Maha Fluid Power
RESEARCH CENTER
PURDUE UNIVERSITY

2015 Annual Report

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Maha Professor of Fluid Power Systems

Volume I

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Preface

The Maha Fluid Power Research Center has completed another very successful year. With an average of 50 graduate students and visiting scholars conducting research we have kept the size of our research team on the Center's highest level since establishment of the Center in 2004. Additional Maha funds were used to create a new Maha teaching lab facility and enlarge the research lab by adding another $200m^2$ of lab space this last year. We are proud to share our discoveries, breakthroughs and innovations in this annual report. This year we decided to split the report in two volumes, volume one will include the achievements and findings of my own research team and volume two the accomplishments of Andrea's team.

In 2015 my own research team successfully continued our research efforts of introducing a new generation of energy efficient hydraulic actuation and drive systems. We also continued our various efforts in discovering the secrets of the operation of positive displacement machines and creating advanced models for virtual prototyping of these important system components. The first test run of the Maha hydraulic hybrid SUV in July 2015 was definitely the highlight of Maha's research achievements this past year. Our research team was able to design and build the world's first hydraulic hybrid SUV utilizing Maha's novel blended hybrid architecture within 10 months. With this project, our research team has not only demonstrated its expertise in power train technology but also its strength in successful team work. My special thanks go to Taylor Bleazard and Mike Sprengel for their leadership and Anthony Franklin for his professional contributions to this car project. The project was supported by Danfoss, Hydac, Sun Hydraulics, ExxonMobile, Casappa and Durst. I would like to thank those companies for sponsoring this exciting project.

Another important research highlight was the successful machine demonstration of Maha's displacement controlled hybrid excavator with an advanced swing control and smooth pump switching technology. The machine demonstration was part of the lab tour conducted during the 2015 Summit of the Industry Engagement Committee (IEC) of the National Science Foundation funded Center for Compact and Efficient Fluid Power (CCEFP). Maha hosted the Summit in June 2015. More than 100 participants from industry and academia had the opportunity to test the new hybrid excavator and also to test drive Maha's other prototype machines such as the world's first wheel loader with a displacement controlled steer by-wire steering system allowing variable steering ratio, variable steering effort, and active safety. Also this last May, Maha again organized and hosted the REU Bootcamp of the NSF Center for Compact Efficient Fluid Power (CCEFP) providing a crash course in fluid power for undergraduate students from various US universities.

Other major breakthroughs and discoveries in 2015 include the successful demonstration of the first implementation of active vibration damping of the swash plate on one of our pump test rigs, the successful operation of our new measurement robot automating the sound intensity and sound power measurements in our semi-anechoic chamber and the completion of the first version of our "high definition" (HD) fluid structure interaction code for simulation of the piston/cylinder interface. This code for the first time allows for the investigation of the fluid film behavior in areas of extreme low film thickness with higher resolution of the fluid grid. The comparison of simulation results with friction force measurements conducted on our tribo test rig shows very promising results. This represents another important discovery in understanding the main physical effects in pump and motor tribological interfaces. Moreover I am very proud to report that our patent on "Axial sliding bearing and method of reducing power losses thereof" which we had filed in 2009 finally was issued as US patent #9,115,748 B2 on August 25, 2015.

In 2015 Maha researchers presented their findings at key international fluid power conferences. Damiano Padovani presented his research on novel actuation systems for rail way machines at the Scandinavian International Conference in Tampere in May 2015. Michael Sprengel attended the IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling where he gave a talk about our implementation of the novel blended hybrid in a sports utility vehicle – "The Maha rangerover". I am proud to report that our paper on *Adaptive Robust Motion Control of an Excavator Hydraulic Hybrid Swing Drive,* which Enrique Busquets presented at SAE Commercial Vehicle Engineering Congress (ComVec) in Chicago has been selected as SAE COMVEC Congress Technical Paper for SAE Journal Publication. In October, Enrique Busquets, Meike Ernst, Hiral Haria, Damiano Padovani and Ashley Wondergem presented their research findings at the ASME/Bath Symposium on Fluid Power and Motion Control in Chicago. It was at this ASME/Bath conference that I had the great honor of receiving the ASME 2015 Robert E. Koski Medal for significant contributions in the area of analysis, design and control of axial piston pumps and hydrostatic-transmission systems, which are used to transmit fluid power in automotive, industrial and aerospace applications; and for efforts to create paths to disseminate fluid power research results. For that reason I was also invited to give the Koski lecture, which I entitled "*Quo Vadis Fluid Power*".

Also in 2015 the Maha Research Center received major donations from industrial partners, which helped us to develop and implement new test rigs, the hydraulic hybrid SUV and further improve our prototype machines. My special thanks go to Danfoss, ExxonMobile, Ford, Sun Hydraulics, Parker Hannifin, Moog, Bobcat, Hydac, Bosch Rexroth, Casappa, Hydraforce and Concentric for donating major equipment and components to the Maha lab. Big thanks also to Ken and Susan Warren who continued their support of Maha again this past year.

Tyler Bleazard completed his Master thesis on "Hydraulic Hybrid Four Wheel Drive Sport Utility Vehicle - Utlilizing the Blended Hybrid Architecture" in July 2015 and left Maha to start working for ExxonMobile. After five years at Maha Mike Sprengel who has been one of the key contributors to our hydraulic hybrid and powertrain research, defended his PhD thesis in December 2015. Mike left Maha to work for CZero, a startup company in Colorado. We wish both of them a great start in their new jobs and hope to get some exciting new collaborations started soon.

I would like to thank all team members for their outstanding contributions in 2015. My special thanks go to Anthony Franklin and Susan Gauger for their professional help, excellent support and enthusiasm. I hope you will enjoy 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 the Maha Fluid Power Research Center much success during 2016.

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

Contents

1 Research Activities

Our research efforts on revolutionizing fluid power technology with complete new system architectures, controls and component design methods continued in 2015 leading to several breakthroughs, which will be described in this section. Our research activities can be broadly divided into two main areas:

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

In general the research activities involve extensive computational, experimental and theoretical work. During the last seventeen 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.

Our research activities are focused in five main areas:

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

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

1. Research into Efficient Hydraulic Actuation and Drive Systems

Advanced Energy-Saving Circuits for Hydraulic Actuation

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

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

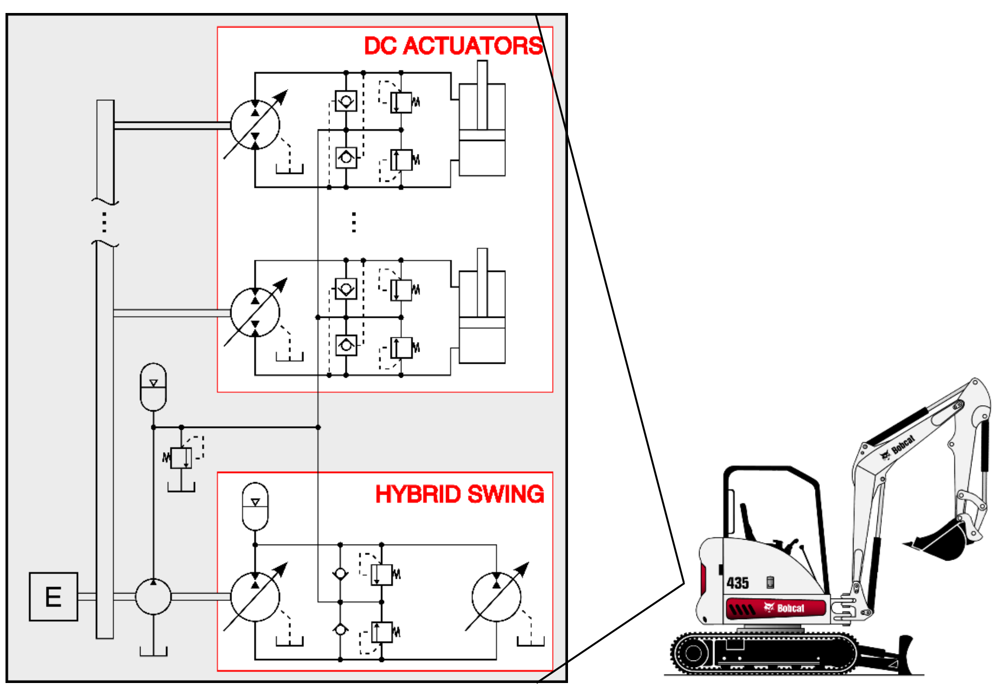


Figure 1: Series-Parallel (S-P) Hybrid Pump-Controlled Excavator Architecture

A novel hydraulic hybrid excavator architecture (Figure 1) was proposed by Zimmerman and Ivantysynova (SICFP, 2011), which retained DC actuation for the boom, arm and bucket functions while employing a series-parallel hydraulic hybrid swing drive. The predicted savings for this new system derive from a possible 50% engine downsizing, while meeting aggressive digging cycles. Using a conservative power management scheme in simulation, predicted fuel savings reached 52% over the standard, valve-controlled 5-t excavator and 20% fuel savings over the non-hybrid DC architecture.

In 2015, the main task in the excavator prototype was to study and develop both an actuator and a supervisory controller for the hydraulic hybrid swing drive. The actuator-level controller objective for this application was to demonstrate that the new architecture is capable of delivering conventional or superior swing operability. Measurements on the prototype of three different control strategies were obtained for the secondary-controlled architecture under a constant high pressure accumulator pressure and constant engine speed. The results show that the excavator drive achieves almost perfect tracking when commanded with a typical 90° truck-loading cycle. Additionally, due to the flexibility of the electronic controls, the swing velocity profile can be very easily modified to satisfy different operation styles.

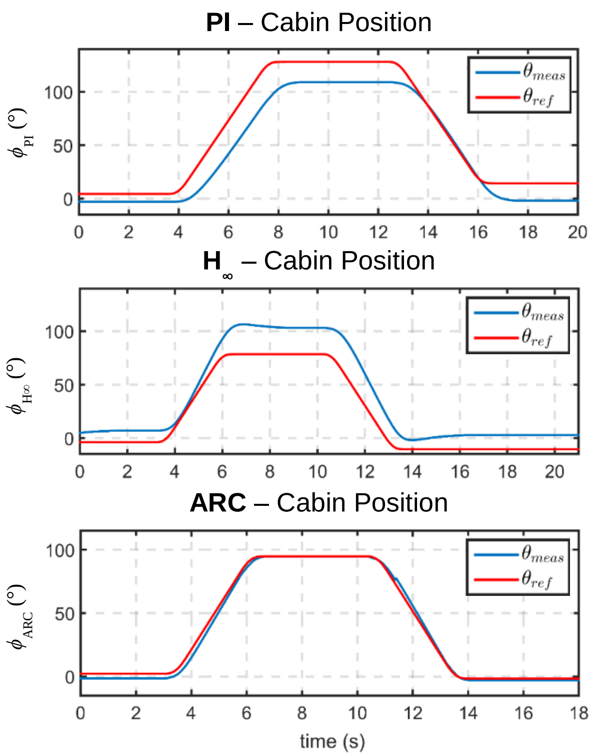


Figure 2: Measurements of the hydraulic hybrid drive position for three different control strategies

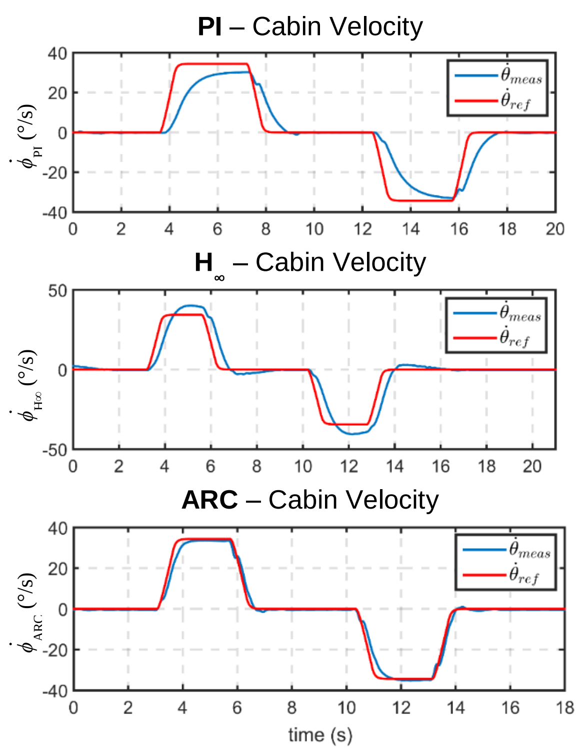


Figure 3: Measurements of the hydraulic hybrid drive velocity for three different control strategies

Since a constant high pressure accumulator pressure and a constant engine speed operation of the secondary controlled swing is meaningless for the hydraulic hybrid, a supervisory-level controller is a must to effectively manage the energy flows in the system, thereby enabling the predicted engine downsizing. This task was achieved through the use of an energy-based feed-forward instantaneous optimization that takes into account the amount of energy demanded by the DC actuators, the amount of energy provided by the engine and the amount of energy stored, recovered or demanded by the hydraulic hybrid swing drive, to minimize engine speed, maximize the hydraulic units' displacements and efficiently utilize the energy from the high pressure accumulator. Figure 4 to Figure 8 show the measured results for a single 90° truck loading cycle.

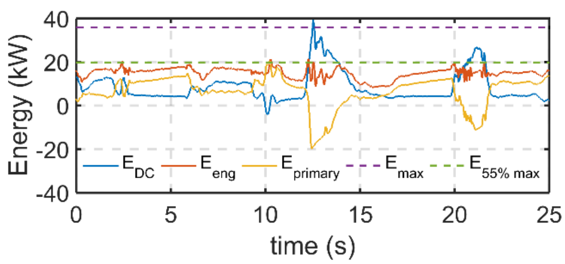


Figure 4: System energies

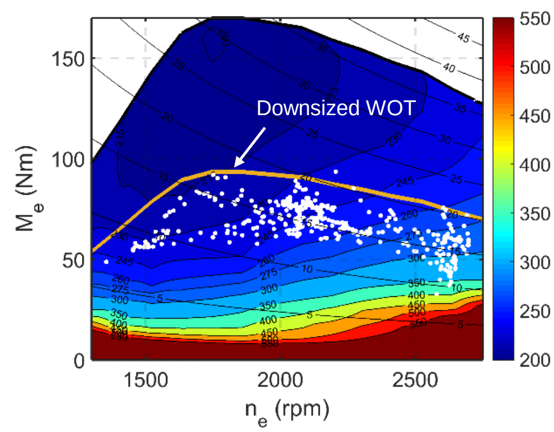


Figure 6: Engine operation

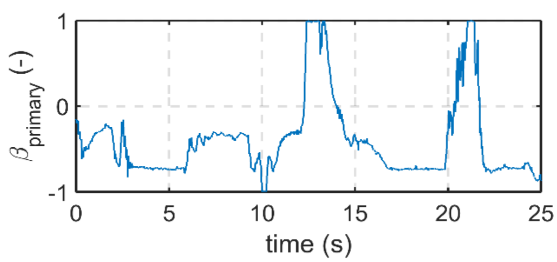


Figure 5: Primary unit displacement

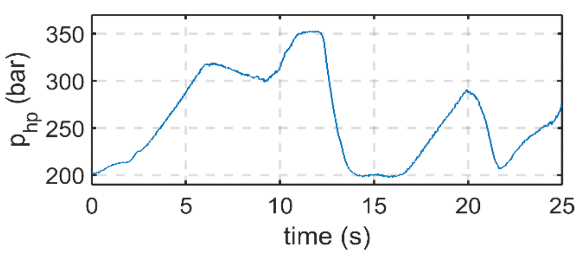


Figure 7: Hybrid accumulator pressure

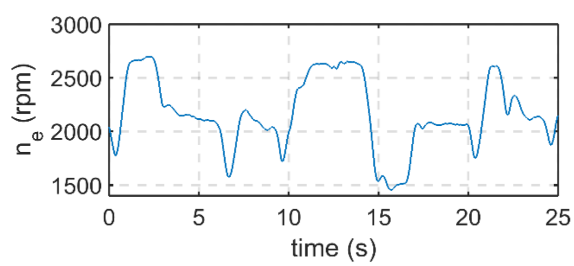


Figure 8: Engine speed

In addition to the investigation of the hydraulic hybrid swing drive, the investigation of DC actuation with pump switching was conducted at Maha. This concept was born from one of the major obstacles for DC multi-actuator machines: the increased production costs due to the one-pump-per-actuator requirement. Up to 2011, research in DC technology at Maha mainly focused on architectures with one pump per actuator. This certainly increases machine production costs especially for large machines where for traditional DC operation the required pump sizes or number are very large. The concept of pump switching was simulated and implemented on a test rig validating its benefits and allowing to create control concepts to mitigate its challenges. With this in mind, a hydraulic architecture was proposed for the mini excavator prototype. The hydraulic circuit of the proposed idea is shown in Figure 9.

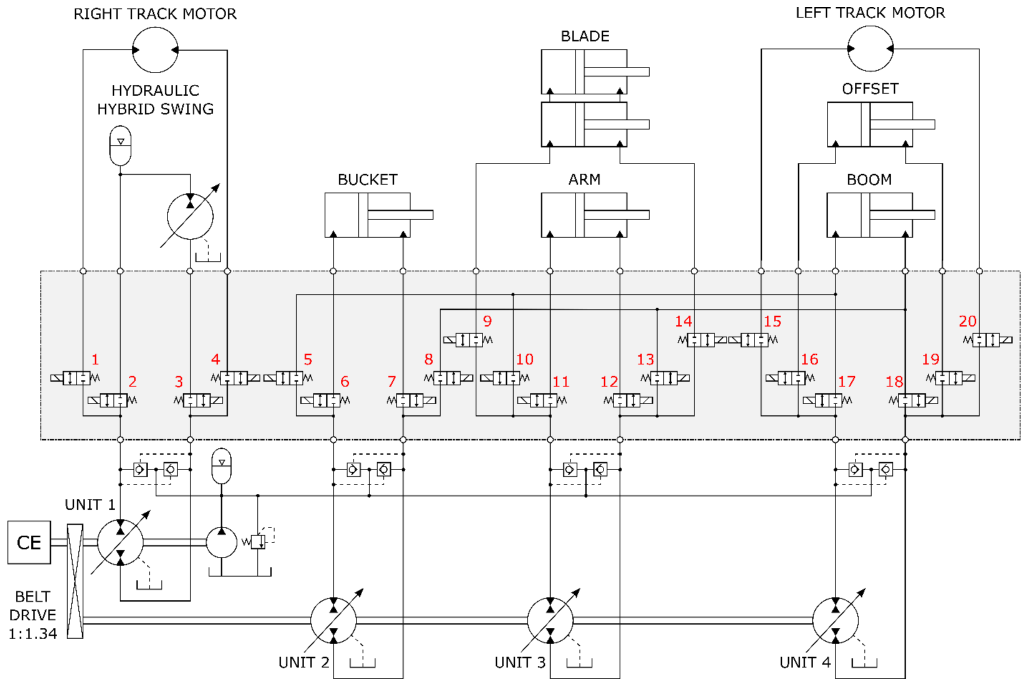


Figure 9: Hydraulic hybrid excavator prototype hydraulic circuit

Measurements of the proposed controller show that the concept is achievable on the actuator level. This is evident by the pressure and actuator position transients observed in Figure 10 a), where no controls were applied, and the complete mitigation off the effects of pump switching shown in Figure 10 b), where proper controls have been implemented.

In addition to the actuator-level controls, supervisory-level controls allow for full exploitation of the pump switching concept. To manage DC actuation with pump switching, a generalized supervisory controller that makes use of operator commands and the total number of actuator combinations (given the excavator architecture) was developed. A search algorithm is employed to index a combination matrix, as shown in Table 1, containing the commanded actuators and transmit these to the corresponding switching valves, hydraulic units and actuators (in this case 1: right track, 2: left track, 3: swing, 4: boom, 5: arm, 6: bucket, 7: blade and 8: offset). Ultimately, the combination of pump switching actuator and supervisory-level control algorithms leads to more efficient, reliable and better performing multi-actuator systems with greatly improved operability.

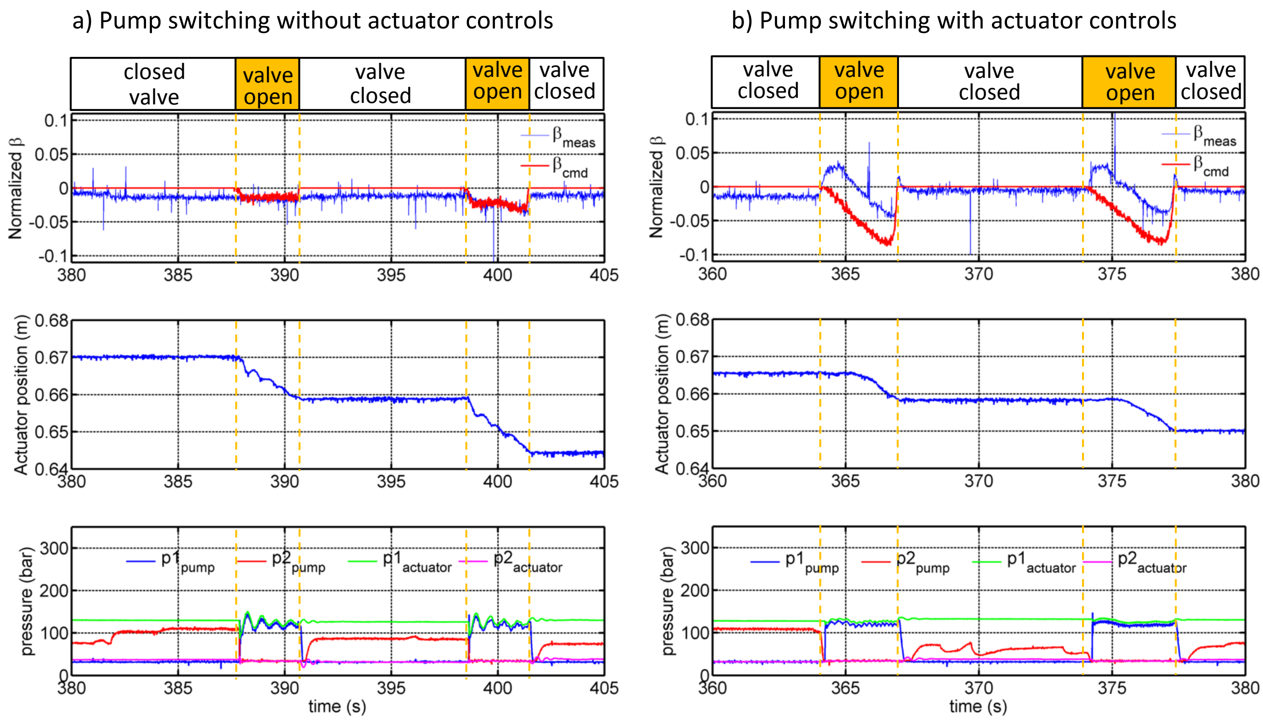
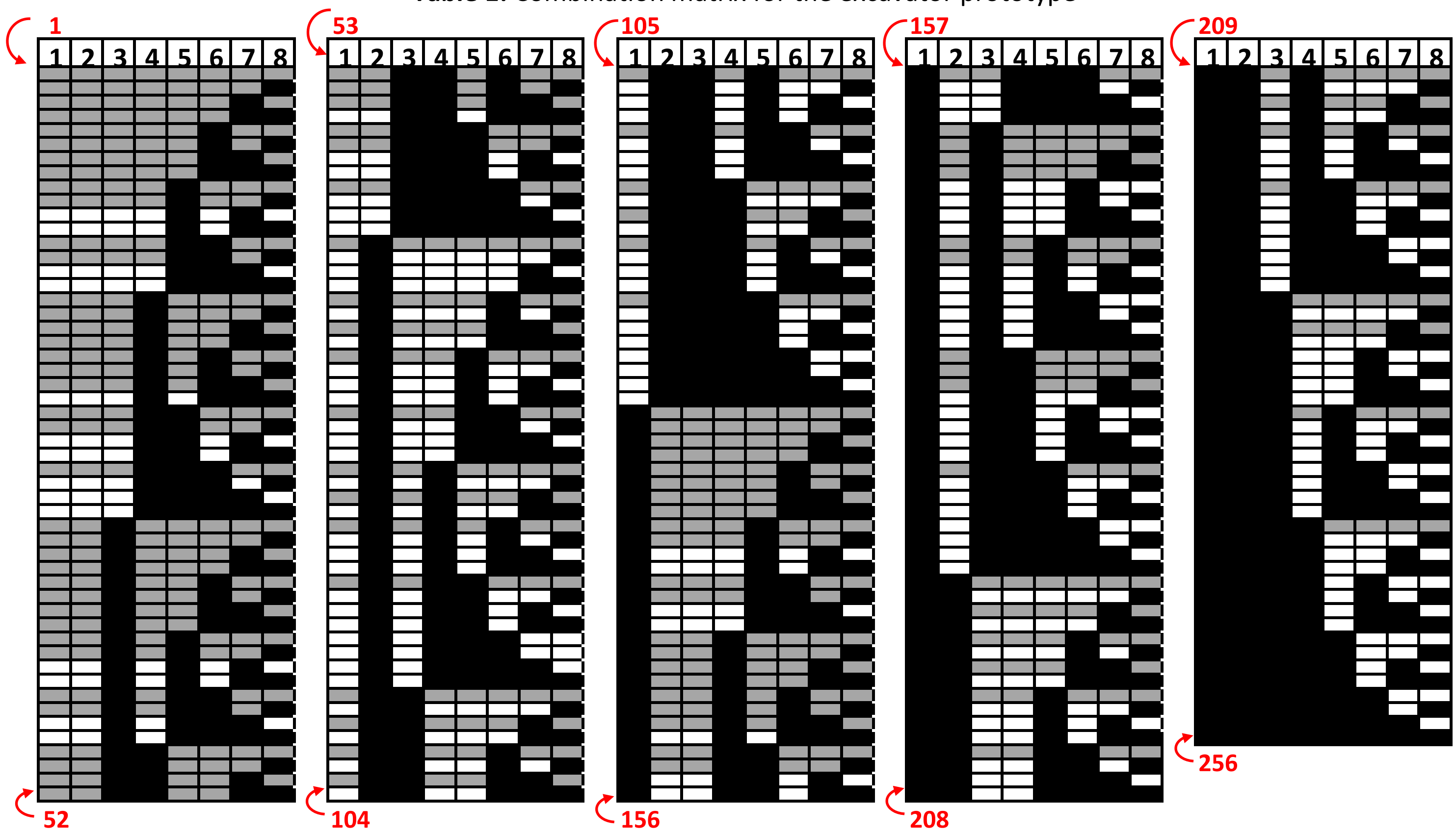


Figure 10: Measurements of the actuator level control pump switching under a moderate load

Table 1: Combination matrix for the excavator prototype



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

Pump displacement control (DC) is an energy-efficient alternative to traditional valve control. A novel steer-by-wire (SBW) technology based on DC actuation is under current research and development. A hydraulic schematic of the proposed system is shown in Figure 11 below. The actuator (8) velocity is controlled by adjusting the pump (2) speed, displacement, or both. The differential fluid flow between the single-rod actuator's uneven sides is overcome by means of pilot-operated check valves (6). The low pressure system has its own fixed displacement charge pump (4) that provides continuous flow to the cylinder's low pressure side. The low pressure level setting is controlled via a pressure relief valve (5). The system is protected against over-pressurization by means of high pressure relief valves (7). The pump control system (3) consists of a proportional control valve that meters flow to a double rod actuator that is mechanically coupled to the pump swash plate.

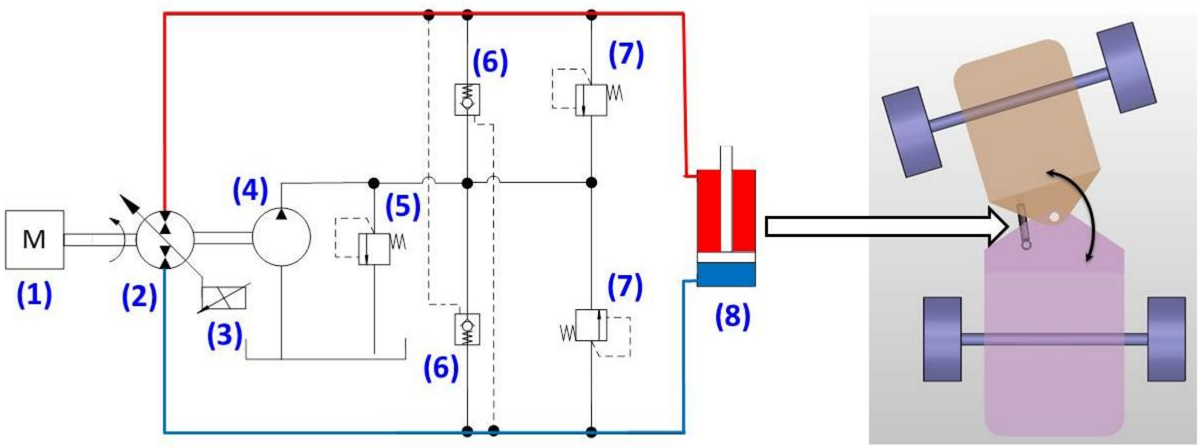


Figure 11: DC electro-hydraulic steering system – hydraulic schematic

Two main components are required by the DC steering system: a dedicated variable displacement pump and a tactile feedback device to control the steering wheel torque level. The two subsystems are controlled by an on-board electronic control unit (ECU) and vary based on vehicle speed, articulation angle, and steering wheel velocity as depicted in Figure 12.

A high-fidelity nonlinear dynamic model is generated for the entire vehicle system, which includes a hydraulics module and a mechanics model as shown in Figure 13. The hydraulics subsystem is modeled in MATLAB Simulink® environment, while the mechanics subsystem is modeled in MSC Adams software. Linear models are derived for each of the hydraulics and the mechanics subsystems, and the two models are coupled at the steering actuator interface. The mechanics subsystem is based on a multi degrees-of-freedom vehicle dynamics model based on Lagrangian mechanics principles. The hydraulics subsystem includes the pressure build-up equations of the steering actuator chambers. The obtained model is a linear time-invariant (LTI) single-input single-output (SISO) system with pump displacement as its input and articulation angle as its output.

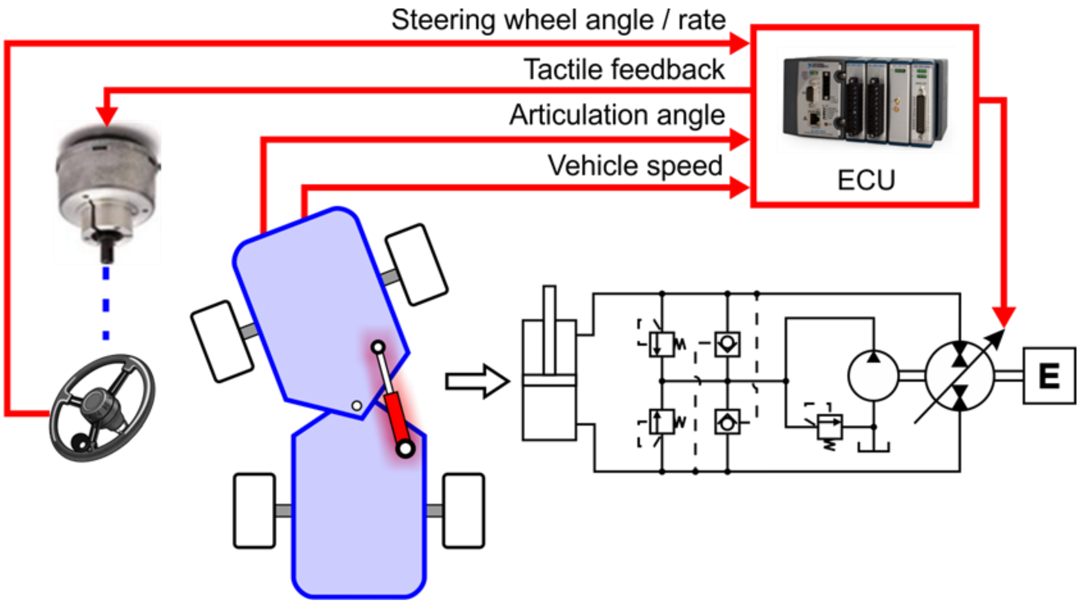


Figure 12: DC steering system depiction

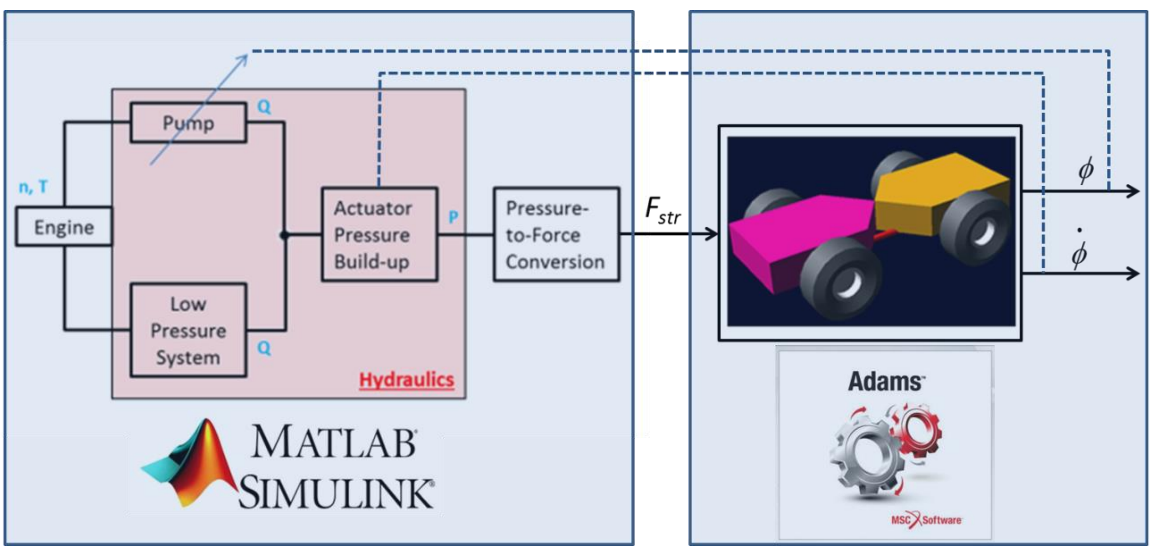


Figure 13: Block diagram of steering system dynamic model

A linear control law that includes feedforward and feedback is designed as shown in Figure 14.

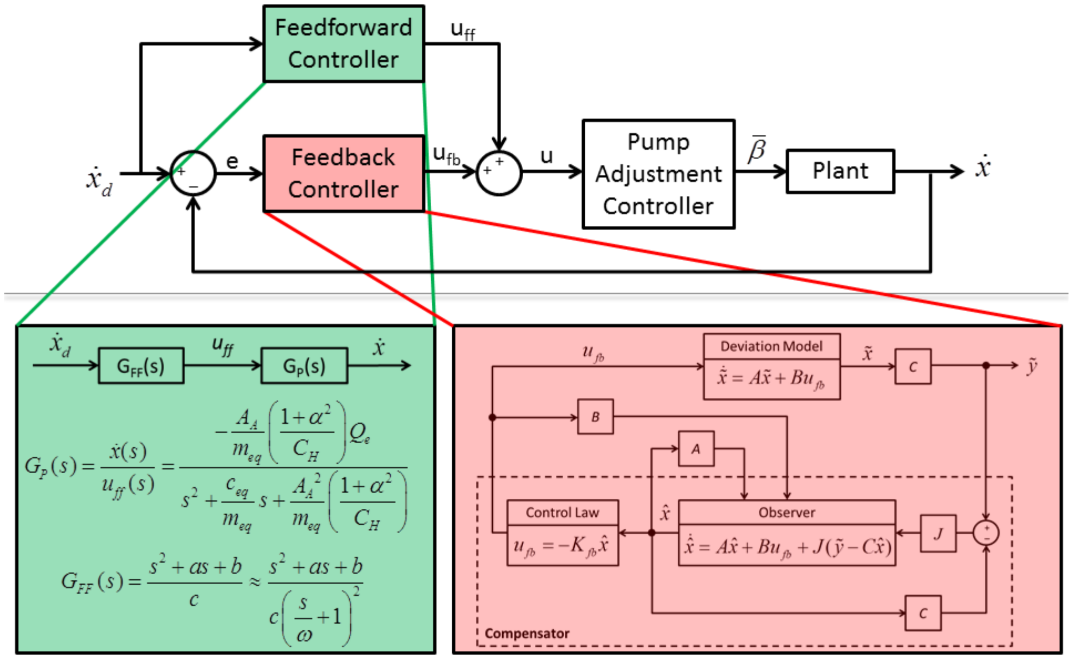


Figure 14: DC steering system controller structure

A designated prototype test vehicle, a compact 5-ton wheel loader, is overhauled to retrofit a DC steering system, which includes the following main hardware components as shown in Figure 15: a variable displacement axial piston pump (dashed red) dedicated to the steering actuator, a proportional control valve (dashed green) to adjust the swash plate angle, a gear type charge pump (dashed blue) to supply flow to the low pressure source, and a tactile feedback device (dashed orange) to provide torque feedback at the steering wheel. For research and algorithm development purposes, a load-cell torque sensor (dashed yellow) is installed to measure driver effort, and a slip ring (dashed purple) is used for cable management (infinite no. of rotations).

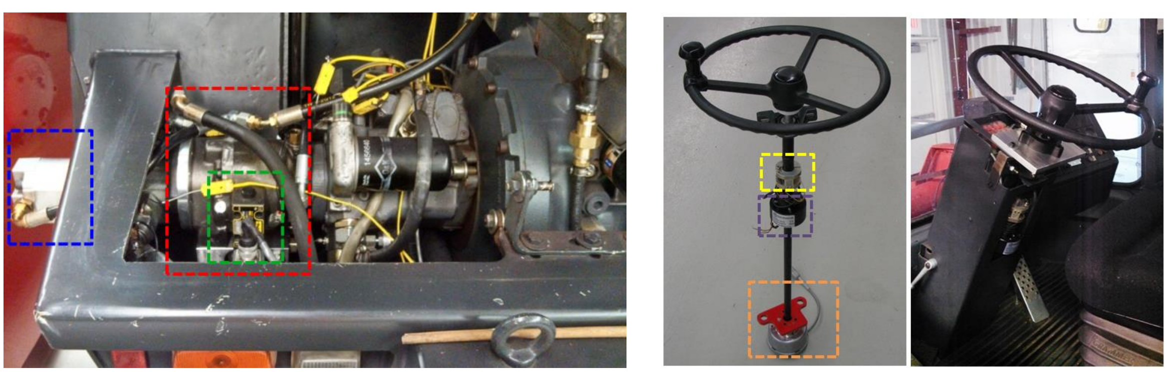
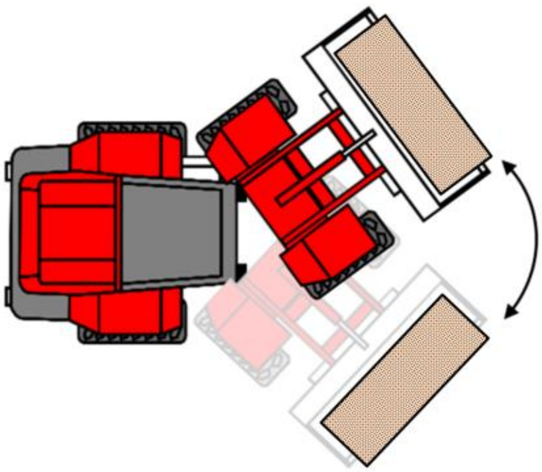


Figure 15: New DC steering system hardware components

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



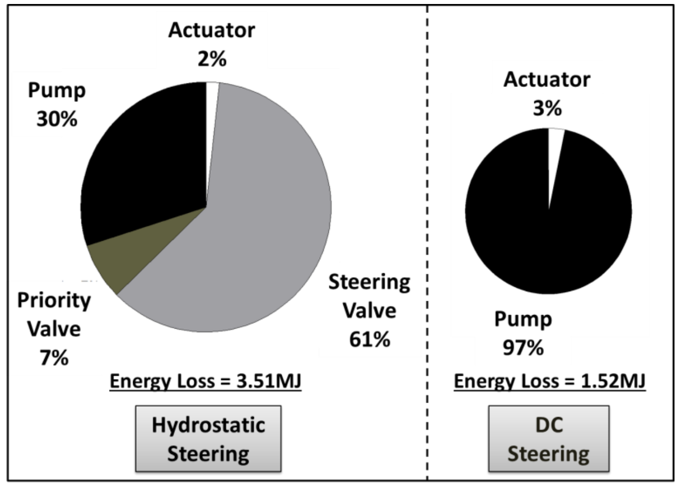


Figure 16: Steering-only cycle (left) and energy losses comparison (right)

The reduced energy losses of the DC steering system translate into 14.5% fuel-savings, 22.6% increased productivity, for an overall fuel usage efficiency boost of 43.5% as shown in Table 2. Fuel consumption is measured by weighing the mass of an auxiliary fuel tank pre- and post-testing. Steering work is computed by integrating the product of steering torque and articulation velocity over the event time. Fuel efficiency is determined by taking the ratio of steering work done per fuel mass consumed.

Table 2: Systems fuel consumption, productivity, and efficiency comparison

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

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

A standard dynamic maneuver, J-Turn, was utilized to evaluate the effectiveness of the stability control algorithm. To induce lateral instability at low-to-moderate speeds that off-highway vehicles typically travel at, a low friction surface was modeled. As depicted in Figure 17, the purpose of the stability controller is to get the vehicle to follow the desired path by the operator, up to the allowable adhesion limits of the road surface. When the yaw stability control system is inactive, the vehicle skids sideways and tracks a larger curvature path, or in some instances loses control and spinout.

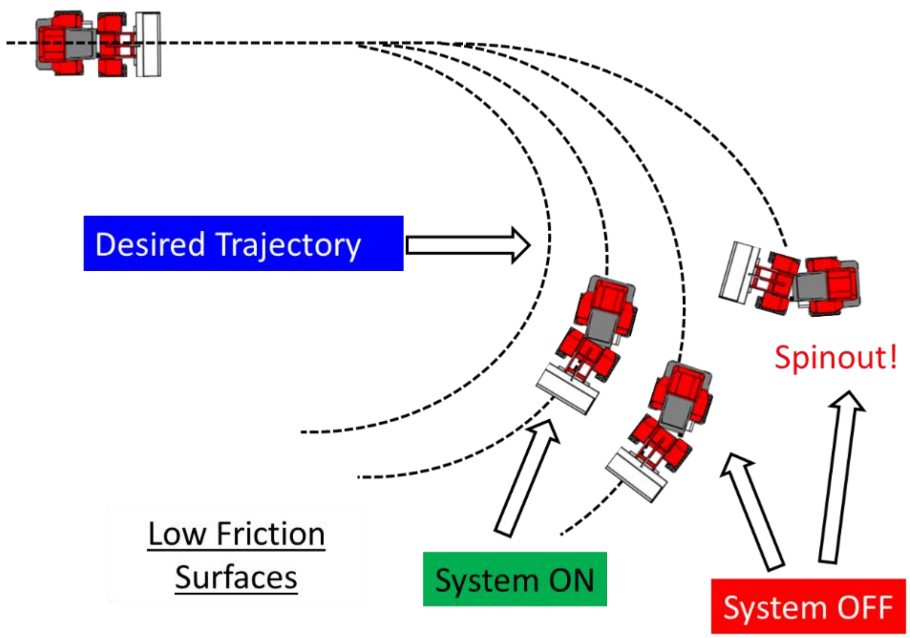


Figure 17: J-Turn maneuver on low friction surfaces

A suitable test track was selected to have the appropriate size and surface conditions that allow for conducting dynamic maneuvers at appropriate speeds in a controlled manner. The prototype test vehicle has a maximum speed of 20km/h. Therefore, in order to induce lateral instabilities in the prototype vehicle, a low friction surface is required. The selected test track is paved with gravel, thus the road surface is composed of snow-covered gravel as shown in Figure 18. Several J-Turn maneuvers are conducted at 20 km/h with the stability control system turned on and off. The results are shown in Figure 19.

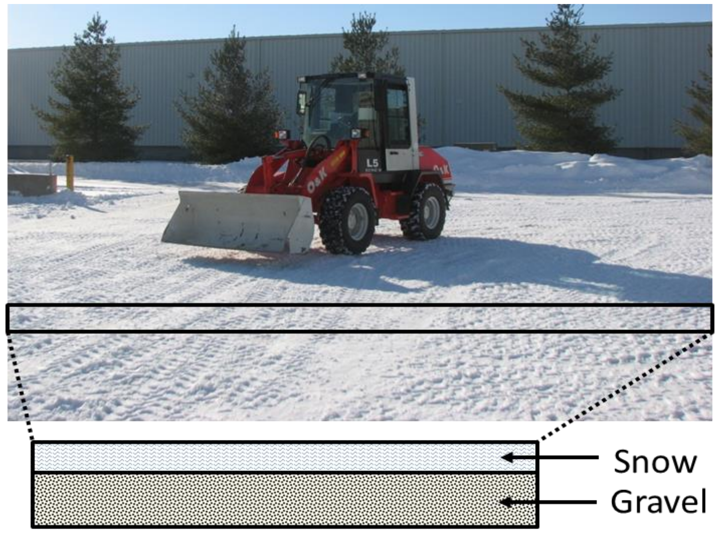


Figure 18: Low-friction surface composition

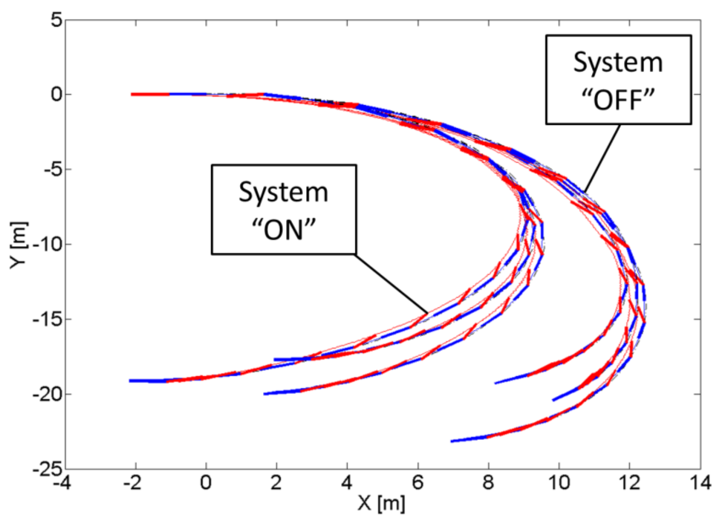


Figure 19: J-Turn maneuver experimental results

Given that in most real-world applications not all of the system states can be measured, for various considerations, the concept of virtual sensing gains favorability for its effectiveness and convenience in providing critical information that would otherwise be hard or costly to retrieve. In this case, a virtual sensor that estimates an articulated frame steering vehicle's front frame yaw angle rate is investigated for its application in the vehicle active yaw stability. Figure 20 shows the block diagram of the designed observer structure.

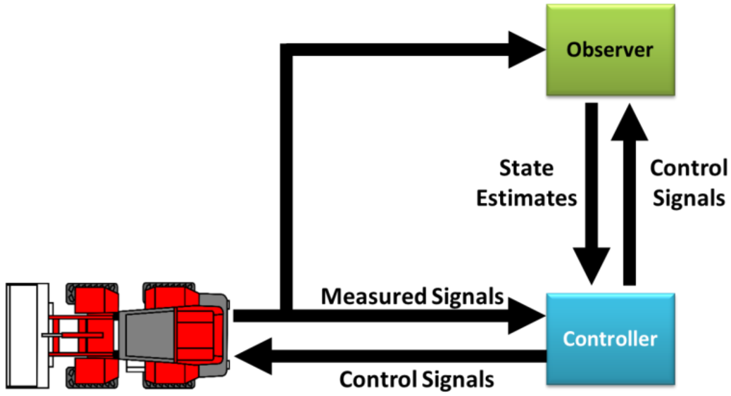


Figure 20: State observer block diagram

To permit executing numerical simulations and conducting measurements on the prototype test vehicle, a controller was first designed to meet specified performance criteria relative to command tracking, response, and stability. An LQE observer design is selected for implementation on the test vehicle, and the results for the comparison between the yaw rate virtual sensor and the measured yaw rate are shown in Figure 21.

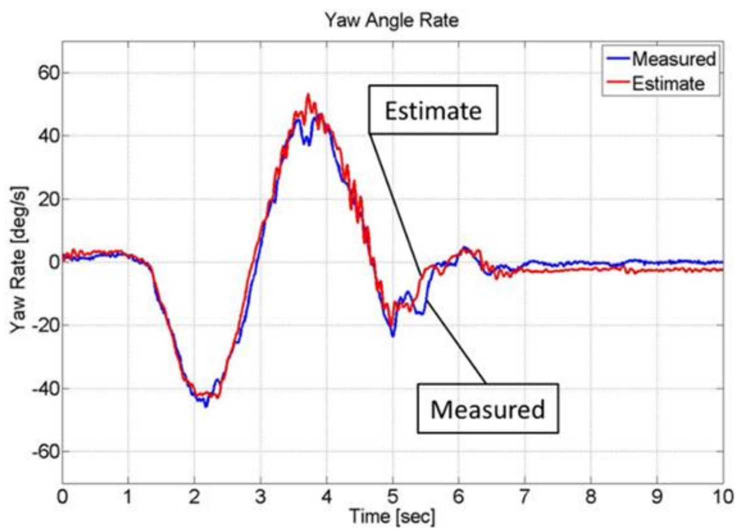


Figure 21: Yaw rate measured and estimated quantities for a lane changing maneuver

In the realm of automotive, agricultural, construction, and earth-moving equipment industries, an additional highly desired feature that has been steadily trending is the capability to offer remote and autonomous operation. One scenario for implementing remote operation, which has gained favorability in the past decade, is by having a central command station where one or more expert human operators can deploy, monitor, and control multiple machines to perform a certain task or set of tasks. At the same time, machines that are equipped with appropriate sensors can be programmed to perform certain tasks without real-time control by a human operator. In the case where machines are required to perform precise motion maneuvers, a global position system (GPS) sensor can be utilized to accurately guide the machine with a precision that can be superior to that of an expert human operator. The new DC steering technology was retrofitted for this purpose. For this work, XBee Series 1 modules are selected given their signal reliability, relative ease of programming and setup, adequate operating range, and reasonable cost given the application on hand. The new system setup is shown in Figure 22.

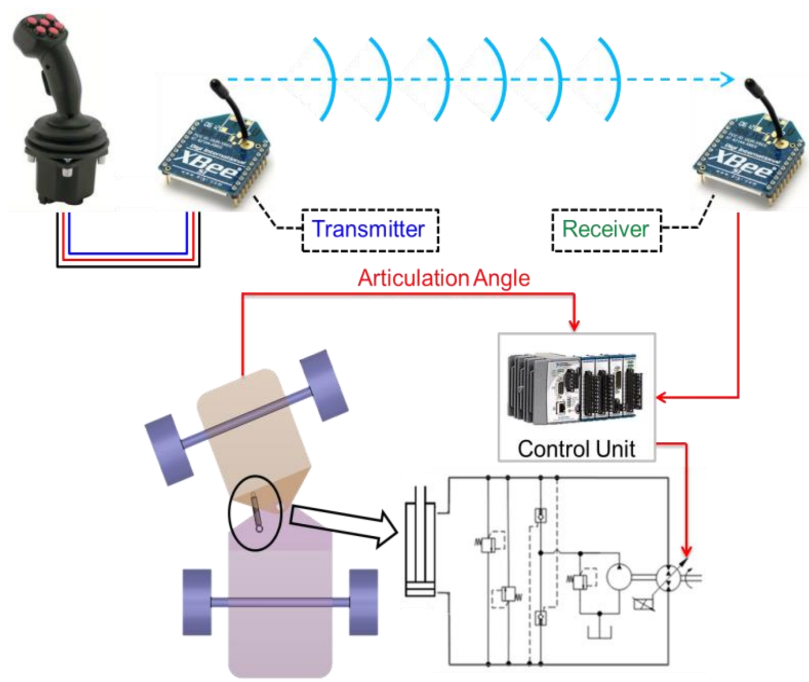


Figure 22: Wireless remote control of DC steering system

2. Advanced Energy-Saving Hybrid Powertrains

Research in this area focuses on investigating the feasibility and performance of alternative powertrain technologies for a variety of on-road and off-highway applications. The aim is to develop system concepts for minimizing fuel consumption and exhaust emissions without negatively affecting vehicle performance or driver perception. Research into hybrid powertrains is supported by custom high fidelity simulation models built in-house using a mix of governing equations and empirically derived component models. To aid in powertrain analysis a sophisticated globally optimal control algorithm has also been developed based on dynamic programming. This algorithm, which can be directly applied to high fidelity simulation models, enables researchers to explore the full capabilities of a given architecture. Simultaneously optimal control provides insight into how best to control a system. Research activities are further supported through steady state pump/motor testing, two dynamic hardware-in-the-loop transmission dynamometers, and a hydraulic hybrid demonstration vehicle. Current areas of research include:

- Investigating novel hydraulic hybrid architectures such as the blended hybrid
- Exploring drivability and driver perception through a hydraulic hybrid demonstration vehicle
- Optimal control of hybrid transmissions to aid in vehicle baselining and optimal sizing
- Development of supervisory control schemes using techniques such neural networks

Novel Blended Hybrid Architecture

During 2015 research continued on a novel transmission architecture for on-road and off-highway vehicles. Termed a "Blended Hybrid" this architecture was originally proposed by Sprengel and Ivantysynova in 2012 (Figure 23) and has several advantages over existing hydraulic hybrid transmission configurations. At its core the blended hybrid combines a hydrostatic transmission with a uniquely connected high pressure accumulator. This partial separation of power transmission from energy storage enables the blended hybrid to maximize efficiency through an optimal combination of system pressure and unit displacements. In contrast conventional series hybrids require the transmission to function at the current accumulator pressure, often resulting in inefficient operation at high pressures and low unit displacements. The hydrostatic path also enables the blended hybrid to rapidly increase pressure to meet the driver's demand yielding a powerful and responsive transmission. This is counter to series hybrids, which due to the compliance inherent in their high pressure accumulators, permit only a relatively slow change in system pressure. The inability of series hybrids to rapidly change pressure may result in sluggish response and poor driver feel if the current system pressure is insufficient to meet the driver's demand, a deficiency which is solved with the blended hybrid architecture.

Finally the blended hybrid removes the need for over center units connected to the wheels which may have benefits in certain applications.

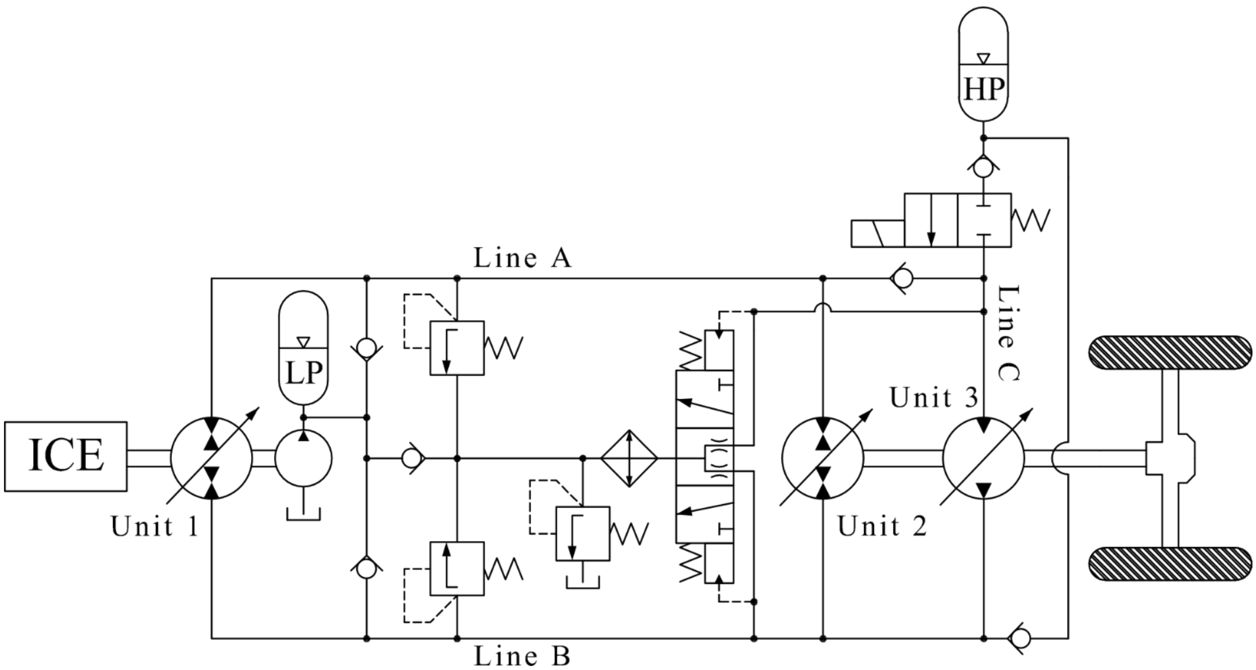


Figure 23: Blended hybrid architecture

During 2015 two research papers, a master's thesis, and a PhD dissertation were published focusing on the blended hybrid architecture. Certainly one highlight of 2015 was the successful conversion of a SUV into a blended hybrid demonstration vehicle. In the first research paper Bleazard et al. details a unique approach to optimal sizing which was used to specify components for this demonstration vehicle. Next Sprengel et al. published a research paper covering the implementation and initial testing of the blended hybrid SUV. A more in depth discussion of the blended hybrid vehicle's sizing, construction, and testing was then given by Bleazard in his master's thesis. Finally Sprengel detailed the past four years of research into the blended hybrid in his PhD dissertation.

Blended Hybrid Demonstration Vehicle

Over the past four years a number of researchers at the Maha Fluid Power Research Center have contributed to the blended hybrid. Select achievements include a detailed comparison of the blended hybrid to competing architectures using optimal control, the proposal of a power split version of the blended hybrid, development of system level controls schemes to replicate the feel of a conventional vehicle, supervisory power management control schemes, and concept validation through hardware-in-the-loop testing. What has not, and cannot, be evaluated in simulation or HIL testing is driver perception. To explore drivability, as well as showcase the technology, an all-wheel drive Ranger Rover was converted into a blended hybrid demonstration vehicle (Figure 24).

Figure 24: Blended hybrid demonstration vehicle

One early goal of the blended hybrid powertrain conversion was to make the final implementation look and feel like a conventional on-road vehicle. An important aspect of this was to create a clean and compact packaging where most all powertrain components would fit underneath the vehicle. This was achieved as seen in Figure 25 with only the low pressure accumulator being placed in the vehicle's cargo area.

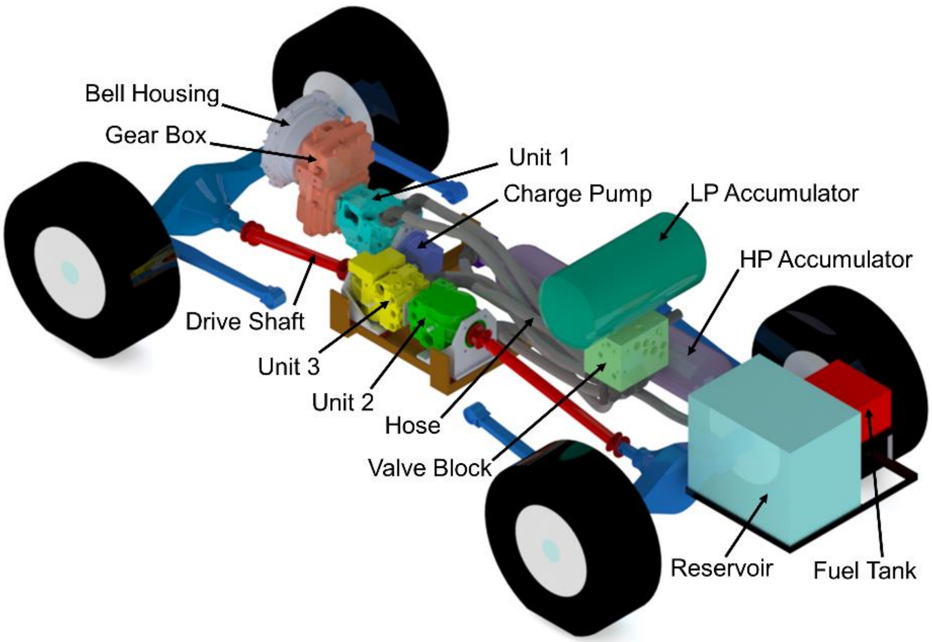


Figure 25: CAD render of the blended hybrid's packaging

A more detailed view of the blended hybrid's implementation and packaging is shown in Figure 26.

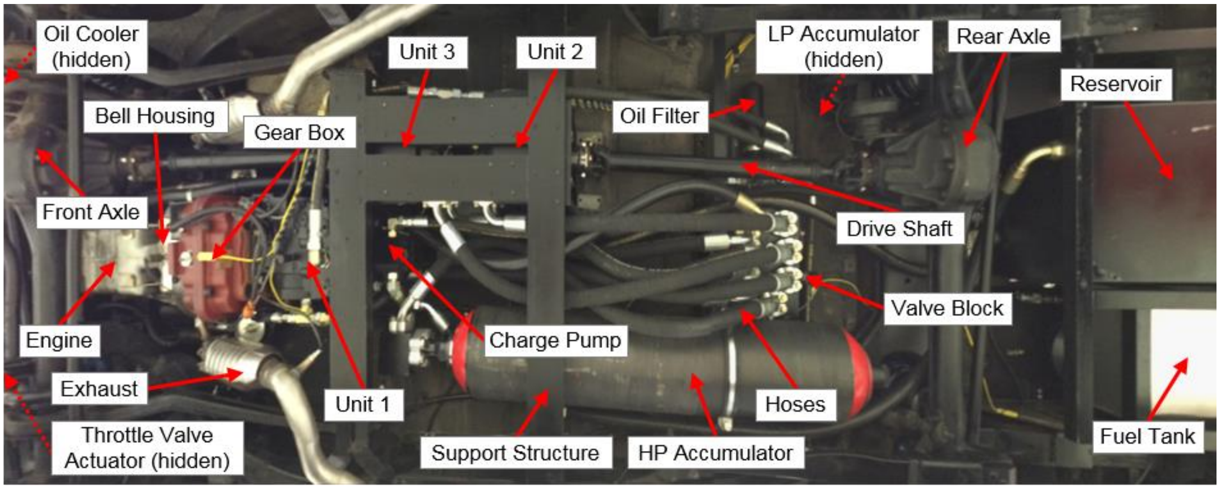


Figure 26: Underbody of the blended hybrid demonstration vehicle

Another important goal of this research was to ensure the blended hybrid possessed a driver feel similar to conventional on-road vehicles. Especially challenging was the blended hybrid's hydrostatic driving mode, an operation which is used almost exclusively off-highway. Had the blended hybrid's hydrostatic mode been controlled in the conventional manner, the demonstration vehicle would have felt more like a wheel loader or tractor. Instead researchers at the Maha lab developed a unique control approach which allowed the driver to continue controlling the engine throttle in the same manner as a conventional vehicle. Unseen by the driver, several layers of control strategies adjusted unit displacements in order to control the powertrain's effective transmission ratio. This can be thought of in a similar manner as to an automatic transmission changing gears. However in this case the blended hybrid has the advantage of an infinitely variable transmission. Fuel efficiency and performance was further enhanced by coupling this lower level transmission control with a supervisory power management control scheme. Measurements from on-road testing of the blended hybrid using this control approach are shown in Figure 27.

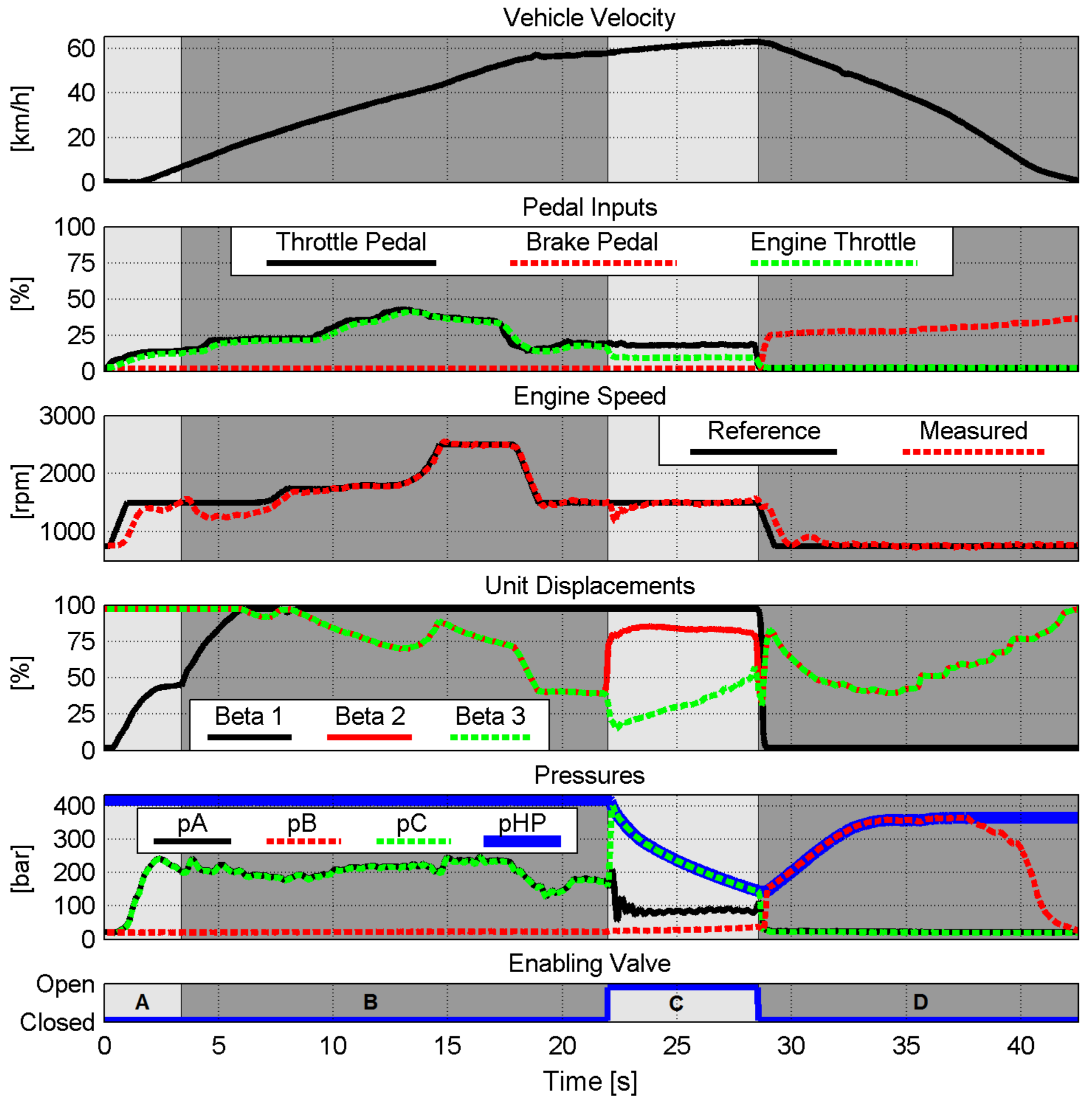


Figure 27: On-road testing of the blended hybrid demonstration vehicle

All of the researches involved with the blended hybrid would like to extend a special thanks to several industrial sponsors including Casappa, Danfoss, Durst, ExxonMobil, Hydac, and Sun Hydraulics for making this demonstration vehicle possible.

Neural Network based Power Management

Another new area of research in 2015 was the application of Neural Networks (NN) to the power management of hydraulic hybrids. Many approaches to power management have been investigated to date, yet none of them can achieve the globally optimal performance of Dynamic Programming (DP). Though highly effective, DP cannot function as an implementable control scheme due to its requirement for complete *a priori* cycle knowledge. Yet analysis of DP optimizations still provides valuable insight. These optimal control studies showed that engine speed and accumulator pressure are the two principle free states which can be controlled to maximize the fuel efficiency of series hybrids. For engine speed, DP analysis shows that fuel efficiency is generally maximized by operating the engine at the minimum speed required to satisfy the instantaneous power demand, regardless of the broader drive cycle. The same analysis also shows that optimal accumulator pressure is strongly influenced by past, present, and future driving demands. These findings indicate that if the optimal accumulator pressure can be predicted, tracked, and combined with a minimum engine speed, then an implementable control scheme can achieve near globally optimal fuel efficiency. To the end researchers at the Maha lab proposed training a NN to generalize the trends contained within the globally optimal state trajectories extracted from DP. Specifically it was found that a NN, supplied with the previous thirty seconds of vehicle velocity, could be trained to predict the near optimal accumulator pressure for a series hybrid powertrain. A schematic of the neural network designed for optimal pressure prediction is shown in Figure 28.

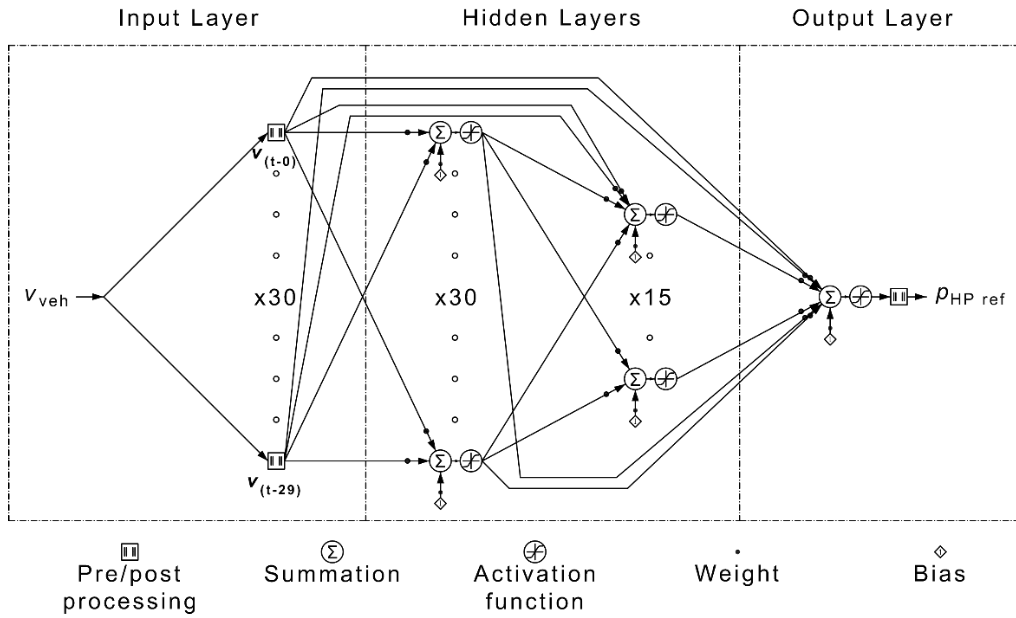


Figure 28: Schematic of neural network used for pressure prediction

Construction of the predictive NN proceeded by training the network to generalize trends between vehicle velocity and optimal accumulator pressure over a 24 hour/750 km long optimally controlled training cycle. The NN's predictive performance was then investigated using an evaluation cycle. This evaluation cycle, which the NN was not trained on, provided an indication of how well the NN could generalize and apply the trends learned from the training cycle to unknown driving events. Figure 29 shows the NN's predictive performance for a segment of both the training and evaluation cycles.

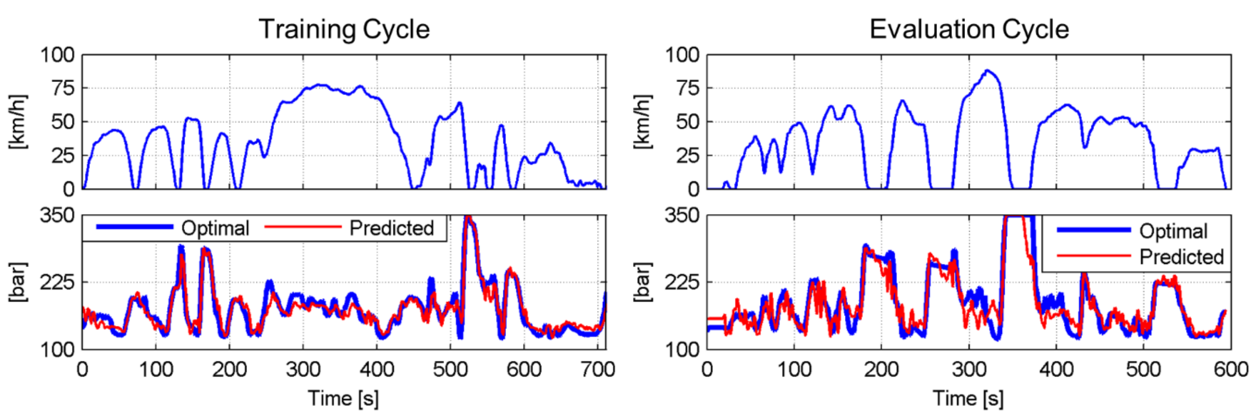


Figure 29: Training and evaluation cycles

The neural network based power management controller was then evaluated in both simulation and measurements. In simulation the NN controller achieved an average fuel consumption rate within 6.7% of the DP globally optimal valve for two evaluation cycles. To further explore the proposed controller a series hybrid was constructed on a hardware-in-the-loop transmission dynamometer. This test rig allowed a complete series hybrid transmission to be run repeatedly over a given cycle while changing only the power management controller, making it an ideal tool for this investigation. A baseline 275 bar constant pressure control strategy was also tested on the HIL dynamometer to evaluate how the proposed approach compared with an existing strategy. Measurement results showed the NN based power management controller improved the average fuel consumption rate by 22.4% compared to the 275 bar constant pressure strategy for two evaluation cycles. These measurement results highlight the NN's ability to learn and generalize optimal trends from DP, and apply them to new and untrained situations.

Optimal Control

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

High Fidelity Powertrain Modeling

One of the principle drivers for using hydraulic hybrid transmissions in many applications are the advantages gained by combining an infinitely variable transmissions with energy recovery and storage. However in order to fully and accurately model these systems, the highly non-linear loss behaviors of all powertrain components must be fully considered. In fact these non-linear losses are often such that analytical models are insufficient accurately describe their behavior. In these cases detailed empirical model are essential for generating high fidelity system models. While empirical models for both engine and vehicle operation are often obtained from outside sources, the Maha lab has made detailed loss measurements on a wide range of hydraulic units which enable very high fidelity transmission modeling. Over the years researchers at the Maha lab have compiled and validated a set of component models in MATLAB Simulink which enables various powertrain configurations to be rapidly constructed and evaluated. An example of a blended hybrid power split transmission being simulated is shown in Figure 30. This tool enables researchers at the Maha lab to rapidly change system architectures and predict, with a high degree of accuracy, how a given system will perform. These component libraries can also be optimally controlled with a new dynamic programming algorithm develop at the Maha lab further increasing the range of discoveries now possible.

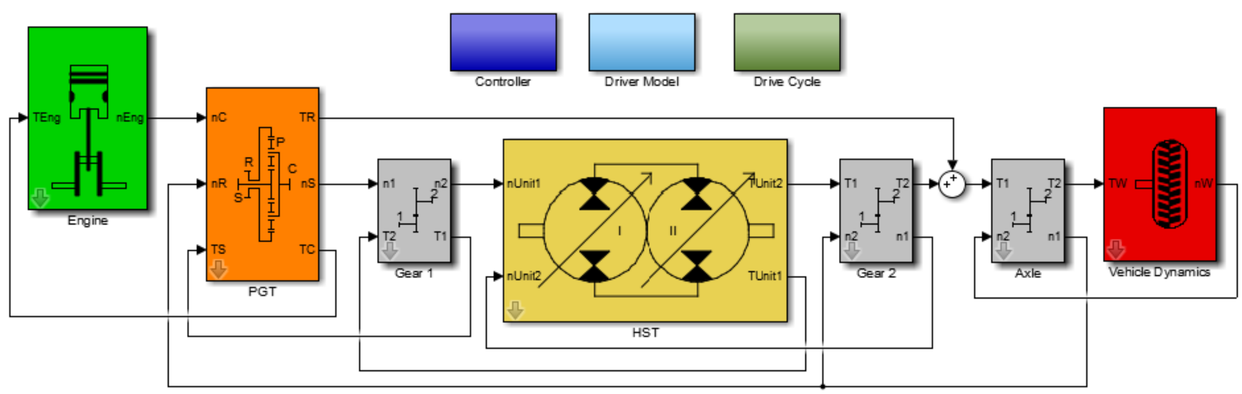


Figure 30: Powertrain simulation model

3. Research into Design and Optimization of Piston Pumps and Motors

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

The novel swashplate type axial piston pump models developed at the Maha Fluid Power Research Center are the product of more than 15 years of experience and research by numerous individuals. While part of the piston pump modeling focuses on reducing noise generation and improving the swashplate controllability, a large effort is made to develop models which simulate the full fluid film lubrication performance between the three primary sliding interfaces of a swash plate type axial piston pump or motor (Figure 31):

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

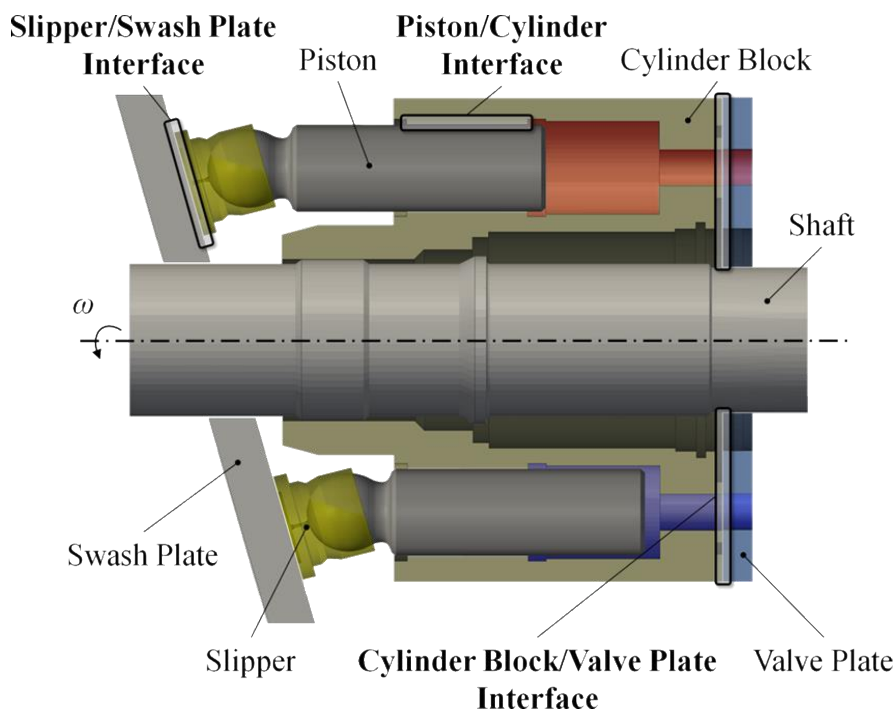


Figure 31: Swash-plate type axial piston machine cross section

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

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

The model couples iteratively different numerical domains and solution schemes, as depicted for the case of the piston/cylinder by Figure 32. 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:

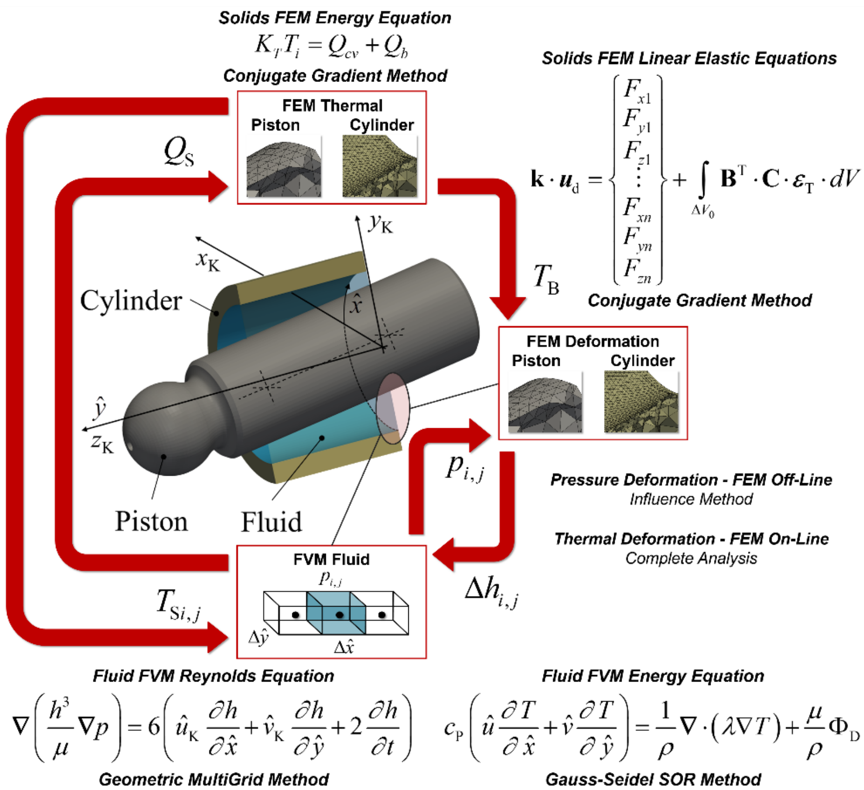


Figure 32: Fluid structure interaction and thermal model

1) **Fluid Film Finite Volume Non-Isothermal Flow Model:** this module predicts the instantaneous pressure distribution and temperature distribution in the lubricating interface fluid film. The solution of Reynolds and energy equations is obtained simultaneously. The change in fluid properties due to pressure field, p, and temperature field, T, is considered. The non-linearity introduced by the change in fluid film due to

pressure surface elastic deformation, Δh, is coupled with the non-isothermal fluid film model via a partitioned fluid-structure interaction analysis, based on an outer fixed-point iteration scheme. The Reynolds equation is solved using a **Geometric Multigrid** algorithm to improve accuracy and performance.

2) **Solids Finite Element Heat Transfer Model:** this module calculates the solid bodies' temperature distributions. The conductive form of the energy equation is solved. Based on the heat fluxes due to viscous dissipation, Q_S, the temperature distribution of the solid parts, T_B, is predicted. The temperature distribution is used as more accurate surface temperature boundary, T_S, for the fluid film and to determine the thermal stress condition for the solid parts. High geometrical accuracy for the solid bodies is allowed through the **unstructured** discretization, which allows generating solid geometries directly from CAD software.

3) **Solids Finite Element Elastic Deformation Model:** this module allows determining the elastic deformation of the solid bodies due to external fluid film pressure and internal thermal loading. Two different methods are used according to the type of load. The solution of pressure surface elastic deformation is obtained using an influence method, running complete FEM analysis off-line. The solution of the thermal deformation is achieved running complete FEM analysis at run-time. The ultimate information provided by this numerical model is the total deflection of the bounding surface, Δh. FEM analysis based on CAD solid models coupled with the inclusion of advanced constraints methods, such as **Inertia Relief**, allows a very accurate prediction of the fluid film boundaries surface elastic deformations.

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

Piston/Cylinder Model Advances

-Model update for grooved piston cylinder interface design

In order to extend the ability of FSTI Piston Cylinder model for grooved piston cylinder interface design, the model has been updated by Maha researchers to recognize the position of the groove on both piston and cylinder bore, and to split the lubricating interface into multiple sealing area based on the positon of grooves. The pressure distribution in each individual sealing area is calculated according to their pressure boundary conditions. These boundary conditions are case pressure, displacement chamber pressure and the pressure in each grooves. The pressure in the groove is calculated from mass conservation of the fluid flow in and out of the groove.

-EHL Model

In some cases the FSTI Piston Cylinder model will predict a collapsed lubricating film. This is shown in an unwrapped lubricating film in Figure 33. Here, film thickness is indicated by the contour lines, fluid pressure is shown in blue, and red indicates areas where the simulated film has collapsed. It is important to understand the true behavior of the fluid film in these areas, as prolonged piston-to-cylinder contact during machine operation will quickly lead to failure. A High Definition FSTI-HD model is being developed to investigate these regions. The FSTI-HD model re-simulates the fluid film in these regions using an adaptive multigrid method. The adaptive grid refinement can reach grid spacings of up to thirty two times finer than the fluid grids used in the FSTI model. This extra resolution in the fluid domain is matched by a linear half space surface deformation model. Together, these models are able to capture small-scale Fluid Structure Interaction effects invisible to the FSTI model. Figure 34 is an example FSTI-HD analysis of the top left collapsed region from Figure 33.

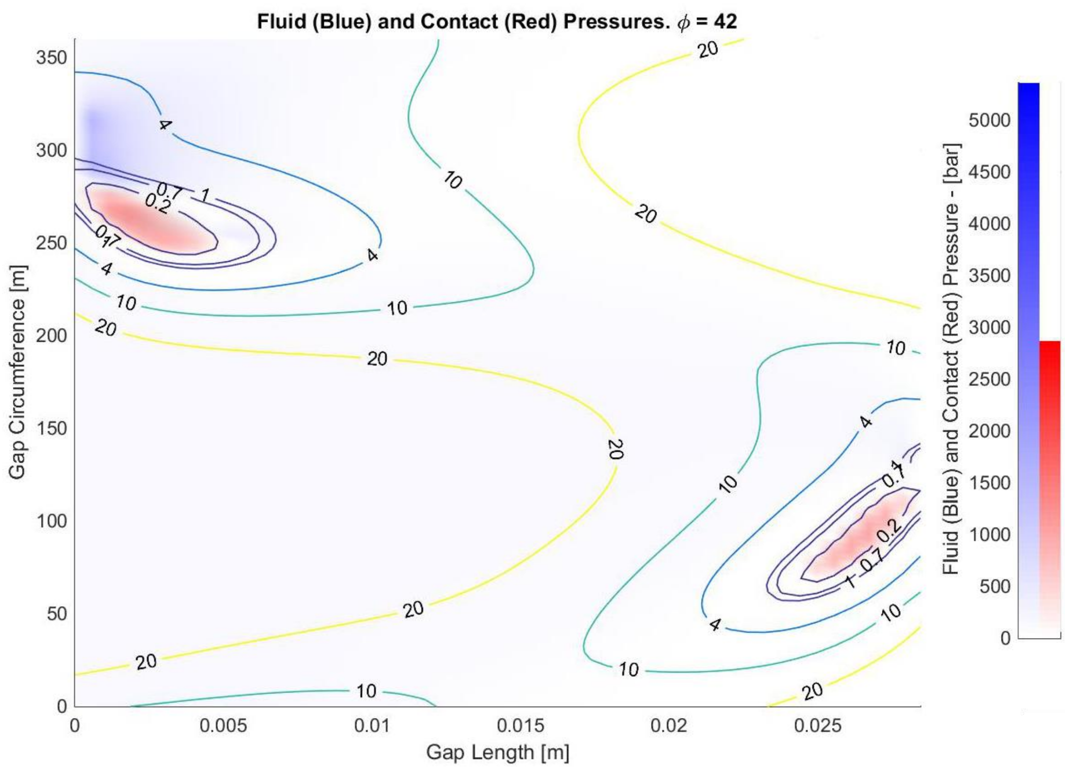


Figure 33: Example unwrapped fluid film from FSTI Piston-Cylinder Model. Film thickness indicated by contours, fluid pressure in blue, contact stress in red

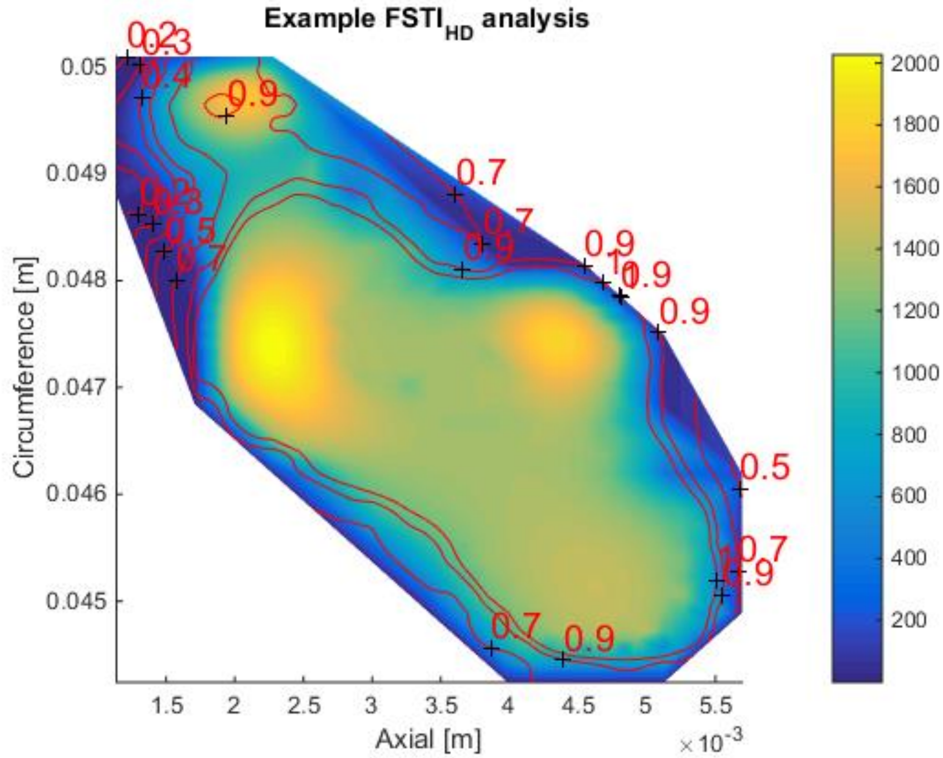


Figure 34: Example FSTI-HD analysis showing film thickness as contours and fluid pressure in color

Virtual Prototyping and Pump Design

Conventional pump design is done through trial and error incurring on high cost experimental set ups. The multi-physics models developed in the Maha Fluid Power Research center previously described form the starting point for a new computational based design approach or virtual prototyping. Virtual prototyping via the utilization of these advanced fluid structure interaction models promises many advantages over the conventional design methodology such as: to reduce design costs by diminishing experiments, design for compactness and reliability, design for controllability, design for quieter machines, design for more energy efficient through the optimization of the lubricating interfaces since these represent the main source of energy dissipation in this type of machines.

Previous research has shown a variety of new design parameters to take into consideration such as solid deformations due to pressure and thermal effects, micro-surface shaping intentional or wear, and different material selection. As mentioned previously, the lubricating interfaces have to bear the external loads exerted on the rotating group components and seal the pressurized fluids in the displacement chambers from flowing into the pump or motor housing. In order for the fluid film to achieve these simultaneous functions, it depends on hydrostatic and hydrodynamic pressure effects in the fluid film. Surface elastic deformations may result in additional hydrostatic pressure due to the wedge effect. Therefore it has a great impact on the fluid film behavior. Hydrodynamic effects can also come from micro-surface shaping (intentional or from wear). A clear example of these effects on the lubricating interfaces is the introduction of a sinusoidal wave in the circumferential direction on the valve plate's surface with a ±1 μm magnitude has proven to be a design improvement for the cylinder block/valve plate interface with an increase in overall pump efficiency up to ~10% at certain operating conditions. Additionally, the slipper/swash plate interface benefits in some designs of a slight wear in the order of a few microns on the leading and trailing edges of the slipper. Both previous examples have been validated with experimental data. A similar behavior is expected from the piston/cylinder interface.

The numerical models will be used to investigate better lubricating interface designs, including novel material combinations and micro-shaped surfaces. These innovative lubricating interface designs will lead to better machine performance and increased efficiency and reliability over a wider range of operating conditions.

Advanced Port and Case Flow Temperature Prediction for Axial Piston Machines

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

As shown in Figure 35, the red dashed line connects the inlet and outlet state in the enthalpy entropy diagram of the hydraulic fluid based on the measured pressure and temperature. Due to the heat transfer, the real compression process does not follow a vertical line. Since in a real axial piston machine, the fluid pressure changes only over a very short time period and the heat transfer occurs under constant pressure mostly, the real compression process has been divided into two vectors as shown in Figure 35. The vertical black vector represents an adiabatic compression and the green vector represents the temperature variation due to the heat transfer at constant pressure. This allows separate study on the temperature variation due to the pressure change and due to the heat transfer.

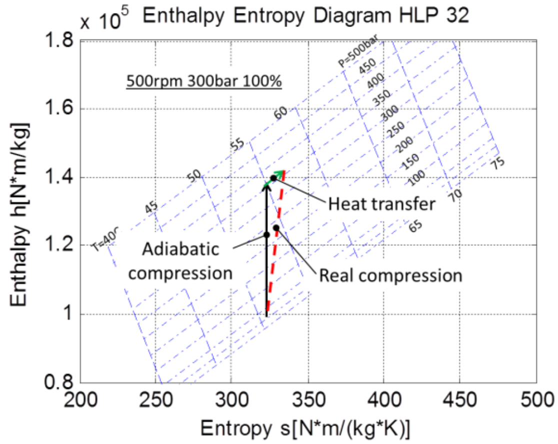


Figure 35: Enthalpy entropy diagram of the hydraulic fluid

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

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

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

In order to use the port and case flow temperature prediction model coupled with the fluid structure and thermal interaction model to support design new pumps and motors, the simulation need to start with given pump design, given inlet port temperature, given fluid properties and estimated outlet port and case flow temperatures. In a second step the pump outlet port and case flow temperature prediction model is used to calculate the outlet port temperature and the case flow temperature based on the power loss and the outlet and case flow rate from the fluid structure and thermal interaction model. In a third step the obtained outlet port and case flow temperature will be used to rerun the fluid structure and thermal interaction model to update the power loss and the outlet and case flow rate. The described iteration cycle between the two models will be repeated until the outlet and case flow temperature converge as shown in Figure 36.

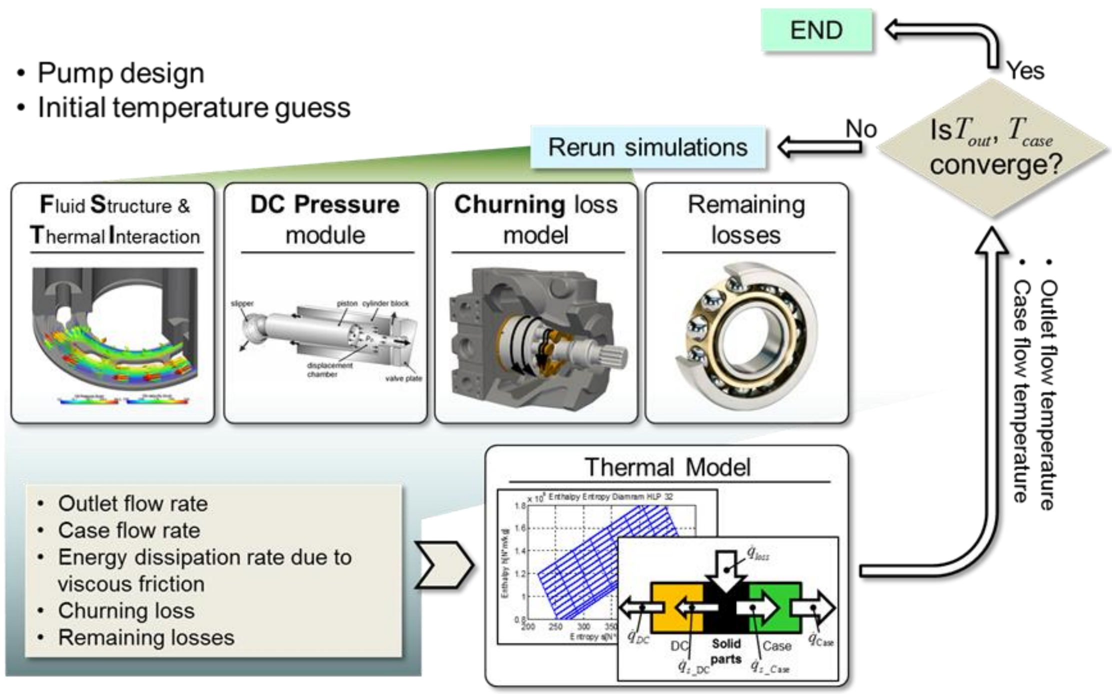


Figure 36: Iteration cycle between the two models

In the year of 2015, this advanced port and case temperature prediction model has been used widely by Maha's researchers. A novel scaling study of axial piston pumps and motors was conducted in Maha research center using this model to calculate the port and case temperature of a scaled unit. A temperature adaptive piston was designed in Maha research center using this model to calculate the port and case temperature of a unit with new design features. Other than that, many industrial projects were conducted using this model.

New Micro-Surface Shapes Study

One of the main activities of the center is focused towards the improvement of current swash plate type axial piston machines through virtual prototyping. Utilizing an in-house fluid structure thermal interaction model in which thermal and elastic deformations are considered, an ongoing investigation of the micro-surface shaping of the piston in relation to the performance of the lubricating interface in which the main goal is to achieve higher efficiency and increase load carrying capacity progresses.

Surface shaping studies were investigated on the cylinder block/valve plate interface. In 2009, Baker proposed a waved micro-surface shaping on the surface of the valve plate predicting up to a 50% reduction in power loss of the interface utilizing the simulation model. A prototype was then manufactured in which a 10% overall improvement in the efficiency of the machine was measured. Based on these results a patent was filed. We are proud to report that the "Axial Sliding Bearing and Method of Reducing Power Losses Thereof" patent (US20110056369) was awarded this year.

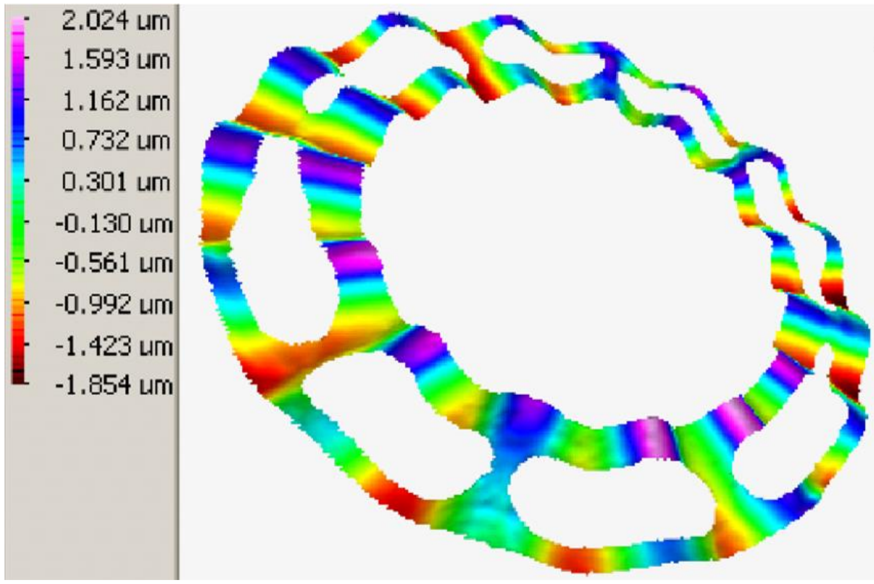


Figure 37: Micro-surface shape introduced on the valve plate surface

Surface shaping was also investigate on the piston/cylinder interface. In 2008 the center had worked on the study of barrel and waved barrel like micro-surface shaping on the pistons surface. Also, in 2009 a sine wave like micro-surface shape, as shown in Figure 37, was introduced on the piston's surface (Filed patent: 61/165, 661). Previous simulations had shown a potential improvement of up to 60% in total power loss; but the results were shown to be highly dependent on operating conditions and limited to an incomplete model in which crucial solid body deformations were neglected. Most recently, the center has been investigating the impact of a variety of micro-surface shapes on the piston, the 5 prominent profiles investigated shown in Figure 38, along with the configuration of varying gap heights on the overall performance of the machine over a wide range of operating conditions, including pumping and motoring mode, with a more complete model. From this model that is able to provide much more accurate predictions, simulations have shown potential improvements of overall energy dissipation and increased fluid support. Through investigation of the complex fluid phenomena in the gap a better understanding of what is occurring between the piston and cylinder can be achieved allowing to even better improve the overall operation of the machine as the clearance can be further reduced between the piston and the cylinder; the hydrodynamic pressure build up in the fluid allowing for this as a surface profile is added to the piston. This combination of surface shaping allowing for reduced clearances for the piston-cylinder interface resulted in up to a 50% reduction in energy dissipation at full displacement (45% decrease overall machine due to the large losses of the piston-cylinder interface at such operating conditions) and 70% at partial displacements (10% overall machine since the piston-cylinder does not have such a large effect at partial displacement) for the flat surface profile. The flat surface profile was found to fail at higher power operating conditions though as load support was no longer provided and therefore the barrel was found to be the best over all of the operating conditions studied leading to a maximum of a 40% decrease (35% decrease overall machine) at full displacement. The barrel micro-surface shape best maintained, or even improved, the fluid support, especially so at higher power operating conditions in which other surface profiles failed, contributing to friction forces that are not largely increased in which the reduction in leakages are then able to dominate leading to reliable performance and increased overall efficiency. Future plans include and optimization study extended to include the consideration of polynomial surfaces in combination with gap height and guide length. Once these numerical studies are concluded, modern manufacturing will be utilized to produce prototypes to be tested on specialized test rigs in order to verify the use of virtual prototyping suggesting a cost and time effective state-of-the-art technology.

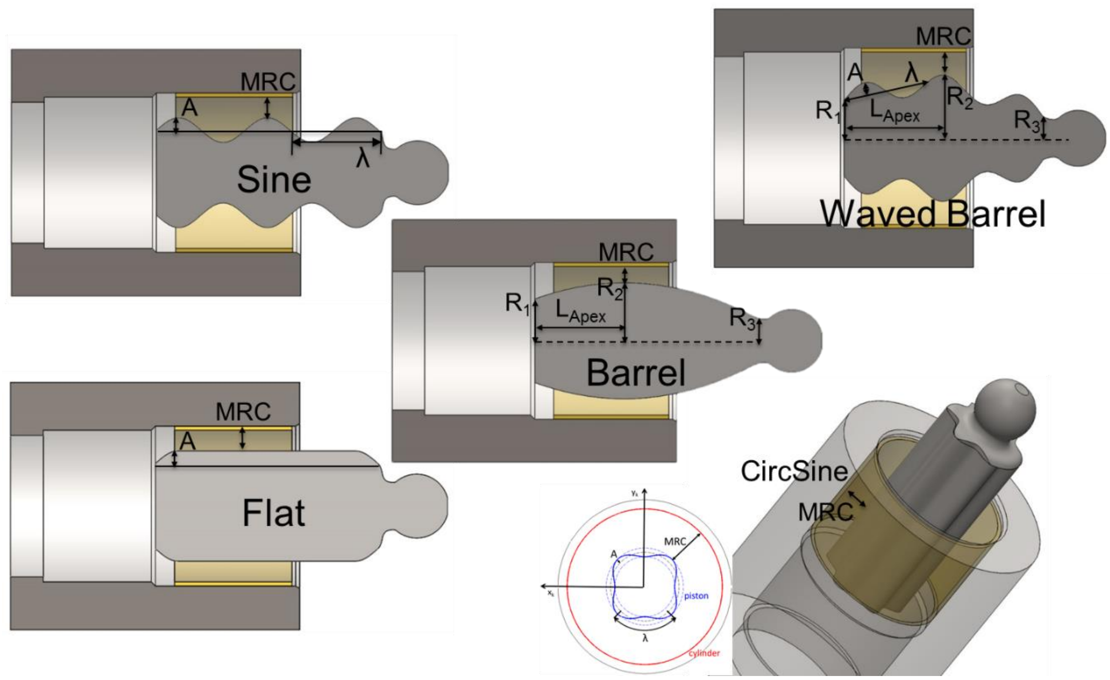


Figure 38: Various micro-surface shapes on the piston surface

Water Hydraulics

Micro surface shaping, material choices, manufacturing tolerances, pump geometry—none of these measures, no matter how carefully construed, will banish from the nature of the most commonly used hydraulic oils of today their flammability, expense, or the environmental risk factors they represent. Designing an axial piston machine of swashplate type means making a choice about what type of fluid(s) it can handle, and not all of the consequences of that choice can subsequently be mitigated via other pump design measures. Choosing water as a working fluid eliminates many of these kinds of issues, but for high pressure systems, it presents two major challenges for the unit's tribological interfaces: leakage and load support. These challenges derive from water's low viscosity, and *these challenges can* be mitigated through micro surface shaping, material choices, manufacturing tolerances, pump geometry, etc. (at least to a certain extent).

The goal of water hydraulics research at Maha vis-à-vis axial piston machines is to push the achievable operating pressures of these units into the 300-400 bar range when using water as a working fluid. The focus is on the piston-cylinder interface, which is particularly difficult to manage in terms of the high side loads acting on the pistons of these hydraulic units. Various forms of piston micro surface shaping have been explored in the search for a possible design solution for water-lubricated units, including the "Lasaar profile" devised by Lasaar, the sine wave profile invented by Ivantysynova, Garrett and Frederickson, and the composed sine wave profile shown in Figure 39. Note: these profiles are exaggerated— the height variation they introduce on the piston surface is on the order of microns. The performance of these designs was assessed by simulating the piston-cylinder interface of a 75 cc unit over the course of a shaft revolution using FSTI.

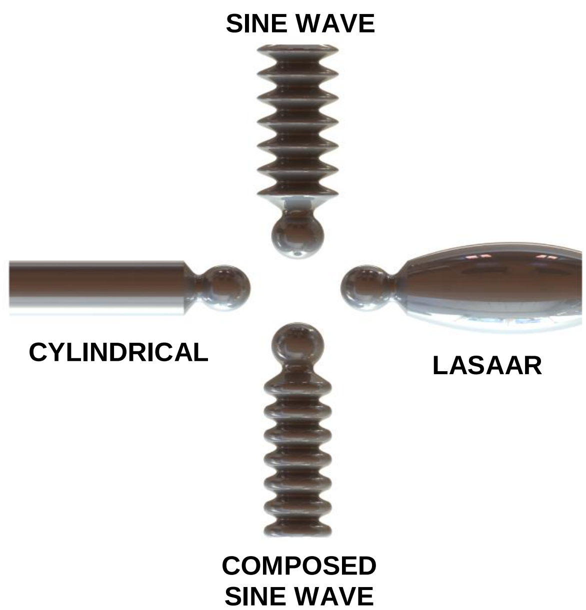


Figure 39: Three piston profiles (sine wave, Lasaar, and composed sine wave) shown next to a cylindrical piston profile without any surface shaping

While these profiles produce a number of interesting effects, the recent focus has been on putting wide grooves into the bushings within which the pistons move (the following patent disclosure has been filed for this: 2015-IVAN-67231). Such a bushing is shown in the lower right-hand corner of Figure 42, in this particular case with one groove. In the figure, the groove has been marked in white to make it visible. In the upper right-hand corner, the rotating kit of an axial piston unit has been cut open in order to show what the bushing with groove looks like within such a unit (note: to make the bushing visible, the corresponding piston has been cut short—this is not part of the design, it was merely done for illustration purposes). The width of the groove is denoted groove_w, and is shown in Figure 41. Also shown is the dimension groove_p, which is the position of the groove relative to the displacement chamber. The groove is assumed to be deep enough for the fluid within it to have a constant pressure. The point of having such grooves in the bushing near the displacement chamber (at the displacement chamber end, aka DC end of the interface) is to distribute the incoming displacement chamber pressure more evenly around the circumference of the interface in this region, thus reducing how hard the circumferentially skewed pressure field pushes the piston into the bushing. The aim is to prevent metal-to-metal contact.

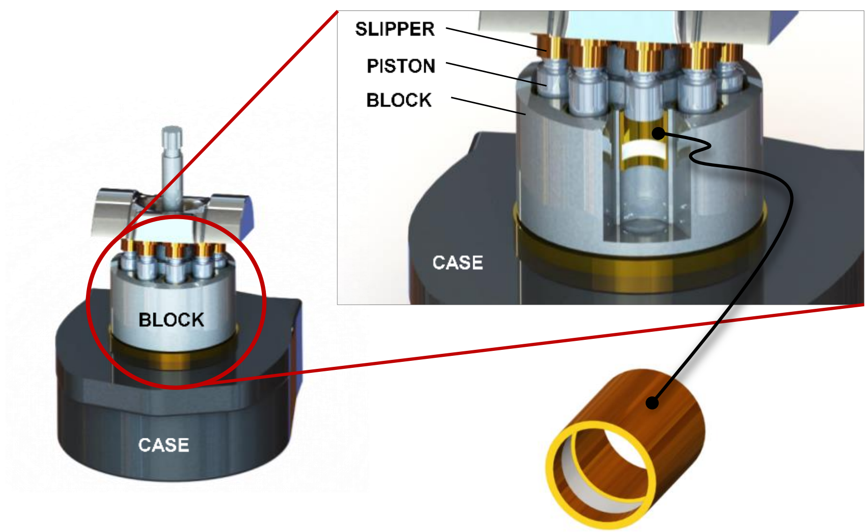


Figure 40: Bushing groove shown in a cutaway section of the rotating kit

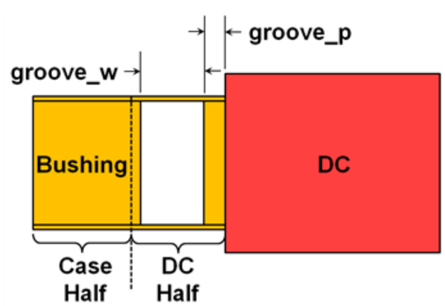
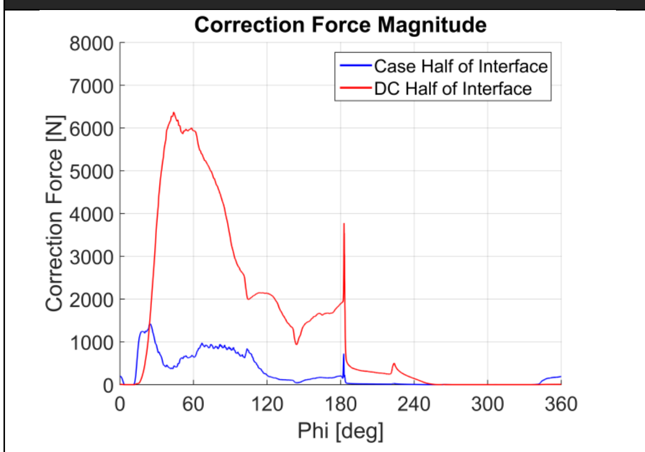


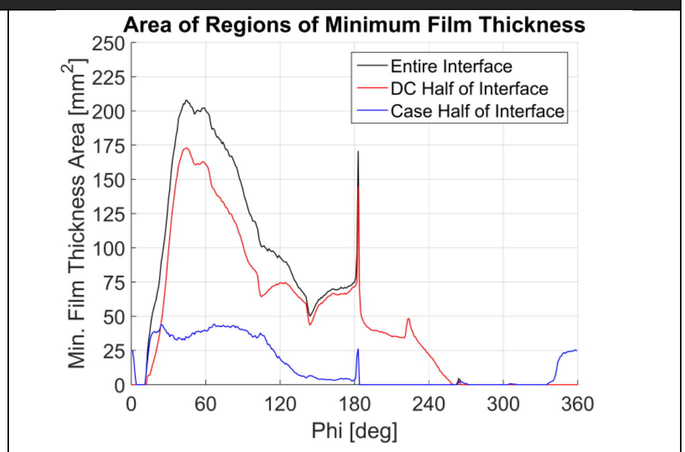
Figure 41: Cross-sectional view of bushing and displacement chamber showing groove width and position

Table 3 shows simulation results for two different simulations, both using a stainless steel cylinder, stainless steel pistons, and brass bushings, both using water as a working fluid, and both run at an operating condition of Δp=300 bar, 3,000 rpm, 100% displacement, and a relative clearance of 0.58 per mill (relative clearance=(diametrical clearance in μm)/(piston diameter in mm)). However, Simulation 1 was run without any micro-surface shaping, while Simulation 2 was run with a bushing groove (groove_p=18% of the bushing length, and groove_w=35% of the bushing length). In these plots, the "DC half" of the interface is the half of the interface closest to the displacement chamber, while the "Case half" is the half closest to the swashplate (see Figure 41). What can be seen is that having a groove in the bushing can dramatically reduce the correction forces in the DC half of the interface, but it can also reduce the areas of minimum film thickness in that region. This means that the load can become more concentrated. Furthermore, the correction forces in the Case half are higher in Simulation 2 than in Simulation 1. The grooves must therefore be designed carefully, and additional design modifications may be needed in order to keep the benefits of the groove without creating regions highly concentrated load or increasing the correction forces in the Case half too much or dramatically increasing the leakage (note that the leakage for Simulation 2 is over four times that of Simulation 1).

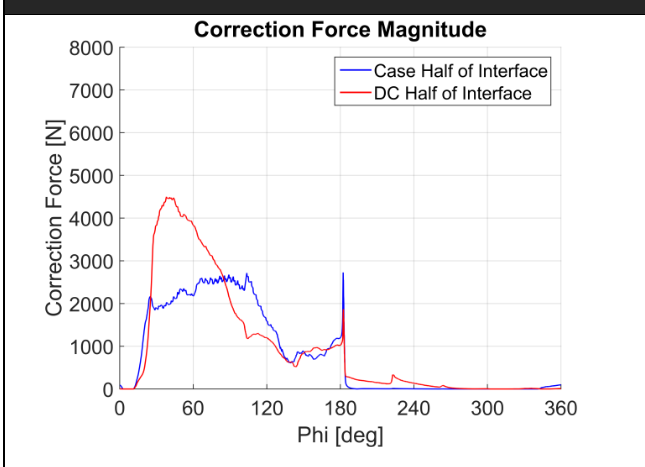
Table 3: Correction forces and area of the regions of minimum film thickness in the case and DC halves of the interface for Simulation 1 and Simulation 2

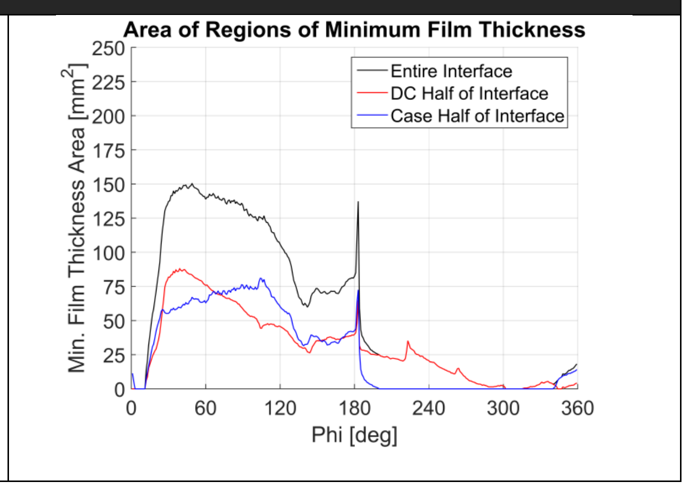
Simulation 1





Simulation 2





Noise Control and Acoustics

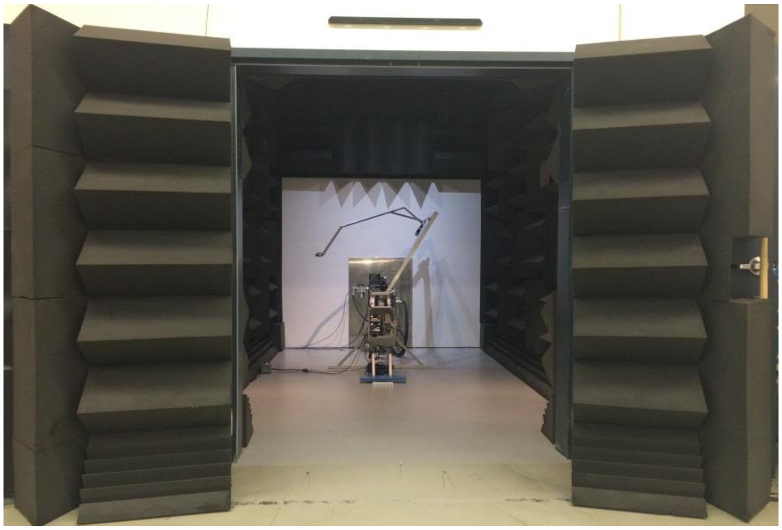


Figure 42: Maha's semi-anechoic chamber

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

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

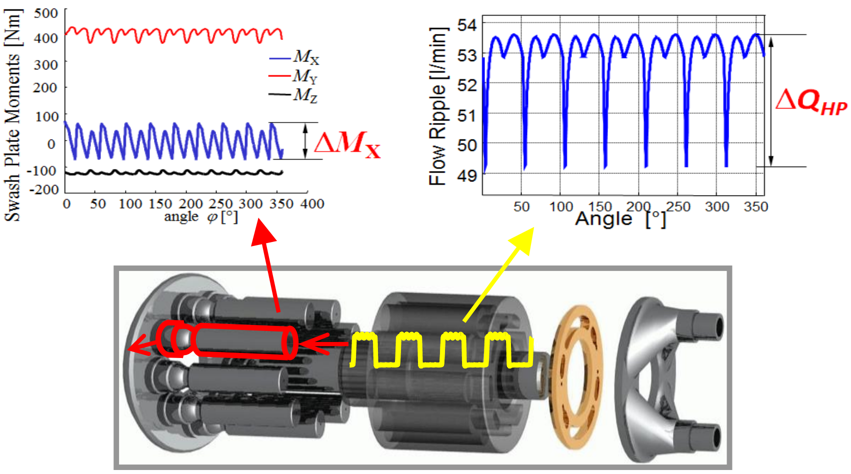


Figure 43: Axial piston pump showing the fluid borne and structure borne noise sources

VpOptim

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

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

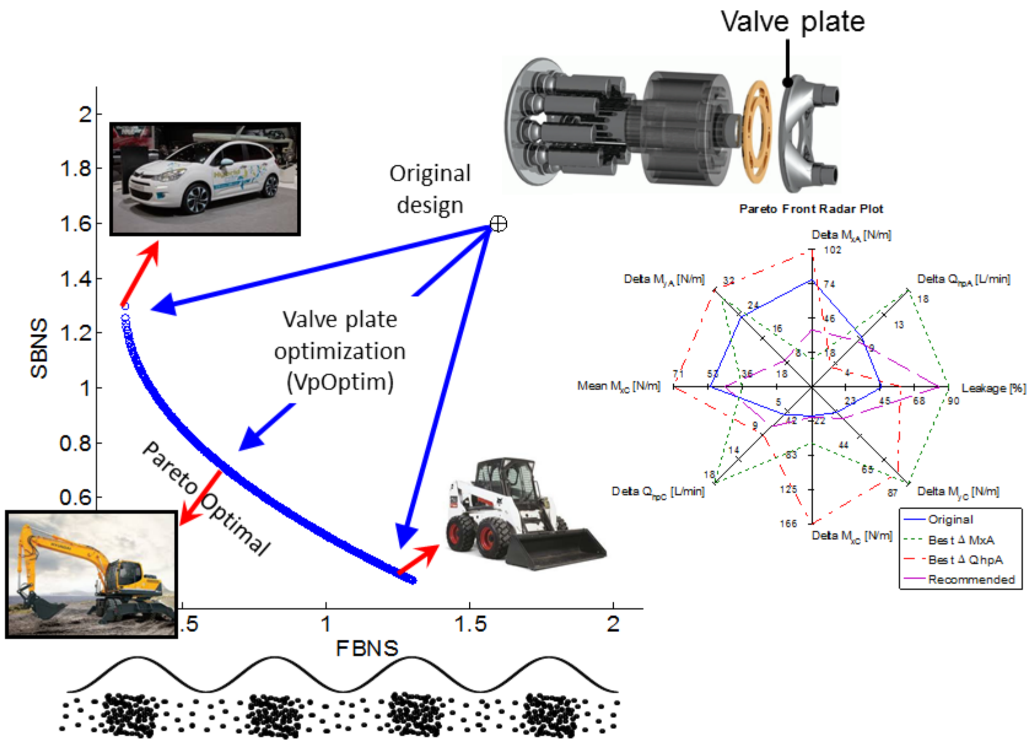


Figure 44: Schematic of the process flow inside VpOptim

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

The valve plate design methodology was completely redesigned in 2015. The complexity of the valve plate designs was increased yet again to allow 55 design variables as compared to 25 in 2014. The computation speed was also increased an additional 8 times as compared with VpOptim in 2014. This creates a 200,000 times speed up as compared with 2012 VpOptim. This enabled a much faster (Wall-clock time) design process.

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

TransModel

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

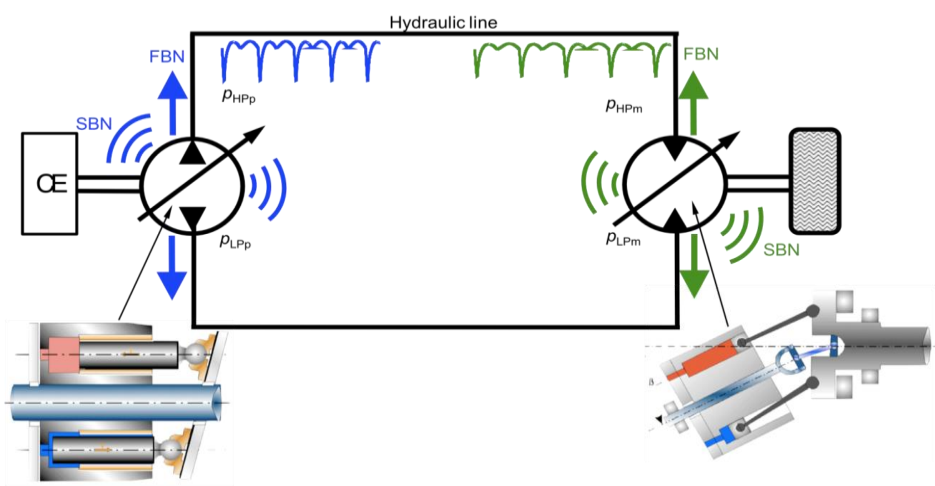


Figure 45: Schematic of hydrostatic transmission implemented in TransModel

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

Swash Plate Active Vibration Control

The third approach aims to reduce noise generated by pumps and motors at the source level (FBNS and SBNS) by controlling Structure Borne Noise Sources (SBNS) which are generated from the pressure changes in the displacement chambers. The oscillating swash plate moments are known as the source of Structure Borne Noise. Passive techniques have been investigated to reduce the amount of Structure Borne Noise Source. However, passive techniques such as valve plate optimization, ideal timing, pre-compression filter volume, cross-angle, etc. are only effective for limited operating conditions or require compromises in design. By adding active vibration control on the swash plate, additional noise reduction and balance between operating conditions are achievable.

The concept of swash plate active vibration control (AVC) is in reducing the swash plate vibration by creating a destructive interference force using the swash plate control. As a pump rotates, the oscillating swash plate moment (M_X) is converted to the oscillating force (F_{SL}) which is acting on the swash plate control actuator. The active vibration control adjusts the high response servovalve and generates a destructive interference force to the oscillating force (F_{SL}) as shown in the Figure 46.

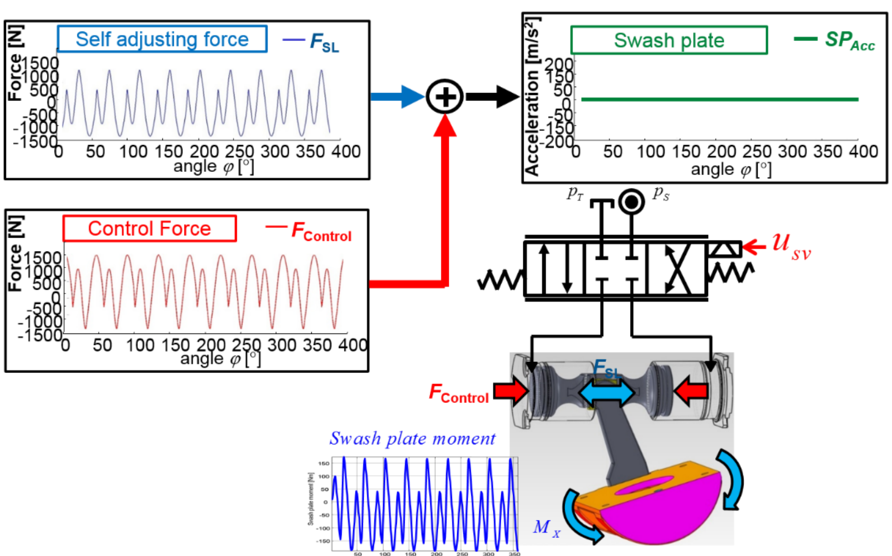


Figure 46: Swash plate AVC concept

The S90 75cc/rev pump is modified based on the requirements for active vibration control using the swash plate. Figure 29 shows a schematic of the high response pump control system for active vibration control. The high response pump control system consists of a high response direct drive servovalve (DDV), an electronic angle sensor, an acceleration sensor, and a speed sensor as shown in Figure 47.

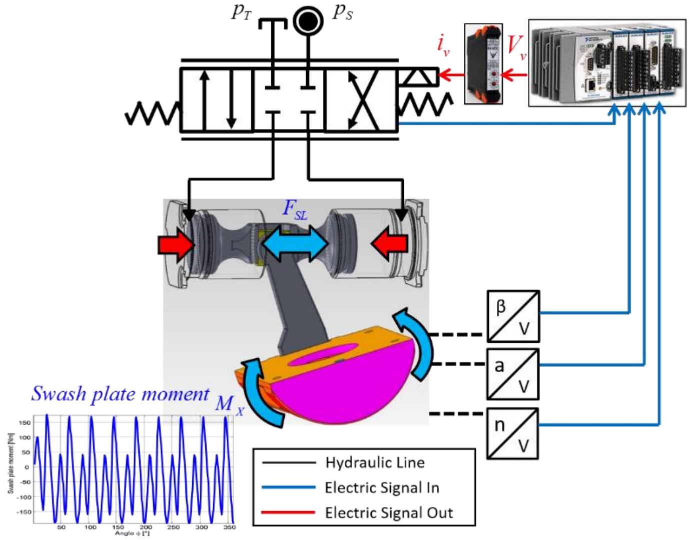


Figure 47: Schematic of high response pump control system

Figure 48 shows a sensor installation of the modified AVC pump with the acceleration sensor, the angle sensor, the high response direct drive servovalve and the speed sensor.

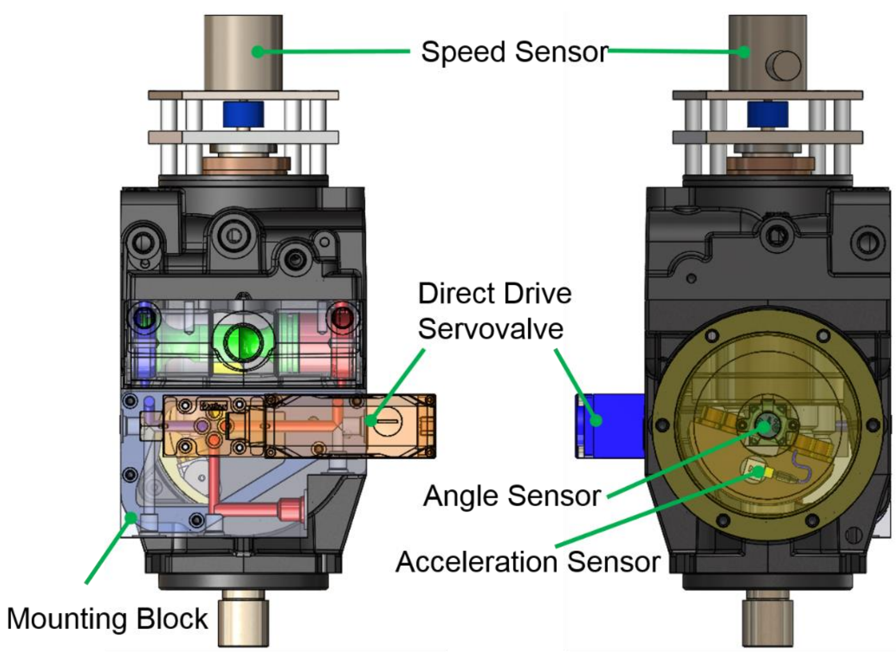


Figure 48: Sensor installation of AVC pump

A feedforward multi-frequency narrowband adaptive LMS filter is designed for active vibration control of the periodic swash plate moment as shown Figure 49. The multi-frequency narrowband adaptive LMS filter is consists of multiple single frequency narrowband adaptive LMS filters connected in parallel. Each single frequency narrowband adaptive LMS filter has function generators which are synchronized with rotation speed and produce harmonic frequency sine and cosine reference signals for the feedforward controller. Delays from the pump control system dynamics are compensated by the delayed reference signal and the adaptive filter which uses the least mean square (LMS) algorithm to minimize acceleration of the swash plate by adaptively changing the weights of the reference signals.

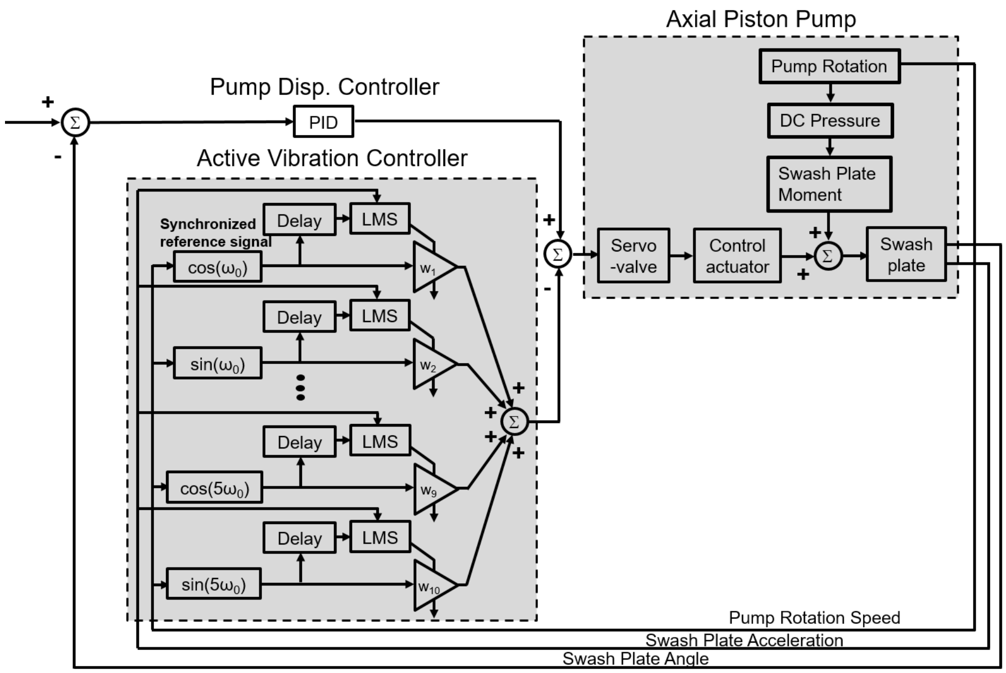


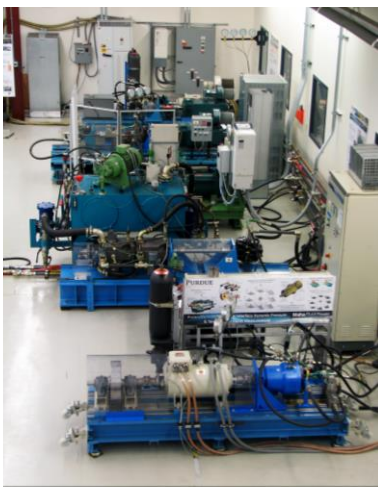
Figure 49: Multi-frequency two-weight LMS filter with delay compensation for swash plate AVC

2 Research Facilities

Lab Space and Test Rigs at Maha

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

Test beds for technological demonstration (Left)

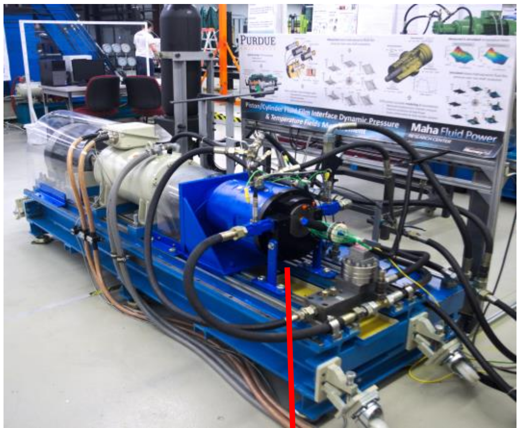


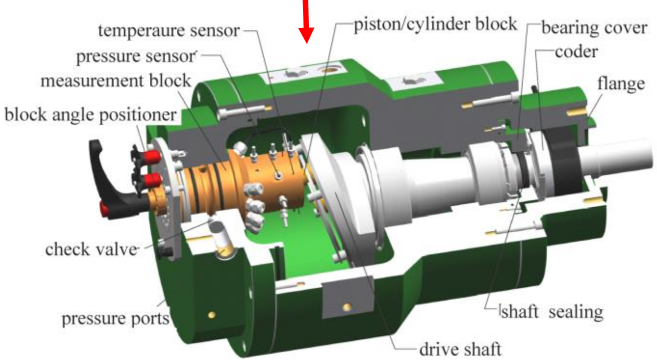
Test rigs and car lift (Above)

and new lab space (Left)

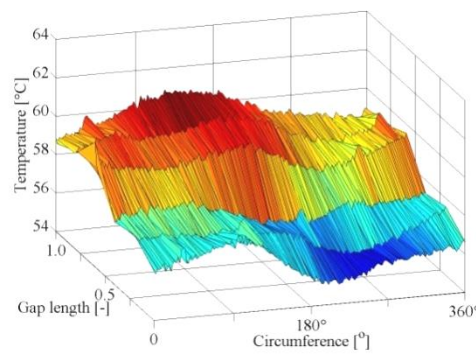
EHD Test Rig

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





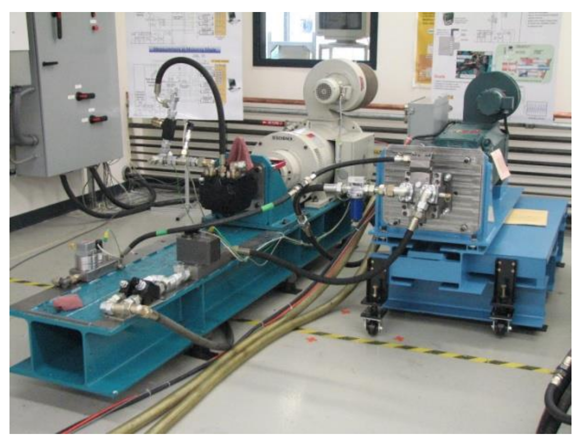
EHD Pump



Measured Temperature Field in the Piston/Cylinder Gap

Test Rigs for Steady State Measurements

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



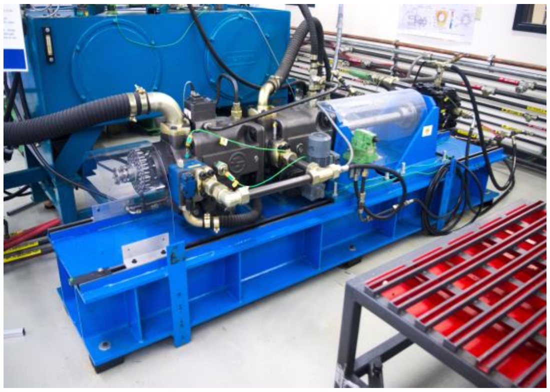
Performance Characteristics

Max. installed electric power: 2 x 120 kW

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

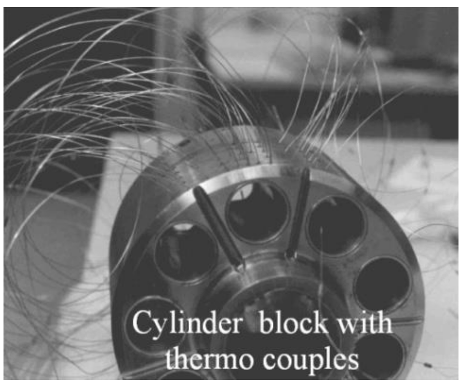
Max. pressure: 450 bar

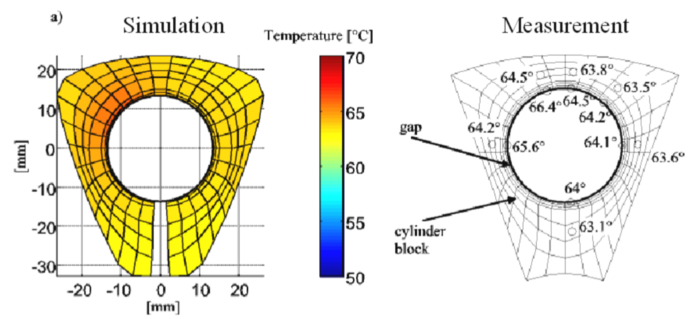
Max. torque: M1 = 300 Nm/ M2 = 500 Nm



OLEMS Test Rig

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

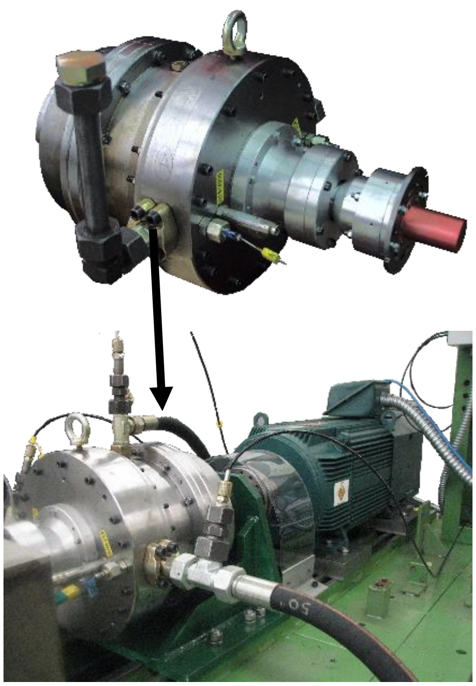


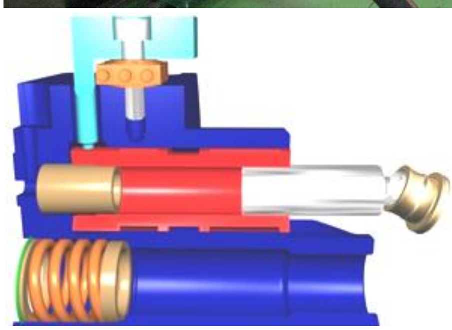


Temperature distribution in the assembly near the slipper slide

Test Rig to Study Active Vibration Damping of the Swash Plate

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





Tribo Test Rig

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

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

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

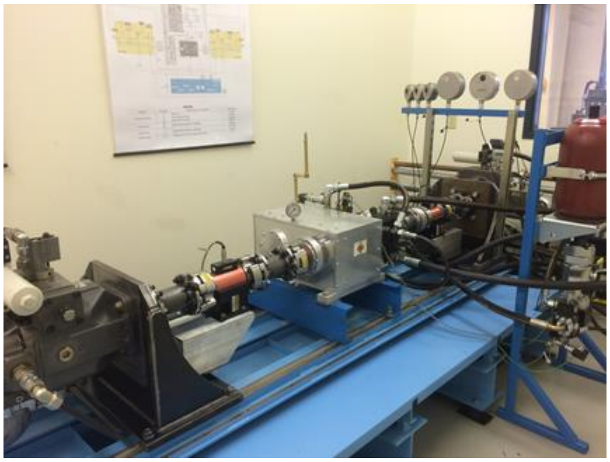
Light Duty Powertrain Hardware-in-the-Loop Transmission Dynamometer

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

Performance Characteristics

Engine simulator: 300 Nm @ 4000 rpm

Load simulator: 500 Nm @ 3600 rpm



Performance Characteristics

Engine simulator: 900 Nm @ 1800 rpm

Load simulator: 900 Nm @ 1800 rpm

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

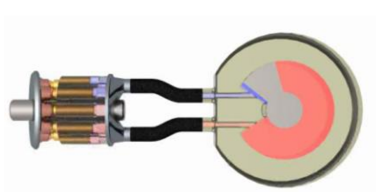
This second HIL transmission dynamometer is used to evaluate heavy duty powertrain architectures and controls. Two secondary controlled hydraulic units function as engine and load simulators enabling the dynamic evaluation of transmissions sized for vehicles up to a class 6 truck. Currently a much smaller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

Performance Characteristics

Max. Torque: 30000 Nm

Max. Pressure: 350 bar

Max. Power: 30 kW



Rotary Actuator

JIRA Test Rig

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

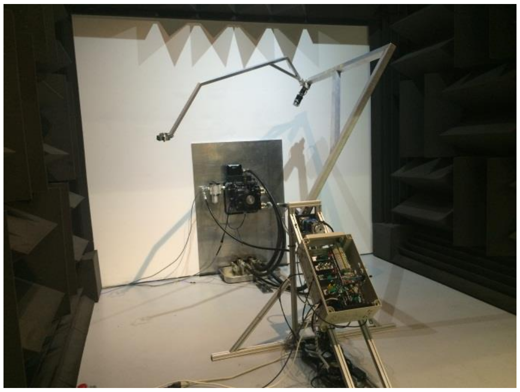
Recent improvements on the test rig have allowed for the demonstration of pump switching for the sequential operation of multiple actuators. New control concepts focused on actuator operability have been developed and demonstrated that DC actuation can be utilized for precise motion actuation. Finally,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

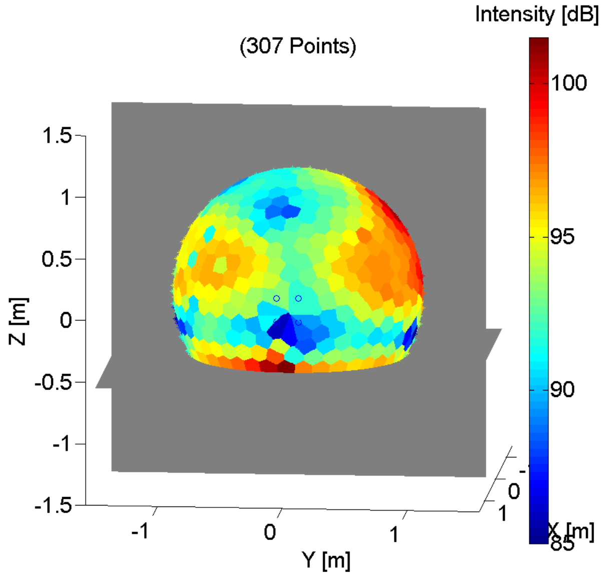
Cavitation/PIV test rig

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

Semi-Anechoic Chamber

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





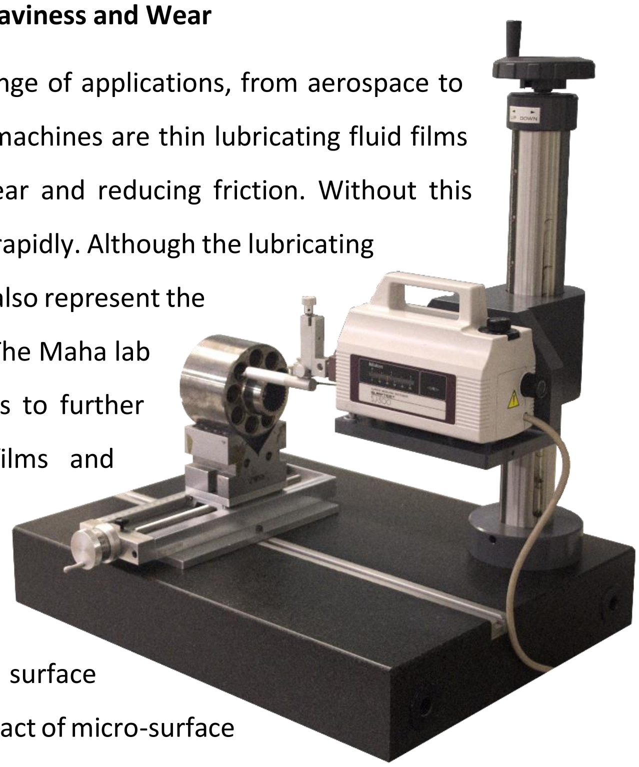
Multi functional test rig for hydraulic components

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

Hydraulic Power Supply

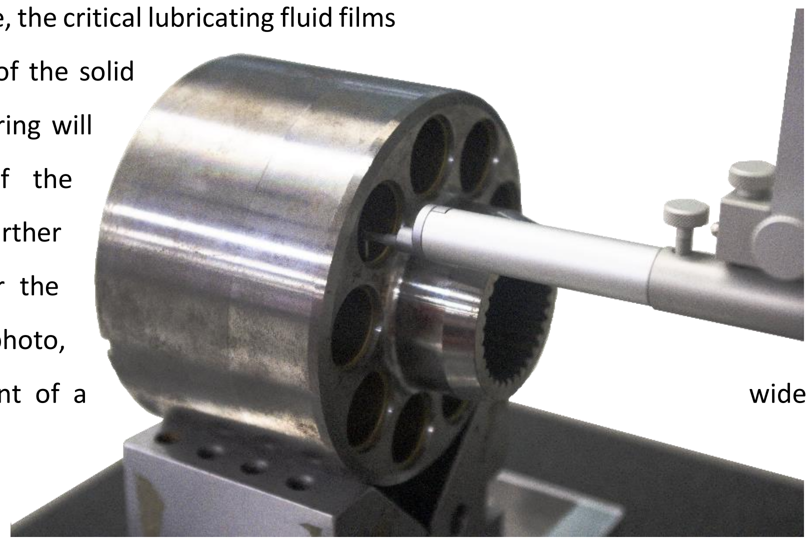
The above test rigs are powered by a 320 kW central hydraulic power supply unit with a 2000 liter tank, a water cooler and heating elements with five individually controlled pressure compensated pumps, 350 bar and 450 lpm output flow and a 60 l/min low pressure installed in 2005. A second medium pressure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

Surface Profilometer for Investigating Micro-surface Waviness and Wear

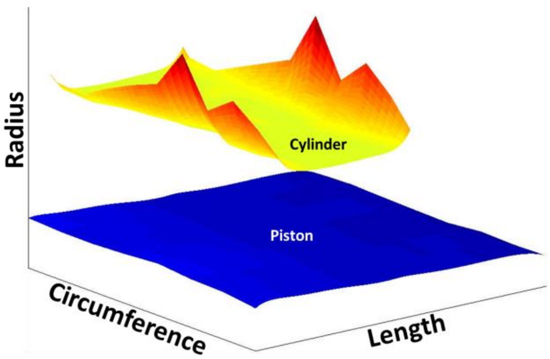


Axial piston pumps and motors are found in a wide range of applications, from aerospace to construction. Key to the successful operation of these machines are thin lubricating fluid films which separate the moving solid parts, preventing wear and reducing friction. Without this proper lubrication, hydraulic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

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

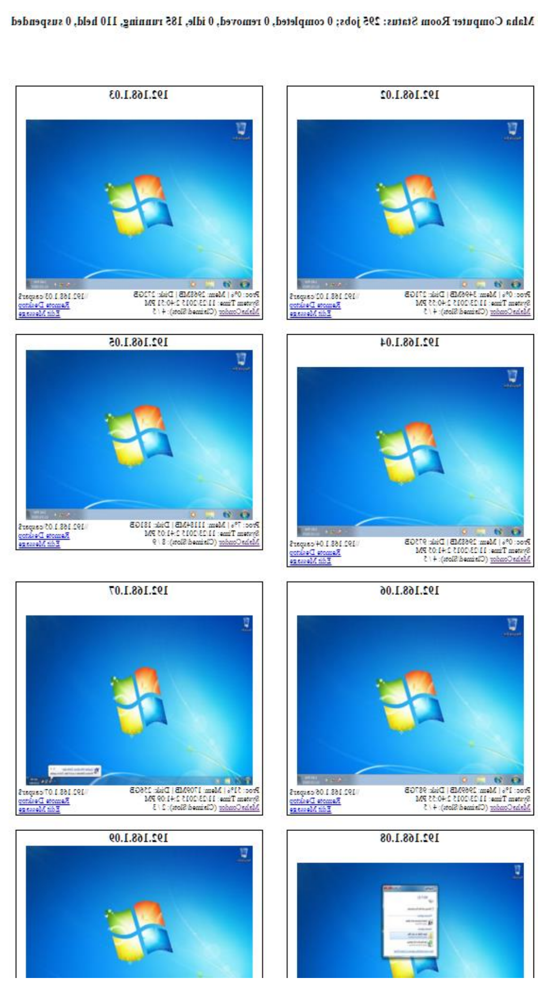


Over the past year the profilometer system has continued to be very useful in determining accurate inputs for our numerical pump modeling efforts. Many lubricating surfaces such as the piston and cylinder shown to the



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

Maha Computing Cluster



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

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

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

Test Vehicles and Machines

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

Hydraulic Hybrid Demonstration Vehicle

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

Performance Characteristics

Engine: 142 kW gasoline

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

High pressure accumulator: 32 l

Maximum system pressure: 450 bar

Wheel Loaders

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

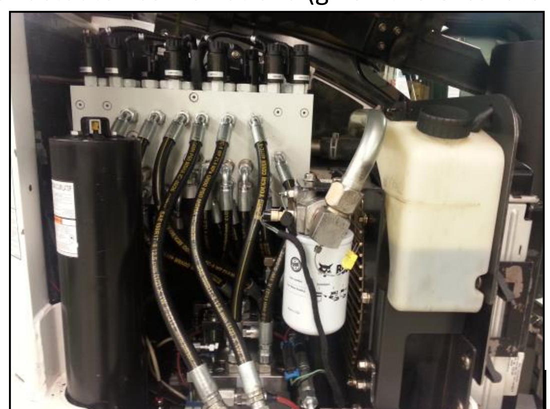
The smaller 5-ton wheel loader originally served as a platform for diagnostics and prognostics on hydraulic systems. In 2013, it was overhauled to implement a displacement controlled (DC) steer-by-wire (SbW) system. The loader served as a prototype test vehicle for investigating and validating adaptive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

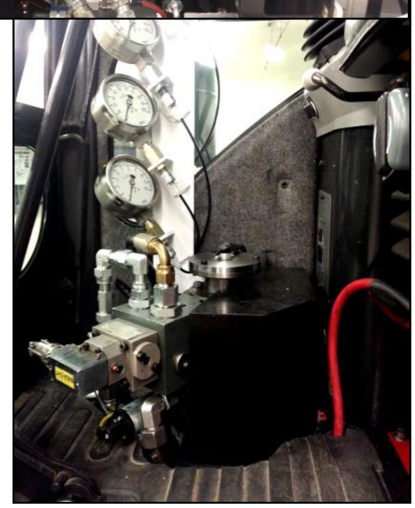
The Case 721F is a 14-ton wheel loader which was donated to Maha in May 2015. It is being used for research into valve-controlled hydraulic systems with such objectives as better control and behavior, lower oscillations, and higher efficiency.

Highly Efficient DC Hydraulic Hybrid Excavator Prototype

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

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





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

Skid-Steer Loader

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

Hydraulic Crane

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

3 Research Grants

Research Grants obtained in 2015: $1,276,955

Engineering Research Center for compact and efficient fluid power. NSF + industry funds = cost share, 10th year funding **$ 522,705.**

Energy saving hydraulic system architecture for next generation of combines utilizing displacement control. John Deere. **$ 333,250.**

Noise Measurements and valve plate design to reduce noise and maintain low control effort for tandem pumps. Bobcat. **$91,450.**

Research donation. Ford Motor Company. **$100,000.**

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

Maha lab support. Maha funds. **$165,000.**

Research donation, Kalamazo **$ 5,000.**

4 Publications, Invited Lectures, Patents, and Reports

Journal Articles

Schenk, A. and **Ivantysynova, M.** 2015. A transient thermoelastohydrodynamic lubrication model for the slipper / swashplate in axial piston machines. *Transaction of the ASME, Journal of Tribology*. , July 2015, Vol. 137, 031701-1-10, doi:10.1115/1.4029674.

Shang, L. and **Ivantysynova, M.** 2015. Port and case flow temperature prediction for axial piston machines. *International Journal of Fluid Power*, Vol. 16, Issue 1, pp.35-51.

Busquets, E. and **Ivantysynova, M.** 2015. Discontinuous Projection-Based Adaptive Robust Control for Displacement-Controlled Actuators. *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 137, No. 8, pp. 081007-1-10. doi:10.1115/1.4030064.

Busquets, E. and **Ivantysynova, M.** 2015. A Multi-Actuator Displacement-Controlled System with Pump Switching – A Study of the Architecture and Actuator-Level Control. *Transactions of the Japanese Fluid Power System Society*, Vol. 8, No. 2, pp. 66-75.

Daher, N. and **Ivantysynova, M.** 2015. Yaw stability control of articulated frame off-highway vehicles via displacement controlled steer-by-wire. *Control Engineering Practice*, Vol. 45, pp. 46-53.

Busquets, E. and **Ivantysynova, M.** 2015. Adaptive Robust Motion Control of an Excavator Hydraulic Hybrid Swing Drive. *SAE International Journal of Commercial Vehicles*, 8(2):568-582, 2015, doi:10.4271/2015-01-2853, online version. **SAE COMVEC Congress Technical Paper Selected for Journal Publication.**

Hippalgaonkar, R. and **Ivantysynova, M.** 2015. Optimal Power Management for DC Hydraulic Hybrid Multi-Actuator Machines – Part 1: Theoretical Studies, Modeling and Simulation. ASME Journal of Dynamic Systems, Measurement, and Control. Accepted

Hippalgaonkar, R. and **Ivantysynova, M.** 2015. Optimal Power Management for DC Hydraulic Hybrid Multi-Actuator Machines – Part 2: Machine Implementation and Measurement. ASME Journal of Dynamic Systems, Measurement, and Control. Accepted

Sprengel, M. and **Ivantysynova, M.** 2015. Neural Network Based Power Management of Hydraulic Hybrid Vehicles*. International Journal of Fluid Power*. **Under Review.**

Padovani, D. ***and*** **Ivantysynova, M.** 2015. Investigation of an Energy Efficient Hydraulic Propulsion System for a Railway Machine. *Journal of Dynamic Systems, Measurement, and Control.* **Under Review.**

Busquets, E. and **Ivantysynova, M. 2015.** A Gain-Scheduled Approach for the Engine Anti-Stall Control of Displacement-Controlled Multi-Actuator Systems. *Elsevier Control Engineering Practice.* **Under Review.**

Conference Proceedings

Padovani, D. and **Ivantysynova, M.** 2015. The Concept of Secondary Controlled Hydraulic Motors Applied to the Propulsion System of a Railway Machine. *Proceedings of the 14th Scandinavian International Conference on Fluid Power (SICFP'15).* May20-22, 2015. Tampere, Finland.

Sprengel, M., **Bleazard, T.**, **Haria, H.**, and **Ivantysynova, M.** 2015. Implementation of a Novel Hydraulic Hybrid Powertrain in a Sports Utility Vehicle. *Proceedings of the IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling (E-COM'15).* Aug. 23-26, 2015. Columbus, OH, USA.

Busquets, E. and **Ivantysynova, M.** 2015. Adaptive Robust Motion Control of an Excavator Hydraulic Hybrid Swing Drive**.** *Proceedings of the SAE Commercial Vehicle Engineering Congress (ComVec).* Oct. 6-8, 2015. Rosemont, IL, USA.

Busquets, E. and **Ivantysynova, M.** 2015. Priority-Based Supervisory Controller for a Displacement-Controlled Excavator with Pump Switching. *Proceedings of the ASME/Bath 2015 Symposium on Fluid Power and Motion Control (FPMC15).* Oct. 12-14, 2015. Chicago, IL, USA.

Ernst, M. and **Ivantysynova, M.** 2015. Micro Surface Shaping of the High-Pressure Operation of Piston Machines with Water as a Working Fluid. *Proceedings of the ASME/Bath 2015 Symposium on Fluid Power and Motion Control (FPMC15).* Oct. 12-14, 2015. Chicago, IL, USA.

Bleazard, T., **Haria, H.**, **Sprengel, M.**, and **Ivantysynova, M.** 2015. Optimal Control Based Design and Application of the Blended Hydraulic Hybrid. *Proceedings of the ASME/Bath 2015 Symposium on Fluid Power and Motion Control (FPMC15).* Oct. 12-14, 2015. Chicago, IL, USA.

Padovani, D. and **Ivantysynova, M.** 2015. Simulation and Analysis of Non-Hybrid Displacement-Controlled Hydraulic Propulsion Systems Suitable for Railway Applications. *Proceedings of the ASME/Bath 2015 Symposium on Fluid Power and Motion Control (FPMC15).* Oct. 12-14, 2015. Chicago, IL, USA.

Wondergem, A. and **Ivantysynova, M.** 2015. The Impact of Micro-Surface Shaping on the Piston/Cylinder Interface of Swash Plate Type Machines. *Proceedings of the ASME/Bath 2015 Symposium on Fluid Power and Motion Control (FPMC15).* Oct. 12-14, 2015. Chicago, IL, USA.

Busquets, E. and **Ivantysynova, M.** 2015. Test Bed 1: A Highly Efficient Displacement-Controlled Hydraulic Hybrid Excavator with Pump Switching. *Proceedings of the Fluid Power Innovation and Research Conference 2015l (FPIRC15).* Oct. 13-16, 2015. Chicago, IL, USA.

Wondergem, A. and **Ivantysynova, M.** 2015. The Significance of Piston/Cylinder Surface Shaping on the Performance of Axial Piston Machines. *Proceedings of the Fluid Power Innovation and Research Conference 2015l (FPIRC15).* Oct. 13-16, 2015. Chicago, IL, USA.

Invited Lectures

Ivantysynova, M. 2015. From Gutenberg to "Cloud Printing" & from Bramah to ? *Faculty Colloquium Series, Purdue University*. Feb. 2, 2015.

Ivantysynova, M. 2015. Quo Vadis Fluid Power. *Proceedings of the ASME/Bath 2015 Symposium on Fluid Power and Motion Control (FPMC15).* Oct. 12-14, 2015. Chicago, IL, USA. **Koski Lecture**

Ivantysynova, M. 2015. Where Are We Going? Research Focus of the CCEFP. *Proceedings of the Fluid Power Innovation and Research Conference 2015l (FPIRC15).* Oct. 13-16, 2015. Chicago, IL, USA.

Patents Filed

Ivantysynova, M. and **Ernst, M. Purdue Research Foundation.** 2015. Circumferential Groove in Cylinder of Piston Machines. 2015-IVAN-67231

Patents Awarded

Ivantysynova, M. and **Baker, J. Purdue Research Foundation.** 2015. Axial Sliding Bearing And Method Of Reducing Power Losses Thereof'. US20110056369.

5 Theses Completed In 2015

PhD Theses

Michael Sprenel 2015. Influence of Architecture Design on the Performance and Fuel Efficiency of Hydraulic Hybrid Transmissions. PhD thesis, Purdue University.

Master's Theses

Paul Kalbfleisch 2015. Computational Valve Plate Design. Master's thesis, Purdue University.

Meike Ernst 2015. Design Solutions for Piston Machines with High Operating Pressures and Water as a Working Fluid. Master's thesis, Purdue University.

Tyler Bleazard 2015. Hydraulic Hybrid Four Wheel Drive Sport Utility Vehicle - Utilizing the Blended Hybrid Architecture. Master's thesis, Purdue University.

6 International Co-operation

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

International students and researchers

In 2015, the following international students and researchers have worked in our team

Bruno

Daniel

Giovanni

Martina

Dongyun

Bruno Silba Emerick	Brazil	Dr. Dongyun Wang	China
Daniel Hasko	Slovakia		
Giovanni Napolitano	Italy		
Martinia Scamperle	Italy		

7 International and National Conferences Attended

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

May 20-22, 2015. Tampere Finland.

Attendees:

Monika Ivantysynova

Damiano Padovani (Paper Presentation)

IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling (E-COSM'15)

August 23-26, 2015. Columbus, OH, USA.

Attendees:

Mike Sprengel (Paper Presentation)

SAE 2015 Commercial Vehicle Engineering Congress (ComVec)

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

Attendees:

Enrique Busquets (Paper Presentation)

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

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

Attendees:

Monika Ivantysynova (Koski Lecture)

Enrique Busquets (Paper Presentation)

Ashley Wondergem (Paper Presentation)

Damiano Padovani (Paper Presentation)

Hiral Haria (Paper Presentation)

Meike Ernst (Paper Presentation)

Fluid Power Innovation & Research Conference 2015 (FPIRC 15)

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

Attendees:

Monika Ivantysynova (Invited Lecture)

Enrique Busquets (Paper Presentation)

Ashley Wondergem (Paper Presentation)

8 Maha Hosted & Organized Events

2015 CCEFP IEC Summit

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

As part of the summit meeting, Maha hosted a wonderful dinner for the attendees after they spent the afternoon touring the Maha lab. During the tour, Maha was pleased to showcase the innovative work taking place on the world's first blended hydraulic hybrid SUV as well as advancements in advanced control strategies for a highly efficient displacement-controlled hybrid excavator that has been developed as a CCEFP sponsored project. Attendees also had the privilege of test-driving the world's first displacement controlled steer-by-wire wheel loader.

Lab Tour & Machine Demonstration

Education and Outreach

A mission of the CCEFP is educational outreach programs that promote the teaching of science and technology concepts related to fluid power. The outreach occurs at both the secondary and graduate levels and encourages participation from underrepresented minorities.

REU Bootcamp

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

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

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

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

More About CCEFP

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

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

Purdue University is one of the seven universities represented in the CCEFP. The other participating universities are the Georgia Institute of Technology, the University of Illinois at Urbana-Champaign, the University of Minnesota, Milwaukee School of Engineering, North Carolina A&T State University, and Vanderbilt University.

Dr. Monika Ivantysynova sits on the executive committee of the CCEFP. She is the leader of Thrust Area 1: Efficiency, leading two projects - Project 1A.2: Control and Prognostics for Hybrid Displacement Control Systems and Project 1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors. She also oversees Test Bed 1: Mobile Heavy Equipment – High Efficiency Excavator.

Currently there are three Purdue faculty members as well as their graduate student teams participating in the CCEFP: Monika Ivantysynova, Andrea Vacca, and John Lumkes.

9 Awards, Honors, and Recognitions

2015 Koski Medal

The American Society of Mechanical Engineers (ASME) awarded Prof. Monika Ivantysynova the 2015 Robert E. Koski Medal last Tuesday at the ASME/BATH 2015 Symposium on Fluid Power & Motion Control in Chicago, Illinois. Prof. Ivantysynova was awarded the medal for significant contributions in the area of analysis, design and control of axial piston pumps and hydrostatic-transmission systems, which are used to transmit fluid power in automotive, industrial and aerospace applications; and for efforts to create paths to disseminate fluid power research results.

The photo from the symposiums is of Prof. Ivantysynova with all of the previous Koski medal recipients in attendance as well as members of Robert Koski's family. Pictured, from left to right, are Prof. Hubertus J. Murrenhoff (RWTH Aachen, Germany), Prof. Jan Ove Palmberg (Linkoeping University, Sweden), Beverly Koski (Robert Koski's wife), Prof. Wayne J. Book (Georgia Tech, USA), Prof. Monika Ivantysynova, Chris Koski (Robert Koski's daughter), and Prof. Richard T. Burton (University of Saskatchewan, Canada).

10 Educational Activities

Courses Taught at Purdue

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

- ABE 691 / ME 697 – Hydraulic Power Trains and Hybrid Systems *(Spring 2008, 2009, 2010, 2012, 2014, and 2015)*
- ME 597/ABE 591 – Design and Modeling of Fluid Power Systems *(Fall 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, and 2015)*
- ME 463 – Senior Design Project *(Spring 2006, 2007, 2008, 2009, and 2011)*
- ABE 697 – Seminar *(Fall 2009)*

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

Spring Semester 2015

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

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

Textbook: None.

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

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

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

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

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

Topics:
1. Introduction and overview of components, circuits and classification of CVT systems
2. Modeling, control and measurements of hydrostatic transmissions
3. Secondary controlled transmissions and hybrid structures
4. Torque converter based CVT, design principle, performance
5. Power split transmissions, classification, output coupled transmission, sizing, modeling and control
6. Input coupled power split transmissions, sizing, modeling and control
7. Advanced power split drive transmissions, dual stage and compound system structure
8. Hydraulic hybrid systems based on power split technology
9. Power train control, concepts and controller design
10. Hardware in-the-loop power train testing and performance measurements
11. Machine Power management
12. Hydraulic steering, braking and suspension system concepts
13. Vehicle active vibration damping based on displacement control
14. Special system design aspects, transmission noise
15. Fluid and structure borne noise sources, design concepts to reduce transmission noise

Computer Usage:
Matlab experience is required.

Laboratory Projects:
Three

Nature of the Design Content:
The design component of this course will consist of students designing two different continuously variable transmissions (CVT) to meet the required vehicle performance. The students will learn to model different types of CVT using a special simulation software (PSDD) and predict their performance. The results of both transmission design projects including system simulation will be summarized in an engineering design project report. A third project will deal with co-simulation of the hydraulic and mechanical system of a working machine.
ABET category content as estimated by faculty member who prepared the course description:
Engineering Science: 1.5 credits or 50%
Engineering Design: 1.5 credits or 50 %

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

Fall Semester 2015

2015 marked the eleventh 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.

<u>Engineering project to be completed during the course</u>

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

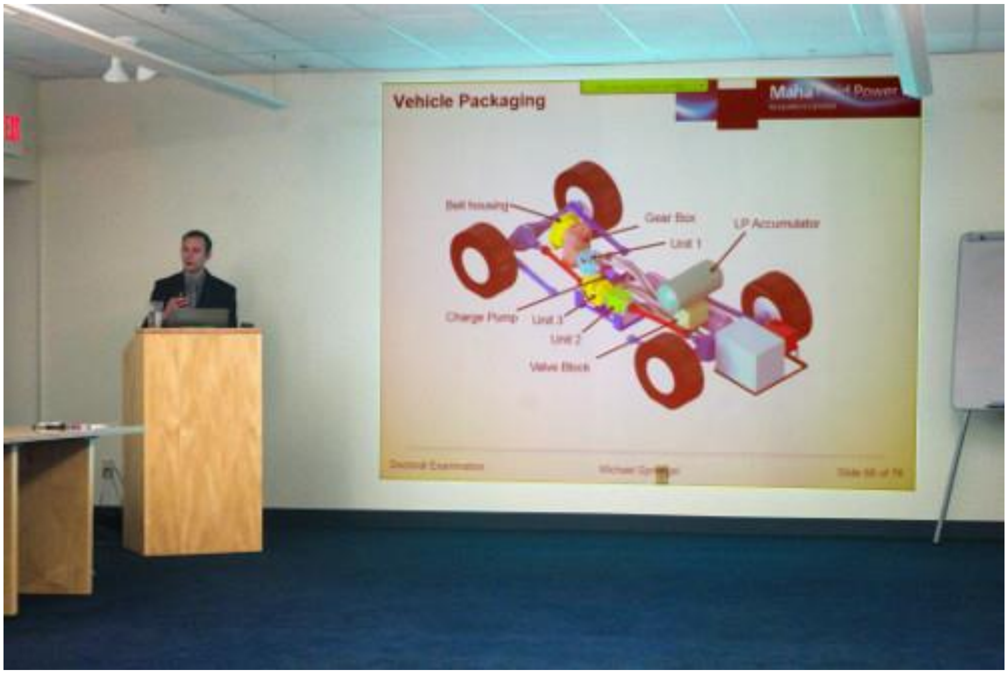
11 Maha Social Events

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.

Summer party at Susan's house

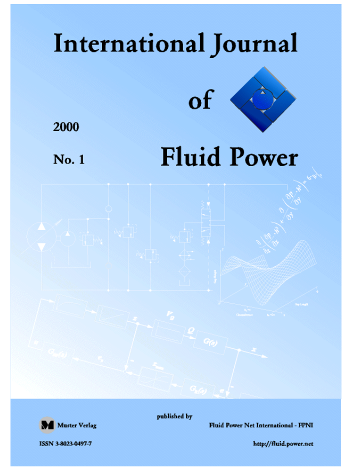
Monika’s Summer Party

Celebrating Mike's successful PhD defense



Christmas / Monika's birthday dinner

12 International Journal of Fluid Power



Dear Associate Editors and Members of Editorial Board,

Another year of publication of the *International Journal of Fluid Power* is coming to its end. This was the second year the Journal was published by Taylor & Francis. With that the International Journal of Fluid Power has completed its sixteen year of publication. The new journal website with its online submission and review tool has been successfully introduced to our readers, authors and reviewers and I hope that after several starting issues you all enjoy this new feature. The Journal's new website http://www.tandfonline.com/loi/tjfp20 allows downloading of all past and current issues and lists most cited and most read articles.

It's that time of year when we look back on our accomplishments and reflect on the friends and colleagues, whose support makes our work possible.

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 and reviewers for their effort and hard work on ensuring the outstanding quality of the Journal. The excellent job of all associate editors and our reviewers is what makes our journal so special. This is increasingly important, as the number of journals is rapidly growing worldwide.

I also wish to give recognition to the Editorial Board for great assistance and advice. Having such a wonderful and knowledgeable group of Members of the Editorial Board, Associate Editors, 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 2016.

Finally, I want to thank Susan Gauger for all her passion and continuous effort as the Journal's technical editor. Susan is doing an incredible job in managing the online submission, the associate editor paper assignment, as well as the communication with authors, reviewers and the Taylor & Francis's production team. Please join me in thanking her for her outstanding service and personal care about all matters of the *International Journal of Fluid Power*.

Let me add some statistical information regarding the Journal's progress this past year. Since the establishment of the Journal in 2000 we have presented 35 different fluid power software tools and introduced 35 fluid power research center spanning 4 different continents. The Journals continues to publish the Fluid Power calendar and abstracts of recently published books and completed PhD theses. There have been authors from 38 different countries that have submitted papers to the International Journal of Fluid Power during the last sixteen years. In order to ensure that the review process is fair and the Journal's final publication is of the highest quality all papers are reviewed by at least two experts. Accepted papers require two positive reviews. The rate of successfully approved papers in the past year was 47%.

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

I wish you and your families a happy New Year, and all the best for 2016.

Best regards,

Monika Ivantysynova   December 30, 2015
Editor-in-Chief

13 Maha Team in 2015

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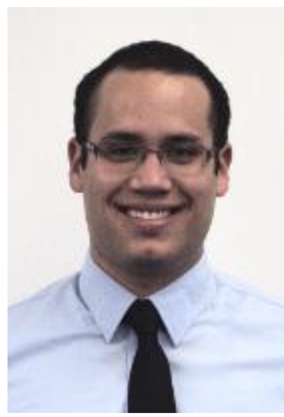

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14 Donors, Sponsors, Partners, & Guests

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

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

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

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

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