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SKYHOOK VIBRATION CONTROL WITH ENERGY REGENERATIVE SYSTEM

SUMMARY

In the paper two-degree-of-freedom system with self-powered active control was considered. The skyhook control scheme was assumed in calculation. The DC motor was used as the energy regenerative damper that converts the vibration energy into electric energy. The regenerative energy was stored in capacitor or battery. The results of numerical simulation of the motion excited by random process were presented and the analysis of energy balance in the system was estimated.

***Keywords**: damping, vibration control, energy regeneration, self-powered system*

AKTYWNA WIBROIZOLACJA Z UKŁADEM ODZYSKU ENERGII

W pracy przedstawiono układ o dwóch stopniach swobody, w którym do zasilania aktywnego tłumienia drgań wykorzystano energię pochodzącą z odzysku. W obliczeniach układu aktywnego przyjęto znany algorytm „skyhook algorithm”. Jako urządzenie zamieniające energię mechaniczną na elektryczną zastosowano silnik liniowy. Założono, że odzyskana energia jest magazynowana w kondensatorze lub akumulatorze. Przedstawiono wyniki symulacji numerycznej ruchu układu pod wpływem wymuszenia w postaci procesu stochastycznego. Oszacowano bilans energii układu.

***Słowa kluczowe**: tłumienie, sterowanie drganiami, odzysk energii, samozasilające się układy*

1. INTRODUCTION

Active vibration control is used in many engineering applications, for instance in vehicle cab suspensions (Fodor and Redfield 1993; Nakano *et al*. 1999). Active control system has better isolation performance than passive or semi-active systems. However active control system has to be supplied by the external energy source. The necessity of using external sources is often the main disadvantage of the active control systems.

The scheme of a typical active vibration control is presented in Figure 1a. The external source supplies the active vibration system. In order to reduce vibrations, the active vibration system acts on the mechanical system according to the assumed control law. In self-powered system, the energy is absorbed from the motion of mechanical system by means of energy regenerative subsystem as shown in Figure 1b.

The regenerative energy is saved in the internal energy source. These sources supply the active vibration system. If the regenerative system produces sufficiently amount of energy, the external sources are unnecessary. The self-powered systems have various sizes, from small self-powered nanosystems (Wang 2008) and self-powered piezoelectric systems (Lallort *et al*. 2008) to large size self powered systems applied in machine vibroisolations. Usually a linear DC motors are used as energy regenerative dampers (Nakano *et al*. 2003; Okada *et al*. 1997) and batteries or capacitors as internal energy sources.

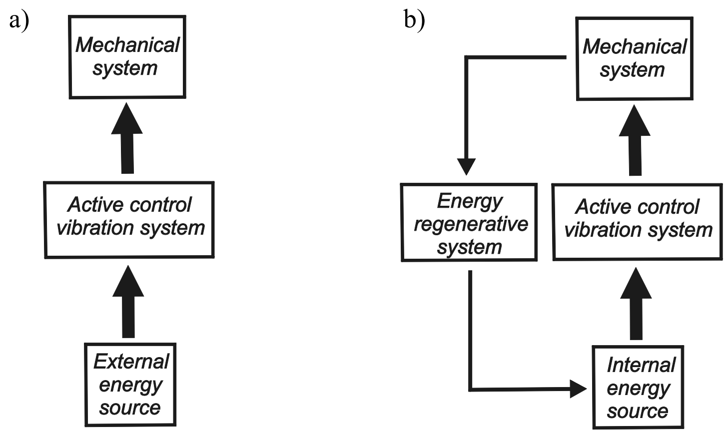

Fig. 1. Schemes of : a) active vibration control system;
b) self-powered active vibration control system

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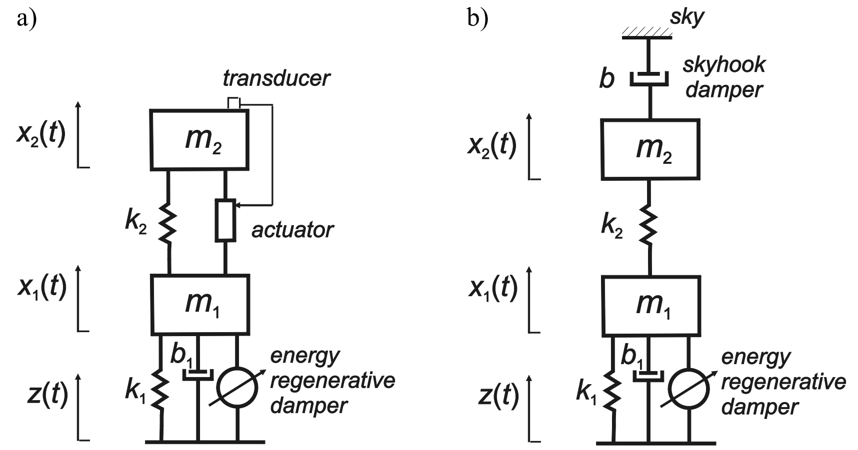

Fig. 2. Scheme of the system a) with actuator; b) with equivalent sky-hook damper

2. PROBLEM DESCRIPTION

The system considered in the study is shown in Figure 2a. Such system is often used as a simple model of truck and cabin suspension systems.

The mass m_1 represents the mass of truck without the cabin, the mass m_2 is the mass of cabin, spring k_1 and damper b_1 represent the stiffness and damping of truck suspension, k_2 is the stiffness of the cabin suspension, the kinematic excitation $z(t)$ is associated with road roughness. The energy regenerative damper is placed in the truck suspension and the actuator is the element of the cabin suspension. The internal energy source is realized by using car battery or capacitors.

The aim of control is to minimize the velocity of the cabin. We assume the closed-loop actuator response to a general feedback law based on the absolute velocity of the cabin. The actuator force is the resisting force proportional to the absolute velocity of the cabin. This control law is usually called sky-hook, because the control force acting on cabin is identical to that of a viscous damper attached to the cabin and to a fixed point in the space (the sky) as shown in Figure 2b. The schemes presented in Figures 2a and 2b are analogies but not equivalent. The skyhook damper force is applied to the cabin whereas the actuator force is applied to the cabin and the truck. It is evident, that the sky-hook is always the energy receiver (it takes the energy from mechanical system) whereas the actuator can be the energy receiver or the energy supplier (it gives the energy to mechanical system) depending on the state of the mechanical system. If the product $\dot{x}_2 \cdot (\dot{x}_2 - \dot{x}_1)$ is positive, the actuator takes the energy from mechanical system, in opposite case the actuator gives the energy to mechanical system.

The energy flow in proposed system is shown in Figure 3. The DC motor, used as the energy regenerative damper, converts the mechanical energy into electric energy. The part of this energy is dissipated in the resistance of the electric circuit and remaining part is stored in internal energy source (capacitor or battery).

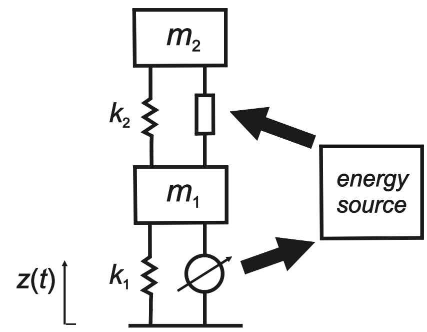

Fig. 3. Energy flow in proposed system

Usually the velocity of the excited base is significantly greater than the velocity of the mass m_2, especially for high frequency components. For this reason it is expected that the energy stored in internal energy source will be sufficient to supply the actuator.

3. STATE EQUATIONS

The system can be described by equations of mechanical subsystem and two equations of electric subsystems (regenerative circuit and skyhook circuit). They are supplemented by constitutive equations of DC motors. It was assumed that DC motors are energy-conserving devices. The skyhook force is derived from the velocity feedback.

The mechanical subsystem is shown in Figure 4a. Vectors in this figure were assumed so as the energy regenerative damper takes the energy from mechanical system and the actuator gives the energy to mechanical system. The figures on the right side present the electric subsystems: the energy regenerative circuit and shy-hook circuit. In energy regenerative circuit the diode enables the charge storing in capacitor or battery in the case of oscillation motion of the frame. In calculations we assume the simplest diode model called "ideal diode" defined as a device having zero resistance when forward-biased and infinite resistance when reverse-biased. From this assumption the current $i_1(t)$ is

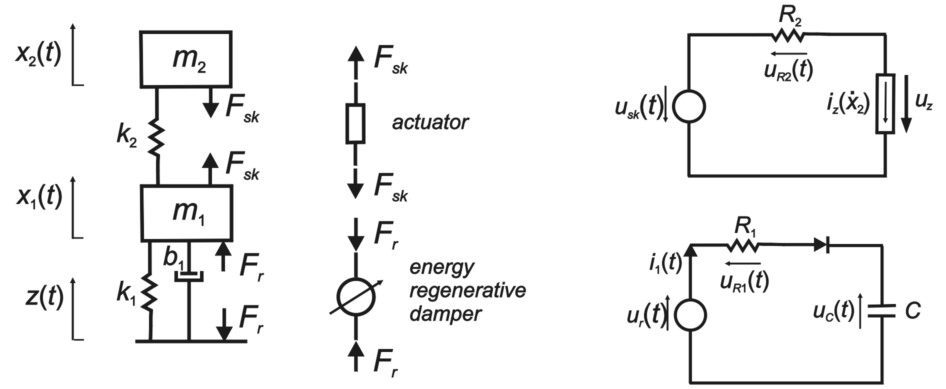

Fig. 4. Schematic sketch of mechanical and electric subsystems

equal to zero if the voltage $u_r(t)$ produced by the DC motor is less than the voltage across the capacitor $u_c(t)$. In the skyhook circuit the current source is controlled by the cabin velocity. In the scheme the current i_z is signed as a function of cabin velocity.

Equations of mechanical subsystem have the form:

$$\begin{cases} m_1\ddot{x}_1 + b_1\dot{x}_1 + (k_1 + k_2)x_1 - k_2x_2 = F_{sk} + F_r + k_1z + b_1\dot{z} \\ m_2\ddot{x}_2 + k_2x_2 - k_2x_1 = -F_{sk} \end{cases} \tag{1}$$

Equations of regenerative circuit and skyhook circuit are written using Kirchhoff"s voltage law:

$$\begin{aligned} u_r(t) &= R_1 i_1(t) + u_c(t) \\ u_z(t) &= u_{sk}(t) + R_2 i_z(t) \end{aligned} \tag{2}$$

An ideal linear DC motor is an energy-storing device. Its property can be described by the following equations:

$$\begin{cases} u_r = \kappa(\dot{z} - \dot{x}_1) \\ F_r = \kappa i_1 \end{cases} \qquad \begin{cases} u_{sk} = \kappa_s(\dot{x}_1 - \dot{x}_2) \\ F_{sk} = \kappa_s i_z \end{cases} \tag{3}$$

where κ is the DC motor constant in regenerative circuit and κ_s is the DC motor constant in skyhook circuit.

According to the skyhook control scheme the desired force F_{sk} is derived from the velocity $\dot{x}_2$ feedback. Thus the equation

$$F_{sk} = b\dot{x}_2 \tag{4}$$

describes the force applied to the masses m_1 and m_2.

The main goal of calculations is the analysis of energy flow in the system. It is expected that the active system reducing the vibrations of mass m_2 can be supplied by the regenerative energy. In this case the energy source should accumulate more energy than it releases.

4. EXCITATION

The excitation of the system is associated with road surface. Road profile can be described by using the power spectral density. This characteristic function can be determined having results of many measurements of road roughness. For different roads, the power spectral density functions are different, but they have a lot of common features. Therefore the typical power spectral density for roads was introduced. The power spectral density (PSD) for the road surface in the case of good quality road is shown in Figure 5a. There are a few formulas describing the power spectral density of road excitation. They can be used to estimate the excitation of the truck.

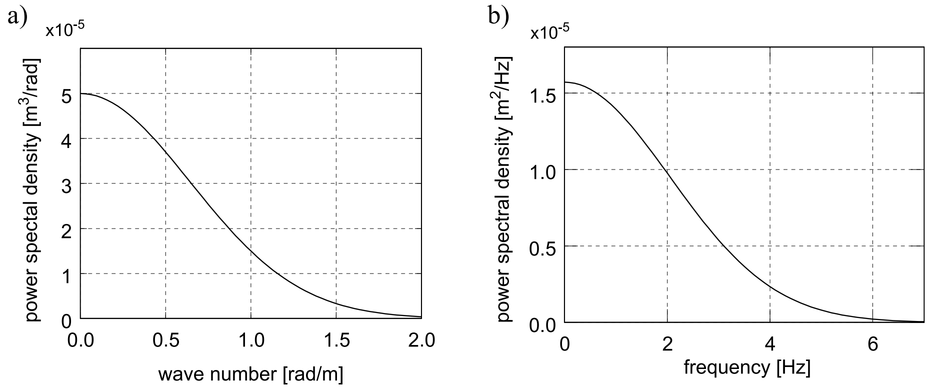

Fig. 5. Power spectral density (PSD) of road surface (a),
power spectral density (PSD) of truck excitation (b)

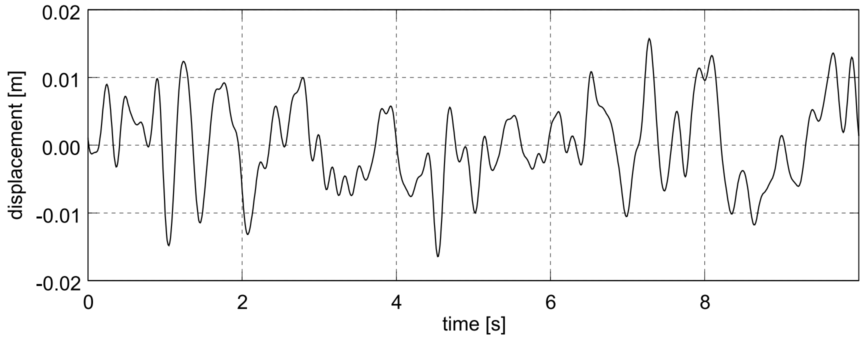

Fig. 6. Example excitation

The displacement of the center of the rolling wheel in the direction perpendicular to the road depends on the road profile, the radius of the wheel and its velocity in direction parallel to the road. If the radius is sufficiently large the short irregularities of the road have not influence on the perpendicular motion of the wheel.

Using a PSD of roughness, the PSD of excitation can be determined assuming the car velocity. In this case the PSD of excitation is a function of frequency. Figure 5b shows the PSD of excitation for the truck speed equals to 72 km/h.

According to assumed random process, the example of excitation is shown in Figure 6. The standard deviation of the roughness height is approximately equal to 7 mm.

5. NUMERICAL CALCULATIONS

The following parameters of the system are assumed in numerical calculations:

$m_1 = 1500$ kg, $m_2 = 300$ kg, $k_1 = 3.58\times10^5$ N/m,

$k_2 = 3.0\times10^3$ N/m, $b_1 = 1.5\times10^5$ Ns/m,

$b = 1.5\times10^3$ Ns/m, $\kappa = 500$ Vs/m, $R_1 = 5\ \Omega$, $C = 0.01$ F,

$\kappa_S = 50$ Vs/m, $R_2 = 15\ \Omega$.

The parameter of DC motors are taken from (Nakano *et al*. 1999).

The following problems are solved:

- the influence of the sky-hook coefficient value on dynamic property of the system,
- charging the internal source (in regenerative circuit),
- supplying the current source in skyhook circuit.

5.1. Dynamic property of the mechanical system with velocity feedback

The dynamic property of mechanical system with velocity feedback can be analyzed using root locus method. It was assumed in calculations that the suspension damping is equal to zero. In this case the system is in the most adverse condition. The sky-hook coefficient b was increased from zero to infinity.

The results of calculations are shown in Figure 7 in the form of root locus diagram.

The increase of the value of sky-hook coefficient is signed by arrows. Figure 7a shows the loci of roots associated with mode in which the frame motion is dominant. The motion with this mode has small damping coefficient. Changes of frequency are insignificant. Figure 7b shows the loci of roots associated with mode in which the cabin

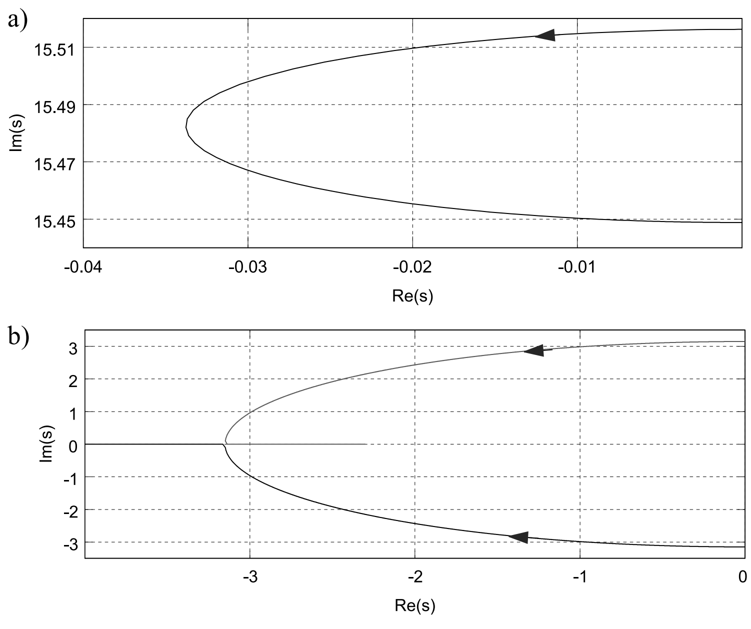

Fig. 7. Root locus diagram

motion is dominant. The following conclusion can be drawn from the analysis of root locus – the system is always stable and the motion of the cabin can be periodic or aperiodic depending on sky-hook coefficient value.

5.2. Charging the internal source

Two internal sources were taking into account in calculation. The first was the 12 V battery. It was assumed that the battery voltage does not depend on charging current and it is the same in any time. The second internal source was the capacitor.

Charging the battery

Figure 8 shows the time history of relative velocity of frame and the time history of charging process of battery in regenerative circuit. The charge of battery increases when the voltage across the energy regenerative damper is greater than 12 V. Because the random process describing the excitation is stationary the battery charge increases almost uniformly. The average current is approximately equal to 0.072 A.

Taking into account the charge and the voltage of battery it is easy to calculate the energy stored in battery. In considered time interval the accumulated energy is equal to 8.64 J.

Charging the capacitor

Results of calculations are presented in Figure 9. It shows the time history of relative velocity of frame and the time history of charging process of capacitor in regenerative circuit.

At the beginning the process of charging is quick and then it goes slow. The initial current equals to 0.14 A, then the current approaches to zero. The limit voltage across the

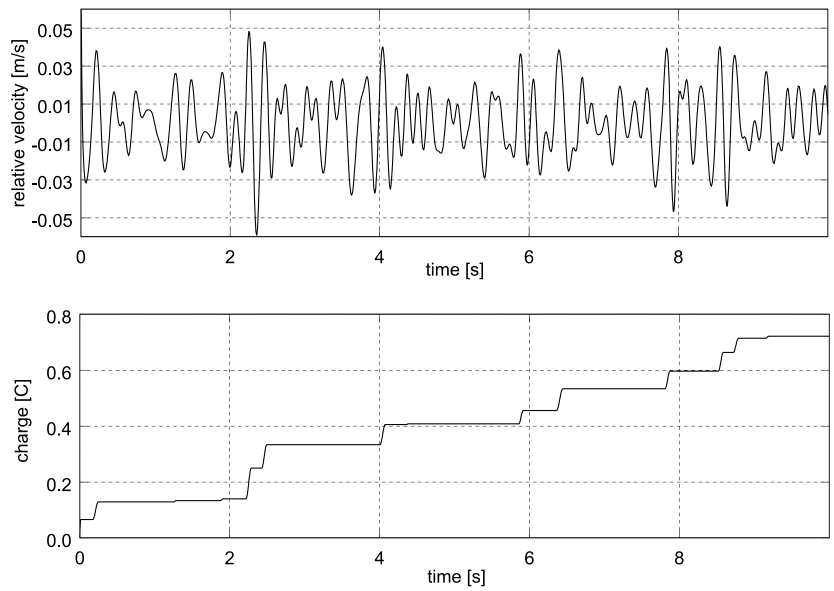

Fig. 8. Relative velocity and battery charge

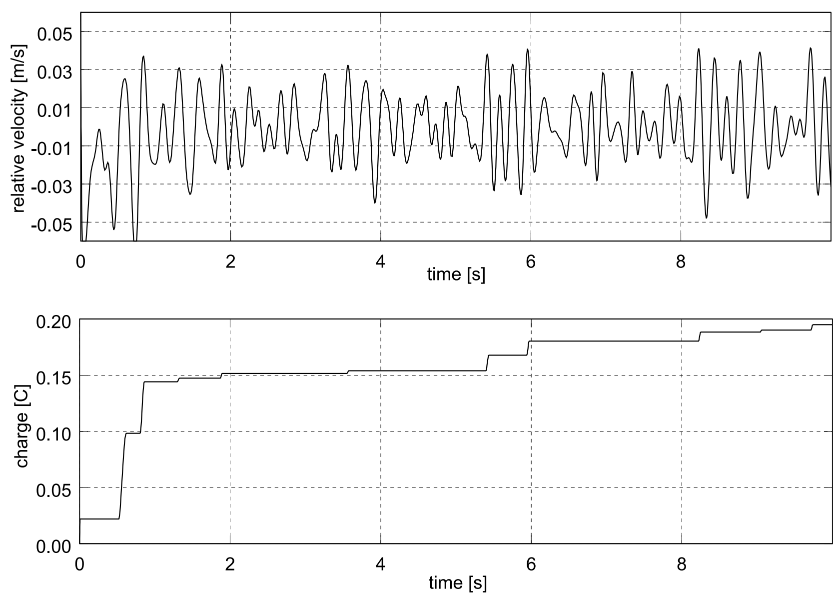

Fig. 9. Relative velocity and capacitor charge

capacitor is equal to 20 V. The limit voltage depends on the size of excitation and DC motor constant. The limit value of energy stored in capacitor depends additionally on the capacitance.

Taking into account the charge and the capacitance of capacitor it is easy to calculate the energy stored in capacitor. In considered time interval the accumulated energy is equal to 2 J.

5.3. Balance of energy in skyhook circuit

According to skyhook control algorithm, the force exerted by transducer has to be proportional to velocity $\dot{x}_2$. As follows from the transducer constitutive equations the force is proportional to the current. Thus the transducer in skyhook circuit has to be supplied by the control current source which is controlled by the velocity $\dot{x}_2$. The current exerted by source in skyhook circuit is shown in Figure 10.

Flow of current in skyhook circuit entails a loss of electrical energy. In skyhook circuit the loss of electrical energy is shown in Figure 11. It is associated with the current work in the resistance R_2.

The work done by the current source is shown in Figure 12.

Comparing the work done by the current source (Fig. 12) with the loss of electrical energy shown in Figure 11 it can be notice that the work done by the source is less than the loss of electrical energy. This difference can be easy to explain taking into account the energy transformed from mechanical subsystem by transducer working in accordance with skyhook algorithm. Mechanical work done by transducer is presented in Figure 13.

As shown the mechanical work is negative. It means that the energy is taken from mechanical subsystem and transformed into skyhook circuit.

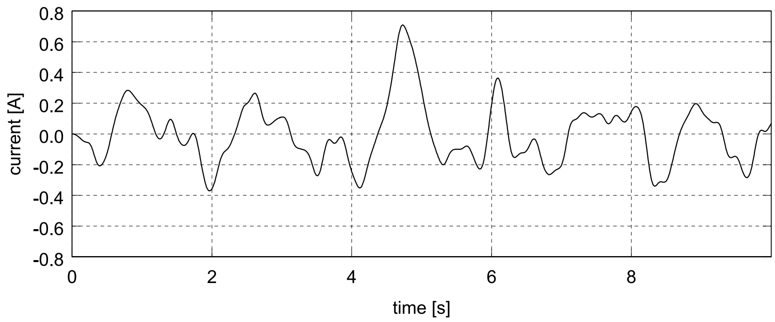

Fig. 10. Current in skyhook circuit

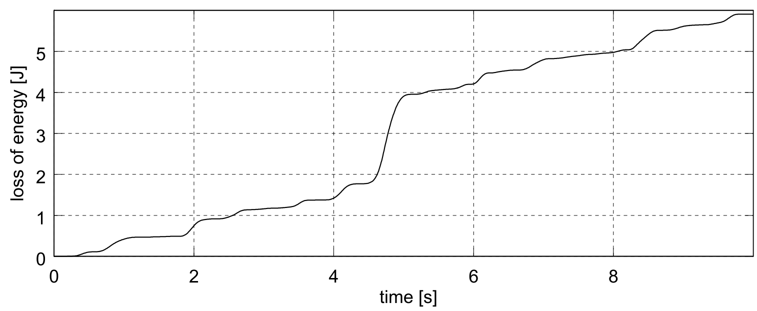

Fig. 11. Loss of electrical energy in skyhook circuit

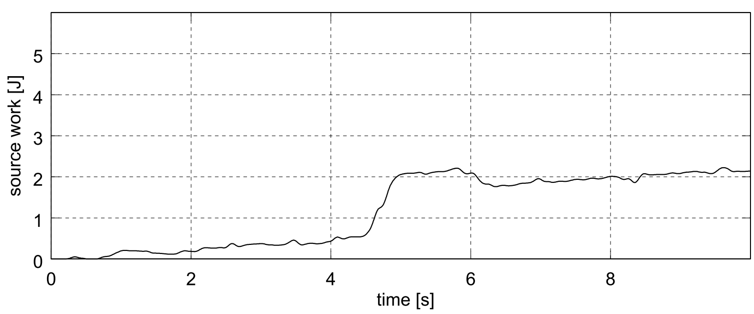

Fig. 12. Work done by the current source

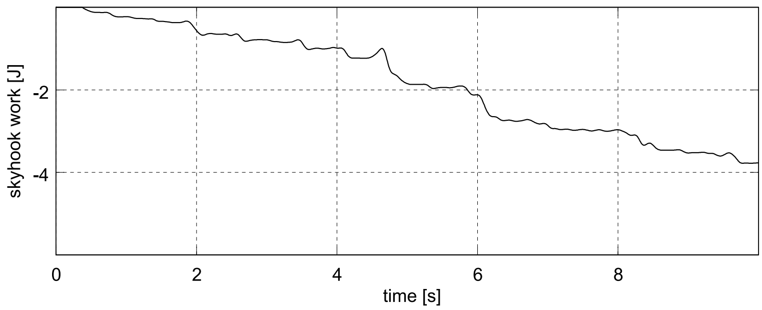

Fig. 13. Work done by the transducer

6. CONCLUSIONS

In the paper the simple model of regenerative system was considered. The regenerative energy was accumulated in battery or in capacitor. It was assumed the random excitation of the system. From the results of calculations the following conclusions can be drawn:

- Considered system with active vibration control based on skyhook algorithm is always stable independently on skyhook coefficient. Depending on the sign of product $\dot{x}_2 \cdot (\dot{x}_2 - \dot{x}_1)$, the transducer in skyhook circuit is the energy input or the energy output, from the view point of mechanical system.
- The energy stored in capacitor is limited. The limit value depends on capacitance of capacitor, DC motor constant and the relative velocity of the armature. The energy stored in capacitor can be used to supply the transducer in skyhook circuit.
- The linear DC motors can be used to transform the mechanical energy into electrical energy which may be accumulated in capacitors or battery. The amount of regenerative energy is rather small but for very efficient devices it can be sufficient to supply the active vibration subsystem.

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References

Fodor M.G, Redfield R. 1993, *The variable linear transmission for regenerative damping in vehicle suspension control.* Vehicle System Dynamics, 22, 1–20.
Lallort M., Lefeuvre E., Richard C., Guyomar D. 2008, *Self-powered circuit for broadband, multimodal piezoelectric vibration control.* Sensors and Actuators: A.Physical, vol. 143, 377–382.
Nakano K., Suda Y, Nakadai S., Tsunashima H., Washizu T. 1999, *Self-powered active control applied to a truck cab suspension*. JSAE Review, 20, 511–516.
Nakano K., Suda Y, Nakadai S. 2003, *Self-powered active vibration control using a single electric actuator.* Journal of Sound and Vibration, 260, 213–235.
Okada Y., Harada H., Suzuki K. 1997, *Active and regenerative control of an electrodynamic-type suspension.* JSME, Series C, 40, 272–278.
Wang Z.L. 2008, *Energy Harvesting for Self-Powered Nanosystems.* Nano Research, vol. 1, 1–8.