THE HISTORY AND FUTURE OF FLUID POWER PUMPS AND MOTORS

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ABSTRACT

Positive displacement pumps have been around for thousands of years, but it was first in the beginning of the 19th century they started to be used for power transmission purposes. At that time, the fluid was water, and the applications were primarily presses. During the century, the technology developed and towards its end, fluid power systems were used to transmit power to hundreds or even thousands of consumers within several cities. However, in the 20th century, these large-scale fluid power transmission systems were outcompeted by the electric grid. But at the same time, the focus for fluid power was shifted towards self-contained, oil-based systems, which were suitable in many mobile applications powered by combustion engines. Once again, fluid power systems are now undergoing a transition. This especially apply to mobile applications, where combustion engines are being replaced by electric motors. This puts new requirements on the hydraulic systems as well as the pumps and motors that are to be used. Electrification means increased focus on energy efficiency, and speed-control becomes more relevant than before. New system designs are therefore highly relevant. Depending on the architecture that is chosen, different requirements will be set on the pumps and motors. Aspects such as multi-mode operation, high- and low-speed performance, and displacement control will be discussed in this paper.
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THE EVOLUTION OF POSITIVE DISPLACEMENT MACHINES

This paper focuses on positive displacement pumps and motors, which are used in fluid power to convert power between the mechanical and hydraulic domains. The term “machine” will hereafter be used to refer to both pumps and motors.

In the following sections, the evolution of positive displacement machines will be presented. An overview of the main events is also shown in Figure 1.

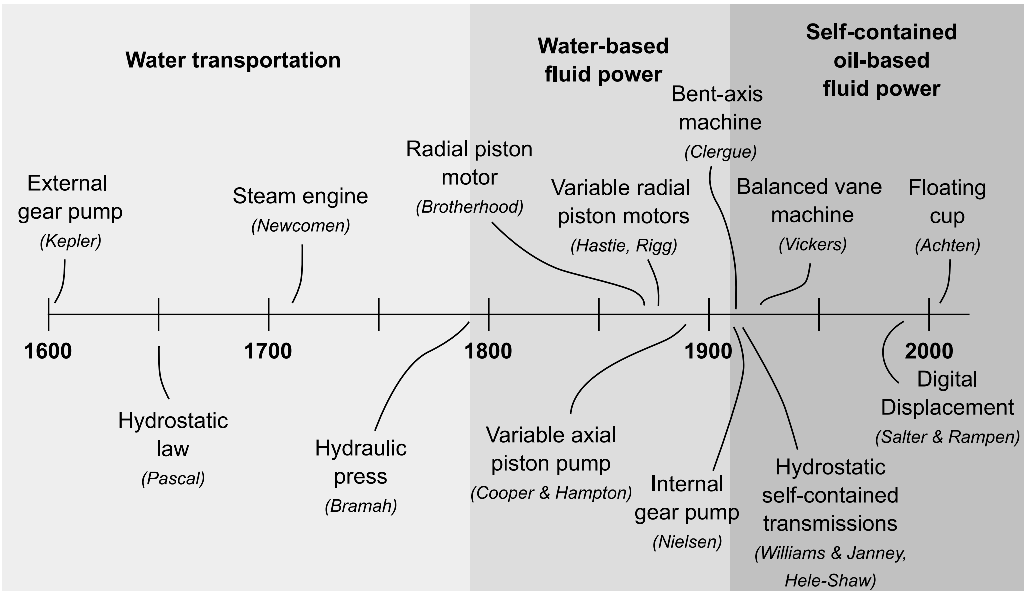

Figure 1 – Timeline

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The Pre-Fluid Power Age

Naturally, there are quite some uncertainties when it comes to the history of positive displacement machines. Words such as “first” are therefore used with caution. However, the first man-made positive displacement machine appears to date back to ancient Egypt. The machine in question was a simple screw pump, often referred to as Archimedes’ screw. It was used to move water from the river Nile [1]. The next major invention in the field appears to have been the piston pump. The invention is usually credited to the Greek inventor Ctesibius, who was active around 250 BC. His pump was based on a reciprocating piston that used check valves for commutation – one for the inlet and one for the outlet. The pump was powered by a lever, but similar pumps with rotational inputs were soon developed. An example where such a pump can be found is Heron’s wind-powered organ. However, piston pumps were not only used for entertainment, but likely also for firefighting purposes [2].

Years passed by without major (documented) happenings regarding positive displacement pumps and motors. However, in 1588, Agostino Ramelli published a book called “Le diverse et artificiose machine del Capitano Agostino Ramelli” [3]. The book is often considered to be the first mechanical engineering handbook. It contains illustrations and descriptions of several pump types, including the first known records of vane pumps, some types of swashplate pumps, and screw pump arrangements. Around year 1600, Johannes Kepler developed what appears to be the first gear pump [4]. This was an external gear pump and several similar gear pump designs came out later in the 17th century, such as the Pappenheim pump. Furthermore, at that time, Blaise Pascal formulated the hydrostatic law, and the first experiments with steam engines were conducted. Then, in the beginning of the 18th century, Thomas Newcomen developed the first commercial steam engine, which later was improved by James Watt. However, the steam engines were mainly used to pump water from mines, and the pumps in question were typically force pumps (i.e. piston pumps similar to the ones Ctesibius invented).

The Age of Fluid Power

So far, almost all applications have been related to some kind of water conveyance. It was not until year 1795, when Joseph Bramah patented the hydraulic press [5], that fluid power really became a power transmission technology. The pump that Bramah used in his invention was principally quite similar to Ctesibius ancient pump. However, now the development in fluid power started to boom. Primarily in Great Britain. Bramah himself came up with several applications for fluid power, such as a simple crane, and a machine that could pull out trees with their roots. He also proposed the idea to have central pumping stations that could be used to provide power to different machines within a city [6]. This idea became reality in several different cities within Great Britain towards the end of the 19th century [7]. The pumps that were used in the early pumping stations were double acting so-called three-throw ram pumps, which is a piston type pump based on crank shafts [8].

In the beginning of the 19th century, typical fluid power applications were presses for packing but also presses for extracting oil from seeds. However, also rotary applications appeared, meaning that the development for rotary actuators got a push forward.

In the second half of the 19th century, many different types of rotary machines started to appear. It was primarily motors, which at that time often was referred to as “water engines”. It is not surprising that William George Armstrong – the inventor of the accumulator – also developed rotary machines. In the 1830’s, he invented a rotary pump with swiveling paddles, but later he focused more on a solution with oscillating pistons placed in line, connected to a crank shaft. Another somewhat similar design was developed by John Ramsbottom, who also invented the split piston ring, which is commonly found in piston machines even today. His motor was widely used in many different applications. The porting to the inlet and outlet (i.e. the commutation) was achieved with the oscillation of the pistons. Another very popular water engine was the Brotherhood engine, invented by Peter Brotherhood in the beginning of the 1870’s. It was a type of radial piston motor with three cylinders placed 120 degrees apart. It could be powered by either, water, steam, or compressed air. A rotary valve (similar to the valve plate used in e.g. axial piston pumps today) was used for commutation. In a paper from 1888 about the hydraulic power network in London, Edward B. Ellington wrote as follows about them: “they are too well known to require detailed description” [8]. It was also stated that the efficiencies were around 60-70 %. The brotherhood engine was a fixed displacement motor. However, variable displacement motors started to appear at this time too. John Hastie took the Brotherhood design and made it variable. For obvious reasons, this is usually referred to as the “Brotherhood-Hastie engine” [9]. Hastie also came up with a variable radial piston motor with oscillating pistons. His motor with automatic control is presented in his paper “On Water-Power Engines with Variable Stroke” from 1879 [10]. At that time, he had had at least one motor in operation for two years. Another radial piston motor with variable displacement was developed by Arthur Rigg during the second half of the 1880s. In the previously mentioned paper from Ellington, it is stated that a Rigg engine is used to drive a dynamo for electric lighting [8].

Until this point, focus has been on radial piston machines and machines based on crank shafts, and most of them have been designed for motor applications. However, in 1893, William Cooper and George Hampton patented a variable axial piston pump of swashplate design [11]. Notice that it was not the first swashplate pump (such pumps were already described by Ramelli in the 16th century), but it appears to be the first variable swashplate pump. In the application, the following sentence can be found: "Our invention relates to a pump adapted for use at either high or low speeds, and especially adapted for use with electric motors or other constant rotary power". The pump suffered from leakage due to non-compensated forces on the valve plate. The problem was, however, solved by Charles Manly, who introduced radial porting [12]. In the beginning of the 20th century, Harvey Williams and Reynold Janney from Waterbury Tool Company came up with several improvements of the swashplate pump, and they incorporated it in a hydraulic transmission, where they had one machine working as a pump and one as a motor [13], [14]. Furthermore, they propagated for the use of oil as the power transmitting fluid, which primarily only had been used in seed presses before [2]. Oil had the advantage of not freezing, offer better lubrication, and prohibit corrosion. Furthermore, at that time, there was a movement towards self-contained hydraulic systems. Fluid power networks were still around (the one in London one closed in 1977), but the electric grid started to outcompete them since the electric grid was more appropriate for longer transmission distances.

Waterbury Tool Company was not alone in developing transmissions based on oil in those days. Henry Selby Hele-Shaw did also work with such development. He came up with the so-called Hele-Shaw pump, which is a radial piston pump with variable displacement that can run as a motor too, and the principal design is still in production today. In an article in the magazine The Commercial Motor from 1912, it is stated that the Hele-Shaw pump could achieve efficiencies above 90 % [15]. Whether this is trustworthy can be argued. Nevertheless, the bent-axis machine also appears to date back to this period. In 1909, Francis Hector Clergue was given a patent on such a machine [16].

Even though oil-based fluid power started to emerge, pumps were naturally still developed for water drainage applications. Around 1910, Jens Nielsen invented the internal gear pump and co-founded the Viking Pump Company [17]. The pump was invented with the application quarry drainage in mind. A main selling point was that the pump was the ability to handle contaminated fluids. The company is still around, producing pumps for harsh applications, but internal gear pumps are nowadays also used in fluid power, where they are known for being quiet.

Another pump that is stated to be quiet is the vane pump. It can be understood that the vane pump has been around for quite some time since it was included already in Ramelli's book from 1588. However, in 1920s, Harry Vickers developed the balanced vane pump [18], in which the forces on the bearings are substantially reduced since it has two strokes per revolution and radial forces are thereby cancelled out.

At this point (i.e. about 100 years ago), most major commercial pump and motor types have been brought up. That includes, external and internal gear machines, balanced and non-balanced vane machines, radial, axial, and inline piston machines. Naturally, there has been quite some improvements of the machines over the years, but the principal ideas are in many aspects still the same. There are, however, some more recent concepts that are getting increased focus. One is the so-called Digital Displacement® technology, which saw light towards the end of the 1980's at the University of Edinburg [19]. Since then, it has been developed under the company Artemis Intelligent Power, which recently was acquired by Danfoss. The technology is based on piston machines, in which the commutation for each piston is electronically controlled. Thereby, individual pistons can be deactivated and hence the displacement controlled. Currently, pumps are available for costumers [20], but machines that can work as both pumps and motors are about to come. Danfoss is focusing much on the excavator market, but their machines have been tested in many other applications, such as transmissions for wind power plants. A main motivator for Digital Displacement is that the technology offers high efficiency even at low displacement fractions, which is not the case for conventional variable machines. It also has very low idling losses and fast response. Another advantage is that it can offer several pump/motors in one unit since pistons can be grouped to serve different actuators.

Another more recent technology is the so-called floating cup technology, invented by the company Innas. It appeared in the early 2000s, both as a pump [21] and a transformer [22]. It has been shown to be very good at low speeds, which is rare among conventional machine types, especially pumps. The floating cup technology has recently been commercialised by Bucher Hydraulics and it is applied in mobile machinery, amongst others in an electrified Mecalac excavator [23].

Additionally, there is a new piston-type pump called floating piston pump [24]. The pump type is, however, not yet commercially available.

ELECTRIFICATION

Since the mid-20th century, combustion engines have typically been used to power hydraulic systems in mobile machinery. In many applications, the combustion engines are now about to be replaced by electric machines, and batteries are often supposed to be used as energy storage, especially for smaller machines. This will likely affect both the general architecture of the hydraulic system and the requirements on the hydraulic machines. One reason is that energy efficiency becomes prioritized since the battery size should be minimized. Another reason is that the characteristics of electric machines are completely different than for combustion engines. For example, electric machines typically have the following properties:

- They can run in both directions.
- They can be controlled down to zero speed.
- They can transfer power in both directions.

This is very different from combustion engines, which usually run in one direction and have a comparatively limited speed range. They are also totally incapable of creating fuel from mechanical power. Furthermore, an electric machine is in general also much simpler and more compact than a combustion engine of comparative power rating. These aspects create headroom for new system architectures. Note that it in some cases also is likely that electro-mechanical actuators will replace hydraulic, but this will not be discussed here.

System Architecture

Most fluid power applications have several actuators that need to be controlled individually. Traditionally, the power is hydraulically distributed to the different actuators, and throttling valves are used to control the distribution. However, that is inherently inefficient, but it does not have to be that way – power can be controlled and/or distributed in other ways. In an electrified system, the power distribution can either be hydraulic, mechanical, or electric. This is exemplified in Figure 2.

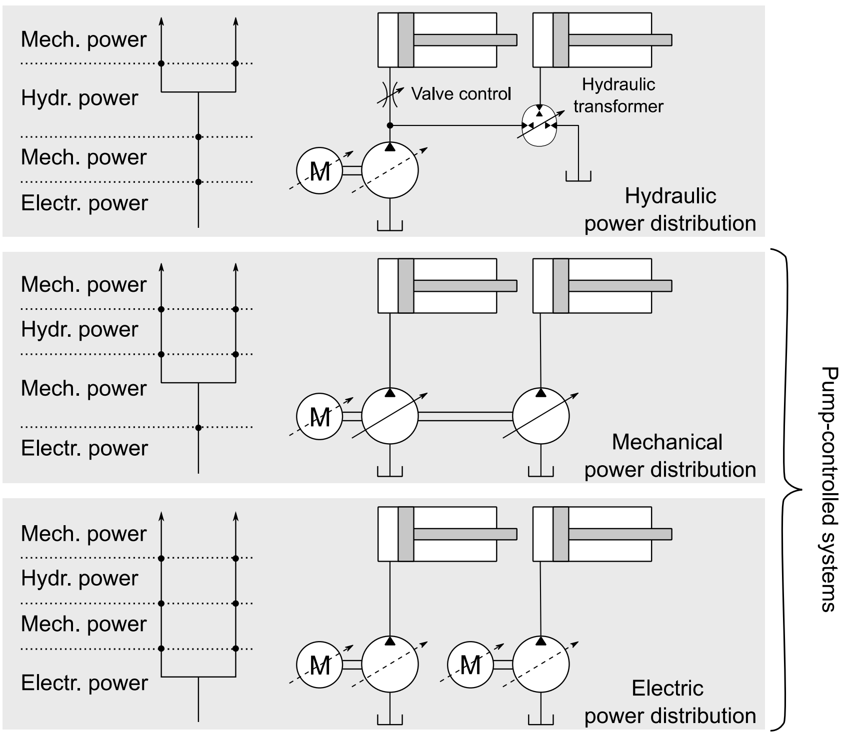

Figure 2 – Power distribution methods

For hydraulic power distribution, transformers can be used instead of valve control. Throttling losses can thereby be avoided, and energy recuperation can also be allowed. Transformers can either be based on rotary machines [22] or on fluid inertial effects [25]. To date, such solutions are, however, not commercially available. Another promising approach within hydraulic power distribution is to make use of multi-chamber cylinders and/or multiple pressure lines [26].

System architectures based on mechanical and electric power distribution are often referred to as pump-controlled systems. At a first glance, it can seem straight forward to design such systems. However, there are many possible solutions. An overview can be found in [27]. The concepts can be displacement controlled and/or speed controlled, they can be based on open or closed circuits, they can use one or more pumps per actuator, and they can be passively or actively controlled. The list of alternatives continues. The question that is left to answer in this paper is, however, how should the hydraulic pumps and motors be designed to match these future hydraulic systems?

THE FUTURE OF FLUID POWER PUMPS AND MOTORS

When considering systems with hydraulic power distribution, hydraulic motors are of high interest for rotary motions. However, these should preferably be displacement controlled, and have the possibility to go over-center (i.e. negative displacement). This to allow bi-directional motions. It is often also desired to have motors that can work as pumps to allow energy recovery. When it comes to linear motions, development on transformers is required. The primary pump in systems based on hydraulic power distribution does not necessarily have to be able to operate as a motor since accumulators often are used to store energy. Furthermore, it typically only needs to work at one or a few defined pressure levels.

When it comes to pump-controlled systems, there are, as stated above, many different possibilities, and each of them put somewhat different requirements on the hydraulic machines. However, in general it can be stated that the machines should be able to work as both pumps and motors. If the machine is supposed to work in an open circuit, only two quadrants of operation is required. If it is supposed to work in a closed circuit, four quadrants are necessary. The quadrants are defined by flow direction and pressure difference and notice that the flow direction principally can be varied with both the displacement setting and the rotational speed. However, since electric machines generally can run in both directions, it is reasonable to have a hydraulic machine that also works well in both rotational directions. Displacement control over-center can be considered as less relevant, assuming that speed-control is used. It should also be stated that it often is desirable to have a pressurized low-pressure side in pump-controlled systems, amongst others to avoid cavitation in motoring mode. The machines should be built to withstand that.

Furthermore, to avoid the need for too large electric machines, it is desired to increase the speed of the pumps. This to reduce the required displacement and thereby the required torque. However, notice that an increased speed might have negative impact of the noise from the pump. Variable displacement can also be used to downsize the electric machine. This is since a smaller displacement can be used at higher pressure levels. Smaller displacement settings can also be used to improve the efficiency at low flow rates, since the machines then can operate at higher speeds, where they typically are more efficient. However, hydraulic machines must still be better at low-speed operation since variable displacement cannot always be used. In fact, many of the most promising pump-controlled systems require two hydraulic machines for each actuator. For this to be commercially relevant, the design should be kept simple.

Currently, there is much research on integrating hydraulic machines into electric machines. This to offer compact and efficient solutions. Obviously, this is of interest for all architectures, and not at least for systems with electric power distribution, where multiple units are required.

CONCLUSION

Traditionally, hydraulic machines have typically had one specific role and the operating conditions have been quite bounded. This is about to change. To meet the requirements that comes with new system architectures, hydraulic machines must be able to work both as pumps and motors, and often in both directions of movement. They should be better at low speeds and at the same time allow higher speeds. Displacement control will still be of interest. Partly because if allows smooth motor control of systems with hydraulic power distribution, but also because it can be used to improve the efficiency and downsize electric machines in other types of systems, but the displacement control must be more efficient than it is in conventional machines. It is easy to write these sentences, but the future will tell how easy it to achieve the desired performance of the hydraulic machines.

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