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DESIGN OF AN ADJUSTABLE HYDRO-PNEUMATIC DAMPER FOR CAB SUSPENSION

Pasi Ruotsalainen[1], Kalervo Nevala[1/2], and Ykä Marjanen*[2]

[1]University of Oulu, Mechatronics and Machine Diagnostic Laboratory
P.O.Box 4200, FIN-90014 University of Oulu, Finland
[2]VTT Information and communication technology
P.O.Box 1100, FIN-90570 Oulu, Finland
paruotsa@cc.oulu.fi

Abstract

The aim of this study was to design and test an adjustable hydro-pneumatic damper for cab suspension**.** The goal was to make a simple and cheap solution. Damping behavior for different terrain types had to be taken into consideration. The terrain types vary from field to road driving.

In this study the semi-active damper has been carried out with a hydraulic direct acting cartridge type 2/2-way proportional flow control valve. The applicability of the valve to the semi-active damper was tested in a cab suspension test environment. The valve was tested with two natural and one artificial vibration stimulation tracks. With these results it was possible to ascertain the proportional valves' capability to work as a multi state damper. Flow-pressure curves and dynamic testing were carried out in the laboratory. The dynamic test with forced vibration was focused on stability in damping frequencies and the step response between different states.

As a result, this research gave a lot of new information about proportional valves' applicability to work as a semi-active damper and information about damping behavior. Also, proportional valves' precise step responses and stability was investigated in a closed hydraulic system. The research showed that a proportional valve can work in cab suspension damper as well as a multi fixed orifice damper. Two-direction flow in the proportional valve was found to remain stable in cab suspension working conditions. The proportional valve has also capability to work as a continuous state damper which could lead to better damping results with the appropriate control system.

INTRODUCTION

Vibration exists in many different forms in off-road vehicles and you can't avoid exposure to it. In damper design you can estimate the vehicle's traveled terrain types and make decisions with that knowledge about damper behavior. You conclude with a compromise for different terrain types in a passive damper and the result is an adequate damper in different driving conditions. Problems increase when the vehicle's total mass or terrain varies dramatically [10]. In that case it's hard to get good damping for all conditions with the traditional passive damper.

Semi-active dampers have been developed to solve problem of different terrain type damping optimisation [4-6,12]. There you can focus in damper design to develop optimal damping states for different terrain types without leading to a compromise. The objective in semi-active damping design is to develop an adaptive system where damping is adjusted in real-time with sensors to fit the terrain type.

In this study, the goal was to design and test a hydro-pneumatic damper solution for an off-road vehicle. The damper will be placed between the cylinder and accumulator. The damper solution should be as good as possible in adjustability, simplicity and economy. It should have at least three states and switching between the states should be as fast as possible. It should be able to work as a multi-state or continuous state damper.

ADJUSTABLE DAMPER DESIGN

The objective was design a semi-active adjustable damper which should be a small size. The response time has to be fast and the flow rate should exceed 30 l/min with a 10 bar pressure difference. Flow is bi-directional in this damper system so it had to be noted in hydraulic components. The flow can be transformed to a directional flow with four check valves and it's considered only if no bi-directional solution is good enough. The cab mass is 1000 kg and the main goal was damp its vertical vibration.

There are different solutions on how to switch to a different orifice size. One can be a rotating disk where fixed orifices are evenly located. This is a small size of solution but there isn't any fast commercial product available. On/off solenoid cartridge valves are very common. Those are very fast and small sized. With one 3/3-way solenoid cartridge valve you can get three states with one valve but the valve body needs to be machined. The same situation applies with 2/2 way valves but you need at least two valves to get over three states. With two valves the damper size increases a lot and the valve body needs to be designed and machined. Both solenoid solutions can produce a multi-state damper which can be operated electrically.

Proportional flow control cartridge valves aren't so commonly used but those can work as a continuous state damper. There is no need for fixed orifices in proportional valves where the orifice size can be adjusted proportionally. Proportional valves are slightly slower than 2/2-way solenoid valves and there is no need for extra machining to a standard valve body. Directional valves are fast and accurate but a bit more expensive than cartridge valves. Also a directional valve needs a special attachment plate to the cylinder when the fairly large valve takes even more space. The directional valve would be a good choice if damper cylinders were specially made for directional valve attachment. Another good feature in directional valves is the possibility to connect flow channels so that flow forces are cancelled in 4/2-way directional valve.

The binary valve is an interesting new valve type [2]. There are only prototypes of it but very fast response and low power consumption would be the key to development of a new electrically controlled damper. Response time is only a few milliseconds so with pulsewidth-modulation you can get a continuous state binary damper. When continuous state damping is not necessary the valve can operate as a multi-state damper in hard or soft setting.

Solution for adjustable damper

The cartridge proportional flow control cartridge valve meets most of the demands. It's simple, small, quite cheap, adjustable and connectable to the cylinder and accumulator. Also proportional cartridge valves are almost as fast as 2/2-way solenoid valves. The only downside is that proportional valves aren't so common. It's quite hard to find valve whose flow-pressure curve is suitable for damping, because most of the valves are at least partially pressure compensated. Also flow-pressure curves are usually presented only for maximum flow. Therefore damping behaviour of these valves is hard to predict in middle positions. Flow-pressure curves should be a little bit dissimilar in flow directions to get asymmetrical damping behaviour which normally should be about 60-70% to rebound.

The Bosch Rexroth KKDSR1 normally open direct operated 2/2-way cartridge valve was the best available valve which could correspond to all demands [1]. There is pressure compensation in another direction but it starts from a 70 bar pressure difference so it's high enough for this cab suspension system. Valve speed is 40/50 ms (closed/ open) so it's a little bit slow when you compare it to the fastest solenoid valve response times. The response time is a feature which should be better in an optimal valve. The valve is a little bit asymmetric but the manufacturer’s flow-pressure curves are so near each other in low pressures that it's hard to give precise asymmetries before measurements.

Flow forces are important to observe in damper design when the valve is used to control damping. There's both stable and unstable flow in a bi-directional system [7,8]. Stable flow tends to close the orifice and unstable flow tends to open it. Because these forces operate in opposite directions in a dynamic system you can end up with a vibrating system. With a symmetric valve structure this could be minimized but in this case the valve behaviour has to be tested in bi-directional flow. Pressures in cab suspension are relatively small compared to the valves’ maximum operating pressure so you can hypothesize that the valve should be stable in cab suspension.

Damping design is based on flow-pressure curves of a proportional valve. There's static pressure in the hydro-pneumatic system and it affects seals which cause friction between the seal and cylinder rod [11]. This friction affects low velocity damping passively and with proportional flow control you can change damping with high velocities. The flow-pressure curve of turbulent flow thought a fixed orifice forms a linear damping ratio curve in the ideal case. Normally the damping ratio is between 0.2-0.6 and it is a good basis for adjustable damper design [3]. There has to be at least one state which is over-critically damped and therefore it is always stable. Racing cars use damping where the damping ratio is over 2 and it is a good estimate value for the stable state in cab suspension. The lowest reachable damping ratio depends on seal friction forces when a 100 N friction force gives a damping ratio of 0.04 at a velocity of 0.7 m/s. This is the lowest possible damping ratio which can be achieved at that speed but in practice it is not reachable because of hydraulic losses in the valve. In other hand, there is no significant difference in damping behaviour if the valve's damping force is smaller than the friction force. Therefore the lowest proportional valve's damping state is designed using the lowest friction damping ratio.

It is possible to define the average orifice size from the manufacturer's flow-pressure curves in different controls with the turbulent flow equation [13]

$$Q = C_d A_k \sqrt{\frac{2 \cdot \Delta p}{\sigma}} \tag{1}$$

Now we can know the approximate orifice size in different controls and by interpolating it is possible define controls for different damping ratios. Damping ratio also depends on the damper velocity. A parabolic flow-pressure curve forms a linear damping ratio curve so in the damping state design it has to be done for a specific average velocity. Damping ratios can be calculated with the equation

$$\zeta = \frac{\rho \cdot v \cdot A_r^3}{4 \cdot A_k \cdot \sqrt{k \cdot m}} \tag{2}$$

By choosing damping ratios for rebound we can calculate control values and bound damping ratios with an approximate accumulator spring constant 15 kN/m and average velocity 0.35 m/s.

Table 1 - Valve damping states

Valve control %	Damping ratio (0.35 m/s)	
	Rebound	Bound
58	0.15	0.09
66	0.3	0.15
72	0.5	0.3
78	1	0.63
82	3	2

DAMPER PERFORMANCE MEASUREMENTS

Flow-pressure curves

A proportional valve was tested in an open hydraulic circuit to obtain flow-pressure curves with the valve body. Measurements especially revealed behaviour in low pressures and with these curves damping states can be designed more accurately. Measurements showed that especially in the rebound direction low-pressure acting was little bit different. The pressure difference was lower in the rebound with low fluid flow. This is opposite to that what was expected from the manufacture's flow-pressure curves. There was also appreciable inaccuracy between 1000% magnification of manufacturer curves and measured curves at low flow. It's understandable because reading resolution is so poor. Pressure compensation begins from 40-50 bar pressure difference in rebound. Higher pressures in the rebound direction make the body start warm up fast, which was also detectable as a hysteresis loop in the flow-pressure curve.

Valve response time

Response time measurement tests were made in open and closed hydraulic circuits. It was possible to use a large flow in the open circuit and in the closed circuit it was limited because of a usable damper movement range and velocity. Results were similar between open and closed circuit at low flow and therefore you can suppose that open circuit measurements in higher flows are also reliable. Measurements showed that the response time varies depending on the pressure difference in the valve. Normally cartridge valve response time measurement is made with a constant 10 bar pressure difference. In this closed circuit case, valve pressure changes along with damper velocity and damping state. Measurement showed that the valve closing response time begins to slow down when the pressure difference is less than 10 bar. Valve closing time started to slow dramatically when the pressure difference dropped below 2 bar. Valve opening is operated by a spring and differences are much smaller than in the closing direction. Pressure compensation in the rebound direction slowed response time with high flows.

Response time tests showed that a valve can work reliably as a multi or continuous state damper below 2 Hz frequency. At very slow velocities the valve response time is slower. Viscose damping begins to affect damping over 0,2 m/s velocities and then response time is below 500ms. In this case, you can suppose that a state shift occurs always when viscose damping is operating.

Dynamics and stability

The proportional valve is a second order vibrating system. Therefore it's important to find out the valve's stability in cab suspension. The valve was tested with damping frequencies 1.5-10 Hz and velocities 0-0.35 m/s with forced vibration. The test signal was a triangle wave where amplitude was increased linearly from zero to maximum.

Also the state shift at a velocity of 0.35 m/s was investigated. The vibration effect was explored by pressure difference in the valve. A triangle wave causes high acceleration at turning points which simulates strong impulses in cab suspension.

Measurements showed that there's no significant overshoot in the pressure difference curve. There was a little overshoot at the turning point but it was hardly more than signal noise. Overshoot was biggest in the lowest damping state. This is logical because electromagnetic forces decrease to lower damping states and the relative effect of flow forces increases. Stability becomes important if cab suspension forces increase a lot from this configuration but in this case the valve can maintain the desired damping state. There's overshoot in state shifting but it's normal for a valve without a feedback loop where you can't influence the final spool position.

The total damping force curve in damping states was also measured in dynamic tests. Increasing amplitude triangle wave position control produces a step-by-step increasing square wave velocity curve. Damping force can be measured in constant velocity fractions.

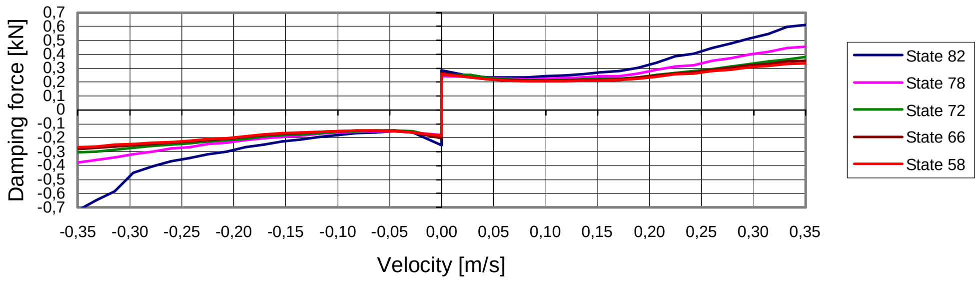

Figure 1 - Total damping forces

A proportional valve can't change damping at low velocities because of seal friction in the cylinder. Friction in the cylinder isn't a very bad thing because it creates a "knee" in the damping curve. Static friction influences at zero velocity and keeps the damper immobile until vibration exceeds friction force. This is known a problem in this system and it should be solved in some way. Especially road excitation is low amplitude vibration which is partially undamped because of high static friction. This could be solved with rubber cushioning in the damper mounting which allows movement at low velocity.

Damper behaviour in cab suspension

Damper behaviour was measured in a cab suspension test environment. Two hydro-pneumatic dampers were mounted at the cab rear corners. The cab front corners were first mounted with air suspension and for second measurements with rigid bars. Damping was measured three times on a 170 second track in the same damping state. Measured tracks were obstacle track, road track and field track. Acceleration was measured in the vertical axis below the driver in the seat, cabin floor and body. The percentage difference of three sequential measurements had to be less than 2%. Measurement reliability was also verified with coherence. Coherence was over 0.8 for all other measurements but dropped to 0.5 lower damping states in the field track because of cylinder end stop impacts. Damping efficiency was compared with percentage transmissibility values [9]. Values were calculated with ISO 2631-1 frequency weighting from body to cabin floor and seat.

The overall result in cab suspension tests was that lowest damping is best in all terrain types. Best cab suspension damping results were achieved in the field track where seat suspension didn't affect much. The road track was the opposite and cab suspension adjustment didn't affect transmissibility to the seat. Hydro-pneumatic cab suspension works well on rough tracks but on a smooth road track there is no significant influence on damping because of seal friction. Transmissibility to the seat improved when air suspension was replaced with rigid bars, because the standard seat is designed for a rigid cabin. However in this vertical damping system cab suspension transmissibility degraded and horizontal vibration came annoying. Rear hydro-pneumatic suspension works well in vertical damping and additional horizontal damping has to be designed for good overall results. Also seat suspension has to be trimmed for the cab suspension.

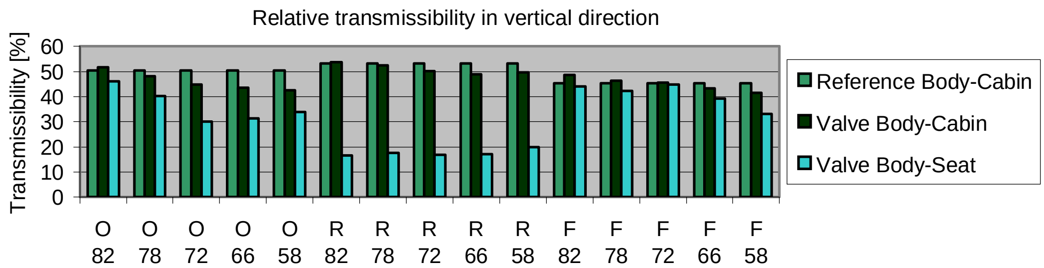

Figure 2 - Body acceleration transmissibility in different damping states to cabin floor and seat with front air suspension. (O=Obstacle track, R=Road track, F=Field track)

Damping was analyzed more precisely with the third-octave band spectrum. Valve damping is best in low frequencies 1.5-4 Hz and damping state adjustment mainly affects in this range. The lowest damping state was found to be best in all terrains in the 0-10 Hz range to cabin floor and seat. Measurements showed that a valve damper can reduce vertical vibration a lot in rough terrain but the smooth road surface was poorly damped. Low amplitude road vibration damping could be improved with a rubber cushion in the damper mounting.

SUMMARY

The proportional cartridge valve suits in hydro-pneumatic cab suspension. It's possible to achieve multi or continuous state damping. Also damper construction is simplified to one controllable valve. Flow directions are a little bit asymmetric so the rebound suspension can be made stiffer. Valve response time didn't fulfill the specifications and it was noticed that valve has a really slow closing response at low flow. The valve is suitable for relatively slow damping adjustment and stays stable in this scale cab suspension system. Damper cylinder end cushioning is needed for optimal behavior in low damping states because the valve response time isn't always enough to react to the cylinder end stop impact.

The proportional valve was verified to fit in the cab suspension damper and damping could be varied over a large range. Cylinder seal friction was a drawback in road excitation and it should be improved in some way. Seal friction implemented a "knee" in the total damping force but it was a disadvantage in low damping states. In this work, the main goal was vertical cab suspension damping but total vibration exposure of the driver was also considered. Horizontal vibration degrades overall damping to the driver and therefore horizontal damping is also needed to achieve good results.

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