Properties of New Adaptive Suspension of Vehicles

A. Dubrovskiy, S. Aliukov, S. Dubrovskiy and A. Alyukov

***Abstract*— Currently, a group of scientists consisting of six doctors of technical sciences, professors of South Ural State University (Chelyabinsk, Russia) has completed a cycle of scientific research for creation of adaptive suspensions of vehicles. We have developed design solutions of the suspensions. These solutions allow us to adjust the performance of the suspensions directly during movement of a vehicle, depending on road conditions - either in automatic mode or in manual mode. We have developed, researched, designed, manufactured, and tested experimentally the following main components of the adaptive suspensions of vehicles: 1) blocked adaptive dampers and 2) elastic elements with nonlinear characteristic and with improved performance. Applications of our developed designs are as follows: suspensions of almost all vehicles (trucks, cars, buses and so on), except "waterfowl", and high-speed tracked vehicles, including special purpose and trailers, aircraft for various purposes, rail transport, particularly high-speed one, motorcycles, etc. Application of our designs will allow harmonizing by optimal way the various performance requirements for vehicles, which are often contradictory: requirements on smoothness and comfort ride, rapidity, stability and control, traffic safety, values of dynamic loads acting on components and units of vehicles, stabilization of their movements and body position. In this paper we analyze the main features of the performance of our designs of adaptive shock absorbers and elastic elements, results of our theoretical and experimental studies.**

***Index Terms*— Suspension, new principle of action, characteristics**

I. Introduction

While designers create a suspension system of a vehicle, they always have to solve the problem of reconciling of two groups of conflicting requirements [1]:

1. Requirements to ensure a given level of smoothness, rapidity, minimize dynamic loads acting on the cargo, nodes, passengers and drivers of the vehicle;

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2. Requirements of manageability, security, stability, stabilization of the vehicle, stabilization of its body.

Besides, it is well known that to reconcile the conflicting requirements mentioned above, it is possible to do the most effectively only if to provide the following three conditions:

1. The suspension system of the vehicle has to contain an elastic element with nonlinear characteristic [2].
2. The suspension system of the vehicle has to contain an adaptive shock absorber with ability to control its performance in accordance with traffic situation while the vehicle moves.
3. When designing the suspension system of the vehicle, it is necessary to ensure optimal coordination of the performance parameters of the elastic element with nonlinear characteristic and the adaptive shock absorber of the suspension of the vehicle, as well as to implement an optimal control algorithm for the adaptive shock absorber.

Analysis of existing approaches to solve this problem in the area of transport engineering practice has shown that there is no yet any optimal, economically acceptable solution for practical realization of these requirements, mentioned above, as well as implementation of these three conditions [3-6]. However, it seems that the implementation of our suggestions will significantly move towards the solution to this complex problem [7-10].

The main aim of our paper is to introduce working characteristics of our developed vehicle suspension and to show its advantages in comparison with existing ones. We do it on example of experimental research with Russian passenger cars named cars VAZ "LADA-GRANTA" and "LADA-KALINA."

Suspension of vehicles equipped with these two nodes, in view of the obvious, essential, fundamental advantages analyzed below, we will henceforth call conditionally as adaptive suspension system of vehicles. We have installed the developed design of the suspension on the cars named VAZ "LADA-GRANTA" and "LADA-KALINA."

II. Main Functional Advantages of our Developed Designs

Lockable adaptive shock absorber with a hyper-wide control range of dissipative characteristics

We list the main functional advantages of our developed shock absorbers in comparison with the existing designs.

1. They allow us to implement the hyper-wide control range of dissipative characteristics depending on value of the first control parameter, namely: the value of "control current" on a coil of electro-hydraulic valve:

• from characteristics of clearly specified, the lowest level of damping;

• to characteristics up to the highest level of damping mode until the "self-locking," when the shock absorber is converted into a single rigid unit, and thus it has an "very high level of damping."

2. They allow us to realize the "self-blocking" mode at any time.

3. Depending on the magnitude of the second control parameter, namely: position of piston, they can implement the following features:

• they allow us to implement any pre-defined dissipative characteristics of the marked hyper-wide control range of the dissipative characteristics in intermediate positions of the piston corresponding to "comfort zone";

• degree of damping of the shock absorbers automatically progressively increases while the piston is approaching to extreme positions, regardless of the magnitude of the control parameter, namely, value of "control current" on the coil of the electro-hydraulic valve;

• they are automatically "self-locking" in a unilateral direction in the extreme positions of the piston.

4. In total, the transition from conventional shock absorbers to usage of our proposed designs of the adaptive shock absorbers does not suppose any increasing of size of existing designs of regular suspension devices of vehicles, and it does not require any significant investments. «Issue price», basically, is the cost of the electro-valve, not taking software into consideration.

How can the shock absorber automatically switch operating modes between a softer and stiffer characteristic, which also includes a maximum “lockout mode”? To solve this problem we have invented new designs of the absorber. These designs are described in patent #2469225RF, #2474739RF, and #2479766RF. In the designs permitted tensions in elastic elements typically do not exceed 800 MPa. The internal pressures in which this damper would be operating, during the “lockout mode” is low enough to provide reliable operating of the damper. We have proved this claim with help of experimental studies. What are the inputs that the damper is adjusting to? They are road conditions and modes of driving of the vehicle.

The resilient element with nonlinear characteristic and automatic optimization of localization of "working zones"

The developed designs of the elastic elements, unlike the well-known ones, have the following advantages:

1. They have significantly non-linear characteristic, which consists of several separate intervals.

2. The basic operating interval («comfort zone») has a very low stiffness. In existing designs we have decreased the stiffness in this interval more than two times in comparison with the known analogs.

3. The subsequent intervals have stiffness in several times larger than in the known analogs.

4. In «spring designs» conventional cylindrical springs with constant pitch winding and constant diameter of the wire are used.

5. The design of the elastic element allows automatically, consistently excluding from further work those intervals, tensions at which have reached a predetermined maximum value. In other words, the design of elastic elements possesses the peculiar property of automatically optimization of localization of the "working zones."

III. Experimental Results

As an example, let us consider the developed experimental model of the elastic element for the front suspension of the car VAZ 2116 "LADA-KALINA" (Figure 1).

Elastic element of the car VAZ 2116 «LADA-KALINA» (prototype) has the following parameters:

$$F_{max} = 5684.9 \text{ N}; \ f_{max} = 0.155 \text{ m}; \ F_S = 3481.36 \text{ N}; \ f_S = 0.048 \text{ m}; \ c_p = 20.59 \text{ N/mm}.$$

Here f_S is deformation of the elastic element corresponding to static load F_S acting on the car; f_{max} is deformation of the elastic element corresponding to the highest load F_{max} acting on the car; and c_p is stiffness of the elastic element (prototype) of the car VAZ 2116 «LADA-KALINA".

Operating characteristic of the elastic element (prototype) is linear, and in Fig. 1 marked in red. But operating characteristic of the developed experimental model of the elastic elements for the front suspension of the car VAZ 2116 «LADA-KALINA" is nonlinear and consists of three line segments. In Figure 1 it is marked in blue.

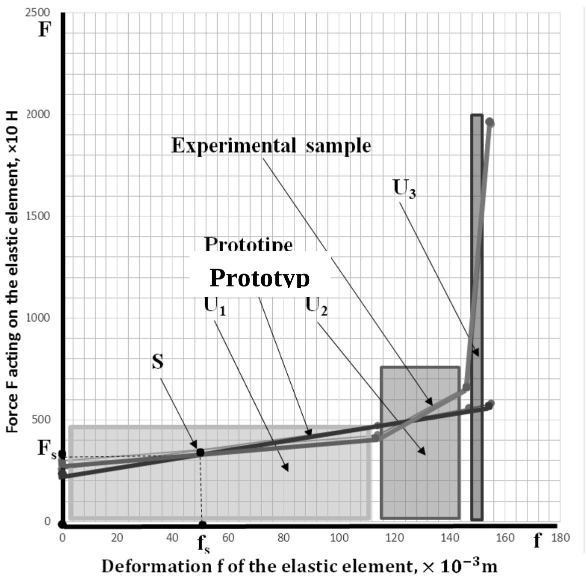

Fig. 1. Comparison of theoretical and experimental results

Commenting on the main design features of the developed experimental model of the elastic elements, it is necessary to pay attention primarily on the following points:

1. In zone U_1 (zone of comfort) stiffness c_1 of the developed experimental model of the elastic element is 10.438 N/mm; consequently the ratio $K_c = c_1 / c_p$, where c_p is stiffness of considered part of the elastic element of the prototype, in this case is as follows

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$$K_{c,U1} = c_1 / c_p = 0.522. \qquad (1)$$

2. In zone U_2 of increased deformations the stiffness c_2 of the developed experimental model of the elastic element is 73 N/mm; consequently the ratio (6) in this case is as follows

$$K_{c,U1} = c_1 / c_p = 3.48. \qquad (2)$$

3. In zone U_3 of high deformations the stiffness c_3 of the developed experimental model of the elastic element is 1610.438 N/mm; consequently the ratio (6) in this case is as follows

$$K_{c,U1} = c_1 / c_p = 76.7. \qquad (3)$$

Thus, as expected, in a broad operational area in the comfort zone U_1, the stiffness of the suspension of the developed experimental model of the car, according to (1), almost is half the stiffness of standard suspension of the car VAZ 2116 «LADA-KALINA". That undoubtedly leads to qualitative improvement of the comfort of the car. However, in the zone of increased deformations U_2, according to (2), the stiffness of the suspension of the developed experimental model of the car is already 3.48 times higher than that of the standard. This fact facilitates faster "pacification" of vibrations of body of the car. And this property is even more enhanced in the zone U_3 of high deformations. In this zone, in accordance with (3), the stiffness of the suspension of the developed experimental model of the car is 76.7 times higher than that of the standard.

And it is very important that, as expected, in our developed designs of elastic elements, maximum stresses in these elements do not exceed 800 MPa.

Fig. 2 shows the experimental work characteristics of one of designs of the blocked adaptive shock absorber designed for rear suspension of the car Lada Kalina. This Figure indicates that the following has place: 1. The regulation of the work characteristics of the adaptive shock absorber is continuous (as opposed to stepped); 2. We can implement any characteristic of the set.

In Fig. 2 the characteristic r2 is working characteristic of shock absorber of rear suspension of the car Lada Kalina.

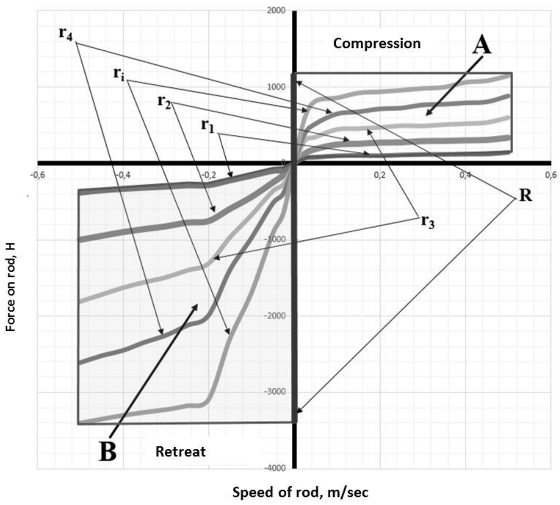

Fig. 2. Work characteristic of adaptive shock absorber

IV. Operating Characteristics of the Developed Units of the Adaptive Suspension

The lockable adaptive shock absorber with a hyper-wide control range of dissipative characteristics

If we characterize the structure of a family of our developed adaptive shock absorbers, it can be concluded that structurally the shock absorbers consist of two interconnected main components:

- the actual shock absorber, i.e. piston-cylinder unit, and
- the electro hydraulic valve.

These two components have different effects on formation of four main variants of operational control of the work (dissipative) characteristics of the shock absorbers.

Firstly, we note that, in contrast to the well-known schemes, in the proposed design of the adaptive shock absorbers their work characteristic has the following structure:

$$Q = Q(\dot{q}, p), \quad p = col(q, i), \qquad (4)$$

here

Q is the force acting on the piston of the shock absorber;

$\bullet \equiv \dfrac{d}{dt}$ is the operator of differentiation with respect to time t;

$p = col(q, i)$ is "control matrix" of the shock absorber - column matrix of size 2 × 1;

i is the value of the control current in the electro-hydraulic valve of the shock absorber (the first control parameter of the shock absorber);

q is a coordinate, determining the position of the piston 1 (Fig. 3) - the distance between this piston and its center position in the work cylinder 3 (the second control parameter of the shock absorber). In the Fig. 3 we have: 1 is the piston; 2 is piston rod; 3 is the work cylinder; 4,5 are back and front sides of the piston. In the Fig.3 the electro-hydraulic valve is not shown.

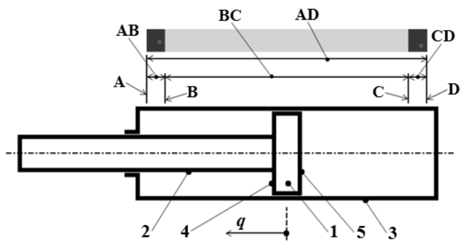

Fig. 3. Scheme of telescopic shock absorber

The main determining regulation component acting on the adaptive shock absorber is, of course, the magnitude of the control current. Mainly, it is variation of value of , that allows us to get the «infinite» (hyper-wide) control range of the dissipative characteristics of the adaptive shock absorber.

Depending on the type of function $i = i(t)$ and the method of its formation, four variants of the organization of the operational control of the dissipative characteristics of the shock absorber may occur:

1.1. Autonomous mode in which the controlled variable i is constant. This mode is the most simple design variant of the control of the dissipative characteristics of the shock absorber. It is realized by natural internal automatism. This mode is limited by zone BC (Fig. 3), and it is approximately 93-95% of the maximum stroke of the piston in compare with the total work area AD. In this mode operating characteristic of the shock absorber remains unchanged and consists of a single curve, namely: curve 1 in rebound phase, and curve 4 in the contraction phase (Fig. 4).

However, when the piston is crossing the boundary positions $q = 0.95q_{\max}$, i.e. when the right side 5 of the piston 1 (Fig. 2) is crossing the point C, or when the left side 4 of the piston 1 is crossing the point B as during its further movement within the corresponding zones AB and CD (zones of intensive damping), up to the approaching of the piston to the extreme positions A and D. The developed design allows us to increase the degree of damping of the shock absorber automatically and progressively. Force Q, acting on the piston 1 (Fig. 3) and, consequently, on the rod 2, starts to increase as well. The corresponding curve of the characteristic starts to approach gradually to the y-axis, consistently taking up the positions 1, 2 (Fig.4), etc.

In Figures 3 and 4, the description of the "lockable adaptive shock absorber" is captured such that the non-linear ramping up of damping at the extreme ends of travel is equivalent in the compression side as it is on the rebound side.

Finally, in the limit, when the piston is in the leftmost position, in which the left side 4 of the piston takes the position A (Fig. 4), the characteristic will automatically be aligned with the upper beam 3 of y-axis. In this position it automatically occurs the mode of "self-blocking", in which the shock absorber is converted into a single rigid element and the further movement of the piston 1 lefter position A is impossible.

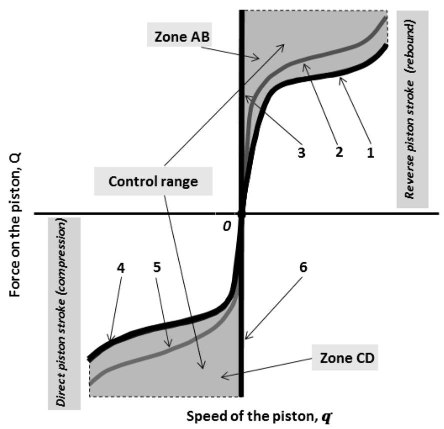

Fig. 4. Operating characteristics of the shock absorber at constant operating influence

We emphasize, that in this mode of operation there is a «one-way blockage» of the shock absorber. The similar situation occurs in the compression phase, when the curve of the characteristic takes consistently the positions 4, 5, and 6.

In addition to these features, the present mode has another very useful practical quality, namely: the ability to implement in any position of the piston and at any time the interlock operating mode. Suppose that the shock absorber is working according to the characteristic 2 (Fig. 5). Suppose that for some value of the velocity of the piston $\dot{q} = \dot{q}_i$, for example, at the position 8, we decided to block it, in other words, to transform it into a single rigid unit. The driver gives the corresponding signals to the control unit, selects a predetermined value of the control current i on the electro-hydraulic valve. In this case, the shock absorber automatically passes at the position 8 from the characteristic 2 to the curve 6 and, further, at the time of stopping of the piston to the segment 4.

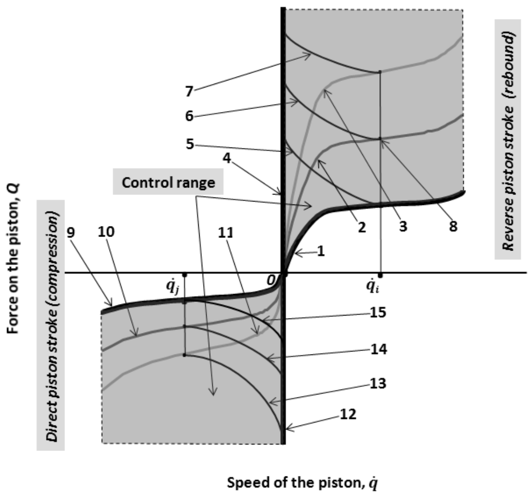

Fig. 5. Operating characteristics of the shock absorber at variable operating influence

The elastic element with a nonlinear characteristic and automatic optimization of the localization of the operating zone

In the following data to evaluate the effectiveness of our developed designs we compare the relevant characteristics of existing real prototypes traditionally used at present elastic elements with linear performance characteristics that work in similar conditions and have similar basic sizes. For a quantitative evaluation of the technical advantages of our designs of the resilient elements we consider the generally accepted valuation parameters:

$$c = \frac{dQ}{dq}, \tag{5}$$

$$k_d = Q_{\max} / Q_s, \tag{6}$$

$$R_d = \int_{q_s}^{q_{\max}} Q(q)dq - Q_s \cdot (q_{\max} - q_s). \tag{7}$$

Here we have:

Q is force on the elastic element;

q is deformation of the elastic element;

$Q_{\max}$ is maximum force on the elastic element;

$q_{\max}$ is maximum deformation of the elastic element;

Q_s is static load on the elastic element;

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q_s is static deformation of the elastic element;

c is stiffness of the considered part of the elastic element;

k_d is dynamic factor;

R_d is dynamic capacity of the elastic element of the suspension.

In addition to the conventional parameters (5) - (7), we consider some additional relative values:

$$K_c = c_1 / c_p, \quad (8)$$

$$K_Q = Q_{\max,1} / Q_{\max,p}, \quad (9)$$

$$K_R = R_{d,1} / R_{dp}. \quad (10)$$

Here we have:

c_1 is stiffness of considered part of the experimental model of the elastic element;

c_p is stiffness of considered part of the elastic element of the prototype;

$Q_{\max,1}$ is the maximum force on the experimental sample of the elastic element;

$Q_{\max,p}$ is the maximum force on the elastic element of the prototype;

$R_{d,1}$ is dynamic capacity of the experimental sample of the elastic element of the suggested suspension;

R_{dp} is the dynamic capacity of the elastic element of the suspension of the prototype.

We have developed two designs of the elastic elements with non-linear characteristics and automatic optimization of the localization of the operating zones. These designs are fundamentally different from each other. Their operating characteristics are shown in Fig. 6.

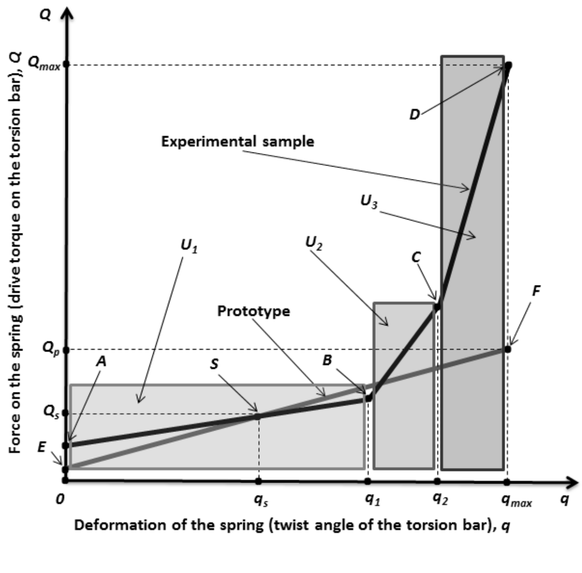

Fig. 6. Operating characteristics of the elastic element (the first variant)

The adaptive suspension of vehicle

Let us consider the operating characteristic of the elastic element under the assumption of using this element in conjunction with the adaptive shock absorber in the vehicle suspension. In fact, we consider adaptive suspension system of the vehicle, including the elastic element and the adaptive shock absorber.

Figure 7 presents the linear characteristic of the prototype of the elastic element (line EF) and the combined operating characteristic of the experimental sample with the developed elastic element and the adaptive shock absorber (OASBCGD curve).

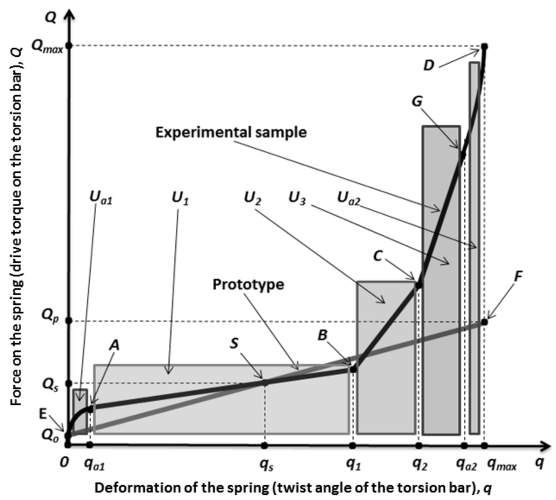

Fig. 7. Operating characteristics of the elastic element based on the availability of the adaptive shock absorber (the first variant)

As well as we have done the analysis of the relevant scheme, it should be noted that in contrast to the case displayed in Fig. 8, the characteristic consist of four sections: U_{a1}, U_1, U_3, and U_{a2}. And in the segment U_3 the characteristic is nonlinear and displayed by smooth curve. This allows during movement outside «the comfort zone» significantly, in comparison with the case described in Fig. 8, reducing the dynamic loads acting on the nodes, transport equipment, and passengers.

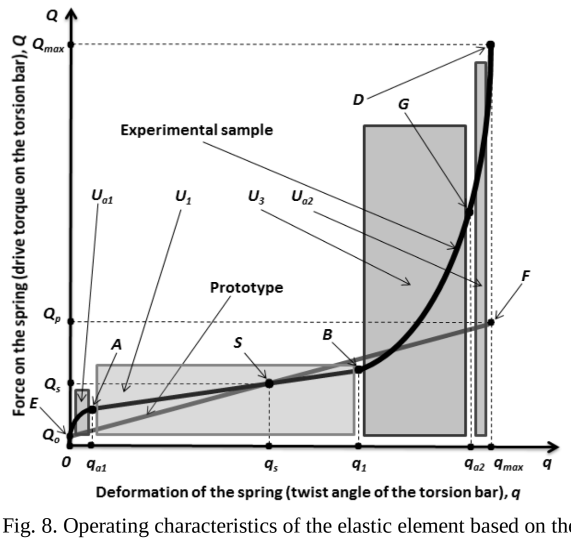

Fig. 8. Operating characteristics of the elastic element based on the availability of the adaptive shock absorber (the second variant)

Thus, by using our developed elastic elements of the vehicle in the "comfort zone", the suspension will be significantly softer, and, at the same time, and it will more

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effective solve the problem of stabilization of the vehicle and its body [11,12].

Figures 9, 10 illustrate the experimental stand for the shock absorber test. In Fig. 11 there is one the experimental characteristics of the shock absorber.

Fig. 9. Experimental stand for the shock absorber test

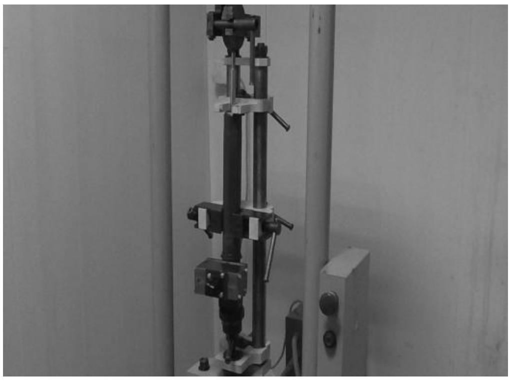

Fig. 10. Experimental stand for the shock absorber test

In Fig. 11 there is the experimental characteristic of the shock absorber.

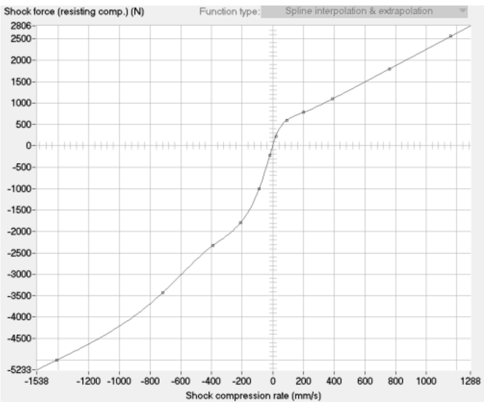

Fig. 11. Experimental characteristic of shock absorber

V. Conclusion

We have developed new designs: 1) the lockable adaptive shock absorber with a hyper-wide control range of dissipative characteristics; 2) the elastic element with the nonlinear characteristic and the automatic optimization of localization of working zones. Our suspensions allow: 1) implementing the hyper-wide control range of dissipative characteristics; 2) realizing the "self-blocking" mode at any time; 3) implementing any pre-defined dissipative characteristics of the marked hyper-wide control range; 4) adjusting the dissipative characteristics of a vehicle while driving in manual mode, by direct control action, and by automatic control; and they have some other advantages. Usage of our suggested designs of the suspensions will help more effective to solve the problem of stabilization of the vehicle and its body.

Summarizing the above, and based on the present state of our experience of work in the development of the adaptive suspension vehicle, the achieved level of our scientific expertise and our research capacity in this field, we can confidently state that, in the case of our proposed designs of the adaptive suspension system, the vehicle is equipped with this suspension system will surpass the known world analogues for technical and economic indicators of quality.

We have installed the developed design of the suspension on the car "Lada-Granta." The experimental results confirmed the validity of the theoretical propositions.

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