# 2009 Annual Report

**Monika Ivantysynova**
**Maha Professor of Fluid Power Systems**

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# Preface

2009 marked the beginning of the fourth year of our research within the National Science Foundation sponsored Engineering Research Center (ERC) for Compact and Efficient Fluid Power (CCEFP). 2009 was a critical year for us in the ERC as it was during this year's NSF site visit that the decision to fund us for an additional seven years would be made. I am very happy to report that the site visit team was thoroughly impressed with our work to date and decided to renew funding for our center. I would like to extend my thanks to all ERC researchers. The CCEFP is a $21 million fluid power research initiative comprised of 7 collaborating universities. The Center is strongly supported by 60 industrial partners including the National Fluid Power Association. At the Maha Fluid Power Research Center, our research within the CCEFP is focused on new technologies to reduce energy consumption in fluid power systems by 30% or more. Simulation studies of displacement control in excavator hydraulics demonstrated possible energy savings of up to 50% over traditional load sensing systems. The team is concentrating on the development of new system solutions including controls for off-road machinery and power trains. We are also discovering ways to improve the efficiency of pumps and motors which form the heart of any fluid power system. In 2008, we began investigating a new method for designing a critical interface in piston pumps and motors. Early this past year we developed, manufactured and tested a prototype valve plate in collaboration with one of our industrial partners and were able to demonstrate an improvement in total pump efficiency of nearly 10% due to this special new surface design. In addition to our involvement in the ERC we continued our successful co-operation with industrial partners. Our achievements were also noted by Purdue University President France A. Córdova and Provost William R. Woodson when they toured the research center on March 30, 2009.

This year I, along with one of my Master's students, travelled to Linkoping, Sweden for the 11th Scandinavian Conference on Fluid Power. From there I journeyed to Finland to participate in a PhD defense at Tampere University, assessed research programs at Helsinki university, and evaluated the progress of Aalto Univeriisity, the first private university in that country. My travels also included the Bath/ASME Symposium on Fluid Power and Motion Control Conference in Hollywood with several of my PhD and Master's students presenting, as well as the ERC Annual Conference at North Carolina Agriculture and Technology State University.

2009 also marked the successful defense and graduation of Ganesh Seeniraj, my first PhD graduate at Purdue since making the transition to the United States. I am very proud to say that he has elected to return to Maha in order to begin his postdoctoral research. We also joined in congratulating three of our master's students, Reece Garrett, Shekhar Degaonkar and Rohit Kumar. Reece is currently working for Electric Boat in Connecticut. Shekhar has returned to his home in India and is working for Eaton India, Private Limited. Rohit graduated with his degree after successfully defending his Master's thesis. We also said goodbye to several other team members. Kyle Williams has joined another former Maha graduate at Parker Hannifin in Cleveland, Ohio and Jonathan Baker moved to Boston this past summer to begin graduate studies in the field of technology-policy at MIT.

Despite the departures, the Maha team continues to grow. Back in the fall, we welcomed two new PhD students and several new Master's students. Andrew Schenk and Jacob Mcleod, both from Kettering University in Michigan, joined as PhD students. The Master's students include Michael Cross from Univeristy of Tennessee at Knoxville, Purdue alumnus Roman Ivantysyn, Matt Kronlage from Iowa State University, and Jess Rose and Brent Warr, both from Brigham Young University in Utah. The lab also enjoys the privilege of hosting visiting scholars from around the world. Marcel Tkocz, new to the lab in 2008, continued his stay here until returning to Germany in May of this past year. New for 2009, the Maha Lab welcomed Marco Zecchi and Federica Franzoni from Italy. Finally, we were very happy to welcome back a former team member, visiting researcher Najoua Jouini.

I would like to thank all team members for their excellent work in 2009. It is a great pleasure to present the following survey of our activities and main achievements during this past year.

I am confident that we will continue our exciting research. I wish all the members of our team much success during 2010.

Monika Ivantysynova

Maha Professor of Fluid Power Systems

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# 1 Research Activities

## *The Center for Compact and Efficient Fluid Power*

Much of the research activity in the Maha Fluid Power Research Center is part of a large research effort called the Center for Compact and Efficient Fluid Power (CCEFP). The CCEFP is an Engineering Research Center (ERC) funded by the National Science Foundation inaugurated in 2006. The center is dedicated to advancing research in fluid power science, technology and education. Purdue is one of seven universities represented in the CCEFP. Other participating universities are Georgia Institute of Technology, University of Illinois at Urbana-Champaign, University of Minnesota, Milwaukee School of Engineering, North Carolina A&T State University and Vanderbilt University. Dr. Ivantysynova sits on the center's executive committee and is the leader of Thrust Area 1: Efficiency. The other two Thrust Areas consist of Compactness and Effectiveness. Together the three Thrust Areas support research aimed at overcoming the current technological barriers facing fluid power with the ultimate goal of making fluid power more efficient, compact and quieter. Currently there are five Purdue faculty members as well as their graduate student teams participating in the CCEFP: Monika Ivantysynova, Steven Wereley, Steven Frankel, John Lumkes and Ashlie Martini. 2009 also saw the graduation of three Purdue ERC students Reece Garrett, Jeff Dougan and John Mahrenholz all three graduated with their Master's degrees this past year. Reece is working with General Dynamics Electric Boat, John is currently working with John Deere and Jeff holds an engineering position at ThyssenKrupp Safway Inc. Jonathan Baker, who graduated as a M.S. student in 2008 but extended his research at Maha for a semester also left the lab in 2009 to go to MIT where he has begun work towards his PhD.

### 2009 Annual Meeting

The second annual CCEFP conference was held October 7 – 9, 2009 at North Carolina A & T State University in Greensboro, North Carolina. Purdue was well represented in the proceedings, as the following list of posters and presentations attests.

***Presentations***

- 1A.2: Optimal Power Management with Displacement Controlled Actuators, *Christopher Williamson (PhD Student)*
- 1B.1: Advanced Surface Design for a New Generation of Pumps and Motors, *Matteo Pelosi (PhD Student) and Marco Zecchi (visiting researcher)*
- 1B.2: Surface Effects on Start-up Friction and their Application to Compact Gerotor Motor Design, *Jose Garcia (PhD Student)*
- 1E.2: Coupled Multi-Domain Modeling and Simulation of High Speed On/Off Valves, *Mark Batdorff (PhD Student) and Gabe Wilfong (MS Student)*
- 1E.3: High Efficiency, High Bandwidth Actively Controlled Variable Displacement Pump/Motor, *Michael Holland (PhD Student) and Kyle Merrill (PhD Student)*
- Test Bed 1: Heavy Mobile Equipment, *Josh Zimmerman (PhD Student)*

***Posters***

- 1A.2: Optimal Power Management with Displacement Controlled Actuators, *Christopher Williamson (PhD Student)*
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- 1E.3: High Efficiency, High Bandwidth Actively Controlled Variable Displacement Pump/Motor, *Michael Holland (PhD Student) and Kyle Merrill (PhD Student)*
- Test Bed 1: Heavy Mobile Equipment - Excavator, *Josh Zimmerman (PhD Student)*

## Industrial Support

Although academic research is the primary focus of the CCEFP, there is considerable support from industrial sponsors. After the 2007 annual meeting in Atlanta, a cadre of industrial representatives was selected to work directly with CCEFP students and faculty to support their research and promote the future transfer of ideas from academia to commercial production. CCEFP Industrial sponsors of Maha research and their representatives included:

- Caterpillar: Chris Beaudin, Bryan Nelson, Jim Aardema
- Eaton:Richard Lyman, Srinivas Patri, Dennis Szulczewski, Jamie LeClair
- Enfield Technologies: Dan Cook, Edwin Howe
- Evonik-Rhomax: William Cleveland
- Gates: Dan Hergert
- HUSCO Intl: Dwight Stephenson, Joe Pfaf
- 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, Kyle Williams
- Poclain Hydraulics: Ludovic Loiseau, Simon Rempfer, Guillaume Charrier
- Sauer Danfoss: Jeff Hansell, Robert Rahmfeld, Jeff Herrin, Mike Betz
- Toro: John Heckel
- Trelleborg: Mark Sitko

## Education and Outreach

Educational outreach is another mission of the CCEFP, with programs to promote the teaching of science and technology concepts related to fluid power at the secondary and graduate levels and to encourage participation from underrepresented minorities. The Research Experience for Undergraduates (REU) program places undergraduate engineering students in ERC laboratories for 10 weeks in the summer, where they work with graduate students doing original research. In 2009, the Maha Fluid Power Research Center hosted four REU students:

- Andreu Husien, Purdue University
- Paul Kalbfleisch, Purdue University
- Jamie Scott, Purdue University
- Nathan Strong, Purdue University

Andreu worked with PhD student Josh Zimmerman, investigating the potential for an alternate hybrid hydraulic system with accumulator energy storage for a 20-ton excavator. Paul worked with PhD student Rick Klop, measureing sound intensity in order to estimate total sound power radiation of a hydraulic pump/motor inside a semi-anechoic chamber and performing a simulation investigation to discover quiet hydrostatic transmission designs. Jamie, supervised by Jonathan Baker and PhD student Matteo Pelosi, worked with Maha's simulation model, CASPAR, investigating the performance and characteristics of the tribological systems characterizing hydrostatic axial piston machines under full film lubrication conditions. Maha's final REU/SURF student, Nathan, worked with PhD student Chris Williamson in developing control strategies for the CCEFP Test bed 1 - a Bobcat Mini-excavator.

# *Research Areas at Maha*

Our research activities are focused in three 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 mostly funded by industry.

## Advanced energy saving hydraulic actuators

The aim of this research is to develop new valveless hydraulic actuator concepts including necessary motion control strategies for different applications that avoid energy dissipation by resistance control. The focus of this work has been on a concept known as "displacement control" in which the motion of a linear cylinder is controlled directly by controlling the oil volume displaced by a variable displacement axial piston pump. In years past this technology has been demonstrated by our research group on wheel loaders and a skid-steer loader, but in 2009 it was successfully demonstrated on a Bobcat excavator. In the past displacement controlled joint rotary actuator concepts have been developed and successfully demonstrated for large mobile robots using our JIRA test rig. This rig has been modified to serve as a test bench for studying the dynamic response and control of the pumps used in displacement controlled actuators. Currently, work is being done regarding active oscillation damping based on displacement control for off-road vehicles. A Bobcat skid-steer front loader serves as the test vehicle for this reasearch.

## Computer based pump & motor design

This research focuses on the performance optimization and noise reduction of pumps and motors. These research efforts have involved the design of special experimental test rigs to develop a fundamental understanding of the complexity of physical effects taking place in displacement machines. One important result of this research on pumps and motors has been the development of the multi-domain simulation program CASPAR (Calculation of Swash Plate Type Axial Piston Pump/Motor). CASPAR represents the first program worldwide that predicts flow ripple, instantaneous cylinder pressure, oscillating swash plate forces, gap heights, friction forces and volumetric losses of swash plate type piston pumps and motors.

Currently, CASPAR is undergoing some significant updates. The aim of the project is to develop a detailed, fully coupled fluid-structure-multi-body model for benchmarking the complex physics of the primary lubricating gap interfaces in axial piston machines. The interaction between the fluid and structure in these type of gaps is very important. Unlike other interfaces, which primarily only fullfill either a bearing or sealing function, these interfaces must simultaneously fulfill both a sealing and bearing function under highly dynamic load conditions. The current kernal of CASPAR includes a fluid-structure interaction model and non-isothermal gap flow model for the piston/cylinder and cylinder block/valve plate lubricating gaps. These modules currently exist outside of the iteration loop.

The objective of the current work with CASPAR is to extend to the gaps the Thermal-Elasto-Hydrodynamic (TEHD) lubrication theory which couples the Reynolds Equation, universally used to model film thickness behavior, with the heat transfer to the solid parts (T) and the surface elastic deformation of the solid parts (EHD) due to pressure and thermal induced strains. Being able to predict the heat transferred from the lubricating gaps to the solid parts will allow an accurate determination of the boundary temperatures, for a better prediction of the fluid viscosity. The fluid viscosity in fact is strongly influenced by the temperature distribution and is very important for the gap behavior. Also, the surface elastic deformation of the solids parts is determined both by the dynamic pressure fields generated inside the gap and the thermal loading condition which leads to thermal expansion. These effects strongly influence the film thickness and therefore the oil load carrying capabilities. The work is currently focused on the development of such a model for the piston/cylinder interface, since this interface is one of the most critical interfaces and special test-rigs (the EHD and OLEMS test-rig) in the lab will allow us to confirm the numerical results. Such work has also begun for the cylinder block/valve plate interface and slipper/swash plate interface.

Using the current kernel of CASPAR, research activities concentrate on developing methods for surface optimization that increase power density and decrease losses in the lubricating gaps. Two patents have been filed for novel micro-structured surfaces applied to the cylinder block and piston respectively. Further research focuses on modeling fluid and structure borne noise sources. A recent PhD thesis focused on the development of an optimization method for the reduction of noise emission from pumps and motors. Work has continued on the development of a model for the prediction of noise in hydrostatic transmissions.

## Investigation of pump and transmission noise sources

This research focuses on one of the main problems of every hydraulic system – high noise levels. The airborne noise emitted from the hydraulic system can be attributed to two main sources, namely, Fluid Borne Noise Source (FBNS) and Structure Borne Noise Source (SBNS). The hydraulic displacement units (pumps and motors) are usually the main source of noise generation in a hydraulic system. And, the demand for the displacement units to be quieter is increasing as the units are widely being employed in systems with varying operating conditions. In this research, the problem of noise in the hydraulic systems is being approached from two directions.

The first approach aims to reduce noise generation at the source (FBNS and SBNS) level i.e. directly at the pumps and motors. A multi-parameter multi-objective optimization procedure has been developed to reduce sources of noises from pumps and motors which operate in a wide range of operating conditions. The optimization procedure has been implemented as a 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.

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. A simulation tool (*TransModel*) has been developed which includes a time-domain model of the transmission coupling the pump and the motor using a line. *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.

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 has two electrical units which are used as electric motor/generator combination. These two electrical units are coupled with hydraulic displacement units to recreate the entire hydrostatic transmission. The facility also enables to investigate noise levels of different design of displacement units and transmissions.

## 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 exhaust emissions and fuel consumption without limiting the vehicle's driving power. A special software tool called PSDD (<u>P</u>ower <u>S</u>plit <u>D</u>rive <u>D</u>esign) has been developed to support virtual prototyping of power split drives, multi-motor hydrostatic transmissions and hydraulic hybrid power train configuarations. 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 dynameters. Some past studies include:

- Working on power split hydraulic transmission for heavy on/off road hydraulic vehicles
- Virtual prototyping of power split drives and hydraulic hybrid power trains
- Advanced system and control strategies for multi-motor hydrostatic transmissions

- Development of generic methods for prognostics of mechatronic systems of off-road vehicles
- Power management or hydraulic hybrid power trains

## *Maha Research Projects in 2009*

In 2009 work has been done on the following research projects:

- Active vibration damping for off-road vehicles using displacement controlled linear actuators
- Optimal power management strategies using displacement controlled actuators
- Development of a elasto-hydrodynamic (EHD) model of the slipper/swash plate for advanced gap flow simulation
- Development of a modeling tool for predicting the performance and losses of bent-axis axial piston pumps and motors
- Investigation of the effect of piston surface shaping on losses in the lubricating gaps of axial piston pumps and motors using CASPAR
- Investigation of micro-waved surface designs for piston pump interfaces
- Development of a coupled line-pump-motor model to investigate transmission noise sources
- Semi-anechoic chamber construction
- Virtual prototyping of power split drives and hydraulic hybrids
- Vehicle drive-line control towards optimized primary power consumption

The described research activities are accompanied by extensive experimental work. During the last ten 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.

# 2 Research Results & Software Tools

## *Research Reports in 2009*

**Ivantysynova, M. and Zimmerman, J**. 2009. *Excavator Baseline Fuel Test Report*. Maha Fluid Power Research Center. Research Report MAHA01-2009-in.

**Ivantysynova, M. and Baker, J**. 2009. Measurement and Simulation Comparison: Sauer H1, 78 cc unit. Maha Fluid Power Research Center. Research Report MAHA02-2009-in.

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**Ivantysynova, M. and Baker, J**. 2009. Efficiency *Measurement Results of 78 cc pump Operating with a Standard Valve Plate and DM.9 Waved Prototype Valve Plate*. Maha Fluid Power Research Center. Research Report MAHA17-2009-in.

**Ivantysynova, M. and Pelosi, M**. 2009. *CASPAR Piston-Cylinder and Cylinder Block Coordinate System Clarifications*. Maha Fluid Power Research Center. Research Report MAHA18-2009-in.

**Ivantysynova, M. and Pelosi, M**. 2009. *CASPAR Piston-Cylinder and Cylinder Block Coordinate System Clarifications*. Maha Fluid Power Research Center. Research Report MAHA18-2009-ex.

**Ivantysynova, M. and Degaonkar, C**. 2009. *Power Split Transmission for Special Truck Application*. Maha Fluid Power Research Center. Research Report MAHA19-2009-ex.

**Ivantysynova, M. and Seeniraj, G**. 2009. *Sound Pressure Level Measurements for Two Different Valve Plates for a 75cc Pump*. Maha Fluid Power Research Center. Research Report MAHA20-2009-ex.

**Ivantysynova, M. and Baker, J.** 2009. *Comparison between Pocket and Waved Structured Surface design Modifications.* Maha Fluid Power Research Center. Research Report MAHA21-2009-in.

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**Ivantysynova, M. and Franzoni, F.** 2009. *Shuttle Valve Testing.* Maha Fluid Power research Center. Research Report MAHA36-2009-in.

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**Ivantysynova, M. and Williamson, C.** 2009. *Pump Mode Oscillation on ERC Excavator Boom Function.* Maha Fluid Power Research Center. Research Report MAHA38-2009-in.

**Ivantysynova, M. and Schenk, A.** 2009. *Fluid Model for the Slipper-Swashplate Interface.* Maha Fluid Power Research Center. Research Report MAHA39-2009-in.

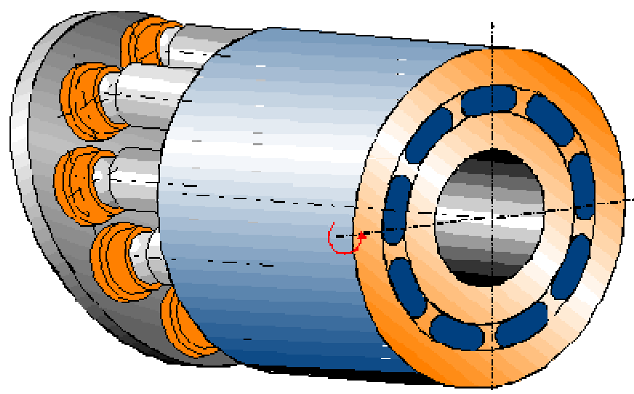
**Ivantysynova, M. and Zecchi, M.** 2009. *A New CAD Based Approach for the Geometric Definition of the Cylinder Block and Valve Plate Interface.* Maha Fluid Power Research Center. Research Report MAHA40-2009-in.

# *Software Tools*

The following special simulation software tools have been developed and are available for commercial use.

## CASPAR

The simulation model, *CASPAR* (Calculation of Swash Plate Type Axial Piston Pump/Motor), is a model for predicting the performance and losses of swash plate type axial piston pumps and motors considering specific machine geometry and operating conditions. The program is based on a non-isothermal gap flow model considering the change of gap heights due to micro-motion of parts and due to surface deformation for the connected gaps of a swash plate axial piston machines. The program calculates the flow ripple at both ports, the instantaneous cylinder pressure, the internal and external volumetric losses, viscous friction forces, gap heights, oscillating forces and moments exerted on the swash plate. The model has been developed to meet the need of the next generation of pump and motor researchers and designers and represents a powerful design tool for this kind of displacement machine.



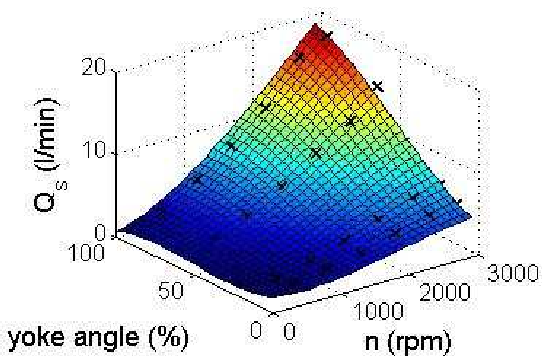
*CASPAR* describes the flow of a compressible and viscous fluid from the ports through the valve plate to the displacement chamber. It further considers non-isothermal gap flow through each of the three lubricating gaps that seal the displacement chamber. The change of pressure in the displacement chamber resulting from the basic working process of the displacement machine causes fluctuating forces and moments leading to oscillating micro-motion of moveable parts of the rotating group which are considered by the model. For the gap flow calculation, *CASPAR* considers a balance between external and fluid forces, i.e. full film lubrication. No mixed friction model is present. Additionally, the model neglects any surface roughness of the solid parts, assuming ideally smooth sliding surfaces. Models implemented and solved in *CASPAR* consider the time dependent change of gap heights due to oscillating forces, the interaction between machine parts, the dependency on design and operating parameters and the energy dissipation within the gaps.

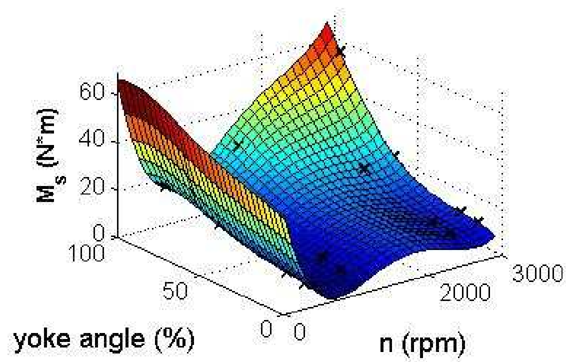
*CASPAR* also considers the influence that surface deformation of parts forming the gaps has on machine performance and behavior. The mathematical description of the fluid flow from the ports to the displacement chamber and through the sealing and bearing gaps leads to a system of partial and ordinary differential equations. A new numerical method based on iterative coupling of separate solvers for fluid/solid domains has been developed to solve this transient nonlinear system consisting of the Reynolds equation and the energy equation for the fluid domain, the equation of elasticity for the solid domain and the determination of gap heights by solving the motion equation of the multi-body system of the rotating group. The initial boundary conditions such as instantaneous cylinder pressure are obtained by solving the fluid flow from the displacement chamber to the ports.

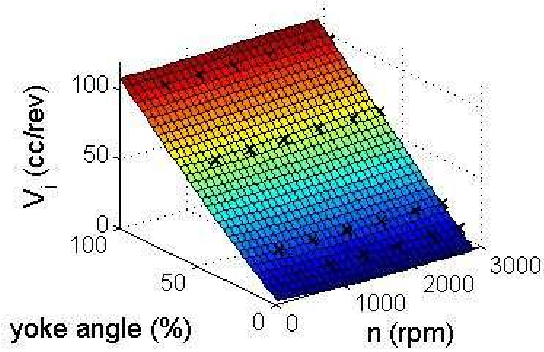
The model is continuously under development with the aim of achieving a fully coupled, multi-domain model that accurately predicts the gap height. Since 2005, the ability to predict the performance of a spherical port plate and a more comprehensive fluid property model has been added. Further updates of the software have included a more accurate description of a pump with a variable piston gap length. This past year, an EHD model for this slipper has been developed as well as a model for considering non-isothermal flow in the cylinder block/valve plate interface. *CASPAR* is currently undergoing a major update. The updated program promises to be more efficient and will incorporate the EHD and non-isothermal gap flow models for the three considered lubricating gaps within the internal calculation loop. *CASPAR* is a stand-alone tool developed using the C++ programming language.

## Polyfitn, N-d Polynomial Linear Regression Model

Polyfitn is a Matlab based software tool used for fitting nth order polynomials, typically to measurement data. Simple statistics such as the coefficient of determination, root mean square error, standard deviations, and variences of the coefficients. It will work using any set of terms as well as positive or or negative exponents. At the Maha Fluid Power Research Center, this is used to create loss models based on steady state pump measurements. These measurements allow determination of derived displacement, which is then used to calculate volumetric and torque losses at those particular measured points. These values then allow the calculation of volumetric and hydromechanical efficiency. Polyfitn uses these discrete points to create a model which predicts the volumetric and torque losses at any given point within the measurement range. These models can then be used in simulation of hydraulic systems. This provides far more accurate predicted losses than linearly interpolating between measured data points.

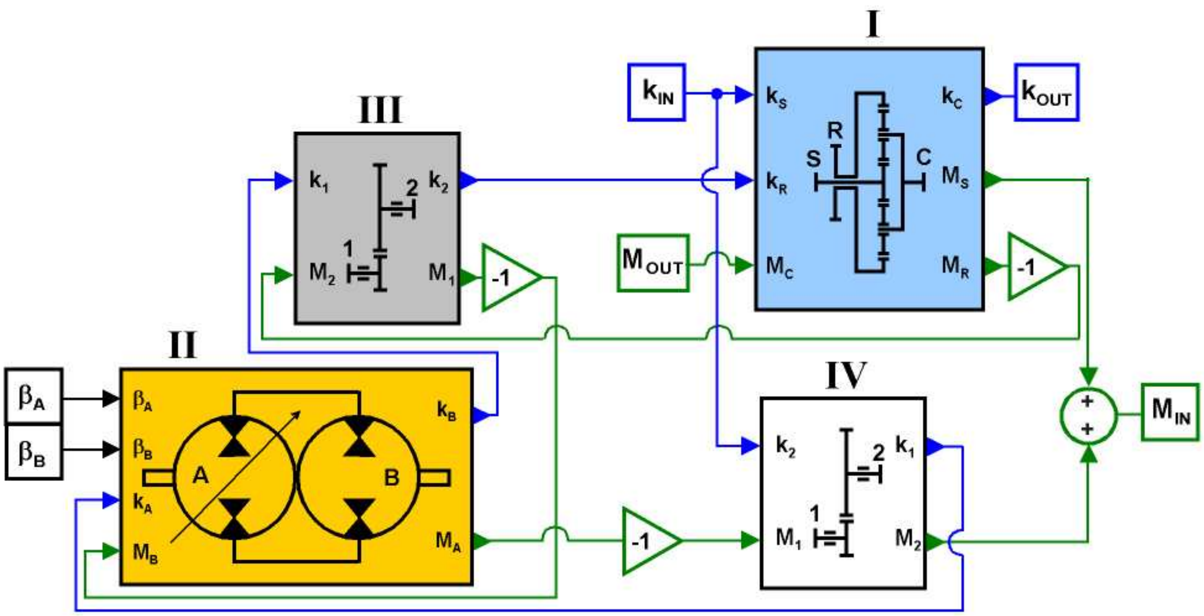


## PSDD - Power Split Drive Simulation

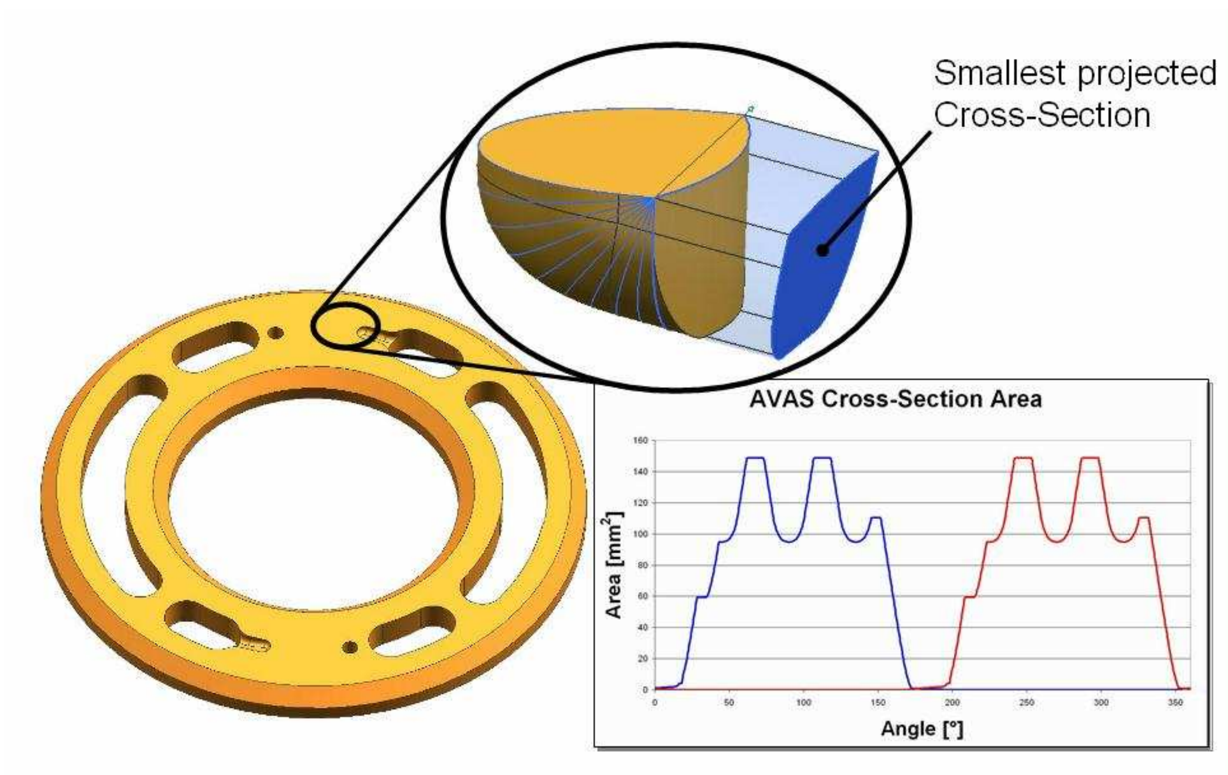
One of the main reasons for the use of power split drives in many applications is the possibility to have a continuously variable transmission with simultaneously high efficiency in a wide range of operating parameters. This requires the consideration of real loss behavior of all parts of the transmission. 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 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, engine 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.




*I: Planetary Gear Simulink model*
*II: Hydrostatic Transmission Simulink model*
*III: Gear Simulink model*
*IV: Gear Simulink model*

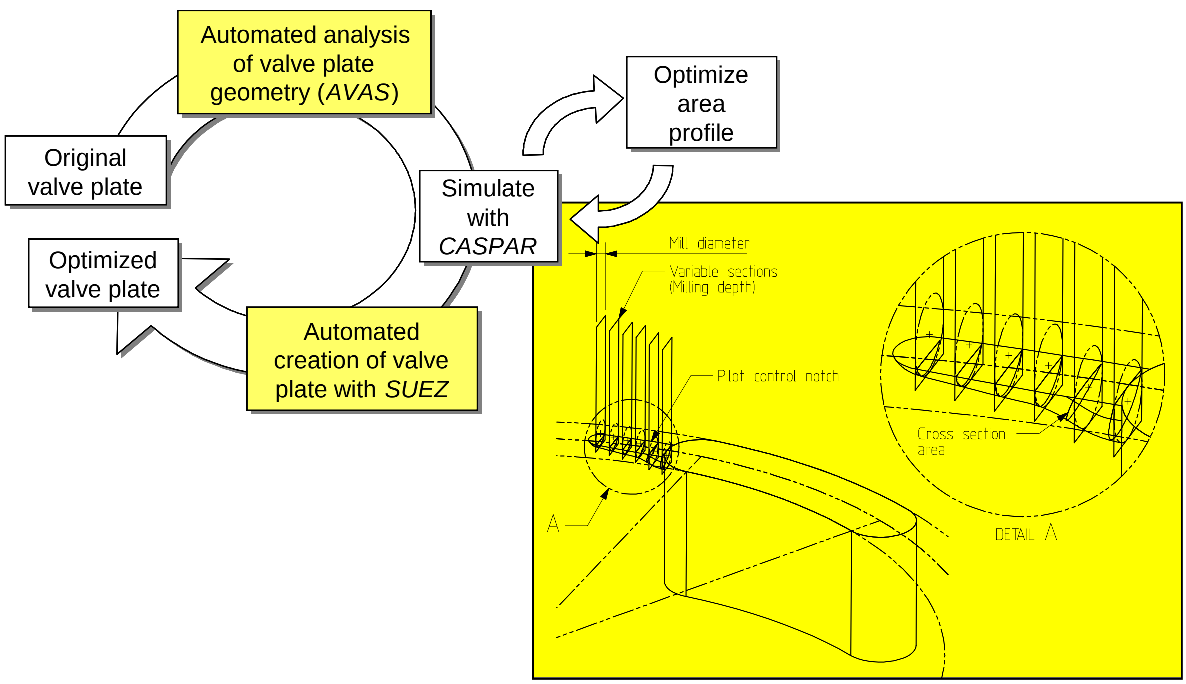
## AVAS

The change of pressure in the displacement chamber of a displacement machine is greatly influenced by the small cross-section of the fluid flow which is formed by the valve plate and the rotating cylinder block. For simulation calculations, it is important to know the exact size of the flow passage opening to the high and low-pressure side, depending on the angle of rotation. Because of the complex geometric sectioning, an analytical description of the cross-section is not possible. In the past the cross-section was measured and interpolated manually to obtain the area profile. Using a 3D-model of the valve plate *AVAS* is able to compute the smallest cross-section of the fluid for a complete revolution of the cylinder block automatically. In the single-step mode every calculated passage area can be visualized. *AVAS* uses *Unigraphics* based routines to determine the smallest cross-section into the estimated flow direction. The program is written in C++ and uses the UG/Open++ interface to start as an internal application in *Unigraphics*. The 3D-model of the valve plate can be imported from any other CAD-System by the STEP interface.



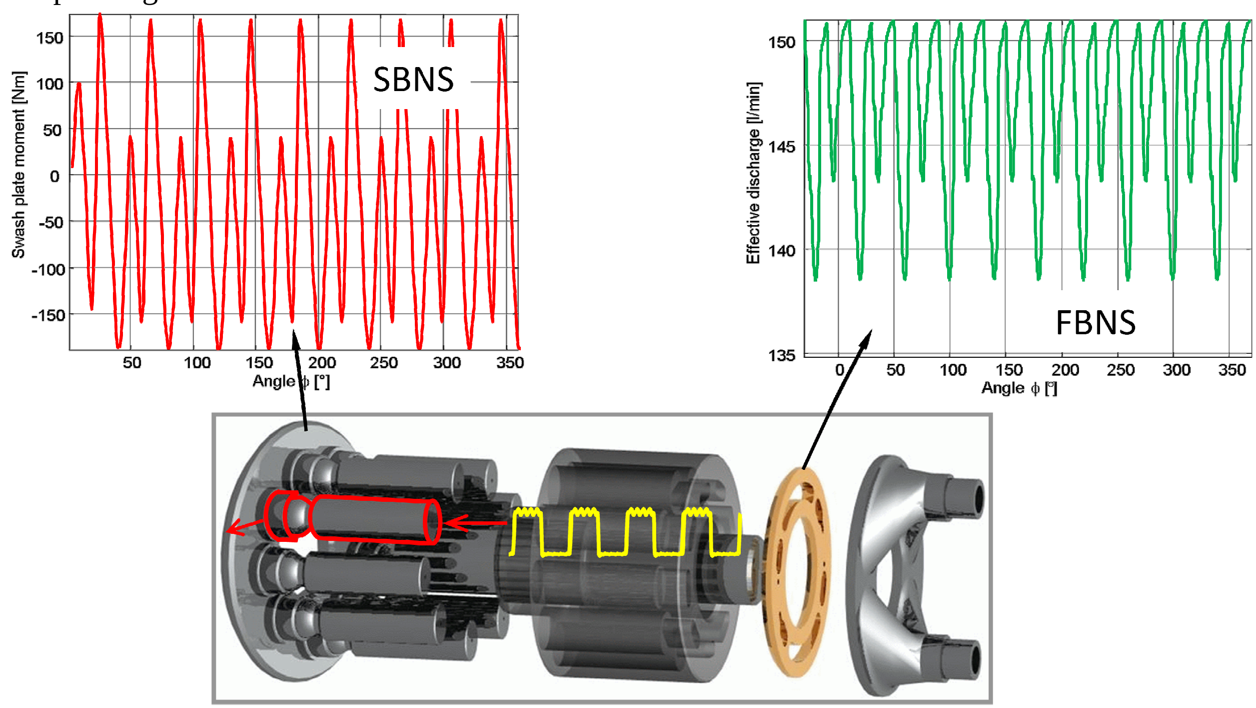
## SUEZ

*SUEZ* automatically creates a design of valve plate openings by reading a corresponding opening area file. *SUEZ* is based on the 3D CAD System *Unigraphics*. The pilot control notches of the valve plate are assumed to be manufactured by ball end milling. The cross section area, the length and the angle of the notches can be manipulated to obtain the desired instantaneous cylinder pressure for given operating parameters. The combination of the simulation tools *CASPAR*, *AVAS* and *SUEZ* allows for an optimization of swash plate axial piston machines in a very cost effective way. This method can also be used for other displacement machines.

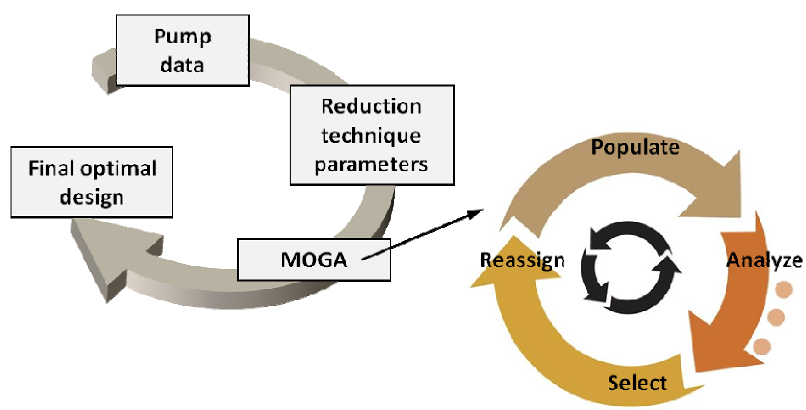


# VpOptim

*VpOptim* stands for Valve plate Optimization. *VpOptim* is a software implementation of a multi-parameter multi-objective design optimization procedure. VpOptim 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. VpOptim allows using two different reduction techniques to be optimized namely relief grooves and precompression filter volume with relief grooves. These two reduction techniques have several parameters which affect the area available for flow transfer between the displacement chamber and the pump 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 FBNS and SBNS over a wide range of operating conditions.



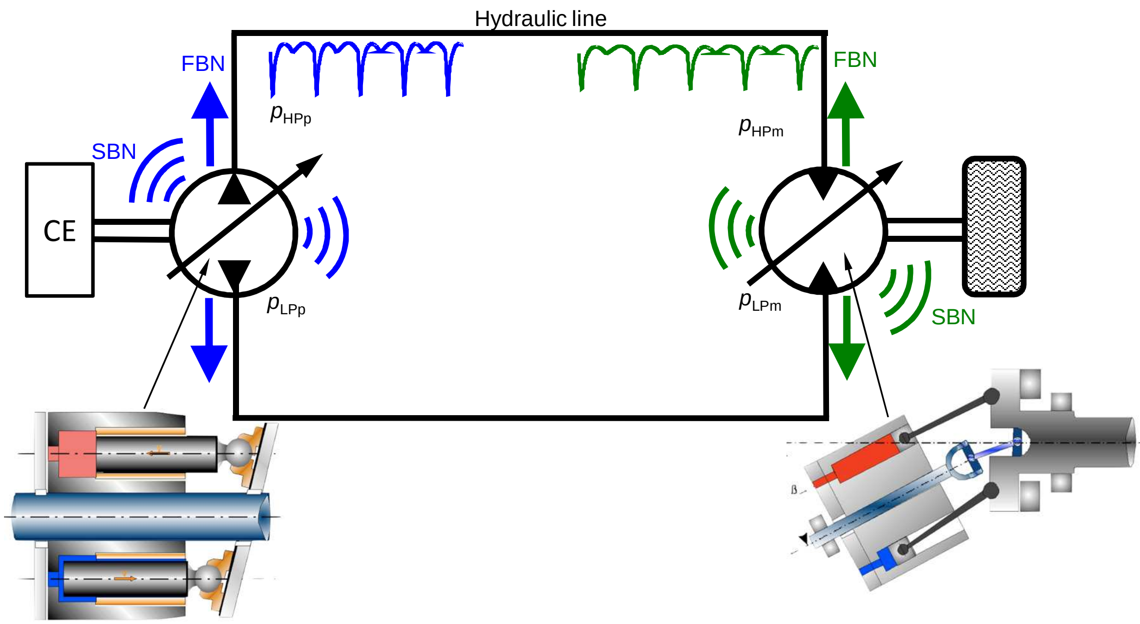

*Axial piston pump showing the fluid borne and structure borne noise sources*




*Schematic of the process flow inside VpOptim*

# TransModel

*TransModel* is a GUI based software program to simulate a complete hydrostatic transmission containing pump and motor connected using a line in time-domain. 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 are quantified. In particular, a time domain line model is necessary to couple time domain dynamic pump and motor models. TransModel is able to estimate both fluid and structure borne noise sources. Fluid borne noise source (FBNS) is quantified by calculating instantaneous pressure and flow ripples throughout the HP line between the pump and motor. Structure borne noise source (SBNS) is characterized by calculating instantaneous swash plate moments in all directions, for both units.

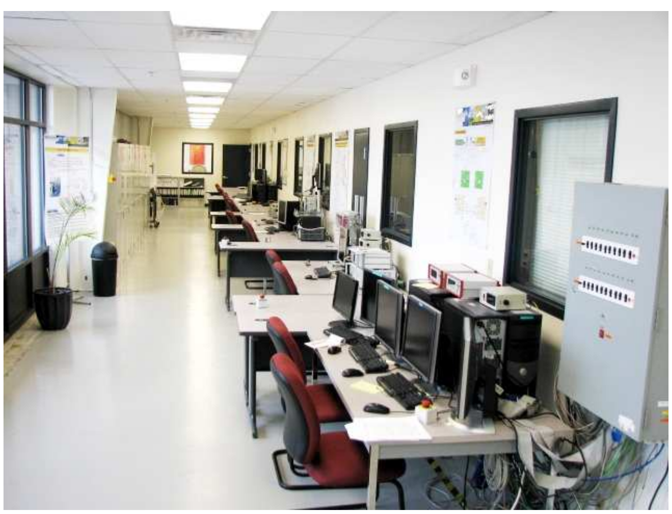



*Schematic of hydrostatic transmission implemented in TransModel*

# 3 Research Center Overview

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

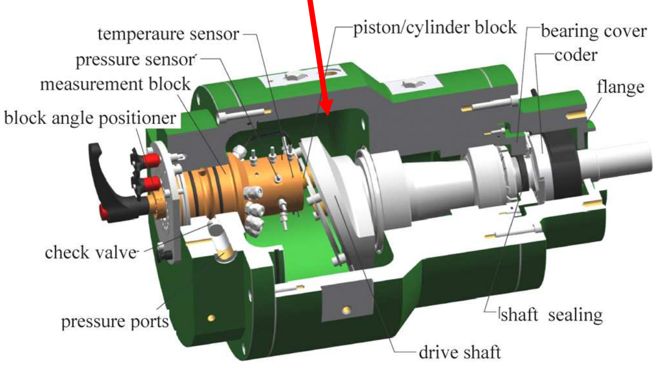
*Test Beds for Technological Demonstration (Above)*



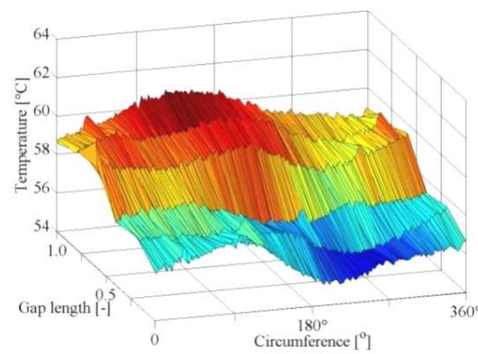
*Test Rigs and Control Room (Above and Left)*

## 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.



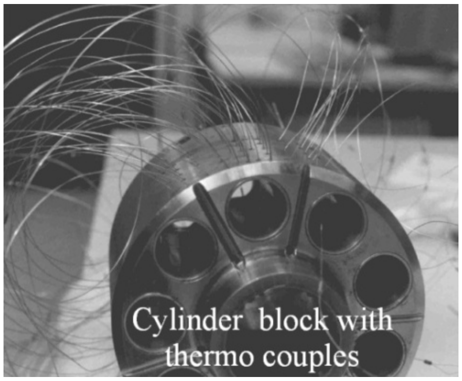

*EHD Pump*

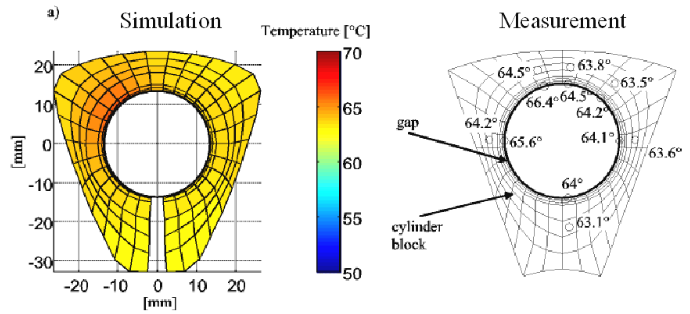



*Measured Temperature Field in the Piston/Cylinder Gap*

## 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.



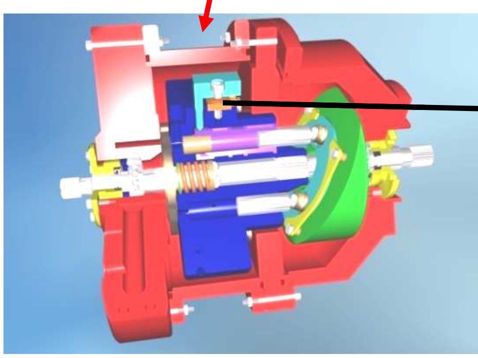



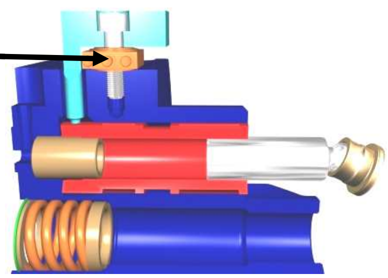

Temperature distribution in the assembly near the slipper side

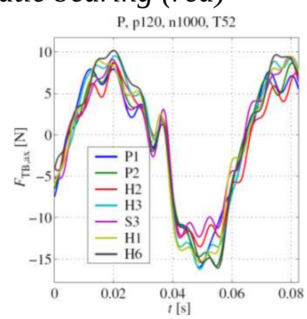
## Tribo test rig

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.

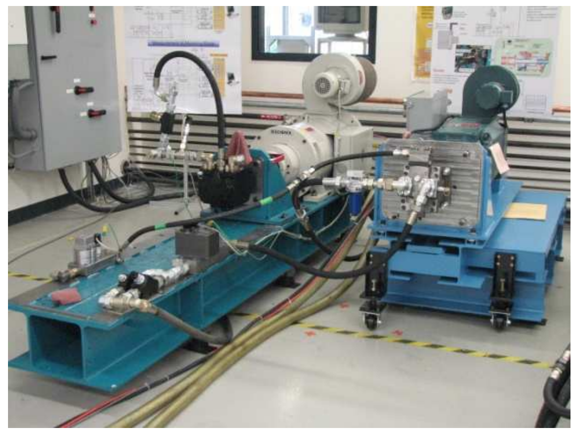
## Transmission test rig

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.

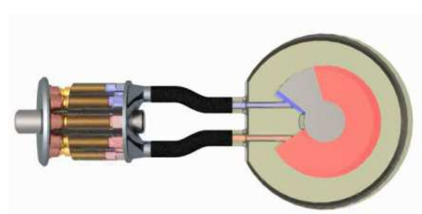
*Performance Characteristics*
Max. installed electric power: 2 x 120 kW
Max. speed: n1 = 7000 rpm/n2 = 3000 rpm
Max. pressure: 450 bar
Max. torque: M1 = 300 Nm/ M2 = 500 Nm



Performance
Max. Torque: 30000 Nm
Max. Pressure: 350 bar
Max. Power: 30 kW

## JIRA test rig

The joint 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.

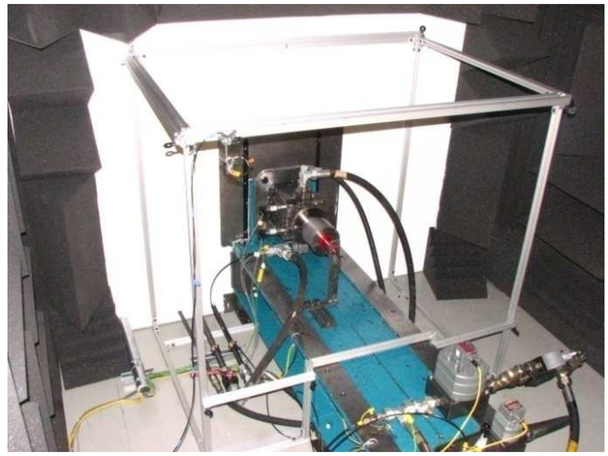


Rotary Actuator

Two new test rigs have been added to facilities at the Maha Fluid Power Research Center. One is designed for the purpose of testing new power trains developed here in the lab. Another is a semi-anechoic chamber to support the research related to noise reduction in pumps, motors and transmissions.

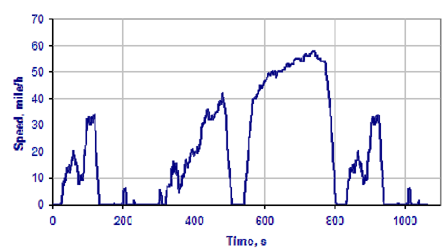
## Semi-Anechoic Chamber

This test rig is designed for noise measurements on pumps, motors and hydrostatic transmissions. The noise measurements are used to support the research in noise reduction conducted at the Maha lab. This test rig has recently been successfully calibrated and used to quantify the sound intensity level emitted from a hydraulic pump using three microphones and a positioning grid.



## 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. The test rig can be used to accurately simulate given drive cycles such as the UDDS drive cycle shown below.



## *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.

## *Test Beds*

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


**Front 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 front wheel loader serves as a platform for diagnostics and prognostics on hydraulic systems.

## Bobcat 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. Current research focuses on improving operator comfort and productivity via active vibration damping. The control concept was successfully demonstrated and showed up to a 34% reduction in vibration experienced by the machine operator.

## Bobcat 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. The excavator was successfully demonstrated in early November. Energy measurements of the hydraulic system showed savings of 50% when compared to the standard load sensing system being used in most production excavators today.

# 4 Industrial Partners & Sponsors

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, 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

# 5 Publications

## *Journal Articles*

**Ivantysynova, M. and Baker, J.** 2009. Power Loss in the Lubricating Gap Between Cylinder Block and Valve Plate of Swash Plate Type Axial Piston Machines. *International Journal of Fluid Power*, Vol. 10, No. 2, pp. 29 – 43.

**Williamson, C. and Ivantysynova, M.** 2009. Active Vibration Damping for an Off-Road Vehicle with Displacement Controlled Actuators. *International Journal of Fluid Power*, Vol. 10, No. 3, pp. 5 – 16.

## *Conference Proceedings*

**Baker, J. and Ivantysynova, M.** 2009. Advanced Surface Design for Reducing Power Losses in Axial Piston Machines. *Proc. 11th Scandinavian International Conference on Fluid Power SICFP'09*, June 2 – 4, Linköping, Sweden, Vol. 10 (2009), No. 2, pp. 15 – 30.

**Pelosi, M. and Ivantysynova, M.** 2009. A Novel Fluid-structure Interaction Model for Lubricating Gaps of Piston Machines. *Proceedings of the Fifth Fluid Structure Interaction Conference*, eds. C.A. Brebbia, WIT Press, Southampton, pp.13 – 24.

**Klop, R. and Ivantysynova, M.** 2009. A Method of Characteristics Based Coupled Pump/Line Model to Predict Noise Sources of Hydrostatic Transmissions. Bath ASME Symposium on Fluid Power and Motion Control (FPMC2009), [DSCC2009-2779].

**Kumar, R. and Ivantysynova, M.** 2009. An Optimal Power Management Strategy for Hydraulic Hybrid Output Coupled Power-Split Transmission. Bath ASME Symposium on Fluid Power and Motion Control (FPMC2009), [DSCC2009-2780].

**Pelosi, M. and Ivantysynova, M.** 2009. A Novel Thermal Model for the Piston/Cylinder Interface of Piston Machines. Bath ASME Symposium on Fluid Power and Motion Control (FPMC2009), [DSCC2009-2782].

**Zimmerman, J. and Ivantysynova, M.** 2009. Effect of Installed Hydraulic Corner Power on the Energy Consumption and Performance of Multi-Actuator Displacement Controlled Mobile Machines. Bath ASME Symposium on Fluid Power and Motion Control (FPMC2009), [DSCC2009-2781].

## *Invited Lectures*

**Ivantysynova, M.** Prius without a battery – an effective way to save fuel and reduce emissions with hydraulic hybrids. 2009 SAE Government/Industry Meeting. Technical Session on Light-Duty Hybrid Vehicle Technologies. February 4, 2009. Washington, D.C.

**Ivantysynova, M.** Hydraulic Hybrid Power Trains - an Opportunity and Challenge for Fluid Power. 7th International Conference on Fluid Power. April 7-10, 2009. Hangzhou, China. - **Keynote Lecture**



***Pictures from Monika's lecture in China***

**Zimmerman, J.** Energy Recovery through Displacement Controlled Actuator Circuits for Multi-actuator Machines. 5$^{th}$ NFPA Educator/Industry Summit, August 21-22, 2009. Wheeling, IL.

## *Posters Presented*

### 2009 ERC Annual Conference, October 7 – 9, 2009. Greensboro, NC.

*Optimal Power Management with Displacement-Controlled Actuators (project 1A.2),* Christopher Williamson

*Advanced Surface Design for a New Generation of Pumps and Motors (project 1B.1),* Matteo Pelosi, Marco Zecchi and Andrew Schenk

*Heavy Mobile Equipment - Excavator (Test Bed 1),* Josh Zimmerman

### The 5$^{th}$ NFPA Educator/Industry Summit, August 21 – 22, 2009. Wheeling, IL.

*Energy Recovery Through Displacement Controlled Actuator Circuits for Multi-Actuator Machines*, Josh Zimmerman

*Noise Source Reduction of Hydrostatic Transmissions and Hydraulic Hybrids,* Richard Klop

*A New Approach in Modeling of Piston/Cylinder Interface by Considering Material & Fluid Properties*, Matteo Pelosi

*Energy Savings Though Optimal Control of Multiple Pump-Controlled Actuators,* Chris Williamson

*Modeling and Design of the Cylinder Block/Valve Plate Interface*, Marco Zecchi

*The Hydraulic Hybrid – a Viable Alternative to Electric Hybrids*, Rajneesh Kumar

## *Patents Filed*

Patent application 65083 P1.US - Axial Sliding Bearing with Structural Sliding Surface

Patent application 65225.00.US – Displacement-controlled Hydraulic System for Multi-function Machines

Patent application 65226.00.US – System and Method for Blade Level Control of Earthmoving Machines

Patent application 65227.00.US – System and Method for Enabling Floating of Earthmoving Implements

Patent application 65230.00.WO – System and Method for Pump-controlled Cylinder Cushioning

# 6 Theses Completed in 2009

## *PhD Thesis*

**Seeniraj, Ganesh**. 2009. *Model Based Optimization of Axial Piston Machines Focusing on Noise and Efficiency*, PhD Thesis, Purdue University.

## *Master's Theses*

**Degaonkar, Shekhar**. 2009. *Power Split Transmission for Special Truck Applications*, MS Thesis, Purdue University.

**Garrett, Reece**. 2009. *Investigation of Reducing Energy Dissipation in Axial Piston Machines of Swashplate Type Using Axially Waved Pistons*, MS Thesis, Purdue University.

**Kumar, Rohit**. 2009. *A Study of the Piston Ring – Cylinder Bore Interface for Bent Axis Axial Piston Pump Using an Advanced Computer Model*, MS Thesis, Purdue University.

# 7 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*

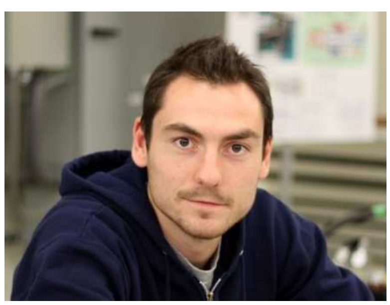
In 2009, the following international students and researchers have worked in our team

Zhao

*Federica*

*Najoua*

Zhao Hui, Wuhan University of Science and Technology (zhao111@purdue.edu)
Federica Franzoni, University of Modena and Reggio Emilia (ffranzo@purdue.edu)
Najoua Jouini, Universität Stuttgart, Germany (njouini@purdue.edu)
Marcel Tkocz, Technical University Dresden, Germany (mtkocz@purdue.edu, mail@tkocz.net)
Marco Zecchi, Università Degli Studi di Parma (mzecchi@purdue.edu)



*Marcel*

*Marco*

# 8 International and National Conferences Attended

**5th Fluid Structure Interaction Conference.** Royal Mare Village, Crete, May 25-27, 2009.
Attendees: Matteo Pelosi (Presenter)

**11th Scandinavian International Conference on Fluid Power (SICFP09).** Linköping, Sweden, June 2 - 4, 2009.
Attendees: Monika Ivantysynova (Session Chair)
Jonathan Baker (Presenter)

**3rd CCEFP Annual Conference.** Greensboro, North Carolina. October 7 - 9, 2009.
Attendees: Monika Ivantysynova (Thrust 1 Leader)
Chris Williamson (Project 1A.2 Presenter and Poster Presentation)
Matteo Pelosi (Project 1B Presenter and Poster Presentation)
Josh Zimmerman (Presenter and Test Bed 1 Poster Presentation)
Marco Zecci (Poster Presentation)

**Bath ASME Symposium on Fluid Power and Motion Control.** Hollywood, California. October 12 - 14, 2009.
Attendees: Monika Ivantysynova (Presenter)
Rich Klop (Presenter)
Rajneesh Kumar (Presenter)
Josh Zimmerman (Presenter)

# 9 Maha in the News

Research at the Maha Fluid Power Research Center has generated quite a lot of public interset. A selection of these articles have been included after the following list of references.

- Boulden, Larry. "Energy-Saving Hydraulics", *Design World*, January 2009.
- EauClaire, Michelle. "Efficient, effective, compact", *OEM Off-Highway*, February 2009.
- Presher, Al. "Four Game-Changing Fluid Power Technology Initiatives", *Design News*, October 2009.

# Energy-Saving Hydraulics

by Larry Boulden, Senior Editor
Friday, January 16, 2009





Hydraulics have won wide acceptance for factory and mobile applications. Traditional strengths of this key technology are centered around power... strength... durability... control. But now, new lines of research are focusing in on efficiency. Check these developments that aim to convert hydraulics from energy-gulpers to dainty sippers.


Small excavator used to test pump-controlled actuation, in which traditional flow-control valves are replaced by with variable displacement pumps.

**Power management with pump-controlled actuators**

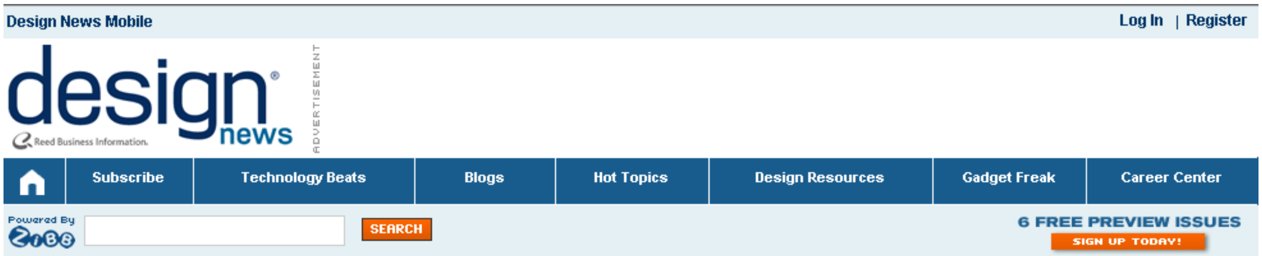
Most mobile hydraulic systems are powered by diesel engines, and they may use more diesel fuel than they have to. A research project at Purdue University, sponsored by the National Science Foundation (NSF) and the National Fluid Power Association (NFPA), is working to test a method for using less power in mobile hydraulic systems.

In a nutshell, the method replaces traditional flow control valves with variable displacement pumps. Rather than connecting multiple hydraulic actuators (cylinders and motors) in parallel to a single pump, each actuator is controlled by smaller, individual pumps. The researchers call this "pump-controlled actuation" or PCA. This approach offers lower power losses and the ability to recover energy, during such tasks as lowering a load. PCA systems also have sufficient flexibility to adjust engine speed and pump displacements to keep the engine operating near its peak efficiency, a technique that is familiar for hybrid vehicles but has not yet been applied to construction machinery. These developments promise to dramatically reduce fuel consumption while simultaneously introducing more sophisticated electronic controls that will improve operator comfort and productivity.

This research is currently being conducted by graduate students Chris Williamson, Josh Zimmerman, and Edward Hughes at Purdue University as part of the Center for Compact and Efficient Fluid Power (CCEFP), a consortium of seven universities and more than 40 companies devoted to advancing the state of the art in hydraulic and pneumatic technology. The project focuses on a compact excavator, although the PCA method is applicable to other machines with multiple actuators that operate simultaneously, such as telehandlers, timber harvesters, and so forth. Detailed simulations have shown that the main source of power loss on these machines is the flow control valves. Common "load-sensing" hydraulic systems attempt to reduce these losses, but are still highly inefficient when multiple cylinders and motors operate simultaneously at different pressure levels. Unfortunately, these machines move multiple actuators almost constantly. The Purdue team's analysis of a 5-ton mini excavator during a typical trenching cycle showed that only about 15% of the engine energy was expended in useful work, and more than 40% of the engine energy was dissipated in valve losses. Pump-controlled actuation eliminates these losses, resulting in a 30 to 40% reduction in total energy for the same duty cycle.

The research team is in the process of building a prototype to confirm these findings. The primary goal is saving fuel, but they also intend to demonstrate other advantages of advanced control systems such as cylinder coordination (for level-bottom trench digging) and manipulator motion optimization. Another CCEFP project at Georgia Tech focuses on force-feedback controls for improving the operator-machine interface.

Industry feedback is cautious on the project so far, citing the increased cost and complexity of adding more pumps to mobile equipment. The researchers respond that these costs diminish with economy of scale and are outweighed by the benefits of higher efficiency and productivity. As the costs of energy continue to rise, this could be an economical solution to the energy problem.



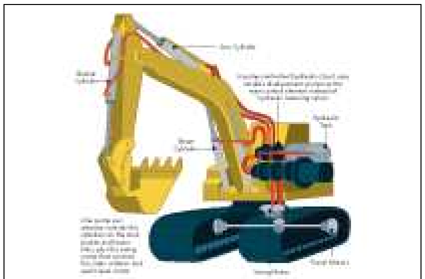

# Four Game-Changing Fluid Power Technology Initiatives

***9.1 From a novel hydro-mechanical system for a hybrid car to a compact, free piston engine for pickups, researchers look to broaden fluid power's reach***

***By Al Presher, Contributing Editor -- Design News, October 1, 2009***

Through the Center for Compact and Efficient Fluid Power, a research consortium sponsored by the National Science Foundation, university teams, along with their industrial counterparts, are working on new technologies that will significantly advance the state-of-the-art in fluid power. Here is a look at four significant initiatives.

## Pump-Controlled Hydraulic Excavator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Researchers at Purdue University are working on a pump-controlled hydraulic circuit that uses variable displacement pumps as the main control element instead of hydraulic valves to power an excavator. The design is very simple, with one pump per actuator to control the cylinders on the stick, bucket and boom links; the swing motor that controls the cabin rotation; and each travel motor.

The variable displacement pumps serve as both the power supply and flow control for the actuators. Pump flow rates are controlled electro-hydraulically by adjusting the pump displacement. The excavator arm is instrumented with position sensors for feedback control. The controller coordinates the actuator motions, allowing the operator to command the bucket trajectory directly for level trenching and vertical lifting.

Elimination of the control valves makes the biggest impact on the new excavator's energy efficiency. The architecture also allows recovery of kinetic and potential energy because the pumps can operate as motors. In all, these efficiency improvements add up to a 50 percent fuel savings for a typical duty cycle.

One technical challenge for the test bed is coming up with the sophisticated engine power management scheme that will be required to adjust the engine speed for efficient operation. Engine power management is a familiar feature in hybrid cars, but has seen only limited application in off-road machinery. The system needs high bandwidth at the actuators, but the engine can't respond as quickly to changes in speeds. Dynamic loads change much more quickly than with a passenger vehicle, so shaking mud from the bucket, for example, requires a very fast response.

OEM Off-Highway
Product development solutions for the off-road market
cygnus

February 12, 2009

# 10 Efficient, Effective, Compact

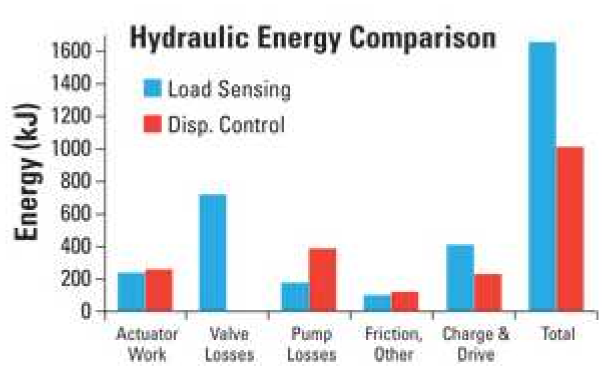
By Michelle EauClaire, OEM Off-Highway

*10.1* The CCEFP brings together students and industry professionals to solve the fluid power industry's biggest dilemmas.

Research is essential for the progression of technology and our engineering capabilities.

The Center for Compact and Efficient Fluid Power (CCEFP) was established in June of 2006 as a National Science Foundation (NSF) Engineering Research Center (ERC). Headquartered in Minneapolis at the University of Minnesota, the center connects fluid power researchers with university faculty in an effort to fill a research void that has developed in the fluid power industry. The CCEFP is currently engaged in over 20 research projects organized into three groups with different goals. One seeks to create more efficient fluid power technologies to reduce petroleum consumption, energy use and pollution. A second focuses on finding a more effective fluid power technology that will be cleaner, quieter and safer for its users. The third will create a more compact fluid power technology to work more cohesively with the evolving equipment landscape.

Professor Monika Ivantysynova (front row, third from right) with CCEFP graduate students and researchers.




Hydraulic Energy Comparison chart

**Project 1A.2**

One such project is 1A.2: Optimal Power Management for Mobile Fluid using Displacement-Controlled Actuators. The project is lead by Professor Monika Ivantysynova at the Maha Fluid Power Research Center at Purdue University, West Lafayette, IN. One of Ivantysynova's graduate students, Chris Williamson says, "The focus of the project is on machines with multiple actuators that work simultaneously, such as excavators and telehandlers." Williamson is responsible for developing the excavator controls.

"The main source of power losses on these machines is the flow control valves," says Williamson. "Even load-sensing systems have high throttling losses when multiple cylinders and motors operate at different pressure levels. Our mini-excavator simulations are showing that more than 40% of the total engine energy is wasted in valve losses during a typical trench-digging cycle. The solution we propose is displacement-controlled actuation, using variable displacement pumps to control the cylinders directly. This eliminates the power losses inherent to valves and allows energy recovery as the pumps can run in motoring mode."

It will also reduce overall machine fuel consumption by avoiding throttling losses and allowing energy recovery. Path optimization and effective engine management could see additional fuel savings. Simulation testing is finding 30-45% savings in total energy (see chart below). The team is currently building a prototype and expecting to have it running by March 1 to verify these findings.

According to the CCEFP website, "The number of professors, graduate students and research projects in hydraulic and pneumatic technology is on the rise. "If these projects are successful, there will be tremendous improvements in components, systems and fluids. If not, a new generation of engineers and scientists with fluid power training will revitalize academic and industrial research in this country for years to come."

**Industry members benefit**

"Our members are companies, not engineers," says CCEFP Director Kim Stelson, Minneapolis. Engineers of member companies can participate actively as a Project Champions. Members have opportunities to meet the researchers and their students, and receive regular updates on the progress of the research projects. All have royalty-free licenses to non-patented discoveries and inventions. They also have access to CCEFP student resumes online, enabling them to identify students available for internships and those approaching graduation. "Getting trained engineers has been a huge problem in fluid power, and we're contributing to that solution," says Stelson. "Our goal is to have every mechanical engineer, and closely related disciplines such as agricultural engineering, know what fluid power is."

# 11 Educational Activities

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

## *ME 597 /ABE 591 – Design and Modeling of Fluid Power Systems Fall Semester 2009*

2009 marked the fifth 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 ap-

ply 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.

**<u>Laboratory Project</u>:**

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! Assistance will be given. Each group needs to make arrangements for performing their tests in the lab with Edat Kaya.
4. Evaluate the test results and complete a report.

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

**Engineering project to be completed during the course**

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

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

**Formulation of problem:**
Students are requested to perform the following work:

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

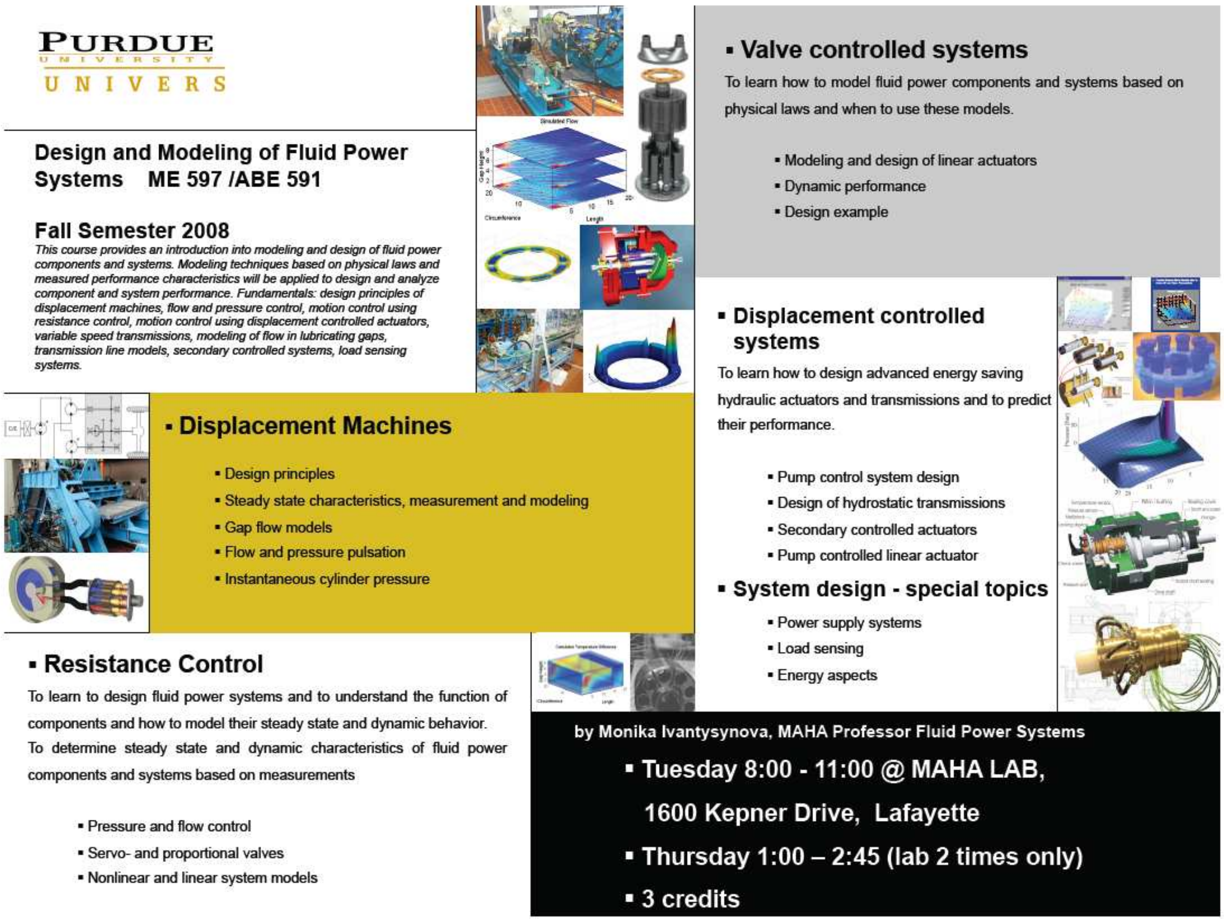
10. Define measurement methods and test procedure for a selected component and your whole actuation system
11. Write the system development report

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

Engineering Science: 1.5 credits or 50%

Engineering Design: 1.5 credits or 50 %

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



## *ABE 691 / ME 697 – Hydraulic Power Trains and Hybrid Systems Spring Semester 2009*

2009 marked the second consecutive year of ABE 691M / ME 697M – Hydraulic Power Trains and Hybrid Systems being offered.

**Course Description:**
ME 697M/ABE 691M Hydraulic Power Trains and Hybrid Systems
1 Semester, 2 Lecture/2 Lab/week, 3 Credits
Prerequisites: ME 475, 575 or ABE 460, ABE 591/ME 597 or ABE 435 or consent of instructor.

The course provides a thorough understanding of continuously variable transmissions and hydraulic hybrid power train systems. It covers the design and modelling 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 are discussed.

**Textbook:** Course Notes

**Coordinator:** M. Ivantysynova, Maha Professor of Fluid Power Systems
**Lecturers:** M. Ivantysynova, R. Klop, K. Williams, R. Kumar, and C. Williamson

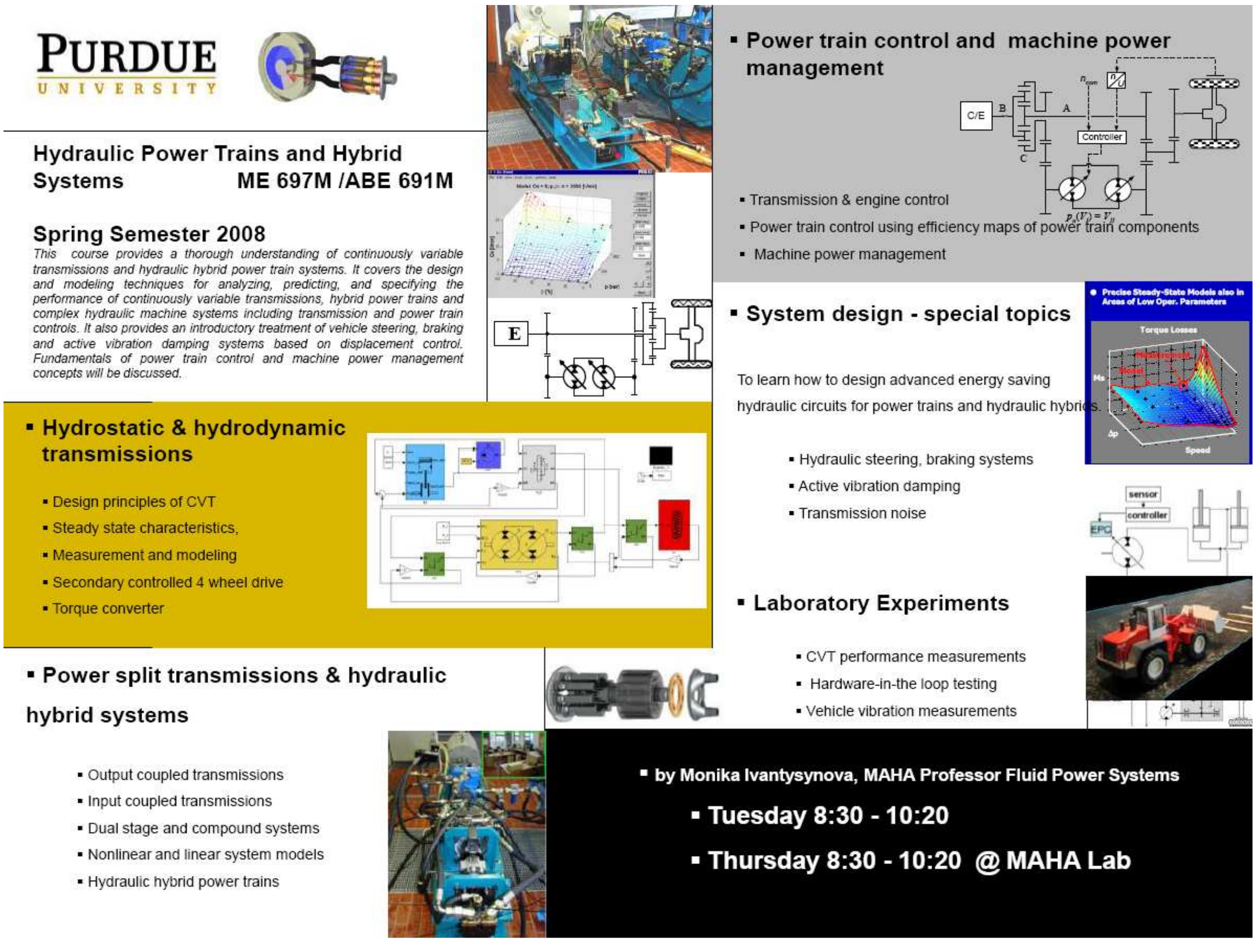
**Goals:**
1. To learn to design, model and analyze continuously variable transmissions (CVT) and hybrid power train systems.
2. To determine steady state and dynamic characteristics of CVT's.
3. To learn how to apply computer software to predict performance of CVT systems and power train structures including controls.
4. To learn how to model and simulate coupled hydraulic-mechanical systems of off-road vehicles and to predict their performance.
5. To become familiar with machine power management strategies for hydraulically powered machinery.

**Topics**
1. Hydrostatic and Hydrodynamic Transmissions
2. Power Split Transmissions and Hydraulic Hybrid Systems
3. Power Train Control and Machine Power Management
4. System Design – Special Topics

**Laboratory Experiments**

1. Hydrostatic Transmission Performance Measurements
2. Hardware-in-the Loop Transmission Testing
3. Power Train Control Performance
4. Vehicle Vibration Measurement

**Grading:** 20 % for each of three design projects and 10 % for each of four measurement reports.



# *ME 463 – Senior Design Spring Semester 2009*

*The hydraulic car*

For the past several years, several teams of undergraduate students have worked on the Maha Fluid Power Research Center's hydraulic car that was originally designed and constructed for the DARPA challenge. The vehicle has progressed through several stages of development. This past spring, a team of undergraduates made several modifications to the vehicle. They changed the steering system from a electrohydraulic skid-steer design to a front-wheel energy efficient displacement controlled hydraulic steering system, making this the first pump controlled (valveless) hydraulically steered vehicle. The team also simplified the controls to a drive-by-wire joystick control system and removed all proportional valves to render the vehicle fully pump controlled. The 2009 team also introduced a hydraulic differential rear wheel drive system and the necessary hydraulic circuitry. The team was formally advised by Dr. Fu Zhao of Mechanical Engineering. Dr. Ivantysynova provided informal consultation as well as use of the Maha lab facilities.

*Hydraulic Pump Controlled Steering System*

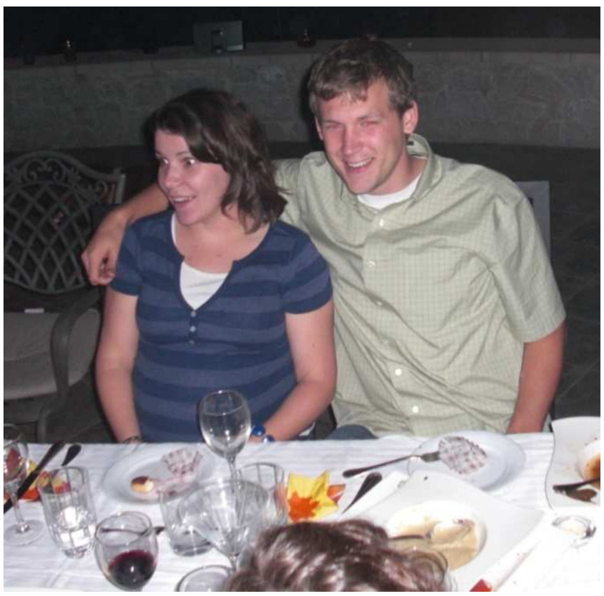
# 12 Maha Social Events

The Maha team isn't always working. Occasionally we get out and have some fun together. Below are some highlights of Maha social events this past year.

## *Celebrating Monika's Birthday Party and Chris, Rajneesh and Rick's PhD Prelim*

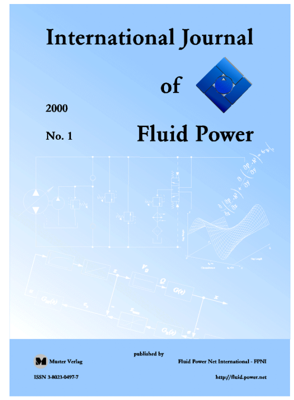
## *Ganesh's PhD Thesis Defense Celebration*

## *Annual Summer Party at Monika's House*



# 13 International Journal of Fluid Power

Dear Associate Editors and Members of Editorial Board,




I announce with great pride that the International Journal of Fluid Power has completed its 10th year of publication. The third and final issue of the tenth volume was printed and sent to our readers this past November. This was the 30th issue of the Journal, and we look forward to the 31st to be published this coming March.

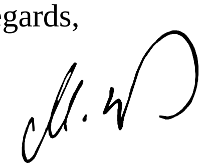
I would like to express my gratitude to all of the members of the fluid power community for your continuous support for the Journal, especially for reviewing papers and submitting manuscripts. In addition, I would like to thank all of the Associate Editors for their great assistance and advice. Having 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 2010.

The journal has been online since 2006 at http://journal.fluid-power.net. This online access has definitely strengthened the position of the journal and increased the number of citations. I mentioned last year that in 2009 we were requesting re-evaluation by the scientific citation index. The request was filed this summer and we hope to get good news within the next year.

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 29 different fluid power software tools and introduced 29 fluid power research center spanning 4 different continents. There have been authors from 32 different countries that have submitted papers to the International Journal of Fluid Power during the last ten years. Twenty papers were submitted to the journal in 2009, which is stable but down slightly from the 26 papers submitted last year. Approximately half of the papers submitted came from the United States and Canada. 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 40%.

Again, I would like to express my thanks to all for your continuous support of the Journal. I wish you and your family a happy and healthy Holiday Season, a Happy New Year, and all the best for 2010.

Best regards,



Monika Ivantysynova
Editor-in-Chief

# 14 Maha Team in 2009


**Maha Faculty**

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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

Jonathan Baker
Master's Graduate
jebaker@purdue.edu
Phone: (765) 448-1456
BS: Davidson College
MS: Purdue University
Origin: USA
June 2006-July 2009


Jim Bartlett
Master’s Student
jcbartle@purdue.edu
Phone: (765) 449-7980
BS: Purdue University
Origin: USA
July 2008-May 2009


Michael Cross
Master's Student
macross@purdue.edu
Phone: (765) 449-7980
BS: Univeristy of
Tennessee at Knoxville
Origin: USA
April 2009-present


Shekar Degaonkar
Master's Graduate
cdegaonk@purdue.edu
Phone: (765) 449-7980
BS: Dr. BA Marathwada
University, India
MS: Purdue University
Origin: India
July 2006-June 2009


Reece Garrett
Master's Graduate
ragarret@purdue.edu
Phone: (765) 448-1456
BS: Brigham Young
University
MS: Purdue University
Origin: USA
June 2007-May 2009


Edward Hughes
Master’s Student
echughes@purdue.edu
hone: (765) 449-7980
BS: Purdue University
Origin: USA
July 2007-April 2009

Roman Ivantysyn
Master's Student
rivanty@purdue.edu
BS: Purdue University
Origin: Germany
May 2009-present

Richard Klop
PhD Student
rklop@purdue.edu
Phone: (765) 449-7514
BS: Michigan State
MS: Purdue University
Origin: USA
August 2005-present

Matt Kronlage
Master's Student
mkronlag@purdue.edu
Phone: (765) 449-7514
BS: Iowa State
MS: Purdue University
Origin: USA
July 2009-present

Rajneesh Kumar
PhD Student
rajneesh@purdue.edu
Phone: (765) 449-7980
BS: Indian Institute of Technology, Madras, India
MS: Purdue University
Origin: India
July 2006-present

Rohit Kumar
Master's Student
kumar35@purdue.edu
Phone: (765) 448-1456
BS: Birla Institute of Technology, India
Origin: India
August 2007-November 2009

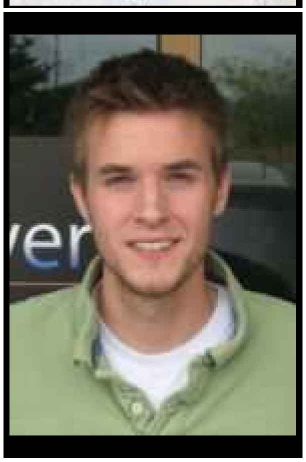
Shinok Lee
Master's Student
lee20@purdue.edu
Phone: (765) 449-7980
BS: Purdue University
Origin: South Korea
July 2008-present

Jacob Mcleod
PhD Student
jmcleod@purdue.edu
Phone: (765) 448-1456
BS: Kettering University
Origin: Michigan, USA
August 2009-present

Matteo Pelosi
PhD Student
mpelosi@purdue.edu
Phone: (765) 449-7514
BS, MS: Università Degli Studi di Parma
Origin: Italy
September 2007-present

Jess Rose
Master's Student
jessrose@purdue.edu
Phone: (765) 448-1456
BS: Brigham Young University
Origin: Washington, USA
August 2009-present

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



Kyle Williams
PhD Student
krwillia@purdue.edu
Phone: (765) 449-7980
BS, MS: Purdue University
Origin: USA
May 2005-July 2009

Ganesh Seeniraj
Post Doctoral Researcher
gseenira@purdue.edu
BS: College of Engineering, Guindy, Anna University, Chennai, India
MS: Kettering University
PhD: Purdue University
Origin: India
August 2004-March 2009, August 2009-present

Brent Warr
Master's Student
bwarr@purdue.edu
Phone: (765) 449-7980
BS: Brigham Young University
Origin: Utah, USA
August 2009-present

Josh Zimmerman
PhD Student
zimmerjd@purdue.edu
Phone: (765) 449-7980
BS: Brigham Young University
MS: Purdue University
Origin: USA
August 2006-present

Chris Williamson
PhD Student
williaca@purdue.edu
Phone: (765) 449-7980
BS: Brigham Young University
MS: Purdue University
Origin: USA
August 2005-present

# Visiting Researchers

Marcel Tkocz
Master's Student
mtkocz@purdue.edu
Phone: (765) 448-1456
BS: Technical University Dresden
Origin: Germany
August 2008-May 2009

Marco Zecchi
Visiting Researcher
mzecchi@purdue.edu
Phone: (765) 449-7514
MS: Università Degli Studi di Parma
Origin: Italy
March 2009-November 2009

Najoua Jouini
Visiting Researcher
njouini@purdue.edu
BS: Stuttgart University
Origin: Tunisia
May 2009-present

Federica Franzoni
Visiting Researcher
ffranzor@purdue.edu
BS: University of Modena and Reggio Emilia
Origin: Italy
June 2009-December 2009

Zhao Hui
Visiting Researcher
zhao111@purdue.edu
BS-Ph.D: Harbin Institute of Technology
Origin: China
Sept 2009-present

## Summer Undergraduate Students

Andreu Husien
Undergraduate
ahusien@purdue.edu
BS: Purdue University
Origin: Jakarta, Indonesia
SURF Summer 2009

Paul Kalbfleisch
Undergraduate
pkalbfle@purdue.edu
BS: Purdue University
Origin: Kentucky, USA
SURF Summer 2009

Jamie Scott
Undergraduate
Email:
jmscott@purdue.edu
BS: Purdue University
Origin: Indiana, USA
SURF Summer 2009

Nathan Strong
Undergraduate
Email:
jnstrong@purdue.edu
BS: Purdue University
Origin: Tennessee, USA
Summer 2009

## Maha Staff

Edat Kaya
Maha Lab Manager
Email: ekaya@purdue.edu
Phone: (765) 448-1587
Dipl.-Eng.: Hamburg University of Applied Science
Origin: Germany
August 2005-present

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

# 15 Visitors & Guests

France A. Córdova – Purdue University (President)
William R. Wilson – Purdue University (Provost)
Robert A. Hyde – AM General (Project Manager)
Jeffrey T. Dowell – AM General (Director of Engineering)
Brent Rajaniemi – AM General (Engineer of International Research and Development)
James B. Amish – General Engine Products, Inc. (Manager of Engineering Operations)
Wendy Woodson – Purdue University Provost
France Cordova – Purdue University President
Stefan Heitzig – RWTH Aachen
Klaus Roosen – Parker Hannifin Corporation, Germany (System Engineering Manager)
Daniel Whitman – Parker Hannifin Corporation
Joe Kovach – Parker Hannifin Corporation
Ray Collett – Parker Hannifin Corporation
Dwight Stevenson – Husco
Matthew A. Franchek – University of Houston (Professor of Mechanical Engineering)
Elton Daniel Bishop – Digital Hydraulic Solutions (Manager)
Cesni Ennis – Purdue University, Development Office (Assistant Director of Foundations Relations)
Linda Terhune – Purdue University, College of Engineering (Senior writer and managing editor)
Blake Carl – Parker
Dan Hirleman – Purdue University, School of Mechanical Engineering (Professor and Dept. Head)
Farshid Sadeghi – Purdue University (Professor of Mechanical Engineering)
Dr. Michael Ramage – Exxon Mobile (retired Executive VP)
Dr. Jay Gore – Purdue University (Professor, Director of the Energy Center)
BYU Hydraulic Race Car Team – BYU
Tom Woody and Students – Ivy Tech (Professor)
John Schneider – Purdue University (Assistant vice President for Industry Research)
Sandy Fleeter – Purdue University (Distinguished Professor, Mechanical Engineering)
Glenn Marlow – Vestas-American Wind Technology, Inc. (Brand Manager)
Marc Lewis – Indiana Michigan Power (Vice President, External Relations)
Akin Ecer – IUPUI (Professor, Mechanical Engineering)
Dimitrios Peroulis – Purdue University (Assistant Professor, Electrical and Computer Engineering)
Jie Chen – IUPUI, (Professor, Mechanical Engineering)
Hazim El-Mounayri – IUPUI (Associate Professor, Mechanical Engineering)
Bob Kramer – Purdue-Calumet (Associate Professor of Physics)
Oleg Wasynczuk – Purdue University (Professor, Electrical and Computer Engineering)
Steve Pekarek – Purdue University (Professor, Electrical and Computer Engineering)
Otto Doering – Purdue University (Professor of Agricultural Economics)
Yerlan M. Ramanculov – National Center for Biotechnology of the Republic of Kazakhstan(General Director)