The control of an open-circuit, floating cup variable displacement pump

Dr.-Ing. Peter Achten, Dipl.-Ing. Sjoerd Eggenkamp
INNAS, Nikkelstr. 15, Breda, The Netherlands E-mail: pachten@innas.com

Abstract

The floating cup principle is a general hydrostatic principle for both constant and variable displacement pumps and motors, as well as for hydraulic transformers. In this paper, the focus will be entirely on the control of the displacement of the variable 28 cc Floating Cup pump (FCVP28). The floating cup principle features two opposed swash plates, for which both angular positions need to be controlled in order to cover the entire range from zero to full displacement. The results of both extended numerical analysis as well as simplified linearized models will be compared to test results on a 28 cc FCVP. Special emphasis will be on the dynamic behaviour of the displacement control.

KEYWORDS: Floating cup, variable displacement, control

1. Introduction

The Floating Cup (FC) principle is a relatively new axial piston principle /1...5/. Unlike in bent axis and slipper type machines, the pistons are locked onto the main rotor i.e. drive shaft. Furthermore, the cylinders are detached and separated from the barrel: each piston has its own, cup-like cylinder, which is ‘floating’ on and supported by a rotating barrel plate. Piston rings are not needed; the piston crown has a cavity, which will make the piston expand to a same degree as the cylinder annex cup, thereby closing the gap between the piston and its paired cylinder under all circumstances.

The FC-principle is essentially a multi-piston principle. The number of pistons is typically somewhere between 24 and 30 pistons, which is three to four times as much as in current axial piston principles. The pistons are arranged in two rings, one on each side of the central rotor. The swash angle of the barrels is limited to about 8°.
In 2005, a variable displacement floating cup pump (FCVP28) was presented by INNAS /6/. The FCVP28 is an open circuit pump with a maximum displacement of 28 cc. The pump is designed for operating pressures up to 350 bar and has the same control options as conventional open circuit pumps, including a position feedback of the swash plates for power control.
This paper is about the control itself. Section 3 describes the general principle of the swash plate control. A special hydraulic control circuit is applied in the FCVP, which is described in section 4. Two simulation models have been developed: a straightforward linear model and a detailed sophisticated non-linear model. Section 5 describes the test results and compares these with the results from the simulation models.

2. The variable displacement FC-pump

There are several challenges to the design of the variable displacement floating cup pump. The first and biggest challenge is the supply of oil to and from the barrels via the swash plates. The barrels run on port plates, which are located on top of the swash plates. The lubricated interface between the rotating barrel and the stationary port plate is one of the most delicate design details of axial piston machines, acting both as a face seal and a thrust bearing. On each side of the pump, oil needs to be supplied to the low-pressure side, via the swash plate and the port plate to the barrel. During the pump stroke, the oil is forced to the high pressure side, through the swash plate to the channels and ducts in the housing.

Another bearing and sealing interface is on the backside of the swash plate, where the oil is passing from the housing to the swash plate and vice versa. Both sealing and bearing interfaces require a minimum deformation of the components, despite the high hydrostatic loads and possible temperature effects.
One of the advantages of the floating cup principle is the small maximum tilt angle of the swash plate: for the open circuit floating cup pump considered here, the swash plate position only needs to be varied between 0 and 8°. The relatively small angular variation facilitates the contact between the moving ports of the swash plate and the stationary ports of the housing.

In the FCVP28, both swash plate positions are varied and controlled. The control does not need to be simultaneous, but could also be sequential, having one swash plate rotating before the other. However, also if both swash plates are controlled in the same way, then the control angles do not need to be exactly equal at all times. In the end, the average angular position of both swash plates will determine the total displacement of the FCVP28. This average swash angle can simply be determined by a small and simple mechanism as shown in Figure 4. The mechanism causes the central pin to move up and down. The pin is connected to the optional control valve, and sets the position of the inner spool valve, thereby limiting the power output of the pump. This option is not further discussed in this paper.

![Power control option with a feedback of the average swash plate position](Fig. 4)

### 3. Swash plate actuation and position control

In the FCVP28, the bias springs and the bias pistons push the swash plates initially to the maximum swash angle. The torque of these pistons and springs is counteracted by the control pistons and cylinders annex cups (see Figure 5). Each swash plate has one bias piston and two control pistons and cups, which are essentially the same as the pistons and cups of the rotating group.
Fig. 5: One of the swash plates piston including the control pistons, the bias piston and the bias spring

The load on the swash plate bearing needs to be reduced to the minimum:

- Impact wear and brinelling are known issues for the bearing races of the swash plate. The wear can only be reduced by means of reducing the load;
- Bearing loads are rather unpredictable reaction forces, which make it much more difficult to minimize the structural deformation of the swash plates;
- Bearing loads create friction and stick-slip effects, which are difficult to handle in control systems. They limit the dynamic performance of the pump control.

In order to fulfil this requirement, several measures have been taken:

- Each barrel has an even number of cups and pistons: the FCVP28 has 24 pistons, 12 on each side, of which 6 pistons are always creating an axial load on the swash plate. This results in an almost constant axial barrel force, which can be balanced by the size and position of the bearing ports at the back of the swash plate;
• Each swash plate has two actuators, which are positioned in opposite directions. As a result, the actuators create a pure torque and there is no net axial force from the actuators acting on the swash plate;
• Hard end stops, to limit the minimum and maximum swash plate positions, are avoided. Instead, a hydraulic valve system is built to limit the swash plate system (see /7/ and /8/ for further details).

4. Damping the swash plate oscillations
The most important load on the swash plates comes from the rotating group of cups. But also the centrifugal forces and the potential friction forces create a torque load, which tends to tip the swash plate /9/. The torque is not constant but varies strongly as a result of the rotating movement of the barrels and the continuous variation between high and low pressure levels. This torque load is counteracted by the actuator or control pistons.

The variation of the torque load results in an oscillation of the angular position of the swash plate. This also occurs in conventional axial piston pumps /10/, but the oscillation behaviour will be somewhat different in the FCVP /7, 8/ due to the larger number of pistons, the even number of pistons instead of odd number of pistons and the much lower friction between the swash plate and its bearing.

In conventional pumps, the actuators act as dampers or shock breakers, thereby using the resistances in control valve to build up pressure in the control cylinders. Aside from the oscillation damping, the resistances used in the valve also define the dynamic behaviour of the pump control. Figure 6 shows the extended and simplified representation of the pump control. The control can be regarded as a series of a variable and a constant resistance. The circuit acts as a pressure divider, which is needed for the variation of the control pressure. But it also uses the resistances to damp the swash plate oscillation. The combined functionality sets limits to both the control and the damping function.
In the FCVP, the double, mirrored construction is used to split these two functions. Figure 7 shows the simplified hydraulic circuit. The pair of actuators of each swash plate is represented in this figure by just a single piston, one for the left swash plate, and for the right. The oscillation of the left swash plate is out of phase with the oscillation of the right swash plate (Figure 8). Oil is therefore transferred from the left actuator to the right, and vice versa, thereby passing the resistances $R_5$. The construction offers much better opportunities for optimisation than the conventional control valve.
Fig. 8: Swash plate oscillation and actuator pressure for the two swash plates of the FCVP, measured at 200 bar and 1500 rpm (see Figure 2 for the definitions of mount and cover side).

5. Swash plate control
The FCVP28-prototype is equipped with a standard DFR-valve of a Bosch Rexroth A10VSO-pump. The valve is integrated in the hydraulic circuit shown in Figure 7, in which resistances $R_3$ and $R_4$ represent the resistances of the DFR-valve. The
resistances indicated with $R_5$ are optimized for damping the swash plate oscillations. These resistances can be found again in the diagram of the test circuit (Figure 9.). In this figure, the floating cup pump is depicted as a combination of two variable displacement pumps, the left side being the mount side, and the right side the cover side.

**Fig. 9:** Test circuit. The FCVP28 is illustrated as a combination of two variable displacement pumps, having a common shaft and housing.

The flow control part of the DFR-valve is set at a $\Delta p$ of 20 bar. The pump flow is delivered to two variable resistances $R_1$ and $R_2$ in series, followed by a pressure relief valve. A 2/2-valve is included parallel to $R_1$. When this valve is opened, the pump flow bypasses this resistance. By doing this, the test mimics a sudden change in the flow demand. The flow-control part of the DFR-valve responses to the change, and increases or reduces the average pressure in the actuators. This results in a change of the swash plate positions and, consequently, in a change of the flow through the metering resistance $R_2$ or the combines resistance of $R_1$ plus $R_2$. The bypass valve is opened manually. The opening time is estimated to be 0.1 seconds.

Figure 10 shows two test results at a pump pressure of 200 bar and a rotational speed of 1500 rpm. Both the pump discharge pressure and the rotational positions of the
swash plates are shown. The measurements show that both swash plates respond almost synchronically: the swash angle variation on the mount side is almost identical to the swash angle variation of the cover side. The swash plates are only linked together via the hydraulic circuit as shown in Figure 9.

**Fig. 10:** Measured and simulated pump pressure and swash angle at 200 bar and 1500 rpm. The time scale on the horizontal axis is 0.1 second per division.

Both a linear and a detailed non-linear model have been developed. The linear model is a straightforward model of the FCVP28, based on similar algorithms as have been applied for conventional slipper type pumps. In order to account for the swash plate
oscillations and other more detailed phenomena, an extended non-linear model has been conceived. The basic outlines of this model are described in earlier literature [11].

As can be seen in Figure 10, both models are adequate to predict the general dynamic behaviour of the pump. The most important differences relate to the variation of the discharge pressure as a response to the switching of the bypass valve of resistance $R_1$.

6. Conclusion and future work

Tests and analysis of a prototype of a 28 cc variable displacement floating cup pump (FCVP28) have proven that it is possible to control both swash plates with a single pump control. The swash plates respond almost identical to the signals of the control valve. A new configuration has been applied in which the damping function of the control valve can be isolated of the control function itself. The response time of the FCVP28 is about 0.1 seconds. In this measurement we have taken the DFR-valve from Bosch Rexroth as it is.

In a next phase of the development, the simulation models will be used to modify and optimize the design of the control valve and its parameters.

7. References


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Mr. Chairman, ladies and gentleman, good afternoon.

Perhaps, you expect me to give a very detailed, technical presentation about pump control. Well, in that case I have to disappoint you. I will not bother you with linearized models, Laplace transformations or Nyquist diagrams.

Of course, I will be most happy to discuss these later on with you, but, for today, my presentation is about…
...innovation.
There are many types of innovations. A first category, are the so-called ‘incremental innovations’. These are relatively small improvements of an already existing technology.

During this conference, many marvelous examples are presented, which belong to this category.

The advocates and supporters of this type of innovation are of the opinion, that many incremental improvements and small evolutionary steps are sufficient to secure the future of the pump industry.
I disagree with that. I don't see the swash plate as ‘the key to the future’.

Instead, I believe that current hydrostatic principles have reached their limit, and that a radical innovation is needed to bring the hydraulic industry forward, to get it out of its isolated position and out of its market niches.

I believe that new design principles are needed, to finally address the demands of todays and tomorrows customers worldwide.

And I am convinced, that only radical, new solutions will allow growth into new territories, markets and applications.
But, before discussing this in more detail, let me take a step back with you, and have a look at the evolution and lifecycle of the swash plate principle.
This is the oldest design I have found, of a machine with pistons and slippers running on a swash plate. It is a patent for a steam engine.

This design belongs to the very origins of the swash plate principle.
This design, for example, from 1923, shows all the elements of a modern pump:

- the swash plate, which can be rotated to change the displacement;
- the pistons and slippers;
- the rotating barrel, which is driven by the shaft;
- and even a charge pump, to avoid cavitation.
The same elements can be found in today's in-line axial piston pumps:

- a swash plate;
- a group of pistons, each having its own slipper;
- a rotating cylinder barrel, driven by the shaft;
- and –if needed– a charge pump.
The previous three examples represent the various lifecycle phases of the swash plate principle:

- the incubation phase;
- the diffusion phase;
- and, finally, the maturity phase.

This diagram shows the improvement of the product performance over time.
A similar diagram can be drawn, showing the total product sales per year.

As before there is:

- an incubation phase;
- a diffusion phase, which is characterized by its strong growth;
- and a maturity phase.

The diagram looks the same as the previous product lifecycle diagram. But, there is an important difference: this diagram has a fourth phase: the decline.

The decline happens when a new solution is offered to the market, which is outperforming the old technology.
Yet, what happens when a technology, in this case the swash plate principle, has become mature and maybe even out of date? What is the response of current companies, and what is wrong with it? Let me try to explain this by means of a simple metaphor: a house.
This is a picture of Holland Island House, close to Washington DC in the US. The house is about as old as the swash plate principle. It has been a wonderful place to live, and many generations grew up in this house.

But it is a bit worn down and sleazy, don’t you agree? Now, suppose, you are still in the business of selling this ‘product’ (and remember, this is a metaphor!). What can you do?
Of course you can scare away the birds, rebuild the chimney of the right wing…
…perform numerous FEM-analysis and CFD calculations…
…have a new roof and repaint the walls.

And if that is still not enough, you can ultimately pimp it up, with some of the latest electronic devices and modern means of communication.
But, all this does not solve the key problem. It is still an old house with a rotten foundation that can not be replaced.
Now, considering that this was a metaphor, what does it tell about the life cycle and future of the swash plate principle? What exactly are its foundations and how rotten are they?

swash plate limitations
One of the key problems is of course the high load in the contact between the piston and its cylinder. The full hydrostatic power is transferred via these sliding contacts. This is most certainly, fundamentally wrong.
Piston pumps and motors are positive displacement machines. They always have sliding interfaces, and therefore always cause friction and wear. But, it is the combination of strong loads and high relative velocities that is the prime cause of high losses and strong wear in these machines.
Dead volumes can also contribute to significant losses. The dead volume can be decreased, simply by having solid pistons. But this strongly increases the piston mass and the centrifugal forces, which, again, results in stronger friction losses and higher wear, but also in an increased tipping torque of the barrel.
This again, increases the required axial bearing force of the barrel, and thus further escalates the friction between the barrel and the port plate.

- Strong lateral loads in sliding interfaces;
- High velocities in sliding interfaces;
- Large dead volumes;
- Strong barrel spring force;
The swash plate principle is also characterized by a very limited number of pistons, typically being nine. The small number of pistons is a fundamental cause of noise, large flow and pressure pulsations and strong torque variations.
So...these are the rotten foundations, which are inherent to the swash plate principle. And let me add another one:

- Strong lateral loads in sliding interfaces;
- High velocities in sliding interfaces;
- Large dead volumes;
- Strong barrel spring force;
- Low number of piston/cylinders
The control of the swash plate position is extremely inefficient. High losses occur in the control valve, and often also in the swash plate bearings.

I am very pleased that finally some research is being performed in this direction. Yesterday, Mr. Jan Lux from IFAS gave an interesting presentation about this most urgent topic.
Mr. Lux also showed that there are possibilities to reduce these losses, for instance by means of electric actuators and modern electronic controls.
But, in the mature phase of a product cycle, these improvements are often offset by other detrimental effects: this is the so-called waterbed effect.

As an example: it is possible to reduce the losses of the displacement control, but the solution easily doubles or triples the costs of the total pump.
what’s wrong with current pump controls?

In order to have a better understanding of the problems of the pump control, we have to go to the basement, to the very foundation of the variable displacement swash plate pump.
This cross section shows a –more or less– standard solution for open circuit pumps. The most important components are:

- the rotating group;
- the swash plate;
- the bias piston and spring;
- the control piston;
- and –of course– the control valve.
The control of a pump can be simplified by showing just two resistors in series.

Pump controls are essentially pressure dividers, similar to the inefficient resistive dividers in the old days of the electric industry.
Now, let’s have a detailed observation and better understanding of what actually happens inside the pump. The swash plate rotates around the indicated axis.

The red arrow represents the resultant force of all the pistons of the rotating group. This force creates a torque load on the swash plate.
The force moves up and down, while the pump rotates. As a result, the torque load on the swash plate is not only very strong, but also very dynamic.

For a rather small 40 cc pump, being operated at 300 bar, this lateral torque can already become about 200 Nm. Driven by this varying torque load, the swash plate starts to oscillate. And, as you can see, this oscillation can be quite hefty.
For a correct operation of the pump, the oscillation amplitude needs to be minimized. There are various options:

- you can either create a lot of friction between the swash plate and the cradle bearing;
- or you can use the resistances of the flow control and let the control piston double as a shock absorber.

But, no matter what solution you choose, all of this is friction, and results in energy dissipation and efficiency reduction. And to make things even worse, in addition, there is a constant flow loss across the pump control.

Both effects, the damping and the flow losses, have a strong negative effect on the efficiency. In the best point, this loss is often as high as 5%. But for average operating conditions, these losses often amount to 10, 20% or even higher.
It is absolutely clear that this situation needs to be solved. We need a solution that reduces the losses of the control system, without deteriorating the dynamic behavior of the pump, or the durability of the swash plate bearings, and without causing an explosion of the costs of the pump.

Whatever the solution will be, it will not be an incremental innovation. It will be a big step, a radical innovation.
The variable displacement floating cup pump is certainly such a radical innovation.
The floating cup principle features a double, more or less mirrored construction. It has two swash plates, both oscillating in counter phase.
The swash plates have a close to 100% balance of the axial hydrostatic forces. As a result, the friction of the swash plate bearings is extremely small.
Furthermore, in the new design, the damping and control functions are separated. The pump control itself is optimized for the control function only, without needing to make a compromise for the oscillation damping.

Due to the minimal friction of the swash plate bearings, the actuators can be small. As a result, only small amounts of oil need to be supplied for changing the swash plate positions.
With the new design we achieved:

- a strong reduction of the bearing load;
- and small oscillation amplitudes.
- The new control is also fast and stable in the full range of operating conditions;
- But, most importantly, we managed to decimate the losses of current pump controls.

- strongly reduced bearing load
- small oscillation amplitudes
- fast and stable displacement control
- decimation of the losses of current pump controls
In the previous years, I have had many discussions with the industry about innovation. Very often, I am told—or maybe I should say, I am warned—that the hydraulic industry is a very conservative industry, and that it is very difficult, if not impossible, to achieve any innovation at all.

what are we waiting for?
But, if there is any industry that should be conservative, than it is the civil aviation industry. Nevertheless, this industry constantly renews itself. In the past 100 years it has had at least 4 radical technology changes or revolutions.
The hydraulic pump and motor industry has had just one. And in the past 30 years nothing happened.
Let us have a last view at our metaphor, the Holland Island house. This house is one of the first victims of climate change.

Since the house was build, the sea level has risen by about 25 cm. Heavy storms have eroded what was left of the island.

To rephrase this in terms of the fluid power industry: our market has changed in the past century, and what used to be a perfect solution -the swash plate principle- is not fit for the new environment anymore.
This was the Holland Island house shortly after the previous photo. In terms of the pump industry: this could be your situation in a few years. Do something about it!
What... are you waiting for?