Parameters control for the damping element hydraulic buffer of the vehicle suspension

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Abstract. The research investigates the impact coming from damping element hydraulic buffer of suspension on the vehicle smoothness. A change in the structural elements of hydraulic buffer for absorber rebound is considered in order to avoid hydraulic shock at the initial moment of its operation.

1. Introduction
In a modern car a lot of attention is paid to the driver’s and passengers’ comfort. Car suspension is one of the key elements largely responsible for this comfort, namely, for the transfer of the lowest possible road-induced loads and the noise that appears as the result of suspension operation [3, 4]. The entire range of suspension operation should be as imperceptible for a consumer as possible. As a rule, the suspension breakdown mode is the most noticeable one to the consumer. Most times this mode occurs in short stroke suspensions. At that, suspension bump stops generally define the impact and sound magnitude. This article covers the method of calculation of the hydraulic rebound stop design parameters aimed to decrease the noise and loads transferred to the auto body in case of suspension breakdown.

2. The method of research
In case of suspension breakdown, there is an evident direct interrelation between the load transferred to the vehicle body and the impact volume. Therefore, to ensure the minimal noise level caused by the suspension breakdown, it is necessary to provide the buffers’ optimal characteristics and their design parameters that would ensure the minimal loads transmitted to the auto body. Though in case of hydraulic buffers, due to its operation character, it is not enough to fulfill these conditions.
Figure 1. The shock absorber fluid flow during the hydraulic buffer operation. On the left: before closing the process chamber, on the right: after closing the process chamber.

When the hydraulic buffer is turned on, the shock absorber fluid that flows between the piston and the cylinder (Figure 1) starts flowing through the throttle slit, and, consequently, the fluid flow decelerates rapidly, which may cause the hydraulic impact phenomenon and by extension trigger the overpressure leading to the sharp increase of thrusts and a loud intense impact. Therefore, it is necessary to take this phenomenon into account when engineering a hydraulic buffer.

To avoid hydraulic impact at the moment of the hydraulic buffer closure, it is necessary for the pressure increase to be less than acceptable value $\Delta P_1 < [P]$, which, in its turn, is determined experimentally for each hydraulic rebound stop design:

$$\Delta P_1 = P_{H.I.} - P_0 \leq [P]$$

(1)

Where:
- $P_{H.I.}$ is the shock absorber fluid absolute pressure after the hydraulic buffer closure,
- $P_0$ is the shock absorber fluid absolute pressure before the hydraulic buffer closure.

When the hydraulic buffer process chamber is instantly closed by the piston, the pressure increase in the chamber will be determined by the Zhukovsky equation [5]:

$$\Delta P_1 = p \cdot c \cdot (V_0 - V_c)$$

(2)

Where:
- $V_0$ is the piston speed,
- $V_c$ is the speed of the fluid flowing from the chamber after the start of the buffer operation,
- $p$ is specific density of the liquid
- $c$ is shock wave propagation velocity

$$V_c = \frac{f_c V_s}{F_c}$$

(3)

$V_s$ is the speed of the fluid flowing through the slit,
$F_c$ is the ring area between the rod and the cylinder,
$f_s$ is the slit area.

We insert (3) $\rightarrow$ (2)
\[ \Delta P_1 = \rho \cdot c \cdot \left( V_0 - \frac{f_s V_s}{F_c} \right) \]  

(4)

The fluid outflow from the slit can also be described by the Bernoulli’s equation:

\[ \frac{1}{\gamma} \cdot (P_{H.I.} - P_0) + \left( \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right) = H_1 = N_p \]  

(5)

Where \( V_1 \) and \( V_2 \) are the rates of the shock absorber fluid flow at the entrance and in the throttle slit respectively,

\( \alpha_1 \) and \( \alpha_2 \) are the kinetic energy coefficients of the shock absorber fluid flow,

\( g \) is the gravitational acceleration,

\( H_1 \) is the inertial head,

\( N_p \) is the specific energy loss.

We neglect the head and the specific energy loss and get the following:

\[ \Delta P_1 = -\frac{\gamma}{2g} \cdot (\alpha_2 \cdot V_2^2 - \alpha_1 \cdot V_1^2) \]  

(6)

As at the start the flow rate was equal to zero (\( V_2=0 \)), we get the following from formula (6):

\[ \Delta P_1 = \frac{\alpha_1 \cdot p}{2} \cdot V_s^2 \]  

(7)

\( \rho \) is the shock absorber fluid density.

This way we can determine the flow rate through the throttle slit:

\[ V_s = \sqrt{\frac{2 \cdot \Delta P_s}{\alpha_1 \cdot p}} \]  

(8)

To calculate the minimum possible throttle slit area, we insert (8) \( \rightarrow \) (4).

\[ \Delta P_1 = p \cdot c \cdot \left( V_0 - \sqrt{\frac{2 \cdot \Delta P_s \cdot f_s}{\alpha_1 \cdot p}} \right) \Rightarrow \frac{\Delta P_s}{p \cdot c} = V_0 = \sqrt{\frac{2 \cdot \Delta P_s \cdot f_s}{\alpha_1 \cdot p}} \Rightarrow f_s = \left( V_0 \cdot \frac{\sqrt{\alpha_1 \cdot p}}{\sqrt{2 \cdot \Delta P_s}} \right) \cdot \frac{1}{c^2 \cdot \sqrt{2 \cdot p}} \cdot F_c \]  

(9)

That means

\[ f_s \geq \left( V_0 \cdot \frac{\sqrt{\alpha_1 \cdot p}}{\sqrt{2 \cdot |p|}} \right) \cdot \frac{1}{c^2 \cdot \sqrt{2 \cdot p}} \cdot F_c \]  

(10)

Therefore, to exclude hydraulic impact at the hydraulic buffer startup the throttle slit area must be no less than \( f_s \). Otherwise there is a high probability of a hydraulic impact occurrence.

In accordance with the obtained formula the throttle slit was calculated for the hydraulic buffer that creates the thrust absorbing the impact due to the flow of the shock absorber fluid through the annular gap between the walls of the working cylinder and its piston, at the initial speed of 1.5 m/s. For the buffer of this particular design (\( f_s \geq 7.5 \text{ mm}^2 \))

Figure 2 shows two hydraulic buffer flowcharts recorded at the speed of 1.5 m/s. The characteristic indicated by the solid line shows the hydraulic buffer with the minimum annular gap equal to \( f_s^{\text{min}} \approx 5 \text{ mm}^2 \), the characteristic indicated by the dotted line corresponds to \( f_s^{\text{max}} \approx 9 \text{ mm}^2 \), straight lines represent the theoretical thrusts based on the previously recorded hydraulic buffer characteristics.
Figure 2. Hydraulic buffer flowchart. Dotted line: the throttle slit area is 9 mm$^2$, solid line: the throttle slit area is 5 mm$^2$.

The charts show the thrusts overshoot for the hydraulic buffer with the throttle slit smaller than the calculated one ($f_s^{\text{min}} < f_s$) and the absence of the overshoot for the hydraulic buffer with the throttle slit chosen according to the calculation ($f_s^{\text{max}} > f_s$).

But it is not always possible to meet this condition, as throttle slits of smaller area must be used to provide the optimum characteristic, which causes hydraulic impact at the hydraulic buffer startup. To decrease the hydraulic impact intensity in these structures, one uses a smooth closing of a process chamber with a hydraulic buffer piston using a relief passage (Figure 3).

Figure 3. The shock absorber fluid movement during the hydraulic buffer operation. On the left: before closing the process chamber, on the right: after closing the process chamber, in the middle: when the piston goes through the relief chamber.
In which case there will be the phenomenon of an indirect hydraulic impact \([5, 6]\) described by the formula:

\[
\Delta P_1 = \rho \cdot c \cdot (V_0 - V_c) \cdot \frac{T}{t} \leq [P] \tag{11}
\]

Where \(T\) is the impact wave propagation time, 
\(t\) is the time of movement of the piston through the relief chamber.

\[
V_0 = \frac{dh}{dt} \tag{12}
\]

\(h\) is the relief chamber length.

While the piston goes through the relief chamber, its speed is \(V_0 \approx \text{Const}\), so, correspondingly, we can write the following:

\[
t = \frac{h}{V_0} \tag{13}
\]

As the length of chamber \(l\) (Figure 3), which consists of the process and relief chambers, decreases, the wave propagation time will be less than

\[
T < \frac{2l}{c} \tag{14}
\]

Therefore,

\[
\Delta P_1 < \rho \cdot c \cdot (V_0 - V_c) \cdot \frac{2lV_0}{ch} \tag{15}
\]

If the right part of the inequation is no more than \([P]\), then condition \(\Delta P_1 < [P]\) will be fulfilled. Given this,

\[
\rho \cdot (V_0 - V_c) \cdot \frac{2lV_0}{h} \leq [P] \tag{16}
\]

Therefore,

\[
h \geq \frac{\rho(V_0 - V_c) \cdot 2lV_0}{[P]} \tag{17}
\]

We insert (2) and (7) into (15) and get the following:

\[
h \geq \frac{\rho \left( V_0 - \frac{2[P][\omega_k]}{\alpha_1 \rho F_c} \right) 2lV_0}{[P]} \tag{18}
\]

Where \(\omega_k\) is the area of the throttle slit that provides minimal loads transmitted to the auto body in case of suspension breakdown.

Taking into account that \(l = H + h\), we get the final formula to calculate the relief chamber length:

\[
h \geq \frac{2\rho V_0 \left( V_0 - \frac{2[P][\omega_k]}{\alpha_1 \rho F_c} \right) H}{[P] - 2\rho V_0 \left( V_0 - \frac{2[P][\omega_k]}{\alpha_1 \rho F_c} \right)} \tag{19}
\]

Thus, the relief passage chosen in accordance with formula (19) excludes the occurrence of hydraulic impact during the operation of the hydraulic buffer with the throttle slit with the smaller area than the area calculated in accordance with formula (11).

For example, the hydraulic buffer design that was considered previously \((\omega_s < f_\delta)\) requires a relief chamber with the length no less than 0.2 mm to exclude a hydraulic impact.
Figure 4. Hydraulic buffer flowchart. The throttle slit area is $5 \text{ mm}^2$. The dotted line represents the buffer with a relief chamber, the solid one represents the buffer without a chamber.

Figure 4 shows the flowcharts of this hydraulic buffer recorded at the speed of $1.5 \text{ m/s}$. The characteristic indicated by the solid line shows the hydraulic buffer with the annular gap equal to $(\omega_s \approx 5 \text{ mm}^2)$, with no relief chamber; the dotted line indicates the characteristic of the same buffer, but with the $1 \text{ mm}$ long relief chamber.

The charts show that if a design has a relief passage chosen in accordance with formula (19), it excludes hydraulic impact at the initial phase of the hydraulic buffer operation.

3. Conclusion

Therefore, in the process of performing the work the formulas were derived to calculate the hydraulic buffer design parameters allowing to avoid hydraulic impact at the initial phase of the hydraulic buffer operation, with any optimum areas of throttle section.

References

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