Sustainable development with water hydraulics–possibilities and challenges

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SUSTAINABLE DEVELOPMENT WITH WATER HYDRAULICS – POSSIBILITIES AND CHALLENGES

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ABSTRACT

Water hydraulics is an old technology area, which has been used already hundreds of years. Earliest applications where water was used as power transmission medium are known already from 2000 years ago. Modern water hydraulics can be comprised as a technology area where new design, material and control technologies are applied to water hydraulic systems. In 1990's very much research and development of water hydraulic systems and components were carried out in several laboratories in many countries. During the new millennium the research efforts has been a little bit smaller, but the continuously rising concern about globe and global climate change has also increased the interest on water hydraulic applications. This paper describes the actual research activities related to development of water hydraulic components and systems. The main focus areas are discussed and the challenges and possible solutions of each subject are analyzed. Water quality aspects, component technology, control aspects and also applications are covered. Also some analysis about water hydraulics' possible role in climate change process and energy saving are presented.

KEY WORDS

Water hydraulics, Oil hydraulics, Sustainable development, Research, Component technology

NOMENCLATURE

CFD : computational fluid dynamics
DOC : dissolved organic carbon
$\beta(x)$: (Number of particles > (x) upstream) / (Number of particles > (x) downstream)

INTRODUCTION

Almost everybody agree that the use of not renewable energy and especially oil have to be decreased in the future. More emphasis have to be put on the use renewable sources like solar, wind and wave energy in the future. Even the consumption of hydraulic oil in the world is of course is much smaller than total oil consumption (over 80 million barrels per day [1]), the number of tons used in fluid power is still quite significant. By reducing this amount fluid power world and machine builders can do their share of global climate work.

The use of water hydraulics is one possibility to develop fluid power systems to more environmental friendly

direction. In this context water hydraulics can be understood as a technology, which is using water or water based fluids for transmission of energy and power.
Water hydraulics is the first fluid power technology, which is used already in 18th century. The modern water hydraulics technology is new application area, which has had strongly increasing trend since 1980's. Using different waters instead of oils in hydraulic systems brings the following benefits: environmental safe, fire safe, explosion safe, low cost fluid, good availability of the fluid, easy storage of the fluid etc.
IHA (Department of Intelligent Hydraulics and Automation, Tampere University of Technology) has put systematically efforts on developing water hydraulics technology during 1990's and during the new millenium. Research have been made in different projects in Finland and internationally.

ROLE OF HYDRAULIC PRESSURE MEDIUM IN SUSTAINABLE DEVELOPMENT

Pressure medium life cycle

If we are thinking about the lifecycle of hydraulic oil and the costs related to every phase, the total sum will grow quite very high. We have to take into account all the investments related to drilling the oil, transportation, refining, marketing, delivery, use and disposal. Naturally it is impossible to find out just costs focused on hydraulic oil, because also other oil products are produced always at the same time.
When comparing the supply of oil and water to each other, the difference is quite essential. Oil drilling is huge business, which needs big investments. For example the oil rigs have to be able to build in deeper water in the future. That means even bigger investments. Water is instead easily available and for example from sea water it is relatively easy to produce water for water hydraulic systems.
One important factor globally is the packages for oil products. All the oil products are packed to barrels, containers, cans etc. The production of these packages requires a lot more extra energy than taking the water from tap.
The use of water in hydraulic system needs extra care considering the water quality. Microbiological growth is a phenomenon, which causes extra costs for maintenance and service. Also when using some additives for preventing microbial growth, some extra costs are generated. On the other hand storage of water is much easier and normally, when tap water is used, no storage costs are generated. Also, water doesn't wear out, so the fluid replacement can be less frequent than with oil. That is also very much according to sustainable development, because less energy is used for fluid replacement and the disposal is every time easier than with oil, which have to be transported to special disposal plants.

Energy efficiency

Energy efficiency of machines and systems will be also very important aspect in the future. The consumption of energy during system building, system use and system disposal have to be minimized. So the whole life cycle of the whole systems have to be considered.
When thinking about water hydraulics, the situation is versatile. Due the material requirements of components, the system building costs are higher than oil hydraulics at present. The reasons for that are, for example, base materials and very small production quantities. In high pressure water hydraulics the price difference can be 3-5 times. However, in low pressures the price difference is decreasing. The energy consumption per system can be evaluated to be higher, because the materials used are requiring longer machining times and more complicated processing that in oil hydraulics.
The use of water instead of oil is offering benefits, when considering energy consumption. The pressure losses in pipes and components are smaller with water than oil, which is clear benefit, with large flows and long pipes. On the other hand the leakages could easily be higher with water. This, of course, leads to use of smaller clearances and seals, which can increase friction and that way energy consumption. However, the basic design and control principle of the system have very big role for the system energy consumption. If the basic design doesn't include relief function when needed, controllable pump rotation speed when needed or the control valve or block have to have small flow paths, the energy losses can rapidly increase. In accurate and fast control tasks with digital water hydraulics, also control algorithms can be optimized considering the minimizing of energy consumption.
When evaluating the system components disposal after the use, no significant differences between water and oil hydraulics can be found.

ACTUAL RESEARCH INTRESTS IN WATER HYDRAULICS

The Department of Intelligent Hydraulics and Automation (IHA) has a long history in water hydraulic research. The motion control has always been one of the most important research areas in both oil and water hydraulics research in IHA. The water hydraulics motion control research has been concentrated both on component research and system level research. In the beginning of new millennium a lot research was made with on/off-control in water hydraulics. On/off –control is very cost effective way to achieve relatively good characteristics, because the cost level of water hydraulic servo valves is very high. At present this work has been transferred to its own research team Digital Hydraulics, which also covers oil hydraulic on/off –systems.

Proportional technology is also an important part of water hydraulic motion control. Proportional valves are undeveloped except some exceptions and on the other hand the system and control technology has not been widely applied to water hydraulic motion control. Both areas are intensively researched in IHA.

Use of water in hydraulic has a great opportunity to cavitation in components where pressure gradients are large. One of these components is a seat valve where the pressure drops in relatively short length. The seat valve is, however, quite cost-effective valve type to water hydraulics, because it is possible to manufacture as non-leaky with reasonable tolerances that makes it interesting for industrial use. The research of cavitation in water hydraulic seat valves is one focus area. Also the leakage flows in water hydraulic spool valves have been studied.

Microbial growth is a problem in hydraulic systems, even though they are considered to be oligotrophic environments. Filtration is one of the possible methods to reduce microbial growth and particle contamination in water hydraulic systems. However, biofilm and particles can block the filter element very rapidly and prediction of the lifetime of the filter element of water hydraulic system is very challenging. IHA has made research in this area over 8 years.

Water quality aspects [2]

Growth and attachment of bacteria in water hydraulic systems is mainly a function of the nutrition concentration in the pressure medium. Hydraulic parameters and system materials have a slight effect on growth and attachment, but the best way to avoid problems with microbes is to maintain nutrition levels on a par with tap water (DOC 2-4 mg/l).

Lowering the nutrient concentration and increasing the system pressure have been reported as the most effective ways for controlling total bacterial numbers and counts of viable bacteria in the pressure medium. Low reductions have been obtained by adjusting the fluid flow velocity in the system. However, an increase in pressure resulted in enhanced microbial attachment on the reservoir as shown in figure 1.

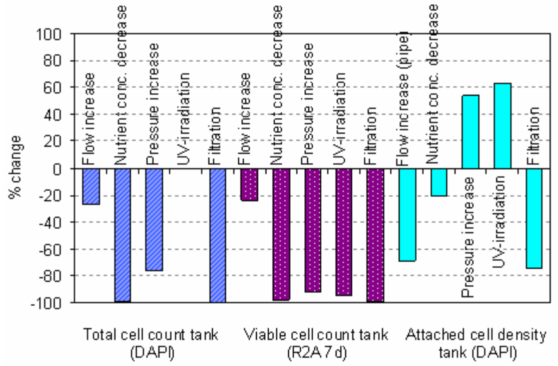

Figure 1. Changes in number of microbes in water hydraulic systems due to adjusted operational parameters and control treatments [3].

Experiments showed that biological or physical contamination can be reduced to acceptable levels in water to secure machine operation, when they are not simultaneously present in significant amounts. Based on the experiments, it is challenging to determine exactly the combined effect of particles and biofilm on a filter. Parallel experiments might contribute to statistical analyses, but, definitely, statistical analyses do not work well in this case because of the nature of microbial growth. For example enhanced microbial growth causes problems with determination of β(microbe)-value because of its bioreactor effect in the filter (Figure 2). That is, biologically active material together with water and suitable temperature promotes an environment for microbes to reproduce in filter cartridge.

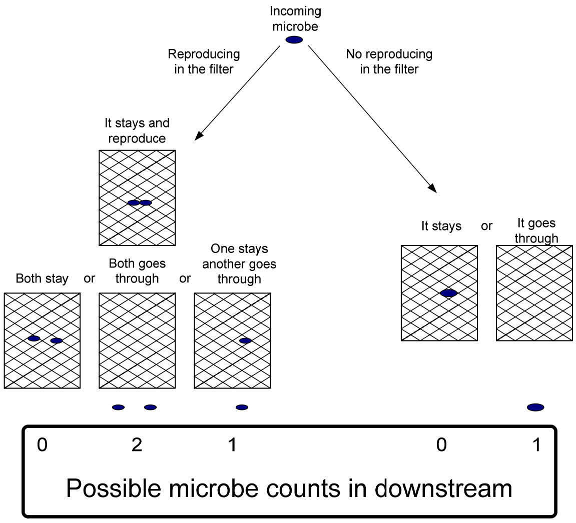

Figure 2. Bioreactor effect on a filter cartridge.

Because of the incomplete knowledge of both physical and biological system parameters, the working conditions of filters cannot be accurately predicted. Preventive maintenance requires more detailed data about hydraulic systems than can be achieved even using pilot-scale systems in laboratory conditions.

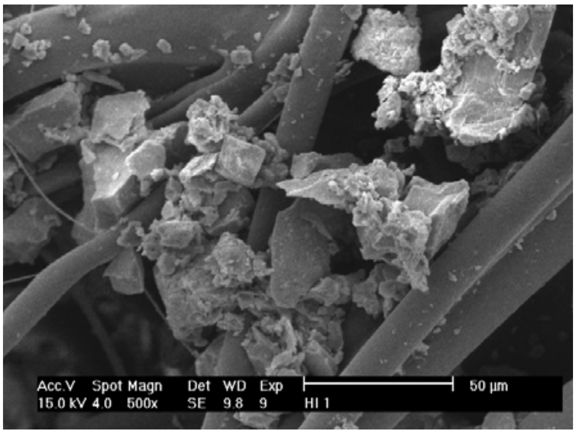

Figure 3. Particle and microbe contamination on filter fibres.

The best and only way to deal with filtering problems caused by both microbial growth and particles (Figure 3) is to use two-phased filtration and make sure that the system has minimum interface with the surrounding environment. A large filtering area ensures better long-term operation of filters, because abrupt malfunctions are more likely to happen with a filter system with a low dirt-holding capacity.

Water flow in valves [4]

Valve is a basic component in a hydraulics system. Its role is to control flow from a volume to another. It is therefore the place where lot of energy is dissipated to heat and makes the field worth of investigation. A seat valve is a good selection for water hydraulics, because low viscosity makes it essential to avoid leakage gaps in the valve structure. Seat valve is easy and cost-effective to manufacture to meet this requirement. Another challenge in water hydraulics is cavitation, which easily occurs in narrow channels of seat valve. Optimisation of the structure is the cure to solve this problem. The traditional method for the optimization, i.e. the product development, is to use prototypes, that however, is laborious and time- and energy-consuming process. The more effective expedient is to calculate flow through a structure and in a case of a complicated geometry, the method of computational fluid dynamics is usually used for this purpose.

The appropriateness and reliability of CFD for simulating flow of water in cavitating conditions in different seat valve structures are investigated with experimental measurements of flow rate, pressure distribution and cavitation occurrence. The experiments show the appearance location and path of travelling vapour produced by the cavitation phenomenon. The place, where cavitation is originated from, may be very minor and the process of the bubble growth is unsteady. This makes the pressure measurement challenging, but in addition, increases risks of simulation errors. For instance, a corner in the seat, which is absolutely sharp in the model, causes the results not to show local pressure drop around the corner, whereas any chamfer on the corner brings it out. Figure 4 represents well the time dependency of the vapour cloud behaviour and the very local origin where the vapour is produced. At one moment, the chamber can full of vapour and at another, full of liquid.


Figure 4. Unsteady situation of cavitating flow.

The differences in the flow characteristics are diverse. Cavitation occurs with the smallest pressure drop over the orifice in valve of chamfered seat. On the other hand, the discharge coefficient of chamfered valve structure is bigger than that of sharp valve structure, which leads to conclusion that the cavitation sensitivity between these two valve types depends more on flow rate than just on pressure drop. The cavitation affects the chamfered seat valve lowering its discharge coefficient, but the performance of the valve with the sharp seat endures despite of vapour in the orifice.

Shape of poppet in a seat valve is mostly effecting on the direction and speed how the jet of vapour behaves in downstream side. This is meaningful considering the risk of damage caused by cavitation, if it can not be fully eliminated by the shape optimization.

Computational investigation of pressure distribution in the valve orifice shows the benefits of valve with multistage pressure drop. It reduces the risk of cavitation, but chamfer on a single corner of stage is still increasing it creating a local low pressure area. Figure 5 shows computational pressure distribution in a case of chamfered seat edge and figure 6 shows pressure distribution with correspondingly defined pressure boundaries when there are two edges instead of continuous chamfer. Clearly, there is no such a local small pressure area if the continuous chamfer surface is replaced with the separate edges. Thus, cavitation appearance is less probable in the latter case.

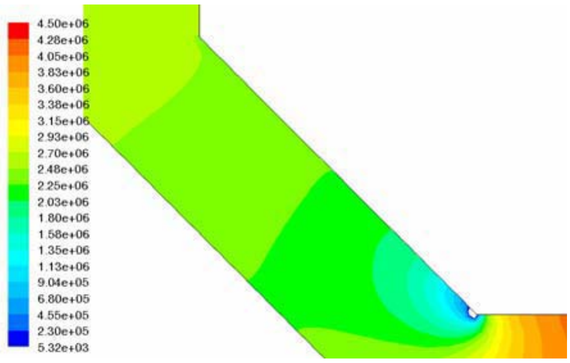

Figure 5. Computational pressure distribution in chamfered orifice (Pa).

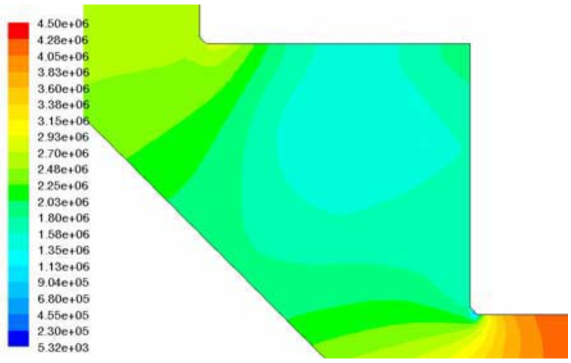

Figure 6. Computational pressure distribution in two-step orifice (Pa).

Even though there are uncertainties in the computational methods solving fluid flow in complicated valve structures, the benefits are undisputed. If thinking about hydraulics, its essence is basically interraction between fluid and solid parts. Combining the simulations of rigid body motions and the fluid dynamics (FSI, Fluid Structure Interaction) is a great opportunity to rise the modelling of hydraulics on to a new level. The availability of computational power is not anymore the limit. The only challenge is anymore the arrangement combinig of these two common modelling technologies in practice. Fortunately, the CDF software packages are developing to the direction making it possible.

Challenges with pumps [5]

The challenges of hydraulic pumps create a need for continued tribological research. One research area is the use of water hydraulics, particularly the use of variable displacement axial piston pumps, in the hydrostatic transmission of mobile machinery.

Axial piston pumps and motors are commonly used in hydraulic applications because of their compact size, wide operating range and controllability. On the other hand these types of pumps and motors are quite complex. To increase the overall efficiency of the system, variable displacement axial piston units are widely used basic components in oil hydraulics nowadays. Axial piston type units are very competitive also in modern water hydraulic pumps and motors. In mobile machines most of the units are axial piston design at the moment. However, there are not commercial variable axial piston pumps or motors for water hydraulics, which is a significant problem in certain applications.

The aim of pump research is to study basic effects caused by the adjustment of the swashplate angle. At first, the attention is focused on measuring the water film thickness between the swashplate and the slipper pad and the forces affecting the piston while tilting the swashplate (Figure 7).

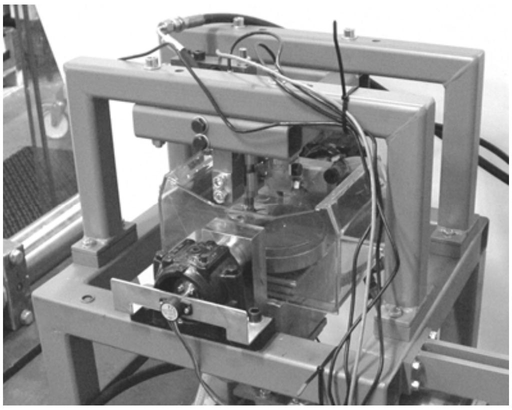

Figure 7. Water film thickness measurement test rig.

There are several different water hydraulic pumps on the market at the moment. Most of the pumps are oil lubricated piston pumps, which are driven by crankshaft mechanism. Only a few of the pumps are totally water lubricated. Water lubricated pumps are usually axial piston pumps with non-adjustable swashplate. Water as a pressure medium requires that all materials should be non-corrosive and all clearances are smaller than in oil hydraulic units.

Sliding pairs of the pumps are usually made of stainless steel and some type of reinforced industrial plastic, for example PEEK. All bearings are sliding because adequate ball or roller bearings are not yet available. Various materials have been tested in pumps in recent years and at least water hydraulic pumps with ceramic pistons are available. Because of the requirements of special design and materials, water hydraulic components, including pumps, are generally more expensive than oil hydraulic components. Costs are high also because of the amount of production is rather low. Usually maximum pressure level is 16 MPa but there is also at least one commercial pump with 21 MPa pressure level. Water flow of the pump varies from a few litres per minute to few hundred litres per minute. The pump body can be the same in pumps with different displacements, the only difference being the angle of the swashplate. However, there is no variable displacement pump available on the market.

Control possibilities

Water hydraulic motion control is one of main focus points in research in TUT/IHA. The research of motion control means the research linear or rotary motion with components, control algorithms and controllers so, that the demanded steady state and dynamic characteristics are achieved. The control valves can be on/off –valves, proportional valves, servo valves or combination of any previously mentioned valves. The control algorithms needed are naturally very different in different system cases.

As an example of the water hydraulic controllability research, an on/off –control case can be mentioned (Figure 8). The idea is to use small, reliable and cheap mass production valves to implement a linear motion. There are several valves, which are controlled so that the best possible control accuracy and good dynamic characteristics can be achieved. The cost level of this kind of digital hydraulic system is only one fraction of a servo valve controlled system for handling the same operation.

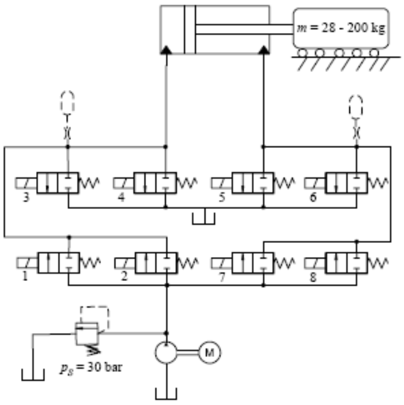

Figure 8. On/off –valve controlled water hydraulic cylinder [6].

New components are developed continuously in water hydraulics, because the variety of present components is still very small compared to oil hydraulics. During the last years, the development has concentrated on developing new control valves, but also some actuator and pump development projects can be found. As an example of resent development results, a new proportional valve presented in figure 9 can be mentioned [7]. The valve is developed by Finnish company Sitek-Palvelu Oy in cooperation with TUT/IHA. The valve enables to build accurate water hydraulic control systems cost-effectively.

Figure 9. New water hydraulic proportional valve for low pressures. (Sitek-Palvelu)

Control of water hydraulic manipulators and booms is also one research interest in IHA (Figure 10). In this work a hydraulic crane was equipped with water hydraulic components. A control system using two PID controllers plus a Feed Forward block (F-PID) was implemented, and in order to study the dynamic behaviour of this kind of system, a series of tests were performed. At first, a characterisation of the system (mechanical and hydraulic) was performed and then the different steps of the controllers design were analysed by means of various end-effector trajectories. The results show a very good behaviour of this kind of system with a low positioning error.

Figure 10. Water hydraulic boom with proportional control valves [8].

NEW APPLICATION AREAS

Mobile hydraulics

In the future mobile machines will also utilize water hydraulics more and more. At the moment there are only few commercial applications and some research projects related to the subject. One good practical example is Renova company in Gothenburg, Sweden [9], which is using water hydraulics in its waste packer lorry. Renova previously used 15,000 litres of hydraulic oil alone in a typical year which had to be purchased,

stored and disposed of. In contrast, water is literally 'on tap', doesn't create a slippery hazard when leaks occur (as hydraulic oil does) and is far easier to dispose of.
Forklift (reach truck) which is used as a research platform in this research is shown in figure 11 [10]. The work movements of the forklift are usually realized using oil hydraulics. In IHA's research forklift all the oil hydraulic components from the work hydraulics of the forklift have been replaced with water hydraulic ones and the main focus is in two work movements, which are lifting and reaching. In the original realization, there are also two other work movements which are shifting and tilting of the fork but lifting and reaching are the most significant and therefore those are chosen here. The driving transmission is electric. 10, 11)

Figure 11. Used research platform (forklift).

The goal of the study is to demonstrate how modern water hydraulics can be applied to mobile machines and to use this forklift as a research platform where developed condition monitoring system with different fault situations and different water hydraulic components with different material pairs and control systems are tested.
Very good future mobile application for water hydraulics is the lawn mover concept developed by Purdue University. For example the golf courses all over the world have very tight environmental regulations. The machines used in courses are creating great risk of leak of hot hydraulic oil.

Motion platform [11,12]

The motion platform developed in IHA will be used in real-time simulator construction that allows simulation of different vehicles with minimal changes. Figure 12 shows the construction of simulator. There are four standard PCs, one for simulation of vehicle (PC 1), one for control and position measurement of platform (PC 2), one for generating graphics (PC 4) and optional PC for main loop (PC 3). System is distributed through local area network (LAN), using UDP (User Datagram Protocol) for communications. More detailed information about the simulator can be found in references 1) and 2).

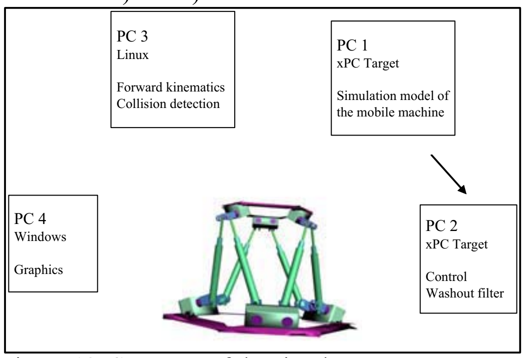

Figure 12: Structure of the simulator.

Commonly motion platforms of this type are used with either oil hydraulic or electric actuators. During the last ten years, water hydraulic control technology has been subject to an intensive research. The interest for an environmentally friendly technology with good controllability and high stiffness and force density has encouraged this development. The development of the water hydraulic motion platform combines water hydraulic research with the increasing interest of virtual technologies and virtual prototyping.
The structure of the platform is a common Stewart platform with six water hydraulic cylinder actuators. The diameter of the bottom plate is 1.2 meters and the diameter of the top plate is 1.0 meters. Actuators are 0.94 meters long on the shortest length. Distance between connection points is 0.16 meters and the mass of the top plate is about 100 kg without extra load.
Figure 13 shows the working area and the coordinate system of the platform.

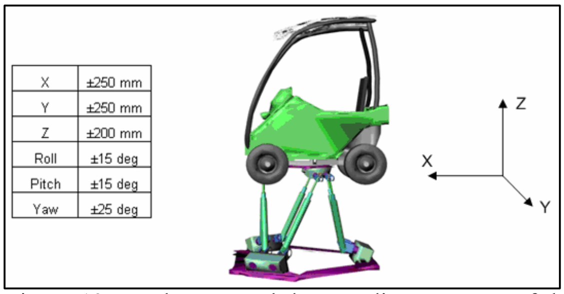

Figure 13. Workspace and the coordinate system of the platform.
The working area of the platform in X and Y direction is ±0,25 m and in Z direction ±0,2 m. The rotating angles are ±15 deg and ±25 deg as shown in figure 13.
The platform is using low pressure proportional valves in the control of the platform. Due to characteristics of these valves, the performance of the platform is not as good as oil hydraulic one with servo valves.

CONCLUSION

It can be concluded that the main challenges for wider usability of water hydraulics are reliability, controllability and price level – and at the same time.

Reliability means that the components have to be able to work longer periods without service and without big risk for brake. It includes the control of water quality so that the components can operate with optimal pressure fluid quality. It also includes the development of components' characteristics so that they are not sensitive for fluid quality, temperature, pressure peaks, cavitation, erosion and wear. And it also means having successful references, where water hydraulics is operation on demanding and long time tasks.

Controllability means that overall ability of water hydraulics to realize more accurate and dynamic control systems have to be improved. This can be done by developing better control valves, control methods and actuators. At the moment, fairly accurate position control systems can be achieved with low pressure by using servo valves or digital hydraulic controls. However, more challenges are in higher pressures (over 20 MPa), where the component supply is very limited. Also components and methods for realizing pressure controls are more needed in the future.

The price level of water hydraulic components is certainly one big challenge. Low pressure water hydraulics is offering one possibility to achieve cheaper costs by using cheaper materials like polymers. However, in general the biggest factors are more expensive materials and small production amounts. Even the components and systems are technically perfect, the price level still affects strongly to machine builders choices. Therefore increasing production amounts along with increasing practical applications, will slowly lead to decreasing price level of the components. And it is important that the machine builders remember always consider total costs for the whole system life cycle including purchase, use, disposal and fluid itself. In addition societal aspects like laws, environmental taxes, insurance costs etc. may also decrease water hydraulics' relative price level in fluid power market.

As a conclusion it can be stated that at present water hydraulics already have many possibilities for building motion control systems and in the future there will be even more, when technical level is still increasing. The major benefits – environmental friendliness and fire safety – are strong drivers for water hydraulics' future development.

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