DEPARTMENT OF ENERGY TECHNOLOGY
AALBORG UNIVERSITY

PhD Public Defence

Title:	Design, Optimization and Testing of Valves for Digital Displacement Machines
Location:	Pontoppidanstræde 111, auditorium
Time:	Tuesday 5 December at 13.00
PhD defendant:	Christian Nørgård
Supervisor:	Associate Professor Michael M. Bech
Moderator:	Associate Professor Lasse Schmidt
Opponents:	Associate Professor Peter Omand Rasmussen, Dept. of Energy Technology, Aalborg University (Chairman) Adjunct Professor Matti Olavi Linjama, Tampere University of Technology, Tampere, Finland Vice Business Area Manager Drives Siegfried Silber, LCM GmbH, Linz, Austria

All are welcome. The defence will be in English.

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Abstract:

The present thesis deals with design, modeling and testing of novel switching valves for an emerging class of variable displacement fluid power machines i.e. digital pump/motors also referred to as Digital Displacement Machines (DDMs). DDMs use several parallel configured pistons, each connected to a high- and low-pressure manifold through two electronically controlled switching valves. By controlling the switching sequence of the valves, each piston may be reconfigured on a stroke by stroke basis to perform motoring or pumping strokes, or the cylinder may be disabled by keeping the low-pressure valve open throughout the cycle also referred to as idling. This enables an effective method for controlling the displacement which may lead to a breakthrough in the achievable efficiency of variable displacement fluid power machines, especially at low displacement ratios.

Combining the improvement of efficiency with well-known benefits of hydraulics, such as high power density, robust operation and rugged design, digital pumps/motors are attractive candidates for several applications incl. hybrid vehicles, wind turbines, wave energy converters, mobile hydraulics etc. Depending on the application, different requirements exist to the electronically controlled valves. The present work focuses solely on high-speed applications where fast switching capability of the valves is essential. The switching valves of digital pump/motors are key components and the nature of DDM operation set tough requirements to the valves, especially for high-speed applications. They must be fast switching to enable accurate and efficient switching, they must have large flow areas to ensure low flow losses, they must be electrically efficient and finally, they must endure billions of switching cycles in several of the potential applications. The objectives being multiple and conflicting make designing these valves relatively difficult and on-the-shelf components fully meeting all requirements do not yet exist.

The present research primarily revolves about two developed prototype valves for DDMs. Both prototypes use actuator topologies relatively new to hydraulics and certainly to the field of digital pump/motors. A model based optimization method is proposed for deriving a moving coil actuator for digital pump/motor valves using a multi-objective optimization algorithm. Evaluation of possible actuator candidates is carried out using several mathematical models representing a wide range of physical phenomena, to facilitate simulating a single digital displacement (DD) cylinder in operation. For each candidate, static axi-symmetric electro-magnetic finite-element-analysis (FEA) is initially carried out. Based on the results, parameters are derived for a fast executable lumped model describing the electro-magnetic dynamics of the moving coil actuator. The valve pressure drop and the induced axial forces acting on the moving valve member as a function of flow are modeled using lumped models with the coefficients derived from computational-fluid dynamics (CFD) analysis. The proposed optimization method is applied to a 50 CC cylinder operating at 800 RPM and is shown capable of deriving actuators ensuring fast and efficient switching of the valves.

Based on the most suited candidate, valve prototypes are designed, built and rigorously tested to verify the simulated valve performance. The mathematical models used for virtual prototyping are compared against a series of measurements generally proving the models sufficiently accurate. Measurements show the valve to have switching times of 2-3.5 ms and a pressure drop of approximately 0.5 bar at the peak flow rate of 125 l/min. A test rig is built to test the valves in DD operation and to establish proof-of concept for novel switching valve and actuator concepts. Using the test rig, DD motoring and pumping operation at 100 bar and 800 RPM is accomplished. During operation, the valve related losses are approximately 1% of the output power demonstrating the developed prototype valve is a promising candidate for efficient DD operation.

Due to the valves of DDMs being compact and integrated units, implementation of direct methods for measuring the displacement of the moving member is impractical. To this end, methods for indirectly observing the valve movement based on the measurements of coil current and voltage waveforms, are presented. One method is proposed for moving coil actuator based valves in combination with an actuator

parameter tracking scheme that gives both accurate tracking of the movement and important information of the health of the valve.

A moving magnet actuated valve have also been developed using an optimization method much similar to the moving coil actuator. Likewise, a valve prototype is designed, built and tested. Measurements show the valve to have switching times around 6 ms and pressure drops of only 0.2-0.3 bar at the peak flow rate of 125 l/min.

In summary, the proposed model based optimization method is demonstrated capable of deriving optimal candidate valve designs satisfying the strict performance requirements set forth by DDM applications. In particular, the research documented in this dissertation concludes that valves actuated by moving coil and moving magnet principles are possible candidates for high-speed DDMs. Future research regarding e.g. wear and reliability will be of fundamental importance in order to mature the proposed valve concepts further.