EVALUATION OF POSSIBILITY FOR RECOVERING OF ENERGY FROM THE SUSPENSION USING AIR SHOCK ABSORBER

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Summary

The evaluation of possibility for recovering of part of vibration energy from automobile has been done in the article. One of the potential possibilities is utilization of fluid pressure in shock absorber to drive turbogenerator applying battery. It can be interesting to utilize air shock absorbers, in Gerard to possibility of direct outlet of expanded air into atmosphere – it can simplify the design of set recovering energy. The aim of researches presented in the article has been to evaluate possibility for recovering of energy from air shock absorber without deterioration of vibration damping level, which can be provided by hydraulic shock absorber. The scheme of proposed air shock absorber, its mathematical model, the results of calculation for pressure increasing in shock absorber during its piston motion, for different velocity of the piston have been shown in the article. The characteristics of hydraulic absorber and air one with energy recovering have been compared. The model of the wheel and the automobile mass connected with that wheel has been presented. Using such model the simulations of the wheel and of the automobile mass motion, for tasked velocity of automobile have been made. The model of road microprofile has been elaborated.. Using the models the recovered energy in the 1 km road section has been calculated.

Keywords: pneumatic shock absorber, hydraulic shock absorber, energy recovery, turbogenerator

Index determinations

a – maximum valve displacement, A_k, φ_k – amplitude and phase angle k-th harmonic component, c – shock absorber damping factor, $c_{ogumienia}$ – damping factor of the tire, k – shock absorber stiffness, $k_{ogumienia}$ – stiffness of the tire, m – wheel mass, $\Delta\omega$ – spectral density discretization step, t_i – the next step computational time, $G(\omega_k)$ – spectral density for the k-th frequency $\omega_{k;}$, M – the mass of the vehicle associated with the wheel, R – the gas constant, T – absolute temperature of air, V – the volume of the air chamber in shock absorber, V_0 – the initial volume of the air cell in shock absorber, $g(p, pj)$ – a modified function of flow rate, h – displacement of the shock absorber piston, p – the air pressure in the shock absorber, p_0 – the ambient pressure, x – the valve displacement, y_1 – displacement of the vehicle mass, y_2- wheel mass displacement, A_{emax} – maximum field of flow, κ – adiabatic exponent, Z1, Z2, Z3, Z4 – check valves, TG – turbogenerator

1. Introduction

Car moving along an uneven road surface in a random way is subjected to vertical excitation acting on its wheels. Each of these excitations is practically independent of each other. The intensity of these excitations is proportional to the linear speed of the car. Excitations acting on the car wheels while driving cause vibrations that are felt by the driver or passengers as some discomfort. Therefore, vehicle designers are trying to isolate these vibrations from the body by springs and dampen them with a shock absorber, whereby each wheel on a car shock absorber, there is one. In most cases, hydraulic shock absorbers are used, in which the energy of vibration of the vehicle is precipitated by the flow of hydraulic fluid through the system throttling valves. The energy of this liquid is converted into heat and work to overcome the flow resistance and, therefore, is lost forever. The aim of research presented in the article is to assess the possibility of recovering at least part of the energy without significantly compromising the level of damping, which provide in most vehicles, hydraulic shock absorbers. Interesting seems to be air springs, because of the possibility of an expanded exit of air into the atmosphere - which can facilitate the construction of energy-recovering.

2. The nature and parameters of the shock absorber

Parameters of motion of the amortized vehicle wheels are generally stochastic in nature, for both the amplitude and frequency of excitations originating from rough roads. At certain intervals, however, can be modelled as a reproducible response to repeated excitation. The excitation frequency is proportional to the speed of the car. The excitation amplitude can be taken as a constant equal to the average size of inequalities in the road, on which the analysed vehicle moves. To estimate the excitations acting to the vehicle wheel on rough roads you need to know the so-called road microprofile. This can be achieved through experimental measurements that are time consuming and costly. Some data can be found in the literature, ie in [1]. For a cobblestone road, and car speed 10 m / s it has been given the characteristics of rough roads spectral density versus frequency. According to [1], the centred stationary process of excitation from rough roads, of a normal distribution, can be represented as an infinite sum of harmonic components (1):

$$q(t)=\sum_{k=1}^{\infty} A_k\left(\cos\omega_k t-\varphi_k\right), \tag{1}$$

where: A_k, φ_k – amplitude and phase angle of the k-th harmonic component.

Estimated mileage excitation of inequality was calculated from the relation (2):

$$q_{estymowany}(t)=\sum_{k=1}^{N}\left[G(\omega_k)\Delta\omega\right]^{0.5}\cos\left(\Delta\omega k t_i-\varphi_k\right), \tag{2}$$

where: $\Delta\omega$ = 0.3 rad/s – spectral density discretization step, t_i – time of the next step calculation, $G(\omega_k)$ – spectral density for the k-th frequency ω_k;-φk – the value of a random variable with uniform distribution, ranging $<0,2\pi>$.

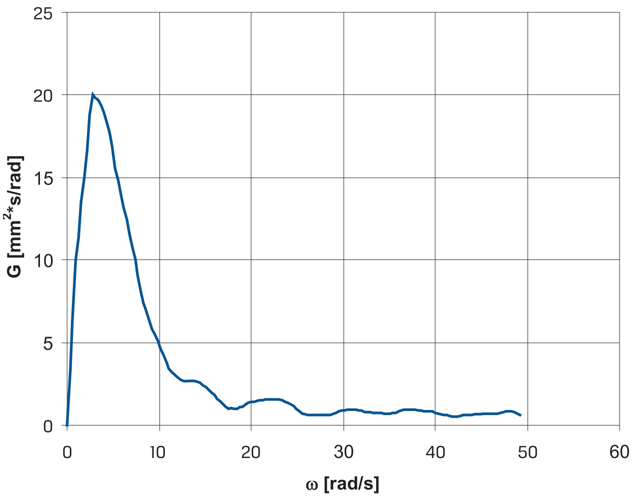

Fig. 1. Density of road microprofile vs. frequency, road, velocity 10 m/s, basing on [1].

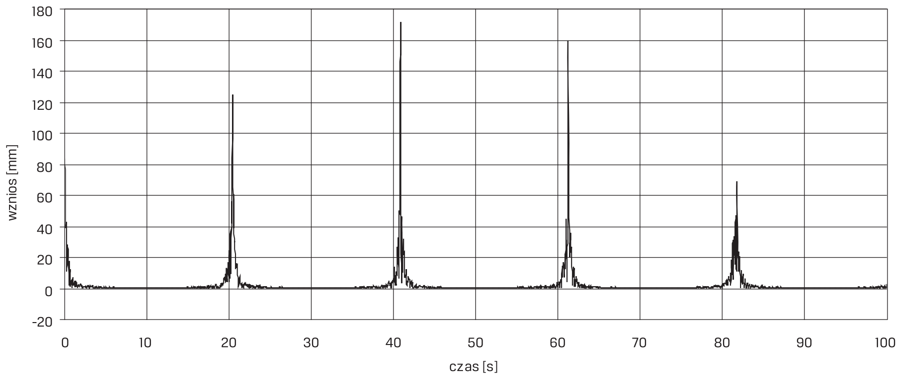

Fig. 2. The generated stochastic realization of loading from road microprofile vs. time.

As a result of the calculations it has been generated the realization of the random excitation from rough roads, as shown in Figure 2. Consciously it has been adopted a sample equivalent to excitation of the road with very large disparities - in order to estimate the maximum amount of energy possible to recover. It has been taken into account the fact that such a way for recovery of energy from the shock absorber should be most effective. During actual driving, for example, the national roads, provincial and district disparities are smaller, and the largest are less common - and so the efficiency of energy recovery must be less.

3. The principle of vibration energy recovery

In addition to studies on reducing fuel consumption in engines and energy recovery from braking process in hybrid cars, car companies also put attention to the shock absorbers. Each car hit on the road inequality is associated with irreversible loss of valuable energy. The energy utilized to move the shock absorber can be recovered, while improving the efficiency of a moving vehicle. One of the ideas for energy recovery is to use the hydraulic shock absorber and connected to the receivers (eg, batteries), turbogenerators submerged in liquid. Every time a shock absorber is compressed, the resulting pressure causes the flow of hydraulic fluid directed through the turbine blades, generating electricity. Schematic installation and operation of such a recovering energy shock absorber are shown in Figure 3. It has been shown the flow of fluid motion during shock compression and expansion. Flow during the compression is done by the valve Z1 and Z3, with a low flow resistance and by the turbogenerator. During the expansion, in turn, is strongly suppressed on the valve Z2.

Sourced energy on the one hand feeds the electronics shock absorbers, so that driving becomes more fluent, on the other, feeds the same vehicle, and if you are dealing with hybrid or electric vehicle, the powertrain. Previous tests of the prototype showed that the system is very efficient. In the case of a truck with three axles, each with 6 shock absorbers, it can be generated almost 1 kilowatt of power. It is enough to eliminate the alternator and thereby reduce the weight of the vehicle itself. From driving on a bumpy road you can get up to 1kW of energy [2, 3]. Removing the alternator seems to be a risky operation, if only because of the need to ensure that the power source to power the lighting for example, a stationary car.

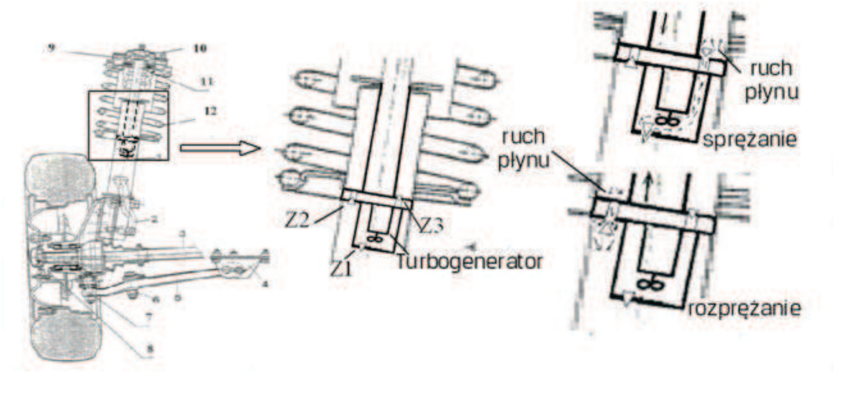

**Fig. 3. The scheme of assembling and performance for the hydraulic shock absorber with turbogenerator;
1 – shock absorber, 2 knuckle arm, 3 – drive shaft, 4 – cantilever of bottom arm, 5 – bottom arm,
6 – axis of joint for bottom arm, 7 – cup-and-ball joint of arm, 8 – steering knuckle, 9 – flexible mounting of column into car body, 10 – top shelf of the spring, 11 – piston rod of shock absorber,
12 – spring of suspension, Z1, Z2, Z3 – valves.**

4. Assumptions for the construction, operation and design of the new pneumatic shock absorber

Another way to recover energy is to use the pneumatic shock absorber. In this case, air-pressing is carried out through a back and forth movement of the shock absorber piston in the cylinder and check valves. Such a system of shock absorbers is a source of compressed air when the car moves. The very fact that there are four shock absorbers independently causes a stabilization of the conveying air. The tank in the system acts as an essential element in stabilizing air pressure. The purpose of conversion of a stream of compressed air to electric energy in the system, the turbogenerator has been placed. Current from turbogenerator can be used to recharge the vehicle battery or power auxiliary equipment, such as windshield wipers. Developed a new shock absorber design must meet several assumptions: The design of such a shock should be compact and fit inside the springs used in the Mc'Person column (Figure 3) – diameter of the shock absorber should not be too distant from the classical diameter of the hydraulic one. Placement of check valves should be projected on the body of the shock absorber. If their size does not allow it - should be used as short lines between the reservoir and the shock absorber. The tank should be connected directly to the turbine.

The diagram of the pneumatic shock absorber of vibration energy recovering chassis has been shown in Figure 4 The equation for pressure change in the individual chambers is described by equation (3):

$$\frac{dp}{dt}V(t)=p(t)Av(t)+\sum \alpha g(p,p_i)\,. \tag{3}$$

The volume is calculated from the following relationship (4):

$$V(t)=V_0-\int_0^t v(t)A\,dt \tag{4}$$

In the above equation, it has been used the following signs (5):

$$\alpha=0.654A_e\sqrt{RT\kappa^3}\;, \tag{5}$$

where: R = 287.14 (N · m / kgK) - gas constant, T = 293 K – absolute temperature of air, κ = 1.4 – adiabatic exponent;

Effective area of air flow was calculated from the relation (6):

$$A_e=\frac{x}{a}A_{e\max}\,, \tag{6}$$

where: x – displacement of the valve, a – the maximum valve displacement, A_{emax} – maximum field of flow.

In the presented dependencies g (p, pj) is the modified function of flow rate, which for the Mietluk-Awtuszko function has the form (7) [5, 6]:

$$g(p, p_i) = \begin{cases} p\dfrac{p - p_i}{1.13p - p_i}, dla\ p_i < p \\ p_i\dfrac{p_i - p}{1.13p_i - p}, dla\ p_i > p \end{cases} . \tag{7}$$

The equation for pressure change in the individual chambers of the shock absorber is described by equations: (8) and (9)

$$\frac{dp}{dt}\left(V(t) + A\frac{dh}{dt}\right) = \alpha p\frac{p - p_0}{1.13p - p_0} \approx \alpha p, \tag{8}$$

$$\frac{dp}{dt}\left(V(t) + A\frac{dh}{dt}\right) = \alpha p\frac{p - p_{zbiornik}}{1.13p - p_{zbiornik}} + \alpha p\frac{p - p_0}{1.13p - p_0}. \tag{9}$$

The efficiency of individual system components is difficult to assess and can be estimated at this stage only in a very simplified way. The real-time compression and expansion of air in the cylinder of a pneumatic shock absorber heat exchange takes place with the walls of the cylinder, but it is relatively short. Therefore you can assume for simplicity that the process is adiabatic. As a result, a conversion of kinetic energy for the motion of piston, combined with the vehicle wheel, into work of air compression or expansion process is linked only with relatively small losses. These losses result from friction process between piston 2 and the cylinder wall 1 and between surfaces of the piston rod and of the shock absorber lid aperture.

After reaching a certain pressure in the cylinder chamber 1, in which there is compression of the air, valve Z4 (Z2) is opened, connecting the chamber 1 via cable to the collector 3. During the flow through the valve throttling losses are created, depending on the design of the valve. They are estimated at a few percent of compressed air energy. These losses are higher, the higher the pressure valve, but their percentage of the compressed gas energy decreases. The collector directs the compressed air to the directly connected channel, in which the turbine T is located, and it is followed by conversion of elastic energy into kinetic energy of air turbine. Losses associated with the movement of compressed gas in the manifold and the turbine blades are a few percent of the energy of compressed air in the cylinder of shock absorber.

Energy from turbine generator G is converted into electrical energy, which is directed through the wires to the battery, for example. Losses related to the generation and current flow are relatively small, typically less than 3%. Z4 valve opening occurs after more than half way the piston 2 in the cylinder 1. If this time is not reached the valve of opening pressure, air flow to a collector does not occur. There is then no possibility of substitution of the elastic energy for kinetic energy. During movement of the piston 2, when in one chamber of the cylinder compression takes place, in the second chamber expansion takes place, until obtaining

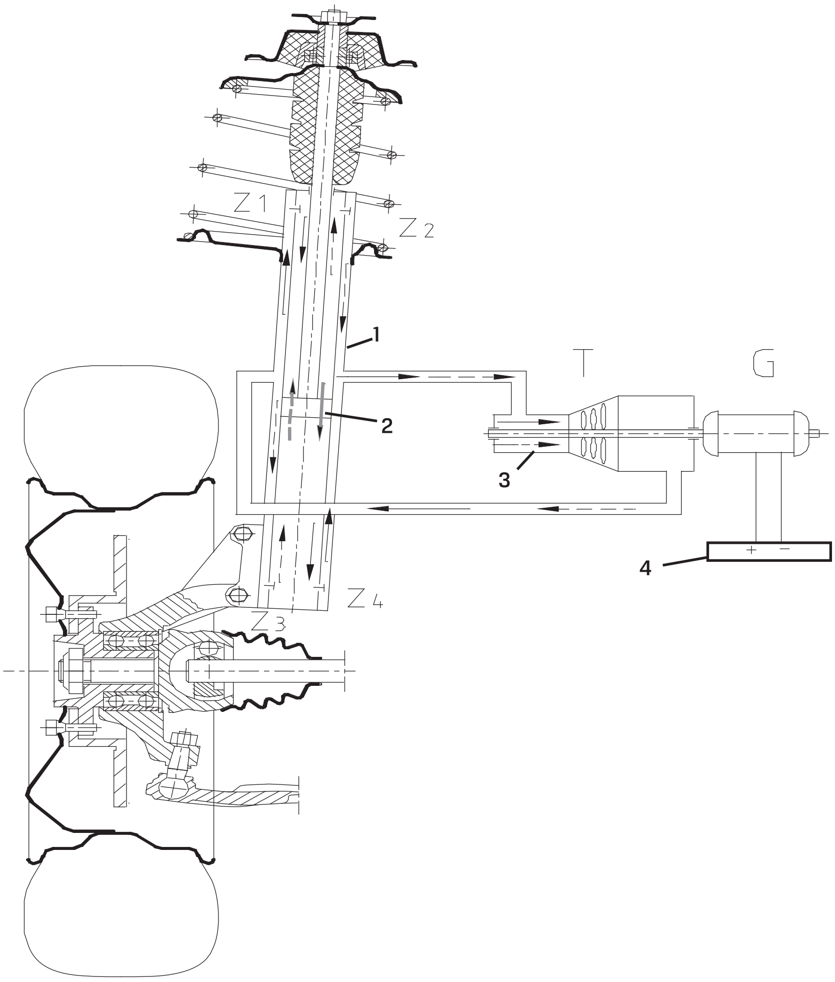

Fig. 4. The scheme of shock absorber recovering the energy of vibrations for the chassis.
Z1, Z2, Z3, Z4 – check valve, TG-turbogenerator, 1 – cylinder of air shock absorber, 2 – piston, 3 - collector, 4 – battery.

the pressure at the output of the generator G. When it is reached the check valve Z1 (Z3)is opened to the channel connecting the cylinder chamber with air vent for the turbogenerator and it begins to be sucked an air into the cylinder chamber. Occurring loss of air flow through the valve are relatively small. During expansion it is not possible to replace the elastic energy of air, accumulated in the cylinder chamber, into electricity.

It follows that the recovery of energy takes place only during the compression of air in each cylinder chambers, and even then only after it reaches the valve opening pressure. Even then there are losses. The estimated efficiency for recovery of wheel kinetic energy, in the form of electricity, accumulated ie. in the battery is below 50%. But anyway this is a gain in comparison with the energy otherwise lost forever in the case of conventional hydraulic shock absorbers.

5. Comparison of the classic characteristics of hydraulic and pneumatic shock absorber with energy recovery

Damping ability of the hydraulic damper is a measure of energy dissipation. It is characterized by the damping factor (decrement). An example of the dynamic behavior of a classical hydraulic shock absorber [6] shown in Figure 5. Damping force changes throughout the speed range of the piston. This helps keep the correct proportions of damping at low and high piston speeds. You can see a significant difference between attitudes damping forces 'zero' and '3 – max'. Piston speeds below 0.13 m / s are typical for excitation due to inhibition, acceleration and other maneuvers the car. Speed range above 0.13 m / s are rather typical for excitations of surface irregularities.

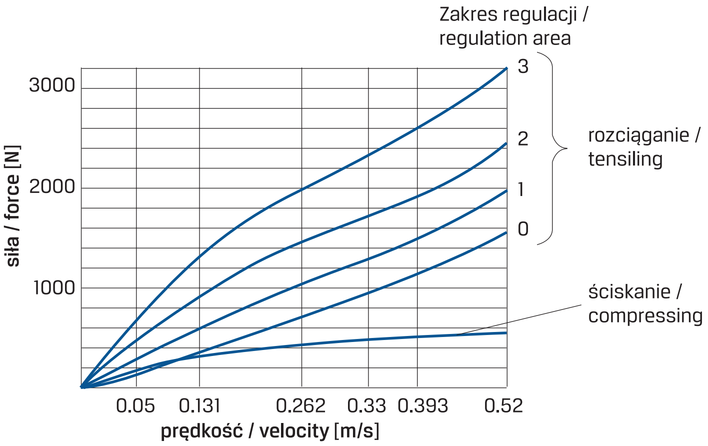

Fig. 5. Damping velocity vs. velocity of piston motion for the hydraulic shock absorber [6].

The hydraulic shock absorbers posses hysteresis characteristics, resulting in the formation of the emulsion fluid. This phenomenon poses like a shock absorber inertia in action. At the point marked by the marginal position of the shock absorber piston by the movement of relaxation (v = 0), shock resistance, however, creates more traffic relief, which gradually decreases the longer the relaxation of traffic to get to zero at the speed of movement of the piston compression of about 0.05 m/s. A similar process is during motion in the final phase of compression. At the point marked by the marginal position of the piston (v = 0), shock resistance force is about 160 N. It was only at the point where the piston has reached the speed of relaxation in the movement of about 0.05 m / s, shock absorber resistance is equal to zero. Flatter part of the relaxation characteristics of the traffic and the movement of shock absorber compression correspond to work with open pressure valves. The refraction of characteristics are clearly visible in the direction of the piston speed axis.

Characteristics of modern shock absorbers are generally in the form of graphs narrow hysteresis loop (Fig. 6). Characteristics shown in the figure were obtained at low frequencies of vibration. In real conditions, natural frequency axis of the car are much higher than the frequency of vibration of the body and are present at small amplitudes. Under such conditions, the frequent change of direction of motion, small amount of liquid flows through a shock absorber valves. This may cause malfunction of shock absorber. Therefore you can not take the drag coefficients k set for high frequencies and small amplitudes to the conditions in which there are low frequency and large amplitude. Energy field for shock absorber with a narrow hysteresis loop has been introduced in Figure 7.

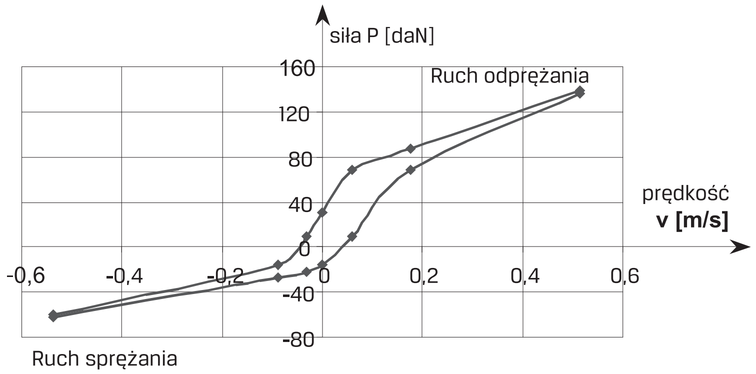

Fig. 6. Damping velocity vs. velocity of piston motion for the hydraulic shock absorber, obtained for small values of vibration frequency [7].

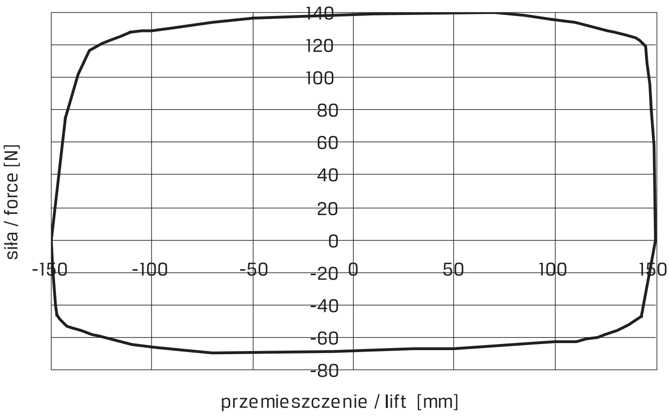

Fig. 7. Energy area for the hydraulic shock absorber.

To determine the characteristics of the pneumatic shock absorber, a number of numerical changes in pressure in the cylinder as a function of displacement and velocity, based on equation (3) - (9). The results of these calculations for the three vehicle speed is given in Figures (8) - (11). Figure 8 charts the forces in the damper as a function of piston displacement, for three different wheel velocity v relative to the chassis. Up to 0.09 m displacement it has been achieved almost exponential increase in shock absorber force, associated with the compression of air in the cylinder. Then, after opening the valve and directing compressed air into the manifold, there is a stabilization of force and the final phase of stroke fall in its value. The rate of descent increases with wheel speed v relative to the chassis. Figure 9 shows the pneumatic shock absorber stiffness changes as a function of piston displacement. Stiffness of the shock absorber, up to 0.09 m displacement, increases almost exponentially, and then decreases in a nonlinear way. Velocity v of the wheel relative to the chassis has got no effect on the course of this relationship in practice.

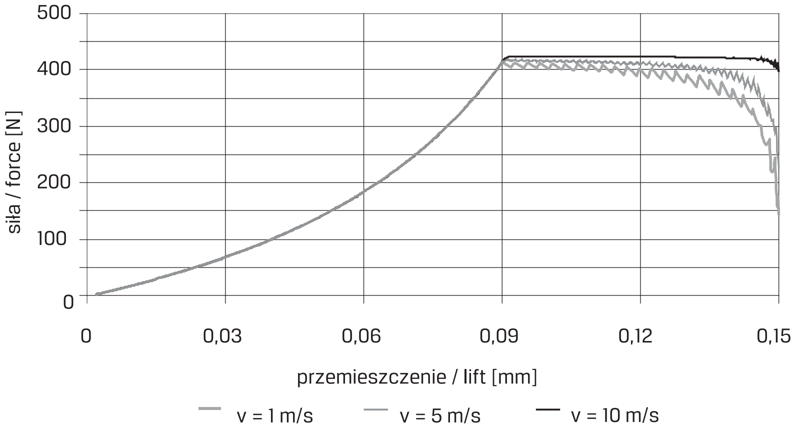

Fig. 8. Force generated in air shock absorber vs. lift of piston, for different velocity v of wheel in relation to the chassis.

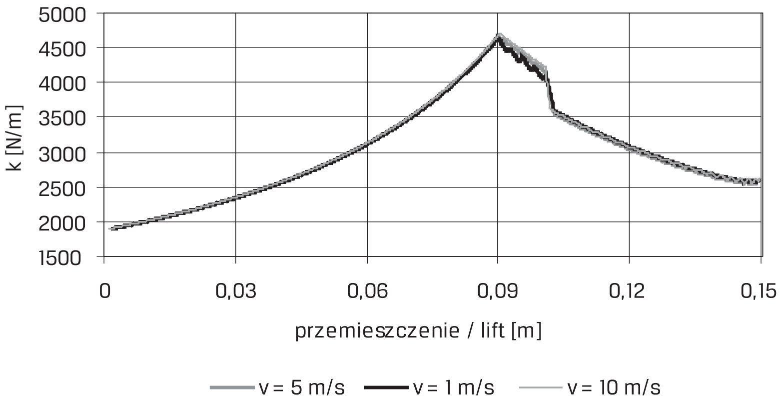

Fig. 9. Stiffness of air shock absorber vs. lift of piston, for different velocity v of wheel in relation to the chassis.

Figure 10 shows the pneumatic shock absorber damping force versus piston displacement, and Figure 11 the shock absorber damping coefficient as a function of wheel speed relative to the chassis for different shock absorber piston displacement. During movement of the piston up to 0.09 m the pneumatic shock absorber damping is small and results only from friction between piston and cylinder walls. A clear loss in the damper is almost the displacement of the piston, from 0.09 - 0.15 m (Fig. 10). The damping force decreases with the increase of the displacement. The increase in wheel speed v relative to the chassis reduces the speed of decline in the strength of that suppression. Shock absorber damping factor decreases with increasing for wheel velocity v relative to the chassis (Fig. 11). With the increase for the value of the piston displacement the ratio decreases slowly, almost linearly.

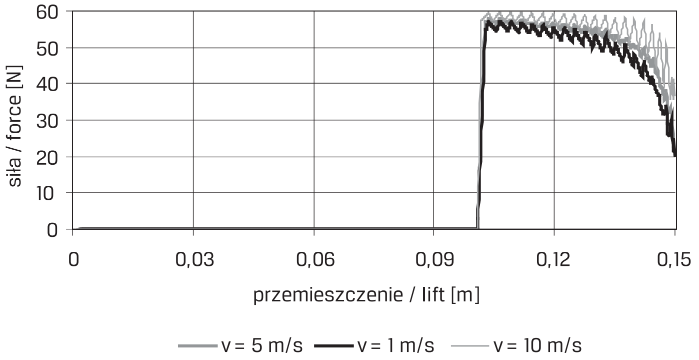

Fig. 10. Damping force in air shock absorber vs. lift of piston, for different velocity v of wheel in relation to the chassis.

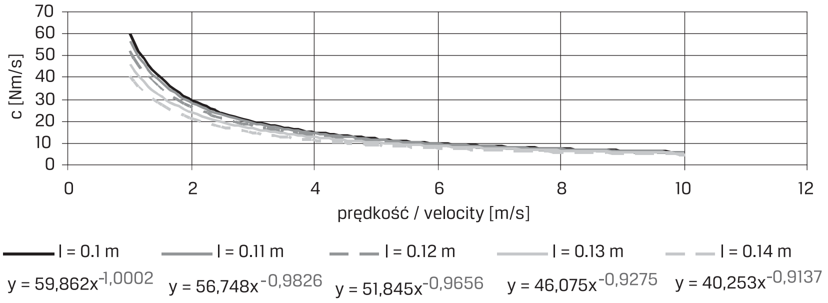

Fig. 11. Damping coefficient in air shock absorber vs. velocity v of wheel in relation to the chassis, for different values of piston lift.

Based on these waveforms forces in the damper set of estimated characteristics of the shock absorber and a graph of the field work. Characteristics of shock absorber and chart of his work show the figures (12) and (13). Predicted characteristics of the pneumatic shock absorber deviates significantly from the characteristics of a hydraulic shock absorber. In reality the energy field of shock absorber takes place between the lines corresponding to the maximum (max designation is Figures 13) and the mean (averaged designation in Figure 13) force for the shock absorber. Characteristics of the air shock absorber is steeper than the hydraulic one (Figure 14). As result of calculations the almost symmetrical characteristics for compression and decompression have been obtained. Potentially there is scope to control the characteristics of shock through the additional electrical load, such as resistor, the generator or by changing the pressure in the tank. The impact of such control on the characteristics of the damper is highly dependent on the construction of such a shock and it can be assessed only on the basis of additional research, particularly experimental.

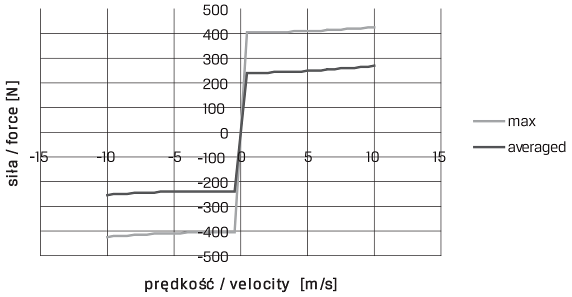

Fig. 12. The estimated characteristic of air shock absorber.

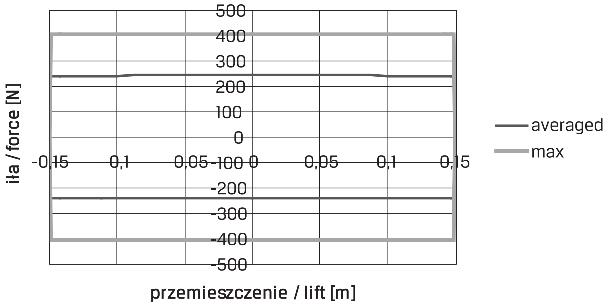

Fig. 13. Estimated energy area for air shock absorber.

Estimated pneumatic shock absorber field work is over two times greater than the hydraulic shock absorber. Estimation of energy obtained from the shock requires knowledge of the wheel motion parameters and the associated weight of the vehicle. Therefore, simulated motion of such a system, using the developed model for this purpose (Figure 16). To simplify the analysis assumes that for each wheel of the vehicle does the same force due to inertia of the vehicle in the vertical direction.

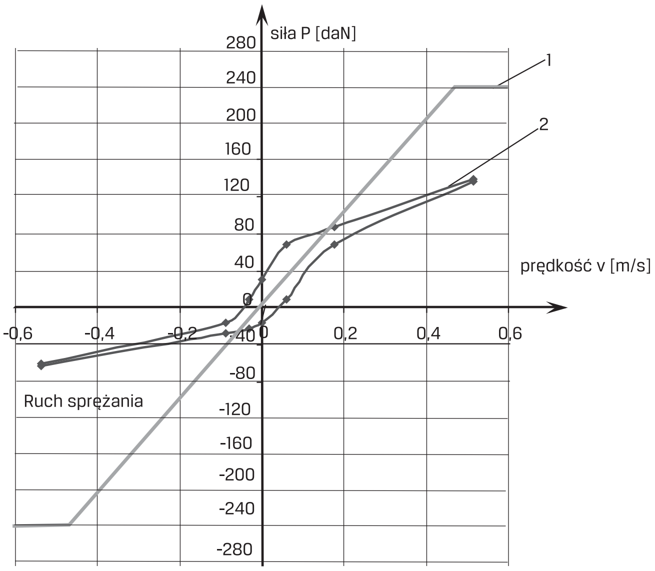

Fig. 14. The comparison of characteristics between the air 1 (averaged value) and the hydraulic 2 shock absorbers.

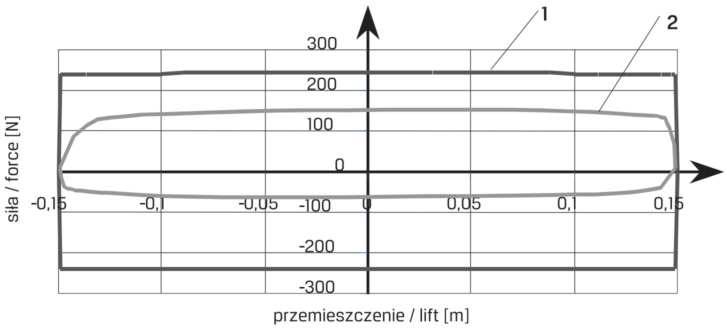

Fig. 15. The comparison of energy areas between the air 1 (averaged value) and the hydraulic 2 shock absorbers.

The equation of motion of the vehicle mass M = 250 kg and mass of the wheel m = 15 kg is reduced to the form (10) and (11):

$$M\ddot{y}_1 + c(\dot{y}_2 - \dot{y}_1) + k(y_2 - y_1) = 0 \tag{10}$$

$$\begin{aligned} &m\ddot{y}_2 + c(\dot{y}_1 - \dot{y}_2) + c_{ogumienia}\dot{y}_2 + k(y_1 - y_2) + k_{ogumienia}y_2 = \\ &k_{ogumienia}h(t) + c_{ogumienia}v(t) \end{aligned} \tag{11}$$

The initial conditions are as follows:

$$y_2 = y_{20},\ y_1 = y_{10},\ \dot{y}_2 = 0,\ \dot{y}_1 = 0,\ p = p_0,$$

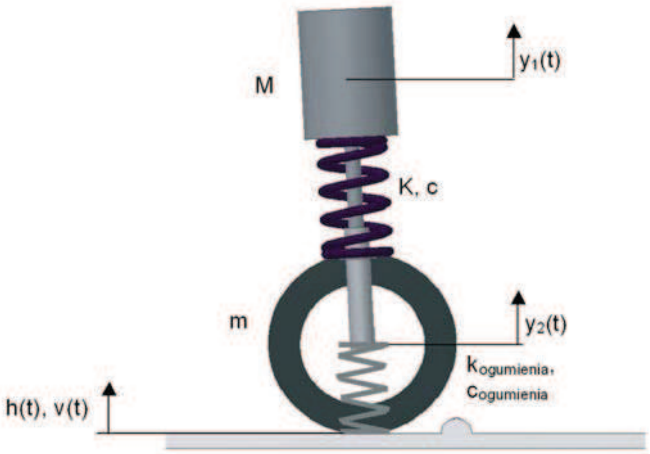

Fig. 16. The model for set of wheel and connected mass of car.

Dynamic model of the pneumatic shock absorber with energy recovery is given in Figure 17. It has been assumed, that the shock absorber operates symmetrically on both sides, guided by the ability to recover a maximal part of the energy potentially dissipated in the shock absorber. As previously mentioned pneumatic shock absorbers uses the power of gas elasticity 1, damping due to operation of the energy recovery system 2 and the friction resistance of motion for the shock absorber piston 3. Calculated, using the model of the pneumatic shock absorber and wheel system model and the associated weight of the vehicle, the wheel motion parameters are provided in Figures (18) - (19). For comparison, the figures also contains various parameters of traffic circles Cushion classically-hydraulically. Mass displacement caused by the swivel-wheel car on the road described above inequality is shown in Figure 18. For comparison, displacement is given for both cases of shock absorber: hydraulic and pneumatic with energy recovery. You can see a small difference in mass movements caused by the car using a pneumatic shock absorber recovering energy. This difference does not affect significantly the comfort of vehicle occupants.

An important issue in assessing the pneumatic shock absorber in question is the amount of recoverable energy. Based on the characteristics of shock waveforms and parameters of the wheels and the suspension was estimated recoverable energy - which normally would be subject to dissipation - in a single shock absorber, when you invade a single bump with a height of 5 cm and during the passage of vehicles along the way paved for the length of 1000 meters, at speeds v = 10 m / s. Charts recovered energy as a function of time is given in Figures (19) and (20). As it was, you can expect the greatest amount of energy can be recovered by invading the large inequalities of the road. While driving the recovery of energy takes place in a manner similar to the ankle, with unequal amplitude.

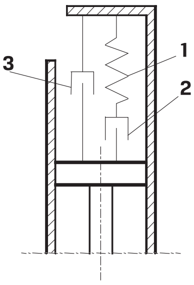

Fig. 17. The dynamic model for air shock absorber recovering energy. 1-stiffness dependent on the set recovering energy, damping for the set recovering energy, 3 – friction resistance of piston motion – dissipated energy.

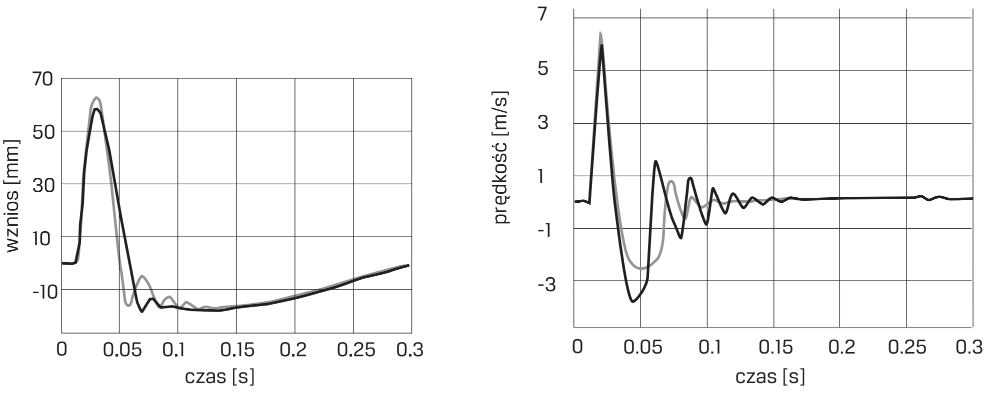

Fig. 18. The lift a) and velocity b) of piston in shock absorber vs. time; gray – hydraulic, black – air with energy recovering.

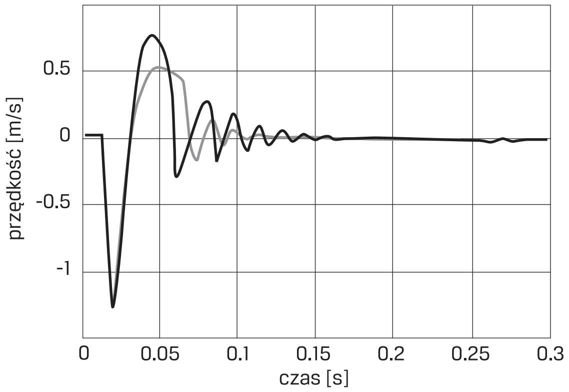

Fig. 19. Forces generated in shock absorber vs. time; gray – hydraulic, black – air with energy recovering.

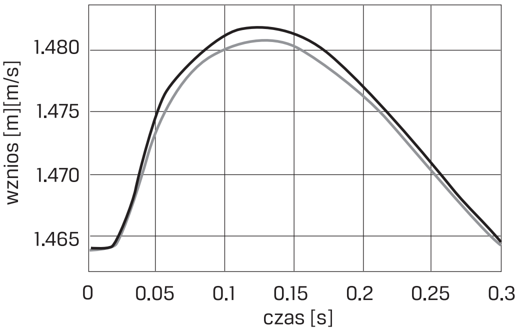

Fig. 20. The lift of car mass vs. time; gray – hydraulic, black – air with energy recovering.

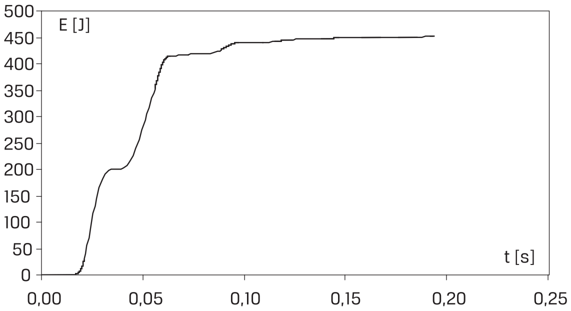

Fig. 21. The energy possible to recover in air shock absorber vs. time; during rising the jut of height equal 5 cm, at the car velocity v = 10 m/s.

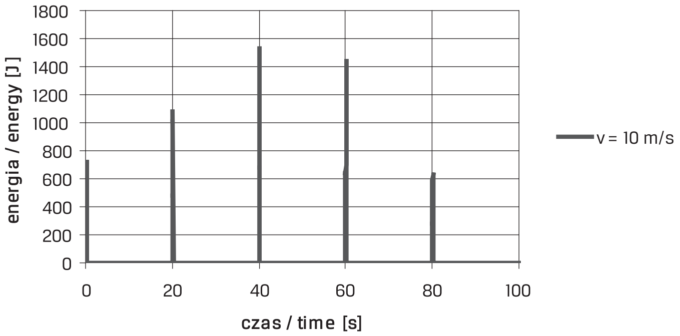

Fig. 22. The energy possible to recover in air shock absorber vs. time; during running the 1000 m segment of pavement road, at the car velocity v = 10 m/s.

6. Conclusion

6.1. There is a possibility of recovering energy air system instead of classical hydraulic shock absorbers. But not very favorable characteristics of such a shock absorber rather qualifies it for the slow-moving vehicles, which run on relatively level roads.

6.2. During the passage of 1 km road section by a car at a speed of 10 m / s the momentary power expected to be recovered from shock absorber is estimated at 7.2 kW, but the average recovered power is at 60W. Large differences between the values of the instantaneous and average recovered power indicate the need for a tank accumulating surplus air pressure from shock absorbers to achieve a more homogeneous values of supply current.

6.3. The characteristics of the pneumatic shock absorber with energy recovery are nonlinear, the damping factor decreases with increasing speed of the piston, which is not too favorable. Shock absorber has a relatively high stiffness even at low speeds the piston movement - it can reduce comfort.

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