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Dynamics and Energy Harvesting Control of an Autoparametric Pendulum-Like System

Abstract. *This paper describes experimental rig used to research system with a pendulum. The pendulum has a double functions. Firstly, it is applied as a non-linear vibration absorber for a simple oscillator. Secondly, an additional magnets-coil subsystem mounted inside a pendulum structure gives possibility of energy recovery. Influence of an oscillator suspension damping and stiffness control on effectiveness of both effects are presented.*

Streszczenie. *Praca opisuje stanowisko eksperymentalne wykorzystywane do badań systemu z wahadłem. Wahadło ma podwójną funkcję. Po pierwsze, jest zastosowane jako nieliniowy eliminator drgań prostego oscylatora. Dodatkowy podukład magnesów i cewki zamontowany na wahadle umożliwia odzyskiwanie energii z jego ruchu. Przedstawiono wpływ sterowania tłumieniem lub sztywnością zawieszenia na skuteczność obu efektów* ***(Sterowanie dynamiką i odzyskiwaniem energii z systemu autoparametrycznego z wahadłem).***

Keywords: nonlinear vibration absorber, energy harvester, magnetorheological damper, shape memory alloy spring.
Słowa kluczowe: nieliniowy eliminator drgań, system do odzyskiwania energii, tłumik magnetoreologiczny, sprężyna wykonana ze stopu z pamięcią kształtu.

Introduction

In engineering applications, a pendulum can often be seen as an element of constructions. Generally, the pendulum introduces the nonlinearity to the system. This nonlinearity can be used to vibration reduction of basic object. For example, a huge pendulum is used as vibration absorber (tuned mass damper) in the skyscraper building Taipei 101 [1]. This system can reduce the displacements of tall building caused by strong winds or earthquakes.

The influence of the pendulum on dynamics of the simple oscillator is presented in the work [2]. Authors shown, that the pendulum can perform different kinds of motion: swings, rotations or make chaotic motion.

In last decade a new trend can be observed. The engineers strive to create ecological constructions. Therefore, system environmentally friendly should allow for energy recovery. In scientific papers the devices to energy harvesting from a pendulum motion are proposed in [3, 4].

In this paper an analysis of the experimental research of an autoparametric system with energy harvester is presented. This system includes both effects, vibration mitigation by the pendulum and energy recovery from its motion. To control of system dynamic, the simple on-off method is applied. Obtained results allow to determine the influence of magnetorheological damping (MR) and stiffness of spring make from shape memory alloy (SMA) on the dynamics of the tested system.

Experimental setup

The crucial elements of the laboratory rig are nonlinear oscillator, pendulum and energy harvester (Figures 1 and 2). The first subsystem is a kinematically excited mass (about 0.7 kg), where its suspension consists of the magnetorheological damper (MR) and spring made from shape memory alloy. The coordinate x describes the vertical displacement of the oscillator. The pendulum is attached to the oscillator. The rotation of the pendulum relative to the oscillator describes the coordinate ϕ. In the first basic version of the experimental stand, the pendulum was used only as vibration absorber [2]. In subsequent studies, the pendulum construction was modified.

An energy harvester was added to the pendulum subsystem. Three magnets (two fixed and one movable – levitating) were placed in the tube. Outside of the tube the inductive coil is mounted. Such a design allows for that one movable magnet can move inside the coil and levitates between two fixed magnets (magnetic orientation of magnets: NS-SN-NS). Values of all parameters of the energy harvester device are presented in paper [5]. Magnet movement relative to the coil generates current flow $i_{harvester}$ in the electrical circuit. Effectiveness of energy recovery by this subsystem strongly depends on dynamics of the oscillator and the pendulum and electrical parameters of harvester device.

Fig.1. A general view of the experimental setup

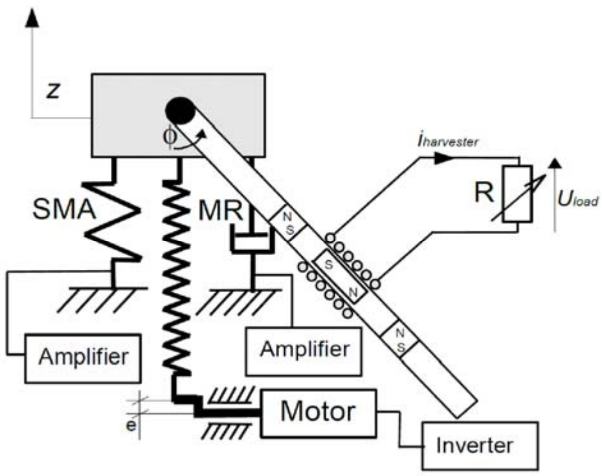

Fig.2. A scheme of the experimental setup

During experimental research, the simple on-off control method of system dynamics were applied. To realization of control, two controllable elements (MR damper and SMA spring) were applied. The magnetorheological fluid can very quickly (time response <25 ms) change properties, density under the influence of magnetic field. The damper RD1097-01 (Fig. 3a) can be supplied with maximum current $i_{d,max}$=1 A [6]. This allows to generate damping force from 9N (0A) to 100N (1A).

Whereas, the oscillator's spring is made from shape memory alloy (nitinol, Fig. 3b) slowly changes properties, change phase from martensite to austenite and vice versa. The phase transformation is caused by temperature and resistance heating activated by power supply (Fig. 3c).

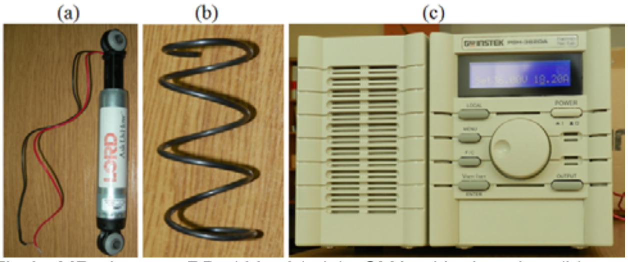

Fig.3. MR damper RD 1097-01 (a), SMA nitinol spring (b) and power supply PSH 3620A dedicated for SMA spring (c)

The amplifier PSH 3620A has a maximum current $i_{s,max}$=20 A. Finally, the stiffness of spring can be change from 500 N/m (100% martensite) to 2000 N/m (100% austenite above 60°C).

Experimental result

Experimental research was made in two stages:

- with MR damper control,
- with SMA spring control.

In both cases the current used to power these components was changed. Control signal $i_{control}(t)$ is described mathematically in the following form

(1) $$i_{control}(t) = i_{on} \cdot H(I(t)),$$

where: i_{on} is value of current when control is on, $H(...)$ the Heaviside's function and $I(t)$ is new variable used to switch the control to the on/off position

(2) $$I(t) = \mathrm{mod}(t, 2 \cdot \Delta t) - \Delta t,$$

where Δt is time window when control is on or off, $mod(...)$ is a modulo operation.

Generally, signal $i_{control}(t)$ can take two values: 0 (control off) or i_{on} (control on). These values were cyclically switched every Δt.

In the first stage the MR damper was controlled. In this case the current level depends on the parameter γ

(3) $$i_{on} = \gamma \cdot i_{d,\max}$$

Whereas, in the second stage SMA spring was supplied. Now, the current level depends on parameter β

(4) $$i_{on} = \beta \cdot i_{s,\max}$$

Parameters $i_{d,max}$ and $i_{s,max}$ were defined in previous section. New parameters γ and β can take value from 0 to 1 (or from 0 to 100%) and they are the ratio of the used value to the limit.

During the experiment two kinds of pendulum motion were compared. In the first type of motion, the pendulum is not activated. Initial condition was $\phi(t=0)=0$. The pendulum moves only up and down with the mass of the oscillator. In second case, the pendulum was activated. The initial condition $\phi(t=0)$ not equal 0. Now pendulum executes swinging (this motion is demand for dynamical absorbers).

Figure 4, 5 and 6 present comparison of system responses for selected measurement. At time t=10 s the control of MR damper was switched from *off* to *on*. For all time series the responses with activated pendulum are marked by black line. Switch of MR damper causes greater reduction of the oscillator's vibration and lower energy recovery level.

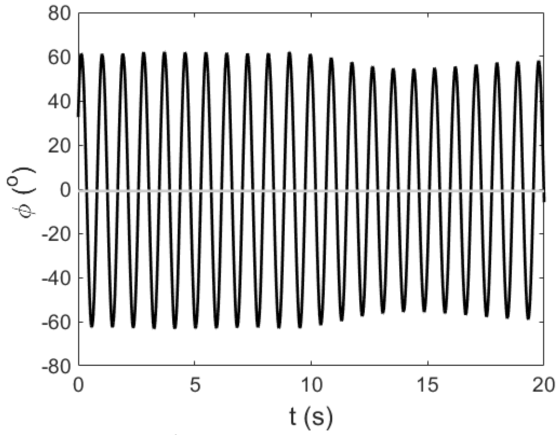

Fig.4. Time series of angle $\phi(t)$. Black line - pendulum is activated, gray line – pendulum is non activated. Switch MR damper control from *off* to *on* at t=10s. Parameter γ=0.09.

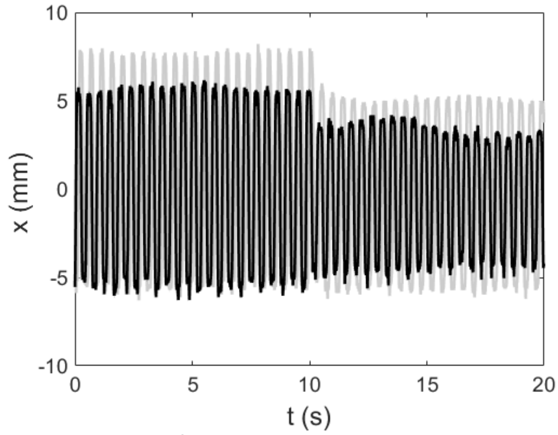

Fig.5. Time series of displacement $x(t)$. Black line – pendulum is activated, gray line - pendulum is non activated. Switch MR damper control from *off* to *on* at t=10s. Parameter γ=0.09.

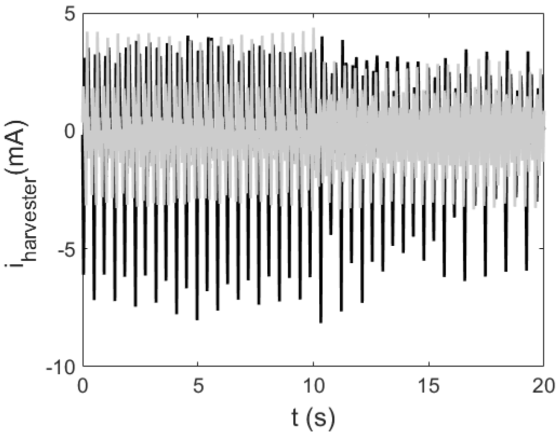

Fig.6. Time series of current $i_{harvester}(t)$. Black line – pendulum is activated, gray line - pendulum is non activated. Switch MR damper control from *off* to *on* at t=10s. Parameter γ=0.09

The effectiveness of vibration reduction and energy recovery is described using the quality indicators [7]:

- for vibration absorption

(5) $$J_1 = \frac{x_{RMS}}{x_{RMS}'}$$

- for energy harvesting

(6) $$J_2 = \frac{i_{harvester,RMS}'}{i_{harvester,RMS}}$$

where bottom index RMS, show that to calculation the root mean square value was taken. RMS values of the oscillator vibrations and harvested current were calculated from time window Δt when control of MR damper or SMA spring was *on*. Whereas, the apostrophe (') is used to indicate when the pendulum was activated (without apostrophe) or not (with apostrophe). A semi-trivial solution (pendulum does not swing), when always $\phi(\tau)=0$ is used as reference.

The value of the quality indicators means:

- $J_i=1$ – responses with and without activated pendulum are the same,
- $J_i>1$ – system without activated pendulum has better response,
- $J_i<1$ – system with activated pendulum has better response.

All curves $J_1(\gamma)$ and $J_2(\gamma)$ or $J_1(\beta)$ and $J_2(\beta)$ were obtained when parameters of excitation were equal: eccentricity e=2.5cm, rotary speed of electrical motor n=130rpm. Whereas, the distance from the axis of pendulum rotation to center of fixed top magnet, center of coil and center of fixed lower magnet were 85mm, 160 mm, 235mm respectively.

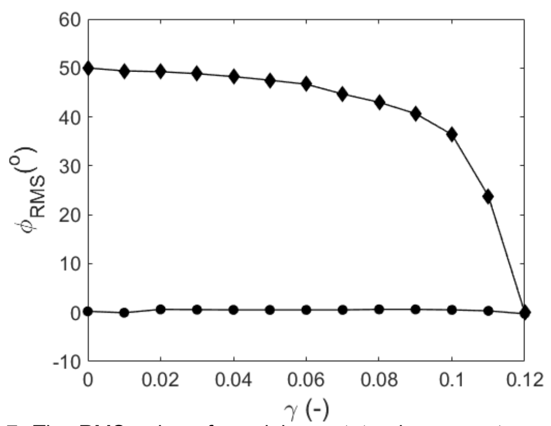

Fig.7. The RMS value of pendulum rotate via parameter γ. Circle marker – pendulum non activated, diamond marker – pendulum activated

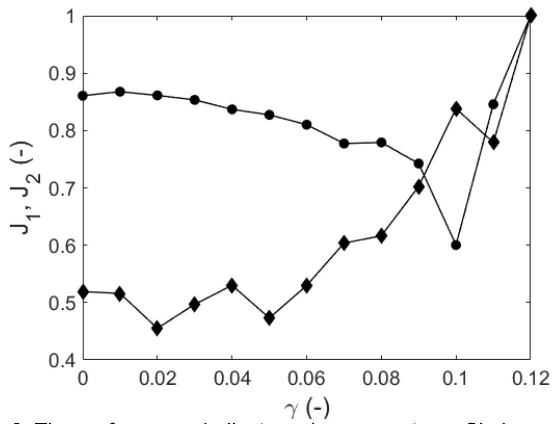

Fig.8. The performance indicators via. parameter γ. Circle marker – J_1, diamond marker – J_2

Figure 7 shows influence of the magnetorheological damping on the pendulum motion. When the damping level increases, then the pendulum motion is decreased. For γ=0.12 the pendulum was deactivated, although the initial condition $\phi(\tau)=0$ was non-zero. Obtained experimental curves $J_1(\gamma)$ and $J_2(\gamma)$ present that activation of pendulum is desirable. Then vibrations of the oscillator are smaller and energy recovery is higher (both indicators are smaller than 1). The presented trends show that the increase of MR damping decrease effectiveness of energy harvesting when pendulum was activated. The values J_2 systematically approaching to 1, responses of current $i_{harvester}$ are more similar to the reference semi-trivial solution. Whereas, the effectiveness of vibration reduction increases in the same situation (values J_1 decreases). Only near the point of deactivation of the pendulum the trend is opposite.

In the second stage of the experimental research the SMA spring were used to the change stiffness of oscillator suspension. Comparison of the system responses with activated and inactivated pendulum is presented in figures 9 and 10. For higher values of parameter β the temperature of SMA spring and also stiffening coefficient are greater. Obtained results show that increasing stiffness caused less vibration of the pendulum (Figure 9 – diamond marker). In this analysis the values of quality indicators indicate that the pendulum activation is preferred. The influence of suspension stiffness on the both criterion can be modeled using periodic function. The observed trends are similar to curve of offset sine function.

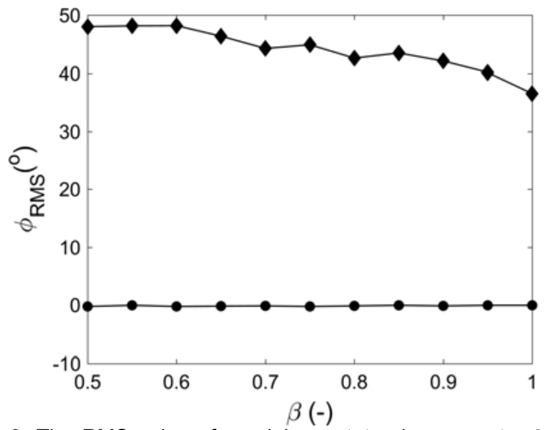

Fig.9. The RMS value of pendulum rotate via parameter β. Circle marker – pendulum non activated, diamond marker – pendulum activated

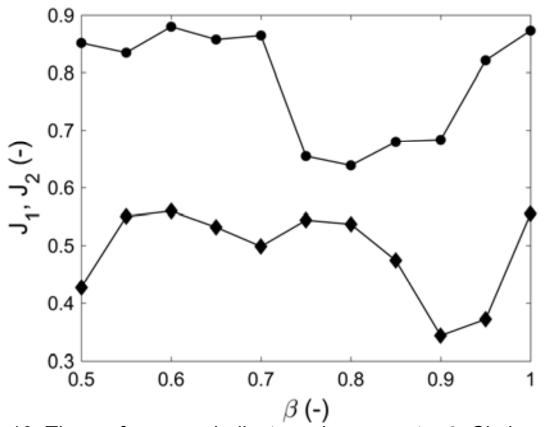

Fig.10. The performance indicators via parameter β. Circle marker – J_1, diamond marker – J_2

Conclusions and remarks

In this paper the experimental investigation of the harvester – absorber system is presented. The influence of the nonlinear damping and the stiffness of oscillator suspension on vibration reduction and energy recovery is shown. The proposed quality indicators can be used to comparison responses system with and without pendulum activation. Obtained results show that activation of the pendulum allows for increased effectiveness of both effects. This means that harvester device added to tuned mass damper can improve vibration mitigation effect, what is very important from practical point of view. In future research obtained results will be used to verification of numerical models and optimization of the suspension's parameters will be done.

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