HPU Design with Piston Accumulator: An engineering approach

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Abstract

For all kinds of systems, a Hydraulic Power Unit (HPU) is used which is equipped with a piston accumulator and pressure vessels filled with nitrogen. For systems with a high peak power, but where this peak power is only required over a small part of the work cycle, the HPU can be chosen smaller. When the power from the HPU is not sufficient, the piston accumulator will also deliver power to the system. When the required power is then lower than what the HPU can deliver, the HPU will fill the piston accumulator again.

In this article a design method is shown to choose the power of the HPU based on the average required power. It will also show how the volume of the piston accumulator and the pressure vessels is chosen. A simulation at the end will give more insight in the design and the responses of the system.

Note that this calculation is based on power to show the behaviour of accumulators, not on actual cylinder dimensions. This means that the actual installed power is larger, as the hydraulic power is determined by the multiplication of flow and pressure. When the HPU is on a constant pressure while the load does not demand the maximum pressure, power is lost.

For most hydraulic equipment, the HPU will deliver power to multiple users. Some users will run simultaneously, for others the maximum power will be determined by one user. In this article the maximum case is assumed to be when one user is running at full capacity, in other cases the maximum power needs to be determined.

Normally the HPU is designed to meet the highest load case, to meet the specifications of the equipment. In the case where the maximum required power fluctuates over the work cycle, the HPU can be chosen smaller, in order to make the HPU cheaper and lower the installed electrical power. When the power of the HPU is lower than the required power, an accumulator can deliver the power difference. The costs of the (piston) accumulator and pressure vessels can be (much) smaller than installing extra or larger pumps.

In this article an example is used to show how it is calculated. First the required mechanical power is calculated, where a force and speed is assumed. For this article it is assumed that the system will not regenerate power. The forces of the actuator are delivered by the HPU, and the load will not drive the actuator. In for instance heave compensation systems this can be the case, but this is not included here.

When the power is known, the installed power of the HPU is chosen and the piston accumulator and pressure vessels can be calculated.

At the end a simulation is made to give the reader more insight in the behavior of the HPU and piston accumulator.

The example assumes a cylinder which pushes and pulls on a mechanical system, as shown in figure 1. The formulas assume SI units. In case other units are used, the conversion should also be included.

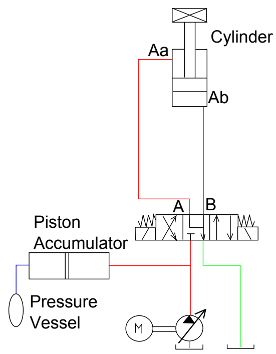

Figure 1: The system which is used as an example in this article, including the piston accumulator and pressure vessel.

A piston accumulator can be used at HPUs which power secondary controlled hydraulic systems or constant pressure systems. It is important that the system is a constant pressure system, because otherwise the pressure in the pressure vessels needs to be adapted constantly, which will make the control much more difficult and adapting the nitrogen pressure will require time.

1 Power Calculation

When a system is designed, the maximum forces and required operational speed is known. As an example a cylinder is chosen which pulls and pushes on a mechanical system. The example is based on a dynamic adjuster, which has very high forces and thus also a very high power demand. The force varies as a sinusoidal signal. The maximum pulling force is $F_{pull} = 7620[kN]$. The maximum pushing force is $F_{push} = 5120[kN]$. The period time is $T = 7[s]$ for this example ($\omega = \frac{2\,\pi}{T}$). In the top graph of figure 2 the force is shown. The force is calculated using:

$$dF = F_{maxpush} + F_{maxpull} \tag{1}$$

$$F = \frac{F_{maxpush} - F_{maxpull}}{2} + \frac{dF}{2}\, sin(\omega\, t) \tag{2}$$

Mind here that the forces $F_{maxpush}$ and $F_{maxpull}$ have an opposite sign, because these act in the opposite direction.

The position (x) will also vary as a sinusoidal, which means that the velocity ($\dot{x}$) can be determined by differentiating the position. The velocity and position are shown in the middle graph of figure 2. The position and velocity are determined as follows:

$$x = A\, sin(\omega\, t) \tag{3}$$

$$\dot{x} = \omega\, A\, cos(w\, t) \tag{4}$$

The power can be calculated by multiplying the force and velocity. Note here that the force is always provided by the HPU, so the power is the absolute value of the multiplication:

$$P_{total} = |F\, \dot{x}| \tag{5}$$

The average value of the power shows the minimum power which needs to be installed on the HPU. The average value is calculated as follows:

$$P_{average} = \frac{1}{T} \int_0^T P\, dt \tag{6}$$

The power as well as the average value is shown in the bottom graph in figure 2. If the power is less than the average power, the HPU is not able to deliver the power continuously, which means that the delivered power will be less and the system will not meet the specifications. For this specific example the average power, which is the minimum required HPU power, is $P_{average} = 1134[kW]$. This is about 51% of the peak power of $2207[kW]$.

In this article an HPU is chosen of $1500[kW]$ (68% of the peak value), which is more than the average value. This will lower the requirements on the piston accumulator.

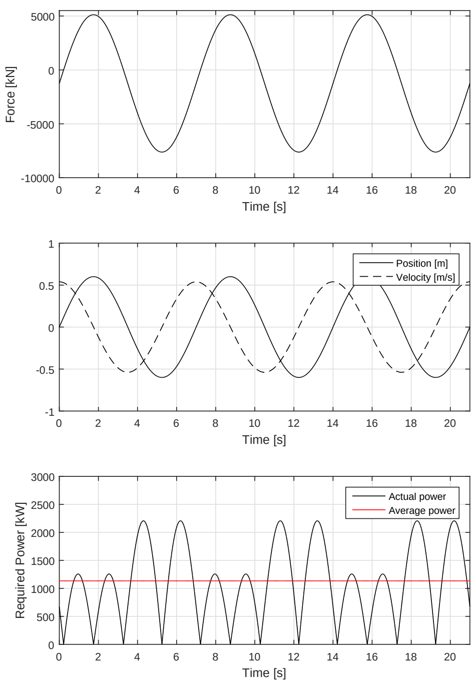

Figure 2: The graphs show the force, speed and power from top to bottom. All graphs show three cycles.

2 Design of the Piston Accumulator and Pressure Vessels

2.1 The Theory

The piston accumulator separates the oil of the hydraulic system from the nitrogen in the pressure vessel. The pressure vessel provides a certain volume of nitrogen, required to prevent the pressure of the nitrogen system to drop below the minimum required pressure.

In the previous section the required power and the HPU power is calculated. Using these two values, the piston accumulator can be calculated. The required flow from the HPU and accumulator can be calculated:

$$Q_{req} = \frac{P_{actual}}{p_{design}} \tag{7}$$

Note here that this flow is only valid for an optimised cylinder. In reality the cylinders are often slightly larger, which means that the flow of the cylinder will also be larger than calculated here. But to show the behaviour and calculation of the accumulator, this will be assumed in this article.

The HPU will deliver the flow up till the maximum flow is reached. The maximum flow can be calculated by dividing the installed power by the pressure setting of the pump. The difference between the required flow Q_{req} and the flow of the HPU Q_{HPU} will be delivered by the piston accumulator. The volume over one cycle can be calculated by the integral, or more simplistic with a the sum of a time calculation:

$$V_{diff} = \frac{1}{n_{cycle}} \int_{t_1}^{t_2} (Q_{req} - Q_{HPU})\, dt \tag{8}$$

$$\approx \frac{1}{n_{cycle}} \sum_{t_1}^{t_2} (Q_{req} - Q_{HPU})\, dt \tag{9}$$

Explanation of the variables	
V_{diff}	Volume difference, to be delivered by accumulator
n_{cycle}	Number of cycles in the calculation
Q_{req}	Required flow by the system
Q_{HPU}	Flow by the HPU

The volume difference is considered to be the minimum volume of the piston accumulator, to make sure the piston accumulator will not reach end of stroke position during operation. When one cycle has two peaks, but these peaks are very far apart, the piston accumulator can even be chosen smaller. This is due to the fact that the time between the two peaks the HPU has the chance to fill the piston accumulator again.

For the calculation of the volume of the pressure vessel, an adiabatic process is assumed. This means that the process of supplying flow to the system and being filled up by the HPU is quite fast (within one minute), so that there is no heat exchange with the environment. From the adiabatic process, the pressure vessel volume can be calculated:

$$p\,V^k = CONSTANT \tag{10}$$

$$p_{min}\,(V_{N2} + V_{diff})^k = p_{design}\,V_{N2}^k \tag{11}$$

$$V_{N2} = \frac{V_{diff}}{\sqrt[k]{\frac{p_{design}}{p_{min}}} - 1} \tag{12}$$

Explanation of the variables	
p	Pressure
V	Volume
k	Adiabatic constant, 1.6 for high pressure
p_{min}	Minimum pressure in the system
V_{N2}	Volume of the pressure vessel
p_{design}	Working pressure of the system

2.2 Solution of the example

As working pressure $p_{working} = 300 10^5 [Pa]$ $(= 300[bar])$ is assumed. The minimum pressure in the system is assumed to be $p_{min} = 270\ 10^5 [Pa]$ $(= 270[bar])$. This means that for this case the cylinder must be calculated at maximum $270[bar]$ to make sure it can deliver the required force even when the pressure drops due to the use of the accumulator. Keep in mind that if the maximum velocity and force have a peak at the same time, the fluid friction in the piping should also be taken in account. Luckily this is often not the case, just as in this example.

For the example in this article, the volume difference for a $1500[kW]$ HPU is just over $0.07[m^3]$ $(70[ltr])$. In practice this will become a medium separator of $100[ltr]$.

The required pressure vessel volume is just over $1[m^3]$ $(1000[ltr])$. In practice this would mean that the pressure vessel is 1050 or $1100[ltr]$. This can be optimized with simulations, because there is some time between the peak values, as shown in figure 2. During this time the HPU fills the piston accumulator again. This calculation is more conservative, because it takes all flow from the accumulator during one cycle. Optimizing should however be done with care, because when the piston accumulator is at the end of stroke, it will affect the speed and thus the cycle time.

3 Simulation

For the simulation there are two scenarios: One is where the piston accumulator is completely filled and the HPU can deliver the required flow, the other is when the HPU cannot deliver the required flow (so at a peak) or when the HPU is filling the piston accumulator again. First step is to calculate the required power (P_{req}):

$$P_{req} = |F\,\dot{x}| \tag{13}$$

$$P_{req} = (\frac{F_{maxpush} - F_{maxpull}}{2} + ... \tag{14}$$

$$\frac{F_{maxpush} + F_{maxpull}}{2}\,sin(\omega\,t))\ (\omega\,A\,cos(w\,t))$$

3.1 HPU has sufficient power

In this case the HPU delivers the required flow and the piston accumulator is pressurized at working pressure. The pressure in the system is equal to the working pressure of the HPU and the piston accumulator does not deliver power to the system. The variables are calculated as follows:

$$Q_{pump} = \frac{P_{pump}}{p_{design}} \tag{15}$$

$$p = p_{design} \tag{16}$$

$$V = V_{N2} \tag{17}$$

$$P_{N2} = 0 \tag{18}$$

3.2 The piston accumulator delivers power

In this case the HPU does not deliver sufficient flow and the piston accumulator delivers the flow which is required to meet the specifications. The HPU runs at full capacity and the flow is the maximum flow it can deliver. The nitrogen volume is dependent on the amount of flow which is delivered to the system or how much the HPU has filled the piston accumulator again. The pressure can be calculated using the adiabatic process between the time steps. The variables are determined between the time steps of the calculation, where a 1 is the previous time step and a 2 is the current time step. The time step is indicated by

dt. The calculations are as follows:

$$P_{pump} = P_{max} \tag{19}$$

$$Q_{pump} = \frac{P_{max\,HPU}}{p_{design}} \tag{20}$$

$$V_2 = V_1 + \left(\frac{P_{req}}{p_{design}} - Q_{pump} \right) dt \tag{21}$$

$$p_2 = p_1 \left(\frac{V_1}{V_2} \right)^k \tag{22}$$

$$P_{N2} = \frac{V_2 - V_1}{dt} \, p_2 \tag{23}$$

3.3 Simulation results

In figure 3 the simulation results are shown. In the top left graph the power is shown. The black line shows the required power, and is the same as figure 2. The power delivered by the pump is shown in red. At the peaks the power drops a bit, because the pressure drops a bit. It is also clearly visible that the pumps deliver full power when the piston accumulator is being filled up again. The blue line shows the power delivered by the accumulator. If the power of the accumulator is negative, the HPU is filling the accumulator. The purple line is the actual delivered power by the HPU plus the accumulator. At the peaks this power is slightly lower due to the lower pressure in the system.

In the top right graph the flow of the pump and piston accumulator is shown. The black line shows the flow from the pump. At the peaks the flow of the pumps is maximum at 3000[lpm]. The red line shows the flow from the piston accumulator. When it is negative, the HPU fills the piston accumulator.

On the bottom left graph the nitrogen volume is shown. The black line shows the actual gas volume. From the shape it is clear that between the two peaks the HPU fills the accumulator again. The red line shows the maximum gas volume due to the volume of the piston accumulator. This cannot be exceeded and when it does, the pressure will drop and the system will not meet the specifications.

On the bottom right graph the pressure is shown. As stated before, the accumulator can be optimized, because the pressure does not drop to the minimum of 270[bar].

The used Matlab code is shown below. This is included to help the reader to reproduce the results when a simulation is desired. Please note that some variables are not in SI units, which explains the factors included in the Matlab code. On request the full Matlab code can be supplied.

```
for tt=0:dt:3*T
    j=j+1;
    tt1(j)=tt;
    % Calculate the required power Pr [W]
    Pr(j)=abs(((Fmaxpush-Fmaxpull)*10^3+...
                      dF/2*sin(w*tt))*(w*A*cos(w*tt)));
          % Now include the two cases
    if Pr(j)<=Pmax*1000 && p(j-1)>=phpu*10^5;
        Pp(j)=Pr(j);                % [W]
        Qp(j)=Pr(j)/phpu/10^5;      % [m^3/s]
         p(j)=phpu*10^5;            % [Pa]
         V(j)=V(j-1);               % [m^3]
         if V(j)>=(Vms+Vbott); V(j)=(Vms+Vbott);end
         Pn2(j)=0;                  % [W]
    else %Pr(j)>Pmax*1000 && V(j-1)<=(Vms+Vbott);
        Qp(j)=(Pmax*600/phpu)/60/1000;% [m^3/s]
         V(j)=V(j-1)+(Pr(j)/phpu/10^5-Qp(j))*dt;%[m^3]
         p(j)=p(j-1)*(V(j-1)/V(j))^k;% [Pa]
         if V(j)>=(Vms+Vbott); V(j)=(Vms+Vbott);p(j)=0;end
        Pp(j)=Qp(j)*p(j);             % [W]
        Pn2(j)=(V(j)-V(j-1))/dt*p(j);% [W]
    end
end
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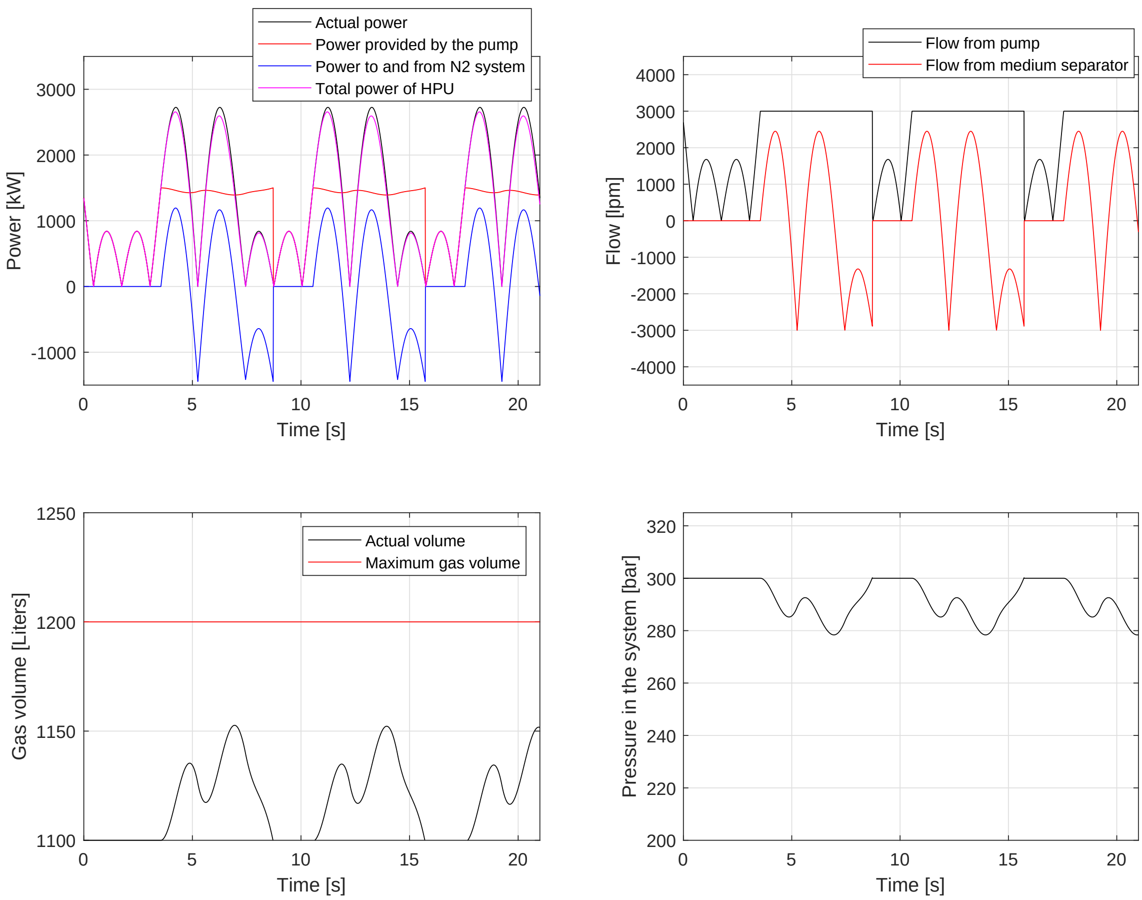

Figure 3: Several plots of the simulation: Top left graph shows the power, top right graph shows the flow from the HPU and the accumulator, bottom left graph shows the nitrogen volume and the bottom right graph shows the pressure in the system.