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A SELECTIVE HYDRAULIC DAMPING VALVE

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Abstract

The aim of this study was to develop a DC – motor operated multi state, selective hydraulic damping valve (SHDV) for the damping of off-road vehicle cab vibration. Usually selective damping is realized with standard on/off – valves. Strict demands with regard to the physical dimensions and financial viewpoints, led to development of an alternative construction.

The structure of the valve is based on two contra-rotating concentrically assembled rings. Orifices are placed on the inner ring, while the outer ring has one flow channel per flow direction. Rotating the rings with respect to each other sets the state of the flow resistance. Rotating movement of the rings is achieved by means of a DC – motor. A single motor can be used to drive two valves at a time, thus reducing the total cost of the suspension system.

The valve was designed to produce three discrete damping rates. After measuring the flow rates, the first damping state was chosen to perform equally to a well-acting passive suspension system. The second damping state was chosen to be more firm and the third state softer than the passive one. The valve was then attached to a hydropneumatic agricultural tractor cab suspension system and the performance of the system was measured.

INTRODUCTION

Recent research has indicated that whole-body vibration acts associatively with other factors to precipitate low back pain [6, 1]. Drivers of off-road vehicles are prone to vibration caused by ground irregularities. Many off-road vehicles are poorly suspended. For example a typical agricultural tractor has a rigid front and rear axle and the only suspension between the driver and road is a suspension seat. The suspension seat typically has very limited capability to suppress severe vibration. Suspension seats are effective only in the vertical direction and they are prone to parameter variations due to mass differences between individuals. A noticeable improvement in vibration attenuation capability can be achieved by means of cabin suspension [7]. A typical cabin suspension is comprised of two or four passive hydropneumatic or pneumatic spring-damper elements incorporated between the vehicle chassis and cabin [5]. Most of the present cabin suspensions are designed to be effective only in a vertical direction.

Passive vibration isolation is a robust and cost effective way to reduce whole-body vibration, but the performance limitations relating to the passive nature of the system have motivated researchers to develop selective, semi-active and active suspension systems. One of the critical aspects related to passive suspension design is the selection of the damping ratio. The damping is the only factor that limits the vibration amplitude at resonance. To achieve a low amplitude at resonance, a high damping ratio is needed. However, at higher frequencies, a high damping ratio provides poor isolation. Designers have to make a trade-off between resonance damping and high frequency isolation. To overcome this problem, a wide variety of semi-active and active suspension systems are proposed [4, 2, 3]. Many of former studies have addressed the possibility to attain good resonance attenuation without the penalty of increased transmissibility at higher frequencies. A typical semi-active suspension scheme requires a fast reacting damping device. However, such devices may be impractical and expensive for serial production vehicles. Furthermore, the possibility to use a slowly varying damping ratio would also provide advantages over a fully passive system. In this paper, a selective hydraulic damping valve (SHDV) is proposed. The term ‘selective’ emphasizes the step-shaped characteristic of the damping ratio. The proposed device is essentially a DC-motor-operated hydraulic valve with a selectable pressure-flow curve. The device is intended to be used in low-cost hydropneumatic suspension systems to provide a suitable damping ratio for different terrains and driving speeds.

STRUCTURE AND OPERATING PRINCIPLE OF SHDV

The SHDV is designed to work as a damping valve in hydropneumatic suspension systems. In a typical hydropneumatic suspension, the spring action is attained by means of a hydraulic accumulator connected to a double-acting cylinder. The damping action is attained by forcing the fluid flow through an orifice between the cylinder and accumulator. The level of the generated damping is dependent on the geometry of the orifice, the properties of the fluid and the flow rate. By using the SHDV it is possible to vary the cross-sectional area of the active orifice, thus a variable damping rate is possible. The damping rate should also be directionally asymmetric in various applications. In SHDV, the asymmetry is attained through the use of check valves which govern the path of the fluid flow.

Selective damping is typically realized through the use of standard on/off – valves. Three different damping rates will require at least two on/off – valves and two orifices. Asymmetric damping requires two additional valves and orifices. Also the flow directions need to be separated, which requires two check valves. The number of valves needed increases the total cost and space claim of the suspension system, especially in the applications with high flow rates. In the configuration described, the two damping states are achieved when one valve is open and the other is closed. The third state is then achieved by opening both valves, in what follows that the third state is dependent on the other states. This dependency might be undesirable in some applications and it can be avoided by adding one more on/off – valve and orifice in parallel with the other valves. However, adding valves increases the overall complexity and cost of the system.

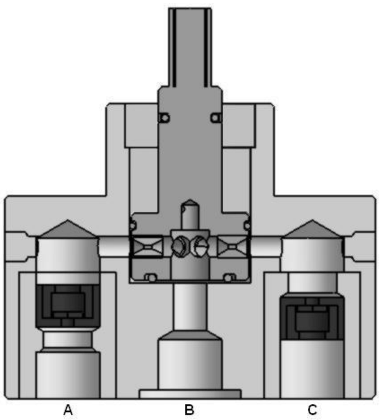

Figure - 1.a. SHDV

Figure - 1.b. The rotor

The SHDV consists comprised of two main components: the valve housing (stator) and the rotor. Six orifices are placed inside the rotor. The rotor has also a connection interface for a DC – motor or similar rotating device. Inside the stator there are two flow channels opposing each other and three flow channels (ports A, B and C) which can connect the SHDV to the surrounding hydraulic system. The stator also includes two check valves govern the flow direction. To ease the rotational movement of the rotor, a thrust bearing is placed between the rotor and stator. The seals are placed on the rotor. To ensure that the rotor does not stick when the SHDV is pressurized, the fluid is allowed to pressurize the chamber above the rotor, thus improving the hydraulic balance over the rotor.

The operating principle of the SHDV is based on the selectability of the active orifice. The rotor is rotated by means of a DC – motor to centralise the flow channels in the stator and rotor. With six orifices in the rotor (two of them working concurrently) three discrete damping rates are attained.

When the SHDV is connected to a suspension system, the ports A and C (See Fig. X) are connected together and the accumulator can be connected to port B. By connecting ports A and C, the check valves in the stator can be used to separate the flow directions: When fluid flows into port B, it flows out from port C; when fluid flows into port A, it flows out from port B. This enables directionally asymmetric damping.

Many suspension systems require two or more shock absorbers. Two SHDVs can be driven with one DC – motor. This simplifies the suspension system and reduces the space claim.

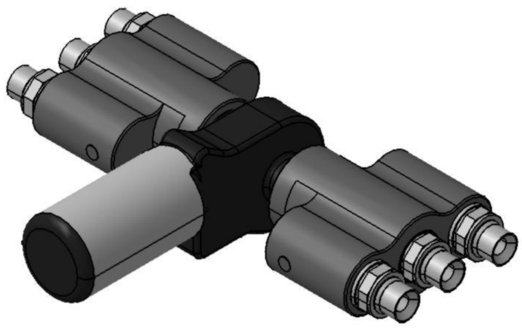

Figure - 2. Two SHDVs and a rotating actuator (DC-motor with gearbox).

PRESSURE LOSS MEASUREMENTS

To ensure that the SHDV can provide three discrete damping rates, each rate was measured. The measurement setup consisted of a hydraulic pump, flow meter and two pressure transducers. The flow meter was used to measure the flow rate going through the SHDV. The pressures before and after SHDV were measured by pressure transducers.

The results of the pressure loss measurements are plotted in figures 3a and 3b. Figure 3a shows all three discrete pressure losses with orifice diameters 1.4 mm, 1.7 mm and 2.0 mm when flows goes through SHDV from port C. There is also a theoretical pressure loss curve plotted for each orifice size and a fitted polynomial curve for each measurement. Picture 3b shows the same curves for the opposite flow direction (from port A to B).

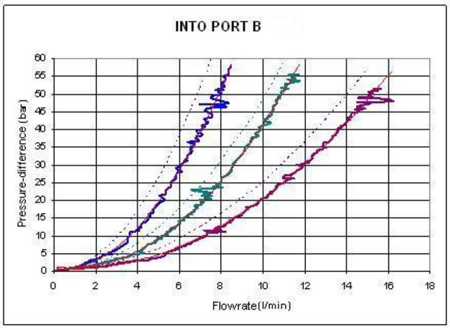

Figure – 3a. Pressure loss (port B)

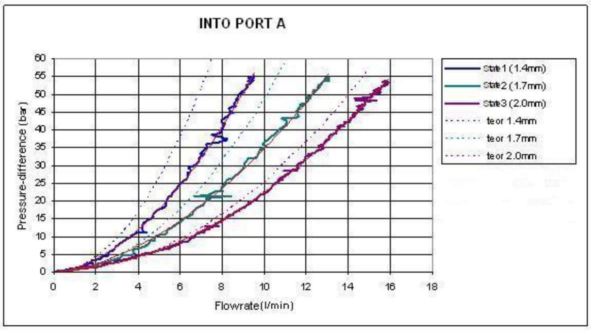

Figure – 3b. Pressure loss (port A)

CAB SUSPENSION PERFORMANCE TESTS

Test environment and test runs

A series of tests were conducted to provide "proof-of-concept". A typical passive hydropneumatic cabin suspension system was taken as a test base. The fixed size orifices in passive system were replaced by two SHDVs driven by a DC-motor (See Fig. 2). The sizes of the orifices were chosen on the basis of the prior knowledge for paved road and harsh terrain driving. Also a suitable orifice diameter for mixed terrain driving was tested.

The tests were conducted on a cab suspension test rig consisting of a two degree of freedom mechanism, which was attached to the cab by means of the suspension under consideration. The chassis of the test rig was driven by two electronically controlled hydraulic cylinders. Displacement controlled cylinders were able to replicate the vibration excitation measured from real driving conditions.

In addition to the SHDV, the suspension system also contained two hydraulic accumulators (volume 1.4dl, pre-charge pressure 40bar) and two hydraulic cylinders. The static and dynamic levelling was managed with a level control system.

Test runs were performed with two kinds of excitation. Both excitations were measured from a agricultural tractor chassis in real driving conditions (from field and from paved road) and reduplicated by the control system of the test rig. In all runs, acceleration was measured in three Cartesian directions from a test rig chassis and from the cabin floor. The acceleration data was saved to a computer.

Test results

Because the cab movement influences the movement of the test rig base, the excitations cannot be reduplicated exactly similarly when using different damping rates, therefore a suitable performance metric of the suspension is the relative transmissibility of acceleration in the frequency domain. With this representation, the 100% transmissibility means that there is no damping achieved (and no amplification either). The frequency band of interest is limited to 0.5 – 10 Hz.

Vertical direction

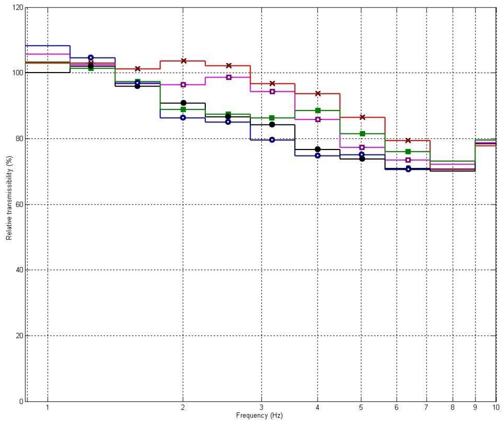

Figure - 4a. Transmissibility on Paved road

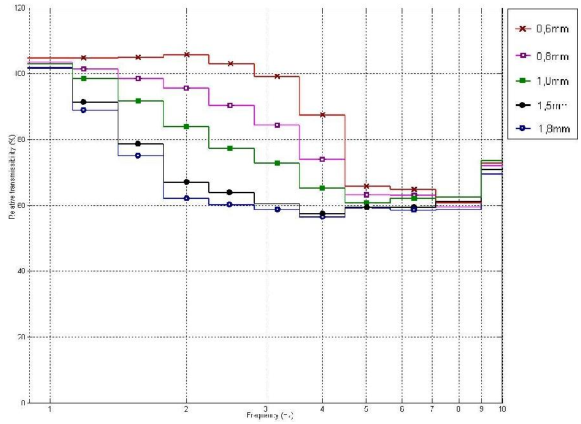

Figure – 4b. Transmissibility on field

The relative transmissibility of acceleration in vertical direction, with use of different size of orifice diameters is plotted in figures 4a and 4b. Figure 4a represents the accelerations transmitted from the chassis to the cab floor when driving on a paved road and figure 4b represents the accelerations transmitted when driving on a field.

The natural frequency of the suspension is about 1 Hz. In the vertical direction the relative transmissibility of acceleration tends to decrease when the system damping is decreased. This means improved ride comfort and it is easily notified when driving in a field. In the field drive the differences in relative acceleration with different damping configurations are as high as 50 %. When driving on a paved road the differences are smaller. This is attributed to the frictional forces within the cylinders.

None of the tested configurations amplified the vertical accelerations at frequencies over 3 Hz. At frequencies 5 – 6 Hz the differences are still in the class of 10-15%, but at this frequency band the change in damping rate doesn't have such a significant effect as it has at lower frequencies. At high frequencies (over 7 Hz) the configurations are performing almost equally regardless of the orifice diameter. That behaviour is somewhat unexpected, but it is probably related to the non-linear characteristics of the suspension. The excitation does not contain significant components at frequencies beyond 5 Hz, so the significance of the viscous damping reduces while the significance of the friction damping increases.

Horizontal direction

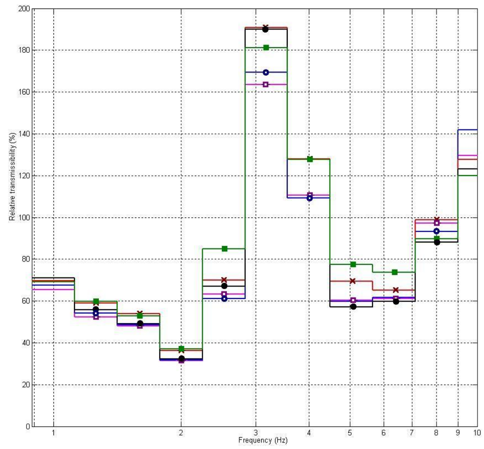

Figure – 5a. Transmissibility on paved road

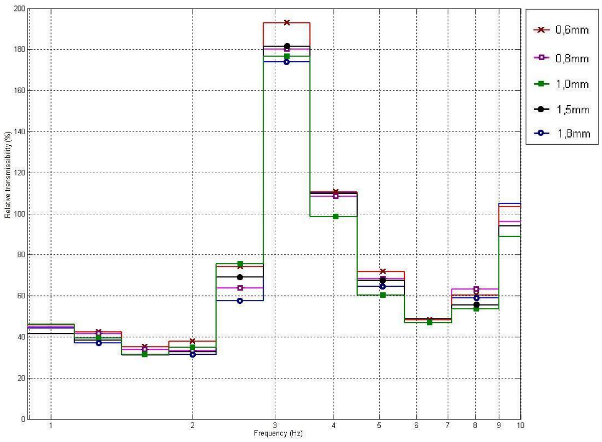

Figure – 5b. Transmissibility on field

Figures 5a and 5b represent the relative transmissibility of acceleration in the horizontal direction (sidewise direction), with use of different size of orifice diameters when driving on paved road and on field. The natural frequency of the suspension in a sidewise direction is in the order of 3 Hz. As can be seen in the Figure 5a and 5b there is not a strong linkage between the acceleration transmissibility and the damping rate.

In field driving the transmissibility is, despite the resonance region, about 10-15% lower than the same with driving on a paved road. The damping achieved at frequencies outside the resonance region is about 40-50% in both situations.

SUMMARY

The SHDV works as a controlled hydraulic orifice. If leaks inside the SHDV can be taken into account, the SHDV can produce the desired damping rates.

On the basis of the test conducted, it can be seen that when the amount of damping is decreased, the ride comfort is improved in the vertical direction. When driving on a paved road, the reduction of vibration level was about 15-20%, and when driving on a field damping was about 30-35%.

According to the cab suspension performance test results, the viscous damping rates in selective damping should be chosen to be as low as possible. The decreased amount of damping improves the ride comfort, but at the cost of increased risk of damper bottoming. End-stop impacts caused by the bottoming, are undesirable for suspension system mountings and impacts have undesirable effects on ride quality. The risk of end-stop impacts can be reduced, for example, by use of position-dependent damping. By choosing this position-dependent damping suitably, the viscous damping can be reduced substantially.

On a paved road decreasing the damping won't improve ride quality as dramatically as on a field. This is due to the high degree of friction damping. The proportion of the friction damping to viscous damping is high at low vibration levels. The only function of viscous damping is to damp down the sudden acceleration peaks arising from the obstacles.

The selective damping has no significant effect in the sidewise direction. Vibrations in the sidewise direction are going to amplify because the cab sits higher than the vehicle chassis. One possibility could be to completely restrict the sidewise movement of the cab to restrain the intensification of vibrations. A way to improve sidewise damping is to separate the vertical and sidewise damping into two independent systems.

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