

AC 2008-2497: THE DEVELOPMENT OF A HYDRAULIC HYBRID VEHICLE LABORATORY: INTEGRATING EDUCATION AND RESEARCH

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Christopher C. Schroeder is a graduate mechanical engineering student at The University of Toledo. He is working with Dr. Mohammad Elahinia on a project to develop "Multipurpose Educational Modules to Teach Hybrid Vehicle Technologies". Specifically Christopher says I am "working with colleagues to make hydraulic hybrid vehicles more suitable for commercialization.... I am excited and thrilled to be part of a university and a project which have the potential to make big changes in the automotive industry."

Mohammad Elahinia, University of Toledo

Mohammad H. Elahinia is an assistant professor in the Department of Mechanical, Industrial and Manufacturing Engineering at the University of Toledo, where he also serves as the Co-Director for the Dynamic and Smart Systems Laboratory. His main research interest is application of smart materials. Currently he is investigating smart material applications for alternative fuel and hybrid vehicles.

Walter Olson, University of Toledo

Walter Olson is a professor of Mechanical Engineering specializing in dynamics in the Department of Mechanical, Industrial, and Manufacturing Engineering at the University of Toledo. His research on Hydraulic Hybrid Vehicles is sponsored by the US EPA as well as MIOH UTC.

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Mark Schumack is Professor of Mechanical Engineering at the University of Detroit Mercy, where he teaches courses in heat transfer, thermodynamics, fluid mechanics, and energy systems. His ongoing pedagogical interests include developing ways to teach energy conservation and sustainability principles. He has held several leadership positions in the Energy Conversion and Conservation Division of ASEE. His research interests include thermal/fluid modeling using computational techniques, with applications in the automotive, manufacturing, and energy fields. Dr. Schumack earned his BS, MS, and Ph.D. degrees in Mechanical Engineering from the University of Michigan.

The Development of a Hydraulic Hybrid Vehicle Laboratory: Integrating Education and Research

Abstract

This paper presents the development of a new hydraulic hybrid vehicle based laboratory course for the Mechanical, Industrial, and Manufacturing Engineering Department at the University of Toledo. The objective of this new laboratory course is to serve as both an educative tool for undergraduate students as well as a tool in advancing the research of hydraulic hybrid vehicle technology. The educative module is based on a problem-solving learning approach that will aid students in gaining a richer understanding of elements from courses of the Mechanical Engineering curriculum such as Fluid Dynamics and Hydraulics, Energy Systems, Vibrations, Mechatronics and Controls. Additionally, the modules developed for the hydraulic hybrid system will become available on the internet for other universities to utilize. The laboratory will also serve as a research tool for the advancement of hydraulic hybrid vehicle technology. To this end, both graduate and undergraduate students will be performing experiments and simulations that will enhance understanding of hydraulic hybrid systems. The knowledge obtained will be utilized to aid in optimizing the design of hydraulic hybrid vehicle technologies.

Introduction

Hydraulic hybrid vehicle technology is an interesting and expanding focus area for researchers concerned with alternative fuels and greener solutions to emissions problems. The hydraulic hybrid concept employs many aspects of engineering fundamentals and therefore, can provide for a convenient means of integrating engineering fundamentals into an application based learning experience. Application of hydraulic hybrid vehicle technology specifically requires knowledge of thermodynamics, fluid dynamics, kinematics, controls and vibrations and acoustics. These subjects however, oftentimes can be very arduous for a student. This is because it is difficult to provide a solid mass of the subject, i.e. something to actually look at and study. The aim of the laboratory herein is to integrate fundamental engineering curriculum in such a way as to provide a hands on application to study the principles at work. The hydraulic hybrid vehicle technology is such an application that can be utilized to study engineering principles.

Additionally, the course shall be offered as both an undergraduate and graduate course. The course will incorporate not only a hands-on problem-solving learning approach, but will also utilize and encourage basic research tools. The course is designed such that the students will perform a research review and assemble a paper that provides a basic survey of current research areas in the field of hydraulic hybrid vehicle technology. This way, the course provides an opportunity for undergraduate students to gain experience in basic research tools and expose them to the kind of work a graduate student is expected to perform. Also, beginning and advanced graduate students can refine and expand their experience performing research-based work. Finally, students will have the opportunity to expand and improve upon basic and advanced communication skills via laboratory interaction and written and oral presentations of work. It is expected that each student can produce a conference publication from their work.

This last point also serves as a great motivating factor in the students' desires to really master the subject matter.

Problem-Solving Learning Approach

The effect of creative education methodologies on student learning has long been the focus of educational researchers. Fink et al. emphasized the need for new methods for education in the field of engineering. Through case studies, the authors showed the effectiveness of such methods in improving the quality of education in different engineering disciplines¹. The authors, however, justifiably count the integration of major components, such as learning tools, learning activities, and learning evaluation of the course as some of the major aspects of effective learning. The authors conclude that by a proper combination of these major components, one can improve the students' willingness and ability to learn. Freuler et al. reported an effort in the College of Engineering at the Ohio State University where the freshman engineering classes were redeveloped into a combined course with hands-on laboratory elements². Teamwork, project management, report writing and oral presentations were the main parts of this program.

Recently, in their research, Smith et al. focused on classroom-based pedagogy of engagement³. The authors recognized that active and collaborative learning provides better ways for students to learn by being intensely involved in the educational process. These learning methods can further be implemented by encouraging the students to apply their knowledge in many situations. The article, as illustrated in, also indicates the superiority of the *problem-based learning* over the *subject-based learning*. The authors have identified the following attributes of the first learning method: (1) Learning is student-centered (2) Learning occurs in small student groups (3) Teachers are facilitators or guides (4) Problems are the organizing focus and stimulus for learning (5) Problems are the vehicle for the development of critical problem-solving skills (6) New information is acquired through self-directed learning. More importantly, the problem-solving approach prepares the students for formulating and solving problems they have never been exposed to before. The authors have observed that the willingness and the desire to learn are directly related to the students' ability to understand how the knowledge can be utilized for a relevant application. This last point, by default, is rehabilitated by providing the students with an applicable problem to solve.

The Mechanical Engineering Department at Virginia Polytechnic Institute and State University has been using a problem-solving approach to teach undergraduate students during laboratories⁴⁵. The laboratories integrate instruction and demonstration of engineering principles with instruction and demonstration of two-way communication. Using this approach, advanced topics have been successfully taught to undergraduate students⁶. At the Central Connecticut State University, Prusak applied the problem-solving approach in order to develop and improve important students' skills through laboratory experiments⁷. The students were given *limited guidance* to develop a projectile device. The assignment was aimed at giving students guided practice in engineering without clearly defined boundaries. The author reported positive outcomes in terms of inter-team communications and organizing.

Morgan and Jones have studied the importance and effectiveness of using computer simulations in engineering education⁸. According to this and similar studies, by using engineering software

it is possible to motivate the students and to provide learning at a number of levels. The authors further elaborated on their experience in using MATLAB for teaching a course on control systems. According to the authors' experience, the use of engineering simulation software can help the students with the process of decision-making and problem solving associated with the discipline of engineering. They also noted that the students find pleasure in the computer-based laboratory exercises. Many publications on engineering education emphasize the importance of teaching the principles. Pitts, using several examples, shows the importance of basic engineering principles in each discipline⁹.

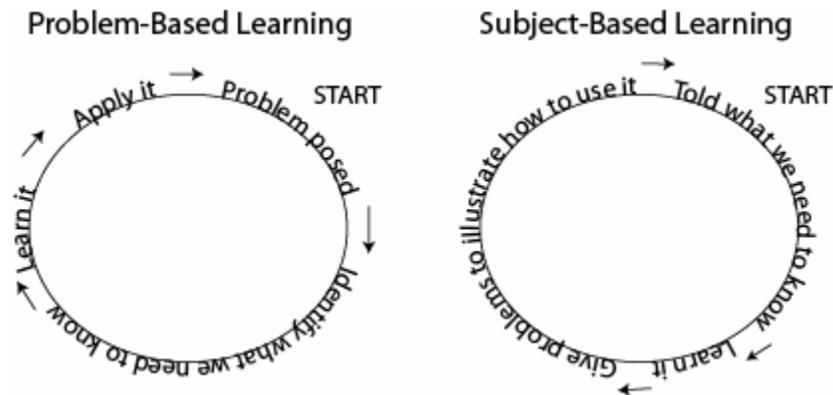


Figure 1 Problem-solving learning contrasted with subject-based learning³.

Recently, Elahinia and Ciocanel employed the problem-solving learning approach to redevelop a Mechanical Engineering Laboratory¹⁰. It has been demonstrated that students respond better when the instructor serves as more of a guide rather than a figure that simply presents facts to be remembered for an exam. This learning approach encourages problem-solving brainstorming and two-way communication between small groups of students in order to come to an understanding about a given problem. The authors have further observed that the ability of students to apply knowledge in the classroom towards the solution of a real world problem is a better index of understanding of the subject matter than a simple examination that is based on invented problems. The ability to demonstrate an idea or principle requires a mastery of that material; therefore, the student that demonstrates the ability to use knowledge is a better index of understanding than convincing a teacher that he or she can remember what was in a textbook.

Course Methodology and Objectives

In developing the laboratory, several methods were considered in order to improve students' learning and to ensure achieving the course objectives. Consequently, a problem solving approach was chosen. In this course, the step-by-step lab procedures are not provided to the students. Instead, a practical problem is designed around each experiment. A memorandum describes each of the problems that the students must solve by performing the experiment. In other words, the course is a problem-solving based course to provide students with experience in different aspects of hydraulic hybrid vehicles. This is achieved through the application of fundamental Mechanical Engineering courses.

The hydraulic hybrid vehicle laboratory course will consist of both lecture and laboratory time. The lecture time will be devoted mainly to exposing the students to research methodologies and

new tools to aid in investigating engineering problems. The research techniques will consist of topics such as how to perform literature queries, how to assemble a survey paper, how to and the importance of submitting work for publication, etc. Additionally, lecture time will be devoted to exposing the students to software tools such as MATLAB/Simulink, AMESim, Labview, LMS Test.lab as well as introducing theory and application of transducer technologies, etc. The students are further encouraged to develop and/or introduce any desired investigative tool that may prove beneficial in solving the problem at hand.

The first lectures of the course will include a tour and demonstration of the hydraulic hybrid vehicle laboratory. This way, the students will have some idea as to how the system works and how the system may aid the students in solving the problem of their choosing. At this time, the students will ask questions and have the opportunity to use the system and become familiar with it. In this fashion, rather than learning how to use the system in a course; the students will solve a problem with the system once the system has been understood. The students will be encouraged to spend as much time as necessary with the system to learn and understand it.

Throughout the first quarter of the course, each student performs a literature review on hydraulic hybrid vehicle (HHV) technology while at the same time working with the instructors and teaching assistants in the lab to understand exactly how the HHV test stand functions. Upon completion of the literature review, the students will be presented with various problems in the form of a memorandum from which they will choose, based on the literature review and knowledge of the test stand, which problem most interests them. Also, a student may choose to originate a problem. Upon selection of the problem, the students will then assemble into groups (2 to 4). The groups will combine the individuals' reviews from each member and begin reviewing specific research that will aid in solving the problem at hand. Meanwhile, the students continue to learn about the functionality of the test rig in the lab and specifically how it can be used to aid in solving the problem. Additionally, in conjunction with the Michigan-Ohio University Transportation Center, Schumack et al. have developed a simulation model of the HHV system using MATLAB/Simulink. The program will be used to introduce many principles of HHV technology to the students via exercises. Preliminary case studies with the program have been performed and positive results have been reported¹¹.

A number of problems concerning aspects of the hydraulic hybrid technology have been invented and presented in memo format. In this way, a small group of students is presented with a request from a customer to investigate a relevant problem. Based on the students' interpretations of the requirements from the customer, the students will propose a method of solving the problem via investigative tools made available through the laboratory. The proposed methodology will then be submitted to the instructor (guide or manager), at which point the instructor will discuss the proposed investigation methodology and provide any necessary feedback, comments, recommendations, etc to the group of students. It will then be the responsibility of the students to carry out the investigation and report their procedures, observations, results and conclusions. This and the previously assembled literature review will serve as the basis for the students' publication submittals.

Sample memorandums are presented in Appendix A, which include the following information: introduction and problem statement, customer requirements and recommendations, some references from the literature and may include additional information as needed.

Hydraulic Hybrid Test Stand

The hydraulic hybrid vehicle test stand simulates the operation of a series configuration type hydraulic hybrid vehicle. The system consists of an electric motor, two hydraulic pump/motor units, a hydraulic circuit and relevant transducers at key locations in the system. Figure 2 demonstrates, in schematic form, the working principles of the system.

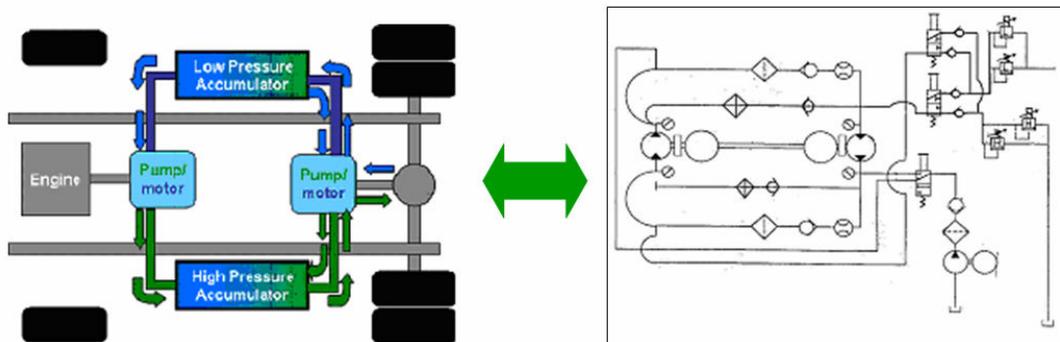


Figure 2 Schematic of the hydraulic hybrid test stand.



Figure 3 Current status of the hydraulic hybrid vehicle test stand.

An additional document has been prepared which details, to the students, the exact workings of the test stand. This document shall serve as a reference for the students as they are becoming familiar with the system and is supplied in Appendix B. The document includes data sheets that can be printed out as well as an inventory of each component of the system such that the students can acquire any necessary data from the manufacturers or the operating manuals. The status of the hydraulic hybrid test stand is under construction, as shown in Figure 3. The hydraulic hybrid test stand is expected to be complete by April of 2008.

Some typical functions the students will be performing with the experimental setup include using Labview to collect pressure, temperature, vibration and noise data. The students will likely have to perform multiple tests at different operating conditions. Depending on the problem that was chosen by the students to be solved, the problem may require all or some of these tasks. The

data collected will then be analyzed by the students on their own time at another location. The students will make appropriate graphs and figures to present the data in a useful form to illustrate their findings. Most of the data that will be collected will not require signal processing, however, whether or not to process the data at this level is at the discretion of the students. This will allow for the students to gain interactive experience with engineering tools and data manipulation processes. The students will then be asked to make conclusions based on their findings and the data that was accrued during the experiments. Additionally, the findings will be prepared in such a way as to present them to the classroom as if to a client. This will also broaden the students abilities to communicate and gain valuable feedback from peers and the instructor as to how well the problem had been solved.

Conclusions

A novel approach of introducing and advancing the hydraulic hybrid vehicle technology has been proposed. The proposed approach utilizes a problem-solving learning approach that emphasizes the use of student validation and two-way communication through a hands-on application-based learning experience. The instructor serves as a guide for the students to perform and advance the research of hydraulic hybrid vehicle technologies. As an additional result, both undergraduate and graduate students will gain invaluable research experience and from it have the opportunity to publish relevant conclusions. Currently the hydraulic hybrid test stand is under construction. Upon completion of the test stand, a case study will be performed to evaluate the effectiveness of the novel research approach.

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6. Elahinia, M., "Teaching Smart Materials to Engineering Undergraduate Students: A Problem Solving Approach," *2004 ASEE Annual Conference* (Salt Lake City: ASEE, June 2004).
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8. Morgan, R., and Jones, K., "The Use of Simulation Software to Enhance Student Understanding," IEE International Symposium on Engineering Education: Innovations in Teaching, Learning and Assessment (Ref. No. 2001/046), 2001, 33/1-33/6.
9. Pitts, G. "How do we teach students to relate to real applications," IEE Colloquium on Engineering Education in the Twenty-First Century (Digest No: 1996/105), May 1996, 5/1-5/5.
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11. Schumack, M., Elahinia, M., Olson, W., and Schroeder, C. "A Hydraulic Hybrid Vehicle Simulation Program to Enhance Understanding of Engineering Fundamentals," *Submitted to 2008 ASEE Annual Conference*.

Appendix A

Friendly Fluid Power, Inc.
8008 LRH Way
Los Angeles, CA

Dynamics and Hydraulics Laboratory,

Hydraulic Hybrid Vehicles are currently being investigated by a number of researchers and organizations in an effort to produce vehicles that are more fuel efficient and environmentally friendly. It is anticipated that a surge in demand will occur for hydraulic hybrid components as a direct result of the ensuing success of these systems. In order to be ready for this demand, Friendly Fluid Power, Inc. has developed some axial piston pump/motor units. As this is the company's first prototype design, it is desired to have a second party perform an evaluation. Consequently, we at Friendly Fluid Power, Inc. would like your research team at the University of Toledo to evaluate the performance of our units. Some general information on the pump/motors has been provided with this request. Specifically, our company would like you to develop and compare the theoretical flow rate with the actual performance as a function of the bent/axis angle and shaft speed. Please include the following in your report:

- Describe theoretical and experimental procedures and methodologies employed.
- Describe the equipment used to acquire data including software used to model or analyze the system.
- Plot theoretical and experimental flow rate as a function of the bent/axis angle and rpm of the pump/motor.
- Discuss the difference between theory and experiment, if any, and provide possible explanations for differences. Also compare the results with the technical data provided by the manufacturer.
- Based on literature and experience, provide recommendations that could improve our design.

For additional information regarding theory and background refer to the references:

1. Skaistis, Stan. *Noise Control of Hydraulic Machinery*. Marcel Dekker, New York, 1988.
2. Cheremisinoff, Nicholas P. *Noise Control in Industry: A Practical Guide*. Noyes Publications, Westwood, New Jersey, USA. 1996.
3. Amin M. Motlagh, Mohammad H. Elahinia, Mohammad Abuhaiba, Walter W. Olson. Application of smart materials for noise and vibration of hydraulic systems. Accepted proceeding of IDETC2007, USA.
4. Amin M. Motlagh, Mohammad Abuhaiba, Mohammad H. Elahinia, Walter W. Olson. *Hydraulic Hybrid Vehicles*. Department of Mechanical, Industrial and Manufacturing Engineering, The University of Toledo. Toledo, Ohio 43606.
5. Akers, A., Gassman, M. P., Smith, R. J. *Hydraulic Power System Analysis*. Taylor & Francis Group. Boca Raton, London, New York. 2006.

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8. Amin M. Motlagh, Mohammad H. Elahinia, Mohammad Abuhaiba, Walter W. Olson. Application of smart materials for noise and vibration of hydraulic systems. Accepted proceeding of IDETC2007, USA.
9. Amin M. Motlagh, Mohammad Abuhaiba, Mohammad H. Elahinia, Walter W. Olson. *Hydraulic Hybrid Vehicles*. Department of Mechanical, Industrial and Manufacturing Engineering, The University of Toledo. Toledo, Ohio 43606.
10. Akers, A., Gassman, M. P., Smith, R. J. *Hydraulic Power System Analysis*. Taylor & Francis Group. Boca Raton, London, New York. 2006.

Dynamics and Hydraulics Laboratory,

We at Friendly Fluid Power, Inc. have successfully evaluated the performance of our bent/axis pump/motors with the help of your lab at the University of Toledo. The evaluation indicated adequate levels of performance in flow rate across the pumps at various operating conditions. Now that we are satisfied with the performance of our pump/motor units with respect to flow and efficiency, we would like to perform a noise and vibration analysis of the units. Specifically, our company would like your laboratory to establish typical noise and vibration levels exhibited by the pump/motors. Please perform the noise and vibration analyses in a series of two separate tests, respectively. Each analysis will require an individual report, one on the airborne noise and another on structural vibrations. Please include the following in your reports:

Report 1: "Airborne Noise"

- Describe theoretical and experimental procedures and methodologies employed.
- Describe the equipment used to acquire data and explain why this equipment was utilized.
- Identify what type of noise is emanating from the pump/motors and develop a standardized means of the most effective way for measuring and evaluating it.
- Measure and plot the level of noise in dB A of the pump/motors and compare any differences observed in "pump mode" versus "motor mode" in the frequency domain.
- Perform any additional measurements and calculations as necessary to fully characterize the noise of the pump/motor units.
- Explain how the physical phenomenon of the system corresponds to the frequency content of the noise levels.
- Provide additional information on how the noise of the system can be better evaluated and characterized, if possible.
- Based on literature and experience, provide recommendations that could provide for a quieter design.

Report 2: "Structural Vibration"

- Describe theoretical and experimental procedures and methodologies employed.
- Describe the equipment used to acquire data and explain why this equipment was utilized.
- Characterize the level of structural vibrations exhibited by the various components of the system (valves, pump/motors, hoses, fittings, etc).
- Plot the magnitude of the response (choose an appropriate parameter) of the various components evaluated in frequency domain.
- Identify the largest source of structural vibration and provide recommendations on how to reduce the level of vibration exhibited by this component.
- Explain how the level of structural vibration contributes to the overall noise of the system.

- Based on literature and experience, provide recommendations that could provide for an improved design with respect to structural vibrations.

For additional information regarding theory and background refer to the references:

11. Skaistis, Stan. *Noise Control of Hydraulic Machinery*. Marcel Dekker, New York, 1988.
12. Cheremisinoff, Nicholas P. *Noise Control in Industry: A Practical Guide*. Noyes Publications, Westwood, New Jersey, USA. 1996.
13. Amin M. Motlagh, Mohammad H. Elahinia, Mohammad Abuhaiba, Walter W. Olson. Application of smart materials for noise and vibration of hydraulic systems. Accepted proceeding of IDETC2007, USA.
14. Amin M. Motlagh, Mohammad Abuhaiba, Mohammad H. Elahinia, Walter W. Olson. *Hydraulic Hybrid Vehicles*. Department of Mechanical, Industrial and Manufacturing Engineering, The University of Toledo. Toledo, Ohio 43606.
15. Akers, A., Gassman, M. P., Smith, R. J. *Hydraulic Power System Analysis*. Taylor & Francis Group. Boca Raton, London, New York. 2006.

Dynamics and Hydraulics Laboratory,

Our company has developed a series of hydraulic fluid power systems that utilize axial piston pump/motors. In order to better streamline our design and prototyping process, our company seeks to build a simulation model that predicts the output torque of the pump/motor units. This model will be employed to simulate the effect various port configurations have on the overall performance of the pump/motor units. To this end, we may evaluate the performance of the design before prototypes are built. We have supplied your lab with a system that we have recently designed and built. According to the geometry of the axial piston pump/motors, develop a model to predict the output torque of the pump/motor units and experimentally evaluate the simulation model.

Please include the following in your report:

- Explain how the theoretical or analytical model was developed. This model should predict the output torque of the pump/motor as a function of the pressure drop across the pump/motor.
- Experimentally evaluate the developed model by measuring and recording the output torque and pressures across the pump/motor. Do this for motor and pump modes.
- Plot the output torque as a function of the pressure drop (theoretical and experimental results) for both pump and motor mode.
- Explain the validity of the developed model based on the experimental results.
- Discuss the difference between theory and experiment, if any, and provide possible explanations for differences.

For additional information regarding theory and background refer to the references:

16. Skaistis, Stan. *Noise Control of Hydraulic Machinery*. Marcel Dekker, New York, 1988.
17. Cheremisinoff, Nicholas P. *Noise Control in Industry: A Practical Guide*. Noyes Publications, Westwood, New Jersey, USA. 1996.
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19. Amin M. Motlagh, Mohammad Abuhaiba, Mohammad H. Elahinia, Walter W. Olson. *Hydraulic Hybrid Vehicles*. Department of Mechanical, Industrial and Manufacturing Engineering, The University of Toledo. Toledo, Ohio 43606.
20. Akers, A., Gassman, M. P., Smith, R. J. *Hydraulic Power System Analysis*. Taylor & Francis Group. Boca Raton, London, New York. 2006.

Dynamics and Hydraulics Laboratory,

Our company has developed a preliminary theoretical model of a parallel hydraulic hybrid vehicle. We would like your laboratory to evaluate our model by doing a series of studies. Each study will assume that the model has been validated. In this first study, we would like your lab to evaluate the potential fuel savings of the vehicle by testing it with different drive cycles. This is a two part study. The first part examines the performance of the vehicle under different drive cycles and the second part will consist of determining what vehicle sizes are suitable for applying this technology to.

Please include the following in your report:

- Describe the type of drive cycles that were tested with the model (whether they were obtained or developed). These drive cycles may reflect city, highway, mountainous, etc.
- Generate a plot that displays the average fuel consumption and the drive cycle for different mass vehicles.
- Determine what kind of drive cycles the vehicle exhibits the best fuel economy and explain why this is so.
- Determine the optimal size of vehicle this technology is applicable for.
- Discuss possible drawbacks from the model and provide recommendations for how it can be improved.

For additional information regarding theory and background refer to the references:

1. Wu, Bin, Lin, Chan-Chiao, Filipi, Zoran, Peng, Huei, Assanis, Dennis, *Optimal Power Management for a Hydraulic Hybrid Delivery Truck*. University of Michigan, Dept. Mechanical Engineering.
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Appendix B

Hydraulic Hybrid Test Rig Specifications

The hydraulic hybrid test rig is designed and constructed such that it approximates the functionality of a series configured hydraulic hybrid vehicle power train. The major purposes of the test stand are to do performance testing, durability testing and educate engineers. It is designed such that the efficiency of the main components of a hydraulic hybrid vehicle can be evaluated. The purpose of this document is to serve as an introduction to the test rig as well as provide technical data for some of the components.

The basic configuration of the test rig, as shown in Figure 4 of Appendix B, will serve as a markup to help students identify components and areas of interest during an experiment. It is provided on a separate sheet to allow the student to print it out and bring it to the lab. The schematic is detailed with some identification numbers for various components of the system. These details are defined in Table 1.

Detail #	Item	Spec 1	Spec 2	Spec 3	Notes
1	Pump/Motor				"Pump Mode"
2	Pump/Motor				"Motor Mode"
3	Torque Sensor				
4	Electric Motor				See Spec Sheet
5	Electric Motor				
6	Supply Pump				Used as compensations
7	Supply Tank				
8	Control Valve				
9	Low Pressure Relieve Valves				
10	High Pressure Relief Valves				
P1	Pressure Transducer 1				
P2	Pressure Transducer 2				
P3	Pressure Transducer 3				
P4	Pressure Transducer 4				
F1	Oil Filter 1				
F2	Oil Filter 2				
F3	Oil Filter 3				
F4	Oil Filter 4				Not Currently Available
Q1	Flow Meter 1				
Q2	Flow Meter 2				

Table (1) Details of test stand

Also included for reference is a document that outlines and explains hydraulic schematic symbols and terminology. Refer to the document entitled “Hydraulic Schematic Symbols” for this information. Additionally, a detailed explanation of how the test rig operates can be found in Appendix C.

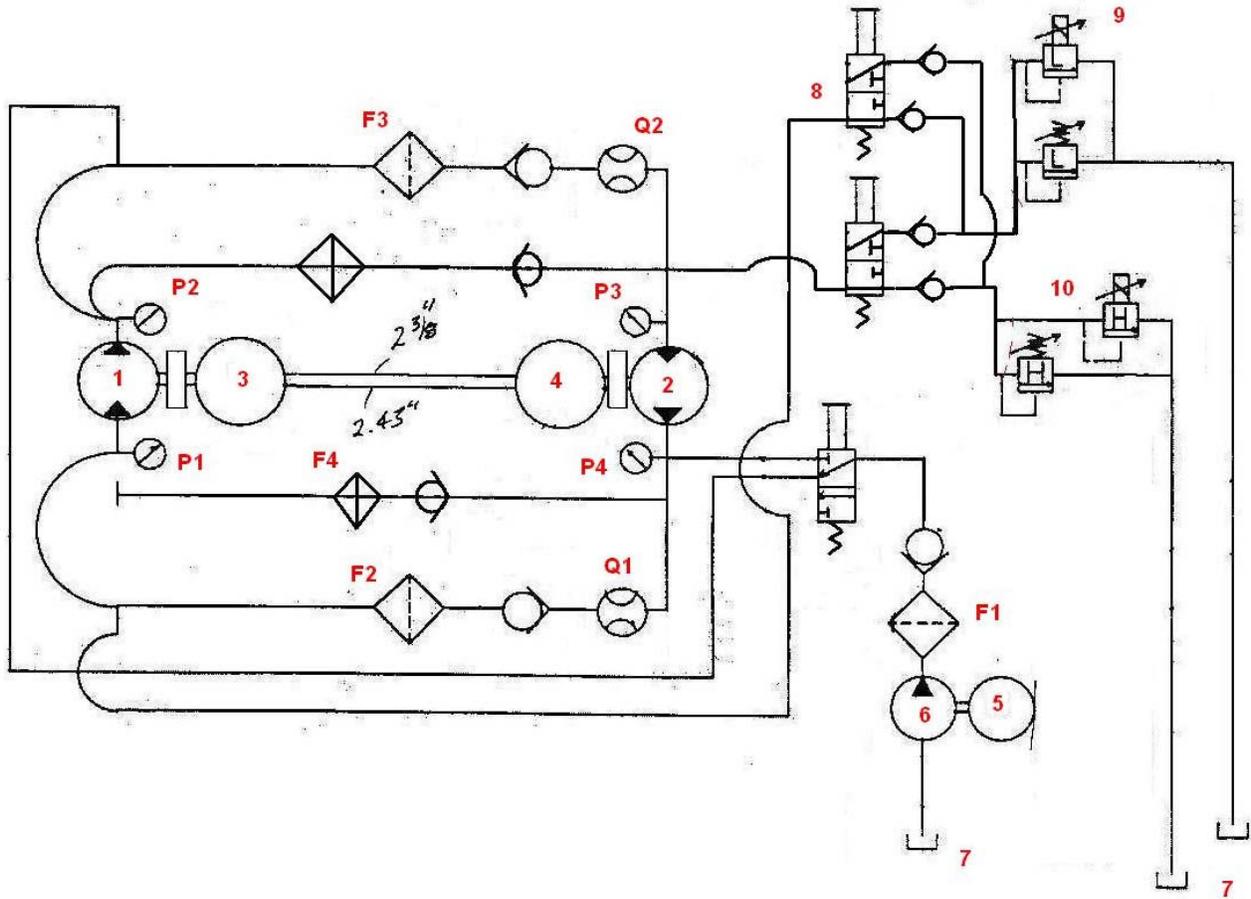


Figure (4) Schematic of Hydraulic Hybrid Test Rig

Appendix C

Hydraulic Pump/Motor Test Rig Operation (Refer to Figure (5)):

A motor at (1) drives a pump at (2) which draws fluid at atmospheric pressure from the supply at (3). This fluid is pressurized as it flows through the pump and goes through a directional control valve (4). The control valve can allow flow to go through line (5) or (6). Through line (6) it serves two functions: as a means of draining the line and also as a compensation to flow on the high pressure side. When directed through line (6) low pressure fluid is input to the pump/motor (serving as a pump) at (7). The pump/motor then pressurizes the fluid to a high pressure and flows along line (8) to another pump/motor at (9) and through a series of directional control valves at (10). The high pressure flow through pump/motor at (9) drives this in motor mode to drive the electric motor at (11). This electric motor then drives the pump/motor at (7) to continue the cycle. The high pressure flow through the directional control valves at (10) is directed to a series of low and high pressure relief valves. These valves limit the maximum pressure in the system as well as serving as means to drain the fluid back to the supply tank at (12).

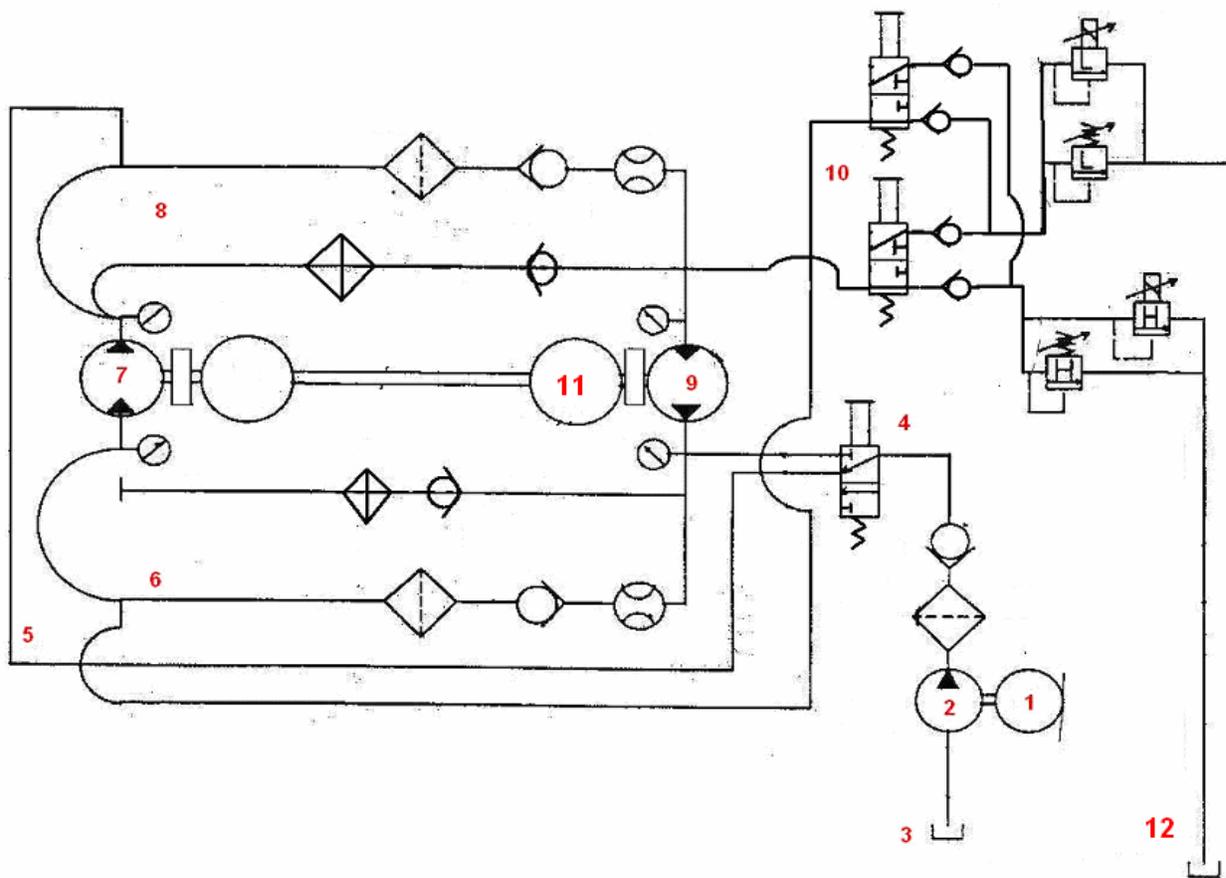


Figure (5) Numbered test stand schematic