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A Review on Electromagnetic Energy-Regenerative Shock Absorbers

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Abstract: This stduy is given the brief review of energy-regenerative shock absorber designs for a wheeled vehicle. It is proposed the compact design of shock absorber based on ball screw mechanism.

Key words: Energy-regenerative shock absorber, linear generator, rotation generator, ball screw, mechanism

INTRODUCTION

The question of vehicle's energy efficiency as well as improvement of their environmental performance is all the more important due to the constantly tightening environmental standards for automobile exhaust emission taken in Europe and North America. In this connection, the main efforts of worldwide car manufacturers are directed to improve the motor design, systems of utilization and neutralization of harmful emission and to increase aerodynamic car properties.

One of the factors to decrease emission due to fuel consumption reduction in vehicles is to provide the shock absorber in the vehicle suspension which is able to regenerate the mechanical fluctuation energy of vehicle's sprung weight when travelling on uneven roads but at the same time in a conventional suspension it is dissipated as heat in external environment. This effect can be realized if mechanical energy is converted into electric one by means of electromechanical converter (generator).

At the present time it has been proposed the number of designs of electromechanical regenerative shock absorbers as a part of vehicle's active suspension. The main emphasis in the active suspension is on the smooth running and improvement of handling performance of the vehicle and in addition the regeneration effect is efficient but it is still a side effect allowing only reducing the extra energy consumption required for suspension operation. It means it is not possible to speak about energy efficiency as in itself.

In this regard it is profitable to consider the possibility for implementation of regenerative shock absorber of various designs in the suspension system of the vehicle in terms of improving its energy efficiency. The objective is to provide the damping characteristic ensuring the resisting force of shock absorber while compressing and rebound, depending on the displacement speed of absorber rod similar to serial hydraulic shock absorber of the car. In this case the mechanical energy of the body fluctuation should be converted into electrical energy directed to the battery charge.

MATERIALS AND METHODS

The slots with neodymium permanent magnets 1 fixed inside, have been milled externally along the full length of the hollow shaft 2. The magnets were stuck at the slots with glue WEICON RK 1500. The magnet material is N38H having the property of transverse magnetization. The magnets are installed so that the directions of magnetization in adjacent magnets go one after the other. The generator stator is placed internally at the shock absorber external pipe. The stator core is formed by installation of 5 mm stator sheets within the body of the external pipe so as to form the slots along the stator for generator windings 3. The stator sheets material is electrotechnical cold-rolled isotropic steel made to GOST 21427.2-83.

The stator windings are the enameled wire having 0.6 mm in diameter. In order to isolate the wire from the core, the film typed electric insulating material Sintoflex C616 0.23 mm in diameter is used. The windings at the end surface are isolated with glass-fiber-reinforced honeycomb shims and shrouded with insulating tubular braid. After the winding done, the stator windings are impregnated in insulating compound.

RESULTS AND DISCUSSION

For estimation of power value which in theory capable to be regenerative in the shock absorber as well as the dynamic loads affected on serial hydraulic shock absorber while moving, it has been

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Table 1: Operating conditions of the freight truck's shock absorber

Motion mode (kmh^{-1})	S_{max} (mm)	V_{max} (m sec^{-1})	V_{av} (m sec^{-1})	a_{max} (g)	a_{av} (g)	P (W)
Asphalt road, 30	20	0.40	0.020	2.5	0.13	26
Asphalt road, 50	23	0.41	0.030	2.1	0.16	26
Asphalt road, 70	23	0.50	0.037	2.7	0.19	60
Fieldstone road, 30	88	2.48	0.110	13.4	0.59	313
Fieldstone road, 45	78	1.54	0.130	23.0	0.64	392
Fieldstone road, 60	47	1.26	0.148	6.4	0.74	464

Table 2: Operating conditions of the shock absorber of a freight truck with loaded semitrailer

Motion mode (kmh^{-1})	S_{max} (mm)	V_{max} (m sec^{-1})	V_{av} (m sec^{-1})	a_{max} (g)	a_{av} (g)	P (W)
Asphalt road, 30	26	0.51	0.022	3.7	0.13	25
Asphalt road, 50	30	0.58	0.033	3.8	0.21	46
Asphalt road, 70	45	0.61	0.043	4.3	0.24	70
Fieldstone road, 30	112	3.45	0.160	22.8	1.10	532
Fieldstone road, 45	97	3.18	0.200	20.6	1.39	684
Fieldstone road, 60	87	2.70	0.240	17.7	1.60	860

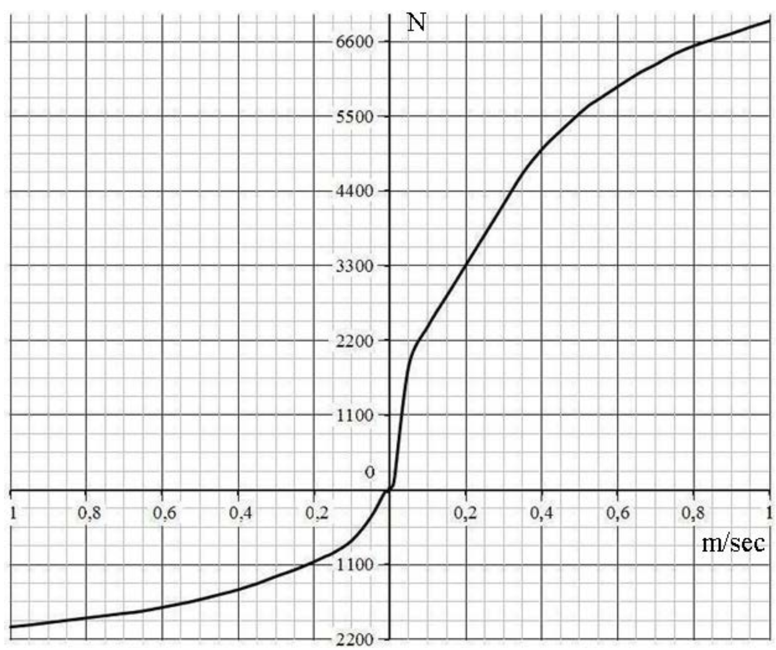

Fig. 1: Characteristic curve of shock absorber's damping force and displacement speed of the rod

performed the number of freight truck running with weight of 7900 kg and wheels formula 4×2 under different truck speeds and on various types of road surface. It has been measured the speed and distance of movement of the rod at the rear shock absorber of the freight truck at the distance of 2000 m. The experimental data processing results are presented in Table 1. The S_{max}, peak displacement of rod during running, V_{max}, maximum rod's speed during running, V_{av}, the average speed value of the rod per running period, a_{ma}, peak acceleration of the rod during running, a_{av}, average acceleration value of the rod per running period, P-average power value dissipated in the shock absorber.

Table 2 gives the similar results of experimental data during the test running of the same freight truck but as a part of a train with loaded 36100 kg semitrailer. Figure 1 shows the damping characteristic of the tested shock absorber while compressing and rebound depending on the speed of the absorber rod.

The measurement results have shown that the maximum energy, converted into heat and dissipated form the external shock absorber surface into the environment is realized in shock absorber during the fast running of the loaded freight truck along fieldstone road (860 W) that in conversion to the rest wheels gives the power over 3 kW. While running along asphalt road the total dissipation power is 100-300 W and it is essentially independent of whether or not the freight truck is loaded. The important fact is the high dynamic loads (over 20 g) arising in the shock absorber during the fieldstone road running which is needed to take into account while designing the energy regenerative shock absorber.

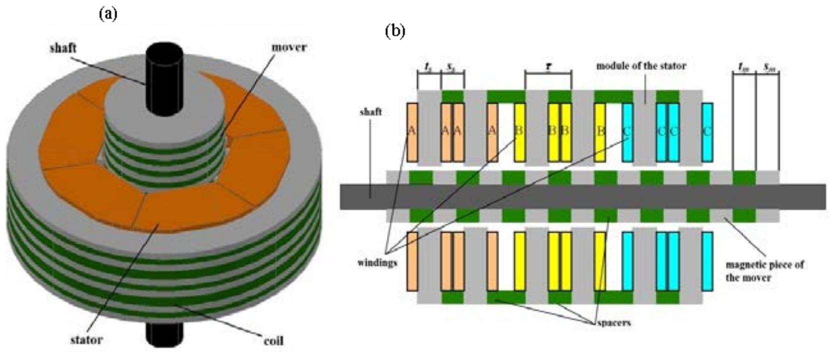

Fig. 2: a) Cylindrical linear generator structure and b) Layout (longitudinal cross section)

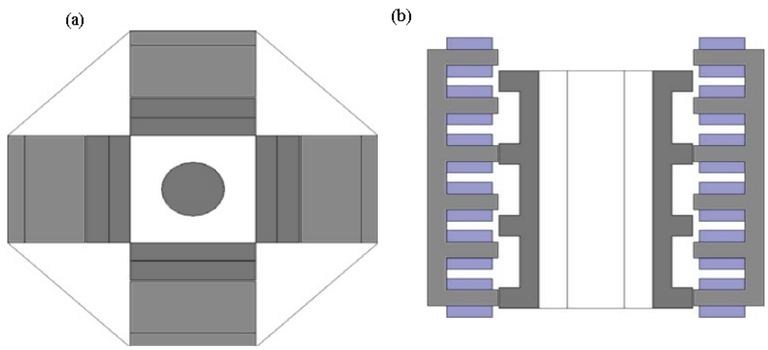

Fig. 3: Linear generator design: a) Transverse cross section and b) Longitudinal cross section

Shock absorber's constructions: Currently the scientific and technical literature proposes a number of regenerative shock absorber's designs as a part of vehicle suspension, capable to convert regeneration of push-pull fluctuation of the body into electric energy. In general, they can be divided into two groups of a type of the generator used for converting mechanical energy into electrical energy: based on linear generator and rotation generator. The linear inductor machine or machine based on permanent magnets can be applied as a linear generator. The disadvantage of conventional flat linear inductor generators is a large force applied perpendicular to the displacement surface of the translator which can be much higher than effective force used for linear displacement of the translator. The solution of this problem is the cylindrical or rectangular four-sided design of the linear inductor generator with the lack of perpendicular force due to the radial symmetry.

The study Popa *et al*. (2013) shows a cylindrical linear inductor machines with transverse flux. The stator and translator have a laminated structure with interleaving of magnetic layer with a nonmagnetic spacer (Fig. 2). Each stator's layer has its own winding. At the same time the winding height is limited by the thickness of nonmagnetic spacer. Several consecutive stator layers are connected with winding as a serial or parallel connection. From practical point of view the number of stator's phases is selected from 3-4.

Another embodiment of linear inductor generator for shock absorber is Zhu *et al*. (2010) design consisted of four identic three-phase linear actuators (Fig. 3). Stator and translator are assembled from steel laminated plates and fixed at the car body and the wheel, respectively. To reduce the unsprung mass of the suspension, the phase windings are located at the stator. The windings of one phase are connected in series.

Inductor machine operation requires the position sensor of the translator, generated signal depending on translator's position (shock absorber rod) which is necessary for correct operation of converter's control system managing the liner generator but it makes shock absorber design more complicated. In addition, the analysis of running experimental data has shown that during asphalt road running the typical rod displacement per one body fluctuation is 5-10 mm which is not enough for switching over the inductor machine to generator mode.

The study Oprea *et al*. (2011) presents alternate designs of permanent magnet linear generator installed at the translator in compliance with alternation of poles in

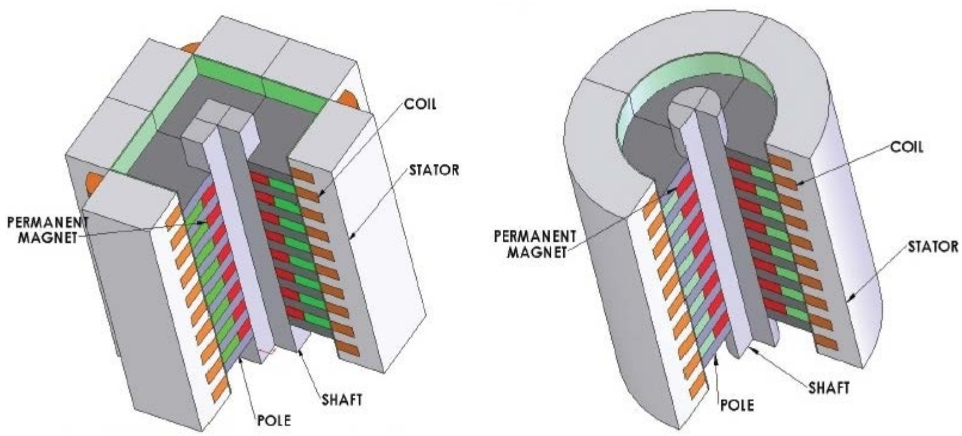

Fig. 4: Permanent magnet linear generator: a) Four-sided and b) Cylindrical

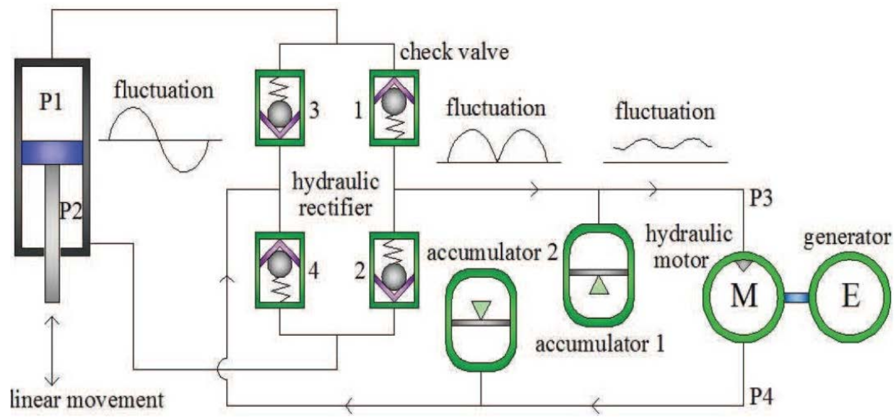

Fig. 5: Scheme of hydraulic electromechanical regenerative shock absorber

the near-by magnets (Fig. 4). Spacers between magnets made of steel are used to conduct magnetic flux through the air gap. The comparison results of cylindrical and four-sided generator structure show that under the same electrical parameters of considered generators, the winding length and the amount of steel in the four-sided generator stator is about a third more than the same indicators of cylindrical one. Accordingly, the losses are more in the four-side generator. Nevertheless, for reasons of manufacturing convenience, it is more preferable to apply the four-sided generator.

Permanent magnets used as the source of linear generator's magnetic field, provide high flux density in the air gap compared with linear inductor generator having the same volume, it leads to mass reducing and it is the main condition for the design of regenerative shock absorber. At the equal volume of active space (winding volume at the stator and air gap volume) the implementation of high energy permanent magnets is essentially efficient than the moving drive winding in terms of force intensity, generated per unit volume and per unit mass and consequently in terms of specific power. Moreover in case of permanent magnets application the power efficiency is higher and cooling conditions are more favorable.

The apparent advantage of shock absorber based on linear generator is the direct conversion of alternating movement into electrical energy without intermediate mechanical conversion and this is very important fact in case of large dynamic loads, affected on shock absorber while running on uneven road surface. However, the calculation proves that the energy regenerative shock absorber, based on linear generator with overall dimension of serial hydraulic shock absorber is not capable to ensure the damping characteristic (Fig. 1) while rebound at the speed up to 0.3 m sec^{-1} due to the negative impact of winding active resistance.

The implementation of rotation generator instead of linear one gives the possibility to minimize the negative effect of winding active resistance under the low speeds

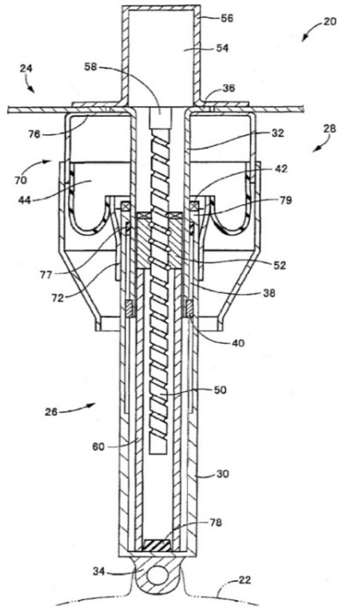

Fig. 6: Energy regenerative shock absorber based on ball screw

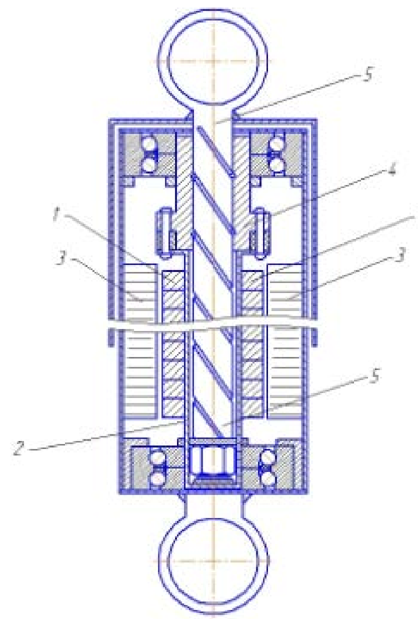

Fig. 7: Compact regenerative shock absorber in compressed view

of rod's displacement. This fact allows us to get the higher generated power and damping coefficient of shock absorber. One of the ways to convert the linear movement into rotary in the vehicle suspension is the application of hydraulic system, based on hydraulic motor (Fang *et al*., 2013) and consisted of hydraulic cylinder, hydraulic rectifier, hydraulic accumulators, hydraulic motor and rotation generator (Fig. 5).

The cylinder piston, fixed into the car's suspension instead of common shock absorber, produces pressure fluctuation in the hydraulic system. Passing through the valves of the hydraulic rectifier, the fluctuations become unidirectional and hydraulic accumulators smooth pressure fluctuation in the hydraulic system. The flow of compressed liquid goes through hydraulic motor which rotates the electric generator shaft. The special feature of this solution is the preliminary conversion of the hydraulic liquid motional energy into mechanic energy of turbine rotation and in consequence its conversion into electrical energy. As the result it impacts greatly on overall effectiveness, especially at the low speed of rod displacement.

To ensure the required rebound force it is necessary to increase the rate speed of rotation generator at the low speed of rod displacement. It is possible to realize if the ball screw mechanism is applied in the design of shock absorber. Figure 6 presents the drawing of the electromechanical energy regenerative shock absorber where the nut 52 of ball screw is fixed at the sleeve 60 which is fixed to guide member 22 at the wheel suspension. The screw rod 50 of ball screw is the extension of generator shaft 54 which is fixed at the vehicle body. The screw rod has the external thread and put into the nut so that the bearing balls are held between the screw rod and the nut. Making the alternating movement, when compressing and rebound of the shock absorber during uneven road running, the screw rod starts rotational movement relative to the nut and therefore it rotates the generator rotor which generates the electric energy for battery charging. In the given design the electric generator is placed outside the ball screw which increases the overall dimension of the shock absorber.

Alternative design of the shock absorber: In order to ensure a more rational layout design and reduce the height of the generative shock absorber, it is reasonable to integrate the generator inside the shock absorber (Fig. 7). In this connection the authors of this article have proposed a new design of regenerative shock absorber. The special feature of this design is the fact that the alternating movement of the screw rod 5 of ball screw, when compressing and rebound of the shock absorber is converted into the rotation movement of the generator hollow shaft 2 fixed at the nut ball screw 4. For this reason the internal diameter of shaft 2 is slightly larger than screw rod diameter 5 which provides the easy running for screw rod within the shaft 2. The rotation of permanent magnets 1, formed generator rotor and fixed at shaft 2, induces current in the generator stator windings 3 located at the inner side of the internal tube 1 in such a way converting mechanical energy of shock absorber alternating movement into electric energy which can be used for the vehicle battery charging. At the same time the generator produces the mechanical force, depending on fluctuation speed of the vehicle body which absorbs these fluctuations providing damping function.

The compact design of shock absorber gives the possibility to install it into mass-produced cars without changing the suspension design which makes the commercialization of the final product more real.

CONCLUSION

The proposed design of energy regenerative shock absorber based on ball screw mechanism allows us to develop a compact shock absorber installing into heavy and light vehicles including serial ones and ensuring damping characteristic similar to the serial hydraulic shock absorber of the car.

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