Influences of System Parameters on Energy Harvesting from Autoparametric Absorber. Numerical Research

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Abstract

In the paper a numerical analysis of an autoparametric system is presented. The two main elements of a tested system are the pendulum (tuned mass absorber) and an energy harvester. The electromechanical model takes into account these both effects. Numerical simulations are made in a MATLAB software environment. The obtained results allowed estimation of influence of the system parameters on efficiency of energy harvesting.

Keywords: Non-linear autoparametric system, Energy harvester, Vibration absorption, Magnetic induction

1. Introduction

Application of the pendulum to the vibration reduction is described in the literature as a tuned mass absorber. A gigantic pendulum (about 700 tons) is applied in skyscraper Taipei 101 building [1]. It is used to reduction of building's movement occurring during earthquakes and high winds. The similar problem was studied intensively at the Lublin University of Technology [2, 3]. The pendulum spring mass system shows regular or irregular (chaotic) responses. The irregular vibrations are very dangerous, especially for dynamic absorber devices.

In the last years the pendulum systems are intensively studied [2-4]. In application where the primary task of the pendulum is vibration reduction (buildings, ship, etc.) a special devices can be added to energy harvesting. An additional harvester can increase functionality of the original system. The new models take into account the possibility of recovery energy from the motion of the pendulum. Generally, in literature exists two different solutions: (I) the rotary harvester [4] and (II) the linear harvester [5]. The word *linear* describes the movement path of the magnet in relative to the pendulum. In this paper the second solution (linear) is proposed.

A strongly non-linear model of electromechanical system and results of simple numerical analysis are shown in paper [5]. In this paper more complex considerations are presented. Influence of the system parameters on induced current level is investigated in detail.

2. Electromechanical model of system

The total system consists of two main subsystems: mechanical and electrical parts. The parts are presented in Fig. 1(a) and (b), respectively. The mechanical subsystem has three basic elements:

- simple oscillator – mass *M* suspended on linear spring k_1 and damper *c*. It is excited kinematically by linear spring k_2.
- non-linear vibration absorber (tuned mass absorber)– pendulum mounted on the oscillator and applied to vibration reduction of mass *M*.
- energy harvester – generally, it is movable magnet located between two fixed magnets (polarity configurations: SN-NS-SN). In presented model this magnetic suspension of movable magnet is modelled as linear spring k_3, for small vibrations [6].

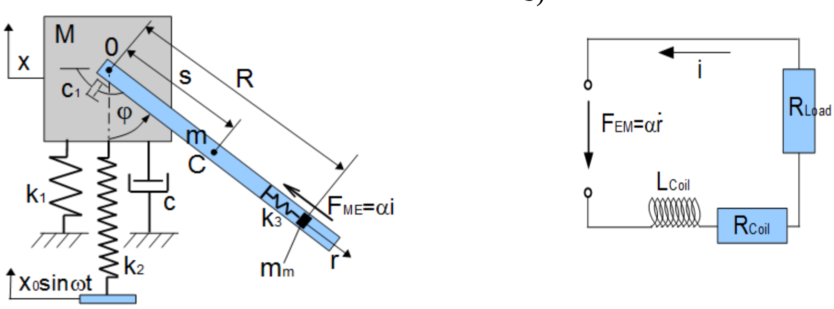

Figure 1. Model of a mechanical (a) and electrical (b) parts of the system

The movable magnet is moving inside the coil. This motion can generate current *i* in electrical circuit (Fig. 1(b)). Both parts, the electrical and the mechanical are coupled by equivalent forces F_{EM} and F_{ME}, which have the same values but opposite directions. These forces depend on the current and velocity of the moving magnet relative to the coil [7]. Differential equations of motion were derived using second kind of Lagrange's equations [5]. The final form of equation of motion has a form:

$$M\ddot{x}+m\ddot{x}+m\ddot{\varphi}s\sin\varphi+m\dot{\varphi}^2 s\cos\varphi+m_m\ddot{x}-m_m\ddot{r}\cos\varphi+2m_m\dot{r}\dot{\varphi}\sin\varphi+ \\ +m_m\ddot{\varphi}(R+r)\sin\varphi+m_m\dot{\varphi}^2(R+r)\cos\varphi+kx+c\dot{x}=Q\sin\omega t \tag{1}$$

$$I_0\ddot{\varphi}+m\ddot{x}s\sin\varphi+m_m\ddot{\varphi}(R+r)^2+2m_m\dot{\varphi}\dot{r}(R+r)+ \\ +m_m(R+r)\ddot{x}\sin\varphi+mgs\sin\varphi+m_m g(R+r)\sin\varphi+c_1\dot{\varphi}=0 \tag{2}$$

$$m_m\ddot{r}-m_m\ddot{x}\cos\varphi-m_m\dot{\varphi}^2(R+r)+k_3 r-m_m g\cos\varphi+\alpha i=0 \tag{3}$$

and for the electrical part:

$$L_{Coil}\dot{i}+R_{Total}i=\alpha\dot{r}\,. \tag{4}$$

2. Numerical results

Numerical simulations of the equations (1-4) were made in MATLAB 2015 software using *ode15i* method. The mechanical and electrical parameters are shown in Tab. 1.

Table 1. Parameters of mechanical and electromechanical models

Description of parameter	Symbol	Unit	Value
The mass of the object main	M	kg	0.65
The mass of the pendulum	m	kg	0.265
The mass of the magnet	m_m	kg	0.02
The mass moment of inertia of the pendulum relative to the rotation axis	I_0	kgm^2	4.96e–4
Distance from the gravity center of the pendulum to the rotation axis	s	m	4.25e–2
Sum of stiffness coefficients of coil springs	$k = k_1 + k_2$	N/m	2700
The substitute stiffness of magnetic suspension of moving magnet	k_3	N/m	2000
Damping coefficient of linear damper	c	Ns/m	10
Damping coefficient of air resistance	c_1	Nms/rad	0.01
Distance from the gravity center of moving magnet to the rotation axis	R	m	3.75e-3
The coil inductance	L_{Coil}	H	1e-3
Sum of resistance of coil and external receiver	$R_{Total} = R_{Coil} + R_{Load}$	Ω	1200
Electromechanical coupling coefficient	α	N/A or Vs/m	3.5
Amplitude of periodic excitation	$Q = k_2 x_0$	N	110

All numerical simulations always start from the same initial conditions $[x, \dot{x}, \varphi, \dot{\varphi}, r, \dot{r}, i]_{initial} = [0, 0, \pi / 2, 0, 0, 0, 0]$. Non zero initial value of the pendulum steady variable φ or $\dot{\varphi}$ causes that semi-trivial solution becomes unstable (pendulum executes motion). This chapter presents influence of the electrical parameters on efficiency of energy harvesting. The following parameters were changed: L_{Coil} from 0 to 0.005 H (first analysis), R_{Total} from 500 to 2000 Ω (second analysis) and α from 0.5 to 5 N/A (third analysis) versus frequency of excitation ω from 20 to 50 rad/s. The efficiency of energy harvesting is described by the quality index. In this paper a simple form of index is proposed (root mean square of current i_{RMS}). RMS values were calculated in a time window $t \in \langle 0, 10 \rangle$ s.

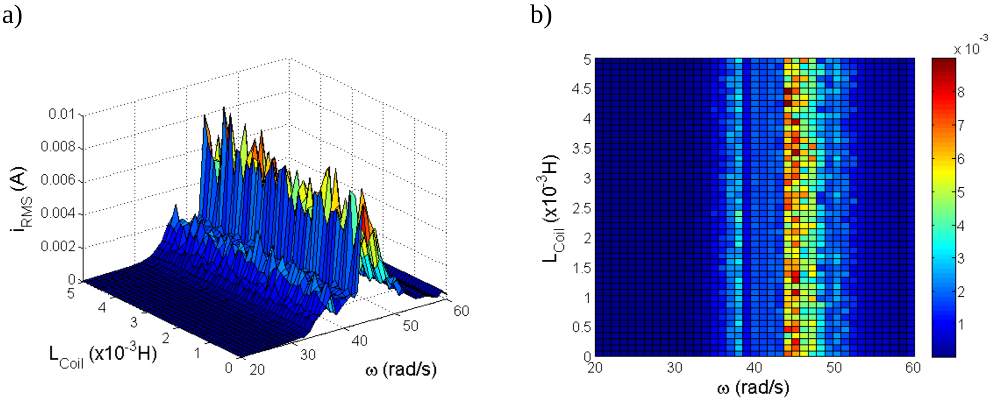

Figure 2. 3D characteristics i_{RMS} versus L_{Coil} and ω (a), and top view (b)

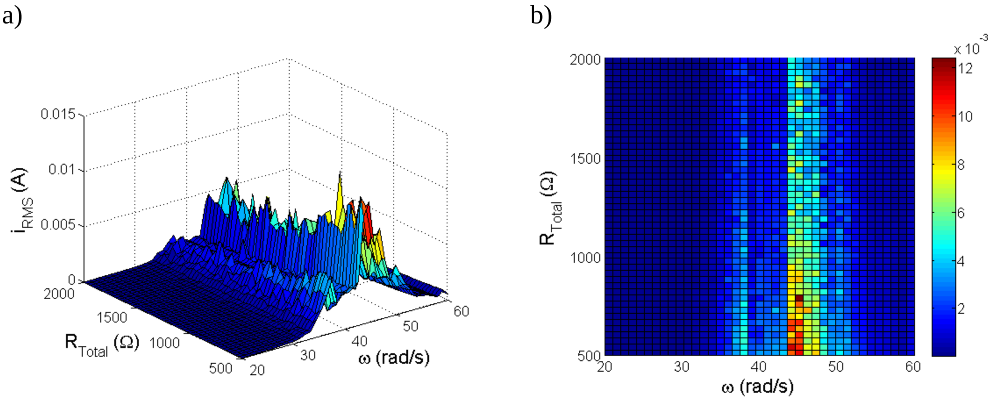

Figure 3. 3D characteristics i_{RMS} versus R_{Totall} and ω (a), and top view (b)

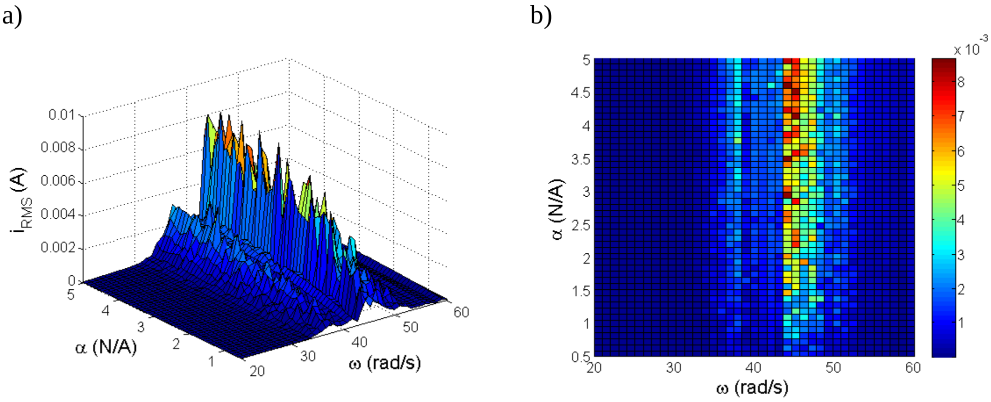

Figure 4. 3D characteristics i_{RMS} versus α and ω (a) and top view (b)

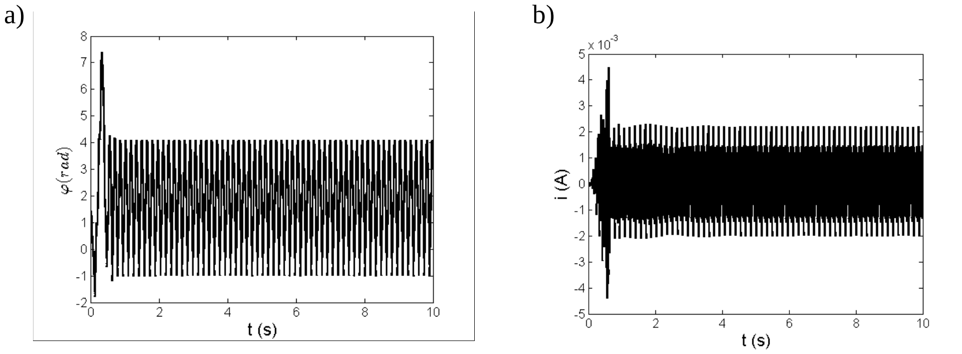

Figure 5. Time series of angle φ (a) and recovered current i (b), for ω=40rad/s

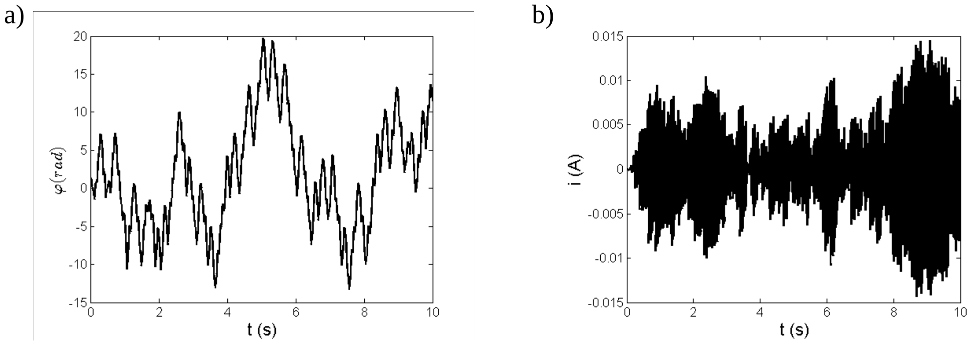

Figure 6. Time series of angle φ *(*a) and current i (b), for ω=45rad/s

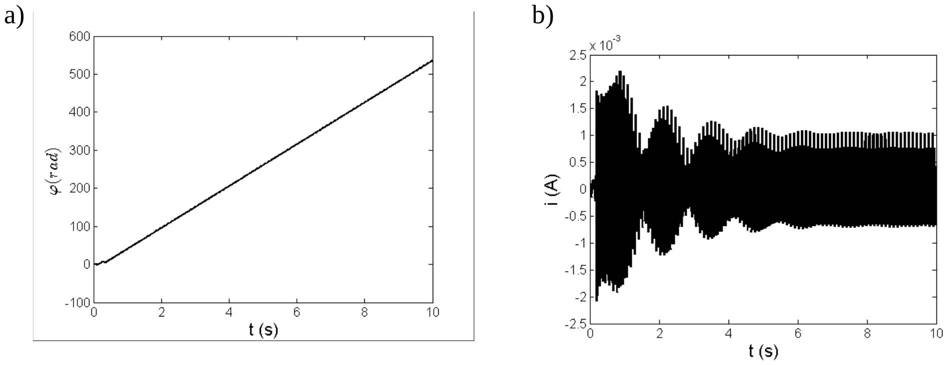

Figure 7. Time series of angle φ (a) and current i (b), for ω=55rad/s

Figures 2-4 present obtained 3D characteristics of recovered current. These results show trend of change the current flowing in the electrical circuit. We observe a significant change of the values i_{RMS} occurring with increasing the resistance R_{Total} and the coupling coefficient α. Increase in the resistance values causes that i_{RMS} decreased slowly (see at a frequency about 45 rad/s). Another trend is observed with an increase of the coefficient α, then the i_{RMS} increases. On the basis on Fig. 2 the definitive conclusions cannot be made. The inductance of electrical coil practically not influences on the energy recovery.

For selected values of the excitation frequency ω, the time series are presented (Figs. 5-7). These times series of the system responses show that pendulum can perform different kind of motion. Namely, pendulum swings (Fig. 5(a)), executes chaotic motion (Fig. 6(a)) and rotates (Fig. 7(a)). The maximal current recovered when the pendulum performs no regular motion (Fig. 6(b)).

3. Conclusions

In this paper numerical analysis of a pendulum vibration absorber with device to energy recovery is presented. The influences of the harvester parameters (L_{Coil}, R_{Total}, α) on value of the recovered current is presented. Energy harvester based on a movable magnet inside the coil, allows recover energy from different kind of the pendulum motion. The 3D characteristics give some information about proper tuning of the electrical parameters. The highest level of energy recovered for the small load resistance and high value of the coupling coefficient. Generally, efficiency of analyzed energy harvester system is low, the obtained current is in mA. However, it can be used to power of small electronic devices consume a little energy, for example sensor in monitoring system.

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