WATER HYDRAULICS MOTION CONTROL – POSSIBILITIES AND CHALLENGES

Matti VILENIUS, Kari T. KOSKINEN and Max LAKKONEN

Institute of Hydraulics and Automation (IHA)

Tampere University of Technology

P.O. Box 589, FIN-33101 Tampere, Finland (matti.vilenius@tut.fi)

ABSTRACT

Water hydraulics is a growing technology area mainly due to environmental, safety and cleanliness reasons. Water hydraulic systems have proved to be the best technology alternative in some industrial sectors such as food, processing, paper, steel and power industry. The main challenges for water hydraulics technology are proper design, good reliability and controllability at a reasonable price level. When these requirements are fulfilled, water hydraulic systems should be fully competitive to other systems.

The objective of water hydraulics motion control research is to improve the controllability of the systems. This paper considers the current possibilities and challenges in water hydraulics motion control. Component technology is shortly discussed, including control valves and actuators. After the component technology, the present control methods in water hydraulics motion control are explained. The challenges in position, velocity and force control are exemplarily described. Finally, two examples of new water hydraulic motion control systems are presented: *Example 1*. Positioning system with on/off valves, *Example 2*. Cavitation free proportional pressure relief valve for water systems.

KEYWORDS

Water hydraulics, motion control, control valves, actuators, control methods

INTRODUCTION

During the last decade, the water hydraulics has been one of the most researched areas in the field of the fluid power. The objective of the research has been to develop a hydraulic technology, which is competitive to other technologies in the industrial sectors such as food, processing, paper, steel and power industry. The main competitor technologies for water hydraulics are electronics, pneumatics and oil-hydraulics. Concerning the motion control, oil-hydraulics sets the objectives for water hydraulic research. Nowadays the uppermost objective is to achieve the same controllability level as in the traditional oil-hydraulics. However, a lot of research is needed to achieve proposed control level. Until now the main obstructive factor in water hydraulic motion control research has been the availability of suitable components. Therefore, the

component research and development are an essential part of the water hydraulic motion control research.

Pure tap water has some general benefits when compared to other pressure mediums such as oil and air. Environmental friendliness, non-flammability and inexpensiveness can be named as the main benefits. On the other hand, if water is considered only in motion control context, stiffness and constant viscosity are the foremost profits. Unfortunately, water has significant drawbacks as well. The limited operating temperature range, poor lubricity and cavitation sensitivity are the worst [1]. For example, cavitation erosion with water has been studied to be multiple times stronger than it is with mineral oil [2].

Water hydraulic motion control can be divided into three main sections: control valves, actuators and

control methods, which are shortly reviewed in this article later on.

CONTROL VALVES

In control systems, the most important components are normally the control valves. The properties of the valves ordain greatly the controllability level, which can be achieved in control systems. The control valves are traditionally divided into three categories according the purposes of use.

Figure 1. Ebara water hydraulic servo valve.

Servo valves are the most sophisticated control valves, which development has so far focused strongly to Japan [3]. The characteristics of present water hydraulic servo valves are good. Therefore, an excellent controllability level in water hydraulic control systems becomes possible [4]. If existing water hydraulic servo valves are compared to corresponding oil hydraulic servo valves, the properties of the valves are at least partially comparable [5]. Unfortunately, the water hydraulic servo valves have one major drawback as well: the manufacturing costs. This makes it practically impossible to implement such valves in cost-effective water hydraulic control applications.

Figure 2. A proportional low-pressure water hydraulic valve.

The proportional control valves are the second type of control valves. Proportional valves are structurally slightly simpler than servo valves. This is probably one reason why the research and development of water hydraulic proportional technology is worldwide more spread than the servo technology. Nevertheless, the supply of proportional valves in the market is almost similar to servo valves. The amount of commercial proportional valves is larger than it is with servo valves, but prices of proportional valves are still quite high as well. The high price reduces possibilities of using these valves in many applications. Hence, the development of alternative low-cost proportional valve solutions has been started. A good example is a pneumatic on/off valve, which has been modified to work as a proportional water hydraulic control valve (Figure 2). The results with this low-cost solution in low-pressure water hydraulics have been promising [6][7].

Figure 3. A low-cost on/off valve.

The most available valves in the market are on/off valves. The structural simplicity compared to servo and proportional valves makes on/off valves easy to produce. Therefore, the price of on/off valves is also remarkably lower than it is for other valve types. The low-price makes on/off valves almost the only used valve type in water hydraulics. However, it is commonly known that a price of the on/off valves is strongly dependent upon the used pressure level. In ultra-high-pressures over 500 bar adequate on/off valves are extremely expensive whereas in low-pressure range up to 50 bar it is possible to use bulk products such as hpac valves (Figure 3), which are very inexpensive [8].

Figure 4. Cavitation position prediction in poppet valve [9][20].

In order to make water hydraulics to a serious competitor for other technologies, a lot of valve research has still to be done. A major part of the control valves are, as just mentioned, very expensive. Therefore, the objective of valve development should be reduction of the price level. One key for that is material research. For example, if the expensive materials such as stainless steel could be replaced by cheaper materials such as plastics, the price of the low- and mid-pressure level valves would be remarkably less. However, a lot of basic research is needed in water hydraulic valve development. For example the basic phenomena such as cavitation, flow forces and leakage flows inside both poppet and spool valves are still very little studied topics. On the other hand, modern research tools such as CFD (computational fluid dynamics) offer new possibilities for make research. The numerical study of the poppet valve has already proved that CFD can be used successfully (Figure 4) [9].

ACTUATORS

The most used actuators are cylinders, which implement linear movement. In the market there are

several cylinder manufacturers present, which have a rather wide range of cylinders to offer. The characteristics of cylinders differ slightly according to the purposes of use. In some of the cylinders friction values are high, but general performance of existing water hydraulic cylinders is quite good. The price difference between oil and water hydraulic cylinders is not as high than it is for the most of the other water hydraulic components. Despite of that, the objective of cylinder research should be towards cheaper cylinders in order to gain competitiveness of water hydraulics against other technologies. One key for that might be new materials such as plastics and composites. These materials decrease the weight of the actuators as well, which gives a wider range of application possibilities. In figure 5 is an example of composite tube water hydraulic test cylinder.

Figure 5. Composite tube water hydraulic test cylinder.

The second main group of water hydraulic actuators are motors, which are used to implement rotational movement. The water hydraulic motor supply in the market is far smaller than it is for cylinders. Partly because of this, the price of the water hydraulic motors is high compared to similar oil hydraulic motors. However, water hydraulic motors are not so much tested in control systems than cylinders are. Therefore, more control research with existing water hydraulic motors should be done in the future.

CONTROL METHODS

For water hydraulic motion control, the same control methods than in oil hydraulics can be used. For example, water as a pressure medium instead of oil does not affect significantly the design of the servo control systems. The main differences are mainly in characteristics of the components [4].

Position control has been the most researched control method in water hydraulics until now. The position control results are strongly dependent upon the used control system. Different ways to execute position control at the moment are servo, proportional and sophisticated on/off technologies. However, as a summary it can be stated that similar results as for oil hydraulic position control can be achieved by using water hydraulic control methods [10][11].

Force control is a much less researched field than position control. However, some publications are written under this topic. If these publications are summed up, the main finding has been that force control can be arranged in water hydraulics with existing components [12].

Velocity control is the least researched field in water hydraulics, but the research of control possibilities has already started. The findings of the first tests have proved that both water hydraulic motors and cylinders can be driven with velocity control methods [13][14].

Accordingly, in future water hydraulic motion control research will focus more to velocity and force control. The uppermost objective of motion control research is to achieve the same controllability level as for oil hydraulics. However, there is still a lot of effort to do in the field of control algorithms and parameters until this objective is fulfilled. One solution for achieving that is the alternative control methods like sophisticated on/off control. Though, new innovations might create the most extraordinary control solutions in the future.

EXAMPLE 1. POSITIONING SYSTEM WITH ON/OFF -VALVES

Positioning by on/off valves has been researched a lot in recent years. The basic idea is to build up a control system by combining inexpensive and primitive on/off valves with sophisticated control methods. The used valves are simple two-way solenoid valves as shown in figure 3. Their main characteristics are rather slow and varying operation times (10-35 ms) and limited flow capacity.

Figure 6. Hydraulic circuit of the on/off controlled cylinder [15].

Figure 6 shows the on/off control circuit, which is used as the origin of the on/off research. Simple three-state control is used and the control principle is that when the target position is different than current position, valves 1 and 3 or 2 and 4 will be opened depending on position correction direction. When the position target is almost achieved both valves are closed simultaneously. A small breaking distance is needed to compensate delays of valves [15]. Even this simple system gives reasonable accuracy under constant loading conditions. The maximum velocity is quite limited because of pressure transients during stopping. Small damping volumes (e.g. short pieces of hoses) reduce pressure transients but the maximum velocity is still only 70 mm/s. Small movements are also difficult to realise with basic algorithms.

Figure 7 presents the hydraulic circuit having two extra valves and flexible volumes, which are used to realise stepwise fine positioning of the load mass [16]. A sophisticated adaptive controller is used, which selects the optimal valve opening combination and fine positioning strategy depending on position error, piston velocity and load force [17]. This system gives almost doubled maximum velocity and 75 percent better positioning accuracy. In addition, it works with all loading conditions. Figure 7 presents the measured small movement test results.

Figure 7. On/off circuit with fine positioning valves and volumes [17].

Figure 8. Results with adaptive fine positioning [17].

The recent on/off research has concentrated on “proportional-like” control in order to achieve servo quality tracking control with low-cost on/off valves. The basic principle is to use parallel connected on/off valves where valve sizes are selected according to binary series 1:2:4:8 etc. This old idea gives 2^n different flow rates with n valves. The benefit of the method is that no continuous high frequency switching of the valves becomes necessary. The velocity control of a water hydraulic motor was studied in [13] where the binary coded valve series with seven valves and commercial proportional valve were compared. The results have shown that on/off valves give better control results with clearly lower costs. This “pseudo-proportional” on/off control approach can be applied also to the position control [18]. Figure 9 presents a step response for a cylinder having four valves at supply and return paths. The results illustrate that smooth and accurate movements are possible with on/off valves without continuous switching.

Figure 9. Results with binary coded valve series [18].

As a summary, the measured position control results with different control algorithms are collected in table 1. The test arrangements have been similar in

every measurement and therefore results are comparable.

Table 1. Measurement results

Control Principle	Number of valves	Velocity [mm/s]	Position Accuracy [mm]
Three-state control	4	70	0.4 mm
Adaptive control with fine positioning	6	130	0.1 mm
Binary coded valve series	8+1	200 (400)*	0.2 mm

* with 10+1 valves

The sophisticated on/off control has proved to be an inexpensive and accurate control method in low-pressure water hydraulic position control. In future it will probably be employed in higher pressure ranges as well. Accordingly, the ongoing research will concentrate on the energy saving issues, elimination of pressure transients and control algorithm development.

EXAMPLE 2. CAVITATION FREE PROPORTIONAL WATER HYDRAULIC PRESSURE RELIEF VALVE

There are only very few commercial water hydraulic proportional pressure relief valves available in the market. The main reason is the difficulty of designing durable pressure valves, which have both good steady state and dynamic characteristics. In addition, this should be done at reasonable costs.

One of the main problems in water hydraulic pressure valve development is cavitation, which creates erosion wearing inside the valves for high pressure differences. The cavitation intensity with water might be up to 100 times more intense than it is with oil [1]. Therefore, the lifetime of water hydraulic valves can be problem. However, it is possible to tackle this problem by using special materials such as ceramics at critical areas like poppet and seat. Unfortunately, this raises the manufacturing costs as well as the price of the valves. Another way to approach the problem is to use special designs, which decrease or even prevent cavitation.

In the example, valve cavitation prevention is based on the use of a cone shaped poppet consisting a series of grooves [19]. Each edge between the grooves acts as a single orifice and thus the pressure is decreased just a little in every orifice. When the pressure is decreased step by step, the actual pressure difference over one

orifice is only a fraction of the whole valve pressure difference. Therefore, the risk of cavitation decreases significantly.

Figure 10. Schematic drawing of cavitation free pressure relief valve [19].

In figures 11 and 12 are shown the examples of steady state and dynamic characteristics of an example valve.

Figure 11. Steady state characteristics of proportional cavitation free pressure relief valve [19].

Figure 12. Dynamic characteristics of proportional cavitation free pressure relief valve [19].

Presented steady state and dynamic characteristics of the valve are competitive to a commercial valve. The steady state characteristics show only a minor pressure rise while flow through the valve increases. The hysteresis is relatively low when dither is used and can be set even to a lower level by improving manufacturing tolerances. Average overshoots in transient situations are about 10 %. Control accuracy is at this stage about 2 bar or less and settling times are relatively short. In endurance test studies, the valve construction has turned out to be extremely durable.

The cavitation free proportional pressure relief valve has shown good results and might be a good alternative to pressure and force control systems in the future.

CONCLUSIONS

Water hydraulic motion control is still behind of oil hydraulics, but the gap is diminishing every day. The reason for improvement is that components, systems and control algorithms are developed continuously. In future the research will be done especially under following topics: material development, cavitation prevention, range widening of suitable components and alternative solutions. Totally new innovations, such as the presented examples, will be in significant part in developing water hydraulics as well.

At present many demanding motion control applications can be established with water hydraulics, but this needs a lot of knowledge and design work, especially from the control point of view. Therefore, one of the main objectives of water hydraulics motion control research should be to develop simple but suitable methods and systems, which could be easily applied all over the world.

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