PAPER • OPEN ACCESS

Energy recovery method of damping oscillations of the vehicle suspension

IOP Conf. Series: Materials Science and Engineering **537** (2019) 032074 doi:10.1088/1757-899X/537/3/032074

Energy recovery method of damping oscillations of the vehicle suspension

D L Okladnikov [1,3], V A Zeer [1], E V Grazhdantsev [2], R M Avdeev [1] and S A Akhremov [1]

[1] Department of Transport and Technological Machines, Siberian Federal University, Svobodny 79, Krasnoyarsk, 660041, Russia
[2] Department of Subsoil Use in the Central-Siberian District, Karl Marx 62, Krasnoyarsk, 660049, Russia

[3] E-mail: LitsCoustCastems@mail.ru

Abstract. The paper analyses the existing methods of energy recovery of vehicle suspension oscillation damping. It reveals the most preferred method in which an electromagnetic device of rotational type with a ball screw gear is used. The influence of the road parameters on the dynamic loads in the drive of an electromechanical generator is determined by mathematical modelling.

The main characteristic of a vehicle suspension shock absorber is the force of resistance to the displacement of the rod, depending on the speed, which in turn is aimed at damping oscillations of the vehicle body [1].

The efficiency of the damper is estimated using the natural logarithm of the ratio of adjacent amplitudes - the logarithmic decrement of oscillations [2].

$$\ln D=\frac{\pi\gamma}{\sqrt{1-\gamma^2}}\approx\pi\gamma \tag{1}$$

This expression is used to determine the relative damping coefficient of γ oscillations from the results of experimental studies of the oscillations of the sprung mass. From the oscillogram obtained during testing, the ratio of adjacent amplitudes is determined, i.e. *D* value, and then γ [3-4]:

$$\gamma=\frac{\ln D}{\pi} \tag{2}$$

The relative amount of energy dissipated by the shock absorber for one oscillation period:

$$\frac{\Delta W_i}{W_i}=1-\frac{1}{D^4} \tag{3}$$

where ΔWi – the amount of mechanical energy transferred to heat energy in one oscillation period; Wi – potential energy of the system when the maximum amplitude of oscillations is reached (the kinetic energy of the system is equal to zero, since the velocity is zero).

For example, the amount of dissipated energy at a given attenuation rate D = 2.57 and the relative attenuation coefficient γ = 0.3 relative to the LADA GRANTA car for front and rear suspension shock absorbers 98% of the energy stored by the oscillating system will be transferred to heat for one full swing and the amplitude decreases by 6.59 times. For two periods it will increase by 43.38 times [5-6].

$$\Delta W_i = \left(1 - \frac{1}{D^4}\right) \cdot W_i \tag{4}$$

Consequently, the amount of mechanical energy transferred to heat in one oscillation period for front and rear suspension shock absorbers will be 72.85 J and 118 J, respectively.

At present, there are known methods for electromagnetic oscillation damping, which can allow for the recovery of damping energy for its subsequent beneficial use [7, 8].

The use of electromagnetic damping is due to the simplicity of the transfer of recovered energy from the damper to the drive / consumer, the ability to control the process of change of resistance forces, the reduction of fuel consumption of the internal combustion engine due to the reduction of drive losses of the main generator and an increase in the electric vehicle power reserve.

There are several options for the design of electromagnetic shock absorbers:

1. Electromagnetic shock absorber with hydraulic drive;
2. Linear electromagnetic shock absorber;
3. Electromechanical shock absorber (EMS) using a rack and pinion transmission;
4. EMS driven by a ball screw drive (ball screw), etc.

Let us consider in detail each of these options. The first option is possible in various versions, but the concept is a generator driven by a hydraulic motor, which in turn is driven by a telescopic hydraulic pump installed in place of the standard shock absorber of the vehicle (figure 1). A similar design is represented by Levant Power Company.

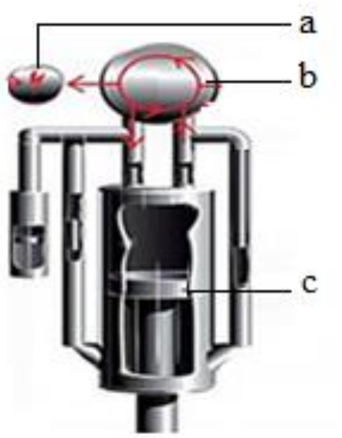

Figure 1. EMS with hydraulic drive: a - generator, b - hydraulic motor, c – piston.

The EMS based on a linear generator (figure 2) has the smallest mass-dimensional parameters, due to the absence of a drive. In this case, this version of the EMS has low efficiency due to the relatively low speed of movement of the rod, which leads to low recuperative and damping properties. One of the developers of electromagnetic dampers based on a magnetic “capsule” is the Eindhoven University of Technology in cooperation with SKF Company .

IOP Conf. Series: Materials Science and Engineering **537** (2019) 032074 doi:10.1088/1757-899X/537/3/032074

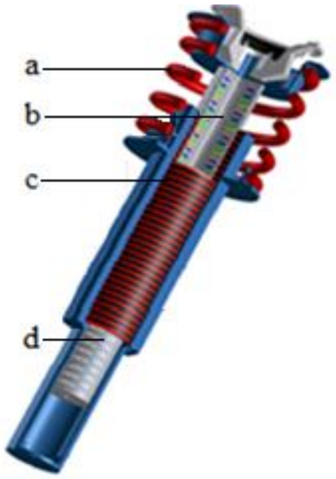

Figure 2. EMS with linear generator: a - a spring, b - a three-phase winding, c - a cassette of permanent magnets, d - a polished rod.

The third variant contains a rack and pinion in the drive, allowing to convert the reciprocating into rotational motion and increase the rotational speed of the generator rotor due to the gear ratio. However, a rigid connection between the suspension arm and the generator rotor entails a significant increase in dynamic loads when starting and changing the direction of motion, both on the drive and on the generator rotor. One of the variants of such a design is the synthesis of a rack and pinion converter of the reciprocating movement into a rotational, bevel gear using overrunning clutches in the hubs of the driven gears and a rotary type generator (figure 3), which can significantly reduce the dynamic loads on the drive due to the constant direction of rotor rotation generator.

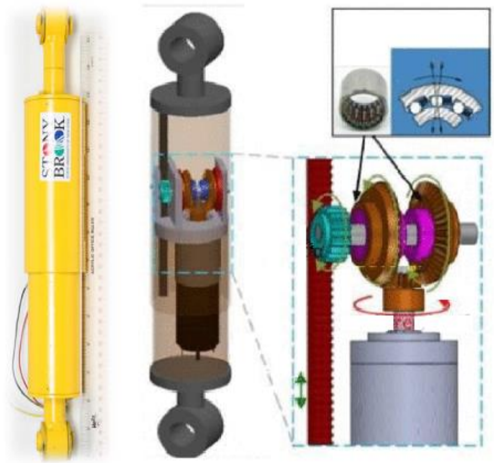

Figure 3. EMS a rack and pinion transmission.

An EMS driven by a ball screw and a rotary type generator (figure 4) is the most promising because it has a simple and robust design with mass dimensions commensurate with traditional shock absorbers, thus enabling efficient energy recovery and control of the resistance force of the damper over wide ranges.

IOP Conf. Series: Materials Science and Engineering **537** (2019) 032074 doi:10.1088/1757-899X/537/3/032074

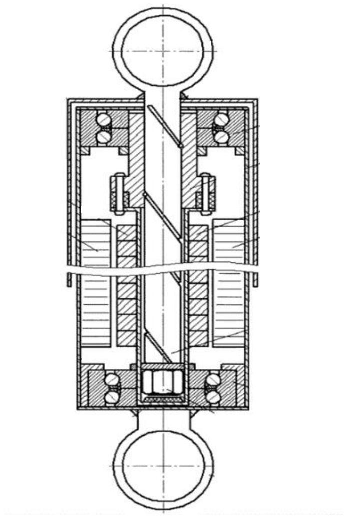

Figure 4. EMS with ball screw drive.

This statement is due to the following: high efficiency of ballscrews; minimum clearances in the ballscrews, which increases the wear resistance and impact strength of parts under the action of significant dynamic alternating loads on them during the operation of the EMS; the ball screw has a high gear ratio with small overall dimensions that are structurally acceptable to traditional shock absorbers of the vehicle suspension; existing technologies for the production of low-speed compact electromagnetic devices of rotational type and their microprocessor control systems.

Figure 5 shows the block diagram of an EMS with ballscrew, which, when X_{np}, is disturbed by it, shows that there are two groups of forces in the shock absorber: inertial forces from the masses and moments of inertia of parts; shock resistance from electromagnetic phenomena in the generator and friction forces.

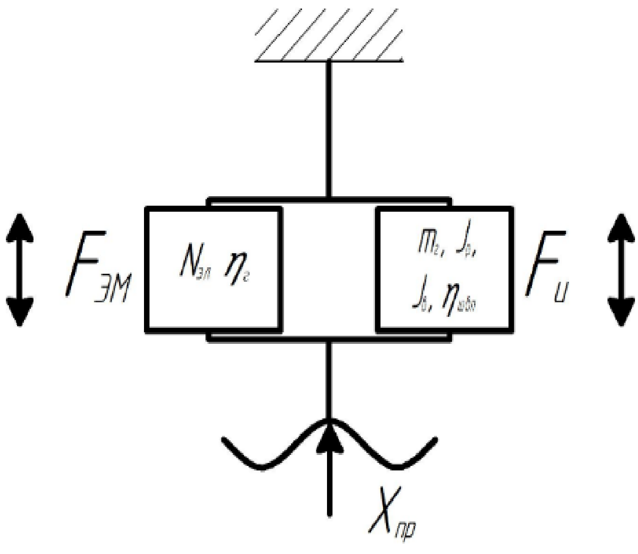

Figure 5. Electromagnetic damper block diagram: F_{em} – electromagnetic component of the resistance force, F_i – inertial component of resistance force, N_{el} – electric power generator, η_r – generator efficiency, η_{bse} – ball screw efficiency, J_s – moment of inertia of the screw, J_r – moment of inertia of the rotor, m_r – generator rotor mass, X_{st} – stock transfer.

The controlled parameters of the EMS depend on the mode of operation of the generator, including the generated power of electricity. The resistance force of an EMS due to friction forces is usually proportional to the speed of movement. The inertial forces arising from the mass and dimensions of moving parts and the effects of accelerations on them are not controllable and constant, therefore an assessment of their influence on the characteristics of the EMS is necessary.

The law of movement of the ball screw nut in the EMS:

$$x_{st}(t)=i_n A\sin(\omega t) \tag{5}$$

where $i_п$ – suspension ratio; A – amplitude, *m;* ω – frequency, *Hz;* t – time, *s.*

Converting equation (5) to describe the driving conditions with the possibility of choosing the following parameters: the speed of the vehicle - *Va, m/s*; height of overcome irregularities - *A*, *m*; irregularity length - *λ*, *m*, we shall get:

$$x_{пр}(t)=i_п A\sin(\omega t)=i_п A\sin\left(\frac{2\pi V_a}{\lambda}\cdot t\right) \tag{6}$$

$$\dot{x}_{np}(t)=i_n A\cos\left(\frac{2\pi V_a}{\lambda}\cdot t\right) \tag{7}$$

$$\ddot{x}_{np}(t)=-i_n A\left(\frac{2\pi V_a}{\lambda}\right)^2\sin\left(\frac{2\pi V_a}{\lambda}\cdot t\right) \tag{8}$$

Figure 6 graphically presents the dependence of displacement, velocity and acceleration on time.

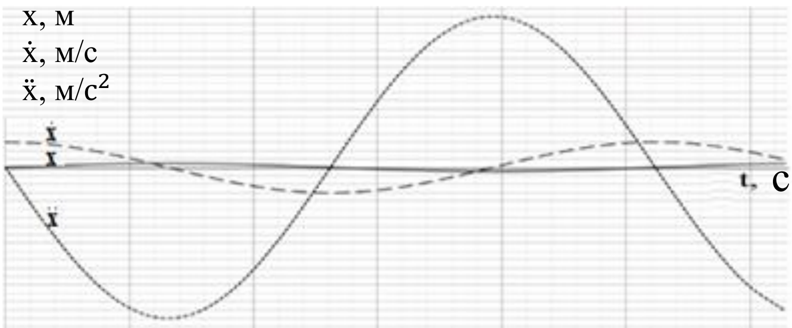

Figure 6. Dependence of movement, speed and acceleration on time.

Then the state of the shaft of the ball screw drive of the electromechanical damper and the generator rotor is described by the following equations:

$$\varphi(x_{np})=\frac{2\pi x_{np}}{Pk}=\frac{2\pi i_n A\sin\left(\frac{2\pi V_a}{\lambda}\cdot t\right)}{Pk} \tag{9}$$

where *P* – ball screw pitch, *(m); k* – the number of threads of the ball screw drive.

$$\dot{\varphi}(x_{пр})=\frac{2\pi\dot{x}_{пр}}{Pk}=\frac{2\pi i_п A\cdot\frac{2\pi V_a}{\lambda}}{Pk}\cos\left(\frac{2\pi V_a}{\lambda}\cdot t\right) \tag{10}$$

$$\ddot{\varphi}(x_{np})=\frac{2\pi\ddot{x}_{np}}{Pk}=-\frac{2\pi i_n A\cdot\left(\frac{2\pi V_a}{\lambda}\right)^2}{Pk}\sin\left(\frac{2\pi V_a}{\lambda}\cdot t\right) \tag{11}$$

The results of calculations of the acceleration of the elements of the EMS under the most characteristic conditions of the vehicle movement (speed, height and length of irregularity) are presented in table 1, from which it is clear that the oscillation frequency has the greatest effect on the magnitude of accelerations caused by an increase in the speed of the vehicle or a decrease in the length of irregularity.

Table 1. The results of the calculation of the acceleration of EMS elements.

Vehicle speed, m/s	Roughness height, m	Roughness length, м	Ball screw nut acceleration, m/s^2	Angular acceleration of the screw ball screw, rad/s^2
5	0.05	1	49.3	967.5125
5	0.05	2	12.3	241.3875
5	0.05	3	5.5	107.9375
5	0.1	3	11	215.875
5	0.15	3	16.4	321.85
10	0.05	3	21.9	429.7875
15	0.05	3	49.3	967.5125

Thus, according to the results of the research we can draw the following conclusions:

- when a vehicle moves in the damping devices of its wheel suspensions, the energy of mechanical oscillations, which is significant, can be recovered into electricity and then used in the vehicle's on-board network, thereby reducing fuel consumption for vehicles with hydrocarbon fuels or by increasing the power reserve for electric vehicles;
- the most promising design variant, is an EMS with a rotary type generator and a ball screw drive;
- the greatest inertial loads acting on the EMS parts are caused by forces at the moments of changing the direction of movement, and the frequency of oscillations has a greater influence on them, caused by an increase in the speed of the vehicle or a decrease in the length of the roughness;
- it is necessary to introduce extinguishing, safety and other elements, the design versions of which are different into the EMS design.

Acknowledgements
The authors thank the FSBU Foundation for the Promotion of the Development of Small Forms of Enterprises in the Scientific and Technical Sphere for supporting the project under the UMNIK programme.

References

[1] GOST 24346-80 *Vibration. Terms and definitions* (Moscow: Rosstandart)
[2] Khusainov A and Selifonov V 2008 *Theory of a vehicle* (Ulyanovsk: UlSTU)
[3] Derbaremdiker A 1969 *Hydraulic car shock absorbers* (Moscow: Machinebuilding)
[4] Khusainov A 2011 *Vehicle performance* (Ulyanovsk: UlSTU)
[5] Perikov D, Okladnikov D, Sorokin A and Evseev P 2013 On the use of electromagnetic devices in car suspensions *Modern technology and technology: problems, status and prospects* 188-92
[6] Zeer V, Sorokin A and Okladnikov D 2015 The possibility of using a rotary-type electromagnetic generator as a vehicle suspension damper *Proceedings of the IV International Scientific and Technical Conference Thermal and technological aspects of improving the efficiency of engineering production*
[7] Yurlin D 2017 Intelligent car suspension systems *NAMI Proceedings*
[8] Styrov A 2015 The approach to the use of energy recovery in the electromechanical active suspension of the vehicle *Collection of scientific works* **2(80)** 106-15