Method of calculating the adaptive damper of the pneumohydraulic spring for the suspension of a high-speed vehicle

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Abstract. This work contains a description and method of calculating the pneumohydraulic spring with the adaptive damper, which is self-regulating depending on the amplitude, frequency, and direction of oscillation of the suspension of a high-speed vehicle on a wheeled and tracked drive.

1. Introduction

In connection with the development of engine-building technology, there is an increase in the average speeds of high-speed vehicles (HSV) on a wheeled and tracked drive. However, the possibility of their implementation largely depends on the quality of the suspension system. When the quality of the suspension is unsatisfactory, the driver is forced to reduce the speed due to excessive overload or high fatigue. Additional requirements to the suspension are also imposed when HSV moves with frequent “fly out” and subsequent “landings” after overcoming the springboards. To meet all these requirements, the pneumatic-hydraulic suspensions with adjustable damping are most suitable. However, in the practice of mechanical engineering there are no simple technical solutions to this complex technical problem [1-5].

2. Description of the design of the pneumohydraulic spring

At the “Automatic Installations” department of Volgograd State Technical University, the design of a pneumohydraulic spring (PHS) for HSV suspension was developed. It provides adaptive self-regulation of damping depending on amplitude, frequency, and direction of oscillations (Figure 1) [6].

PHS consists of hydraulic 1 and pneumohydraulic 2 cylinders installed in housing 3, piston 4 with rod 5 and floating piston 8. The piston cavity 6 and the hydraulic cavity 9 are constantly communicated with each other through the opening 14 made in the housing, the longitudinal channel 11 and the main orifice hole 15 with great resistance. In addition, cavities 6 and 9 can periodically communicate in a parallel line, since the longitudinal channel 11 communicates with the cavity 9 through the transverse channel 16, the valve of the maximum compression stroke 18, the valve of the maximum rebound stroke 26 and the additional orifice hole 17 with low resistance. Valves 18 and 26 are made in the form of spring-loaded stepped plungers with time delay systems for returning them to their original position, designed for 1.5...2 periods of natural oscillations of the vehicle body.

When PHS operates with small amplitudes, valves 18 and 26 are constantly open, so the fluid between
Cavities 6 and 9 flows with low resistance through the main 14 and additional 17 orifice holes.

When large oscillation amplitudes occur, the valves 18 and 26 close the transverse channel 16 and the liquid between the cavities 6 and 9 flows with great resistance only through the main orifice hole 15. At the same time, during compression of PHS, the plunger 18 moves up to the stop under the action of high pressure, additionally compressing the spring 23, and during PHS rebound stroke, the plunger 26 moves down to the stop under low pressure. After reducing the oscillations of the PHS, valves 18 and 26 are opened.

**Figure 1.** Pneumohydraulic spring with the adaptive self-regulating damping unit.

3. **Determining the response conditions of the valve of the maximum compression stroke**

The method of calculating the adaptive self-regulating damping unit of PHS unit consists in determining the response conditions of valves 18 and 26 depending on the amplitude, frequency, and direction of vibration of the suspension.

It is necessary to know the elastic characteristic of the suspension, which equations for deformations along the coordinates \( \lambda \) and \( h \) have the following form:

\[
P_r = \left( \frac{V_{in}}{V_{in} - F \lambda h^i} \right)^n \frac{p_{in} F}{i}
\]

or

\[
P_r = \left( \frac{V_{st}}{V_{st} - F \lambda h^i} \right)^n \frac{p_{st} F}{i},
\]

where \( p_{in} \) and \( V_{in} \) – initial pressure and initial volume of gas; \( p_{st} \) and \( V_{st} \) – pressure and volume of gas in the spring under static load; \( n \) – polytropic coefficient (for PHS with a floating piston \( n = 1.3 \ldots 1.4 \)); \( F \) – the area of the spring displacer (piston or rod); \( i \) – gear ratio in the suspension; \( \lambda \) – the crawler wheel stroke on the compression stroke from a fully stretched PHS; \( h \) – the crawler wheel stroke from the static position (in the compression stroke, it is taken with “+” sign, in the rebound stroke with “−” sign).

To calculate the parameters of valve 18 (anti-vibration suspension valve with a large amplitude), let us specify the condition for its operation (closing) by moving upward depending on the magnitude of the compression stroke:

\[
h \geq \Delta,
\]

where \( \Delta \) – the most probable amplitude of suspension deformations when moving the HSV on a relatively flat road surface causing acceleration of “shaking” (for example, equal to 5 cm).

Then the pressure of the beginning of the closing of the valve 18 is determined by the dependencies:
This pressure corresponds to the force of the preload of the spring 23:

\[ P_{spr1} = p_1 F_{pl1} = \left( \frac{V_{st}}{V_{st} - F \Delta i} \right)^n \cdot P_{st}, \]

where \( F_{pl1} \) – the area of the smaller step of the plunger 18.

\[ P_{spr1} = c_1 x_{01}, \]

where \( c_1 \) – the stiffness of the spring 23; \( x_{01} \) – the value of the pre-compression of the spring 23.

Values \( F_{pl1}, c_1 \) and \( x_{01} \) are selected on the basis of the layout of the valve 18 in the housing 3 and the minimum diameter of the smaller step of the plunger 18.

A check valve 24 is installed in the bigger step of the plunger 18; it is made in the form of a spring-loaded plate with a throttle 25, the diameter of which is determined from the following equation:

\[ P_{spr1} = \Delta p_{pl1} F_{pl,c1} = \frac{\rho F_{pl,c1}^3}{2 \mu^2 f_{thr}^2} \cdot v_{pl1}^2, \]

where \( F_{pl,c1} \) – the cross-sectional area of the circular cavity of the plunger 18; \( \Delta p_{pl1} \) – pressure drop at a bigger step of the plunger 18 between the cavities 20 and 21; \( \rho \) – density of the liquid (\( \rho = 0.85 \text{ g/cm}^3 \)); \( \mu \) – flow coefficient (for PHS \( \mu = 0.8 \ldots 0.9 \)); \( f_{thr} \) – the cross-sectional area of the throttle 25; \( v_{pl1} \) – the speed of plunger 18 by downforce of the spring 23, provided that the pressures in cavities 9 and 10 are smaller than \( p_1 \).

The plunger speed can be found from the equation:

\[ v_{pl1} = \frac{\delta_1}{t_{open1}} = \frac{\delta_1}{(1...3)T} = \sqrt{\frac{g n F}{i V_{st}}} \cdot \frac{\delta_1}{(1...3)2\pi}, \]

where \( \delta_1 \) – full stroke of the plunger 18; \( t_{open1} \) – the opening time of the plunger 18 (equal to 1 ... 3 periods of suspension oscillation); \( T \) – period of natural oscillations of the spring; \( g \) – gravitational acceleration.

With the speed \( v_{pl1} \) and knowing the force of compression of the spring 23 with the valve 18 closed, it is possible to determine the area of the orifice hole in the check valve 24:

\[ f_{thr1} = \frac{\rho F_{pl,c1}^3}{2 \mu^2 P_{spr1}^2} \cdot v_{pl1}, \]

where \( P_{spr1}^* \) – preload force of the spring 23 when the valve 18 is closed,

\[ P_{spr1}^* = c_1 (x_1 + \delta_1). \]

Then the diameter of the orifice hole in the check valve 24 is calculated by the formula:

\[ d_{thr1} = \sqrt{\frac{4 f_{thr1}}{\pi}}. \]

4. Determining the response conditions of the valve of the maximum rebound stroke
To calculate the parameters of the valve 26 (valve for protection against breakdown of the suspension after the full expansion of the PHS when the crawler wheels are separated after overcoming the springboard and subsequent landing) we set the condition for its activation (closing) by moving downwards, depending on the rebound stroke:

\[ h \geq -\Delta_{reb}, \]

where \( \Delta_{reb} \) – the amount of tension of PHS when it is necessary to close the valve 26 (for example, equal to 80% of the static suspension stroke).
Then the pressure of the beginning of the closing of the valve 26 is determined by the dependencies:

\[ P_2 = \frac{V_{st}}{V_{st} + F \Delta_{reb}} \cdot P_{st}, \]

(12)

This pressure corresponds to the force of the preload of the spring 31:

\[ P_{spr} = P_2 F_{pl2} = \left( \frac{V_{st}}{V_{st} + F \Delta_{reb}} \right)^n \cdot P_{st} F_{pl2}, \]

(13)

where \( F_{pl2} \) – the area of the smaller step of the plunger 26.

\[ P_{spr} = c_2 x_{02}, \]

(14)

where \( c_2 \) – spring stiffness 31; \( x_{02} \) – the amount of pre-compression of the spring 31.

Values \( F_{pl2}, c_2 \) and \( x_{02} \) are selected on the basis of the layout of the valve 31 in the housing 3 and the minimum diameter of the smaller step of the plunger 26.

A check valve 32 is installed in the bigger step of the plunger 26, it is made in the form of a spring-loaded plate with a throttle 33, the diameter of which is determined from the following equation:

\[ P_{spr} = \Delta P_{pl2} F_{pl,c2} = \frac{\rho F_{pl,c2}^2}{2\mu^2 f_{thr}^2} \cdot V_{pl2}, \]

(15)

where \( F_{pl,c2} \) – the cross-sectional area of the circular cavity of the plunger 26; \( \Delta P_{pl2} \) – pressure drop at a bigger step of the plunger 26 between the cavities 28 and 29; \( v_{pl2} \) – the speed of plunger 26 by downforce of the spring 31, provided that the pressures in cavities 9 and 10 are bigger than \( p_2 \).

The plunger speed can be found from the equation:

\[ v_{pl2} = \frac{\delta_2}{t_{open2}} = \frac{\delta_2}{(1...3)T} = \sqrt{\frac{gnF}{iV_{st}}} \cdot \frac{\delta_2}{(1...3)2\pi}, \]

(16)

where \( \delta_2 \) – full stroke of the plunger 26; \( t_{open2} \) – the opening time of the plunger 26 (equal to 1 ... 3 periods of suspension oscillation).

With the speed \( v_{pl2} \) and knowing the force of compression of the spring 31 with the valve 26 closed, it is possible to determine the area of the orifice hole in the check valve 32:

\[ f_{thr} = \frac{\sqrt{\rho F_{pl,c2}^2 \cdot V_{pl2}}}{2\mu^2 P_{spr}^2}, \]

(17)

where \( P_{spr}^* \) – preload force of the spring 23 when the valve 18 is closed,

\[ P_{spr}^* = c_2 (x_2 + \delta_2). \]

Then the diameter of the orifice hole in the check valve 24 is calculated by the formula:

\[ d_{thr} = \frac{4f_{thr}}{\pi}. \]

(19)

The damping characteristic of the PHS is calculated by the formula:

\[ R_r = \frac{\rho F^3}{2\mu^2 f_0^2 i^2 \cdot \nu_r^2}, \]

(20)

where \( f_0 \) – the area of the orifice hole in the head of the PHS; \( \nu_r \) – the speed of the crawler wheel vertical movements.
5. Calculating the main parameters of the PHS with an adaptive self-regulating damping unit

Below you can see an example of calculating the main parameters of the PHS with an adaptive self-regulating damping unit for pneumatic-hydraulic suspension of HSV with the following initial data:

- static volume of gas $V_{st} = 270 \text{ cm}^3$;
- piston area $F = 19.63 \text{ cm}^2$;
- full suspension stroke $h_{full} = 32 \text{ cm}$;
- suspension ratio $i = 2.5$;
- static pressure $p_{st} = 10 \text{ MPa}$;
- stepped plungers 18 and 26 have the same dimensions: $d_{pl1} = 6 \text{ mm}$ and $d_{pl2} = 22 \text{ mm}$.

Diagrams of static and dynamic elastic characteristics of pneumatic-hydraulic suspension received using the calculation by the formula (1) are shown in Figure 2.

![Figure 2. Elastic characteristics of HSV pneumohydraulic suspension: 1 – static characteristic $(n = 1)$; 2 – dynamic characteristic $(n = 1.39)$.

From condition (2) let us set the trigger parameter of valve 18 during the course of compression of the suspension from the static position $\Delta = 5 \text{ cm}$. Then it follows from the formula (3) that the pressure at which the valve 18 starts to close is $p_1 = 12.45 \text{ MPa}$. This pressure with the area of the smaller step of the plunger 18 $F_{pl1} = 0.283 \text{ cm}^2$ corresponds to the force of the preliminary compression of the spring 23 $P_{spr1} = 352 \text{ N}$.

Knowing the force of the preload of the spring 23, you can choose the spring itself according to GOST 18793, or, knowing the outer diameter, length and stroke of the spring, to design your own spring.

In our case, the spring 23 has the following parameters (Figure 3): outer diameter $D_{out} = 18 \text{ mm}$, bar diameter $d = 2 \text{ mm}$, inner diameter $D_{in} = 14 \text{ mm}$, length without load $l_0 = 322 \text{ mm}$, test length $l_1 = 92 \text{ mm}$, spring force at $l_1$ $F_1 = 352.55 \text{ N}$, test length $l_2 = 80 \text{ mm}$, spring force with $l_2$ $F_2 = 370.94 \text{ N}$, length in compressed state $l_3 = 53 \text{ mm}$, spring force with $l_3$ $F_3 = 412.33 \text{ N}$, distance between turns $t = 12.76 \text{ mm}$, working number of turns $n = 25 \text{ pcs.}$, spring stiffness $c_1 = 1.53 \text{ N/mm}$, material – steel 60C2A GOST 14959-79.

When the valve 18 opening time is $t_{open} = 2T$, according to the formula (7), the speed of plunger movement is $v_\text{pl1} = 0.6 \text{ cm/s}$.

Knowing the speed $v_\text{pl1}$ and the force of compression of the spring 23 with the valve 18 closed, it is possible to determine the area of the orifice hole in the check valve 24 according to the formula (8): with an circular area of plunger $18 F_{pl1} = 1.72 \text{ cm}^2$, the area of the orifice hole $f_{eh1} = 5.4 \times 10^{-4} \text{ cm}^2$. This area, according to the formula (10), corresponds to the diameter of the orifice hole in the check valve 24 $d_{eh1} = 0.26 \text{ mm}$. 
To calculate the parameters of the valve 26 (valve for protection against breakdown of the suspension after the full expansion of the PHS when the crawler wheels are separated after overcoming the springboard and subsequent landing) we set the condition for its activation (closing) by the suspension rebound when $\Delta_{reb} \geq 10$ cm. Then, according to the formula (12), the pressure of the beginning of closing of the valve is $p_2 = 7$ MPa. This pressure with the area of the smaller step of the plunger 26 $F_{pl1} = 0.283$ cm$^2$ corresponds to the force of the preliminary compression of the spring 31 $P_{spr2} = 198$ N.

Knowing the force of the preload of the spring 31, you can choose the spring itself according to GOST 18793, or, knowing the outer diameter, length and stroke of the spring, to design your own spring.

In our case, the spring 31 has the following parameters (Figure 4): outer diameter $D_{out} = 18$ mm, bar diameter $d = 1.8$ mm, internal diameter $D_{in} = 14.4$ mm, length without load $l_0 = 214$ mm, test length $l_1 = 62$ mm, spring force at $l_1$ $F_1 = 184.09$ N, control length $l_2 = 50$ mm, spring force at $l_2$ $F_2 = 198.62$ N, length in compressed state $l_3 = 38.7$ mm, spring force at $l_3$ $F_3 = 212.31$ N, distance between turns $t = 10.57$ mm, working number of turns $n = 20$ pcs., spring stiffness $c_1 = 1.21$ N/mm, material – steel 60C2A GOST 14959-79.

When the opening time of the valve 26 is $t_{open1} = 2T$, according to the formula (16), the speed of movement of the plunger 26 is equal to the speed of movement of the plunger 18: $v_{pl1} = v_{pl2} = 0.6$ cm/s.

Knowing the speed $v_{pl2}$ and the force of compression of the spring 31 with the valve 26 closed, it is possible to determine the area of the orifice hole in the check valve 26 according to the formula (17): with an circular area of plunger 26 $F_{pl2} = 1.72$ cm$^2$, the area of the orifice hole $f_{thr2} = 7.2 \times 10^{-4}$ cm$^2$. This area, according to the formula (19), corresponds to the diameter of the orifice hole in the check valve 26 $d_{thr1} = 0.3$ mm.

The damping characteristics of this suspension, calculated by the formula (20) with the valves 18 and 26 open and closed, are shown in Figure 5. These characteristics are received with the following initial data: diameter of the main orifice hole $d_{main} = 5$ mm; diameter of additional orifice hole $d_{add} = 10$ mm.
Figure 5. Damping characteristic of PHS: $R_1$ – with valves 18 and 26 closed during compression stroke; $R_2$ – with valves 18 and 26 opened during compression and rebound strokes.

5. Conclusions
The designed PHS has a simple structure with a damping unit that is self-regulating in amplitude, direction and frequency of oscillation and allows one to significantly reduce the acceleration of "shaking" when moving along small irregularities (valves 18 and 26 are open), virtually eliminating suspension breakdowns. It happens when a vehicle body has large vertical and angular vibrations (valve 18 is closed). It allows dampening maximally the suspension after full extension of the rod (valve 26 is closed) when HSV moves in wheel or caterpillar mode through springboards with pull-off wheels or crawler wheels from the supporting surface.

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