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Editorial

Energy Efficiency and Controllability of Fluid Power Systems

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1. Introduction

Fluid power refers to the discipline that involves the use of fluids to perform mechanical actuations, it is a well-established and independent discipline that has a defined research area and scholarly activities since at least seven decades. The research activities related to the fluid power discipline serve a large and wide spread industry reaching from agriculture, construction, transportation, aerospace, marine, manufacturing, and entertainment industries. Recent advances in control and efficiency of fluid power systems, along with the integration with electric technology is enabling new robotic systems and biomedical devices. Compared with the other technologies for transmitting mechanical energy (i.e., electric, or pure mechanical systems), fluid power has a clear power to weight ratio advantage. However, current state-of-the-art fluid power drives are inefficient: a recent study published by the United States Department of Energy estimated their average energy efficiency at only 21% [1]. Therefore, there is a tremendous opportunity to improve the efficiency and reduce energy demands of fluid power systems by investigating the fundamental fluid-mechanical relationships and developing new fluid power solutions.

Advancements in technology for fluid power components also benefit other engineering fields. Examples are advances in positive displacement machines, which are also used in high-pressure injection systems, such as aerospace fuel pumps, which often represent one of the most critical components in terms of the reliability of aircrafts, helicopters, and spaceships. Advances in pump design are also beneficial in applications that traditionally have less stringent pump requirements, such as automotive lubrication, transmission and exhaust after-treatment systems, washing systems, and other fluid transport systems.

Another challenge related to fluid power is the low acceptance level of this technology in applications that require quiet actuation, zero leakage, and no risk of fire or explosion. In the majority of existing systems, the working fluid is based on mineral oil, leading to environmental concerns, and the high noise emissions of hydraulic components limit use in sensitive applications. These factors, along with concerns for human health, the need for environmental protection and conservation of energy resources, are incentives for improving—or innovating—current fluid power machines.

This Special Issue of *Energies* on the subject area of "Energy Efficiency and Controllability of Fluid Power Systems" is dedicated to the most recent research efforts made by both industry and academia to improve fluid power technology.

The topics of interest for the initial call included, but were not limited to:

- New approaches for the analysis, modeling, and design of hydraulic and pneumatic components
- New design solutions for hydrostatic pumps and motors
- Hydrostatic and hydraulic hybrid transmissions
- Control design methodologies and techniques for fluid power systems
- Digital and switched fluid power systems

- Reduction of oscillations and vibrations of fluid power machines
- New system configurations to reduce fuel consumption and increase productivity of fluid power machines
- Safety, reliability, fault analysis, diagnosis, and prognostic of fluid power systems
- Noise and vibration of fluid power components
- Human scale applications of fluid power technology
- Water hydraulics
- Applications of fluid power in the field of renewable energy
- Fluid power in manufacturing
- Fluid power teleoperation and haptics
- Fluid power in mobile and industrial robots
- Environmental aspects of fluid power
- Smart fluids and materials for fluid power systems

This book contains the successful invited submissions [2–17] to the Special Issue.

2. Statistics of the Special Issue

Response to our call had the following statistics:

- Submissions (22);
- Publications (16);
- Rejections (6);
- Article types: Research Article (16);

Authors' geographical distribution (published papers) is:

- USA (4)
- Italy (4)
- China (2)
- Spain (2)
- UK (1)
- Finland (1)
- Austria (1)
- Germany (1)

Published submissions are all closely related to fluid power technology and its application.

As Guest Editor, I found the task of editing and selecting the papers for this collection to be both stimulating and rewarding. I also would also like to thank the editorial staff and reviewers for their efforts and help during the process.

3. A Short Review of the Contributions in this Issue

The sixteen published papers in the Special Issue can be grouped into two broad categories: fluid power systems and fluid power components. In the first category (fluid power systems), there are contributions that address energy efficiency aspects of the entire fluid power system, and propose solutions or methods to lower the energy consumption of the system either by acting on the layout architecture of the hydraulic system or by adopting a better control strategy. In the second category (fluid power components), there are contributions that improve the state of the art of the existing components used in the hydraulic systems. In the following, a brief description of the papers in each one of the two categories is provided.

3.1. Fluid Power Systems

Despite the general applicability of the proposed solutions, several contributions of this Special Issue consider the case of hydraulic excavators as a reference mobile machine. Hydraulic excavators are indeed one of the most significant applications of mobile hydraulics, where reliability, cost, and fuel consumption are factors of primary interest. Technology improvements on mobile hydraulics very often start from hydraulic excavators, and usually rapidly reflects in other mobile hydraulic applications, even outside the construction field.

Other contributions of this Special Issue related to systems address basic concepts of hydraulic control, including digital hydraulics, hydraulic converters, and control optimization strategies.

The first contribution by Vukovic et al. [2] addresses the important aspect related to the metric used to evaluate and lower the fuel consumption in mobile hydraulic machines. The authors conducted a comprehensive analysis of the components comprising the hydraulic machine and the cycles these machines usually perform. Taking as reference the case of a hydraulic excavator, they emphasize that a design centered on the standard definitions of efficiency, especially hydraulic efficiency, can be rather misleading. From this statement, the authors carefully analyze the energy losses in the system, starting from the thermal combustion engine to the net actuator power and considering the actual working cycles of the reference machine. Using an original approach, they show all the potential fuel consumption improvements, with a break down structure that distinguish the hydraulic losses from the engine losses due to idle, and further highlight the potentials given by energy recovery systems.

Considering again the case of an excavator, Siebert et al. [3] propose a novel hydraulic load sensing system architecture able to reduce the system inherent pressure losses due to throttling at the pressure compensators. The system utilizes a hydraulic accumulator and it is able to decrease the pressure losses by approximately 44%, estimated in simulation.

Casoli et al. [4] presents a study on a hydraulic hybrid solution for mobile machines that allows for energy recovery during the assistive phases of the linear actuators. The proposed solution is easy to implement and it can retrofit an existing load sensing system. In their work, they apply their proposed solution to an excavator, for which they developed a numerical simulation model validated against experiments performed on actual prototype machines. Their results demonstrate the capability of reducing the fuel consumption in an actual digging cycle of about 5%, with respect to the reference load sensing solution.

Nurmi and Mattila [5] addresses the energy-inefficiency of typical hydraulic manipulators used for heavy-duty material handling on mobile machines. In their study, supported also by experiments, they show that both the typical load sensing and constant pressure system architectures could consume 15–20% less hydraulic energy using proper dynamic programming approaches.

The contribution of Pan et al. [6] relates to the development of efficient digital hydraulic systems. In particular, they present a study on a switched inertance hydraulic system, which is a novel high-bandwidth and energy efficient digital device which can adjust or control flow and pressure by a means that does not rely on throttling the flow and dissipation of power. In this work, the authors describe a theoretical study of a switching valve configuration supported by experiments, and determine the best efficient valve configuration.

Finally, Gradl and Scheidl [7] describes an energy efficient low power stepper drive, intended for applications where traditionally hydraulic servo drives are used. The converter consists of a hydraulic cylinder piston unit controlled by a fast switching valve to displace a defined fluid quantum by the limited forward stroke of the piston in its cylinder. Energy saving is achieved by storing the pressure surplus intermediately in the kinetic energy of the piston to displace a part of the fluid quantum without hydraulic energy from the supply line. Such a system would permit significant energy saving advantages and higher robustness against oil contamination, with respect to the standard servo hydraulic systems, particularly in applications that do not require a continuous use of the hydraulic system. Their manuscript details the simulation and the experiments they performed to show a potential of energy efficiency increase up to 30% with respect to the standard servo valve solution.

3.2. Fluid Power Components

The manuscripts published in this Special Issue involving hydraulic components focus on several key design aspects of the most commonly used hydraulic components, including positive displacement pumps, hydraulic cylinders, and hydraulic manifolds. The common goal of these studies is always to provide design solutions or tools for improving the current state of the art, with respect to the reduction of energy loss, induced mechanical vibrations, and radiated noise.

Several types of positive displacement pumps are featured in this Special Issue.

Axial piston pumps are the preferred solution for many hydraulic systems, due to their high energy efficiency levels and their capability to operate at high pressure levels. For this reason, significant research has been done in the last decades to study the source of the power losses within the units and possible improvements to their design. In this area, the contribution by Zhang et al. [8] clarifies the mechanism of generation of churning losses, which is particularly relevant at high pump shaft speeds. Their study is supported by a test rig they purposely designed for this research. The results show how, beyond a critical speed, the churning losses are mostly dominated by the cylinder block and that for this reason, its design should be carefully investigated for units operating at high rotational speeds.

On the topic of swash plate type axial piston pump design, Kim and Ivantysynova [9] describe a method to eliminate the mechanical vibrations of the swash plate through an active vibration control technique. In their work, they designed the controller and they performed experiments an actual pump prototype, instrumented in such a way to measure the swash plate acceleration. Their results clearly show the potential of using such techniques to reduce vibrations, thus enabling the design of units capable of reducing pump induced system vibrations and noise.

Other papers put focus on the other widely adopted family of pumps commonly used in fluid power system: the case of gear pumps.

In [10], Thiagarajan and Vacca explore a new modeling technique for the internal lubricating interfaces of external gear pumps for high pressure applications. These units usually implement internal pressure compensation mechanisms to reduce the internal gaps during pump operation. These gaps play a key role in determining the energy efficiency of the pump as well as its durability. While traditional study approaches for these lubricating interfaces assume full film lubrication, in [4] a numerical method that include the presence of mixed lubrication effects is investigated. The simulation results and an experimental activity on a commercial unit show how mixed lubrication effects allow for a better understanding of the pump lubricating mechanism also in normal operating ranges.

Woo et al. [11] consider a similar design for a pressure compensated external gear pump, and perform instead a study related to the numerical prediction of the airborne noise emitted by the pump. In their work, they present a simulation model than includes the numerical prediction of the noise at all the domains: fluid-borne noise, structure-borne noise, and air-borne noise. The method they propose to couple all these physical domains allows for a fairly good prediction of the noise in terms of overall sound power level, but also in terms of noise directivity and sound pressure level maps. The results shown in the papers are validated from measurements performed in a semi-anechoic test cell.

An important contribution in the field of modern pump design is Gamez-Montero et al. [12]. In their work, they present the GeroMAG concept, which is an integrated compact, non-shaft driven gerotor pump with a magnetically driving outer rotor. The unit allows for flow-on-demand capabilities through direct speed regulation of the brushless motor that powers the driving outer rotor. In their work the authors detail the design features of the proposed unit and the experimental results achieved by a proof of concept unit. This design has certainly the potential to directly impact automotive applications, such as a lube pump, or AWD systems, etc. However, it can also have advantages for other modern electro-hydraulic systems.

Internal gear pumps are gaining more and more attention in certain fields, particularly those that require simple construction units, with high tolerance to fluid contamination and cavitation and with limited noise emissions. Despite many works available in the literature for the case of gerotor units, very limited work is available as pertains to a simulation model for crescent type internal gear pumps. Rundo and Corvaglia [13] filled this gap, presenting a modeling approach for internal gear pumps of crescent design able to simulate the displacing action and the features of the flow through the units. In their work, they also validate the model with experimental results, in terms of steady-state flow rate and of port pressure oscillations.

Zardin et al. in [14,15] tackle the problem of estimating the pressure losses in the hydraulic manifolds present in almost all mobile hydraulic machines. The design of these manifolds present challenges related to the complex layout and the requirements of low cost and compactness. These challenges make it quite difficult for the designers to minimize the pressure losses, which reflect in a lower energy efficiency of the hydraulic system. In [14], Zardin's research team first present their simulation of a CFD based simulation strategy, properly validated against experiments for single path manifold designs. In [14], they extend their approach for the case of multiple path manifolds.

A well-known key aspect of linear hydraulic actuators relates to the cushioning system, which always presents design challenges. With [16], Algar et al. make a significant contribution in this area, presenting a detailed CFD simulation study supported by experiments to describe the 3D motion of the piston during the cushioning and the starting phases. In their study, they investigated and well describe the effect of parameters, such as joint orientation, and the presence of circumferential grooves in the piston.

Finally, in [17], Zhang et al. investigate a novel application of magnetic fluids, whose use is established in devices such as dampers, sealing, and biomedical treatments for the control of hydraulic servovalves. In particular, they apply magnetic fluids in the torque motor of a servovalve to exert damping and resistance for vibration and noise suppression purposes. The work is based on a mathematical model based on a bi-viscosity constituted relationship to determine the damping force due to the magnetic fluid when it is used to fill the working gaps of the torque motor. An experimental activity supports the simulated results and shows the potential of the method for suppressing the self-excited noise inside the servovalve.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Love, L.J.; Lanke, E.; Alles, P. *Estimating the Impact (Energy Emissions and Economics) of US Fluid Power Industry*; Oak Ridge National Laboratory (ORNL): Oak Ridge, TN, USA, 2012.
2. Vukovic, M.; Leifeld, R.; Murrenhoff, H. Reducing Fuel Consumption in Hydraulic Excavators—A Comprehensive Analysis. *Energies* **2017**, *10*, 687. [CrossRef]
3. Siebert, J.; Wydra, M.; Geimer, M. Efficiency Improved Load Sensing System—Reduction of System Inherent Pressure Losses. *Energies* **2017**, *10*, 941. [CrossRef]
4. Casoli, P.; Riccò, L.; Campanini, F.; Bedotti, A. Hydraulic Hybrid Excavator—Mathematical Model Validation and Energy Analysis. *Energies* **2016**, *9*, 1002. [CrossRef]
5. Nurmi, J.; Mattila, J. Global Energy-Optimal Redundancy Resolution of Hydraulic Manipulators: Experimental Results for a Forestry Manipulator. *Energies* **2017**, *10*, 647. [CrossRef]
6. Pan, M.; Plummer, A.; El Agha, A. Theoretical and Experimental Studies of a Switched Inertance Hydraulic System in a Four-Port High-Speed Switching Valve Configuration. *Energies* **2017**, *10*, 780.
7. Gradl, C.; Scheidl, R. Performance of an Energy Efficient Low Power Stepper Converter. *Energies* **2017**, *10*, 445. [CrossRef]
8. Zhang, J.; Li, Y.; Xu, B.; Pan, M.; Lv, F. Experimental Study on the Influence of the Rotating Cylinder Block and Pistons on Churning Losses in Axial Piston Pumps. *Energies* **2017**, *10*, 662. [CrossRef]
9. Kim, T.; Ivantysynova, M. Active Vibration Control of Swash Plate-Type Axial Piston Machines with Two-Weight Notch Least Mean Square/Filtered-x Least Mean Square (LMS/FxLMS) Filters. *Energies* **2017**, *10*, 645. [CrossRef]
10. Thiagarajan, D.; Vacca, A. Mixed Lubrication Effects in the Lateral Lubricating Interfaces of External Gear Machines: Modelling and Experimental Validation. *Energies* **2017**, *10*, 111. [CrossRef]

11. Woo, S.; Opperwall, T.; Vacca, A.; Rigosi, M. Modeling Noise Sources and Propagation in External Gear Pumps. *Energies* **2017**, *10*, 1068. [CrossRef]
12. Gamez-Montero, P.J.; Castilla, R.; Codina, E.; Freire, J.; Morató, J.; Sanchez-Casas, E.; Flotats, I. GeroMAG: In-House Prototype of an Innovative Sealed, Compact and Non-Shaft-Driven Gerotor Pump with Magnetically-Driving Outer Rotor. *Energies* **2017**, *10*, 435. [CrossRef]
13. Rundo, M.; Corvaglia, A. Lumped Parameters Model of a Crescent Pump. *Energies* **2016**, *9*, 876. [CrossRef]
14. Zardin, B.; Cillo, G.; Rinaldini, C.A.; Mattarelli, E.; Borghi, M. Pressure Losses in Hydraulic Manifolds. *Energies* **2017**, *10*, 310. [CrossRef]
15. Zardin, B.; Cillo, G.; Borghi, M.; D'Adamo, A.; Fontanesi, S. Pressure Losses in Multiple-Elbow Paths and in V-Bends of Hydraulic Manifolds. *Energies* **2017**, *10*, 788. [CrossRef]
16. Algar, A.; Codina, E.; Freire, J. Experimental Study of 3D Movement in Cushioning of Hydraulic Cylinder. *Energies* **2017**, *10*, 746.
17. Zhang, W.; Peng, J.; Li, S. Damping Force Modeling and Suppression of Self-Excited Vibration due to Magnetic Fluids Applied in the Torque Motor of a Hydraulic Servovalve. *Energies* **2017**, *10*, 749. [CrossRef]