

New Energy Saving Counterbalance Valve

Bernd Zaehe and David Herbert
Sun Hydraulics Corp.

ABSTRACT

Counterbalance valves are used in hydraulic circuits to avoid uncontrolled movements of cylinders and Motors. They are often installed in the return line of the cylinder or motor. The flow control valve on the meter in side then sees a positive load regardless of external forces on the cylinder. The counterbalance valve can be seen as a relief valve with a setting high enough to support the highest expected load. The setting of the counterbalance valves is reduced when the cylinder or motor moves. Usually the inlet pressure of the cylinder is used as a Pilot Pressure for the counterbalance in the return line. The so called Pilot Ratio describes how much the setting of the CB valve is reduced per increase in Pilot Pressure. A high Pilot Ratio of 10 e.g. reduces the setting by 100 bar when the Pilot Pressure increases by 10 bar. The selection of the Pilot Ratio is a compromise between stability (low Pilot Ratio) and efficiency (a high Pilot Ratio allows to move the cylinder with lower pressures). The application engineer must select the counterbalance valve with a Pilot Ratio low enough to ensure stable movement although that may lead to higher inlet pressures to drive the cylinder. The new 'triple ratio counterbalance' valves allows lower inlet pressures and offers the same stability since it uses the low Pilot Ratio (that leads to lower efficiency) only when it is required for stability. It has a higher Pilot Ratio when the cylinder doesn't move yet (Pilot Pressure reduces the setting but the cylinder doesn't move yet) and when there is no overrunning load that could cause instability. A comparison shows that the new valve allows the same cylinder/motor speed with inlet / Pilot Pressures that are 15% to 40% below the ones required for a standard counterbalance valve.

CITATION: Zaehe, B. and Herbert, D., "New Energy Saving Counterbalance Valve," *SAE Int. J. Commer. Veh.* 8(2):2015, doi:10.4271/2015-01-2858.

INTRODUCTION

The proper selection of a counterbalance valve for fluid power circuits with overrunning (gravity assisted) loads is important to ensure optimum system performance. In particular the balance between energy efficiency and dynamic stability must be considered in detail. Many times unfortunately efficiency is compromised at the expense of stability due to the limited nature of the counterbalance valves commercially available for the installation.

Energy efficiency is particularly important for mobile equipment where pump and fuel tank size is limited.

Although this paper will delve deeper into these topics, a complete examination of all the factors related to load motion stability and efficiency is too exhaustive for this treatment. However, the references below site several of the numerous studies, articles and patents related to this topic. Suffice to say that counterbalance valve efficiency is fairly simple in that lower Pilot Pressures (hence higher Pilot Ratios) result in reduced power consumption. Counterbalance valve-system stability is much more complex but as a broad rule higher Pilot Ratios can result in the counterbalance valve's internal relief spring being over-compressed and going into low frequency oscillation thereby forcing the valve to open and close in a non-controlled manner. Hence lower Pilot Ratios contribute to better stability.

This paper will explore the stability - efficiency trade off and present a possible mechanical valve which bridges the gap. The paper will also present a novel graphical and empirical method for evaluating counterbalance valve performance.

LOAD CONTROL CIRCUITS

There are several basic concepts to control hydraulic consumers with a proportional or directional valve. [Figure 1](#) shows two very typical concepts for controlling overrunning loads with proportional or directional valves. Note that overrunning loads are also sometimes referred to as gravity assisted or "positive" loads.

If the maximum load induced pressure was always the same a simple relief valve in the return line with a setting just above that pressure would be an appropriate valve to avoid loads from overrunning and to avoid the resulting cavitation in the meter-in line.

In fact loads vary considerably throughout a machine's duty cycle. Consider the very typical situation where a crane or tele-handler lifts a heavy load and deposits it at an elevated worksite then must return unloaded back to earth. In this case there is no gravity assisted Load Pressure to open a relief valve. Hence the need for Pilot Pressure assist to return an unloaded implement back to its lower elevation starting point in a controlled fashion. Counterbalance valves are good for this type of application.

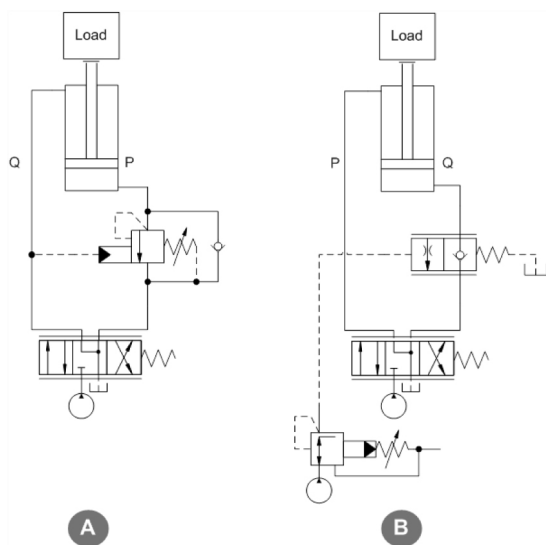


Figure 1. Typical Circuits for Controlling Overrunning Loads

A counterbalance (CB) valve can be seen as a relief valve with a setting high enough to support the highest expected Load Pressure. Most counterbalance valves incorporate an additional “pilot assist” function which further reduces the valve setting and assists opening and releasing a load.

Reference [8] below provides a good primer on counterbalance valve operation and circuit applications.

Figure 2 shows a typical CB valve with Load Pressure on Port 1, tank pressure on Port 2 and Pilot Pressure on Port 3. This type valve also includes a free flow check valve for efficient motion in the load advance direction.

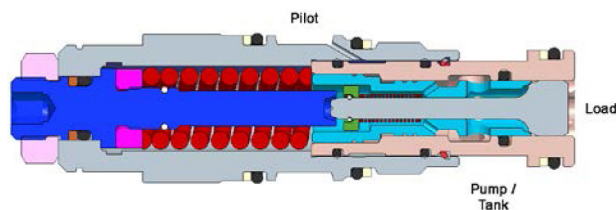


Figure 2. Typical Counterbalance Valve

Figure 3 is the schematic symbol for the CB valve.

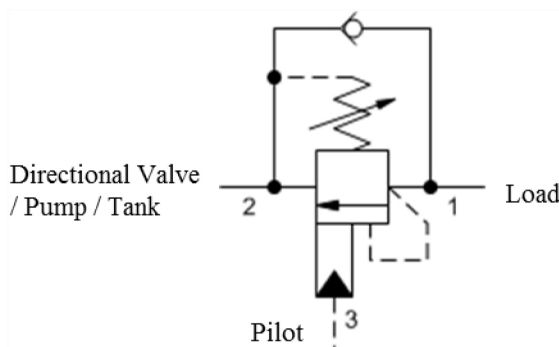


Figure 3. Typical Counterbalance Valve Schematic Symbol

CB valve relief settings (crack pressure without pilot assist) are usually recommended to be 30% above the highest possible load induced pressure. This safety factor of 1.3 allows the valve to fully close despite hysteresis and prevents nuisance openings of the valve due to relatively small pressure disturbances. It also provides additional pressure in the return line to decelerate maximum loads in a controlled manner.

The “Pilot Ratio” describes how much the setting of the CB valve is reduced per increase in Pilot Pressure. For example if the Pilot Ratio is 10 and a 10 bar Pilot Pressure is applied, the valve setting is reduced by 100 bar. Or, a Pilot Ratio of 3 implies a Pilot Pressure of 3 bar reduces the valve setting by 9 bar.

$$\text{Valve Setting} = F_{\text{spring}} - (P_3 \times PR)$$

[1]

Where

Valve Setting = pressure required to open the valve at Port 1

F_{spring} = Spring Pre-Load, mechanical spring force holding the valve closed

P₃ = Pilot Pressure, hydraulic pressure applied at Port 3

PR = Pilot Ratio, geometric ratio between the valve's load port area and pilot port area

So, the pressure required to open a CB valve is a function of the initial mechanical setting, Pilot Pressure, Pilot Ratio and load induced pressure.

The setting of the counterbalance valve needs to be high for high overrunning loads. But if the load varies, particularly if it is reduced, the setting is unnecessarily high and requires additional Pilot Pressure to open the valve. This leads somewhat counterintuitively to the conclusion that less Pilot Pressure is required to *lower* a heavy load than to lower a light load. This obviously can lead to wasted energy in the load down direction.

THE RELATIONSHIP OF LOAD PRESSURE, PILOT PRESSURE AND PILOT RATIO

By definition Pilot Ratio is the ratio of pressure areas internal to the valve, but it can be measured hydraulically per Figure 4.

The test conditions of Figure 4 are:

- Pump flow is introduced at Port 1 and is limited to 20 L/min maximum by a pressure compensated flow control valve
- Pilot Pressure (Port 3) is gradually increased to reduce the valve's setting (open Port 1 to Port 2)
- P1 and P3 are measured and plotted per Figure 5 for various Pilot Ratios.

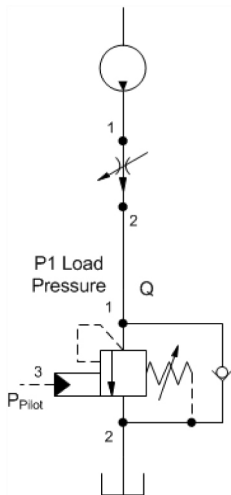


Figure 4. Pilot Ratio Test Set-up

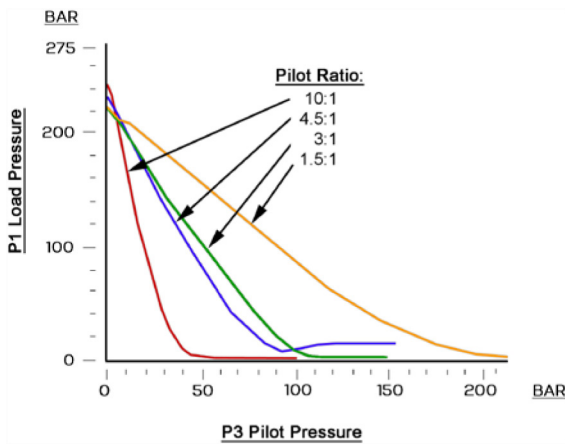


Figure 5. Load Pressure -v- Pilot Pressure -v- Pilot Ratio

Note from [Figure 5](#) that:

- All lines represent a maximum constant flow of 20 L/min as set by the flow control valve upstream of the counterbalance valve.
- See [Figures 9](#) and [10](#) below for the effects of other flow rates.
- At Pilot Pressure (P3) = 0 the valve is at its mechanical setting (spring preload only).
- As Pload decreases the physical load will be lowered or released.
- Higher Pilot Ratios require less Pilot Pressure applied to reduce Pload.
- The slope of the lines approximates the Pilot Ratio, i.e., a 3:1 slope ~ 3:1 Pilot Ratio valve.
- Curves to the left (higher Pilot Ratios) tend to improve energy efficiency while at the same time dynamic stability tends to decrease.

Again, the system designer's challenge is to select the proper Pilot Ratio to optimize stability and energy efficiency. This is particularly important on mobile equipment where safe operation is critical while pump size and fuel tank size are limited. Many times the engineer will select a 3:1 ratio as the best overall compromise.

COUNTERBALANCE VALVE EFFICIENCY AND STABILITY AS A FUNCTION OF LOAD CONDITIONS

[Figure 6](#) shows the P1 vs P3 diagram for a cylinder and counterbalance valve combination and shows possible pressure combinations that balance the gravity assisted external load force.

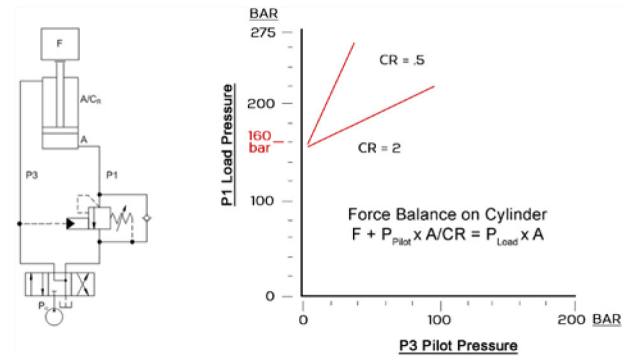


Figure 6. Force Balance on a Cylinder

$$F + P_{pilot} \times \left(\frac{A}{CR} \right) = P_{load} \times A$$

[2]

Where

F = the mechanical load force

P_{pilot} = Pilot Pressure (P3)

A = cylinder piston area (cap end)

CR = cylinder ratio = piston end area / rod end area

P_{load} = hydraulic pressure load (P1)

The mechanical load force can be balanced by a combination of pressures on both sides of the cylinder. Higher pressure on rod end side of cylinder creates higher pressure on the piston side also.

The two lines in [Figure 6](#) show two cylinders with the same load induced pressure but different cylinder ratios (piston area/rod end annular area).

- The effective area for P1 is 'A'.
- P3 is additive to the load induced pressure P1 with a factor of 0.5 if the cylinder ratio = 2.
- P3 is additive to the load induced pressure P1 with a factor of 2 if the cylinder ratio = 0.5.
- Neglects friction

The counterbalance valve sees the same pressures P1 and P3 that the cylinder does. With no pressure P3 on the inlet side of the cylinder, the load induced pressure P1 (160 bar in [Fig. 6](#)) keeps the cylinder in position against the load force F .