LATVIAN JOURNAL OF PHYSICS AND TECHNICAL SCIENCES
2017, N 2

DOI: 10.1515/lpts-2017-0008

PHYSICAL AND TECHNICAL ENERGY PROBLEMS

ELECTRIC GENERATOR IN THE SYSTEM FOR DAMPING OSCILLATIONS OF VEHICLES

A. Serebryakov, E. Kamolins
Riga Technical University
12/1 Azenes Str., Riga, LV-1048, LATVIA
e-mail: edmunds.kamolins@rtu.lv
N. Levin
Institute of Physical Energetics
11 Krivu Str., Riga, LV-1006, LATVIA

The control systems for the objects of industry, power generation, transport, etc. are extremely complicated; functional efficiency of these systems determines to a great extent the safe and non-polluting operation as well as convenience of service and repair of such objects. The authors consider the possibility to improve the efficiency of systems for damping oscillations in transport using a combination of electrical (generators of rotational and linear types) and hydraulic means. Better efficiency of functioning is achieved through automatic control over the operational conditions of such a system in order to make it adaptive to variations in the road profile and ambient temperature; besides, it is possible to produce additional electric energy.

Keywords: *damping system, hydraulic damper, permanent magnet generators.*

1. INTRODUCTION

The contemporary technical objects are complex aggregates of elements that should operate reliably fulfilling all the functions to ensure their normal operation. This relates to all kinds of technical means, including transport [1]–[3].

For example, in a usual car that runs on a low-quality motor road the oscillations of its frame and body not only make the driving more complicated, but also jeopardize the safety of traffic; they introduce discomfort to the passengers, and, besides, can cause damage to the car itself as well as to the transported freight.

Therefore, these oscillations should be damped, which is done with the help of special elements of the car suspension – suspension dampers (shock absorbers) [4]. Hydraulic (oil) dampers are among the most widespread elements used for this purpose.

The efficiency of a hydro-damping system can be raised by introducing special electric generators into it. This would allow carrying away heat losses due to oscillations beyond the limits of hydraulics, thus saving it from overheating and making it possible to receive an extra source of electric energy.

In this case, utilisation of the oscillation energy and its conversion into the electric one happen simultaneously.

Apart from that, a possibility arises for fast adaptation of a damping system to the variations in the road conditions, running speed, and ambient temperature. Such a possibility is considered below.

2. ELECTRIC GENERATOR IN THE SYSTEM FOR DAMPING OSCILLATIONS IN A CAR

In order to justify the above-mentioned statements, in Fig. 1 a block diagram of structural design is shown for a combined electro-hydraulic system for damping oscillations in a car. The figure displays: spring (1), with which and with car body (2) hydro-pump (3) with plunger (4) are rigidly connected. Rack of the chassis (5) is linked to hydro-pump plunger (4) and spring (1). With both cavities of hydro-pump (3) through hydro-distributor (7), hydro-motor (8) is connected, which brings electro-generator (9) into rotation.

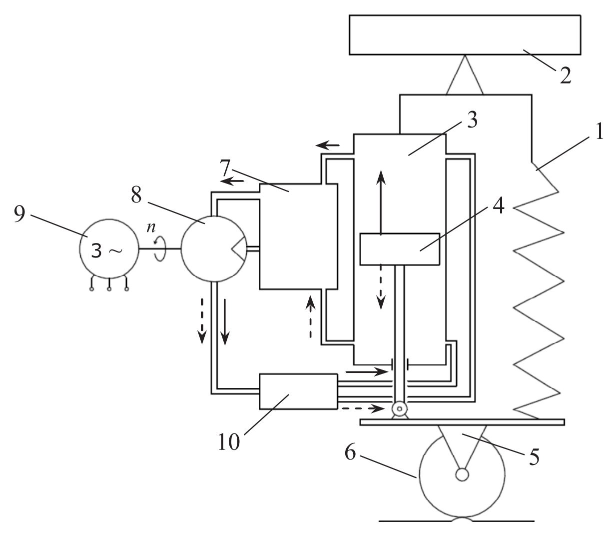

Fig. 1. Block diagram of structural design of the system for damping the car oscillations with rotational (type) electric generator: 1 – spring; 2 – car body; 3 – hydro-pump, 4 – plunger; 5 – rack of the chassis; 6 – wheel; 7 – hydro-distributor; 8 – hydro-motor; 9 – electric generator; 10 – compensative capacities.

The scheme operates as follows: when wheel (6) is running over road asperity, spring (1) is compressed, and plunger (4) in hydro-pump (3) is going up. The oil (hydraulic liquid) is squeezed out of the upper cavity of hydro-pump (3) through hydro-distributor (7) into hydro-motor (8). At reverse movement of the plunger (i.e., down), after the wheel has run down from the obstacle, the oil from the lower cavity of hydro-pump (3) enters the hydro-motor – the same cavity that in the previous case. As a result, the hydro-motor is rotating in one and the same direction – independently of the plunger movement. The oil that under high pressure finds its way into the hydro-motor ensures the required rotational speed for it (and, respectively, for the electro-generator), thus transforming the kinetic energy of oil motion into the rotational movement of the generator rotor, overcoming its electro-magnetic resistance moment. The working process is controlled by the hydro-distributor (7). Compensative capacities (10) provide, respectively, discharging of excessive oil and replenishing the deficient oil in the cavities of hydro-pump. Hence, the latter is here functioning as a hydro-absorber.

To demonstrate the efficiency of the damping system under consideration, we will describe its operation mathematically, using a differential equation. For simplicity, the following assumptions have been made:

- all the forces and movements in the system are directed vertically (along the *y*-axis);
- the forces and movements directed along other coordinate axes (*x*, *z*) do not affect the process that is going in the *y*-direction;
- the temperature, magnetic and mechanical effects exerted on the system in the direction of variations in its parameters are ignored;
- the curve of spring rate is linearized, its value is constant and takes into account the processes going in the pneumatic system of wheels;
- the viscosity of oil and the geometrical sizes of individual system elements – along with the friction coefficient – are assumed to be constant;
- the mutual influence of wheels and of related masses is absent.

Taking into account the above-mentioned assumptions, the expression for acceleration of the car body movements as related to one wheel can be written as follows:

$$\frac{d^2(y_t - y_0)}{dt^2} = \frac{G - F_c - F_a - F_g - F_l}{m}. \tag{1}$$

Here G is the weight of the car part that falls on one wheel, N, and m is its mass, kg;

$F_c = c_y(y_t - y_0)$ is the opposing force of spring at shifting the point y_t of its fastening to the body relative to original point y_0 of equilibrium state, N; C_y is the spring rate, N/m;

$F_a = \dfrac{2\,iC\Phi(C\Phi V_r - U)}{D\sqrt{R_a^2 + X_a^2}}$ is the maximum opposing circumferential force of generator as related to the piston rod, where i is the reduction coefficient determined by hydraulic transmission of the force; C is a design constant of the generator; Φ is the magnetic flux, Wb; V_r is the circumferential speed of generator rotor, m/s; D is the rotor diameter, m; $R_a + jX_a = Z_a$ is the complex adjustable resistance connected between the generator and the accumulator cell, Ω; U is the voltage of accumulator cell, V;

$F_g = K_g \frac{dy}{dt}$ is the friction force due to hydraulic line, N, with K_g being the friction coefficient, Ns/m;

F_l is the occasional force stemming from collision of wheel with the roadway covering, N; this chaotic and short-term force upsets the balance of car body-spring-absorber system with deviation y.

Taking into account the character of action of force F_l and the absence of re-covering force, the oscillations arising in the system are free and damped.

Substitution of the above components into Eq. (1), taking into account that in the equilibrium state $G = C_y y_0$, gives a finite differential equation for the car body movements in the form:

$$\frac{d^2 y}{dt^2} + \left[\frac{2iC\Phi\left(C\Phi V_r - U\right)}{Dm\sqrt{R_a^2 + X_a^2}} + \frac{K_g}{m} \right] \frac{dy}{dt} + \frac{C_y}{m} y = \pm \frac{F_l}{m}. \tag{2}$$

The characteristic equation describing free oscillations after occasional road shock takes the form:

$$y^2 + \left[\frac{2iC\Phi\left(C\Phi V_r - U\right)}{Dm\sqrt{R_a^2 + X_a^2}} + \frac{K_g}{m} \right] y + \frac{C_y}{m} = 0. \tag{3}$$

The roots of Eq. (3) will thus be:

$$P_{1,2} = \pm j\sqrt{\frac{C_y}{m} - \left[\frac{iC\Phi\left(C\Phi V_r - U\right)}{Dm\sqrt{R_a^2 + X_a^2}} + \frac{K_g}{2m} \right]^2} - \frac{iC\Phi\left(C\Phi V_r - U\right)}{Dm\sqrt{R_a^2 + X_a^2}} + \frac{K_g}{2m}. \tag{4}$$

Solution of equation (3) will have the form:

$$y = \left(Y_0 - y_0\right) e^{-kt} \cos \omega_0 t, \tag{5}$$

where $\left(Y_0 - y_0\right) = y_m$ is the maximum deviation of the car body from the equilibrium state as a result of occasional road shock at time t_0 (the beginning of the process), with Y_0, y_0 being the car body ordinates relative to the lower fastening point of spring before and after car running over the obstacle (Fig. 2).

In Eq. (5):

$$k = \left[\frac{iC\Phi\left(C\Phi V_r - U\right)}{Dm\sqrt{R_a^2 + X_a^2}} + \frac{K_g}{2m} \right] - \tag{6}$$

is the coefficient of oscillation damping, and

$$\omega_0 = \sqrt{\frac{C_y}{m} - \left[\frac{iC\Phi\left(C\Phi V_r - U\right)}{Dm\sqrt{R_a^2 + X_a^2}} + \frac{K_g}{2m}\right]^2} - \quad (7)$$

is the natural angular frequency of undamped continuous oscillations.

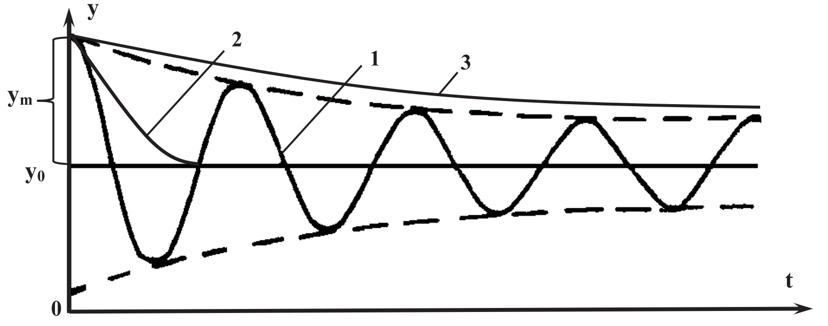

Fig. 2. Oscillation curves for different parameters of the damping system.

Inferences that could be drawn based on the analysis of expressions (5–7) are as follows:

- The parameters of the electro-hydraulic damping system exert influence on the formation of body movement process. In Fig. 2, the curves of possible processes of the type are plotted: curve 1 – for the damped vibrations at $k > 0, \omega_0 > 0;$ curve 2 – for the limiting case of periodic movement at $\omega_0 = 0, k > 0;$ curve 3 – for the asymptotic movement at $k = 0, \omega_0 = 0.$
- Each of these transient processes can be implemented varying the impedance Z_a or magnetic flux of generator Φ. This could be done automatically, with the help of generator while the car is running, by setting the most favourable at the given motion speed, road covering quality, and ambient temperature.
- By adjusting the system for damping vibrations, it is possible to avoid the resonance phenomena, thus excluding consequences of emergency situations; besides, the operation at low-frequency vibrations (dangerous to human life) is ruled out, which increases the efficiency of the damping system.
- The controlled adaptation of the system to ambient temperature variations also increases the system efficiency. This is achieved varying the power of generator, and, correspondingly, the elastance rate of the electrical part of combined absorber under winter and summer conditions. Thus, at freezing weather the oil thickens, its viscosity increases; this makes the hydro-absorber more rigid; correspondingly, the car motion smoothness becomes worse. Such being the case, decreasing the elastance rate of the electrical part of combined absorber at the cost of decreased generator

power would weaken the impact of low temperature. Vice versa, under high summer temperatures the oil becomes less viscous, while the hydro-damper – softer, the road grip of a wheel is worsening, and, therefore, the road safety also becomes worse. In this case, increase in the rigidity of damper due to greater power of generator will moderate the effect of high temperature.

- One and the same obstacle on the road produces different action on the damping system. At a high running speed this action might be stronger, which at constant rigidity of damping system would lead to a greater vibration amplitude, weaker road grip of the wheels, worse safety and comfort of travel, etc. The same occurs at the speed being slower but the obstacle higher. However, raising the power of generator moderates the action of these factors, and will, therefore, serve to improve the damping system performance.

A deeper analysis of Eqs. (5–7) might result in discovery of other important factors; for example, when the oil is too viscous while the friction coefficient is increasing the system becomes uncontrollable and passes to aperiodic operational condition. Such being the case, no additional electric energy is produced. Another example is dealing with a spring of high rigidity, when the damping system passes to the operation with constant oscillations of elevated frequency and amplitude, which might cause excessive discomfort for the passengers and damage to the transported freight – especially if the roadway is with gravel or cobble-stone covering.

All the mentioned nuances should be taken into account when designing the damping systems and their operation.

At the same time, if such a system provides a combined electro-hydraulic control of damping oscillations of cars or other identical objects (buses, railway vans, etc.), its use simplifies to a great extent the problem of achieving better performance for a damping system, making it also possible to derive extra electric energy due to operation of a generator in this combined system.

One of the benefits of a combined system for damping vibrations with a generator of rotational type is the possibility to dispose separately its elements: the hydro-cylinder on chassis, while the hydro-motor, the hydraulic control valve and the electric generator – inside the car body. This would significantly simplify the implementation of the damping system and its operation.

3. DESIGN OF THE ELECTRIC GENERATOR FOR EFFICIENT DAMPING OSCILLATIONS AND UTILISATION OF THEIR ENERGY

In order to make a judicious selection among the designs of a generator as part of the combined system for damping the car body oscillations and utilisation of their energy, it is necessary to define the criteria for such a selection.

The electric machines employed in modern vehicles are usually subject to severe conditions. These could be: jolting, vibrations, impact loads, varying ambient temperatures and humidity, operation under the action of aggressive media as well as of electric and magnetic fields – that is, under unfavourable conditions.

Taking all this into account, it is necessary that the design of generator is the simplest and most reliable, providing a high specific torque (force), improved thermal stability – and, therefore, wide possibilities for the use of low-temperature permanent magnets with high enough specific energy, and to meet many other requirements that are not imposed upon electric machines working under standard conditions.

The electric generator to be used in a car damping system should be a power element that would be capable of developing a damping force comparable with the weight of this car as related to one wheel, i.e., several hundreds of newtons. Therefore, it is of little sense to use a gearless direct-driven generator – mainly due to big forces and low rates of magnetic-flux linkage of windings with magnetic field.

Since the mass of an electric machine is determined by its electro-magnetic force (torque), the generator is to be used in a high-speed condition. This means that such a generator should have a gear for decreasing the output speed and increasing the force applied to the rod, which would counteract the pressure applied to the spring. Under these conditions, it is expedient for excitation of the generator to use permanent magnets, which should be reliably protected from overheating. Such a protection can be provided by placing the magnets on the rotor, while the armature winding – on the stator.

It is tempting in many cases that execution of generator is direct-driven and linear. But then on the stator both the magnets and the winding must be placed, which would substantially complicate the use of low-temperature permanent magnets; besides, in this case the machine must be of inductor type, i.e., of much worse efficiency due to the edge effect typical of electric machines with open-chain magnetic circuit.

Thus, for example, if length l of the mobile part of the generator is comparable with its width b (l/b ≤ 3÷4), the efficiency decreases from 0.8 to 0.6 as in a conventional electric machine [5]–[7].

Under these conditions for a direct-driven generator special design solutions are required, which would provide better cooling of the generator and raise its linear load.

Therefore, the following rational design stands out for a rotational type of generator: a multipole rotor with permanent magnets from magnetically hard material (e.g., NdFeB); a stator that is capsulated in order to separate it thermally from the rotor which might have between the magnets and the shaft an impeller, i.e., a turbine for intensive heat removal from the generator.

The calculated version of the considered design of eight-pole generator has the following main technical indicators:

- rotor diameter and length – 0.75 m;
- rotational speed $n = 3000\ \text{min}^{-1}$;
- nominal power $P = 0.5\ kW$;
- electromechanical torque $M_{em} = 1.6\ N \cdot m$;
- radial force of the generator $F = 40\ N$;
- mass of the generator $G = 3.8\ kg$;
- specific power $P_{sp} = 140\ W/kg$.

Linear generators [8]–[10] can also be used in a car damping system. The arrangement of the damping system (Fig. 3) in this case is much simpler than in the system with a rotating generator (Fig. 1). However, due to low specific parameters of linear generators [11]–[13] compared to rotating generators (3÷4 times or more) the linear generator application in the direct damping system is not always rational.

It should be noted that – despite lower indices of linear electric machines (LEMs) as compared to machines of rotational type – these former generators are conveniently arranged in the suspension of a vehicle and, in principle, are able to operate at reciprocating movements of the mobile part. This means that LEMs can be used for creation of active adaptive systems to damp the oscillations of a car.

For instance, SKF company has worked out the suspension with a spring as the elastic element, and absorber in the form of a linear generator as the damping one [14].

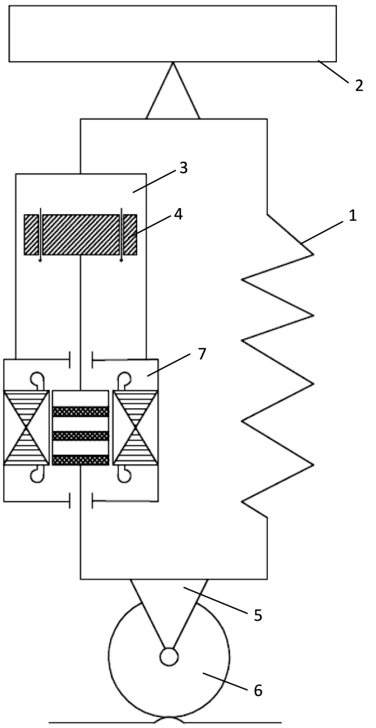

Fig. 3. Block diagram of structural design of the system for damping the car oscillations with linear (type) electric generator: 1 – spring; 2 – car body; 3 – hydro-absorber; 4 – plunger; 5 – rack of the chassis; 6 – wheel; 7 linear generator.

To control the operation of absorber, a controller is used, which contains sensors providing data on the road condition, motion speed, ambient temperature, etc.; the corresponding information is computer-processed, while the received signal is used for control over the absorber. In addition, the energy of vibrations is converted into the electric energy.

In turn, BOSE Company used an electric machine as the electro-magnetic suspension; the essence of this design is that instead of a spring and an absorber there is a controller-operated LEM [15].

The active suspension systems made it possible to significantly improve the efficiency of such systems to be used in cars. However, serious flaws – complexity, considerable energy consumption, high cost – discourage the use of adaptive suspensions in all types of transport, and so far they find application only in expensive top-class cars.

It is, therefore, reasonable to consider in this paper simpler and cheaper damping systems with combined absorbers whose application is possible in a wide range of vehicles.

The most important requirement for the electric machines to be used in active suspension systems is the possibility to control their operational modes with maximum speed of response; taking into account that such machines operate in unsteady transient conditions (in the motoring mode – starting-up, braking, reversing, variations in the load moment and rotational speed, while in the generator mode – variations in the load torque, power, rotational frequency, and in the motion speed of mobile part) the required speed of response is ≤ 1 ms. This means that these electric machines are to be controllable.

4. CONCLUSIONS

The method considered in the paper is based on the combination of electrical and hydraulic parts in the damping system. According to this method, the damping is performed both at the cost of energy loss in the hydraulic part and removal of this energy beyond the hydraulics, using for this purpose an electric generator. Therefore, the hydraulic part presents one of the channels for transformation of oscillation energy into heat, and is the reduction gear of a type to be used for ensuring the serviceability of the electrical channel for damping oscillation.

The main benefits to be derived from the use of such a combined system are the following:

- possibility to control the operational condition of the system through the use of electric generator by varying the power of which the system automatically adapts to unsteady conditions of transport motion: its speed, the road quality, ambient temperature, etc. Thus, better efficiency of the system is achieved during transportation – comfort and safety of passengers, preservation of freight; besides, additional electric energy is produced;
- partial heat removal beyond the hydraulics with the help of the electrical part of the system and, therefore, its higher reliability at the cost of lesser oil overheating in its hydraulic part;
- inadmissibility of the system operation at low-frequency vibrations that are dangerous for the life of people as well as at resonance (phenomena) that can cause an emergency situation;
- accessibility and simplicity of the control over the system operational conditions by varying the braking torque of generator;
- reduced costs of operation owing to smaller wear of the system components;
- saving the car resources at the cost of better operational conditions;

- increase in the volume of freight-passenger transportation owing to the improved availability (factor) of the car for operation.

REFERENCES

1. Vinogradov, R. I., & Ponamerov, A. N. (1991). *Development of World Aircrafts* (in Russian). Moscow: Mechanical Engineering.
2. Twidell, J., & Weir, T. (1986). *Renewable Energy Resources*. London: Routledge.
3. Tamoyan, G.S., Afonin, M.V., Sokolova, E.M., & Myo Tet Thu. (2007). Perspectives of the synchronous generators with the permanent magnets and reciprocation of an inductor (in Russian). *Elektrichestvo, 16*, 54–56.
4. Raympel, Y. (1986). *Car Chassis. Shock Absorbers, Tires and Wheels* (in Russian). Moscow: Mechanical Engineering.
5. Sturman, G. I. (1975). Induction machines with an open magnetic circuit (in Russian). *Elektrichestvo, 10*.
6. Levin, N. N., & Sturman, G. I. (1966). *Multi-Pole Synchronous Machine with an Open Magnetic Circuit* (in Russian). Moscow: VNIIEM BEM. (No. 1).
7. Levin, N. N., & Sturman, G. I. (1964). *Multiphase Inductor Machines in an Arc and Flat Design* (in Russian). Riga: Brushless Electrical Machines. (No. 3).
8. Hiterer, M. Y., & Ovchinnikov, I. E. (2008). *Synchronous Electric Machines with Reciprocating Motion* (in Russian). Sankt-Peterburg: Korona print.
9. Visocky, V. E. (2010). Linear permanent magnet generator for power supply systems of autonomous objects (in Russian). *Mechanical Engineering, 1*, 80–82.
10. Budikova, N. L., Sattarov, R. R., & Polihach, E. A. (2009). To the question of classification of linear electric generators (in Russian). *Gazette of Ufa State Aviation Technical University*, *12*(2), 145–149.
11. Visocky, V. E., Tarashev, S. A., Sinicin, A. P., Zlobina, E. K., & Minenko, S. I. (2012). Development and design of linear permanent magnet generators for autonomous electric power systems (in Russian). *Southern Federal University Engineering Science*, *128*(3).
12. Kecaris, A. A., & Duhanin, V. I. (2010). Linear generator issues with a workflow reciprocating (in Russian). In the 77th International Scientific and Technical Conference (pp. 36–42). Moscow: Moscow State Technical University.
13. Visocky, V. E., Shamesmuhometov, S. L., & Staruhin, A. A. (2010). *Forming Computational Model for Determining the Basic Characteristics and Parameters of the Linear Generator with Permanent Magnets* (in Russian). Samara: Samara State Technical University.
14. Terehov, I. (2011). *Dutch scientists have developed an electromagnetic suspension for cars* (in Russian). Retrieved 6 March 2017, from https://3dnews.ru/609190.
15. Shuldiner, H. (2007). *Bose says suspension drawing interest from OEMs*. Retrieved 6 February 2017, from http://wardsauto.com.

ELEKTRISKAIS ĢENERATORS TRANSPORTLĪDZEKĻU SVĀRSTĪBU SLĀPĒŠANAS SISTĒMĀ

A. Serebrjakovs, E. Kamoliņš, N. Levins

Kopsavilkums

Vadības sistēmas rūpniecībā, enerģētikā, transportā u.c. ir ļoti sarežģītas un to funkcionēšanas efektivitāte nosaka ekspluatācijas drošumu, apkārtējās vides tīrību, ekspluatācijas un remonta ērtumu. Autori apsver iespēju uzlabot transportlīdzekļu svārstību sistēmas funkcionēšanas efektivitāti, pielietojot kombinētus elektriskos (rotējošus un lineārus ģeneratorus) un hidrauliskos līdzekļus. Funkcionēšanas efektivitātes paaugstināšana tiek nodrošināta ar automātisku svārstību sistēmas režīma regulēšanu atbilstoši ceļa profilam un apkārtējās vides temperatūrai, kā arī nodrošinot papildus elektroenerģijas izstrādi.

07.03.2017.