Maha Fluid Power
RESEARCH CENTER
PURDUE UNIVERSITY

2011 Annual Report

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Maha Professor of Fluid Power Systems

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Preface

The presentation of our pump controlled mini-excavator at the CONEXPO trade show in Las Vegas was definitely one of the key highlights of our research activities in 2011. The excavator, which represents the test bed #1 of the National Science Foundation sponsored Engineering Research Center (ERC) for Compact and Efficient Fluid Power (CCEFP), was well positioned in the CCEFP booth. During the 5 days of the CONEXPO thousands of visitors stopped by and learned about the Maha pump controlled actuation technology, which can save up to 50% of fuel for heavy duty equipment and other hydraulically powered machines. The CCEFP 2011 NSF site visit took place during the CONEXPO in Las Vegas. In addition to the site visit presentations, eight members of the Maha team presented their recent research results at the 52nd National Conference on Fluid Power, which also took place during the CONEXPO in Las Vegas. The National Conference on Fluid Power was not the only conference where the Maha team presented their newest research findings. Maha researchers traveled to Tampere, Finland and Okinawa, Japan and gave presentations at the ASME/Bath workshop in Washington and the SAE 2011 Commercial Vehicle Engineering Congress in Chicago. I am proud to report that Andrew Schenk received the best paper award at the 8th JFPS International Symposium on Fluid Power in Okinawa, Japan last October for our paper *"An Investigation of the Impact of Elastohydrodynamic Deformation on Power Loss in the Slipper Swashplate Interface".* The organizing committee of the 4th ICMEM International Conference on Mechanical Engineering and Mechanics invited me to give a keynote lecture on *Displacement control - the future of fluid power systems* at the international conference in Suzhou, China. In addition to these important conference publications, the Maha team increased the number of their journal publications by 50%.

In 2011, we successfully continued our research efforts in the area of energy saving actuation and drive concepts. Maha researchers proposed a new hybrid technology that takes advantages of displacement controlled actuation combined with energy storage in hydraulic accumulators. A patent has been filed for the hybrid design which uses displacement controlled actuation for the hydraulic cylinders and secondary controlled (having a hydraulic accumulator for energy storage) rotary actuators with accumulators for energy recovery. The technology allows effective engine downsizing up to 50% and fuel savings of more than 50%.

Maha researchers have successfully continued the 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. A novel non-isothermal fluid structure interaction model coupled with a multi-body dynamic simulation model that considers elastic surface deformation due pressure and thermal load has been first-time verified by laboratory measurements for two of the pump interfaces. With the help of this new model, we discovered that the 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. This represents a major discovery, which explains why all pumps and motors working at extreme high pressures have to have a brass bushing in order to achieve a reliable operation and acceptable efficiency values. This discovery, together with the developed multi-physics model, forms the starting point for a new computational-based design approach. It will form a very important basis for the development of the next generation of highly efficient high pressure pumps and motors.

Our continued research activities and recent results generated a record in research funding with more than 2 million US$ in 2011. Our industrial funding was more than doubled with several major projects on displacement controlled actuator technology, new powertrain systems and computational pump design. Our achievements were also noted by several international visitors like the R&D team of Toyota and many other researchers and industrial partners when they toured the Maha research center last year.

The year 2011 also marked the successful defense and graduation of five of our master's students, Michael Cross, Roman Ivantysyn, Jess Rose, Brent Warr and Matt Kronlage. Michael started his career at Dynetics Incorporated in the Unmanned Systems and Aerodynamics Department. Roman went to Germany to begin his research at the Institute for Fluid Power at Technical University Dresden. Jess works as Product Engineer in the Siemens Graduate Program and Brent went to Idaho National Labs USA, where he continues his work on hydraulic hybrids as an advanced vehicles test engineer. Matt is now working for Sauer-Danfoss in Ames, Iowa. Also Ganesh Seeniraj left Maha in June 2001 to start his industrial carrier at LMS North America.

Despite the departures, the Maha team remains strong through hiring new graduate students and visiting scholars. Back in the fall, we welcomed four new PhD students. Dan Mizell from Michigan Technological University, Enrique Busquets from The University of Texas, Paul Kalbfleisch a Purdue Alumnus and Naseem Daher joined us after he had worked five years for TRW. The lab also enjoys the privilege of hosting visiting scholars from around the world. Tohoyto Uchizono, new to the lab in 2010, continued his stay here until returning to Japan in August of 2011. New for 2011, the Maha Lab welcomed Daniel Gronberg from Sweden. During the summer 2011 we again hosted three SURF students; Kilian Cooley, Cheng Lu and Jennifer Wu.

Jennifer continued her research at Maha during the fall semester. Finally, after the departure of Edat Kaya we were very happy to welcome Susan Gauger as a new Maha member last June.

I would like to thank all team members for their excellent work in 2011. 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 2012.

Dr. Monika Ivantysynova

Maha Professor Fluid Power Systems

Contents

1 Research Activities

The year 2011 was one of our most successful years, and saw the Maha Lab have the highest number of publications ever, and draw the highest amount of funding ever in research grants.
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 2011

- Prof. Ivantysynova and Josh Zimmerman proposed and filed a patent for a novel hydraulic hybrid circuit for DC multi-actuator machines. This new architecture allows 50% engine downsizing and additional fuel savings (upto 20%) over the non-hybrid DC excavator.

- A fully-coupled model of the piston-cylinder interface was developed by Matteo Pelosi. The model represents the first fully coupled fluid-structure interaction model that considers also thermal deformation of parts on fluid film behavior and pump performance. The model admitted the Maha team to discover that surface waviness through thermal expansion helps current high pressure pumps and motors to operate reliable.

- The first complete slipper deformation model for the slipper-swashplate interface of axial piston machines was developed by Andrew Schenk and presented at the 8th JFPS, International Symposium in Okinawa, Japan in October 2011. Andrew won the best paper award for his work.

- First time a methodology for pump design using a fully computational design approach was developed and presented in the Master thesis of Roman Ivantysyn this last spring.

- Andrew Schenk installed a 64-core research computing cluster, which enables design optimization and large-scale simulations in a timely fashion @ Maha.

- Michael Cross and Josh Zimmerman introduced successfully dynamic programming as a new method for dynamic sizing of components in hydraulic hybrid powertrain and multi-actuator DC systems, respectively. First results were published in Michael's Master's thesis (May 2011) and in the proceedings of the prestigious ASME–Bath Fluid Power Symposium by Josh in Washington, DC (November, 2011).

- Last spring senior design students have built a hydraulic hybrid system demonstrator to help explain the technology to the public.

Our research activities are focused in five main areas:

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

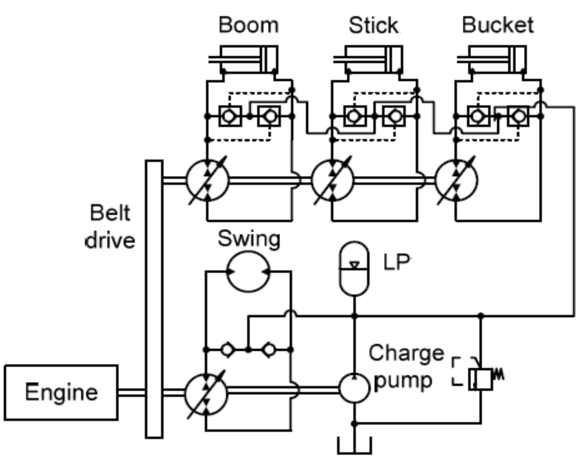
Research related to the first three listed areas is supported by the NSF through participation in the CCEFP and by several industrial partners. The other topics are funded by separate industry sponsors.

2. Research into efficient hydraulic actuation and drive systems

Advanced energy saving circuits for hydraulic actuation

This research area involves the development of novel valve-less hydraulic actuation concepts together with necessary motion control strategies, to ultimately improve system efficiency and fuel consumption in multi-actuator applications while maintaining or improving system productivity. The focus of this research has been on a concept known as "displacement control" (DC) in which the motion of a linear or rotary hydraulic motor is controlled directly by controlling the oil flow rate from a variable displacement axial piston pump. In addition displacement controlled actuation allows energy recovery in case of aiding loads or braking. In 1998 Displacement controlled linear actuation involving a single rod cylinder was first successfully tested in Professor Ivantysynova's Lab at Duisburg University in Germany. Since then much research effort has been spent to introduce these energy saving concepts into mobile machines like wheel loaders, skid-steer loaders, excavators and other machines.

In August 2010, fuel consumption and productivity measurements of the CCEFP prototype DC excavator (5-t) were conducted in co-operation with Caterpillar Inc. Through this study, measurements were taken on both a standard load-sensing (LS) system and the prototype system (Figure 1) performing a truck loading cycle. It was found that the DC machine used about 40% less fuel and about 13% less time than the standard system while performing the same task. These are landmark results showing that the DC system performs nearly 70% more work per fuel consumed. These measurements followed simulation of the DC excavator system wherein a fuel savings prediction of nearly 40% was made over the standard system.



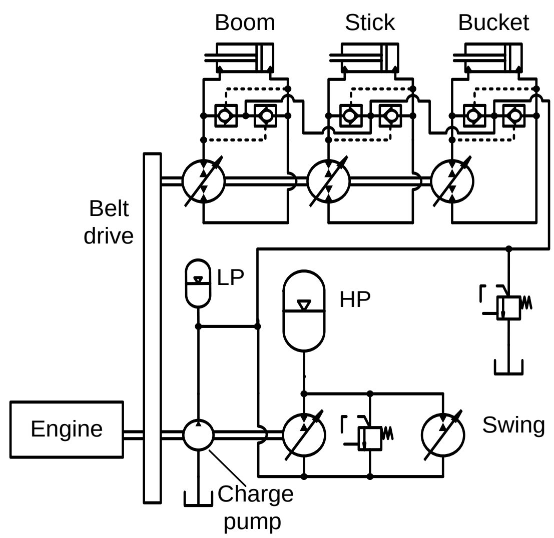


Figure 1: CCEFP Prototype DC Excavator **Figure 2: Hybrid Architecture for DC Excavator**

In the year 2011, DC actuation was extended to hybrid hydraulic systems (Figure 1). A novel hydraulic hybrid circuit, called the series-parallel hybrid, was proposed and investigated in simulation for multi-actuator applications. The circuit allows capture of energy from rotary actuators, and storage of energy in an accumulator, without requiring the addition of an extra pump/motor on the engine shaft. Simulations (Figure

3) predicted up to 52% fuel savings for the series-parallel hybrid DC excavator over the standard LS excavator, while allowing up to 50% engine downsizing, considering performance requirements of working actuators.

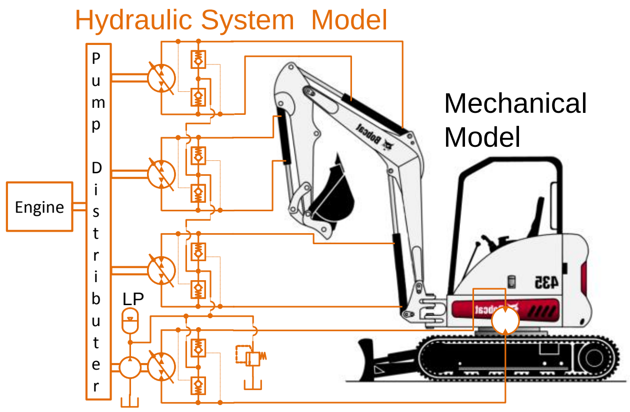


Figure 3: High Fidelity Co-simulation Model

For the series-parallel hybrid DC excavator, parameter variation studies were undertaken to find optimal designs for multi-actuator DC systems, in order to allow maximum fuel savings. This involved using dynamic programming results for any given design, and evaluating the designs in terms of fuel consumption (Figure 4). The design process was thus also made independent of control. Preliminary investigations were also undertaken to derive implementable power management schemes that replicate optimal control trends.

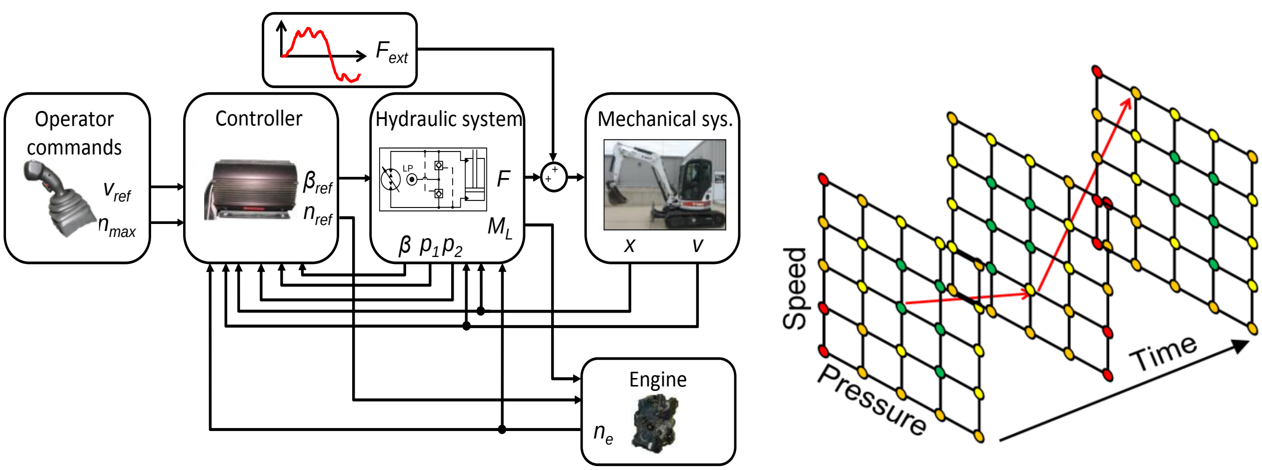


Figure 4: Power Management and Optimal Control for Efficient Operation

A project studying active vibration damping in DC skid steer loaders was also completed, showing a reduction of up to 33% in cab vibration when driving over rough terrain. 2011 is set to be another great year in this research as the focus moves from basic displacement control circuits to hybrid systems where the improvements are expected to be even greater.

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 2011 two theses were successfully completed in the area of hybrid drivetrains. First Michael Cross investigated using optimal control as an effective sizing tool. Optimal control, executed through dynamic programming, eliminates the effects of controller design on system performance. In turn this permits a fair comparison between various system architectures. Michael employed this technique to optimally size a vehicle by simulating a full DOE of 2000 system architectures. Such computationally intensive analysis has only recently been made possible through Maha's new Condor research cluster.

2011 also so the completion of Brent Warr's thesis titled 'Methodology for Designing a Hydraulic Hybrid Transmission for Real World Drive Data'. Brent installed data loggers in 4 parcel delivery trucks and collected over 500 hours worth of real world data. A methodology and tool for analyzing this real world data was developed and used to create an artificial, though representative, drive schedule. This drive schedule (Figure 5) was used to more accurately size a hydraulic hybrid transmission for a delivery vehicle.

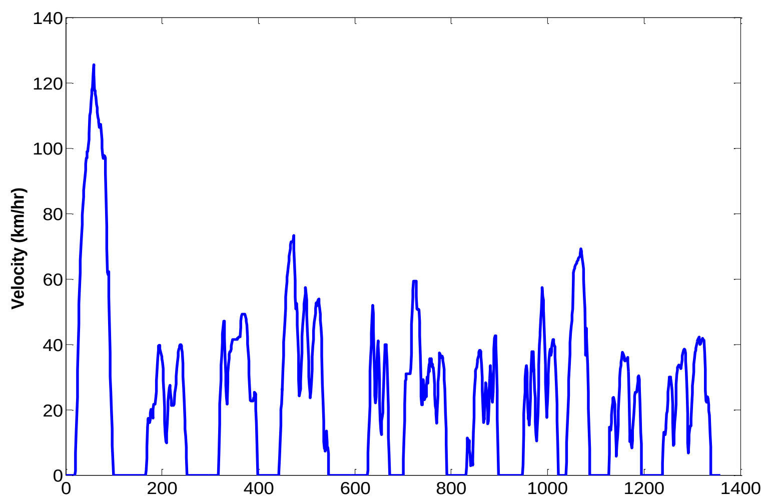


Figure 5: Statistically Derived Drive Schedule

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 6) 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.

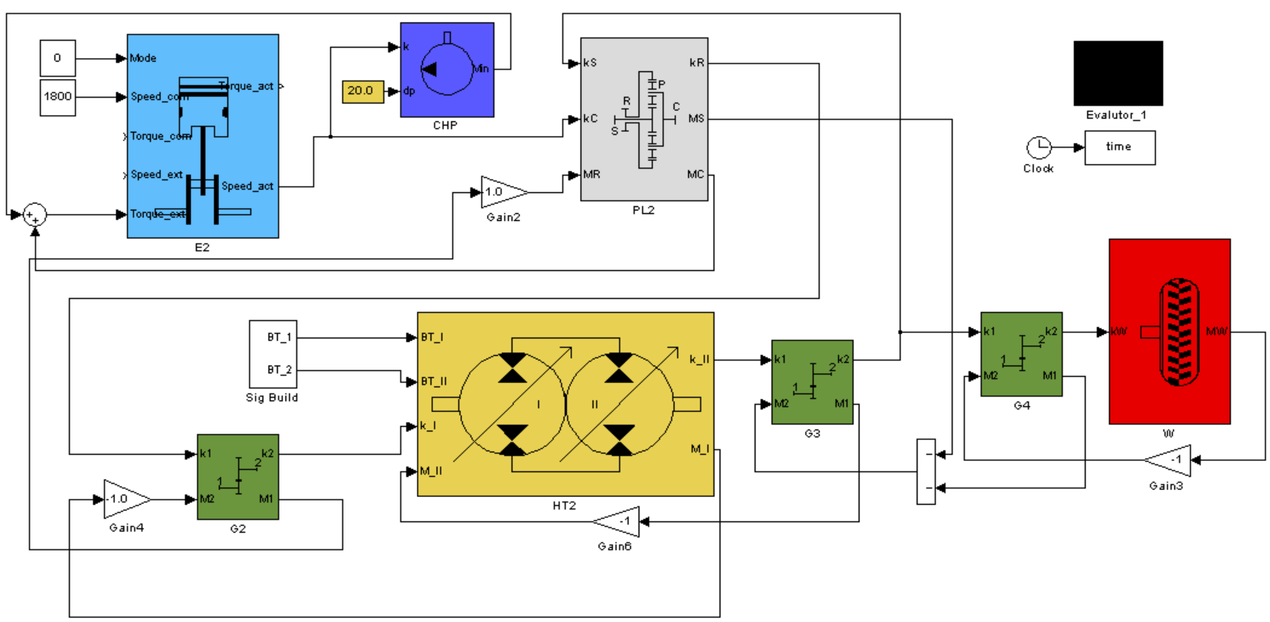


Figure 6: PSDD Simulation Model

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 model, to achieve a fundamental understanding of the complexity of physical effects taking place in displacement machines.

The simulation model focuses of the rotating kit of axial piston machines, since it represents the most important component. In particular the 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 are 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 a 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 of 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 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 7. 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:

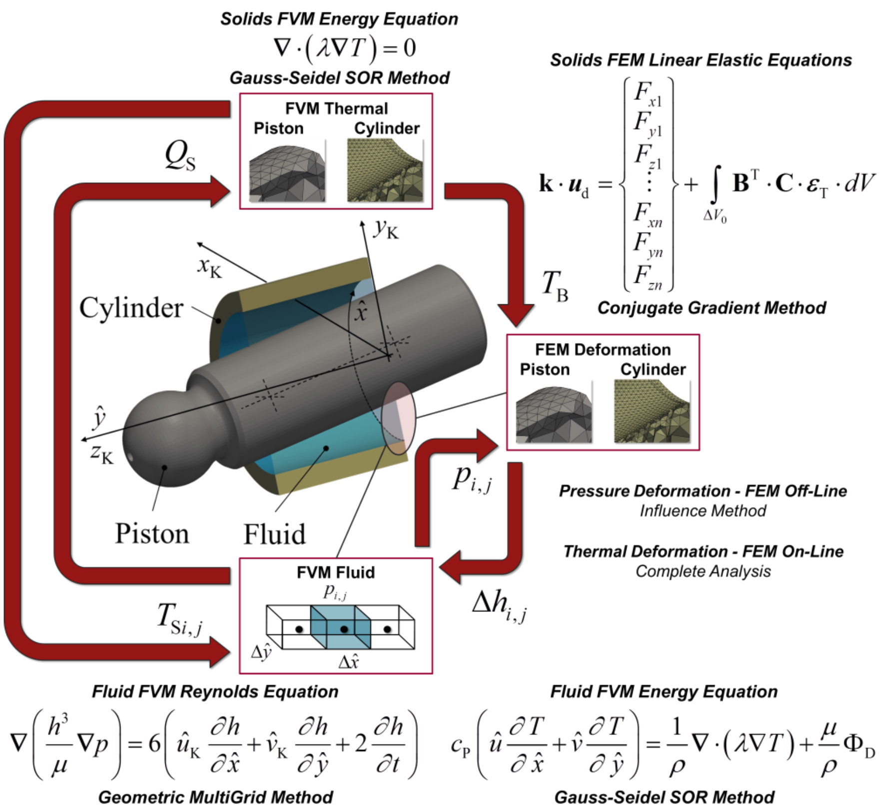


Figure 7: Piston/cylinder interface fluid structure interaction and thermal model

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 importing 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.

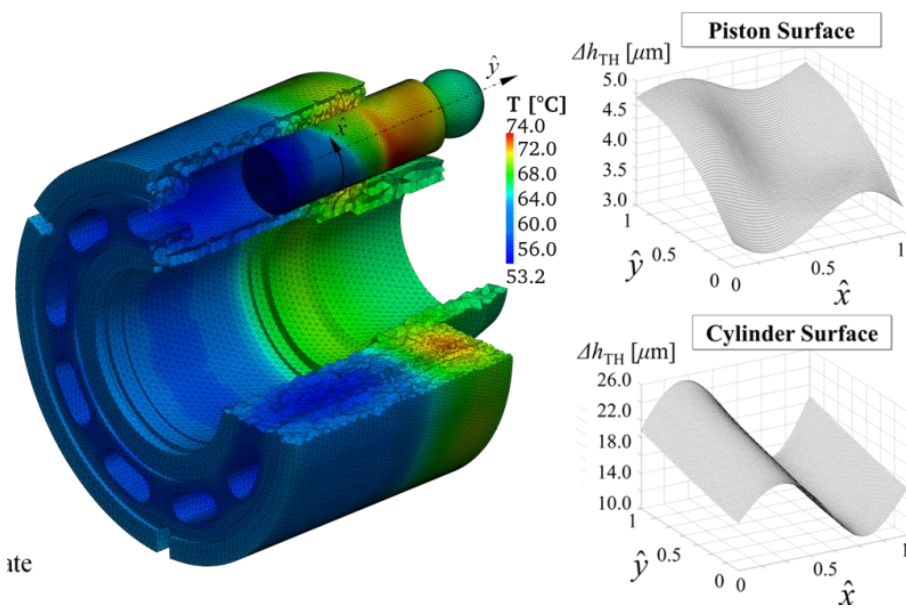


Figure 8: Axial piston machine piston/cylinder block temperature distribution (left) and surface thermal deformations for a high load operating condition (right)

Recently, Maha researchers discovered that the 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 8. This represents a major discovery, which 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.

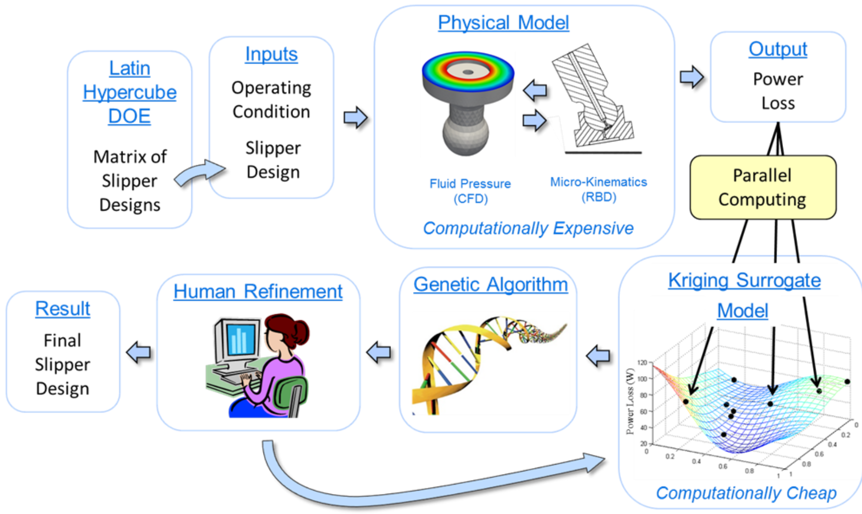
The discovery together with the developed multi-physics model forms the starting point for a new computational based design approach. It will form a very important basis for the development of the next generation of highly efficient high pressure pumps and motors. The model will be used to investigate 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

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 9). The numerical model is similar in principal to the models used in the cylinder-block and piston-cylinder interface in that it considers the micro-motion force balance of the slipper, the lubricating fluid film pressure, and non-isothermal effects of the fluid. 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

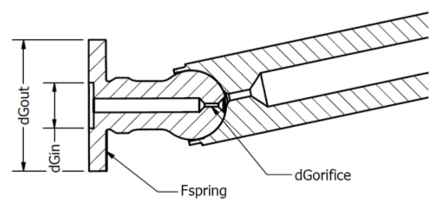


Figure 9: Optimization Methodologies for Slipper Design

Further work was also made on advancing the Fluid-Structure-Interaction model of the slipper swashplate interface. Similar to the other two lubricating interfaces, the deformation calculation is now made using an unstructured tetrahedral mesh and flexible interpolation between fluid and solid grids. This allows simulation of complex geometry bodies and can capture the global deformation accurately. The new model considering fully coupled pressure deformation was compared with the old rigid model on an 18cc pump with a specific focus on looking at the changes in predicted power loss. This work was presented in a paper at the 2011 JFPS and won a best student paper award. An overview illustration of the deformation comparison between models and selected power loss results is presented in Figure 10.

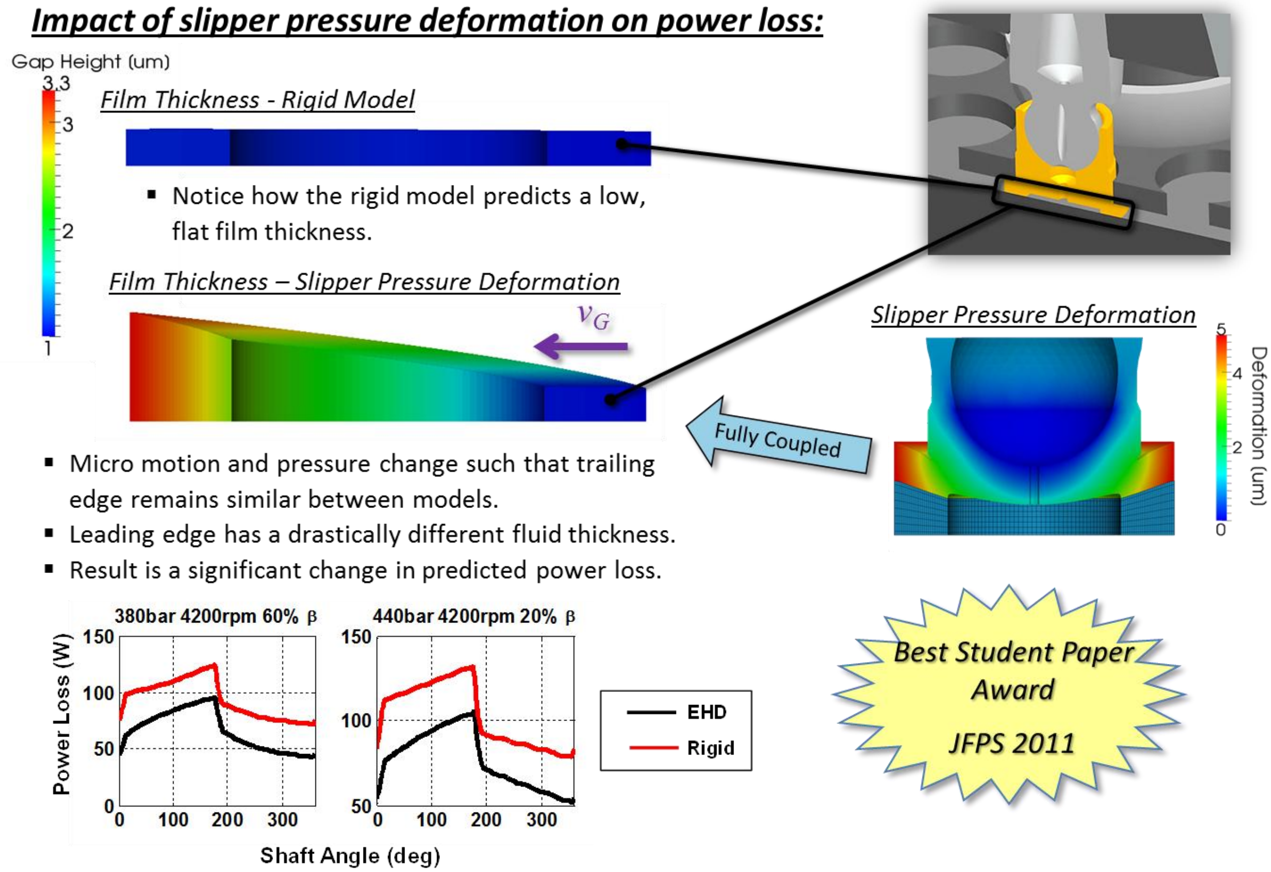


Figure 10: Impact of Slipper Pressure Deformation on Power Loss

Cylinder block / valve plate interface

The cylinder block / valve plate interface model has been further expanded this year and is now able of coupling together elasto-hydrodynamic and thermal effects. The structure of the new model is shown in Figure 11. Three 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.

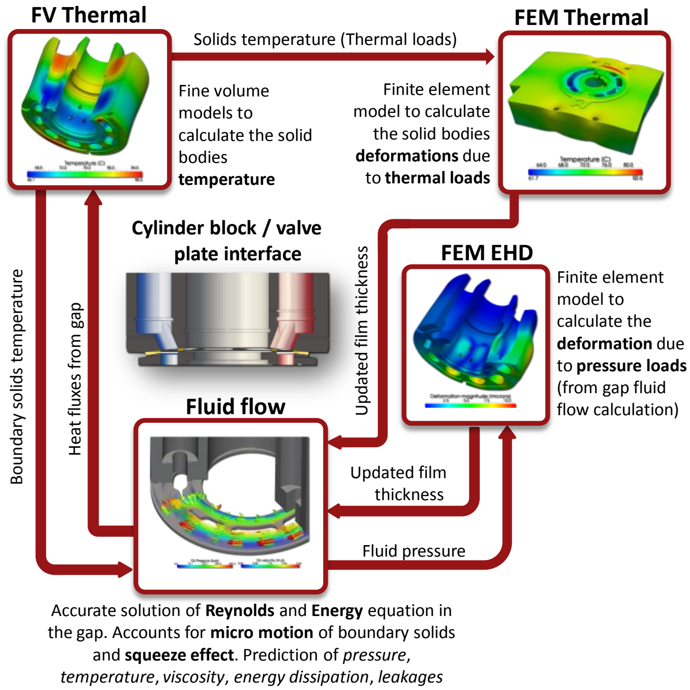


Figure 11: Cylinder block / valve plate interface fluid structure interaction model

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 with the FEM solver. Since the thermal problem is assumed to be "quasi-stationary" the thermal analysis is carried out just once per revolution. 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 developed cylinder block / valve plate interface model has been used to investigate the thermal behavior of the interface: Figure 12 shows the comparison of the simulated and measured valve plate surface temperature.

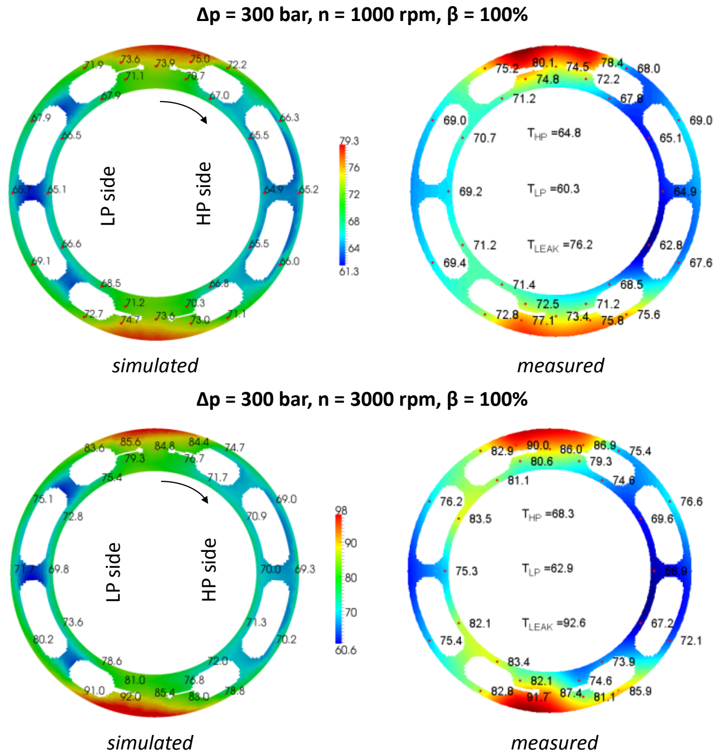


Figure 12: comparison of simulated and predicted valve plate surface temperature

The current model have shown a substantial improvement in accuracy respect the past and is much more mature to be used for practical computational design.

New micro-surface shapes study

One of the main activities of the center towards the improvement of current swash plate type axial piston machines is the investigation of micro-surface shaping and novel material combination in relation to the 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 it was introduced a waved like 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 in the center, in order to achieve the maximum performance. The study have shown the possibility to improve up to 60% the efficiency of the cylinder block / valve plate interface respect 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. The center has also worked on the study of waved like micro-surface shaping on the pistons surface (Filed patent: 61/165, 661). Even in this case, simulations have shown a potential improvement up to 60%.

These results represented a major breakthrough in this research direction and suggested a deeper study of the new technology; in particular the center has been investigating the impact of micro-surface shaping on the lubricating interfaces performance through the new fully coupled fluid structure interaction model. The new model is able to provide much more accurate predictions and therefore it allows a better optimization of the micro-surface shaping design.

Computational design of swash plate type axial piston pumps

For the first time, this year the Maha research center proposed a computational based design methodology for swash plate type axial piston machines. The methodology is divided in three design phases; preliminary design, computational design and computational based design optimization.

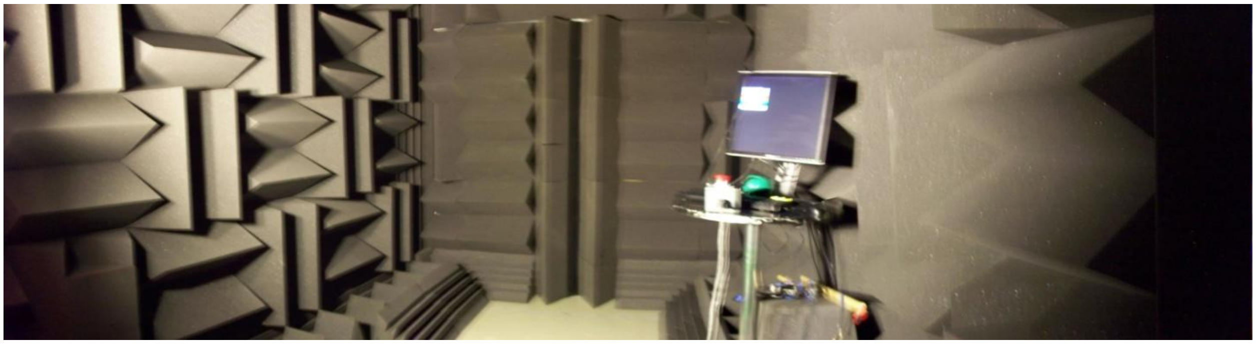
The preliminary design is based on basic calculations that are based on textbook methods and empirical equations similar to the methods used in traditional pump design.

Phase two incorporates the computational design. A methodology has been developed to use these two phases in order to develop a pump from start to finish. The computational part of the design process is based on the use of the complex interface models developed recently at Maha for the piston cylinder, the slipper swash plate and the cylinder block / valve plate interface. The valve plate design and optimization is conducted using the in house developed design software VpOptim.

An optional phase three allows an optimization loop after design phase two. This can be used to allow for studying the influence of new part and surface shapes and new materials on pump performance and efficiency. In order to test the proposed methodology, an example pump was developed. The proposed new design approach can replace the current trial and error process and will hopefully lead to better designed pumps, that achieve higher efficiencies and use new materials and or coatings. The use of sophisticated computer models will give the designer much better understanding of the influence of individual design parameters on the pump behavior than the current trial and error approach.

The methodology was tested through the design of the rotating group of a 24cc pump, demonstrating that the proposed approach is feasible and even a non-experienced pump designer can create a design that has better performance and is more compact than existing industrial standards.

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.

A major milestone of 2011 was a detailed case study of valve plate optimization focusing on noise reduction with high volumetric efficiency. This case study involved pre-compression filter volume to reduce both FBN and SBN with high volumetric efficiency in a wide range of operating conditions.

VpOptim

The first approach aims to reduce noise generation at the source (FBN and SBN) level i.e. directly from the pumps and motors. A multi-parameter multi-objective optimization procedure has been developed to reduce sources (FBN and SBN) of noises from pumps and motors which operate in a wide range of operating conditions (Figure 13). The optimization procedure has been implemented as design software (VpOptim) which assists a pump designer in a search towards an optimal rotating group design which will have the minimum possible noise sources in a wide range of operating conditions.

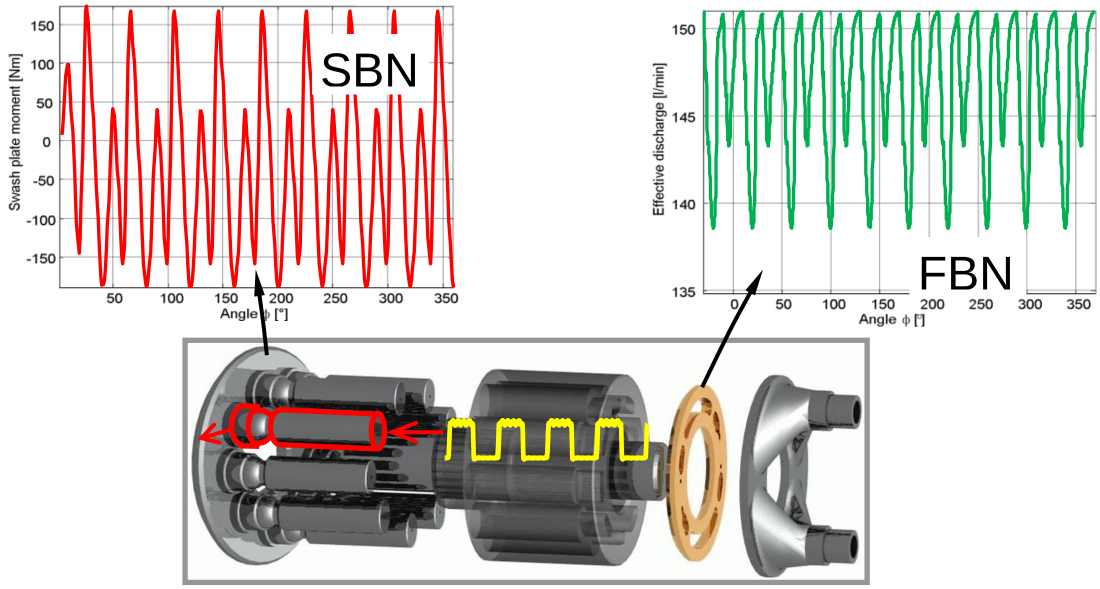


Figure 13: Axial piston pump showing the fluid borne and structure borne noise sources

VpOptim stands for Valve plate Optimization. VpOptim is designed to make the most of two reduction techniques. The program enables relief grooves and precompression filter volume with relief grooves to be optimized. These two reduction techniques have several variables which influence the time dependent area available for flow between the displacement chamber and the pump's external ports. The parameters of the reduction techniques are subjected to a Multi Objective Genetic Algorithm (MOGA) to select an optimum area profile which will have the minimum possible FBN and SBN over a wide range of operating conditions (Figure 14).

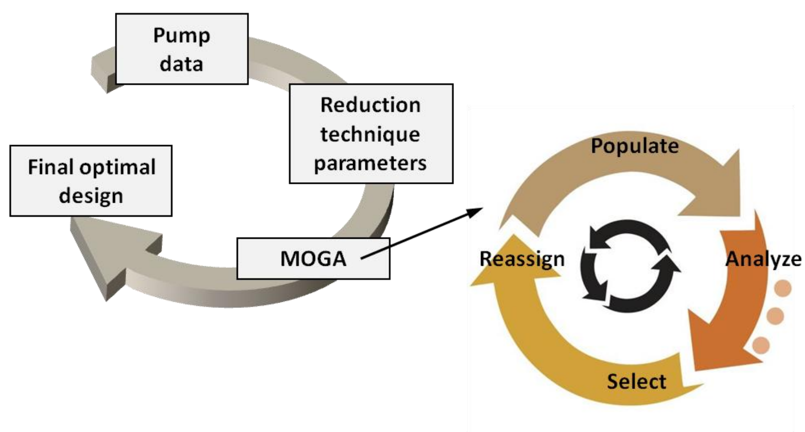


Figure 14: Schematic of the process flow inside VpOptim

TransModel

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

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, see Figure 15. 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.

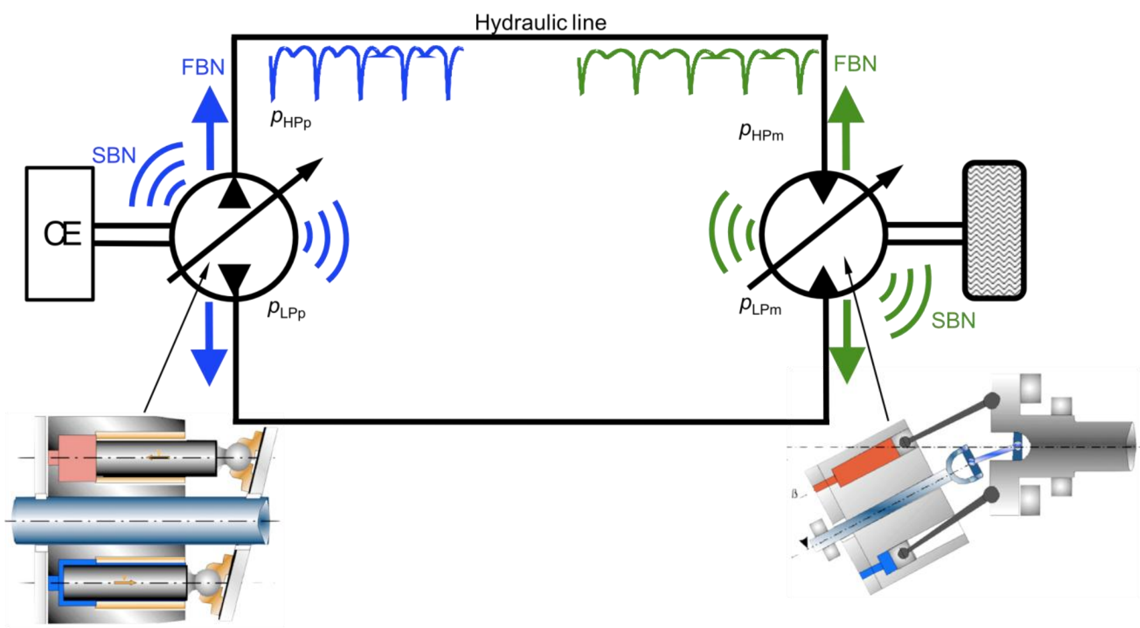
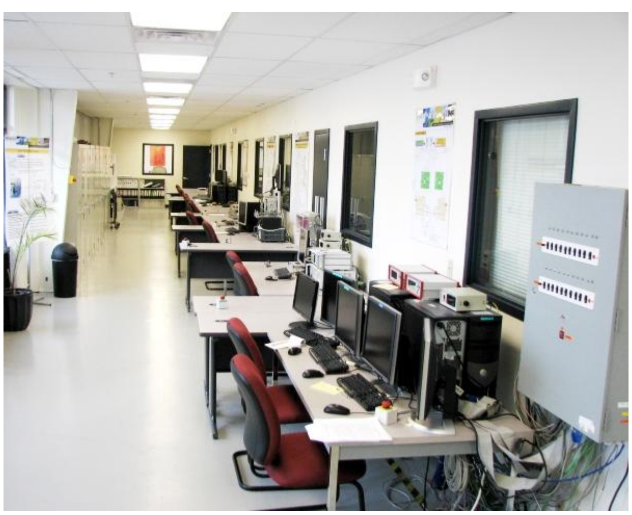


Figure 15: Schematic of hydrostatic transmission implemented in TransModel

2 Research Facilities

Lab Space and Test Rigs at Maha The lab currently houses ten test rigs designed to support our research.

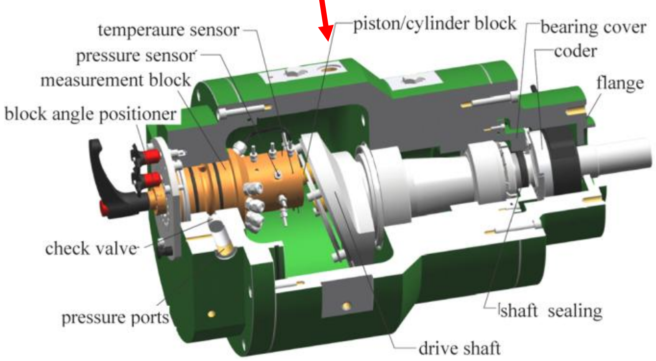
Test Beds for Technological Demonstration (Above)

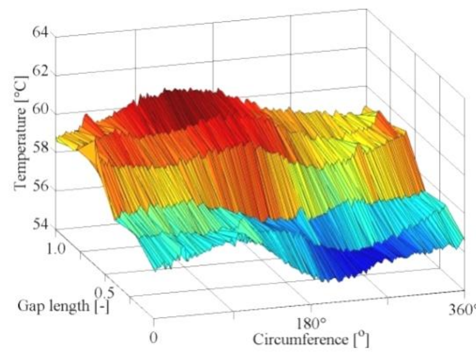


Test Rigs and Control Room (Above and Left)

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.



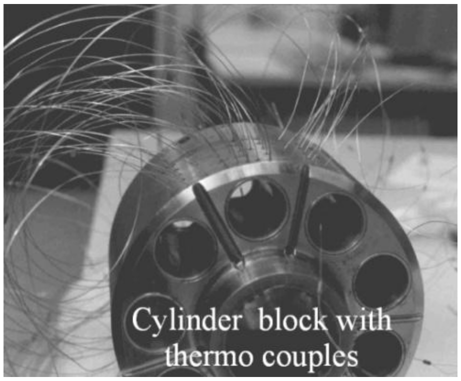


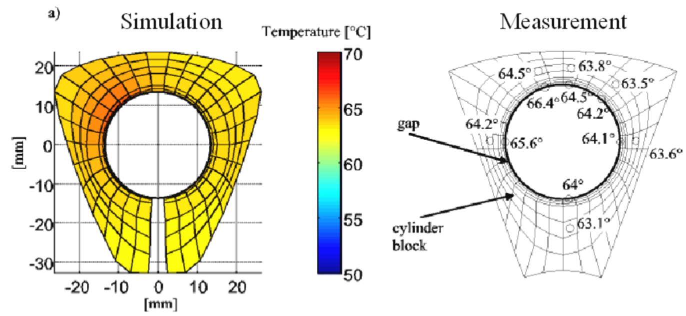
Measured Temperature Field in the Piston/Cylinder Gap

EHD Pump

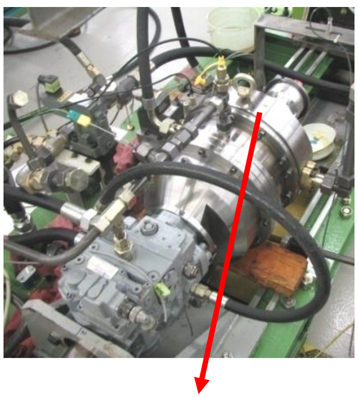
OLEMS test rig

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.



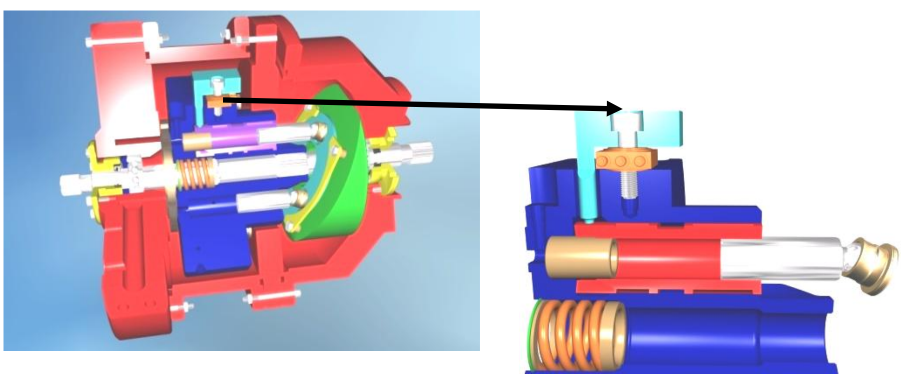


Temperature distribution in the assembly near the slipper slide

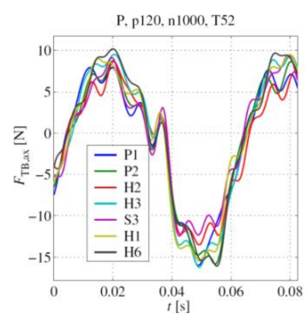


Tribo test rig

The heart of the test rig, the Tribo pump, is designed to measure the dynamic axial and the circumferential friction force between the piston and cylinder. The data can be processed during high speed using a telemetry system. The Tribo pump can be operated in either pumping or motoring mode from 1 rpm up to 1800 rpm. The measurements can be taken during steady state conditions at different oil viscosities.



Tribo pump - Hydrostatic bearing (red)



Cavitation/PIV test rig

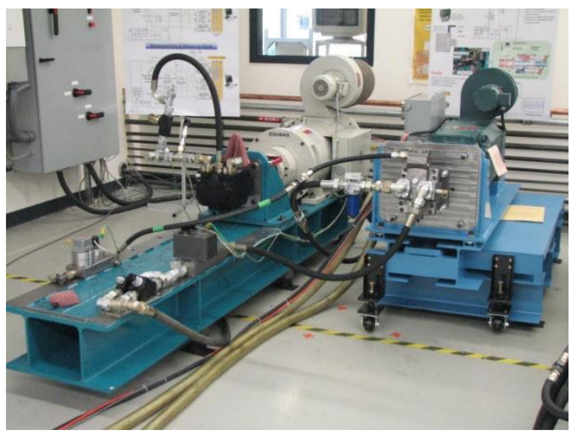
This test rig was designed to visualize and conduct Particle Image Velocimetry (PIV) analysis of cavitation in hydraulic oil. This test rig was designed in support of CCEFP project 3C and will support the computational studies in modeling cavitation in hydraulic components.

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

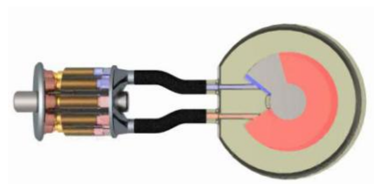
The joint integrated rotary actuator test rig (JIRA) has been built for experimental investigations of displacement controlled rotary actuators for use as end effector drives in mobile robots and large manipulators. The developed system and control concepts can also be used for applications such as stabilizers in cars or ships.

Performance

Max. Torque: 30000 Nm

Max. Pressure: 350 bar

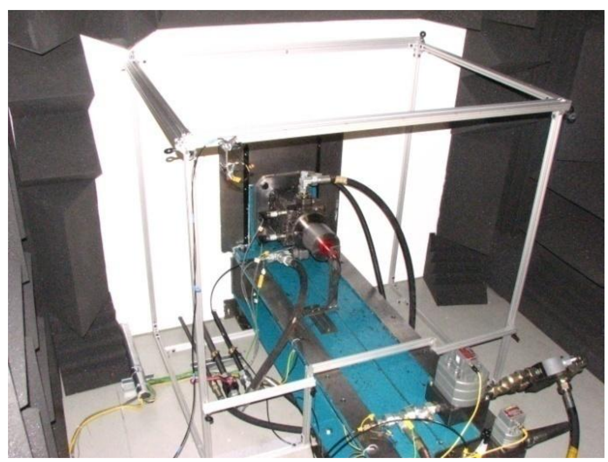
Max. Power: 30 kW



Rotary Actuator

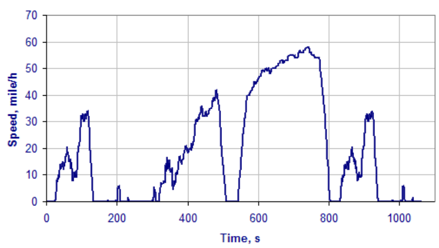
Semi-Anechoic Chamber

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. Enabling 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 (Fig. 1, left) 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 intentional 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 is possible all increasing the accuracy and confidence of the developed numerical models. Contrary to conventional industry belief, waviness of the solid bodies actually reduces the power loss and improves lubrication, and patent applications have been filed for introducing waviness on the fluid film surfaces. To prove these claims, a prototype valve plate was manufactured with a micro-wave (Fig 1. Right Top) and when compared to the original design inside a hydraulic pump, it measured a 10% reduction in power loss under moderate operating conditions. The profilometer enables measurement of the 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.

(Left) The Mitutoyo stylus surface profilometer.
(Right Top) A manufactured waved valve plate.
(Right Bottom) Exaggerated illustration of a micro-wave shaped piston.

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. 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, Condor (http://research.cs.wisc.edu/condor/), 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. Condor 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 Condor 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. Shown below on the left is a graph of the total thousand CPU hours consumed each month for the past year using the Condor job system and the right is a photograph of the physical Maha computing cluster.

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).

In Summer 2011, a fault-detection and display system was conceptualized and implemented by Cheng Lu, an undergraduate researcher. Additionally, collaboration with Georgia Tech. led to the implementation and testing of a phantom operator interface on the test-bed.

3 Research Grants

Research Grants obtained in 2011: $2,183,576

Funding from CCEFP: $793,706

Engineering Research Center (ERC) for Compact and Efficient Fluid Power (CCEFP). NSF + affiliated-industry funds, 6th year funding $793,706

Funding from Industry Projects: $ 1,389,870

- Advanced Energy Saving Hydraulic System Architecture for a Wheel Loader
- Displacement Control System Implementation and Machine Testing on a Large Excavator
- Analysis of Pump Noise Sources
- Modeling and Analysis of the Cylinder Block/Valve Plate and Slipper/Swash Plate Interfaces of an Axial Piston Pump
- CASPAR Dynamic Model Development
- Efficiency Measurements on a Unique Axial Piston Pump

Maha was announced part of the Hoosier Heavy Hybrid Center of Excellence (H3CoE), funded by the US Department of Energy and established in October 2011.

Maha led the initiative for a new NSF funded Science and Technology Center on Water-Based High Pressure Systems. The preliminary proposal, which covered a research partnership between researchers from Purdue, UC Berkeley, UC Irvine, UC Santa Barbara, North Carolina AT&T State University and Argonne National Labs was submitted to NSF on May 1, 2011. Despite a very good overall evaluation, the proposal was not selected for funding.

4 Publications, Patents and Reports

Journal Articles

Seeniraj, G. and Ivantysynova, M. 2011. A Multi-Parameter Multi-Objective Approach to Reduce Pump Noise Generation. International Journal of Fluid Power, Vol. 12, No. 1, pp. 7 - 17.

Kumar, R. and Ivantysynova, M. 2011. An Instantaneous Optimization Based Power Management Strategy to Reduce Fuel Consumption in Hydraulic Hybrids. International Journal of Fluid Power, Vol. 12, No. 2, pp. 15 - 25.

Seeniraj, G. K., Zhao, M. and Ivantysynova, M. 2011. Effect of Combining Precompression Grooves, PCFV and DCFV on Pump Noise Generation. International Journal of Fluid Power, Vol. 12, No. 3, pp. 53 - 64.

Klop, R. and Ivantysynova, M. 2011. Investigation of Noise Sources on a Series Hybrid Transmission. International Journal of Fluid Power, Vol. 12, No. 3, pp. 17 - 30.

Pelosi, M. and Ivantysynova, M. 2012. A Geometric Multigrid Solver for the Piston/Cylinder Interface of Axial Piston Machines. Tribology Transactions, in print.

Conference Proceedings

Zimmerman, J. and Ivantysynova, M. 2011. Hybrid Displacement Controlled Multi-Actuator Hydraulic Systems. Proceedings of the 12th Scandinavian International Conference on Fluid Power, May 18-20 2011, Tampere, Finland, pp 217 - 233.

Hippalgaonkar, R., Zimmerman, J. and Ivantysynova, M. 2011. Investigation Of Power Management Strategies For A Multi-Actuator Hydraulic Hybrid Machine System. SAE 2011 Commercial Vehicle Engineering Congress, Sep 13-14 2011, Rosemont, IL, USA. SAE Technical Paper 2011-01-2273

Schenk, A. and Ivantysynova, M. 2011. An Investigation of the Impact of Elastohydrodynamic Deformation on Power Loss in the Slipper Swashplate Interface. 8th JFPS International Symposium on Fluid Power, Okinawa, Japan.**- Best paper award.**

Pelosi, M. and Ivantysynova, M. 2011. Surface Deformation Enables High Pressure Operation of Axial Piston Pumps. ASME/Bath Symposium on Fluid Power and Motion Control, Arlington, VI, USA.

Zimmerman, J., Hippalgaonkar, R. and Ivantysynova, M. 2011. Optimal Control for the Series-Parallel Displacement Controlled Hybrid Excavator. ASME/Bath Symposium on Fluid Power and Motion Control, Arlington, VI, USA.

Cross, M. and Ivantysynova, M. 2011. Practical Considerations for Pump / Motor Selection in Hydraulic Hybrid Vehicles. Proceedings of the 52nd National Conference on Fluid Power 2011, NCFP I11-2.3

Pelosi, M. and Ivantysynova, M. 2011. The Influence of Pressure and Thermal Deformation on the Piston/Cylinder Interface Film Thickness. Proceedings of the 52nd National Conference on Fluid Power 2011, NCFP I11-9.3

Rose, J. and Ivantysynova, M. 2011. A Study of Pump Control Systems for Smart Pumps. Proceedings of the 52nd National Conference on Fluid Power 2011, NCFP I11-27.1

Schenk, A. and Ivantysynova, M. 2011. Design and Optimization of the Slipper-Swashplate Interface Using an Advanced Fluid Structure Interaction Model. Proceedings of the 52nd National Conference on Fluid Power 2011, NCFP I11-4.2

Zecchi, M. and Ivantysynova, M. 2011. A Novel Fluid Structure Interaction Model for the Cylinder Block/Valve Plate Interface of Axial Piston Machines. Proceedings of the 52nd National Conference on Fluid Power 2011, NCFP I11-9.2

Zimmerman, J., Busquets, E. and Ivantysynova, M. 2011. 40% Fuel Savings by Displacement Control Leads to Lower Working Temperatures - A Simulation Study and Measurements. Proceedings of the 52nd National Conference on Fluid Power 2011, NCFP I11-27.2

Invited Lectures

Ivantysynova, M. Modeling and Optimization of Piston Pumps and Motors. 52nd National Conference on Fluid Power. March 23-25, 2011. Las Vegas, NV. - **Keynote Address**

Ivantysynova, M. Displacement Control - The Future of Fluid Power Systems. 4th ICMEM International Conference on Mechanical Engineering and Mechanics. Aug 10-12, 2011. Suzhou, P. R. China, pp. 21-30. – **Address**

Patents Awarded

US Patent No. 7,896,125 – “Hydraulic Steering Device For Vehicles” (Ivantysynova, M., Weber, J., Grabel, J.)
US Patent No. 7,942,208 - "System and method for blade level control of earth-moving machines" (Hughes, E., Williamson, C., Zimmerman, J. and Ivantysysnova, M.)

Patents Filed

U.S. Provisional Patent Application Serial No. 61/453,368 – “Multi-Function Machine And Hydraulic System Thereof” (Ivantysynova, M and Zimmerman, J.)

Research Reports

Ivantysynova, M. and Klop, N. 2011. *Modeling and Analysis of a Swash Plate Type Axial Piston Unit Piston/Cylinder and Slipper/Swash Plate Interface.* Maha Fluid Power Research Center. Research Report MAHA01-2011-ex.

Ivantysynova, M. and Sprengel, M. 2011. *Advanced Energy Saving Hydraulic System Architecture for Wheel Loaders – Pilot Study.* Maha Fluid Power Research Center. Research Report MAHA03-2011-ex.

Ivantysynova, M. and Pelosi, M. 2011. *CASPAR piston-Cylinder Balance.* Maha Fluid Power Research Center. Research Report MAHA04-2011-ex.

Ivantysynova, M. and Zhao, M. 2011. *Investigation of Configurations of Parasitic Demands for a Transit Bus Hydraulic Hybrid.* Maha Fluid Power Research Center. Research Report MAHA05-2011-ex.

Ivantysynova, M. and Sprengel, M. 2011. *Running the Steady State Measurement Test Rig.* Maha Fluid Power Research Center. Research Report MAHA06-2011-in.

Ivantysynova, M. and Hippalgonkar, R. 2011. *Bobcat Excavator Ride & Drive Feedback.* Maha Fluid Power Research Center. Research Report MAHA07-2011-in.

Ivantysynova, M. and Zimmerman, J. 2011. *Effect of Sample Rate on Dynamic Programming.* Maha Fluid Power Research Center. Research Report MAHA08-2011-in.

Ivantysynova, M. and Sprengel, M. 2011. *Efficiency Measurements of an Axial Piston Pump.* Maha Fluid Power Research Center. Research Report MAHA09-2011-ex.

Ivantysynova, M. and Busquets, E. 2011. *NI cRIO-9074 IP Settings and NI VeriStand New Project Instructions.* Maha Fluid Power Research Center. Research Report MAHA10-2011-in.

Ivantysynova, M. and Kim, D. 2011. *Running Improvement of Roman's Valve Plate by Using Pre-CompressionFilter Volume.* Maha Fluid Power Research Center. Research Report MAHA11-2011-in.

Ivantysynova, M. and Zhao, M. 2011. *Running the Powertrain Test rig.* Maha Fluid Power Research Center. Research Report MAHA12-2011-in.

5 Theses Completed In 2011

Master's Theses

Cross, Michael. 2011. Optimal Control : An Effective Method for Sizing Hybrid Hydraulic Vehicles.

Warr, Brent. 2011. Methodology for Designing a Hydraulic Hybrid Transmission from Real World Drive Data.

Ivantysyn, Roman. 2011. Computational Design of Swash Plate Type Axial Piston Pumps - A Framework for Computational Design.

Rose, Jess. 2011. Pump Adjustment System Design for Displacement Control.

Kronlage, Matt. 2011. Displacement Controlled Excavator with CAN Bus Control.

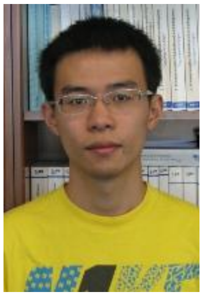
6 International Co-operation

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

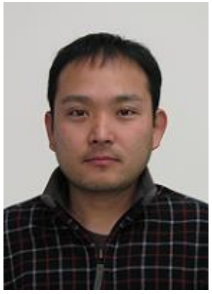
In 2011, the following international students and researchers have worked in our team

Daniel

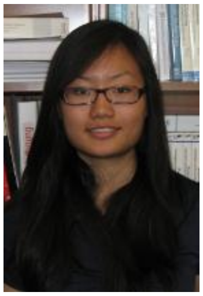


Cheng

Amin



Touohito



Jennifer

Junwei

Daniel Grönberg, Sweden

Cheng Lu, Purdue University (lu108@purdue.edu)

Amin Mehdizadeh, Iran (amehdiza@purdue.edu)

Toyohito Uchizono, Japan (Tuchizono@purdue.edu)

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

Junwei Zhang, China (zjw36927@163.com)

7 International and National Conferences Attended

12th Scandinavian International Conference on Fluid Power. Tampere, Finland, May 18-20, 2011.

5th CCEFP Annual Meeting. (Held in conjunction with the 52nd National Conference on Fluid Power), Mar 22-25 2011, Las Vegas, NV, USA.

Attendees:

Monika Ivantysynova (**Keynote Address :** Modeling and Optimization of Piston Pumps and Motors)

Michael Cross (Paper Presentation and Poster Presentation)

Rohit Hippalgaonkar (Poster Presentation)

Matteo Pelosi (Paper Presentation and Poster Presentation)

Jess Rose (Paper Presentation)

Andrew Schenk (Paper Presentation and Poster Presentation)

Marco Zecchi (Paper Presentation)

Josh Zimmerman receiving the best poster award and the 5th Annual CCEFP Meeting

4th ICMEM International Conference on Mechanical Engineering and Mechanics, Aug 10-12, 2011. Suzhou, P. R. China.

Attendees:

Monika Ivantysynova (**Keynote Address :** Displacement Control - The Future of Fluid Power Systems)

SAE 2011 Commercial Vehicle Engineering Congress, Sep 13-14 2011, Rosemont, IL, USA

Attendees:

Monika Ivantysynova

Rohit Hippalgaonkar (Presenter)

8th JFPS International Conference on Fluid Power, Oct 14-15 2011, Okinawa, Japan.

Attendees:

Monika Ivantysynova

Andrew Schenk (Presenter, **Best Paper Award**)

Andrew Schenk receiving the best paper award during the 8th JFPS International Conference on Fluid Power

Bath/ASME Symposium on Fluid Power & Motion Control (FPMC 2011). Oct 29 – Nov 1, 2011. Bath, UK.

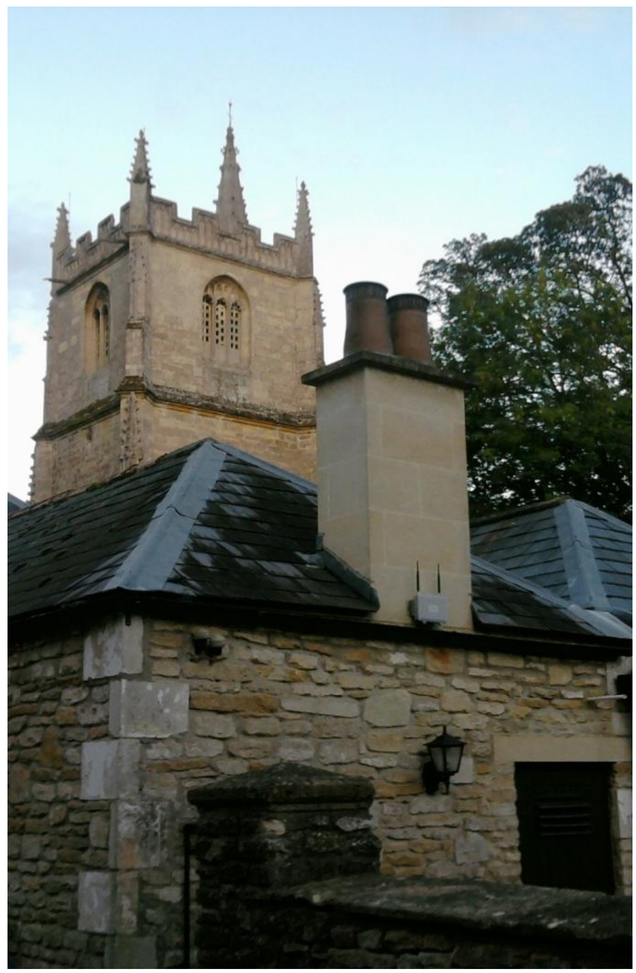
Attendees:

Monika Ivantysynova

Matteo Pelosi (Presenter)

Joshua Zimmerman (Presenter)

FPM2011



8 CCEFP Annual Meeting

The CCEFP annual meeting this year was held March 22-25 in conjunction with CONEXPO-CON/AGG and the International Fluid Power Exposition (IFPE), 2011 held at Las Vegas, Nevada. This trade show/conference is one of the largest of its kind worldwide and takes place every three years. Enormous crowds are drawn in from the construction and agriculture industries around the world. Amidst all of this the CCEFP was highlighted as a premiere research center focused on advancing fluid power technology. The CCEFP had a booth for showcasing its research advancements and front in center in this booth was the prototype displacement controlled excavator system designed and built by researchers from the Maha Fluid Power Research Center. The CCEFP prototype excavator, which is a project led and driven by Maha, had demonstrated an impressive 40% fuel savings in independent side-by-side measurements with a standard 5-t excavator, in August 2010 at a Caterpillar facility. At IFPE 2011, it attracted a lot of attention from both industry as well as academia. It was show-cased at a central location, and was the main draw among all CCEFP exhibits.

In addition to hosting a booth at the convention, CCEFP researchers played a major role in IFPE, the academic half of the convention. Presentations at the meeting included presentations concerning the 4 CCEFP test beds together with individual research project presentations. Numerous publications were also presented, and Maha was well represented in the proceedings as the following list of presentations and posters attests.


CHATEAU
MANILOW


PURDUE
Bobcat

Presentations

- ‘ Practical Considerations for Pump / Motor Selection in Hydraulic Hybrid Vehicles’, Mac Cross (Master’s Student)
- ‘The Influence of Pressure and Thermal Deformation on the Piston/Cylinder Interface Film Thickness’, Matteo Pelosi (PhD Student)
- A Study of Pump Control Systems for Smart Pump‘, Jess Rose (Master’s Student)
- ‘Design and Optimization of the Slipper-Swashplate Interface Using an Advanced Fluid Structure Interaction Model’, Andrew Schenk (PhD Student)
- ‘A Novel Fluid Structure Interaction Model for the Cylinder Block/Valve Plate Interface of Axial Piston Machines’, Marco Zecchi (PhD Student)
- ‘40% Fuel Savings by Displacement Control Leads to Lower Working Temperatures - A Simulation Study and Measurements’, Josh Zimmerman (PhD Student)

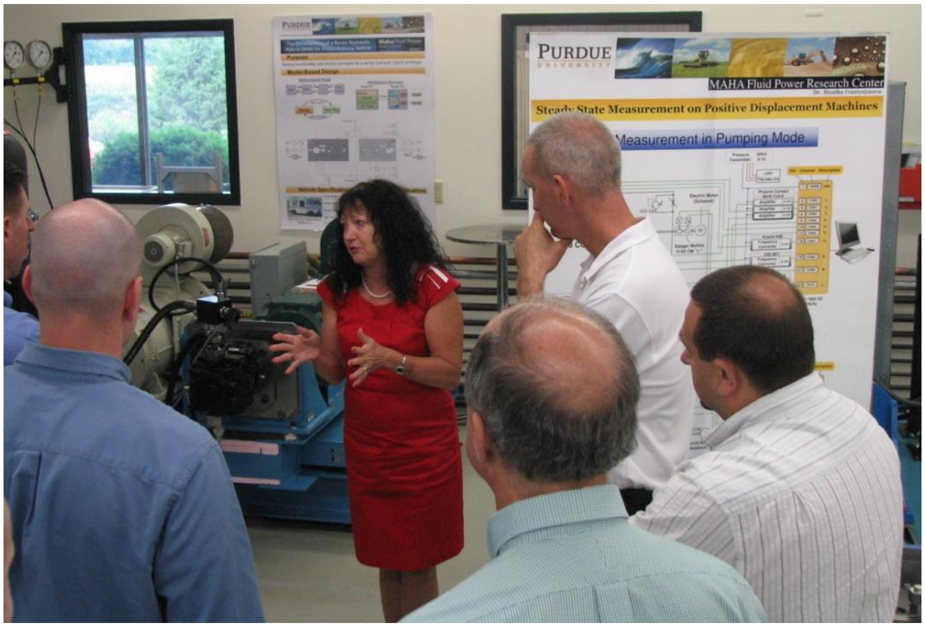
Posters

- CCEFP Project 1A.2: Multi-Actuator Hydraulic Hybrid Machine Systems, Rohit Hippalgaonkar (PhD Student)
- CCEFP Project 1B.1: New Material Combinations and Surface Shapes for the Main Tribo-systems of Piston Machines, Matteo Pelosi , Andrew Schenk and Marco Zecchi (PhD Students)
- CCEFP Test-bed 1: Heavy Mobile Equipment - High Efficiency Excavator, Josh Zimmerman (PhD Student)

9 IAB Meeting

Several times a year the CCEFP's Industrial Advisory Board (IAB) meets to evaluate progress and give the Center direction. This past September the Maha lab hosted a combined IAB meeting and site visit. The two day event held 9/13-14 involved presentations from Purdue and UIUC researches along with lab tours and a dinner.

Presentations during the IAB meeting



Monika explaining the series hybrid transmission test rig

Andrew showing of the tribo test rig

Josh discussing displacement controlled actuation

Dinner for IAB members and researchers

10 Awards, Honors, and Recognitions

Best paper award

Schenk, A. and **Ivantysynova, M.** 2011. An Investigation of the Impact of Elastohydrodynamic Deformation on Power Loss in the Slipper Swashplate Interface. 8th JFPS International Symposium on Fluid Power, Oct. 14-15, Okinawa, Japan.

Best Poster award

Josh Zimmerman. 2011. Test-Bed 1. 5th Annual CCEFP Meeting in conjunction with the 52nd National Conference on Fluid Power, Mar 22-25, Las Vegas, NV, USA.

Maha in the News

Interest in Maha's research extends beyond the hydraulic industry and academia. In July Paul Heney from Design World visited the Maha Research Center and wrote a two part article about ongoing research and resent discoveries.

11 Educational Activities

CCEFP : Education and Outreach

Another mission of the CCEFP is educational outreach through programs that promote the teaching of science and technology concepts related to fluid power. This occurs at both the secondary and graduate levels. The Research Experience for Undergraduates (REU) program places undergraduate engineering students in ERC laboratories for 10 weeks of the summer, where they work with graduate students doing original research. In 2011, the Maha Fluid Power Research Center hosted three REU students:

- Cheng Lu, Purdue University
- Jennifer Wu, Purdue University
- Killian Cooley, Purdue University

Cheng Lu worked with PhD student Rohit Hippalgaonkar, to design and implement a preliminary fault detection and display unit on the CCEFP prototype excavator. Jennifer Wu worked with PhD student Andrew Schenk, undertook investigations to model the slipper hold-down force at the slipper/swash-plate interface in axial piston machines. Since the summer Jennifer has continued to work as a part-time undergraduate researcher in our lab. Finally, Killian Cooley worked with PhD student Marco Zecchi investigating the impact of the boundary solid's thermal deformation on the performance at the cylinder block/valve-plate interface.

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

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

Fall Semester 2011

2011 marked the seventh 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:

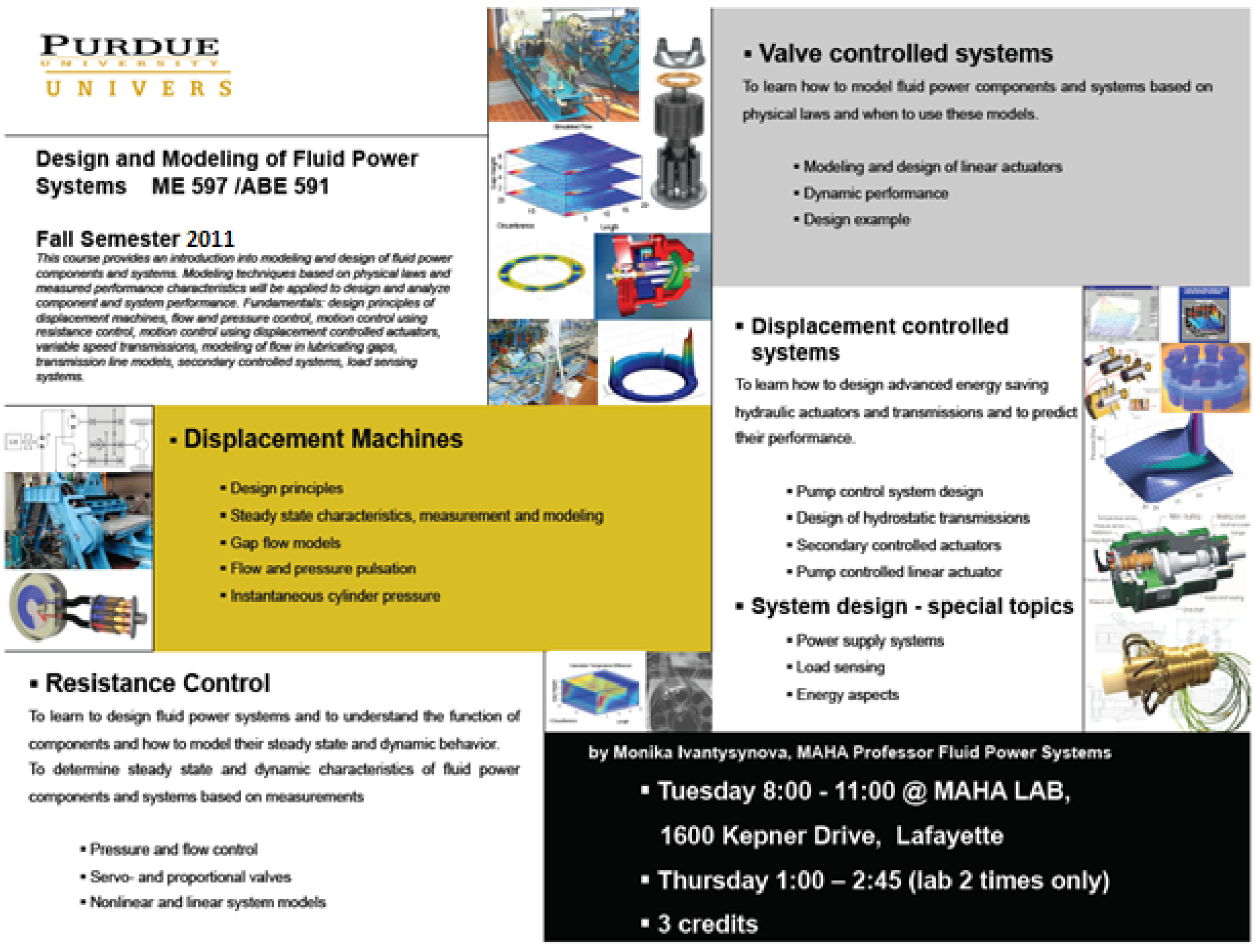
1. Choose and define your own system design project, i.e. define a hydraulic actuator, drive system or transmission as a part of a machine or vehicle. Describe briefly the machine or vehicle function.
2. Specify the system requirements (work task, operating parameter range, safety issue, energy consumption, 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

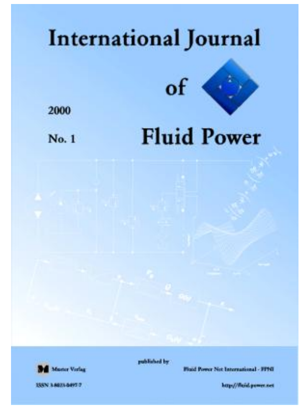
Life in the Maha lab is not always about work. Occasionally we are able to get together and enjoy each others' company. Below are some highlights of the past year.

Celebrating Daniel's Last Day In Lab

Annual Party at Monika's House


HAPPY BIRTHDAY

13 International Journal of Fluid Power



Dear Associate Editors and Members of Editorial Board,

The International Journal of Fluid Power has completed its twelfth year of publication. The third and final issue of the twelfth volume was printed and sent to our readers this past November. This was the 36th issue of the Journal, and we look forward to the 37th 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 reviewing papers and submitting manuscripts about recent research results. My special thanks goes to all the Associate Editors who have taken on their new roles in managing the paper review. This step was necessary after Dr. Ganesh Seeniraj left the Maha Research Center for his new position in industry. I would like to thank Ganesh for his great support in his function as Technical Editor of the Journal.

I am very pleased to welcome Susan Gauger as the new Technical Editor. Please join me in welcoming Susan to the Journal's team. Finally, I want to give recognition to Editorial Board for your great assistance and advice. Having such a wonderful and knowledgeable group of Associate Editors, Editorial Board Members, and reviewers has further ensured the papers published in the Journal are only of the highest quality. The new list of reviewers will be published again in the first issue of 2012.

The journal has been online since 2006 at http://journal.fluid-power.net. Online access has certainly strengthened the position of the journal and increased the number of citations. This past year we received twenty-eight manuscripts. Six of the manuscripts were rejected and several of the remaining twenty-two are still in the review process.

My appreciation goes to all of you for your continuous support of the Journal. I wish you and your family a healthy New Year, and all the best for 2012.

Best regards,

Monika Ivantysynova
Editor-in-Chief

14 Maha Team in 2011

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Origin: Mexico
July 2011-present

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April 2009-May 2011

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M.Eng.: Cornell Univ
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June 2010-present

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Oct 2011-present

Matt Kronlage
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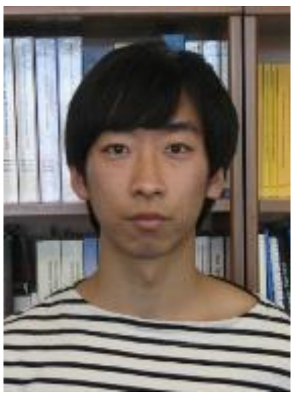
MS: Purdue University
Origin: USA
July 2009-July 2011

Currently at Sauer-Danfoss, USA.



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May 2011-present

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July 2010-July 2011

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September 2007-present

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Aug 2009-July 2011

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July 2009-present

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Origin: Missouri, USA
August 2010-present

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MS: Purdue University
Origin: USA
April 2009-May 2011

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April 2010 - Present

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August 2010-present

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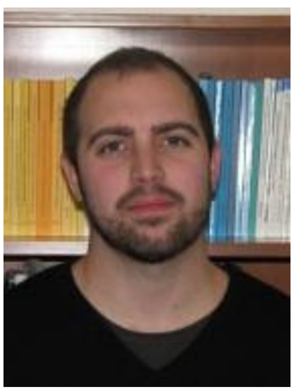
Origin: USA
August 2006-present

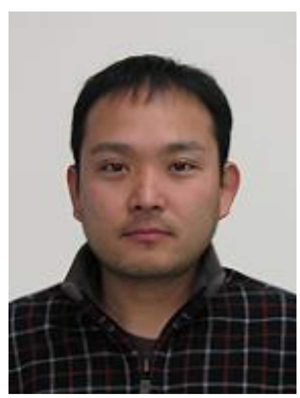
Visiting Researchers



Daniel Grönberg
Visiting Researcher
Origin: Sweden
Jan 2011-June 2011

Najoua Jouini
Visiting Researcher
BS, MS: Stuttgart University
Origin: Tunisia
Sep 2006-Feb 2007
Sep 2007-Aug 2008
May 2009-present

Amin Mehdizadeh
BS,MS: Shiraz University
MS: The Royal Insititute of Technology, Sweden
Origin: Iran
Dec 2011-Present



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Jan 2010-Jul 2011

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Origin: China
Nov 2011-Present

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Maha Secretary/ Assistant
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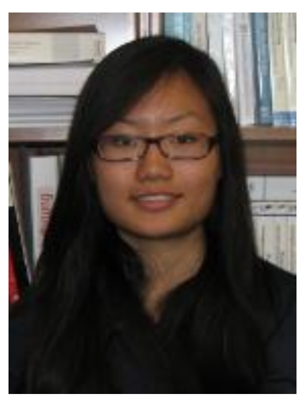
Origin: Lafayette, IN, USA
June 2011 - present

Anthony Franklin

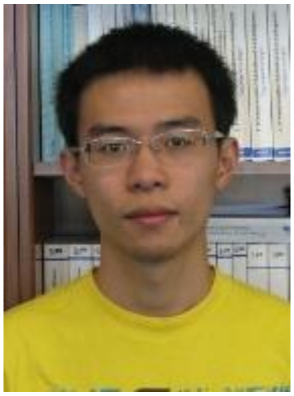
Maha Lab Technician
Phone: (765) 448-1587
Origin: Kokomo, IN
November 2008-present

Summer Undergraduate Students

Kilian Cooley
Undergraduate
BS: Purdue University
SURF Summer 2011



Jennifer Wu
Undergraduate
BS: Purdue University
SURF Summer 2011



Cheng Lu
Undergraduate
BS: Purdue University
SURF Summer 2011

Past Maha Staff

Edat Kaya
Maha Lab Manager
Dipl.-Eng.: Hamburg Univ. of Applied Science
Origin: Germany
Aug. 2005-May 2011
Currently at Sauer-Danfoss, Germany.

Ganesh Seeniraj
Postdoc: August 2009-April 2011
BS: Anna University, Chennai, India
MS: Kettering Univ.
PhD: Purdue Univ.
Origin: India

15 Sponsors, Partners & Guests

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

We would like to thank our large list of industry collaborators. Specifically, we had the pleasure of working with the following individuals in 2011:

- Bobcat: Thomas Sagaser, Daniel Krieger, Gunter Matt
- Caterpillar: Chris Beaudin, Bryan Nelson, Jim Aardema, Viral Mehta, Jordan Liu
- Eaton: Richard Lyman, Srinivas Patri, Dennis Szulczewski, Jamie LeClair
- Enfield Technologies: Dan Cook, Edwin Howe
- Evonik-Rhomax: William Cleveland
- Gates: Dan Hergert
- HUSCO International: Dwight Stephenson, Joe Pfaff
- John Deere: Jeff Dobchuk, Mike Brammer
- Netshape Technologies, Inc: David Moorman, Wiley Abner
- Moog, Aircraft Group: Thomas A. Greetham
- Parker Hannifin: Joe Kovach, Bruce Larkin, Rollin Christiansen, Blake Carl, Rajneesh Kumar
- Poclain Hydraulics: Ludovic Loiseau, Simon Rempfer, Guillaume Charrier
- Sauer Danfoss: Robert Rahmfeld, Jeff Herrin, Mike Gandrud, Jeff Hansell, Mike Betz, Olver Meincke.
- Toro: John Heckel
- Trelleborg: Mark Sitko

Guests

The Maha Lab has always attracted numerous guests, and 2011 was no different with the following people visiting our facilities or working with us at various times of the year:

Ben Wansten – Toyota Technical Center
Bill King – UIUC
Brad Bohlmann – University of Minnesota
Brad Reynolds – John Deere
Brian Rhode– Afton Chemical
Dalsik Jang – Doosan Infracore
Dan Williams – TRW
Dave Holt - ExxonMobil
Dave Scheetz – ExxonMobil
Dewey Tirdevholm – University of Minnesota
Doug Scott – Eaton
Enrico Balocciai – Casappa
Frank Conney – LZA
Gary Kassen – CNH
Hiroyukia Ogamn – Toyota Motor Company
Howard Zhang – Parker
JD Huggins – Georgia Tech
Jean-Claude Ossyra – Eaton
Jeff Herrin – Sauer-Danfoss
Jeke Alles – DFDA
Jerry Wear – Caterpillar
Joe Pfaff – Husco
John Mahremhah – John Deere
Jon Poiniel - Woodward
Kim Stelson – University of Minnesota
Larry Castleman – Trelleborg Sealing Solutions
Larry Yilhsmil – Rochester Institute of Technology
Lizhsiao Wecksler – University of Illinois
Matt Simon – Parker
Mike Grandrud – Sauer-Danfoss
Nadim Chelhoul – Poclain Hydraulics
Navneet Gulet – CNH
Paul Heney – WTWH Media
Pawel Sobolewski – Woodward
Pete Alles – NFPA
Qing Hui Yuan – Eaton
Richard McDonnel - Parker
Rick Lindner – JNA
Roger Jenkins – Precision Pump and Power
Scott Lane – Linde
Shahbaz Hydari – Woodward
Shubhamita Basu – Lubrizol
Stephen White – Parker
Steve Herzog – Evonik
Tom Tuffs – Eaton
Tyler Kelsch – John Deere