A new energy saving load adaptive counterbalance valve

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Abstract

The paper shows standard circuits with load reactive and non load reactive counterbalance valves. A Matlab simulation based on a linear model for the circuit with load reactive counterbalance valves shows what parameters have a significant influence on the stability of the system. The most important parameters of the counterbalance valve that influence the stability are pilot gain and relief gain. The factors describe how pilot pressure and load pressure affect the flow across the counterbalance valve. A new counterbalance valve (patent pending) has the pilot gain and relief gain required for stability only in operating ranges that require the parameters for stability. When the load is not moving or the counterbalance valve is not required for positive (non overrunning) loads, the new valve has a higher pilot ratio, which means that the valve opens further at lower inlet pressures. The new counterbalance valves saves about 30% power compared with a standard counterbalance valve that has the same parameters for stability when it is lowering an overrunning load. The standard counterbalance can be replaced with the new load adaptive valve in the same cavity. The paper shows test results and the design of the valve.

KEYWORDS: Counterbalance, load holding, energy efficiency, stability, simulation

1. Load reactive versus non load reactive counterbalance valves

Counterbalance valves are often used in the return line of cylinders or motors to prevent uncontrolled overrunning of the load and to ensure a leak free positioning of the actuator when the directional valve is in a center position. **Figure 1** shows the two basic circuits.

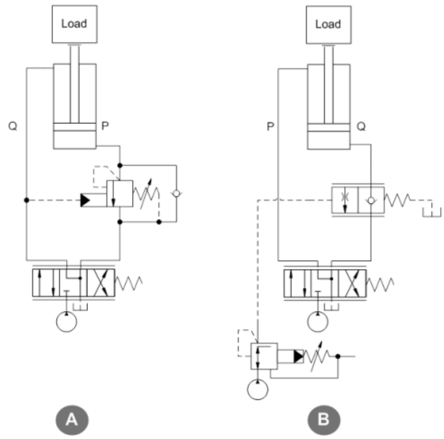


Figure 1: Circuits with two types of counterbalance valves

Circuit A uses a directional or proportional valve to control the flow to the cylinder or motor. The counterbalance can be seen as a relief valve that preloads and limits the pressure in the return line. Circuit B uses a pressure reducing valve (not shown) to control the pressure on the inlet side, or the directional valve connects p to a low pressure source. The non-load reactive counterbalance valve in the return line functions as a flow control valve piloted from an additional pressure control valve. That circuit is more stable than circuit A since the counterbalance valve sees a constant pilot pressure that doesn’t change with the speed of the cylinder, but the circuit is also more expensive and the counterbalance valve has no built in relief function. The counterbalance valve in this paper is a load reactive counterbalance valve, typically used in circuit A.

Figure 2 shows a typical circuit with a load reactive counterbalance valve in the return line. The stability of the circuit can be calculated based on two equations that describe the pressure build up in both sides of the cylinder (1) and a third equation that describes the force balance of the cylinder piston with attached mass (2).

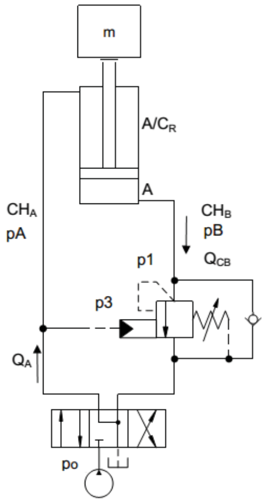


Figure 2: Typical circuit with a load reactive counterbalance valve

$$\dot{p} = \frac{1}{C_H}(\text{in flow - out flow}) \tag{1}$$

$$mcdot\ddot{x} = p_A * A / CR - p_B * A \tag{2}$$

2. Linear model and calculation of stability (Hurwitz criterion)

The parameter in the linear model that varies more than all others with the operating point is the change in flow per pressure drop across the directional valve. The flow across the directional control valve or proportional valve:

$$Q_{AOP} = \alpha_D * D^2 * \sqrt{\frac{2*(p_0 - p_A)}{\rho}} \tag{3}$$

can be linearized. G_{DCV} describes the change in flow per change in pressure differential

$$G_{DCV} = \frac{dQ}{d\left(p_0 - p_A\right)} = \frac{\alpha_D * D^2}{\sqrt{2*\rho*\sqrt{p_0 - p_A}}} \tag{4}$$

The flow across the directional valve is

$$Q_A = Q_{AOP} + G_{DCV} * (p_0 - p_A) \tag{5}$$

with Q_{AOP} the flow in the operating point calculated from the nonlinear orifice equation (3). The flow across the counterbalance valve is a function of pilot pressure (in the circuit

p_3 on port 3 of the counterbalance valve which is identical with the inlet pressure p_A while p_1, the pressure on port 1, is identical with p_B.

$$Q_{CB} = G_{pilot} * p_A + G_{relief} * p_B \tag{6}$$

The equations can be combined to describe the system in a matrix form

$$\begin{pmatrix} \dot{p}_A \\ \dot{p}_B \\ \ddot{x} \end{pmatrix} = \begin{pmatrix} -\frac{G_{DCV}}{C_{HA}} & 0 & -\frac{A}{C_{HA} * C_{HB}} \\ -\frac{G_{Pilot}}{C_{HB}} & -\frac{G_{relief}}{C_{HB}} & \frac{A}{C_{HB}} \\ \frac{A}{CR * m} & -\frac{A}{m} & 0 \end{pmatrix} * \begin{pmatrix} p_A \\ p_B \\ \dot{x} \end{pmatrix} \tag{7}$$

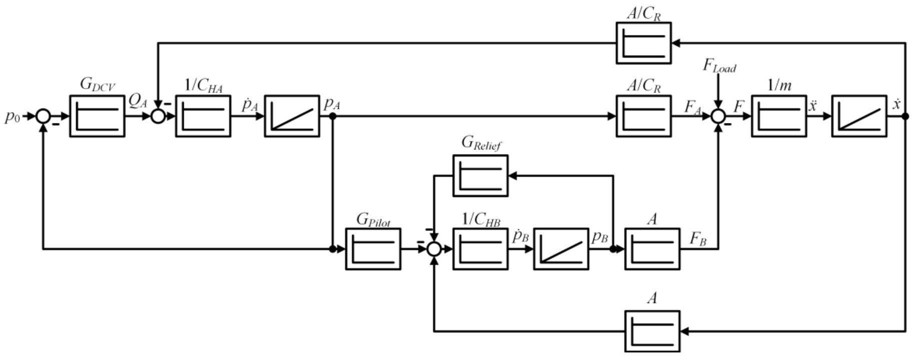


Figure 3: Block Diagram of the 3rd order model

Figure 3 shows the block diagram of the model. The corresponding 3rd order differential equation describes a stable system if the coefficients of the characteristic equation met the Hurwitz or Routh criterion (see /1/). That leads to:

$$\frac{C_{HA}}{C_{HB}} + \frac{G_{DCV}}{G_{relief}} \frac{C_{HB}}{C_{HA} * CR^2} + \frac{m^2}{A^2} \left(\frac{G_{DCV} * G_{relief}}{C_{HB}} + \frac{G_{DCV}^2}{C_{HA}} \right) \quad > \quad \frac{G_{pilot}}{G_{relief} * CR} \tag{8}$$

and

$$\frac{G_{DCV}}{C_{HA}} + \frac{G_{relief}}{C_{HB}} \quad > \quad 0 \tag{9}$$

and

$$G_{DCV} * CR^2 + G_{pilot} * CR + G_{relief} > \quad 0 \tag{10}$$

Equation (10) describes the 3rd Hurwitz criterion under the assumption that $\frac{G_{pilot}}{G_{relief} * CR}$ is positive. Equation (8) shows:

1. Two parameters of the counterbalance valve affect the stability: G_{pilot} which is the change in flow per pilot pressure change and G_{relief} the change in flow per load pressure change. The pilot gain G_{pilot} needs to be low for stability, which means that valves with a low pilot ratio and a low nominal flow (restrictive) valves improve the stability. The pilot ratio of counterbalance valves is the ratio of the effective area for pilot pressure divided by the effective area for load pressure. A pilot ratio of 3 means that a pilot pressure 10 bar reduces the setting by 30 bar. In equation (8) the ratio of pilot gain and relief gain is identical with the pilot ratio:

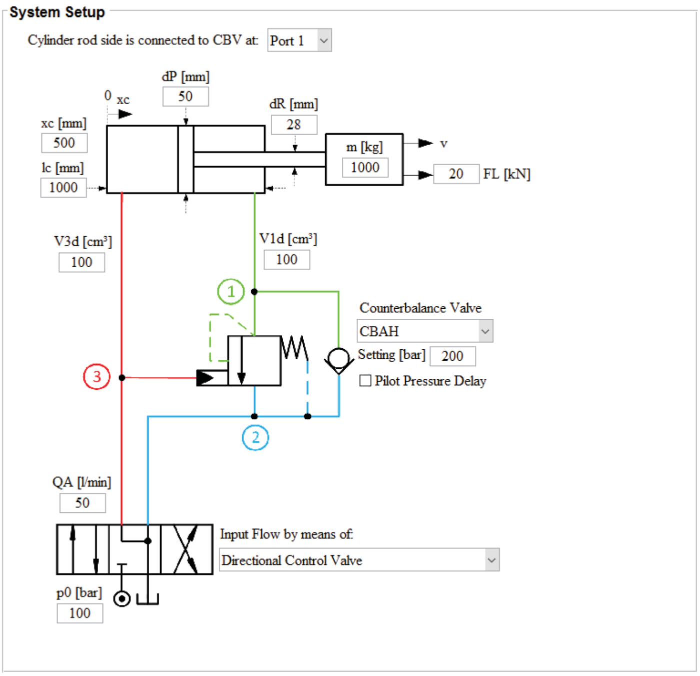
$$\frac{G_{pilot}}{G_{relief}} = \frac{dQ/dp_3}{dQ/dp_1} = \frac{dp_1}{dp_3} = PR \qquad (11)$$

2. The directional valve should have a high flow gain G_{DCV} which means that the damping is better if flow changes when the pressure differential changes. The flow does not change if the directional control valve is a pressure compensated flow control valve.

Equations 10 and 11 show that negative numbers for one of G_{pilot}, G_{relief} or G_{DCV} need to be compensated by positive gains of the others. Simulations show that in some cases stability is possible with negative numbers for the flow gain of the directional control valve G_{DCV}, but in general positive numbers helps to improve stability.

3. Simulation based on a linear model

The Matlab based simulation program is based on parameters that describe a linearized model. The user enters the following parameters: supply pressure, meter in flow, cylinder dimensions, attached mass, capacitance in A and B, he selects the counterbalance valve from a list (see **Figure 4**). The valve is described by pilot gain and relief gain. The most nonlinear element in the circuit is the directional control valve that functions like an orifice on the meter in side. The user can define the flow and the supply pressure, the program will calculate the orifice size and linearize it in the operating point (see eq. 3,4,5,6).



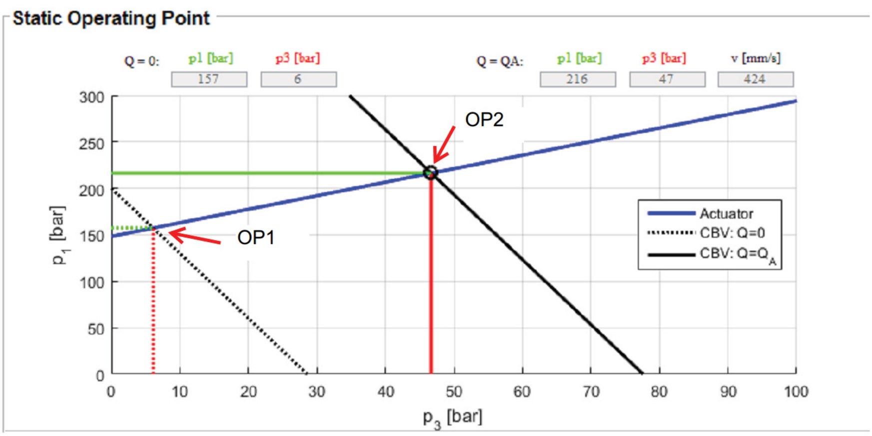


Figure 4: Menu for entering parameters of the complete circuit and diagram with effective setting p1 vs pilot pressure at two different flows

The program calculates the pressures p1 and p3 on both sides of the cylinder**.** Figure 4 shows an example for the static operating point. The blue line shows combinations of pressures p1 and p3 that are in equilibrium with the given external force on the cylinder. The dotted line shows the performance curve of the counterbalance valve for very low flow (crack pressure →O1). The example shows a counterbalance valve with a setting of 250 bar which is above the load induced pressure of the load of 200 bar. Increasing pilot pressure reduces the effective setting of the counterbalance valve. The gradient is the pilot ratio of the counterbalance valve. The black line parallel to the dotted line shows the performance of the counterbalance valve at a higher flow (50 l/min →02).

An advantage of the linearized model is that results are available within fractions of a second. After entering 10 parameters the user sees the static operating point (required inlet pressure to move the cylinder with the required speed) and the system dynamic.

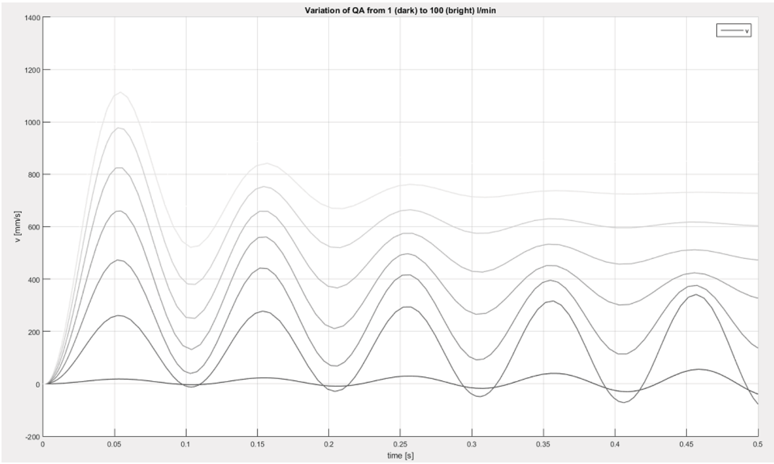


Figure 5: Parameter variation. Flow 1-100 l/min in 8 steps.

Figure 5 shows a parameter variation in that the flow changes from 1 to 100 l/min for a given supply pressure. The damping changes because the directional valve sees a lower pressure differential at higher flow (the supply pressure remains constant, but the inlet pressure is higher for higher flows) and (more important) because the valve is opened further for higher flow. Equation 4 shows that the flow gain G_{DCV} is higher at higher flows because the valve is further opened, the effective diameter D is larger, so the directional valve contributes more to damping than at low flows (compare with stability criterion eq.8).

4. New loadadaptive counterbalance valve

The calculation and the simulation shows that pilot gain and pilot ratio influence the stability. Since stability is required the application limits the maximum pilot gain and the maximum pilot ratio. Therefore a customer can’t use a counterbalance valve with higher pilot ratio or pilot gain without affecting the stability that moves with a negative load. A load is negative if it pushes in the direction of the movement.

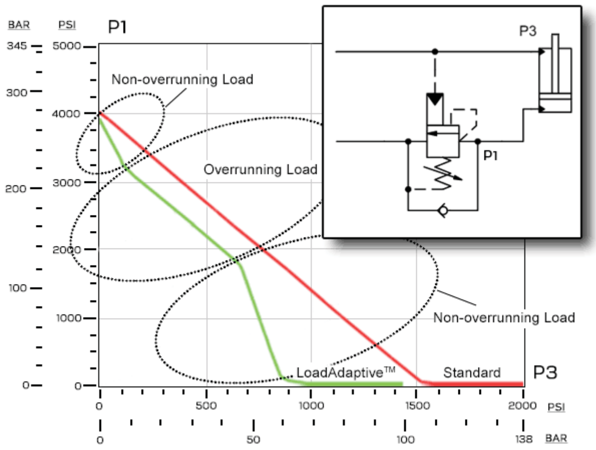


Figure 6: Performance curve of a standard (red) and a loadadaptive (green) counterbalance valve. Setting vs pilot pressure

But the load isn't always negative and it isn't always moving. **Figure 6** shows the performance curve of a standard counterbalance valve (red). Increasing pilot pressure reduces the setting of the valve. The curve is measured at a constant flow. There are three different operating areas. The valve controls the movement of a negative load in only one of them. For very low pilot pressures the counterbalance valve is not open yet. Initially it has a setting about 30% above the highest expected induced load pressure. So the setting can be reduced rapidly with high pilot ratio by about 20% without causing instability since the actuator is not moving yet. When the pilot pressure further increases the load will eventually move. At that stage a low pilot ratio (a flat gradient) is required for stability. Very high pilot pressures are not required on actuators with negative load since the load helps to open the counterbalance. Combinations of high pilot pressure and low 'load pressure' occur when the actuator sees positive loads. In that operating range the counterbalance valve causes unnecessary pressure losses. A counterbalance valve to control a negative load is not needed since there is no negative load. The new load adaptive counterbalance valve fully opens at pressures about 30% below the pilot pressure that is required to fully open the equivalent standard counterbalance.

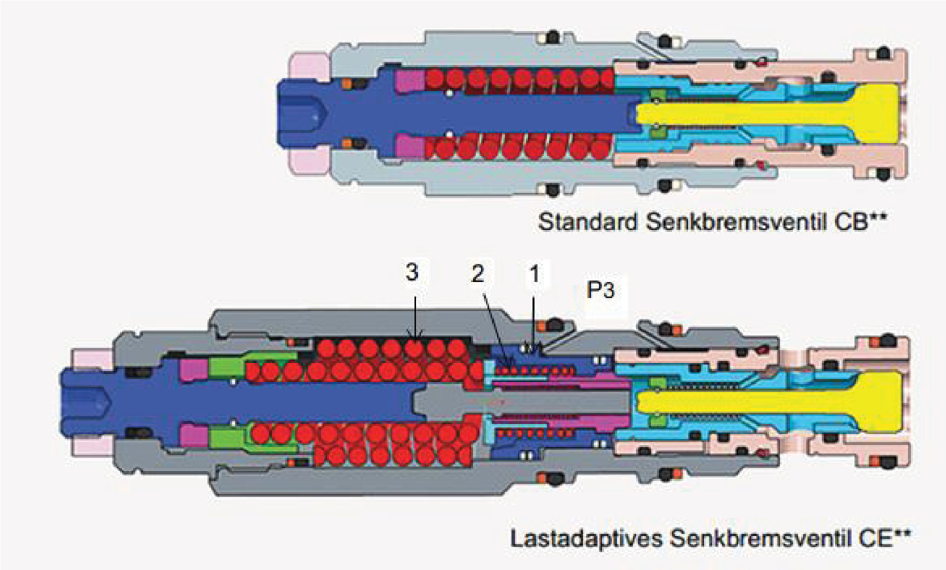


Figure 7: Standard counterbalance and new load adaptive version (below)

Figure 7 shows the cross section of a standard counterbalance and the new load adaptive version. An additional sleeve (1) is active to reduce the setting of the valve by about 20%. The setting is not further reduced because the inner spring (2) limits the maximum force between the sleeve and the adjust spring (inner spring). The sleeve will stop on the preloaded outer spring (3) when pilot pressure further increases. So it doesn't affect the performance of the valve. The same main stage elements are active to control negative loads as in the standard 'base' model. Eventually higher pilot pressure times an effective area will exceed the preload of the outer spring (3) and the sleeve (1) will help to fully open the counterbalance valve. So the additional sleeve is active-inactive-active with increasing pilot pressure resulting in an effective pilot ratio (gradient in the p1-p3 diagram) that is steep-flat-steep.

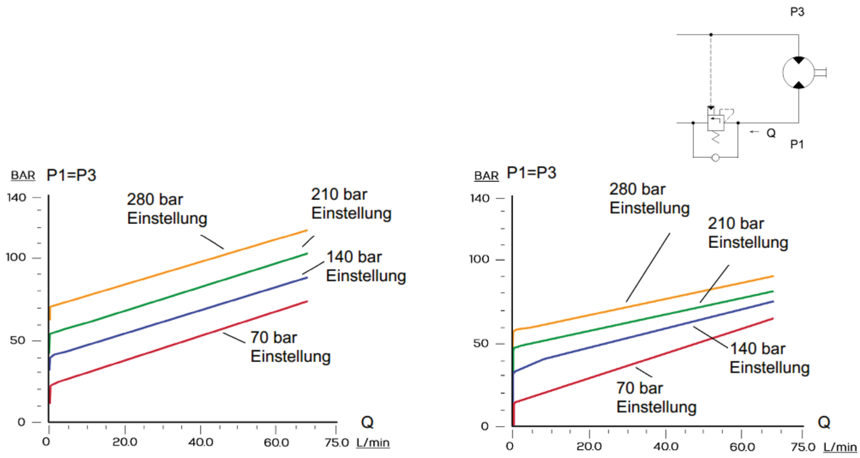


Figure 8: Pilot pressure vs flow to drive a winch without external load. Left: with standard counterbalance. Right: with load adaptive counterbalance

Figure 8 shows the performance the required inlet pressures to drive a motor that sees no outer force. A counterbalance valve with pilot ratio 3:1 avoids cavitation on p3 and would stop overrunning load. The curves show the inlet pressure vs flow for different settings of a standard counterbalance valve (left) and a load adaptive counterbalance (right). The savings are about 30%. The stability of the circuit is expected to be the same for negative loads when stability is critical.

5. Circuits with changing effective pilot ratio to save energy

Circuits with standard counterbalance valves in parallel to improve stability and/or efficiency are common. The purpose is to control negative loads at low speed with a 'stable' low capacity counterbalance valve and to open a second valve for high speed when the circuit is more stable (see above, parameter study). Other circuits use throttles in the pilot line to influence the performance of the counterbalance valve. **Figure 9** shows an example. The circuit uses a needle valve (N) and a pressure compensated flow control valve (F) in the pilot line of the counterbalance. At low pressure differential p3-p2 the compensator in flow control valve is not saturated yet and both the needle valve and the flow control function as orifices. As a result the pressure between both valves is a fraction of p3, so the effective pilot ratio of the counterbalance is reduced. At higher inlet pressures (positive load on the cylinder) the pilot flow increases until the flow control valve limits the pilot flow. At higher pilot pressures the pressure drop across the needle valve will remain constant and will no longer be reduced to a fraction of the inlet pressure.

The diagram on the left hand side shows the resulting performance curve for different flows. The performance is similar to the performance of load adaptive valve.

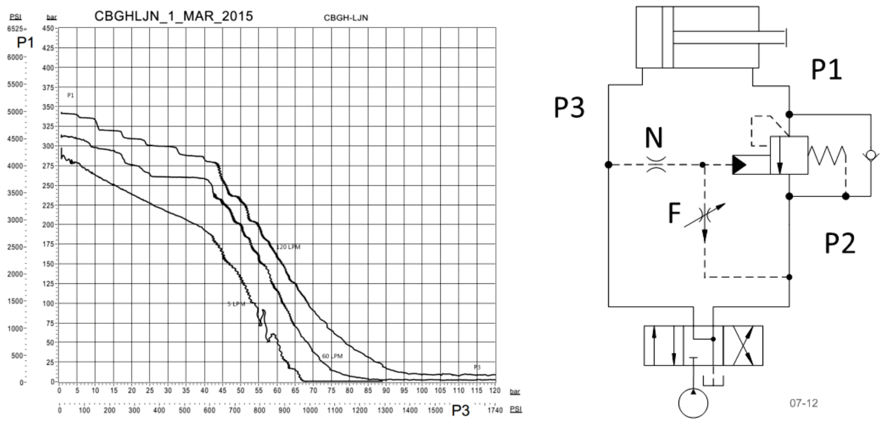


Figure 9: Standard counterbalance and new load adaptive version (below)

6. Summary

The paper describes which parameters affect the stability of a circuit with a counterbalance valve that is used to control negative loads. A Matlab based simulation program shows static and dynamic performance. The results of parameter variations on the dynamic performance can be shown in curves for pressure or velocity vs time or as poles in the Laplace-plane. Pilot gain and pilot ratio of the counterbalance valve influence the stability. A low pilot ratio is often required to achieve stability but reduces the efficiency of the circuit. A new load adaptive counterbalance valve has the low pilot ratio only when it is required for stability. That is when the actuator moves a negative load. The valve has a higher pilot ratio when the load is not moving or when a positive load requires no counterbalance valve. The valve saves on average 30% power compared with a standard counterbalance valve.

7. References

/1/ Otto Föllinger: ‚Regelungstechnik‘, 5.Auflage, Heidelberg 1985

/2/ Peter Chapple: Principles of Hydraulic Systems Design, Second Edition‘, Momentum Press, New York 2015

8. Nomenclature

A	Cylinder Area
C_{HA}, C_{HB}	Capacitance A/B
CR	Cylinder Ratio
D	Effective Orifice Diameter
F	External Fore on Cylinder
G_{DCV}	Gain of Directional Control Valve, Change in Flow per Change in pressure Differential $(p_O - p_A)$
G_{Pilot}	Pilot Gain of Counterbalance Valve, Change in Flow per Change in Pilot Pressure p_A
G_{Relief}	Relief Gain of Counterbalance Valve, Change in Flow per Change in Load Pressure p_B, p_1
m	Mass of Cylinder incl. attached Load
p_0, p_A, p_B	Supply Pressure, Pressure in A, B
p_1, p_3	Pressures on Port 1 (load), Port 3 (pilot) of the Counterbalance Valve
PR	Pilot Ratio of the Counterbalance Valve
	(Change in effective setting per change in pilot pressure)