energy Efficient Hydraulics and Pneumatics Conference in Chicago last November. The Maha team formed with six papers, and two posters, one of the strongest research teams at the 7th FPNI PhD Symposium in Reggio Emilia, Italy last July. I am very proud to report that Andrew Schenk won the prestigious Backe medal for the best paper presented at the 7th FPNI PhD Symposium. This is the fourth time in the twelve years of history of the Symposium that this award went to a PhD student of Maha. Marco Zecchi's paper was honored as one of the three selected recognized papers of the Symposium. We presented also two papers at the Bath/ASME Symposium of Fluid Power and Motion Control in Bath, UK. I am delighted to report that Matteo Pelosi received the best paper award for his paper on *Surface Deformation Enables High Pressure Operation of Axial Piston Pumps,* which he presented in 2011 at the Bath/ASME Symposium in Washington. Finally two of our researchers Paul Kalbfleisch and Mike

Sprengel traveled to Russia, where they presented their research work at International Sci-Tech Conference on Machine Dynamics and Vibro Acoustics in Samara.

In 2012, we successfully continued our research efforts in the area of energy saving actuation and drive concepts. Maha researchers successfully continued their efforts in discovering ways to improve the efficiency of pumps and motors, which form the heart of any fluid power system. I am proud to report that we have achieved major breakthroughs in developing a better understanding of the fundamental physical behavior in critical tribological pump and motor interfaces. We were able to extend the non-isothermal fluid structure interaction model previously developed for the piston/cylinder interface to the other two important interfaces of piston machines. Our major breakthroughs in discovery of fundamental effects in pump interface design have created major interest of several pump manufactures.

With more than 2 million US$ of research funding we had another record year of successful research activities. 60% of the total funding came from our industrial partners. In addition to the research funding the Maha team received major donations from industrial partners, which helped us in creating important new test rigs and prototype machines. My special thanks go to Sun Hydraulics, Parker Hannifin, Moog, Bobcat, Sauer-Danfoss and Exxon Mobile for donating major equipment and components to the Maha lab. When talking about sponsors I have to report a very special case. The year 2012 started with a very unusual phone call. Ken Warren, who is with Parker aerospace, called me asking me if I would welcome a personal gift of $10,000 to support the fluid power research of Maha. Ken is a colleague of Rick Klop, one of the former PhD students of the Maha team. Ken was impressed by the excellent knowledge Rick had received during his stay at Maha and therefore decided to support our learning and discovery efforts with a personal gift. I would like to thank Ken and his wife Susan for their generous personal gift, which they will give to Maha every year after their first donation in 2012.

The year 2012 also marked the successful defense and graduation of two PhD students Josh Zimmerman and Matteo Pelosi and two master's students, Minming Zhao and Dongjune Kim. Josh started his career at Smart Hydraulic Solutions, LLC as Chief Engineer and Matteo went to Sweden where he is working for a Formula One suspension system supplier. Minming started his career at Cummins and Dongjune went back to South Korea for his military service. Also Najoua left Maha in August 2012 after nearly 4 years of successful research work at Maha to start PhD research at University of Wisconsin.

Despite the departures, the Maha team remains strong through hiring new graduate students and visiting scholars. Paul Kalbfleisch joined the Maha team as new PhD student last January. In August we welcomed five new PhD students. Rene Portillo, Taeho Kim, Daminao Padovani, and two female graduate students Natalie Spencer and Ashley Wondergem joined Maha. The lab also enjoys the privilege of hosting visiting scholars from around the world. While Wei Shen and Junwei Zhang continued their stay here until returning to China in December 2012, Amin Mehdizadeh extended his stay until summer 2013. Hideaki Usami from Japan joined the lab last summer and plans to say for another 18 month. New for 2012, the Maha Lab welcomed Jan Schmidt and Fabian Zimber, both from Germany as IEASTE exchange students. During the summer 2012 we hosted six SURF students; Tridib Saha, Cary Wood, Bruce Vonniederhausern, Cory Raizor, Chuang (Chris) Wang, and Lizhi Shang. Jennifer Wu former SURF student and Chuang (Chris) Wang continued their research at Maha during the fall semester. Lizhi Shang will join Maha as new PhD student in January 2013. Finally, we were very happy to welcome Connie McMindes as a new staff member last October.

I would like to thank all team members for their excellent work in 2012. 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 2013.

Dr. Monika Ivantysynova
Maha Professor Fluid Power Systems

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1 Research Activities

After declaring the year 2011 as Maha’s most successful year in history with the highest number of publications and the highest amount of funding ever, we are proud to report that we kept the high level of funding and publications in 2012. Therefore we conclude that 2012 was again a very successful year for the Maha Lab with several Ph.D. and Master students graduating, multiple patents awarded, and many new undergraduate and graduate students joining the Maha team. Research activities at the Maha lab are broadly divided into two 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. Research Highlights in 2012

- The Maha team builds the first hydraulic hybrid excavator based on the patent filed by Prof. Ivantysynova and Josh Zimmerman in 2011. The novel hydraulic hybrid system for DC multi-actuator machines allows 50% engine downsizing and additional fuel savings (upto 20%) over the non-hybrid DC excavator. First machine measurements will be made in spring 2013.
- Matteo Pelosi and Monika Ivantysynova win the Bath/ASME award for their paper on “*Surface Deformation Enables High Pressure Operation of Axial Piston Pumps”* presented in Arlington 2011.

- The first fully-coupled fluid-structure interaction model that also considers thermal deformation of main interfaces and their influence on fluid film behavior and pump performance has been created by the Maha team. The model will be used to investigate the impact of surface shape and material properties on fluid film behavior and energy dissipation.
- Mike Sprengel investigated new concepts for combined displacement controlled actuation and hybrid power trains. Simulation results showed up to a 73% reduction in energy consumption for a one of the combined circuits implemented in a reach stacker when compared to the baseline machine during a reference cycle. Results were published at the 7th FPNI PhD Symposium in Italy in July 2012 and at the Bath/ASME conference in UK in September 2012.
- Andrew Schenk won the Backe Medal for his paper on "*The influence of swashplate elastohydrodynamic deformation* presented at the 7th FPNI PhD Symposium in Reggio Emilia, Italy.
- The Maha team built a 22t displacement controlled excavator and measured 33% fuel savings compared to the standard valve controlled machine in December 2012.
- Enrique Busquets successfully rebuilt Maha's Jira test rig in order to study displacement controlled actuation with pump switching.
- Dongjune Kim and Paul Kalbfleisch successfully developed and tested a new version of VpOptim which considers volumetric efficiency within the algorithm while evaluating potential pump designs. The program allows for the first time an effective computational tool for valve plate design and optimization.

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 related to the first three listed areas is supported by the NSF through participation in the CCEFP and by several industrial partners. The other topics are funded by industry sponsors.

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, skid-steer loaders, excavators for the purpose of throttle-less actuation, active vibration damping and steering.

In 2010, following predictions in simulation to the same effect, the prototype 5-t DC excavator built at Maha, showed 40% fuel savings over the standard 5-t excavator using a load-sensing architecture in measurement. The Maha team built a prototype of a displacement controlled 22-t excavator in 2012, which showed 33% fuel savings over the standard, valve-controlled excavator of identical size.

Research toward hybrid displacement controlled architectures has been ongoing, with a novel series-parallel hybrid DC architecture being conceptualized in 2011 (Figure 1). Previous simulations have shown the feasibility of 50% engine downsizing with this architecture, while maintaining performance of the working functions, and leading to fuel savings in excess of 52% over the standard 5-t excavator, using a conservative power management scheme. The system has been implemented in Maha's ERC test bed, the 5-t displacement controlled mini-excavator (Figure 2). The machine represents the first hybrid displacement controlled excavator and at present is ready for testing.

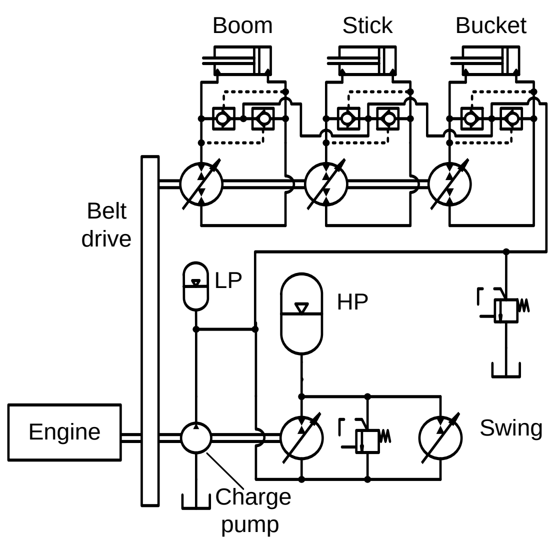


Figure 1: Series-Parallel (S-P) Hybrid Displacement Controlled (DC) Excavator

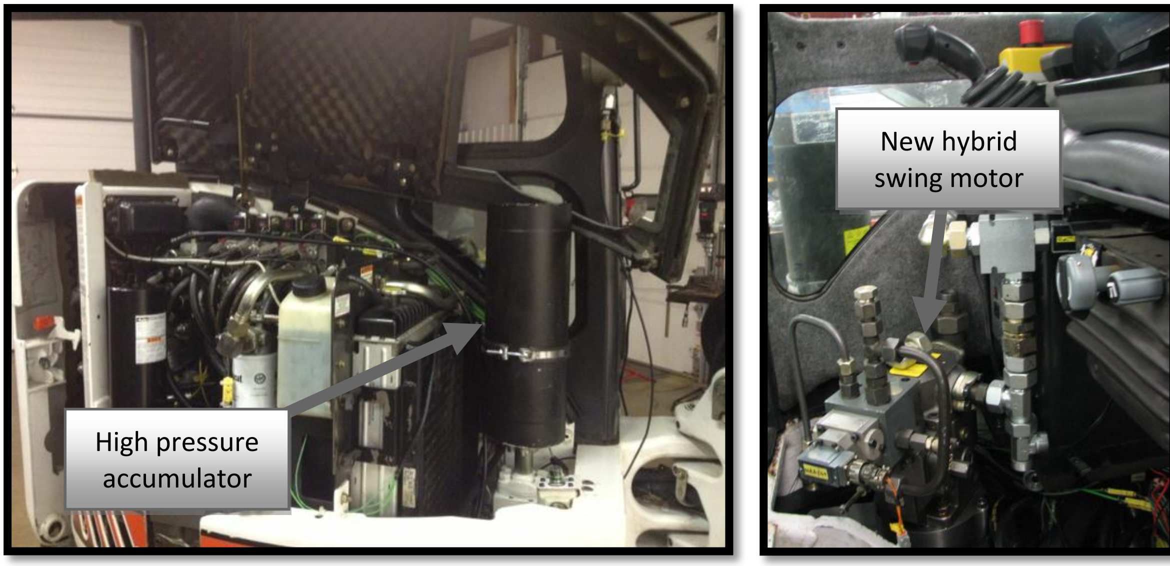


Figure 2: 5-t DC Hybrid Excavator

In 2011, optimal control and sizing problems were first solved for multi-actuator hydraulic hybrid machines including the S-P hybrid DC excavator. Optimal control is performed using dynamic programming which is a backward-facing recursive algorithm, which ensures optimality. Coupling dynamic programing with a high fidelity co-simulation model provides the Maha lab with a powerful tool for designing and evaluating new systems and control methodologies.

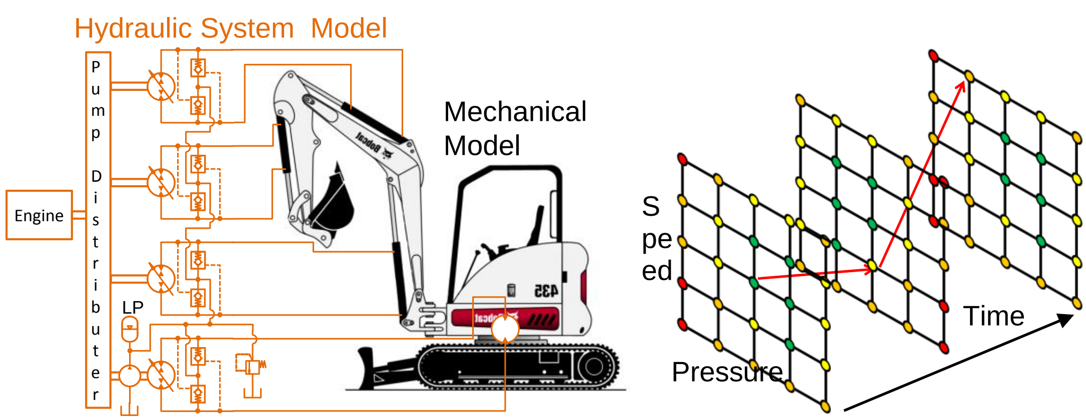


Figure 3: Co-Simulation Model and Dynamic Programming Algorithm

Building on this, in 2012 the results from the optimal control study were analyzed and trends identified for the design of an implementable power management schemes. A rule-based power management strategy was devised that not only took advantage of all available system degrees of freedom but also replicated optimal state trajectories and control histories (Figure 4) for the expert loading cycle, using the simulation model (structure shown in Figure 3 and Figure 6). This strategy is also applicable to the parallel-hybrid DC architecture.

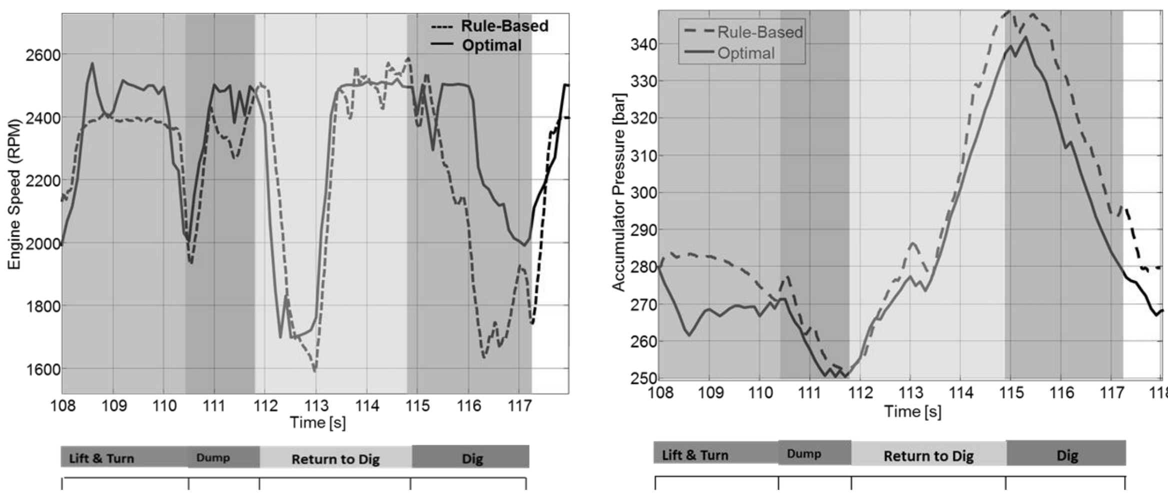


Figure 4 : Engine Speed and Accumulator Pressure Comparison with Optimal Results

From Figure 4 it can be seen that optimal engine speed varies significantly even during an aggressive, expert-operated loading cycle with fast cycle times (9-10 sec). At least one of the DC pumps (supplying the 3 linear actuators) is kept at 100% (Figure 5), implying the engine stays at a minimum allowable speed while meeting DC flow and power requirements. Optimal DC pump commands are also replicated by the rule-based strategy.

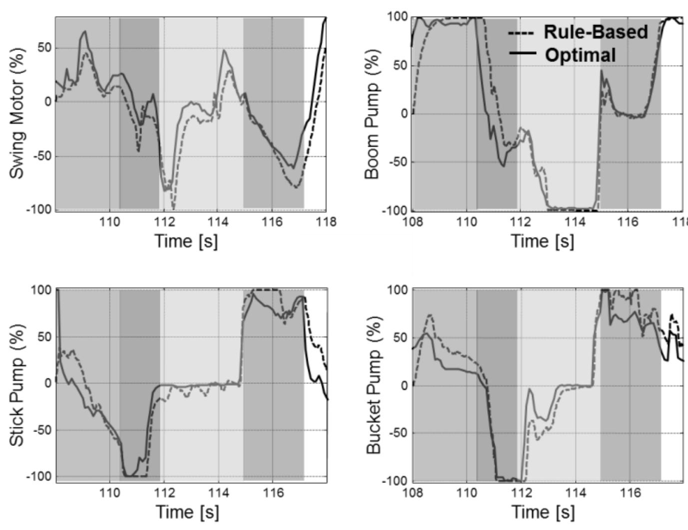


Figure 5 : Pump Commands – Comparison with Optimal Results

The previously developed co-simulation model, used for dynamic modeling, energy and fuel consumption predictions for the non-hybrid DC prototype (2009) was extended to model the hybrid DC system as well as evaluate any power management strategies. The rule-based system ensures that the accumulator assists the engine when required (e.g. digging), and charging of the accumulator through actuator braking or excess engine power.

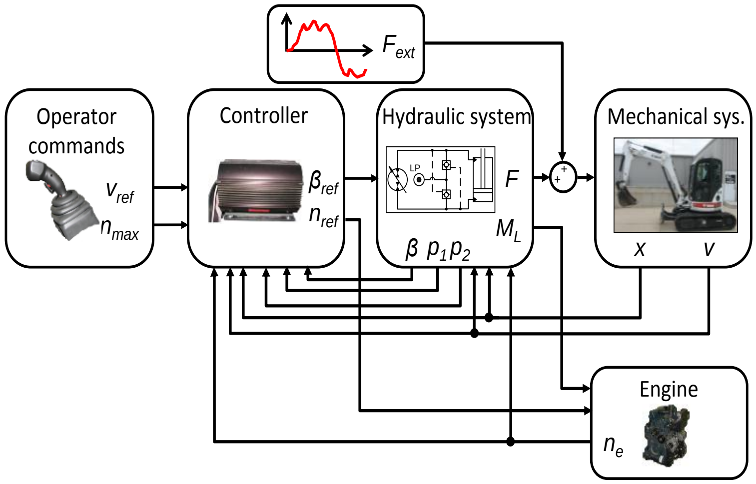


Figure 6 : Dynamic Co-Simulation Model for Multi-Actuator DC Hybrid Systems

Novel energy saving electro-hydraulic steering system via pump displacement control pertaining to articulated steering vehicles

Pump displacement control (DC) has been proven to be an energy-efficient alternative to traditional valve control. However, DC has never been researched nor implemented on vehicles' chassis systems. The objective of this research project is to investigate the feasibility of implementing DC on the steering system of articulated steering vehicles e.g. wheel loaders. Preliminary analysis, system sizing, dynamic modeling and simulation have shown that DC is in fact a feasible option for the hydraulic steering system of mobile machines. A hydraulic schematic for the proposed system is shown in Figure 7 below.

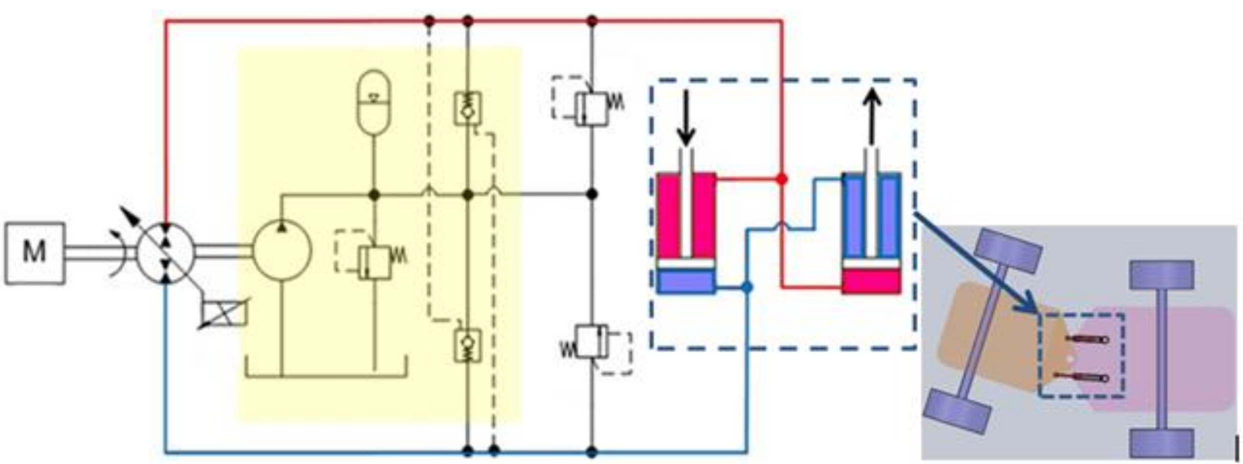


Figure 7: DC Electro-hydraulic Steering System – Hydraulic Schematic

Then in order to allow for simulating dynamic maneuvers, a more advanced vehicle dynamics model had to be generated. After elaborate investigation, the vehicle dynamics model was based on the Lagrangian approach to formulating the equations of motion, as opposed to the Newtonian approach due to the complexity of the involved constraints, forces, and accelerations (Figure 8). As an added benefit, the equations of motion could be formulated into the state-space format, which inherently lends itself to controller design.

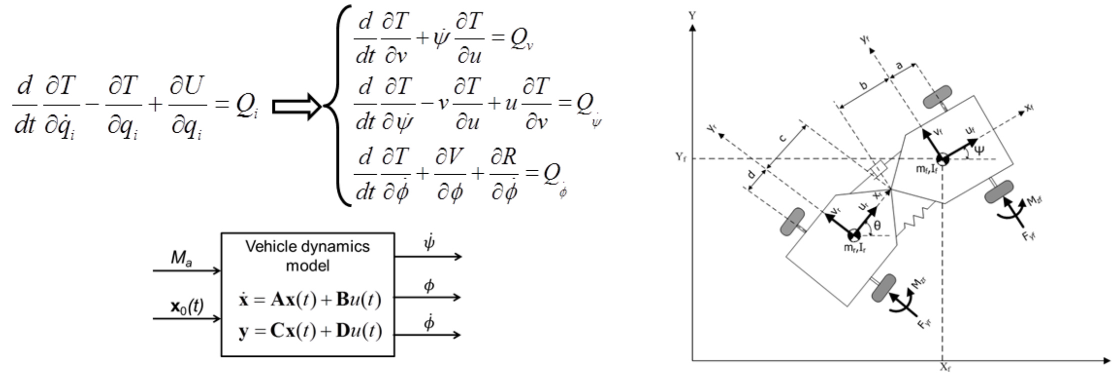


Figure 8: Advanced Vehicle Dynamics Model – Lagrangian Approach

A high-fidelity co-simulation dynamic model was then generated containing a hydraulic subsystem (pump, valves, actuators, etc.) as well as a mechanics module based on the developed multi-degree-of-freedom vehicle dynamics model, which allows for simulating and analyzing typical steering maneuvers (Figure 9).

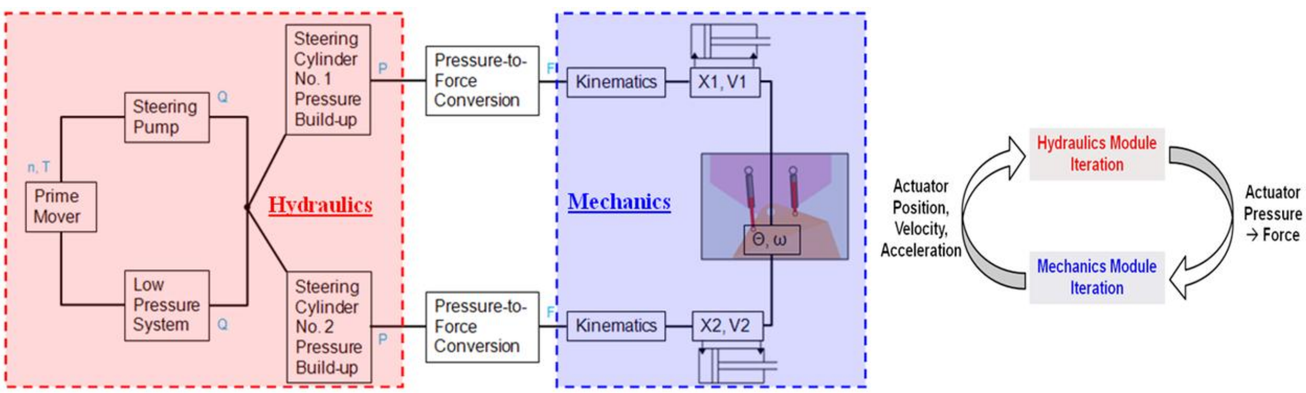


Figure 9: Steering System Co-simulation Dynamic Model

Current research is focused on instrumenting a wheel loader for performing baseline testing of a state of the art valve controlled steering system, after which the vehcile will be converted to DC steering and reevaluated for performance, efficiency, productivity, and others. At the same time, research will focus on proposing supervisory control algorithms based on both classical and modern approaches.

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. Areas of research include:

- Working on power split hydraulic transmission for heavy on/off highway hydraulic vehicles
- Virtual prototyping of power split drives and hydraulic hybrid power trains
- Power management for hydraulic hybrid power trains using implementable stochastic dynamic programming techniques

During 2012 Minming Zhao completed his master's thesis entitled "Optimal Control Based Design of Output Coupled Power Split Hydraulic Hybrid". This work furthered previous research performed in the lab by optimally sizing all power train components of an output coupled power split hydraulic hybrid Toyota Prius. Optimally sized and controlled, the hydraulic hybrid Prius was able to obtain a fuel economy of 65.1 mpg, up from the EPA's published value of 48 mpg for the 2004 electric Prius on which the study was based.

Combined displacement controlled actuation and hybrid power trains

Coupling displacement controlled actuation with a power split transmission creates a highly efficient and flexible machine architecture. In 2012 a new architecture combining these technologies was proposed and investigated for a reach stacker (a type of shipping container handler). Simulation results showed up to a 73% reduction in energy consumption over the baseline machine during a reference cycle (Figure 10).

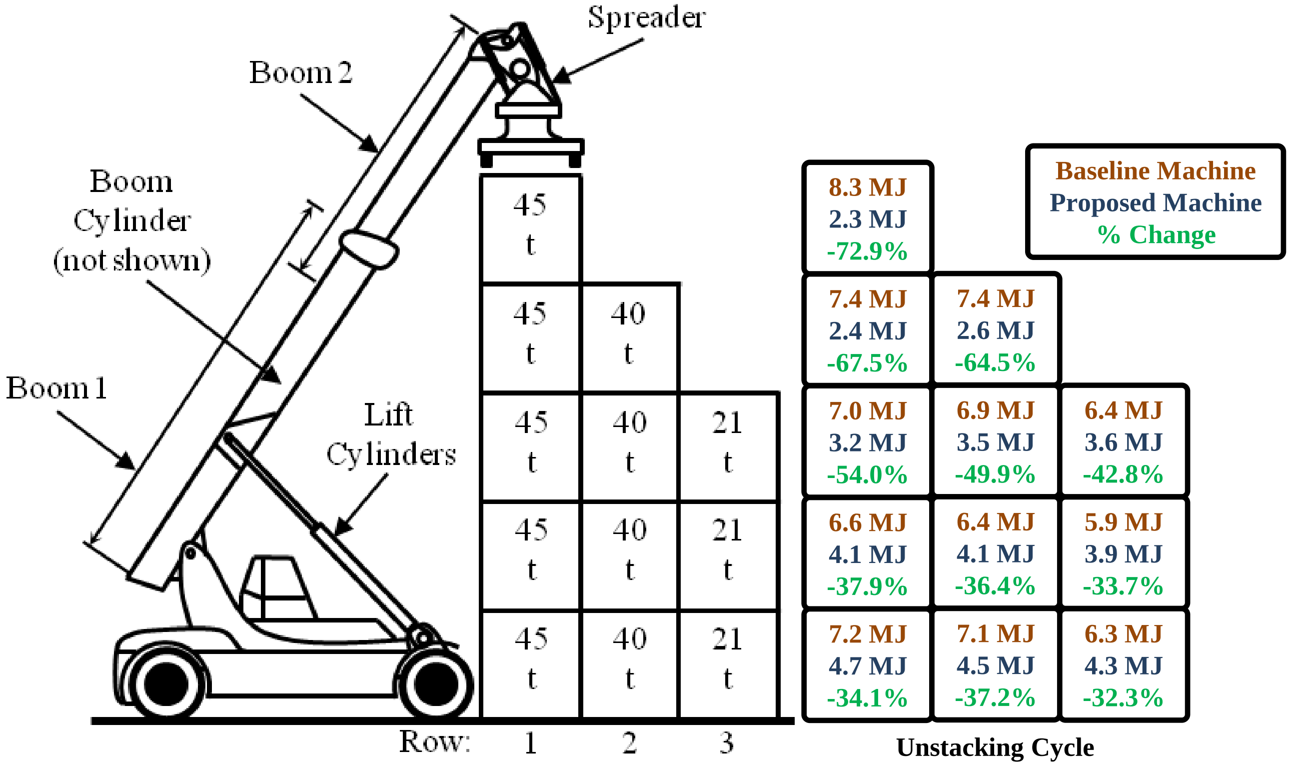


Figure 10: Reach Stacker Simulation Results

PSDD - Power Split Drive Design Simulation

One of the main reasons for the use of power split drives in many applications is the possibility of having a continuously variable transmission with simultaneously high efficiency in a wide range of operating parameters. This requires the consideration of real loss behavior of all parts of the transmission. Due to the strong dependence of losses of displacement machines on operating parameters the integration of precise loss models is necessary. The PSDD software tool (Figure 11) allows for the calculation of system parameters including power losses in the whole range of operation for any kind of power split drive structure. This provides the design engineer with very good support during the design process and helps him to find an optimal structure of the power split drive. The tool has libraries for hydrostatic components, gears, clutches, planetary gear sets, engines and accumulator models. These libraries can be extended and completed by the user easily. An open database of the most common structures of power split drives is implemented in the CAE tool. The PSDD software tool is built in a modular way on the Matlab and Simulink platforms. To increase the fidelity of simulation models highly accurate empirically based loss models should be used.

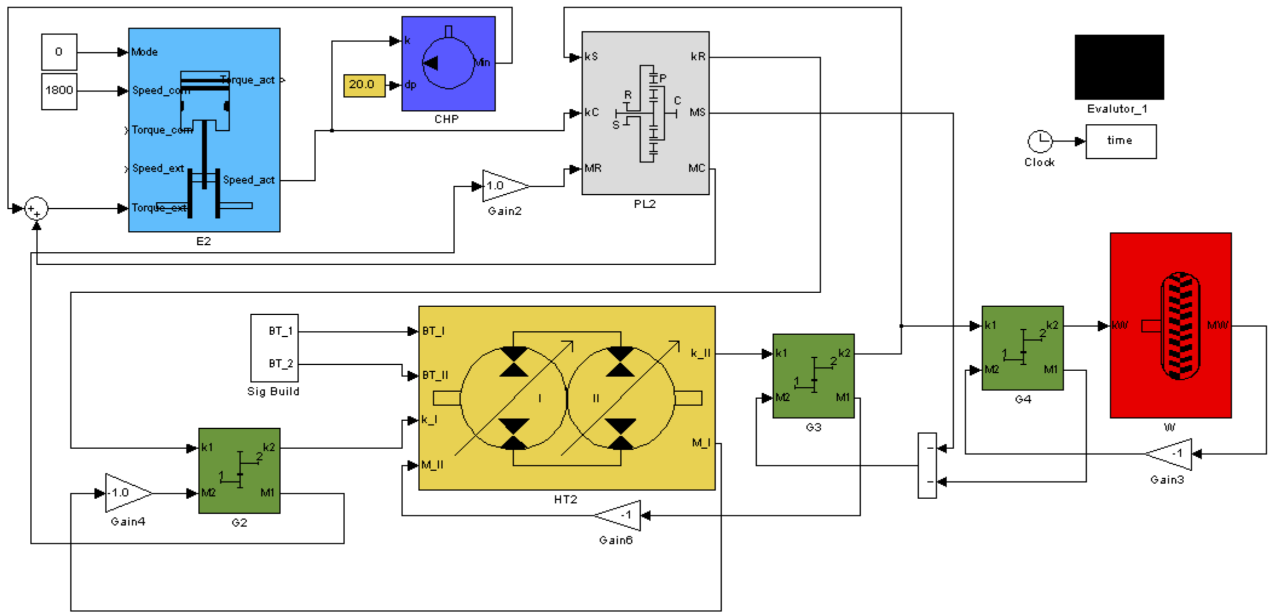


Figure 11: PSDD Simulation Model

3. Research into design and optimization of piston pumps and motors

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

This research focuses on the performance optimization and noise reduction of axial piston pumps and motors. These research efforts have moved in two directions: the design of special experimental test rigs and the development of multi-domain simulation models, to achieve a fundamental understanding of the complexity of physical effects taking place in displacement machines.

The focus of the simulation model is the rotating group of axial piston machines with its three main interfaces; the piston/cylinder, slipper/swash plate and the cylinder block /valve plate interface. The three lubricating interfaces are certainly the most critical design issue, since they have to fulfill a fundamental bearing and sealing function, but at the same time form the major sources of energy dissipation. Moreover, the change of pressure in the displacement chambers, resulting from the basic working process of the displacement machine, causes fluctuating forces and moments, leading to a complex oscillating micro motion of moveable parts of the rotating group.

The main goal of the modeling is the prediction of the fluid film thickness in the main lubricating interfaces, which are used to separate the highly dynamically loaded machine parts under relative motion and to ensure reliable operation without wear. This information is crucial for the design of positive displacement machines, because the correct working process, the main achievable operating parameters, the energy dissipation and power loss are directly linked to the fluid film behavior.

Our recent research on axial piston machines has pointed out the fundamental importance of elasto-hydrodynamic and thermal effects on film generation and film stability. These phenomena are responsible for substantial modification of the fluid film thickness and need to be considered to achieve a correct prediction of the machine performance. 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. For this reason what was in the past a monolithic entity, has become a complex system where the different interfaces still interacts with each other, but in the same time represent dedicated multi-physics models.

Piston / Cylinder interface

The piston/cylinder interface model represents the world’s first fully coupled multi-body dynamics simulation model for this interface. The model allows capturing of the complex fluid-structure interaction and thermal phenomena affecting the piston/cylinder non-isothermal fluid film conditions. In particular, the model considers the squeeze film effect due to the piston micro-motion and the change in fluid film thickness due to the solid boundaries elastic deformations. The elastic deformation of the piston and cylinder is related to the fluid film pressure and thermal stresses.

The model couples iteratively different numerical domains and solution schemes, as depicted by Figure 12. 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:

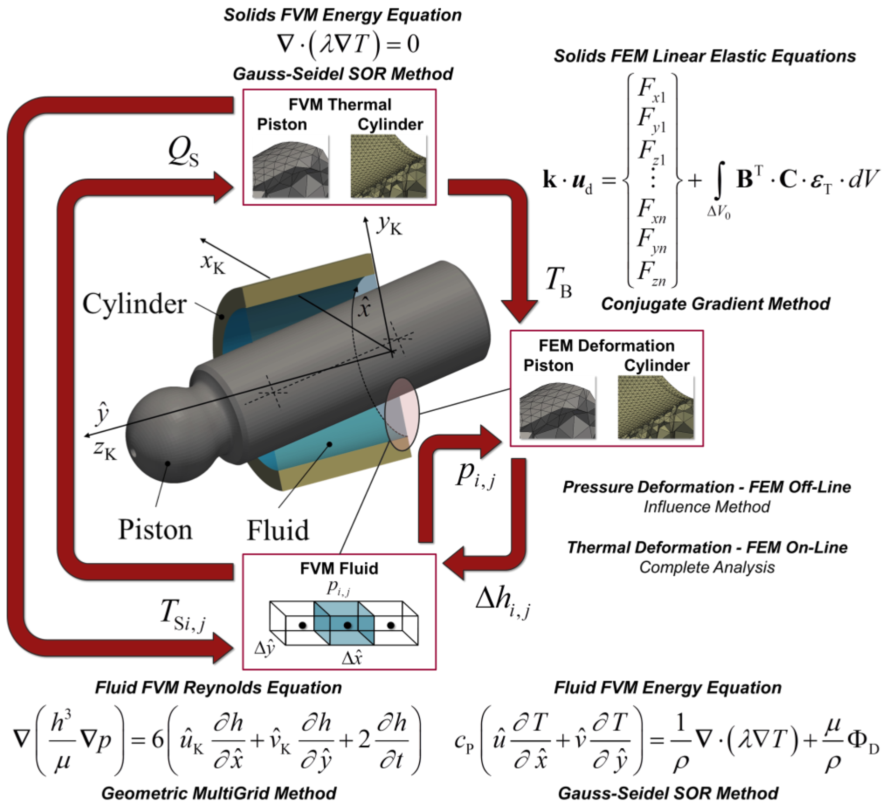


Figure 12: Piston/cylinder interface fluid structure interaction and thermal model

1) **Fluid Film Finite Volume Non-Isothermal Flow Model:** this module predicts the instantaneous pressure distribution and temperature distribution in the piston cylinder 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 Volume Heat Transfer Model:** this module calculates the piston and cylinder solid bodies temperature distributions. The diffusive 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.
3) **Solids Finite Element Elastic Deformation Model:** this module allows determining the elastic deformation of the piston and cylinder 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 run-time. The ultimate information provided by this numerical model is the total fluid film thickness geometry elastic deflection, Δh. FEM analysis based on CAD solid models coupled with the possibility of advanced constraints methods, 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 the Maha researchers to discover the piston/cylinder interface physical behavior and to study the energy dissipation through viscous friction and leakage flow.

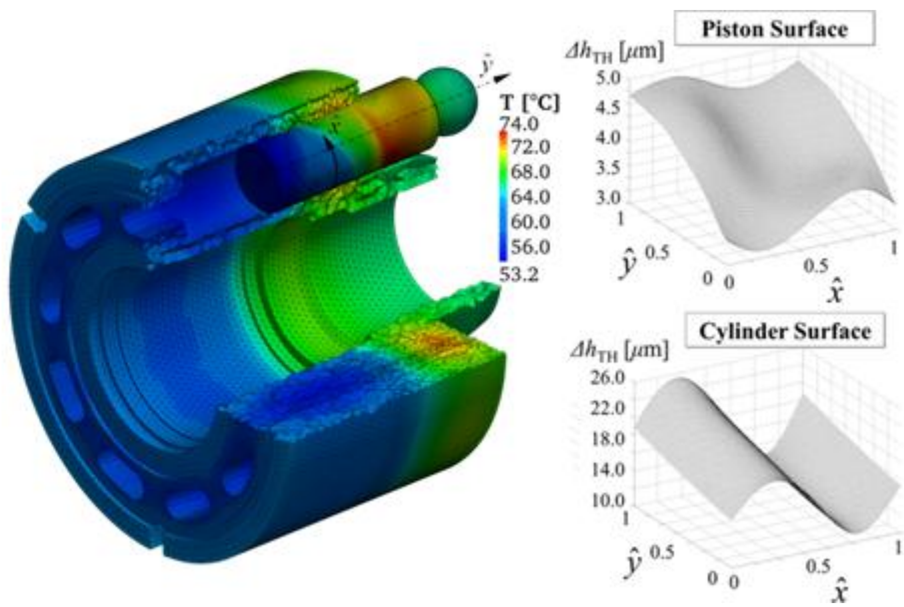


Figure 13: Axial piston machine piston/cylinder block temperature distribution (left) and surface thermal deformations for a high load operating condition (right)

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 Figure 13. 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.

The discovery together with the developed multi-physics model forms the starting point for a new computational based design approach. It will form a very important basis for the development of the next generation of highly efficient high pressure pumps and motors. The model will be used to investigate better interface designs, including novel material combinations and shaped surfaces. These innovative piston/cylinder designs will lead to better machine performance and increased efficiency over a wider range of operating conditions.

Slipper / swash plate interface

The slipper swashplate interface numerical model received significant improvements during 2012. Pressure deformation of the swashplate was finally included to the core computational model and the paper titled *"The influence of swashplate elastohydrodynamic deformation in the slipper-swashplate interface"* presented at the 7th FPNI PhD Symposium in Reggio Emilia, Italy received a best paper award. Although the overall swashplate pressure deformation typically has magnitudes multiple times the fluid film thickness, because a single slipper only "feels" part of the deformation at one time the influence on overall operation varies. In addition to the new swashplate pressure deformation, a FEM thermal solver was developed to solve for the non-uniform temperature distribution in the slipper and swashplate bodies as well as the thermal deformation of the slipper. This additional module provides the lubricating fluid film with more accurate thermal boundaries and considers how the slipper may deform due to localized heating. Figure 14 highlights how all of these physical effects combine to enable successful lubrication of the slipper and swashplate.

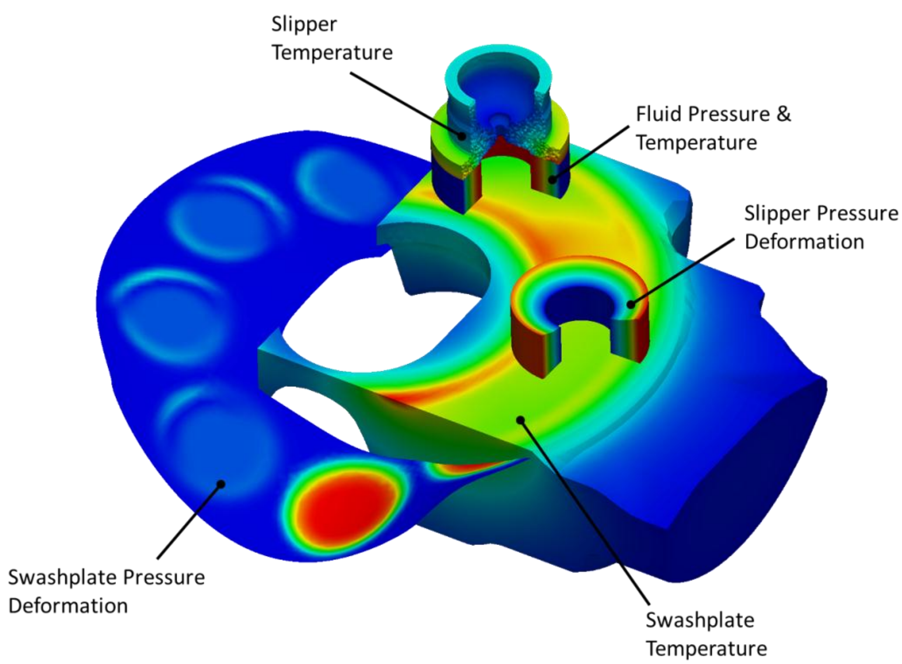


Figure 14: Slipper / swashplate fluid-structure-thermal interaction model

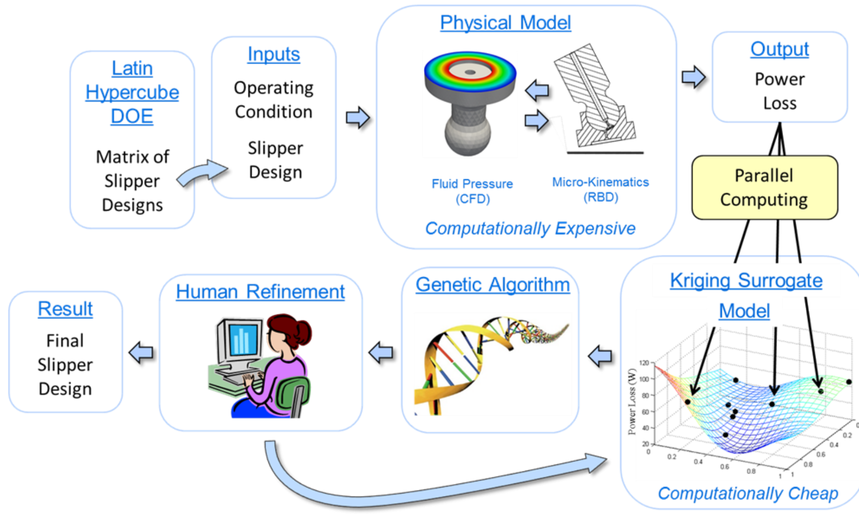
Another important factor realized from the numerous slipper simulations conducted this past year was the importance of slipper wear coming from the pump wear-in process. In particular, slipper designs which frequented low fluid film thicknesses were prone to having microns of wear during the initial 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 slipper wear (Figure 15).

Figure 15: Measuring slipper wear using the Mitutoyo stylus profilometer

A semi-rigid numerical model of the slipper swashplate interface was used to conduct a broad design space optimization for a 24cc axial-piston pump design (Figure 16). Although the model has the capability to consider solid body pressure deformation, this was fixed to reduce the computational effort of this first study. The numerical model takes geometrical parameters and the operating condition of the pump as input and predicts an overall power loss in the slipper swashplate interface.

The goal of the optimization is to minimize average power loss over a number of operating conditions by allowing four geometrical parameters to change. To further reduce the computational burden of the optimization process, computationally cheap surrogate models were built using the Kriging method on top of the physical model described previously. A genetic algorithm was then used on the surrogate model to find designs exhibiting minimum power loss. A human-in-the-loop refinement was used to enhance the accuracy of the surrogate modes in promising locations and further guide the optimization. Finally, an optimized design was found. A diagram of this process along with the variables and results can be found in the figure below:

Optimization Methodology:



Optimization Results

	dGorifice (mm)	dGin (mm)	dGout (mm)	Fspring (N)	Average Power Loss (W)
Baseline	0.5	6.6	19.0	33.3	59.4
Optimized	0.921	7.97	16.75	44.7	27.6

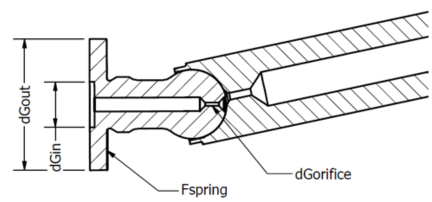


Figure 16: Optimization Methodologies for Slipper Design

Cylinder block / valve plate interface

The model structure of the cylinder block / valve plate interface has not changed much since the last year, and it is represented in Figure 17. Four main modules, coupled together, account for all the main physical phenomena in the lubricating interface. The first module solves the Reynolds and the Energy equations using the Finite volume method, describing the fluid flow in the lubricating gap. A precise prediction of the main oil properties (pressure, temperature, viscosity, velocity) is calculated as a dynamic reaction to the oscillating external loads allowing for the interface carrying ability, leakages and torque losses to be estimated. From the knowledge of the pressure field, the elastic deformations of block and valve plate & end case assembly are calculated using an in house FEM solver. The relative deformations of the gap boundary surfaces are extracted and used to correct the film thickness in the fluid flow module.

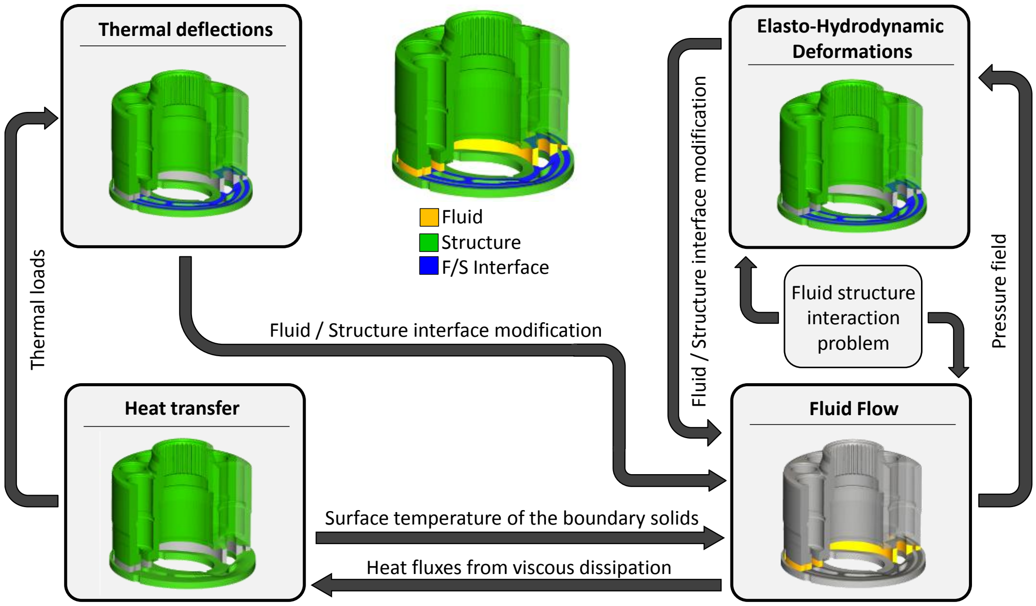


Figure 17: Cylinder block / valve plate interface fluid structure interaction model

When the film thickness is sufficiently thin, the elastic deformations have a direct impact on the pressure field and the lubrication regime is in the elasto-hydrodynamic condition. Since this is the most common scenario in the lubricating interfaces of axial piston machines, a partitioned fluid structure interaction algorithm takes care of solving the instantaneous mutual interaction between pressure and elastic deformation.

Also the heat transfer is characterized by an interaction between the lubricating interface and the boundary solids. In the solution of the Energy equation the surface temperatures of block and valve plate are important boundary conditions that strongly affect the calculated temperature field. On the other hand, the energy dissipated by viscous friction generates heat fluxes towards the boundary solids. Using these fluxes as boundary conditions, the cylinders block and valve plate & end case assembly temperature fields are calculated through an unstructured finite volume solver, specifically developed for this purpose. From the knowledge of these temperature fields, the thermal loads are estimated and the corresponding thermal expansions are calculated through a new thermo-elastic Finite Element solver. As for the elastic deformation due to pressure, the deformations deriving from the thermal expansion affect the fluid film thickness with substantial modification of the lubrication behavior.

The validation of the described model through surface temperature measurements has been presented in March at the 8th IFK International Conference on Fluid Power, Dresden, Germany through the paper *"Cylinder block/valve plate interface - a novel approach to predict thermal surface loads".*

A second publication, focused on the load exchange between the pistons and the cylinder block, has been presented in September at the Bath/ASME Symposium on Fluid Power and Motion Control, Bath, UK. The paper *"A novel approach to predict the cylinder block / valve plate interface performance in swash plate type axial piston machines"* introduced a new methodology for the calculation of the load transferred from the piston / slipper assembly to the cylinder block body and demonstrated how it can further improve the model accuracy.

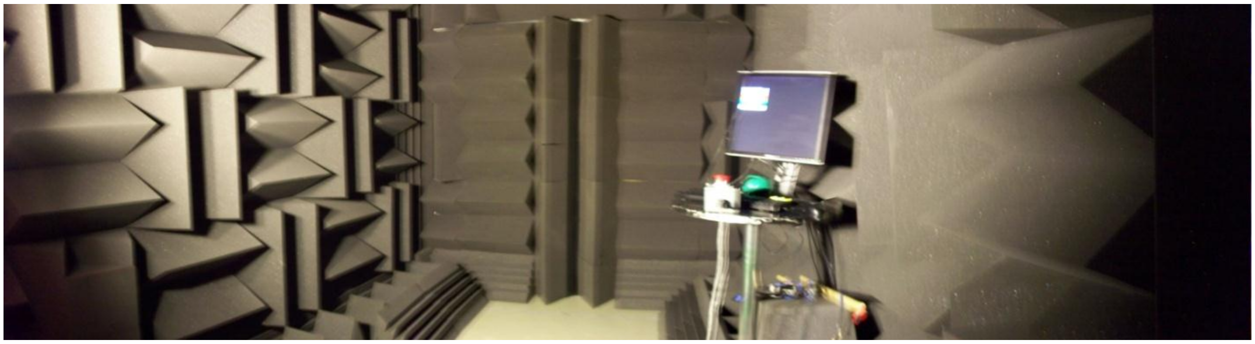
New micro-surface shapes study

One of the main activities of the Maha pump modeling team 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 especially at low displacement and low pressure.

In 2008 Maha researchers introduced first time a waved micro-surface shape pattern on the valve plate surface (patent application 65083 P1.US). The original idea, resulting from the improved understanding of the lubricating film behavior of the cylinder block / valve plate interface, was investigated and optimized through the computer simulation tool developed at Maha, in order to achieve the maximum performance. The researchers showed the possibility to reduce losses created in the cylinder block / valve plate interface up to 60% compared to the standard design. Especially at low pressure and low displacement this would lead to a substantial improvement in the machine efficiency, being the cylinder block / valve plate interface the most penalizing one in term of losses. The proposed designed was tested on a prototype, and measurements have shown increment in overall efficiency up to 10% at moderate operative conditions. Maha researchers have also studied waved like micro-surface shaping of the piston (Filed patent: 61/165, 661). First simulation results showed a potential reduction of losses up to 65%.

These results represented a major breakthrough in this research direction and suggested a deeper study of the new technology; in particular the Maha team has been investigating the impact of micro-surface shaping on the lubricating interfaces performance through the new fully coupled fluid structure interaction model. The results of this study were presented at the 7th FPNI PhD Symposium in Reggio Emilia, Italy, in the paper "*An investigation of the impact of micro surface shaping on the cylinder block/valve plate interface performance through a novel thermo-elasto-hydrodynamic model*". The paper has been recognized with the distinguished paper award. The study had confirmed the effectiveness of the micro surface wave pattern in improving the efficiency of the cylinder block / valve plate interface; nevertheless, for the same wave pattern parameters, the new model predicted remarkably lower loss reduction compared to the previous simulation study of 2008. It was shown that the reason of this lower reduction was in the elasto-hydrodynamic and thermal effects: the associated deformations represented a major modification to the film thickness, making the micro surface shaping less effective. Therefore, in the future optimization studies the new fluid structure interaction and thermal model will be widely used.

Noise Control and Acoustics



The goal for this area of research is to understand the sources of noise within hydraulic systems. The use of complex hydraulic systems has led to the demand for a more comprehensive understanding of audible noise. The utilization of axial-piston based hydraulic systems by numerous industries with a wide range of operating conditions has motivated our research to center on the design of a pump/motor or system.

The Airborne Noise (ABN) emitted from the hydraulic system can be attributed to two main sources, namely, Fluid Borne Noise (FBN) and Structure Borne Noise (SBN). It is important that all projects consider both sources of noise (Figure 18).

A major milestone of 2012 was the finalization of a new version of VpOptim including the addition of volumetric efficiency to the algorithm evaluating potential pump designs.

A new area of research of Modal analysis was started this summer 2012 with preliminary measurements and model parameters estimation algorithms to begin researching the field of vibrations caused by hydraulic systems.

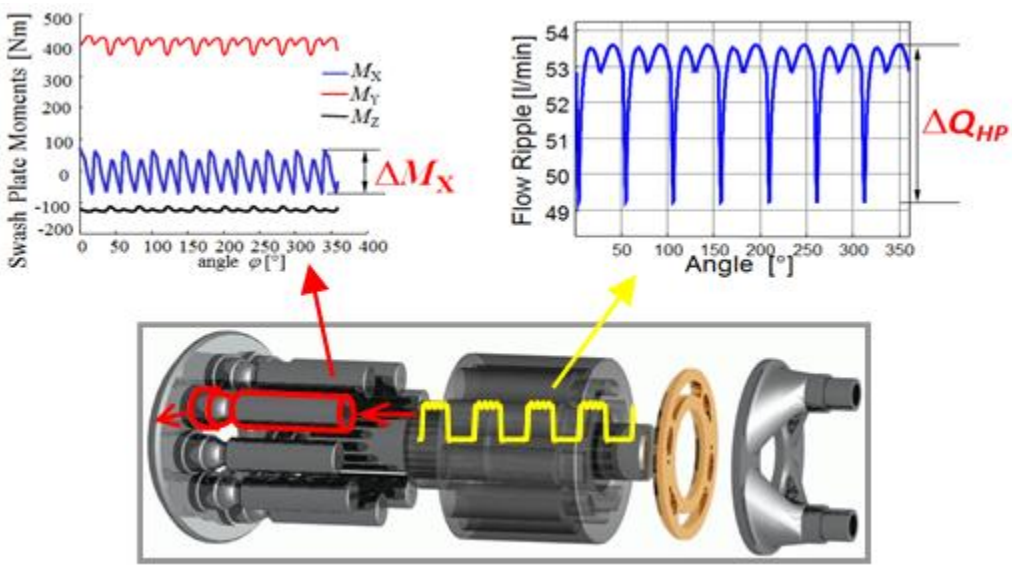


Figure 18: Axial piston pump showing the fluid borne and structure borne noise sources

VpOptim

The program forms the basis of a computational design and optimization tool for valve plates in order to reduce noise generation at the source (FBN and SBN) level i.e. through pump and motor design. A multi-parameter multi-objective optimization procedure has been developed to reduce sources (FBN and SBN) of noises from pumps and motors, when operating in a wide range of operating conditions. The optimization procedure has been implemented as design software (VpOptim) which assists a pump designer in a search towards an optimal valve plate design which will introduce minimum possible noise sources in a wide range of operating conditions.

VpOptim receives its name from optimizing the valve plate of a pump. The program enables a designer to optimize independently the relief grooves and pre/post compression filter volumes. The relief groove reduction technique is characterized by multiple input/ 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. The reduction techniques are inputs to a Multi Objective Optimization algorithm to select an optimum set of relief grooves and/or Compression filter volumes which will have the minimum possible FBN and SBN over the selected range of operating conditions.

TransModel

The second research area focus on reducing 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 (Figure 19). 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.

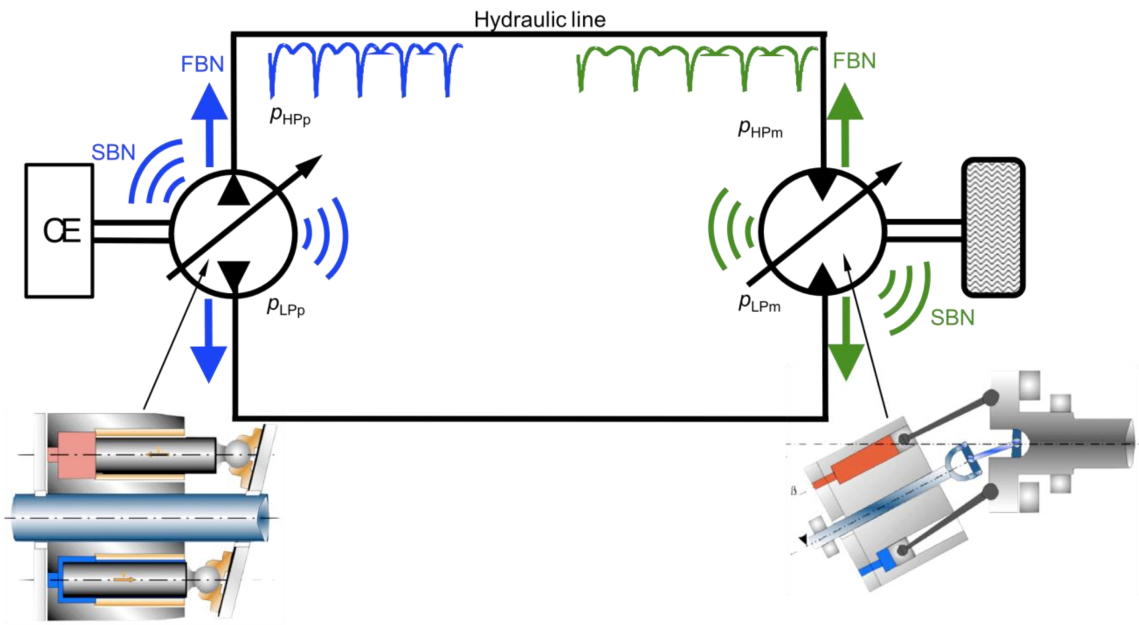


Figure 19: Schematic of hydrostatic transmission implemented in TransModel

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

2 Research Facilities

Lab Space and Test Rigs at Maha

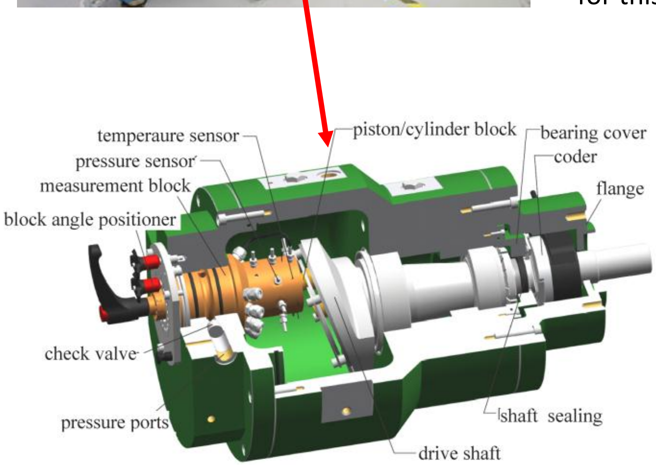
The lab currently houses ten test rigs designed to support our research.

Test Beds for Technological Demonstration (Above)

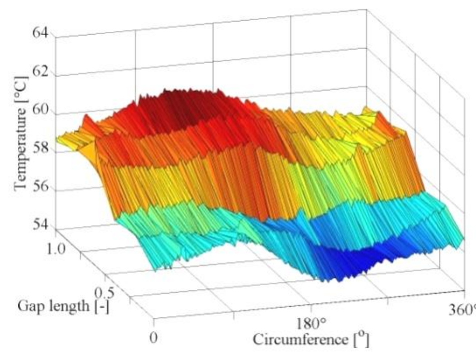
Test Rigs and Control Room (Above and Left)

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.



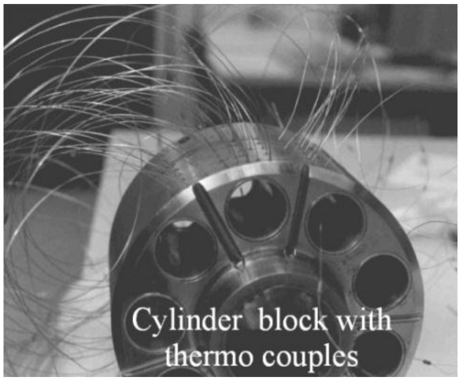
EHD Pump

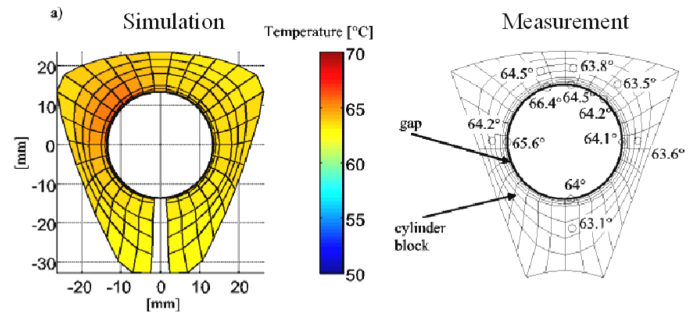


Measured Temperature Field in the Piston/Cylinder Gap

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.

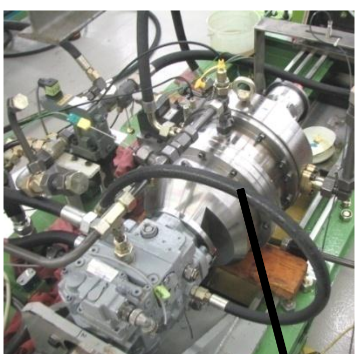




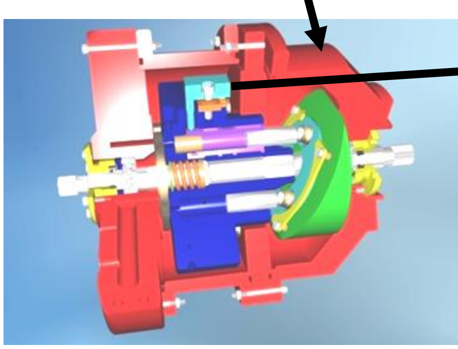
Temperature distribution in the assembly near the slipper slide

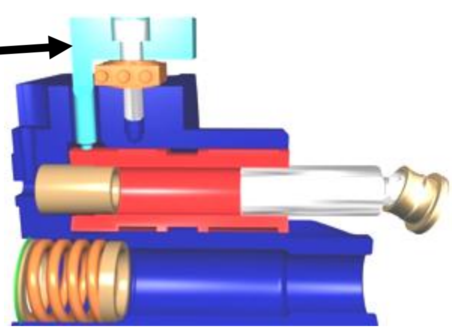
Tribo test rig

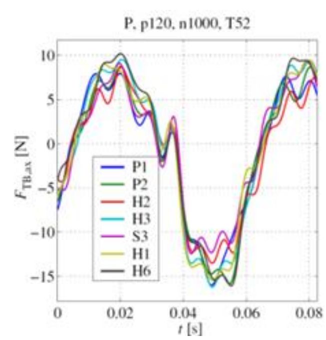
The heart of the test rig, the Tribo pump (below, left), is designed to measure the dynamic axial and circumferential friction forces between the piston and cylinder. Data is transmitted wirelessly from the rotating kit to a data acquisition via a telemetry system. The Tribo pump can be operated in either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



The Tribo test stand is in the process of receiving a new variable speed electric drive motor (above, left). This change will enable improvements to the hydraulic circuit allowing much closer control over fluid temperature. Much of the data acquisition and control hardware is also being updated.







Cavitation/PIV test rig

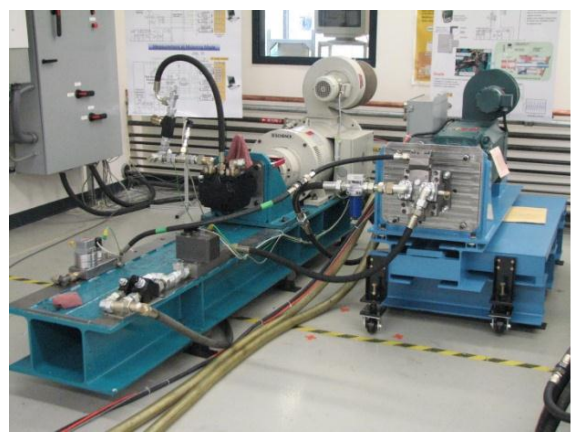
This test rig was designed to visualize and conduct Particle Image Velocimetry (PIV) analysis of cavitation in hydraulic oil. This test rig was designed in support of CCEFP project 3C and will support the computational studies in modeling cavitation in hydraulic components.

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.

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

JIRA test rig

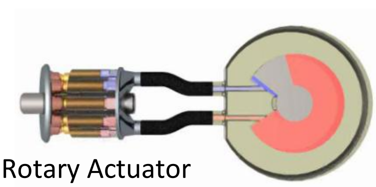
T The joint integrated rotary actuator test rig (JIRA) has been built for the experimental investigation of displacement controlled rotary actuators. This technology can be used as end effector drives in mobile robots and large manipulators as well as for applications such as stabilizers in cars or ships. A new National Instruments controller has been implemented in the test rig and a number of modifications are in process to implement pump switching strategies.

Performance

Max. Torque: 30000 Nm

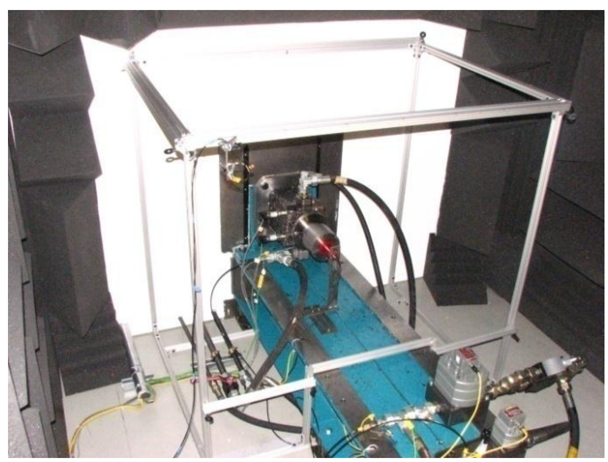
Max. Pressure: 350 bar

Max. Power: 30 kW

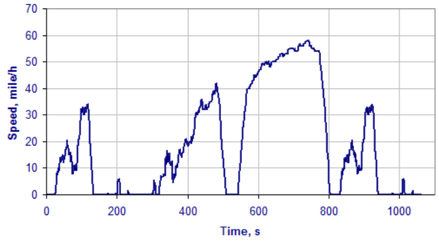


Semi-Anechoic Chamber

A semi-anechoic hydraulic transmission test facility is available in Maha Fluid Power Research Center to measure the sound power radiated from the sources. The facility enables the investigation of noise levels for different designs of displacement units and transmissions. The facility has the capabilities to use two electrical units which are used as electric motor/generator combination. These two electrical units are coupled with hydraulic displacement units to recreate an entire hydrostatic transmission.



Power Train test rig



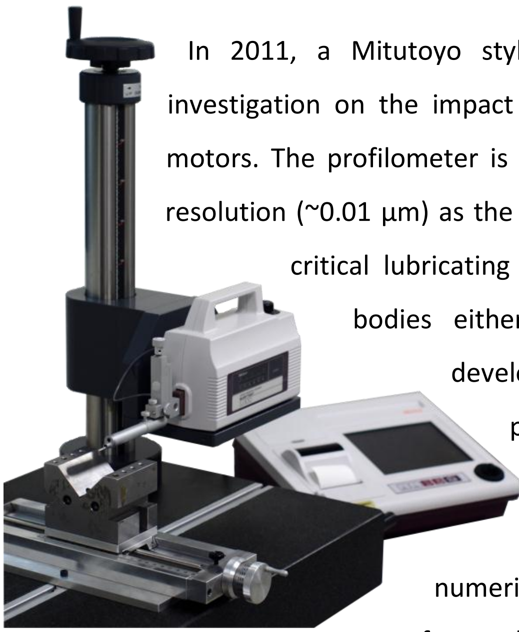
This test rig has been designed for the purpose of testing power trains and power train control concepts developed here at the Maha lab. A hydraulic motor supplies input shaft power to the power train being tested, while a hydraulic pump creates a simulated load at the output shaft of the power train. Pictured is a series hydraulic hybrid transmission intended for use in a Toyota Prius. The test rig can be used to accurately simulate given drive cycles such as the UDDS drive cycle shown below.

Hydraulic Power Supply

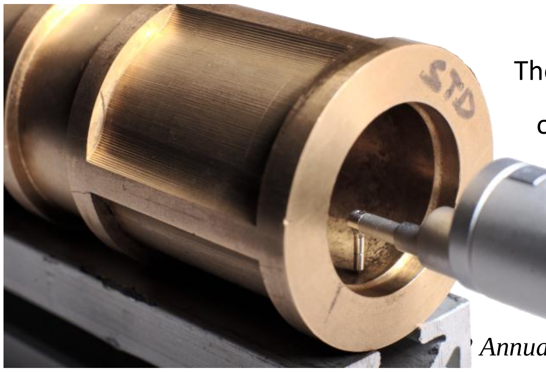
The above test rigs are powered by a 320 kW central hydraulic power supply unit with a 2000 liter tank, a water cooler and heating elements with five individually controlled pressure compensated pumps, 350 bar and 450 lpm output flow and a 60 l/min low pressure installed in 2005. A second medium pressure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



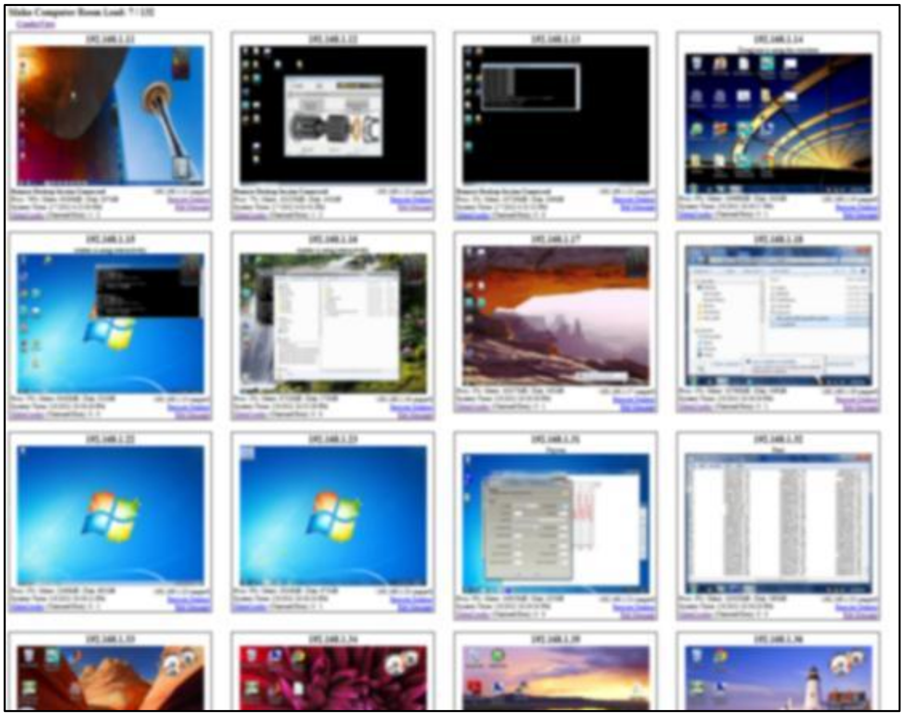
In 2011, a Mitutoyo stylus surface profilometer was purchased to allow for further investigation on the impact of micro-surface shaping and wear inside hydraulic pumps and motors. The profilometer is able to graph the change in height of a specimen with excellent resolution (~0.01 μm) as the stylus slowly 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. Now with the acquisition of the profilometer, actual measurements of component wear-in, surface roughness, and manufacturing validation are possible, all increasing the accuracy and confidence of the developed numerical models. The profilometer also enables measurement of any manufactured micro-surface shaping ensuring it meets design tolerances, and measuring any wear following run-in enabling further confidence in this advanced research of axial piston pumps and motors. 2012 saw the further acquisition of a measurement stand for the profilometer which can be seen in the photo, allowing for the measurement of a wide array of part surfaces more quickly and accurately.



The value of the profilometer system was demonstrated on several occasions during the past year. Predictions of wear in a particular region of the slipper of an axial-piston unit were validated by measurements made with the profilometer system. This demonstrates the utility of the profilometer 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 using this front wheel loader. Due to the elimination of throttling valves, displacement control technology is also sometimes referred to as "valve less" technology.

This smaller wheel loader serves as a platform for diagnostics and prognostics on hydraulic systems.

Skid-Steer Loader

Pump-controlled technology has also been demonstrated on compact machinery. A Bobcat skid-steer loader has been modified so that the boom and bucket functions are controlled by variable displacement hydraulic pumps. Previous Maha researchers have implemented active vibration damping using the displacement controlled hydraulic system.

Mini Excavator

The excavator is being used for the purpose of testing displacement controlled technology and engine power management concepts to improve fuel economy developed here at the Maha lab. The excavator serves as the CCEFP test bed #1. This excavator has been compared side by side with the production valve controlled version and has demonstrated fuel to work efficiency gains of nearly 70% (August 2010).

3 Research Grants

Research Grants obtained in 2012: $2,007,826

Funding from CCEFP: $952,035

Engineering Research Center (ERC) for Compact and Efficient Fluid Power (CCEFP). NSF + affiliated-industry funds, 7th year funding $952,035

Funding from Industry Projects: $ 1,055,791

- Advanced Energy Saving Hydraulic System Architecture for mobile machines
- Analysis of Pump Noise Sources & Design Optimization
- Modeling and Analysis of the Cylinder Block/Valve Plate and Slipper/Swash Plate Interfaces of an Axial Piston Pumps and motors
- Efficiency Study & Measurements on Hydraulic Hybrid Systems

4 Publications, Patents and Reports

Journal Articles

Pelosi, M. and **Ivantysynova, M.** 2012. Heat Transfer and Thermal Elastic Deformation Analysis on the Piston/Cylinder Interface of Axial Piston Machines"; ASME Journal of Tribology.

Pelosi, M. and **Ivantysynova, M.** 2012. A Geometric Multigrid Solver for the Piston-Cylinder Interface of Axial Piston Machines. Tribology Transactions, Vol. 55, Issue. 2, pp. 163 – 174.

Busquets, E. and **Ivantysynova, M.** 2013. Temperature prediction of Displacement Controlled Multi-actuator machines. International Journal of Fluid Power, accepted for publication.

Conference Proceedings

Zecchi, M. and **Ivantysynova, M.** 2012. Cylinder block / valve plate interface – a novel approach to predict thermal surface loads. Proceedings of 8th IFK International Conference on Fluid Power. Dresden, Germany, Vol.1. pp. 285-298.

Hippalgaonka, R., J. Zimmerman and **Ivantysynova, M.** 2012. Fuel savings of a mini-excavator through a hydraulic hybrid displacement controlled system. Proceedings of 8th IFK International Conference on Fluid Power. Dresden, Germany, Vol.2. pp. 139 – 154.

Sprengel, M. and **Ivantysynova, M.** 2012. Coupling Displacement Controlled Actuation with Power Split Transmissions in Hydraulic Hybrid Systems for Off-Highway Vehicles. ASME/Bath Symposium on Fluid Power and Motion Control (FPMC 2012), Bath, UK, pp. 505-517.

Zecchi, M. and **Ivantysynova, M.** 2012. A novel approach to predict the cylinder block / valve plate interface performance in swash plate type axial piston machines. ASME/Bath Symposium on Fluid Power and Motion Control (FPMC 2012), Bath, UK, pp. 13-28

Busquets, E. and **Ivantysynova, M.** 2012. Cooling power reduction of displacement controlled multi-actuator machines. Proc. of the 7th FPNI PhD Symposium, Reggio Emilia, Italy, pp 453 - 466.

Sprengel, M. and **Ivantysynova, M.** 2012. Energy saving system architecture for hydraulic hybrid off-highway vehicles. Proc. of the 7th FPNI PhD Symposium, Reggio Emilia, Italy, pp 517 - 533.

Kim, D. and **Ivantysynova, M.** 2012. Valve plate optimization focusing on noise reduction in the axial piston machine with high volumetric efficiency. Proc. of the 7th FPNI PhD Symposium, Reggio Emilia, Italy, pp 571 - 588**.**

Zecchi, M. and **Ivantysynova, M.** 2012. An investigation of the impact of micro surface shaping on the cylinder block/valve plate inter-face performance through a novel thermo-elasto-hydrodynamic model. Proc. of the 7th FPNI PhD Symposium, Reggio Emilia, Italy, pp 589 - 610.

Schenk, A. and **Ivantysynova, M.** 2012. The influence of swashplate elastohydrodynamic deformation. Proc. of the 7th FPNI PhD Symposium, Reggio Emilia, Italy, pp 611 - 632. -**Backe Medal for best paper**

Daher, N. and **Ivantysynova, M.** 2012. Electro-hydraulic energy-saving power steering systems of the future. Proc. of the 7th FPNI PhD Symposium, Reggio Emilia, Italy, pp 929 - 952.

Sprengel, M. and **Ivantysynova, M.** 2012. Novel Transmission Configuration for Hydraulic Hybrid Vehicles. Proceedings of the International Sci-Tech Conference “Machine Dynamics and Vibro Acoustics”, Samara, Russia, pp. 207 - 209.

Kalbfleisch, P. and **Ivantysynova, M.** 2012. Noise Reduction in Hydraulic Axial-Piston Pumps and Motors. Proceedings of the International Sci-Tech Conference “Machine Dynamics and Vibro Acoustics”, Samara, Russia, pp. 209 - 210.

Invited Lectures

Ivantysynova, M. 2012. The piston cylinder assembly in piston machines - a long journey of discovery. Proceedings of 8th IFK International Conference on Fluid Power. March 26-28, 2012. Dresden, Germany, Vol.3, pp.307-332. - **Keynote Lecture**

Ivantysynova, M. 2012**.** Prius without a battery – an output coupled powersplit hydraulic hybrid power train. 2012 SAE International Commercial Vehicle Engineering Congress & Exhibition, Rosemont, IL, USA. Invited Panel Session on Hybrids

Ivantysynova, M. 2012**.** Future Technology Focus – Displacement Controlled Actuation. Energy Efficient Hydraulics and Pneumatics Conference, Nov. 27-29, 2012 Chicago. -**Keynote Lecture**

Patents Awarded

US 8,191,290 B2 issue June 5, 2012. Displacement –controlled hydraulic system for multi-function machines. (Ivantysynova, M. Hughes, E., Williamson, C. and Zimmerman, J.)

US Patent No 8,277,352 B2 issued October 2, 2012. Power split transmission with energy recovery. (Ivantysynova, M., Carl, B.A. and Williams, K.R.)

Research Reports

Ivantysynova, M. and **Hippalgonkar, R**. 2012. *Pump Commands Using Loss Models.* Maha Fluid Power Research Center. Research Report MAHA01-2012-in.

Ivantysynova, M., Jouini, N., and **Kalbfleisch, P**. 2012. *Analysis of Noise Sources for Parker Hybrid Transmission.* Maha Fluid Power Research Center. Research Report MAHA02-2012-ex.

Ivantysynova, M. and **Zhao, M.** 2012. *Running Powertrain Test Rig (Update).* Maha Fluid Power Research Center. Research Report MAHA03-2012-in.

Ivantysynova, M. and **Kretsch, L.** 2012. *Development of a Low Cost Hydraulic Hybrid Power Train and Prototype Vehicle Integration.* Maha Fluid Power Research Center. Research Report MAHA04-2012-in.

Ivantysynova, M. and **Schenk, A.** 2012. *Pocket Pressure Model for the Slipper-Swashplate Interface.* Maha Fluid Power Research Center. Research Report MAHA05-2012-in.

5 Theses Completed In 2012

PhD Theses

Matteo Pelosi 2012. An Investigation on the Fluid-Structure Interaction of Piston/Cylinder Interface. PhD thesis, Purdue University.

Joshua Zimmerman 2012. Toward Optimal Multi-actuator Displacement Controlled Mobile Hydraulic Systems. PhD thesis, Purdue University.

Master's Theses

Minming Zhao 2012. Optimal Control Based Design of Output Coupled Power Split Hydraulic Hybrid. Master's thesis, Purdue University.

Dongjune Kim 2012. Contribution to digital prototyping of axial piston pumps/motors. 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 could be strengthened even further by using 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

International students and researchers

In 2012, the following international students and researchers have worked in our team

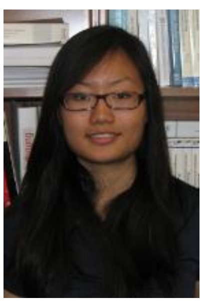
Amin

Chris

Fabian

Hideaki

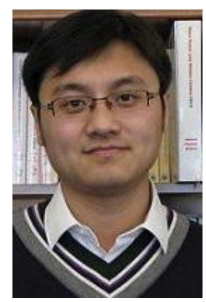
Jan



Jennifer

Junwei

Lizhi



Wei

Amin Mehdizadeh, Iran (amehdiza@purdue.edu)

Chuang (Chris) Wang (wang1310@purdue.edu)

Fabian Zimber, Germany

Hideaki Usami, Japan (h.i.d.e.usami@gmail.com)

Jan Schmidt, Germany

Jennifer Wu, Purdue University (wu46@purdue.edu)

Junwei Zhang, China (zjw36927@163.com)

Lizhi Shang, China

Wei Shen, China (sws10@163.com)

7 International and National Conferences Attended

8th IFK International Conference on Fluid Power. Dresden, Germany, March 26-28, 2012.

Attendees:

Monika Ivantysynova (**Keynote Lecture**: The piston cylinder assembly in piston machines - a long journey of discovery)

Rohit Hippalgaonkar (Paper Presentation)

Marco Zecchi (Paper Presentation)

STLE 2012 Annual Meeting & Exhibition. St. Louis, Missouri, USA, May 6-10, 2012.

Attendees:

Monika Ivantysynova

7th FPNI PhD Symposium on Fluid Power. Reggio Emilia, Italy, June 27-30, 2012.

Attendees:

Enrique Busquets (Paper Presentation)

Naseem Daher (Paper Presentation)

Paul Kalbfleisch (Poster Presentation)

Dongjune Kim (Paper Presentation)

Daniel Mizell (Poster Presentation)

Andrew Schenk (Paper Presentation, **Best Paper Award – Backe Medal**)

Mike Sprengel (Paper Presentation)

Marco Zecchi (Paper Presentation, **Recognized Paper Award**)

Andrew Schenk receiving the Best Paper Award (Backe Medal) at the 7th FPNI PhD Symposium on Fluid Power.

Marco Zecchi receiving the Recognized Paper Award at the 7th FPNI PhD Symposium on Fluid Power.

Machine Dynamics and Vibro Acoustics. Samara, Russia, September 5-6, 2012.

Attendees:

Paul Kalbfleisch (Paper Presentation)

Mike Sprengel (Paper Presentation)

Bath/ASME Symposium on Fluid Power and Motion Control. University of Bath, Bath, England, September 12-14, 2012.

Attendees:

Monika Ivantysynova

Mike Sprengel (Paper Presentation)

Marco Zecchi (Paper Presentation)

2012 SAE International Commercial Vehicle Engineering Congress & Exhibition. Rosemont, Illinois, October 2-4, 2012.

Attendees:

Monika Ivantysynova (Invited Panel Session on Hybrids: Prius without a battery – an output coupled powerplsit hydraulic hybrid power train)

Energy Efficient Hydraulics and Pneumatics Conference. Rosemont, Illinois, Novermber 27-29, 2012.

Attendees:

Monika Ivantysynova

8 Awards, Honors, and Recognitions

Best Paper Award ASME/Bath on Fluid Power & Motion Control (FPMC), 2011, **M. Pelosi** and **M. Ivantysynova** 2011. Surface deformations enable high pressure operation of axial piston pumps.

Backe Medal for best paper – 7th FPNI PhD Symposium, Reggio Emilia, Italy, **Schenk, A.** and **Ivantysynova, M.** 2012. The influence of swashplate elastohydrodynamic deformation. Proc. of the 7th FPNI PhD Symposium, Reggio Emilia, Italy, pp 611 - 632.

Zecchi, M. and **Ivantysynova, M.** 2012. An investigation of the impact of micro surface shaping on the cylinder block/valve plate interface performance through a novel thermo-elasto-hydrodynamic model. Proc. of the 7th FPNI PhD Symposium, Reggio Emilia, Italy, pp 589 - 610. - **Recognized paper**

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

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

Spring Semester 2012

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.

Textbook:

None.

Course notes:

All lecture material can be downloaded from Maha lab website,
https://engineering.purdue.edu/Maha/

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:

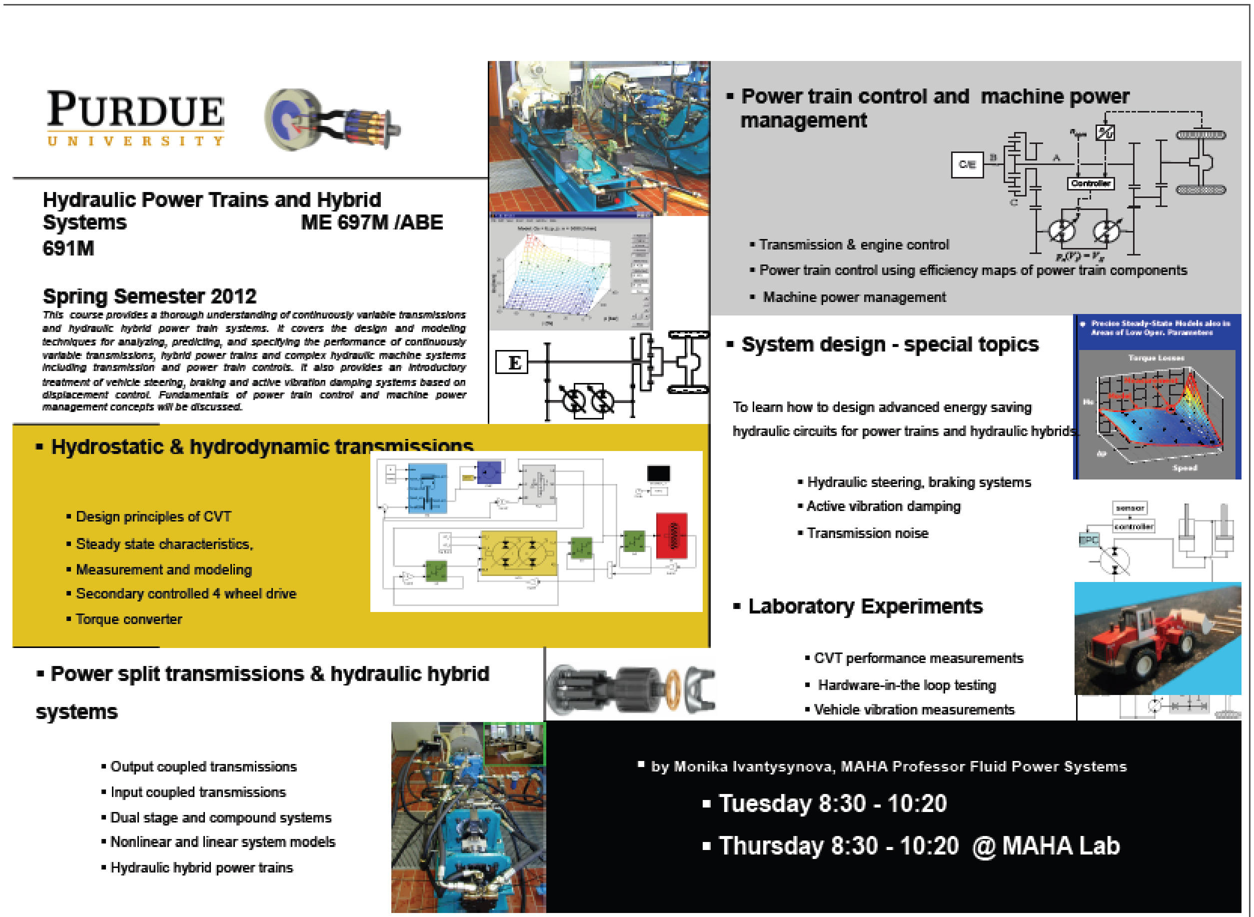
The design component of this course will consist of students designing two different continuously variable transmissions (CVT) to meet the required vehicle performance. The students will learn to model different types of CVT using a special simulation software (PSDD) and predict their performance. The 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 %

Course Flyer:



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

Fall Semester 2012

2012 marked the eighth consecutive year of ME 597/ABE 591 being offered.

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.

Textbook:

Course Notes

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:

Required in solution of homework problems and final design project. 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

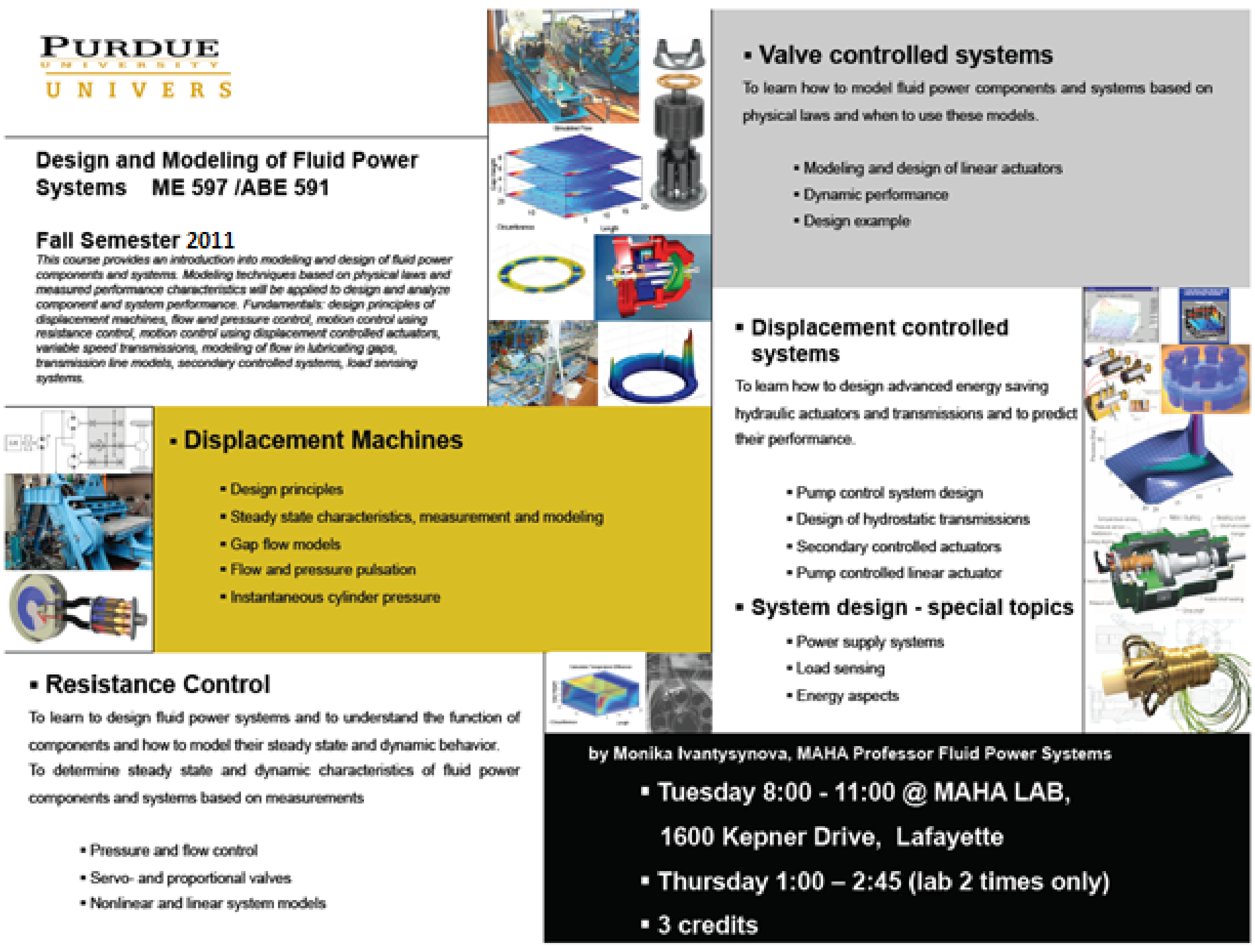
9. Create models to predict system behavior including dynamics (system parameter as function of time)
10. Define measurement methods and test procedure for a selected component and your whole actuation system
11. Write the system development report

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



12 Maha Social Events

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

Celebrating Matteo's successful PhD defense

Josh's PhD Defense Party

A friendly game of soccer between Monika's and Andrea's research groups

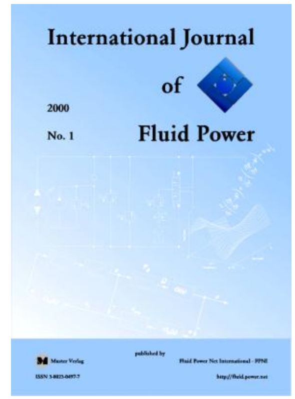
Dinner with the majority of Maha members in Reggio Emilia, Italy

Annual dinner party at Monika's house

Christmas lunch at the Maha lab

Monika's birthday lunch

13 International Journal of Fluid Power



Dear Associate Editors and Members of Editorial Board,

The International Journal of Fluid Power has completed its thirteen year of publication. The third and final issue of the thirteen volume was printed and sent to our readers this past November. This was the 39th issue of the Journal, and we look forward to the 40th to be published this coming March.

I would like to express my gratitude to all members of the fluid power community for its continuous support for the Journal, especially for continuously submitting manuscripts about recent research results. I would 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 2013.

My special thanks goes to all the Associate Editors who have done an excellent job in managing an increasing number of paper reviews. Without the tremendous support and voluntary work of all associate editors the journal would not be possible.

I am very fortune to have Susan Gauger as the Journal's Technical Editor working with me. Please join me in thanking her for her outstanding service and personal care about authors, associate editors, reviewers and customers.

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

I would like to 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. There have been authors from 34 different countries that have submitted papers to the International Journal of Fluid Power during the last thirteen years. Twenty-seven papers were submitted to the journal in 2012. All papers that were received by the Journal were sent to at least two experts and in many cases a third reviewer was involved to ensure the review process is fair and the Journal's final publication is only of the highest quality. The rate of successfully approved papers in the past year was approximately 45%. From the fifteen papers published in Volume 12 one paper was submitted in 2010, twelve were submitted in 2011 and two in 2012.

After failing the Journal's re-evaluation by the Scientific Citation index in 2009 we will be allowed to request a re-evaluation in 2013. I have already submitted the new request in August 2012. As this is one of the most important goals of the Journal I would like to encourage your help increasing the number of citations by referring your publications as well as the publications of others in the International Journal of Fluid Power more often.

My appreciation goes to all of you for your continuous support of the Journal. I wish you and your families a wonderful Holiday Season, a happy New Year, and all the best for 2013.

Best regards,

Monika Ivantysynova December 20, 2012

Editor-in-Chief

14 Maha Team in 2012

Maha Faculty

Dr. Monika Ivantysynova

Maha Professor of Fluid Power Systems

Joint appointment in ABE/ME

Supervisor of the Maha Fluid Power Research and Education Center

mivantys@purdue.edu

Phone: (765) 447-1609

Origin: Germany

August 2004-present

Maha Graduate Students

Enrique Busquets

PhD Student

BS: U. of Texas at El Paso

Phone: (765) 449-7980

Origin: Mexico

July 2011-present

Rene Chacon Portillo

Master's Student

BS: University of Texas at El Paso

Phone: (765) 449-7514

Origin: Mexico

July 2012-present

Naseem Daher

PhD Student

BS, MS: Lawrence Technological University

Phone: (765) 418-6665

Origin: Lebanon

Aug 2011-present

Rohit Hippalgaonkar

PhD Student

B.Tech. : IIT Bombay

M.Eng.: Cornell Univ

Phone: (765) 449-7980

Origin: India

June 2010-present

Paul Kalbfleisch

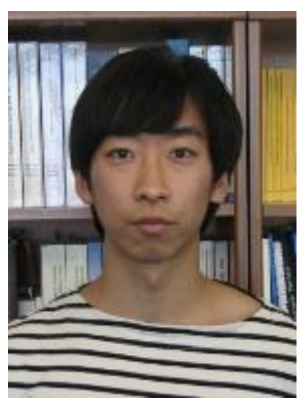
PhD Student

BS: Purdue University

Phone: (765) 448-1456

Origin: Kentucky, USA

Oct 2011-present



Dongjune Kim

Master's Graduate

BS: Yokohama National University, Japan

Origin: South Korea

May 2011-August 2012

Taeho Kim
PhD Student
BS: Ajou University, South Korea
MS: KAIST, South Korea
MS: University of Florida
Phone: (765) 448-1456
Origin: S. Korea
Aug 2012-present

Dan Mizell
PhD Student
BS: Michigan Technological University
Phone: (765) 449-7514
Origin: Michigan, USA
July 2011-present

Damiano Padovani
PhD Student
BS, MS: Polytechnic University of Turin
Phone: (765) 449-7980
Origin: Italy
August 2012-present

Matteo Pelosi
PhD Graduate
BS, MS: Università Degli Studi di Parma
Origin: Italy
September 2007-March 2012
Currently at Ohlins, Sweden

Andrew Schenk
PhD Student
BS: Kettering University
Phone: (765) 449-7514
Origin: Michigan, USA
July 2009-present

Natalie Spencer
Master's Student
BS: Embry-Riddle Aeronautical University
Phone: (765) 448-1456
Origin: Arlington, WA, USA
August 2012-present

Michael Sprengel

PhD Student

BS: Missouri S&T

Phone: (765) 418-6665

Origin: Missouri, USA

August 2010-present

Ashley Wondergem

PhD Student

BS: Saginaw Valley State University

Phone: (765) 448-1456

Origin: Michigan, USA

August 2012-present

Marco Zecchi

PhD Student

BS, MS: Università Degli Studi di Parma

Phone: (765) 449-7514

Origin: Italy

April 2010 - Present

Minming Zhao

Master's Graduate

BS: Shanghai Jiaotong University

Origin: China

August 2010-June 2012

Currently at Cummins, USA

Josh Zimmerman

PhD Graduate

BS: Brigham Young University

MS: Purdue Univ.

Origin: USA

August 2006-May 2012

Visiting Researchers

Amin Mehdizadeh

BS,MS: Shiraz University

MS: The Royal Insititute of Technology, Sweden

Origin: Iran

Dec 2011-Present

Wei Shen

BS: Northeast Foresty University

MS: Yan Shan University

PhD: Harbin Institude of Technology

Origin: China

Feb 2012-Present

Hideaki Usami

BS, MS: Meiji University

Origin: Japan

Aug 2012-Present

Maha Staff

Anthony Franklin

Maha Lab Technician

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

Summer Undergraduate Students

Cory Raizor

BS: Purdue University

SURF Summer 2012

Tridib Saha

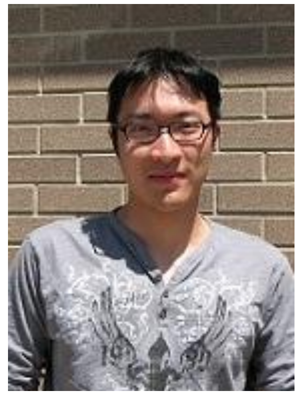
BS: Purdue University

SROP Summer 2012

Bruce Vonniederhausern

BS: Utah State University

SURF Summer 2012



Chuang (Chris) Wang

BS: Purdue University

SURF Summer 2012

Cary Wood

BS: Purdue University

SURF Summer 2012

15 Donors, Sponsors, Partners, & Guests

Generous donors, Mr. Ken Warren and his kind wife Susan, support Maha research with $10,000 every year!

Mr. Ken Warren and his wife Mrs. Susan Warren have decided to support Maha research activities with $10,000 every year. The Maha team delightfully welcomed Ken and Susan to the lab on Friday February 10, 2012. During their visit, Monika gave an overview presentation of the Maha research followed by presentations of Marco, Mike, Najoua, and Paul about their ongoing research projects. They also got to tour the Maha lab facilities and learn more about the available test beds and prototypes.

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 newest additions to 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

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

Doosan Infracore, Seoul, South Korea

Deltrol Fluid Power, Milwaukee, 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

Hägglunds Drives Inc., Columbus, USA

Hense Systems, Bochum, Germany

Honda R&D Americas Inc., Raymond, USA

Honeywell Aerospace, South Bend, USA

HYDAC International GmbH, Sulzbach/Saar, Germany

INNAS, Breda, Netherlands

Jungheinrich AG, Norderstedt, Germany

Komatsu Ltd., Tokyo, Japan

Linde AG, Aschaffenburg, Germany

Linde Hydraulics Corp, Canfield, USA

Mecalac, Annecy-le-Vieux, 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

TRW Automotive, Lafayette, USA

WIKA Instruments Corporation, Lawrencewille, USA

ZF Luftfahrttechnik, Kassel, Germany

Guests

A. Larson – Dow Chemical

Areum Seo – Doosan Infracore

Brett Brooks – Harsco Rail

Choi Eun Seok – Tecpos

Colin Macqueeh? – Trellebory

Dave Scheetz – Exxon Mobil

Howard Zhang – Parker Hannifin

James Howland – Parker Hannifin

Joe Almon – Emerson

Jude Hueber – LHI

Ken and Susan Warren – Donors

Kwang Ho Lim – Doosan Infracore

Lew Kasper – Parker Hannifin

Mark Jones – JWS

Mike Boland – Triumph

Mike Rhoda – Doosan Infracore

Nicholas Nagel - Trihmph

Peter Perrine – Triumph

Rajneesh Kumar – Parker Hannifin

Ray Gillies – Trellebory

Rick Lindner – Jaquet

Ron Keepecn – Jaquet

Samuel Flores-Torres – Exxon Mobil

Steve Herzog – Evonik

Andrea Wardlow – Exxon Mobil

Bill Affley ?– Tesco

Chad Renbarger– Jaquet

Chris Meyer – Emerson

Dave Kintzez – General Petroleum

David Hoover – Triumph

Hubertus Murrenhoff – Aachen University

Jay Anderson – Triumph

John Treharm – Parker Hannifin

Keiju Abo - Jatco

Kim Kwang Sun – Tecpos

Kwang-Sun Kim – Korea University of Technology and Education

Lori Martinelli – Parker Hannifin

Michael Gratton – John Deere

Mike Miltenberger – Exxon Mobil

Min Ha An – Doosan Infracore

Nick White – Parker Hannifin

Qingfeng Wang – State Key Laboratory of Fluid Power Transmission and Control

Ray Collett – Parker Hannifin

Rick Klop – Parker Hannifin

Roger Jenkins – Precision Pump & Power

Sage Jiang – Parker Hannifin

Sean West – John Deere

Terry Ryan – John Deere