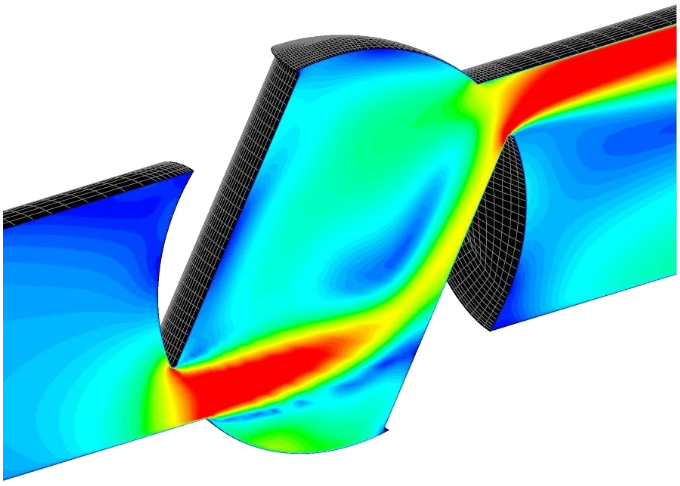
Bath/ASME Symposium on
Fluid Power and Motion Control



FPMC 2022

14th – 16th September 2022

Contents

FPMC 2022

14th – 16th September 2022

I wish you a warm welcome to our international symposium on Fluid Power and Motion Control, on behalf of the University of Bath's Centre for Power Transmission and Motion Control (PTMC) and the Fluid Power Systems & Technology Division (FPST) of the American Society of Mechanical Engineers (ASME). This is the 35th Symposium in the series which has taken place annually since 1988. We are very proud to host a variety of high-quality papers and presentations by worldwide experts in the field of fluid power and motion control, and we look forward to some lively discussions. Thank you for your participation.

Nigel Johnston
Symposium Organiser
ptmc@bath.ac.uk

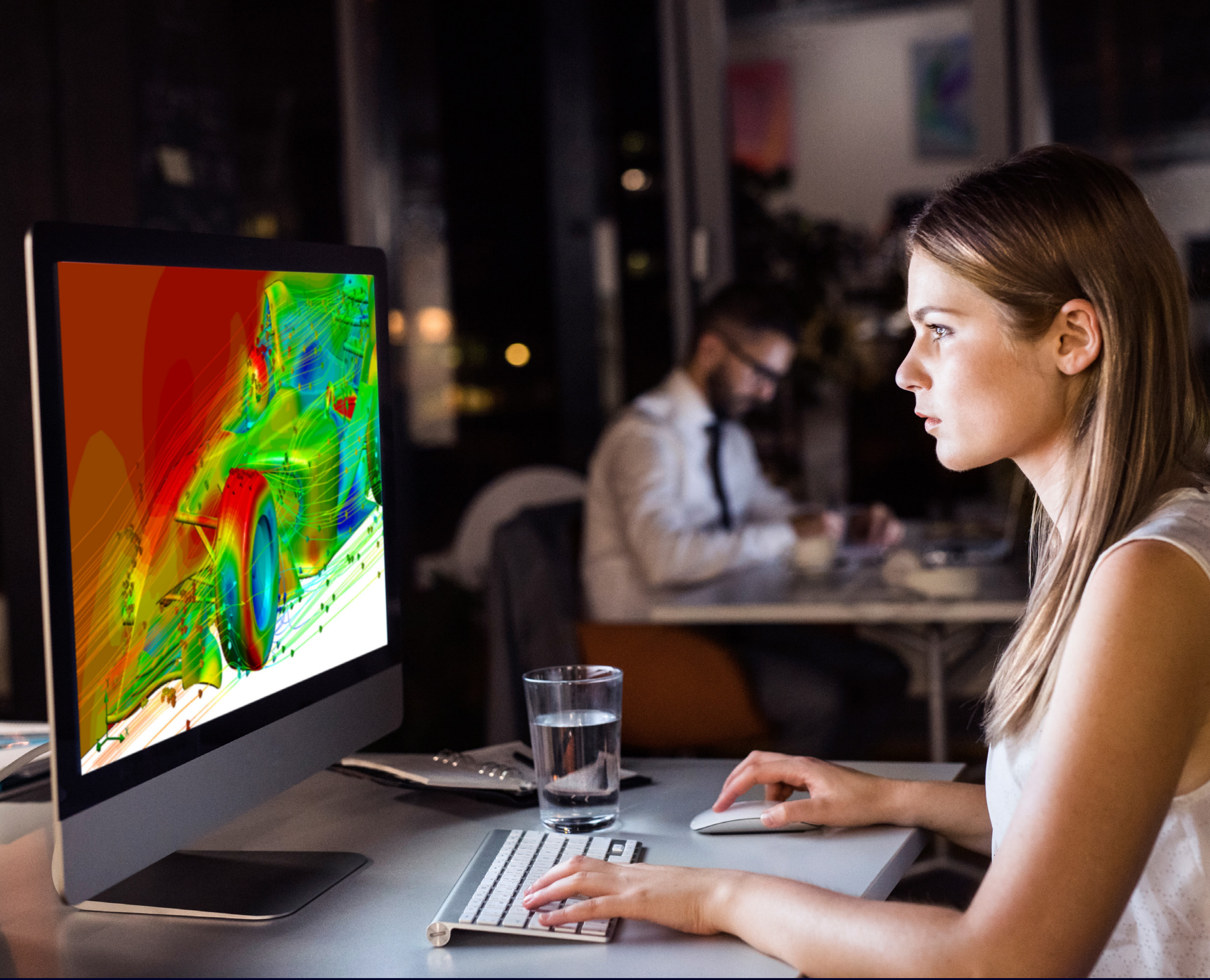
Lecture Room CB 2.6, Chancellors' Building, University of Bath

Delegates can register and pick up Symposium files in the
Chancellors' Building Foyer on Wednesday 14th September from 08:00.

Please wear your name badge at all times during the Symposium.

To aid in the smooth running of the Symposium, Presenting Authors and Chairs are asked to meet in the lecture room 15 minutes before the start of their session so that their presentations can be set up. If possible, presentations should be brought on a flash drive and copied onto the lecture room PC.

For wi-fi access, 'WiFi Guest' or (for registered users) 'EduRoam' are available.



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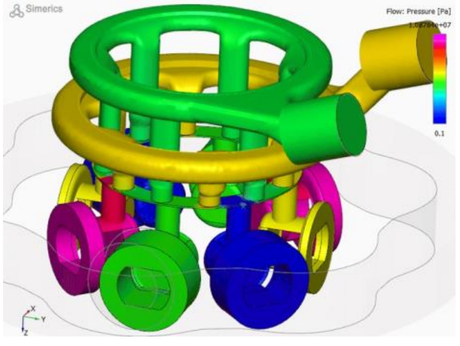

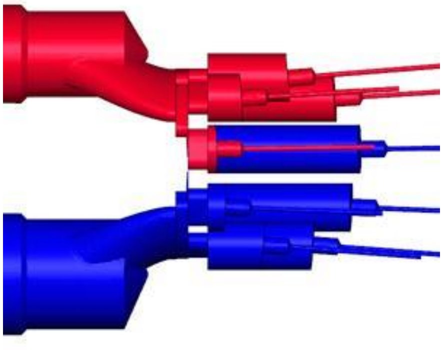

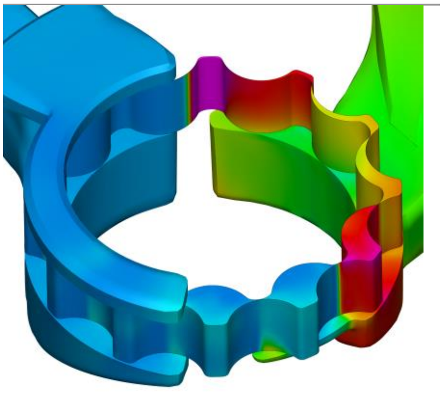

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- Less than an hour from CAD to Simulation
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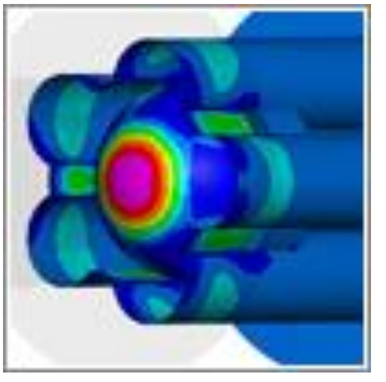

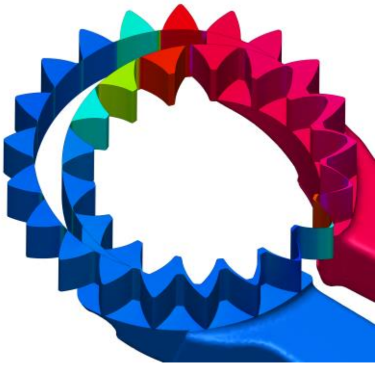

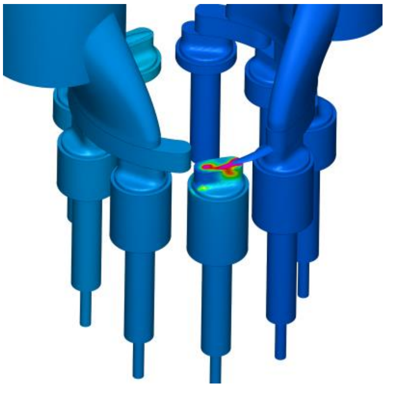

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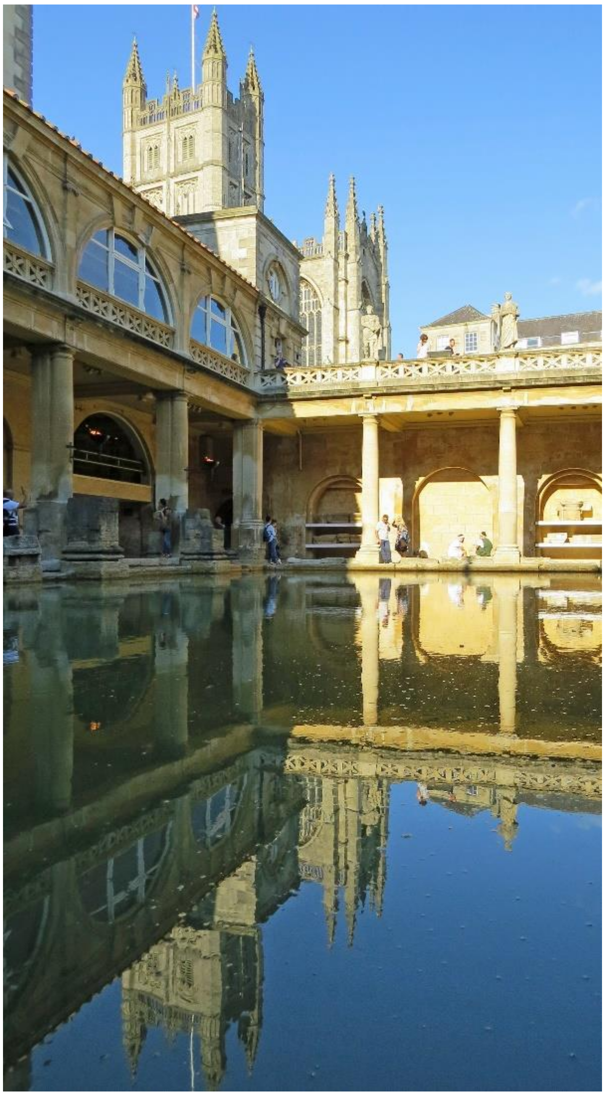
Images in and around Bath…

Pulteney Street and the Holburne Museum

The Circus

Pulteney Bridge



The Roman Baths

Castle Combe, near Bath

Programme for Wednesday 14th September

09:00 – 09:15		**Introduction**
09:15 – 10:30		**Session 1: Zero Carbon Technologies** — **Chair: Eric Barth**
09:15	88967	Daniel Escobar-Naranjo, Kim A. Stelson and Biswaranjan Mohanty, *Experimental Validation of Extremum Seeking Control for a Midsize Hydrostatic Transmission Wind Turbine*
09:30	89567	Qin Zhou, Yue Yang, Shuming Shang, Jiarui Zhang, Chao Ai and Wenting Chen, *Research on High Precision Control of Maximum Power Point Tracking for Offshore Hydraulic Wind Turbine*
09:45	89650	Kim A. Stelson, Daniel Escobar, Biswaranjan Mohanty and Justin Chen, *Optimizing Viscosity for Maximum Power in a Hydrostatic Transmission Wind Turbine*
10:00	89985	Lucas Zanatta Manosso, Victor J. De Negri, *Design and Analysis of a Digital Hydrostatic Transmission for Wind Turbines*
10:15		Discussion
10:30 – 11:00		**Refreshments**
11:00 – 12:30		**Session 2: Efficient and Intelligent Systems 1** — **Chair: Jim Van de Ven**
11:00	87665	Tobias Vonderbank and Katharina Schmitz, *Energetic Investigation of Common Pilot Operation and the Energy Saving Potential of Electromechanical Valve Actuators*
11:15	89547	Lasse Schmidt, Kenneth Vorbøl Hansen and Søren Ketelsen, *Perspectives on Component Downsizing in Electro-Hydraulic Variable-Speed Drive Networks*
11:30	89847	Matthias Scherrer and Rudolf Scheidl, *An Improved Elastic and Non-Contact Smart Sealing Concept for Digital Micro Hydraulic Valves*
11:45	89900	Andrea De Martin, Giovanni Jacazio, Massimo Sorli and Andrea Ruffinatto, *A Novel Hydraulic Solution to Simulate Inertial Forces on a Landing Gear Qualification Test Rig*
12:00	89984	James Gallentine, Eric J. Barth, Kourosh Shoele, Brian Van Stratum, Jonathan Clark and Kevin Galloway, *A Multimodal Climbing-Swimming Soft Robotic Lamprey*
12:15		Discussion
12:30 – 14:00		**Lunch (Lime Tree Restaurant)**
14:00 – 15:30		**Session 3: Control** — **Chair: Perry Li**
14:00	88959	Christian Haas, Andreas Opgenoorth, Arne Schneider and Katharina Schmitz, *Practical Evaluation of a Control Concept for a Remote Controlled 1.8T Excavator Using a 3D Input Device*
14:15	89019	Heng Liu, Hao Sun, Wei Sun, Jianfeng Tao and Chengliang Liu, *A Deep Koopman-Based Model Predictive Control Method for Valve-Controlled Hydraulic Cylinder Systems*
14:30	89072	Hao Sun, Honggan Yu, Jianfeng Tao and Chengliang Liu, *Fuzzy-Based Adaptive Model Predictive Control for Deteriorating Model Uncertainty of Hydraulic Servo Systems*
14:45	89548	Lasse Schmidt, Kenneth Vorbøl Hansen and Søren Ketelsen, *State Decoupling & Stability Considerations in Electro-Hydraulic Variable-Speed Drive Networks*
15:00	90575	Bobo Helian, Marcus Geimer and Sebastian Beiser, *High Precision Nonlinear Motion Control of a Hydraulic Orbital Motor-Driven Linear Rack*
15:15		Discussion
15:30 – 16:00		**Refreshments**
16:00 – 17:30		**Session 4: Digital and Switched Fluid Power Systems** — **Chair: Rudolf Scheidl**
16:00	88503	Samuel Kärnell and Liselott Ericson, *Analysis of a Digital Pump With Variable Speed Drive*
16:15	88601	Bing Xu, Jiaming Wu, Feng Wang and Zongxuan Sun, *A Digital Hydraulic Load-Sensing System Based on Hydraulic Free Piston Engine*
16:30	88893	Daniil Dumnov and Niall Caldwell, *A Cylinder Enabling Algorithm for Reduction in Low Frequency Pulsation From Digital Displacement Pumps*
16:45	89366	Mikko Huova and Matti Linjama, *Control of Multi-Pressure Hydraulic Supply Line Using Digital Hydraulic Power Management System*
17:00	90598	Justin Darnet and Eric Bideaux, *State-of-the-art of Variable Displacement Technologies for Radial Piston Hydraulic Machines*
17:15		Discussion

Evening: Reception, Holburne Museum, Bath. See page 9 for details.

Programme for Thursday 15th September

09:15 – 10:30 **Session 5: Noise and Vibration** **Chair: Win Rampen**

09:15	88101	Zubin Mistry, Andrea Vacca, Manuel Rigosi and Sujan Dhar, *Modeling Fluid Inertia Effects in External Gear Machines Through Lumped Parameter Approach*
09:30	88957	Rudolf Scheidl, Helmut Kogler and Philipp Zagar, *A Hydraulically Controlled Multiple Buck Converter System*
09:45	89042	Jing Yao, Juntao Zhao, Pei Wang, Yuwang Cheng and Yupeng Wang, *Active Pressure Pulsation Suppression Method by Parallel-Series Structure in DFCU Based on Variable Step Size FXLMS Algorithm*
10:00	89855	Gudrun Mikota, Rainer Haas and Rudolf Scheidl, *Sensor Placement in a Hydraulic Drive System*
10:15		Discussion

10:30 – 11:00 **Refreshments**

11:00 – 12:30 **Session 6: Pumps and Motors** **Chair: Emma Frosina**

11:00	88469	Israa Azzam, Sujan Dhar, Dipak Maiti, Veeranagouda Patil, Paul Asunda, Jose Garcia Bravo and Farid Breidi, *Gerotor Pump Simulation Modules for Enhancing Fluid Power Education*
11:15	89002	Paul Michael, Kim Stelson, Daniel Williams and Hassan Malik, *Dynamometer Testing of Hydraulic Fluids in an Axial Piston Pump Under Simulated Backhoe Loader Trenching Conditions*
11:30	89380	Elias V. Hansen, Per Johansen, Jens Rendbæk and Lasse Almind Jensen, *In-Situ Lubrication Film Thickness Measurements in a Radial Piston Motor Using Adaptive Ultrasound Reflectometry*
11:45	89553	Evan D. Sand and Perry Y. Li, *Incorporating a Rotatable Valve Cam to Improve the Efficiency of a Hydraulic Motor in an Inline Hydro-Mechanical Transmission (i-HMT)*
12:00	89718	Shanmukh Sarode, Lizhi Shang, Andrea Vacca and Scott D. Sudhoff, *Flux Weakening Operation Based Design of an Integrated Electrohydraulic Axial Piston Unit*
12:15		Discussion

12:30 – 14:00 **Lunch (Lime Tree Restaurant)**

12:30 – 14:00 **FPST Executive Meeting (cold buffet lunch will be provided)**

14:00 – 15:15 **Koski Lecture**

15:15 – 15:45 **Refreshments**

15:45 – 17:15 **Session 7: Components and Systems** **Chair: Kim Stelson**

15:45	88614	Brendan Deibert, Sophia Scott, Allan Dolovich and Travis Wiens, *The Use of Additive Manufactured Plastic in Small-Scale Poppet Valves and Pressure Vessels*
16:00	89252	Jianbin Liu, Jürgen Weber and André Sitte, *Investigation of Temperature Influence on Flow Mapping of Electrohydraulic Valves and Corresponding Application*
16:15	89721	Per Johansen, Uffe N. Christiansen, Sune Dupont, Anders Bentien, David N. Østedgaard-Munck, Jens L. Sørensen and Michael M. Bech, *An Experimental Study on High-Flowrate Ultrasonic Particle Monitoring in Oil Hydraulics*
16:30	89927	Emil Nørregård Olesen, Torben Ole Andersen and Poul Ennemark, *Active Damping of a Hydrostatic Steering Circuit for an Articulated Vehicle*
16:45	90897	Emil Nørregård Olesen and Torben Ole Andersen, *Investigation of a New Orbital Steering Concept with Focus on the Control Loop Performance*
17:00		Discussion

Evening: Symposium Dinner and Awards Presentation, The Pump Room, Bath. **See page 9 for details.**

Programme for Friday 16th September

09:00 – 10:30		**Session 8: Efficient and Intelligent Systems 2**	**Chair: Victor de Negri**
09:00	88563	Rituraj Rituraj and Rudolf Scheidl, *Advancements in the Control Strategy for Digital Hydraulically Driven Knee Exoskeleton*	
09:15	89099	Zichang Lin, Bing Xu and Feng Wang, *Improving Wheel Loader Energy Efficiency With a Series Electric Hybrid Powertrain*	
09:30	89509	Annalisa Sciancalepore, Andrea Vacca and Steven Weber, *Control Strategy of Adjustable Pilot Counterbalance Valves for Efficient Hydraulic Actuation*	
09:45	89646	Zhiyong Su, Jingfu Wang, Tianbao Zhu, Haodi Tang and Xu Zang, *Design and Modeling of Heave Compensation System Based on Secondary Regulation Technology*	
10:00	90090	Xu Han, Manu Leinonen and Tatiana Minav, *Design and Simulation Analysis of a Pump-Controlled Actuation System for Heavy-Duty Booms*	
10:15		Discussion	
10:30 – 11:00		**Refreshments**	
11:00 – 12:30		**Session 9: Fault Analysis and Diagnosis**	**Chair: Eric Bideaux**
11:00	88249	He Xu and Feng Sun, *Research on Life Extension of Water Hydraulic Control Valve Based on Augmented Reality for Fault Diagnosis*	
11:15	88646	Faried Makansi and Katharina Schmitz, *Fault Detection and Diagnosis for a Hydraulic Press by Use of a Mixed Domain Database*	
11:30	89083	Terkil Bak-Jensen and Lasse Schmidt, *Prognostics in Custom-Build Electro-Hydraulic Variable-Speed Drive Applications*	
11:45	89107	Andris Rambaks, Paul Knipper, Niklas Bauer and Katharina Schmitz, *Autofrettage and Its Impact on High-Cycle Fatigue of Hydraulic Components*	
12:00	89359	Hao Yin, He Xu, Feng Sun and Yuhan Zhao, *Research on Application of Elastic Consolidation Algorithm in Fault Diagnosis of the Control Valve*	
12:15		Discussion	
12:30 – 14:00		**Lunch (Lime Tree Restaurant)**	
14:00 – 15:15		**Session 10: Modelling and Simulation**	**Chair: Travis Wiens**
14:00	89105	Philipp Zagar and Rudolf Scheidl, *The Connection Between Sliding Mode Analysis and Singular Perturbation Theory for Modelling Fast Hydraulically Fed-Back Switching Valves*	
14:15	89636	Jeffrey J. Bies and William Durfee, *Fluid-Structure Optimization of Small-Scale Hydraulic Conduits*	
14:30	90184	Jackson Wills and Perry Y. Li, *Accumulator Sizing for the Hybrid Hydraulic Electric Architecture (HHEA) Using Dynamic Programming*	
14:45	90185	Bernhard Manhartsgruber, *A Set of Benchmark Problems for Fluid Power System Simulation*	
15:00	90715	Zihan Wu, Feng Wang, Bing Xu and Wieslaw Fiebig, *An Electric-Hydraulic Hybrid Wheel Loader With Mode-Driven Control Strategy*	
15:15		Discussion	
15:30 – 15:45		**Closing Remarks**	
15:45 – 16:00		**Refreshments**	
16:00 – 17:00		**Commercial Modelling Software Presentations**	
16:00 – 16:30		Siemens Digital Industries Software, *A vision for fluid power and motion control integration driven by digitalization*	
16:30 – 17:00		80/20 Engineering, *Template Driven, Three-Dimensional CFD Simulation of Positive Displacement Hydraulic Machinery*	

Transport

A free coach service will operate between the city of Bath and the University Claverton Down campus as follows. The coach operator is Berkeley.

08:15 - depart from Terrace Walk, Bath city centre (see map on page 37), arriving on campus about 08:30.

17:45 - depart from Campus, arriving at Terrace Walk, Bath at about 18:00.

Alternatively there is a regular bus service (U1), or it is a pleasant (if hilly) walk of about 30 minutes between the University and the city centre.

Social Programme

Wednesday Evening: Reception and Buffet Dinner at Holburne Museum, Bath

18:30 – 21:00	Reception and buffet. You are free to explore Bath afterwards.

Thursday Evening: Symposium Dinner and Awards Presentation

19:00	Reception drinks at the Terrace of the Roman Baths (entrance near the front of the Abbey).
19:30	Dinner in The Pump Room, followed by presentations.

The 2022 Robert E. Koski Medal, the 2021 IMechE Joseph Bramah medal, the 2022 Charles Russ Richards Memorial award and the FPMC 2020 and 2021 Best Paper awards will be presented at the dinner.

https://www.bathvenues.co.uk/venues/pump-room

The Robert E. Koski Medal

The Robert E. Koski Medal, established in 2007, recognizes individuals who have advanced the art and practice of fluid power motion and control through education and/or innovation.

The Medal was established by the Fluid Power Systems and Technology Division to honour Robert E. Koski's contributions to the field of Design Engineering and Dynamic and Systems and Control.

The 2022 Robert E. Koski Medal will be awarded to Professor Rudolf Scheidl of Johannes Kepler University, Linz, Austria.

Professor Rudolf Scheidl

Previous Recipients

2021 Huayong Yang
2020 Shinichi Yokota
2019 Peter Achten
2018 Luca Zarotti
2017 Werner Dieter
2016 Kim Stelson
2015 Monika Ivantysynova
2014 Hubertus Murrenhoff
2013 Wayne J. Book
2012 Siegfried Helduser
2011 Richard T. Burton
2010 Yongxiang Lu
2009 Jan Ove Palmberg
2008 Clifford R. Burrows
2007 Wolfgang Backe

The Joseph Bramah Medal

The Joseph Bramah Fund was established in 1968 at the instigation of Mr Frank Towler, a Fellow of the Institution of Mechanical Engineers (1932-1977), who arranged for its support by industry to commemorate Joseph Bramah, the inventor of a patent lock, the hydraulic press and other inventions concerned with pumps, water supply and the production of pipes and tubes by the extrusion process.

The 2021 Joseph Bramah Medal will be awarded to Dr Nigel Johnston of the University of Bath.

Previous Recipients

2020 David Phillips
2018 Professor Kim Stelson, *University of Minnesota*
2017 Professor Huayong Yang, *Zhejiang University*
2016 Professor Andrew Plummer, *University of Bath*
2015 John Savage, *National Fluid Power Centre*
2014 Professor Win Rampen, *Edinburgh University and Artemis Intelligent Power*
2013 Professor Richard Burton, *University of Saskatchewan*
2011 Professor Shinichi Yokota, *Tokyo Institute of Technology*
2010 Professor Rudolf Scheidl, *Johannes Kepler University*
2009 Professor Monika Ivantysynova, *Purdue University*
2008 Professor Siegfried Helduser, *Technical University of Dresden*
2007 Dr Peter Achten, *Innas BV*
2006 Professor Serge Scavarda, *INSA Lyon*
2005 Professor Matti J. Vilenius, *Tampere University*
2004 Professor Hans-Heinrich Harms, *Technical University, Braunschweig, Germany*
2003 Mr Roy Cuthbert
2002 Mr John Bentley
2001 Professor Hubertus Murrenhoff
1999 Professor J Watton
1998 M D Kelley
1997 Professor Jan-Ove Palmberg
1996 Mr Norman Way
1995 Dr W Dieter
1994 P J Wilson
1993 Professor Cliff Burrows
1992 Robert Koski
1991 Professor Dr Ing Wolfgang Backe
1990 Dr Kevin Edge
1989 G Allison
1988 R B Walters
1987 R E Knight
1986 F B Levetus
1985 J F Nosworthy
1984 G C Knight
1982 M J Fisher
1981 F W Baggett
1980 D Bick
1979 E H Bowers
1978 Professor D E Bowns
1976 P M M Price
1975 J G Keenan
1974 C M Edgehill
1973 Professor W M J Schlosser
1972 R H Y Hancock
1971 K Foster
1970 G P Copping
1968 B Lengyel

FPMC Best Paper Award

The FPMC Best Paper award is awarded based on scoring by the Symposium delegates, on the basis of technical quality and presentation quality, and is normally presented in the following year's Symposium. This year we will present awards for the previous two years.

The FPMC 2020 Best Paper Award will be awarded to William Durfee, Brett Neubauer, Jonathan Nath, Saeed Hashemi and Andrew Ries for their paper entitled "*Hydraulic Ankle Foot Orthosis Emulator for Children with Cerebral Palsy*".

The FPMC 2021 Best Paper Award will be awarded to Fabian Guse, Enrico Pasquini and Katharina Schmitz for their paper entitled "*Consideration of Air Bubble Dynamics in 1D Hydraulic Pipeline Simulation: Source Term Development and Verification Utilizing Transmission Line Theory*".

Previous Recipients, 2008-2019

2019 Paul Michael, Pawan Panwar, Michelle Len, Ninaad Gajghate and Ashlie Martini, *Fluid Effects on Mechanical Efficiency of Hydraulic Pumps: Dynamometer Measurements and Molecular Simulations*

2018 Andrew Robison and Andrea Vacca, *Multi-Objective Geometric Optimization of Elliptical-toothed Gerotor Pumps for Kinematics and Wear by Genetic Algorithm*

2017 Divya Thiagarajan, Andrea Bratto and Andrea Vacca, *Influence of Surface Roughness Effects on the Lubrication Performance of External Gear Machine.*

2016 Tian Yu, Andrew Plummer, Pejman Iravani, Jawaad Bhatti, Saeed Zahedi and David Moser, *The Design, Analysis and Testing of a Compact Electrohydrostatic Powered Ankle Prosthesis*

2015 Stefan Heitzig, Gregor Bultel and Hubertus Murrenhoff, *Efficiency Improvement of Common-Rail Pumps by Gap Compensation based on Hollow Pistons*

2014 Johannes Willkomm, Matthias Wahler and Juergen Weber, *Process-Adapted Control to Maximize Dynamics of Speed- and Displacement-Variable Pumps*

2013 Johannes Schmitz, Milos Vukovic and Hubertus Murrenhoff, *Hydrostatic Transmission for Wind Turbines – an Old Concept, New Dynamics*

2012 Henrik C Pedersen, Anders H Hansen, Rico H Hansen, Torben O Andersen and Michael M Bech, *Design and Control of Full Scale Wave Energy Simulator System*

2011 Matteo Pelosi and Monika Ivantysynova, *A Novel Thermal Model for the Piston/Cylinder Interface of Piston Machines*

2010 Rico Hansen, Torben Andersen and Henrik Pedersen, *Development and implementation of an advanced power management algorithm for electronic load sensing on a telehandler*

2009 Joshua Zimmerman and Monika Ivantysynova, *Effect of Installed Hydraulic Corner Power on the Energy Consumption and Performance of Multi-Actuator Displacement Controlled Mobile Machines*

2008 José Riofrío and Eric Barth, *Experimental assessment of a free elastic-piston engine compressor with separated combustion chamber*

FPMC 2022 Organisers

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Perry Li, *University of Minnesota*
Andrew Plummer, *University of Bath*
Steve Weber, *Sun Hydraulics*

Technical Program Chair:

Nigel Johnston, *University of Bath*

Administrator:

Gillian Elsworth, *University of Bath*

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Katharina Schmitz, *RWTH Aachen University*
Kim Stelson, *University of Minnesota*
James Van de Ven, *University of Minnesota*
Travis Wiens, *University of Saskatoon*

Abstracts

Session 1: Zero Carbon Technologies

Wednesday 12th September 09:00 – 10:30

09:15 88967 Daniel Escobar-Naranjo, Kim A. Stelson and Biswaranjan Mohanty, *Experimental Validation of Extremum Seeking Control for a Midsize Hydrostatic Transmission Wind Turbine*

Extremum Seeking Control (ESC) is a model-free control strategy that uses a dither signal to enable a gradient search to find an optimal operating point. The adaptability and model-free nature of the ESC can be beneficial to improve power capture of wind turbines because the Cp (power capture coefficient) vs. λ (tip speed ratio) curve is constantly changing in time and is dependent on uncertain parameters that are not easily available. For conventional gearbox wind turbines, ESC is used to continuously search for the optimal torque gain, k, of the commonly used $k\omega^2$ law, improving the power capture when compared to control using a fixed k gain. Our group has expanded the studies of ESC to Hydrostatic Transmission (HST) wind turbines through simulation. The work studied the effectiveness of ESC for a midsize HST wind turbine, under steady, step, and turbulent wind, and its robustness to changes in the Cp vs. λ curve. Previous simulation results are experimentally validated here using the HST dynamometer at the University of Minnesota. Experiments show that ESC can effectively adapt to changing Cp vs. λ curves and results are compared to the simulations validating the results. Use of an anti-windup algorithm is also discussed.

09:30 89567 Qin Zhou, Yue Yang, Shuming Shang, Jiarui Zhang, Chao Ai and Wenting Chen, *Research on High Precision Control of Maximum Power Point Tracking for Offshore Hydraulic Wind Turbine*

This research takes the fixed displacement hydraulic pump-variable displacement hydraulic motor transmission system of offshore hydraulic wind turbine as the research object, to solve the parameter uncertainly problem of maximum power point tracking (MPPT) control of wind turbine. The feedback linearization method is used to deal with the non-linear state space model of the system. Aiming at the problem that the feedback linearization method needs an accurate mathematical model and the hydraulic transmission system of the wind turbine has the characteristics of parameter uncertainly, the RBF neural network adaptive control theory is used to deduce the control strategy. Taking the hydraulic pump speed and power as the output respectively, the MPPT control strategy is realized. The theory proposed above is verified by Matlab/Simulink. With the hydraulic pump speed as the output, although the speed can track the optimal speed well, there are large fluctuations in high pressure and pump output power. With the hydraulic pump power as the output, by contrast, the pump speed can track the optimal speed well, meanwhile, there is no large fluctuation in high pressure and pump output power. The simulation results under fluctuating wind speed show that the MPPT control strategy has good robustness.

09:45 89650 Kim A. Stelson, Daniel Escobar, Biswaranjan Mohanty and Justin Chen, *Optimizing Viscosity for Maximum Power in a Hydrostatic Transmission Wind Turbine*

In basic hydraulic theory, efficiency is dependent on volumetric and mechanical losses. Components dominated by mechanical losses favor low viscosity fluids, while those dominated by volumetric losses favor high viscosity fluids. For a hydrostatic transmission (HST), efficiency of both the pump and motor must be considered. The goal of this work is to model the HST viscosity-efficiency curve for finding the optimal viscosity and to validate the results with experiments.

This study uses a mathematical efficiency model that is dependent on non-dimensional viscosity, two non-dimensional length ratios, and fractional swash plate displacement. Rather than using physical dimensions for the non-dimensional length ratios, these parameters were determined for the pump and motor through constant viscosity experiments. The predicted results of the model were compared to validation experiments where viscosity was varied by changing temperature.

Results showed high accuracy for the pump model at all tested conditions, but the accuracy of the motor model was lacking, deviating significantly from experiments at low viscosities. For future studies, it is recommended to increase the number of data points at low dimensionless viscosity to create a more accurate model fit.

10:00 89985 Lucas Zanatta Manosso, Victor J. De Negri, *Design and Analysis of a Digital Hydrostatic Transmission for Wind Turbines*

This paper presents the design, modelling, and simulation of a digital hydrostatic transmission (D-HST) for wind turbines using fixed and variable displacement hydrostatic machines. A sizing algorithm is developed considering real efficiency data in order to optimize the selection of components and set the most energy efficient configuration. The design of a D-HST for a 28.5 kW wind turbine is carried out. Considering the use of a synchronous generator, the best D-HST configuration is set with two fixed pumps and a variable motor. A computational model is developed according to the designed system. The D-HST is compared to a conventional hydrostatic transmission (C-HST), made up by a fixed pump and a variable motor. The model of the C-HST used as a baseline was validated using an experimental setup and that is modified according to the new designed system. Steady-state and dynamic analysis are done, in order to identify the pros and cons of each concept. Furthermore, a comparison with other wind turbine drivetrains is carried out including: a widespread solution drivetrain made up by a gearbox and a doubly-fed induction generator with frequency converter; a digital displacement hydrostatic transmission; and a direct-drive wind turbine.

Session 2: Efficient and Intelligent Systems 1

Wednesday 12th September 11:00 – 12:30

11:00 87665 Tobias Vonderbank and Katharina Schmitz, *Energetic Investigation of Common Pilot Operation and the Energy Saving Potential of Electromechanical Valve Actuators*

Small hydraulic valves are usually actuated by electromechanical transducers such as solenoids or voice coils. Normally, the necessary actuation forces grow with increasing size of the valve. Therefore, the application of direct electromechanical actuators is nowadays limited to valves of nominal size 10 or smaller. Larger valves are usually pilot operated, which is characterized by high power density and large achievable forces. However, these systems are inefficient due to the principle-related drain oil and further system specific losses in the pilot circuit.

As shown in previous research, electromechanical actuation systems can be implemented on large sized directional control valves as a viable alternative to pilot operated valves. In this contribution, the energy saving potential of alternative electromechanical actuation systems is analyzed. Therefore a comparison of the overall energetic output in common hydraulic pilot circuits and electromechanical actuation based on a prototype of a designed electromechanical actuation system is carried out. Beyond the pure actuator, the study also addresses the complexity of the entire hydraulic system. The influence of the system design and the control approach are taken into account to depict the entire system.

11:15 89547 Lasse Schmidt, Kenneth Vorbøl Hansen and Søren Ketelsen, *Perspectives on Component Downsizing in Electro-Hydraulic Variable-Speed Drive Networks*

The field of electro-hydraulic variable-speed drive technology is expanding, and application areas are increasing across both stationary and mobile industry segments. Developments have mainly concerned standalone drives, and the effective compensation of asymmetric volume variation in cylinders, fully closed circuit functionalities and so forth. In multi-cylinder systems, conventional valve-controlled drives supplied by centralized power units, provide for flexible power distribution among cylinders but generally suffer from poor efficiencies. On the contrary, standalone electro-hydraulic variable-speed drives provide much improved efficiency in comparison, but suffer from inflexible power distribution necessitating maximum cylinder power to be installed for each actuator, hence resulting in potentially high cost levels. Component downsizing potentials of electro-hydraulic variable-speed drive systems with multiple cylinders have only been considered to a minor extend at this point. In this area, recently introduced electro-hydraulic variable-speed drive networks allow for a more flexible distribution of hydraulic power compared to standalone drives, while providing efficiencies on a similar level. Furthermore, such drive networks may eliminate the necessity for various auxiliary valves and potentially allow to reduce the number of variable-speed drives to be installed compared to standalone solutions. The study presented aims to demonstrate that components in electrohydraulic variable-speed drive networks may be substantially reduced compared to standalone drive systems, via considerations on the dimensioning load cycles for a given application. A case study on a crane application is used to exemplify the downsizing potential, and results here demonstrate a reduction in the required installed power of up to 25% compared to standalone solutions.

11:30 89847 Matthias Scherrer and Rudolf Scheidl, ***An Improved Elastic and Non-Contact Smart Sealing Concept for Digital Micro Hydraulic Valves***

A non-contacting sealing concept is presented which employs an elasto-hydrodynamic principle to reduce an initially large gap between seal and counter surface to a small value for tolerable leakage. The seal is a circular ring made of polymeric material to enable the intended radial deformation. It has basically rectangular cross section but two slightly conical surfaces: The outer girthed area in order to get a hydrostatic feedback from the pressure field in the sealing gap; and the lower pressure sided front face to limit the radial ring deflection. An analytical model based on a perfect geometry assumption demonstrates the function principle and analysis the role of main design parameters. An FEM model which can take complex ring deformation and partial contact of seal with its counter surface into account shows provides a deeper insight to effects not covered by the analytical model and shows a reasonable agreement with experimental investigations made with a prototype.

11:45 89900 Andrea De Martin, Giovanni Jacazio, Massimo Sorli and Andrea Ruffinatto, ***A Novel Hydraulic Solution to Simulate Inertial Forces on a Landing Gear Qualification Test Rig***

The E-LISA research project, under way within the Clean Sky 2 framework has the objective of developing an innovative iron bird to qualification and performance tests for the landing gear of an executive aircraft with a fully electrical landing gear system, thus with electro-mechanical landing gear actuators and electrical brake. The proposed test rig consists of a multi-functional intelligent test facility with the objective to perform all the tests and analyses required to assess the maturity of an electro-mechanical landing gear and demonstrate the feasibility of Prognostics and Health Management (PHM) functionalities for the electrical brake system. One of the most critical elements in the design of such iron-bird is the definition of the system replicating the aircraft inertia, which presence is necessary to properly assess the behavior of both the brake and its anti-skid logic during landing. The most common solution foresees to bring the landing gear leg in contact against a rotating cylinder, or runway simulator, which moment of inertia is equivalent to the aircraft mass. Although it is possible to reduce the system encumbrance through the introduction of a geared reducer, such architecture is usually extremely heavy and requires significant space in the test facilities. This architecture is also difficult to adapt to different aircrafts, since it would require the addition or replacement of these heavy flywheels, which is both difficult and dangerous. This paper deals with the definition of a possible alternative, based on a hydraulic solution, where two variable-displacement hydraulic motors, connected to a light rotating cylinder, are used to replicate most of the aircraft inertial forces during braking. The paper opens with the preliminary sizing of such system, presents the high-fidelity simulation environment used to assess its expected performances and compare the behavior of the hydraulic solution with that of the traditional configuration, finally presenting both the benefits and the disadvantages of the proposed architecture.

12:00 89984 James Gallentine, Eric J. Barth, Kourosh Shoele, Brian Van Stratum, Jonathan Clark and Kevin Galloway, ***A Multimodal Climbing-Swimming Soft Robotic Lamprey***

Here, we present a multimodal, lamprey-inspired, 3D printed soft fluidic robot/actuator based on an antagonistic pneu-net architecture. The Pacific Lamprey is a unique fish which is able to climb wetted vertical surfaces using its suction-cup mouth and snake-like morphology. The continuum structure of these fish lends itself to soft robots, given their ability to form continuous bends. Additionally, the high gravimetric and volumetric power density attainable by soft actuators make them good candidates for climbing robots. Fluidic soft robots are often limited in the forces they can exert due to limitations on their actuation pressure. This actuator is able to operate at relatively high pressures (for soft robots) of 756 kPa (95 psig) with a -6 dB bandwidth of 2.6 Hz to climb at rates exceeding 20 cm/s. The robot is capable of progression on a vertical surface using a compliant microspine attachment. The paper also presents the details of the 3D-printed manufacturing of this actuator/robot.

Session 3: Control

Wednesday 14th September, 14:00 – 15:30

14:00 88959 Christian Haas, Andreas Opgenoorth, Arne Schneider and Katharina Schmitz, *Practical Evaluation of a Control Concept for a Remote Controlled 1.8T Excavator Using a 3D Input Device*

Tele-remote control of excavators poses challenges for operators. While conventional operation already requires complex motor skills and thus extensive training, both the feeling for the machine and the 3D view are missing in a tele-remote scenario. This can result in operators being unable to estimate distances and performing movements more slowly and less accurately. Possible solutions to facilitate the operation of remote-controlled construction machinery are to improve visibility conditions through more sophisticated camera systems, or to provide motion feedback to the operator station. However, these solutions may be limited, for example, by higher demands on data transmission. Another solution could be to adapt the control of the machine. Therefore, this paper presents a control concept for a tele-remote operated excavator using a 3D-input device. First the test machine and the general structure of the control concept are introduced. For controlling the tool-position, an approach with direct position control and one with secondary velocity control are presented. For evaluation, both approaches are tested and compared. Finally, operator trials are presented and the usability of the concept is evaluated.

14:15 89019 Heng Liu, Hao Sun, Wei Sun, Jianfeng Tao and Chengliang Liu, *A Deep Koopman-Based Model Predictive Control Method for Valve-Controlled Hydraulic Cylinder Systems*

Hydraulic servo systems are widely applied in construction machinery due to their simple structure and strong bearing capacity. However, considering the nonlinearity and asymmetry in such systems, it is not easy to establish a precise discrete prediction model for the design of the MPC controller, which is a key factor affecting the precision of motion control. To address this issue, this paper proposes a deep Koopman-based model predictive control (MPC) method for valve-controlled asymmetric hydraulic cylinder (VCHC) systems. Significantly, a linear predictor is developed based on the ability of the Koopman operator to lift a nonlinear space to a linear space globally. The simulation results show that the MPC algorithm combined with the Deep Koopman operator has more excellent control performance.

14:30 89072 Hao Sun, Honggan Yu, Jianfeng Tao and Chengliang Liu, *Fuzzy-Based Adaptive Model Predictive Control for Deteriorating Model Uncertainty of Hydraulic Servo Systems*

The deterioration of model uncertainties is an important factor restricting the control precision for hydraulic servo systems. This paper proposes a fuzzy-based adaptive model predictive control (MPC) method with a linear extended state observer (LESO) for such systems. As for the output feedback MPC, the influence of key parameters on observation errors is analyzed and revealed in the face of deteriorating model uncertainties. Based on this, a fuzzy-based weight coefficient self-tuning strategy is developed to achieve the bounded observation errors. That is, during the repeating optimization, the defined and estimated disturbances could be dynamically adjusted, simultaneously. By simulation analysis, the results indicate that the proposed fuzzy-based adaptive MPC controller shows an excellent tracking performance in the case of the deterioration of the model parameter uncertainty and the unmodeled uncertainty.

14:45 89548 Lasse Schmidt, Kenneth Vorbøl Hansen and Søren Ketelsen, *State Decoupling & Stability Considerations in Electro-Hydraulic Variable-Speed Drive Networks*

The recent introduction of so-called electro-hydraulic variable-speed drive networks offers actuation of multi-cylinder systems by few component types, no throttle losses, small reservoir volume and provide for significantly improved efficiencies compared to valve controlled systems. Furthermore, such drive networks provide a more flexible hydraulic power distribution and potentially fewer components and lower installed power as compared to standalone electro-hydraulic variable-speed drives. These features are realized by interconnecting cylinder chambers by electro-hydraulic variable-speed drives at a system level, or even by short-circuiting cylinder chambers where the load permits this, while also sharing the electric supply. Hence, such drive networks are interconnected both electrically and hydraulically. Especially the latter feature renders electro-hydraulic variable-speed drive networks highly coupled systems, and individual control of piston motion or force can generally not be realized by the individual electro-hydraulic variable-speed drives in such systems. Hence, conventional control methodologies cannot be directly applied in such systems. The presented study considers decoupling of the cylinder motion/forces and the system pressure level by analytical methods, and a case study suggests effective decoupling by means of pressure and position measurements, cylinder and pipe/hose dimensions as well as control parameters. The stability boundaries related to the control parameters are assessed and it is shown that conventional controls combined with the proposed decoupling method provide for individual control of system pressure level and piston motions.

15:00 90575 Bobo Helian, Marcus Geimer and Sebastian Beiser, *High Precision Nonlinear Motion Control of a Hydraulic Orbital Motor-Driven Linear Rack*

In this paper, a high precision motion control strategy of a hydraulic orbital motor-driven linear rack is proposed. The reference system is a forest walking machine, which is designed for moving on wet soils. The high-order nonlinear dynamics and uncertain parameters of the cabin movement that is driven by an electro-hydraulic motor system are the control difficulties. The control accuracy is limited by nonlinear friction, unknown disturbance, dead-band of the proportional valve, etc. To deal with these control difficulties, an adaptive robust backstepping controller is designed based on the nonlinear model of a hydraulic motor driving system. The controller consists of two steps: a position tracking step and a motor torque tracking step. In each step, the uncertain parameters are adapted in real-time to achieve effective model compensation and high tracking accuracy. Simulations with comparative control strategies demonstrate that the proposed controller can achieve high control response and robust tracking accuracy in the presence of nonlinear dynamics and uncertain parameters of the orbital motor driving system.

Session 4: Digital and Switched Fluid Power Systems

Wednesday 14th September, 16:00 – 17:30

16:00 88503 Samuel Kärnell and Liselott Ericson, *Analysis of a Digital Pump With Variable Speed Drive*

Many mobile working machines are about to be electrified. This means that speed-control is of higher interest than ever before. In turn, this means that it is tempting to use fixed pumps in applications where variable pumps traditionally have been used. However, it can be beneficial to use variable pumps in combination with variable speed drives since it can allow downsizing of the electric machines and also reduce losses. But, there are downsides with variable pumps too. Disadvantages are increased complexity and cost. Variable displacement machines also tend to have low efficiency at low displacement settings, which limits the above-mentioned loss reduction potential. A solution that addresses the problems that come with conventional variable pumps is the digital pump. This paper is focused on the performance of a digital pump and shunt-based concepts that can improve the dynamics during switching are proposed.

16:15 88601 Bing Xu, Jiaming Wu, Feng Wang and Zongxuan Sun, *A Digital Hydraulic Load-Sensing System Based on Hydraulic Free Piston Engine*

The hydraulic load-sensing system is a more efficient system solution than constant pressure system in mobile machine. However, the overall system efficiency for multiple actuators is still low since this centralized hydraulic control system only adapts to the highest load pressure. Therefore in this paper, a distributed hydraulic control system where each function is powered by a hydraulic free piston engine is proposed. Compared with centralized solution, it is more efficient since the power of hydraulic free piston engine is tailored to each function. By integrating small inertia linear engine and pump piston in one unit, the hydraulic free piston engine is an efficient and fast response hydraulic power source. Since the hydraulic free piston engine is essentially a digital hydraulic power source, a digital load-sensing control is proposed in this study. The system architecture, modeling, controller design and performance of the digital hydraulic load-sensing control system are presented. A test bench is developed to verify the system feasibility and performance.

16:30 88893 Daniil Dumnov and Niall Caldwell, *A Cylinder Enabling Algorithm for Reduction in Low Frequency Pulsation From Digital Displacement Pumps*

Digital Displacement® hydraulic pumps are a type of radial-piston machine with solenoid operated on/off valves used to individually control the pressurization of each cylinder on a stroke-by-stroke basis, thus adjusting the pump's overall displacement. Previously developed cylinder enabling strategies based on using full strokes can lead to low frequency vibration, whereas partial stroke strategies pose challenges in audible noise and component lifetime. A new enabling algorithm is proposed, Quantized Part Stroke (QPS), which seeks to minimize the low frequency content in the pump output, as well as limiting transients due to actuating the valve near mid-stroke. The operating displacement fraction is quantized such that only integer fractions of displacement are permitted, the fraction's denominator relating directly to a minimum allowable frequency in the pump output. This quantization is applied such that the chosen displacement fraction is higher than the demand and then part strokes are used to exactly achieve the desired flow. Simulation results are presented comparing this algorithm with well-known alternatives, as well as test data from a 12-cylinder pump showing a clear decrease in low frequency pulsation in the hydraulic system pressure, without a significant change in audible noise from the pump.

16:45 89366 Mikko Huova and Matti Linjama, *Control of Multi-Pressure Hydraulic Supply Line Using Digital Hydraulic Power Management System*

Multi-pressure hydraulic supply line, i.e., hydraulic bus enables efficient use of energy in multi-actuator systems of off-road machinery. Number of constant pressure supply lines, each providing unique pressure level, are routed to every actuator in the machine. Significant amount of the power losses related to conventional load sensing systems are avoided by enabling energy recuperation and reduction of total throttling loss. Pressure control of such multi-pressure hydraulic supply line can be realized using hydraulic accumulators, which are charged using conventional pump and logic valves. However, more advanced features are available if Digital Hydraulic Power Management System DHPMS is utilized. The DHPMS is in essence, a digital pump/motor/transformer with multiple outlets. Controller design of DHPMS in hydraulic bus application is described in the paper and simulation results show the system's ability to simultaneously control the supply line pressures and input power of the DHPMS. By controlling the input power, the prime mover such as Diesel engine can be driven in optimal operation point or it can be even downsized. If electric motor is used as prime mover, smaller and therefore less expensive motor can be used.

17:00 90598 Justin Darnet and Eric Bideaux, *State-of-the-art of Variable Displacement Technologies for Radial Piston Hydraulic Machines*

The hydraulic motor is one of the main parts of hydrostatic transmission implemented in some off-road vehicles for instance. It uses hydraulic power to convey energy from the generator of the machine to the wheels and other actuators. As the hydraulic circuit may contain several hydraulic actuators, each of them needs to be controlled independently since the only control of the pump displacement may impact the entire circuit and all its actuators simultaneously.

To properly drive the vehicle, the hydraulic actuators have to be accurately controlled. This paper aims to present a state-of-the- art of the different ways of changing hydraulic pumps/motors displacement ratios because it is one of the most important parameter to control the torque/speed (resp. pressure/flow rate). Some hydraulic machines enable a continuous change of this displacement ratio thanks to their specific architectures, whereas other machines use hydraulic valves to pilot this ratio. Most of the technologies, from variable displacement axial solutions to new digitally modulated displacement machines will be presented and compared. Digital Displacement solutions and their valve timing control solutions will then be depicted. Finally, technological locks in Digital Displacement will be exposed based on the modeling of a radial piston motor.

Session 5: Noise and Vibration

Thursday 15th September, 09:15 – 10:30

09:15 88101 Zubin Mistry, Andrea Vacca, Manuel Rigosi and Sujan Dhar, Modeling Fluid Inertia Effects in External Gear Machines Through Lumped Parameter Approach

Lumped parameter modeling is a consolidated technique for analyzing the fluid dynamic behavior of positive displacement machines, owing to their computational swiftness and the ease to integrate other physical domains affecting the operation of the machine. With some very limited exceptions, this modeling technique typically neglects fluid inertia and momentum effects. This paper proposes an approach for studying the effects of fluid inertia affecting the pressurization and depressurization of the tooth space volumes of an external gear pump. The approach is based on considering the fluid inertia in the pressurization grooves and, inside the control volumes with a peculiar sub-division. Further, frequency dependent friction is also modeled to provide realistic damping of the fluid inside these channels. Validation of the model has been performed by comparing the lumped parameter model with a full three-dimensional Navier Stokes solver. The quantities compared such as tooth space volume pressures and outlet volumetric flowrate show a good match between the two approaches for varying operating speeds. The paper lastly, also discusses what operating conditions and geometries play a significant role that governs the necessity to model such fluid inertia effects in the first place.

09:30 88957 Rudolf Scheidl, Helmut Kogler and Philipp Zagar, A Hydraulically Controlled Multiple Buck Converter System

The hydraulic buck converter with a pipe as inertance element is mostly considered with magnetically actuated fast switching valves. These valves are hardly available on the market and are costly. A further burden of most buck converters are the high hydraulic capacitances added on load side to flatten pulsation. They lead to a softness which requires sophisticated control.

A previous study on a phase shifted operation of several buck converters showed a low pulsation which may make an extra pulsation attenuation device obsolete. Another study suggested a hydraulic actuation of the switching valves. In this paper a combination of these concepts is analyzed. It realizes a constant switching frequency with a variable duty cycle and a phase shifted switching of the several converter units. The performance is compared to control by a single servo valve and a multiple converter system using electrically actuated valves.

09:45 89042 Jing Yao, Juntao Zhao, Pei Wang, Yuwang Cheng and Yupeng Wang, Active Pressure Pulsation Suppression Method by Parallel-Series Structure in DFCU Based on Variable Step Size FXLMS Algorithm

Pressure pulsation is the challenge in digital hydraulics owing to its switching characteristics, which makes control performance worse. This study proposed the parallel-series structure for active pressure pulsation suppression, based on variable step size FXLMS (Filtered-X Least Mean Square) algorithm. The pressure pulsation performance in DFCU (Digital Flow Control Unit) is analyzed under PNM and PWM control for better suppression effect. On this basis, the active pressure pulsation suppression control algorithm is designed utilizing the principle of pressure wave destructive interference, so that the reverse pressure pulsation generated by the parallel-series structure, including an in-series valve arranged in line between the DFCU and the load and a by-pass valve arranged in parallel with DFCU, offsets with the pressure pulsation at the load end. The adaptive FXLMS algorithm with variable step size is used to identify the secondary path online for better effect of pressure pulsation suppression and achieve the "alignment" between the reverse pressure signal and the initial pressure signal. The experimental results show it can suppress pressure pulsation by 78.96%, 53.85%, 36.96% and 29.17% at 10 Hz, 30 Hz, 50 Hz, 70 Hz for single valve and 76.56% for DFCU. It has been demonstrated that the proposed structure has significant effect and guiding relevance for pressure pulsation suppression of DFCU.

10:00 89855 Gudrun Mikota, Rainer Haas and Rudolf Scheidl, *Sensor Placement in a Hydraulic Drive System*

Hydraulic drive systems consist of hydraulic and mechanical components, whose dynamic behavior is coupled by fluid structure interaction. The validation of hydraulic drive models relies on an appropriate placement of pressure and vibration sensors. Based on a vibroacoustical approximation of the model, this question can be treated by potential and kinetic energy related modal assurance criteria (POTMAC and KINMAC). In this paper, the KINMAC criterion is applied for the sensor placement problem in a hydraulic drive system. The system consists of a valve block, a pipeline with fluid structure interaction, a double acting cylinder, and a mass attached to the piston. Modal analysis of a distributed parameter model is carried out for theoretical assessment of the sensor placement along the pipeline. The resulting mode shapes are used to calculate the auto KINMAC matrix, which is expected to be diagonal. The same type of assessment is made with mode shapes from a modal test. Under the limitations of the given sensor placement, the distributed parameter model is validated by the KINMAC matrix of mode shapes from theory and experiment. Based on the model, alternative sensor distributions with different sensor locations are investigated.

Session 6: Pumps and Motors

Thursday 15th September, 11:00 – 12:30

11:00 88469 Israa Azzam, Sujan Dhar, Dipak Maiti, Veeranagouda Patil, Paul Asunda, Jose Garcia Bravo and Farid Breidi, *Gerotor Pump Simulation Modules for Enhancing Fluid Power Education*

Fluid power is one of the courses required for most engineering technology programs and thus enrolls more than 200 students annually. Studies show that fluid power modules related to hydraulic and pneumatic systems result in a relatively high W/D/F rate (Withdrawals, D and F grades), where many students struggle to connect the theory with practice. From a pedagogical perspective, this rate is due to the traditional laboratory syllabus that is insufficient to address the complexity of hydraulic and pneumatic systems. This work aims to enhance fluid power education by conducting a research study for testing and examining the efficacy of integrating state-of-the-art simulation courseware into the laboratory work of fluid power courses. For conducting the study, interfaceable Computational Fluid Dynamics (CFD) modules of a hydraulic Gerotor pump are developed and incorporated into the laboratory syllabus of the MET:23000 Fluid Power course at Purdue University. The CFD simulation modules were designed and implemented in the labs in collaboration with Simerics. A survey was designed and conducted with 93 students to measure their perceived learning of fluid power concepts and examine their attitudes toward the CFD simulation used for instruction. The survey outcomes revealed that the executed CFD simulation assisted the students in understanding the overall operation of the Gerotor pump. The results show that the simulation courseware supported students in acquiring the fundamentals of fluid power, which could assist them in conducting future engineering decisions. Besides the conceptual understanding, students were engaged in the lab modules. They enjoyed visualizing the variation in pressure contours, velocity vectors, and cavitation bubbles.

11:15 89002 Paul Michael, Kim Stelson, Daniel Williams and Hassan Malik, *Dynamometer Testing of Hydraulic Fluids in an Axial Piston Pump Under Simulated Backhoe Loader Trenching Conditions*

The standard method for determining the efficiency of hydraulic pumps is specified in ISO 4409. This method requires that performance measurements be made under steady state conditions. In this investigation, the efficiency of a variable displacement axial piston pump was evaluated under both steady state and dynamic conditions. The dynamic conditions were derived from an analysis of measurements collected during multiple backhoe loader soil trenching cycles. The trenching cycle was replicated in the dynamometer by controlling pump swashplate motion, outlet pressure, and rotational frequency. In dynamic testing, data was collected at 1000 Hz and the duration of the trenching cycle was 12 seconds. In steady state testing, input values for swashplate position, outlet pressure, and rotational frequency were extracted from the duty cycle at 0.05 s intervals. Fifteen seconds of data was collected for each of the resulting 583 test points. Thus, several hours of testing were required to reproduce the trenching cycle under steady state conditions. Under steady state conditions pump volumetric efficiency was approximately 2% higher than in dynamic testing. The difference in volumetric efficiency was attributed to pump inlet line dynamics. The dynamic response of the pump inlet line was studied using a transmission line model that was based upon well-established methods for the characterization of line resistance, inertance, and capacitance. Non-linear terms for resistance and capacitance were included to investigate the effects of these properties on inlet line pressure ripple. Data from inline viscosity and density sensors was used in a sensitivity analysis. Inlet line pressure ripple was found to increase as the fluid viscosity decreased. This effect was also seen as polymer additives sheared. These findings provide insights into the effects of fluid properties on pump inlet line dynamics.

11:30 89380 Elias V. Hansen, Per Johansen, Jens Rendbæk and Lasse Almind Jensen, ***In-Situ Lubrication Film Thickness Measurements in a Radial Piston Motor Using Adaptive Ultrasound Reflectometry***

Lubrication film thickness monitoring between moving contact surfaces within industrial machinery is of great research interest because it is linked to the efficiency and rate of maintenance of the machine. Ultrasound reflectometry shows potential within this field of research, primarily because the ultrasound transducers can be conveniently implemented in operation-ready machinery. In this article, the lubrication film thickness inside an operational radial piston motor is estimated using two adaptive ultrasound reflectometry methods. A new Gaussian random walk based adaptive ultrasound reflectometry method is compared against the existing layer phase-lag method with adaptive Extended Kalman filter based calibration. It is found that the new method proposed gives less noisy and more accurate lubrication film thickness estimates, but it is more difficult to tune. It is found that both methods can detect the significant lubrication film thickness dynamics present in a radial piston motor, but they need further investigation regarding their robustness and reliability.

11:45 89553 Evan D. Sand and Perry Y. Li, ***Incorporating a Rotatable Valve Cam to Improve the Efficiency of a Hydraulic Motor in an Inline Hydro-Mechanical Transmission (i-HMT)***

A hydro-mechanical transmission (HMT) transmits power both hydraulically and mechanically, allowing higher efficiencies than hydrostatic transmissions while maintaining continuously variable transmission ratios. Ordinary HMTs consist of a hydraulic pump/motor pair in parallel with a mechanical transmission, but their large sizes and high costs are major disadvantages. The Hondamatic inline HMT (iHMT) significantly reduces the size, cost, and complexity of an HMT through an inline design that eliminates gears. However, low power efficiency is the principal barrier to its more widespread use. A dominant loss is throttling due to fluid compressibility and non-ideal valve timing. In this paper a method of controlling the motor displacement is proposed, using a rotatable motor valve cam and check valves in conjunction with the Hondamatic’s existing adjustable swashplate. The proposed modifications implement near ideal precompression and decompression, resulting in estimated power efficiency improvements of 4.8% to 14.4% at various operating conditions.

12:00 89718 Shanmukh Sarode, Lizhi Shang, Andrea Vacca and Scott D. Sudhoff, ***Flux Weakening Operation Based Design of an Integrated Electrohydraulic Axial Piston Unit***

With the recent electrification trends affecting mobile hydraulics, there is a rising demand for the development of energy-efficient and compact hydraulic supply units driven by electric machines. Such units capable of multi-quadrant operation are commonly known as electrohydraulic units (EHUs). Owing to inherent differences in the power densities of the two machines, efforts are required to make more compact electric machines in order to reduce the overall size of the resulting EHU. This paper discusses the optimal design of such an integrated EHU with a radial flux permanent magnet synchronous machine with flux weakening operation for a swashplate type axial piston machine. A flux weakening mode current control strategy extends the operating speeds of the electric machine to its maximum power by injecting a negative d-axis current.

Such a flux weakening mode of operation can allow optimal sizing of the EHUs if the peak flow and pressure demands do not coincide. Based on a given work cycle and a reference hydraulic unit, a multi-objective genetic algorithm based design optimization is used to optimize the electric machine of the integrated EHU for the best efficiency and compactness. The EM design with flux weakening mode of operation are compared to the ones with max torque per amp mode of operation in terms of mass, torque density, and efficiency. Flux weakening based electric machine design allows sizing for maximum achievable power and helps not only to downsize the electric machine by 30% but also to save on the cost of the power electronics required.

Session 7: Components and Systems

Thursday 15th September, 15:45 – 17:15

15:45 88614 Brendan Deibert, Sophia Scott, Allan Dolovich and Travis Wiens, *The Use of Additive Manufactured Plastic in Small-Scale Poppet Valves and Pressure Vessels*

Small-scale (<100 W), low-pressure (4 MPa), low-cost hydraulic components, such as pumps and cylinders, have recently become more available. These components have potential uses in demanding applications such as in a pump-controlled electrohydrostatic actuators (EHA)s. Limiting this is the fact that the unbalanced flows of a single-rod cylinder require a valve to reconcile the imbalance, which is commercially unavailable in this size and price range. We have hypothesized that it would be feasible to produce this component using additive manufactured (3D printed) plastic. Such a system would be relatively low cost with a high specific power, and could have applications in hand tools, prosthetics, robotics, and more.

This paper focuses on some of the challenges in the use of 3D printed plastic for small-scale poppet valves and pressure vessels. The objectives of this research include the investigations of the sealing performance of 3D printed plastic poppet valves and the mechanical strength of 3D printed plastic pressure vessels. Experimental results included in this paper reveal the effects of surface finish and poppet and seat geometry on sealing performance. The influences of print process, material, and orientation on the strength of a 3D printed pressure vessel are examined and the results can inform valve casing design considerations. Mechanical tensile testing of fused deposition modelling (FDM) printed polyethylene terephthalate glycol (PETG) and stereolithography (SLA) printed acrylonitrile butadiene styrene (ABS)-like test specimens provided insight to the corresponding burst strength of that material and print process. The work presented in this paper advances the state-of- the-art of using 3D printed plastic for the construction of small scale hydraulic components.

16:00 89252 Jianbin Liu, Jürgen Weber and André Sitte, *Investigation of Temperature Influence on Flow Mapping of Electrohydraulic Valves and Corresponding Application*

Electrohydraulic valves are crucial components in hydraulic systems, especially for the flow control or velocity control. With increased accuracy requirements of hydraulic drives, the electrohydraulic valves are required to have precise flow mapping. Starting with research on flow mapping under consideration of control signal, pressure drop and temperature, the novel flow mapping formula for flow mapping of electrohydraulic valves has been deduced. Through theoretical and experimental investigation, temperature influence on flow mapping could not only be qualitatively but also quantitatively analyzed. In particular, the mechanism of temperature affecting flow rate is further revealed. To verify the new flow mapping formula of the electrohydraulic valves, a test rig in laboratory has been set up. In order to obtain the evolving flow mapping of a Valvistor valve, the flow mapping formula at the institute has been applied and exemplified. The comparison with the experimental data indicates that the developed formula shows promising capabilities to describe the temperature influence on the flow mapping of electrohydraulic valve accurately. At the end, the capabilities of the developed solution are shown with a virtual real-time demonstrator accessed via an OPC UA data link inside a simulation environment with consideration of temperature compensation for feedforward control.

16:15 89721 Per Johansen, Uffe N. Christiansen, Sune Dupont, Anders Bentien, David N. Østedgaard-Munck, Jens L. Sørensen and Michael M. Bech, *An Experimental Study on High-Flowrate Ultrasonic Particle Monitoring in Oil Hydraulics*

In this article an experimental analysis on detection of particle in oil hydraulics by an in-line, high flowrate ultrasonic sensor is presented. This experimental study is conducted by the implementation of a particle concentration sensor prototype in a simple hydraulic circuit. In this system the contamination particles are introduced in an open tank. The sensor prototype is based on the particle scattering of ultrasound measured in a 90◦ angle in relation to the incoming wave. An experimental analysis of the sensors ability to detect specific concentrations of silicon dioxide particles in oils of varying viscosity grade is presented. Furthermore, an experiment involving a used hydraulic oil from an industrial plant is shown, where the sensor is able to detect increased particle contamination in the system, when the open tank is actively stirred. It is from the experimental analysis found that the prototype can detect particles of above 40 microns in common hydraulic oils, however the background field intensity and frequency could be increased to lower the size of the detectable particles. The paper is concluded with a theoretical analysis, which is examining the background field intensities and frequencies needed to meet standards within measurements of oil cleanliness.

16:30 89927 Emil Nørregård Olesen, Torben Ole Andersen and Poul Ennemark, *Active Damping of a Hydrostatic Steering Circuit for an Articulated Vehicle*

This paper investigates the steering performance of an articulated vehicle with a hydrostatic steering circuit, where the objective is to evaluate the steering performance and comfort level of the vehicle with and without active damping. The steering system is based on a hydraulic actuated system, which response often is underdamped. The operator of such a vehicle is placed on top of the articulation point and the hydraulic cylinders, which then directly translates the underdamped cylinder oscillations into undesired lateral motion of the operator. Active damping is therefore a promising concept for increasing the comfort level of the hydraulic steering circuit.

16:45 90897 Emil Nørregård Olesen and Torben Ole Andersen, *Investigation of a New Orbital Steering Concept with Focus on the Control Loop Performance*

This paper investigates a new asymmetric steering concept within orbital steering units called OSPS, which asymmetry enables new steering features for the operator of the vehicle compared to traditional OSP variants. A traditional orbital steering unit functions as a proportional valve system with a certain overlap, where the operator input to the steering wheel will initiate the rotation of the wheels with a small dead-band of 2-3 degrees. The new asymmetric unit functions instead as a proportional valve system with a certain under-lap, where the operator will initiate the rotation of the wheels directly related to the steering wheel rotation instead. The objective with this paper is to evaluate the closed loop performance for the new asymmetric concept, because the right and left control loop is changed compared to a traditional OSP unit.

Session 8: Efficient and Intelligent Systems 2

Friday 16th September, 09:00 – 10:30

09:00 88563 Rituraj Rituraj and Rudolf Scheidl, *Advancements in the Control Strategy for Digital Hydraulically Driven Knee Exoskeleton*

Compared to electromechanical drives, hydraulic drives can be a good actuation alternative for exoskeleton devices due to their advantages in terms of high force density and capabilities of energy recuperation, motion damping and locking. However, to promote a wider adoption of hydraulically driven exoskeleton devices, key challenges related to the compact lightweight design and energy efficient operation and control are needed to be addressed.

To tackle these challenges, the authors have recently developed a novel design of digital hydraulically driven knee exoskeleton. In this work, the authors address the control challenges during the operation of the knee exoskeleton over multiple gait cycles. Proper control methods for different phases of the gait cycle are adopted. Furthermore, these methods are augmented with strategies to accomplish knee motion repeatability across gait cycles. These strategies involve steps to ensure that at the beginning of every gait cycle: (a) the knee angle returns to the same position, and (b) the pressure in the hydraulic chambers return to the same levels.

These control strategies are investigated via a numerical model of the knee exoskeleton. The simulation results indicate that the device is able to repetitively track the motion of the knee over multiple gait cycles while delivering the required torque.

09:15 89099 Zichang Lin, Bing Xu and Feng Wang, *Improving Wheel Loader Energy Efficiency With a Series Electric Hybrid Powertrain*

Engine-powered wheel loader is widely used in the construction field. However, it suffers from poor engine operation, torque converter losses and low efficiency of working hydraulic function, showing great potential in energy saving and emission reduction. To address these problems, a series electric hybrid wheel loader powertrain with decoupled main functions is proposed to improve the overall energy efficiency. The system includes a downsized engine, an electric generator, battery pack as energy storage device and three electric motor for drivetrain and lift/tilt hydraulic circuits. The drivetrain is electric motor driven and the lift/tilt functions are powered by fixed displacement pump load sensing system based on variable-speed control. Simulation study based on experimental data are carried out to provide an efficiency comparison between conventional and the proposed powertrain. Rule-based energy strategy is developed for the hybrid wheel loader to check its potential on fuel saving. Results show that the electric hybrid system saves 43.6 % of fuel consumption compared to conventional wheel loader, with engine mean efficiency increases from 27.8% to 33.9%. Efficiency comparisons of system components between conventional and proposed powertrain are also presented.

09:30 89509 Annalisa Sciancalepore, Andrea Vacca and Steven Weber, ***Control Strategy of Adjustable Pilot Counterbalance Valves for Efficient Hydraulic Actuation***

Counterbalance Valves (CBVs) are commonly adopted in load handling machines such as cranes, winches, and telehandlers. Besides their load-holding and relief functionality, they allow establishing a counterpressure so that simple meter-in control approaches can properly operate in case of overrunning loads. However, their operation often implies excessive energy consumption due to an over-pressurization of the hydraulic system. Past work performed by the authors' team addressed a solution for using CBVs with controllable pilot, which permits to achieve up to 90% energy saving during overrunning load conditions, when compared to the traditional configuration of CBVs. This past effort focused on steady-state operation, without providing a proof that such high energy efficiency solution can operate in the typical dynamic conditions of many load handling machines. To address this aspect, this paper built on the mentioned past work and propose a control strategy that minimizes the energy consumption of the system while meeting the dynamic requirements of a reference application, a truck mounted hydraulic crane. The proposed controller was designed by using a numerical model of the reference machine, and it was afterwards tested on real experiments. The results allowed confirming the previous prediction of up to 90% improvement in efficiency, while meeting or exceeding the dynamic performance, as quantified by the measurements of the acceleration signal of the crane arms.

09:45 89646 Zhiyong Su, Jingfu Wang, Tianbao Zhu, Haodi Tang and Xu Zang, ***Design and Modeling of Heave Compensation System Based on Secondary Regulation Technology***

The heave movement caused by the movement of the mother ship during the operation of the marine crane has great harm to the safety of equipment and personnel. In this paper, the structural model of the marine crane is established. According to the rigid-flexible coupling system existing in the marine crane, the Newton-Euler method and the Lagrange method are used to model the rigid part and the flexible part respectively, and the rigid part and the flexible part are modeled. The kinematics and dynamics were analyzed in this model, and the influence of the in-plane angle and out-of-plane angle generated by the swing of the hanging object cable on the heave direction of the hanging object was studied. Considering the influence of the in-plane angle and the out-of-plane angle, a heave compensation system based on the secondary adjustment technology is established, and the compensation for the heave compensation is realized through the hydraulic secondary adjustment technology. The heave compensation of the lifting and lowering working conditions of the hoisting object is simulated under the sea state 4. Finally, the heave displacement compensation of the hoisting object when the hoisting object is suspended under the sea state 4-6 is simulated. Simulation analysis verifies the accuracy of the marine crane structural model and the effectiveness of the heave compensation control system.

10:00 90090 Xu Han, Manu Leinonen and Tatiana Minav, ***Design and Simulation Analysis of a Pump-Controlled Actuation System for Heavy-Duty Booms***

The electrified pump-controlled hydraulics receives increasing attention from both industry and academy. Its combined advantages of hydraulic and electric actuators result in an expanding application in heavy-duty actuation. One example of such actuation application is the boom. Despite the diverse achievements from the academy, the commercial application has not started yet. This is partially caused by the absence of the auxiliary functions of the conventional hydraulic actuation, e.g. thermal management, filtration, maintenance convenience, in proposed academic solutions. This paper proposes a new design of the pump-controlled actuation solution for heavy-duty booms, which takes both the primary and auxiliary function requirements into consideration. Then, the proposed system is modeled and simulated using a crane study case, which requires 50 kW power for moving each axis. The primary functions, e.g. the control performance, the energy efficiency, and the auxiliary functions are both analyzed. The control methods are proposed for supporting the upper-level control modes. A conventional load sensing actuation system is also simulated as a comparison. The simulation results demonstrated 51.2% energy saving advantages and comparable auxiliary functions of the proposed system over the conventional system. The achieved results prove the applicability of the proposed system and promote the application of the pump-controlled actuation in the heavy-duty booms.

Session 9: Fault Analysis and Diagnosis

Friday 16th September, 11:00 – 12:30

11:00 88249 He Xu and Feng Sun, *Research on Life Extension of Water Hydraulic Control Valve Based on Augmented Reality for Fault Diagnosis*

The life extension of the control valve is deserving of research. The study of life extension associated with control valves is a multidisciplinary problem, but it is mainly dependent on the failure of the control valve. To monitor the operating state of the control valve, this paper provides decision-making suggestions for extending the service life of the control valve by AR based cavitation analysis. The valve plug is an essential part of the control valve and is often exposed to cavitation. To study the cavitation area near the control valve core, the analysis of the transparent control valve body made of polymethyl methacrylate (PMMA) material was carried out in this study. The emergence of PMMA eased the capturing of images by high-speed photography. A feature-based algorithm was written using Python software to visualize the cavitation area. Furthermore, we combined AR based cavitation observation and fault diagnosis to guide the life-extension process of the control valve with the visual flow field information.

11:15 88646 Faried Makansi and Katharina Schmitz, *Fault Detection and Diagnosis for a Hydraulic Press by Use of a Mixed Domain Database*

An automated detection and diagnosis of machine and process faults is a core element of modern maintenance strategies. Data-driven methods, often summarized by the term machine learning, potentially provide manifold advantages in this area compared to conventional approaches. However, the necessity of a comprehensive database, which covers a variety of operation and fault cases, poses a remaining challenge for the application of data-driven methods. One way to mitigate the issue of costly data acquisition is to merge datasets from different, but related systems and applications to a larger dataset. In this contribution, the mixing of data obtained from a hydraulic press and a corresponding simulation model is investigated. For this, datasets comprising regular and faulty machine operation are generated in both domains. Using different mixing ratios of real and simulated data-instances, models for fault classification are derived and evaluated. The results show that an instance-based transfer from the simulated domain to the real domain can help reducing the amount of training data required from the physical machine. The mixing ratio appears to be decisive for a beneficial effect of mixing data from the two domains.

11:30 89083 Terkil Bak-Jensen and Lasse Schmidt, *Prognostics in Custom-Build Electro-Hydraulic Variable-Speed Drive Applications*

Developments in the field of condition monitoring for hydraulic applications have gained interest and a solid foundation of knowledge is largely established. The interest to further develop this into prognostics has increased, as the ability to predict outages and faults implies higher reliability and economical gain. This article presents a short review focusing primarily on the possibilities to enable prognostic control and identifies important features to enable prognostics. In addition, a definition of prognostic quality is proposed including aspects such as isolability, monitorability, cause, and predictability. This is followed by the modeling of an electro-hydraulic variable-speed drive, which is used to design an algorithm to predict maintenance and possible prognostic actions. This is done through monitoring different physical and artificial indicators utilizing the states measured in the system and using the information to predict future health conditions. Thus enabling the possibility to determine if a change in the control would be beneficial in order to extend the duration where the system can fulfil its design requirements. This creates a foundation for a possible methodology to obtain prognostic control for custom-build systems. The strategy proposal involves the identified methods and relates them to the covered topics in the review.

11:45 89107 Andris Rambaks, Paul Knipper, Niklas Bauer and Katharina Schmitz, *Autofrettage and Its Impact on High-Cycle Fatigue of Hydraulic Components*

Aluminum alloys represent a cost-effective alternative to titanium alloys for hydraulic components in the aerospace industry. However, the inferior mechanical properties of these materials have so far limited their use at high pressures and hence prevented their wider adoption in the sector. Application of the strain hardening autofrettage process overcomes these deficiencies and enables the use of aluminum alloys in high-pressure systems. In this paper, the impact of autofrettage on fatigue life is investigated by means of FEM simulations and application of the stress-life concept. Two components are analyzed in detail: a thin-walled pipe and a cut out from a valve body. Numerical calculations demonstrate that by subjecting these hydraulic components to the autofrettage process significant increases in the number of cycles until failure are achievable.

12:00 89359 Hao Yin, He Xu, Feng Sun and Yuhan Zhao, ***Research on Application of Elastic Consolidation Algorithm in Fault Diagnosis of the Control Valve***

Deep neural network learning is a commonly used method for fault diagnosis of the control valve. However, the catastrophic forgetting problem of deep learning in multi-task affects the fault diagnosis accuracy. Moreover, the traditional training model can be improved by using parameter constraint control or adding a few parameters, but it has many limitations. Therefore, we proposed a fusion of elastic weight consolidation algorithm and residual shrinkage network method, sharing common feature layers. According to the weight of the same or similar parameters of the previous task, the correct solution of the current task could be obtained, and the forgetting degree of the previous task could be reduced. It improved the generalization ability of the training model. The control valve data were collected and compared with the stochastic gradient descent algorithm in different valve openings. The results indicate that this method has a high accuracy for the condition identification of the control valve. This method can effectively alleviate the problem of the catastrophic forgetting of deep learning in multi-task identification of control valve.

Session 10: Modelling and Simulation

Friday 16th September, 14:00 – 15:15

14:00 89105 Philipp Zagar and Rudolf Scheidl, ***The Connection Between Sliding Mode Analysis and Singular Perturbation Theory for Modelling Fast Hydraulically Fed-Back Switching Valves***

In most cases modeling of fast switching valves in hydraulics results in fast and slow subsystems. System equations which incorporate fast and slow dynamics are called stiff systems and one can apply singular perturbation theory to reduce the system order and get handy approximate expressions in a lower-order description. This is not only useful to reduce complexity to numerically solve the system efficiently, but also to understand the system's key parameters and how they affect the behavior which is of great interest during design phase.

In a previous paper the authors published an approach which uses switched systems and sliding modes to get a reduced system description of hydraulically fed-back switching. There, one models a hydraulic valve as either completely open or closed. A partially opened valve is then modelled as a sliding mode which can be interpreted as a pulse-width modulation of a fast switching digital valve. Even though, the resulting sliding mode dynamics approximation does not preserve topological properties of the full system dynamics an advantage of this approach is that the system incorporates the nonlinearities which arise due to end-stops of valves in a very natural way. Therefore, it is capable of describing system dynamics which results from such non-smooth properties. In this paper the authors work out the naturally suggested – even though not obvious - connection between both approaches for reducing systems with hydraulically fed-back switching valves.

14:15 89636 Jeffrey J. Bies and William Durfee, ***Fluid-Structure Optimization of Small-Scale Hydraulic Conduits***

Fluid-structure optimization is well-suited for reducing system weight and improving flow efficiency for small-scale hydraulic systems such as for wearable exoskeletons. While single-objective optimization algorithms exist, little work has been done to optimize flow channels under internal and external loads. This study constructed a computational pipeline that connects Open-Source Field Operation and Manipulation (OpenFOAM) to additional software applications to enable fluid-structure topology optimization using the continuous adjoint method. The pipeline was used to optimize the flow path and surrounding structure of small-scale hydraulic conduits with varying bends and external load conditions.

We found that the optimized flow path balances path length with curvature to minimize pressure drop. For a non-optimized conduit with a sharp 45-deg bend, the pressure drop was 750 Pa, while the optimized conduit has a pressure drop reduction of 22.5%. Sharp bends create stress concentration points where structural supports are formed, while optimized flow paths reduce stress up to 42.5%, and further distribute support structures. Bending loads can be a restorative force for sharp bends and, therefore, reduce the maximum stress.

14:30 90184 Jackson Wills and Perry Y. Li, ***Accumulator Sizing for the Hybrid Hydraulic Electric Architecture (HHEA) Using Dynamic Programming***

The Hybrid Hydraulic Electric Architecture (HHEA) has been proposed previously and preliminary studies have shown promising results for energy savings in mobile machines. The HHEA utilizes a set of common pressure rails along with a small hybrid hydraulic electric control module (HECM). To achieve a desired force at the actuator, pressures can be selected from the available common pressure rails; but by selection of these rails alone, only discrete forces can be generated. The HECM unit modulates the pressure difference so that the desired force can be exactly met. Each common pressure rail has an accumulator, which keeps the pressure of each rail near constant as long as the volume in the accumulator does not change much. A main pump adds or removes fluid from each accumulator as needed to reduce volume changes in the accumulators. It is the operation of this main pump which is investigated here.

In previous analysis it was assumed that the size of the accumulators was large enough to account for any difference in fluid volume without significantly changing the pressure. In this study, an algorithm for operation of the main pump is presented. With this addition, the required sizes of the accumulators are calculated. At each time step the inlet and outlet of the main pump could be connected to any of the common pressure rails. These decisions for the main pump were optimized to minimize the required accumulator size using a dynamic programming approach. The optimal flow rate of the main pump can also be estimated. While the optimized required accumulator size and pump flow rate depend on the specific drive cycle that needs to be known ahead of time, the results can provide insight for the requirements in the real-time operation.

Case studies are conducted using drive cycles from a 5-ton excavator. The required accumulator sizes depend on a number of factors, but under most conditions were found to be less than 10 liters. Required accumulator size was found to vary with the frequency at which the pump/motor was able to change operating conditions. More frequent switching between rails was found to decrease the required accumulator sizes, but a physical pump/motor can only switch between pressure rails so quickly.

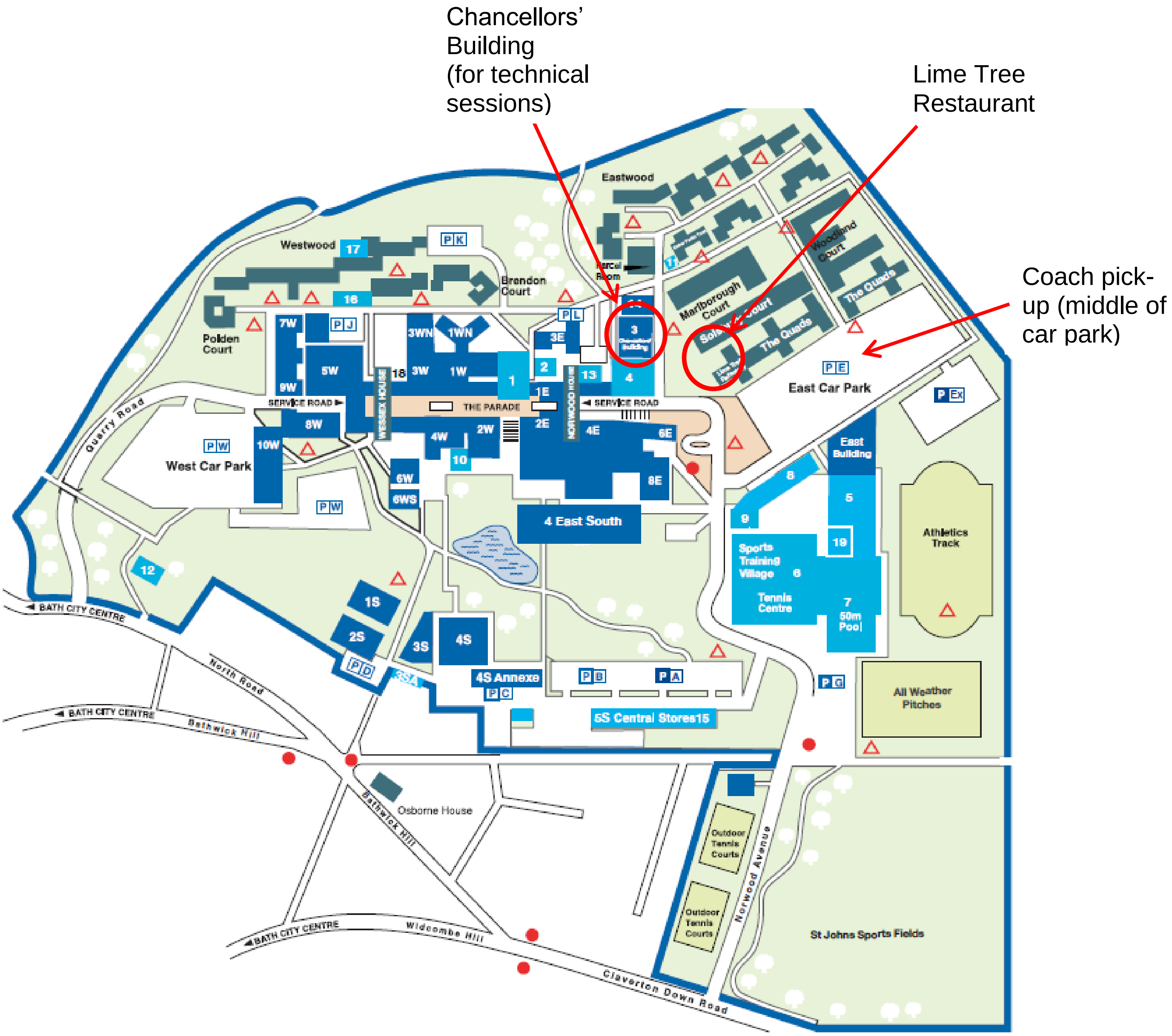
14:45 90185 Bernhard Manhartsgruber, *A Set of Benchmark Problems for Fluid Power System Simulation*

Mathematical modelling and simulation have become widespread tools in the fluid power industry. The sheer number of available software packages of commercial and academic nature as well as the abundance of published modelling strategies for certain components gives multiple possibilities for modelling one and the same fluid power system. The mathematical model is required to capture the behaviour of the real system with a certain degree of accuracy while using a minimum of computational resources for reaching this goal. This tradeoff cannot be assessed by looking on model complexity on the level of differential equations only. The computational efficiency is defined by the combination of mathematical modelling on the high level of differential equations, the choice of a solver, i.e. the time discretization, and the details of software implementation like the optimized compilation of right hand sides for the solvers. In order to compare different modelling strategies on various software platforms, well defined benchmark problems are needed. This paper presents a first attempt towards such a set of benchmark problems targeted at the specific problems of fluid power simulation. In a first benchmark case, a system with reversing flow at an orifice under the additional difficulty of a stiff differential equation system is presented. A second benchmark case uses the coupling between dry friction in a hydraulic cylinder and wave propagation in a transmission line which has been shown to give notorious modelling problems in the literature. The goal of the present publication is to present a proposal for such benchmark systems in order to make the accuracy and computational performance of simulation approaches more comparable.

15:00 90715 Zihan Wu, Feng Wang, Bing Xu and Wieslaw Fiebig, *An Electric-Hydraulic Hybrid Wheel Loader With Mode-Driven Control Strategy*

The powertrain electrification is an effective solution to emission reduction of mobile machines. To overcome the low power density of electric drive, a hydraulic accumulator is introduced as a supplementary power source. In this paper an electric-hydraulic hybrid powertrain solution is studied for wheel loader propulsion system, where it combines the energy density of electric drive and high power density of hydraulic drive. The energy management strategy is essential for hybrid powertrain since it determines how efficiently the power is transferred between different energy sources. In this paper a mode-driven control strategy for electric-hydraulic hybrid wheel loader is proposed to achieve electric power reduction over power follower strategy (baseline strategy), without sacrificing electric energy use and vehicle operation hours. In the strategy four modes are defined and the expected hydraulic SOC (system pressure) profile in each mode is scheduled to provide supplementary power assist and capture regenerative braking energy. By setting the pressure profile, the hydraulic charge sustaining is guaranteed. The system operation with mode-driven strategy is compared with power follower strategy through simulation studies. Results show that peak powers of battery and electric motor with mode-driven strategy are reduced by nearly 30% compared to power follower strategy. Results also show that the vehicle operation hour has been slightly increased by 3% by using mode-driven strategy. These results verify the effectiveness of proposed strategy for electric-hydraulic hybrid wheel loader.

Map of Campus



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Map of Bath, showing venues for receptions