Multiple solutions and corresponding energy output from a nonlinear maglev harvester

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Abstract

Dynamics analysis and energy harvesting of a nonlinear magnetic levitation harvester under harmonic excitation is presented in this paper. The system, for selected parameters, has shown two stable possible solutions with different corresponding energy outputs. The main goal is to analyse the influence of harvester's parameters on the multi-stability zones and energy recovery which can help to tune the system to improve the energy harvesting efficiency.

Keywords: energy harvesting, magnetic levitation, coexistence of attractors, vibrations

1. Introduction

The term "Energy harvesting (EH)" is commonly defined as the conversion of ambient energy into electrical energy. Possible energy sources are vibrations (mechanical energy), temperature gradients (thermal energy), solar energy (light) or electromagnetic waves (radiation). Each method utilizes different processes to transform energy from the environment into usable electrical energy: thermoelectric, photovoltaic, electromagnetic, piezoelectric, magnetostrictive, and electrostatic.
The one of the most popular vibrations based harvesters is an electromagnetic harvesters which uses the motion of a permanent magnet to induce a voltage across the terminals of a coil of wire. This type of the energy harvesters can be divided in two main types, depending on a relative velocity between the coil and the magnet. The first are called "linear" and characterize the magnet moving along a straight line relative to the coil [1]. The second called "rotational" use magnets mounted on a spinning rotor with stationary coils placed around the rotor [2].
Another interesting type of the electromagnetic harvesters are those devices using a magnetic levitation phenomenon to energy induction. These harvesters are called "maglev" and and characterized by simplicity (lack of mechanical elements: springs, dampers etc.), low cost and reliability.

2. Design and Modelling of the Maglev Harvester

2.1. Maglev system

A prototype of the energy harvester with the magnetic levitation system is shown in Fig.1. The system consist of a cylindrical tube made of the nonmagnetic material (plexiglass). A part of the cylinder is wrapped in a multilayered coil on the outer surface of the tube. Two permanent ring magnets (bottom and top) are attached to the end of the tube. The third cylindrical permanent magnet (middle-levitating) moves along the tube, between the fixed magnets and experiences the repulsive force. The magnetic repulsive force is created by two fixed magnets and acts on the moving mass as a magnetic spring.

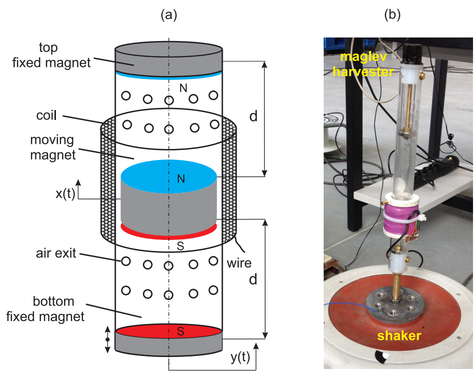

Figure 1: Maglev harvester: (a) model and (b) experiment view.

When an external mechanical vibration is applied to the harvester, the middle magnet starts to oscillate and generates an AC voltage induction in the coil. A change of the magnets separation distance d allows modification in the maglev stiffness and the resonance position.

2.2. Modelling

The maglev system is modeled as mechanical suspension composed of a nonlinear spring (k, k_1) and a linear damper (c), [1, 3]. The nonlinear stiffness comes from the magnets configuration, the linear damping is proportional to the relative velocity and accounts for the mechanical loss of energy. Applying Newton's law to the moving magnet (m), the governing equations of motion can be expressed as:

$$m\ddot{z}(t) + c\dot{z}(t) + kz(t) + k_1 z(t)^3 + \alpha i(t) + mg = -m\ddot{y}(t), \tag{1}$$

$$L\dot{i}(t) + (R_l + R_c)i(t) - \alpha\dot{z}(t) = 0. \tag{2}$$

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The parameter α is the transduction factor (coupling coefficient) and it is assumed as fixed value. It depends on the magnet position in the coil. However, as shown in [3], a fixed value of the coupling coefficient can be accepted, provided it is properly chosen.
The displacement of the middle magnet measured from its static equilibrium position is represented by coordinate $z(t)$, the periodic excitation of the base is $y(t) = Asin(\omega t)$. Equation (2) describes the current induction $i(t)$ in the coil, where R_l and R_c are the load and coil resistances, L is the inductance.

3. Vibration Response and Energy Harvesting

The real maglev pendulum harvester plays a role of the dynamic vibration absorber attached to the oscillator [4]. Therefore, the construction of maglev harvester and ranges of parameters are strictly defined. The identified parameters have values: $m = 0.09(kg)$, $c = 0.054(Ns/m)$, $k = 38.7(N/m)$, $k_1 = 160000(N/m^3)$, $R_c = 1.2(k\Omega)$, $L = 1.46(H)$, $\alpha = 60(Vs/m)$, $A = 0.014(m)$.

The resonance curves for the magnet and the recovered current are shown in Figs. 2 and 3, respectively. The black line corresponds to the case where the load resistance is $R_l = 0.8(k\Omega)$, the blue line to $R_l = 1.2(k\Omega)$ and the green to $R_l = 1.6(k\Omega)$. The bifurcation points are labelled as: SN - a saddle-node bifurcation and PD - a period doubling bifurcation. The stable periodic solutions are marked by the solid line, while the dashed-dotted line denotes the unstable solutions.

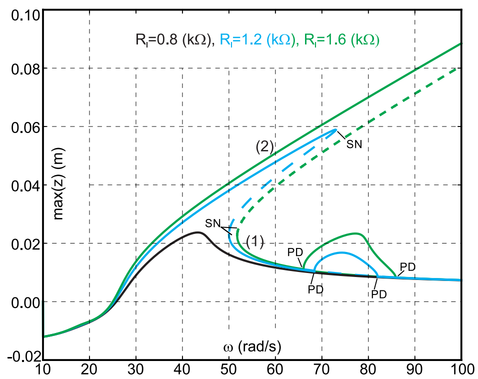

Figure 2: Resonance curves for the maglev harvester.

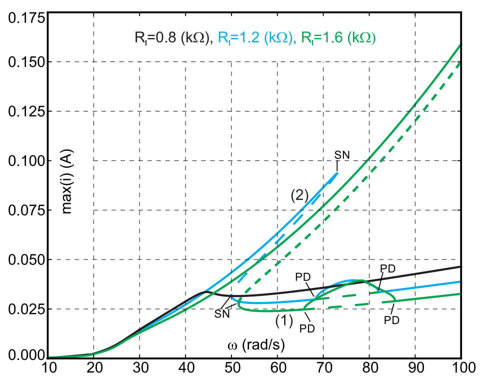

Figure 3: The resonance curves of recovered current from the maglev harvester.

Analyzing the results in both diagrams, we can conclude that the load resistance R_l can introduce new solutions and is responsible for the strong bending of the curve to the right, namely and hardening behaviour. For some parameters, two stable periodic solutions are observed. One of the solutions is characterized by higher energy input (top branch (2)). Additionally, the loss of stability caused by the PD bifurcation appears within the range of $\omega \approx 65 - 85(rad/s)$.

Figure 4 shows the basins of attraction (BA) and coexistence of the two stable solutions. The attractors are marked by black dots and numbered (1) with the yellow basins of attraction, and $(2^1$ and $2^2)$ with the red or orange basins of attraction.

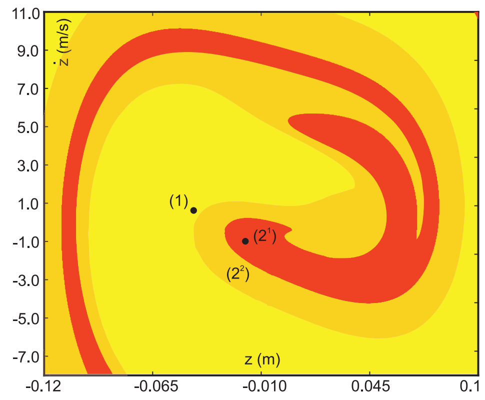

Figure 4: Basins of attraction calculated for $\omega = 51(rad/s)$ and $R_l = 1.2(k\Omega)$. The shadow (orange colour, solution no. 2^2) shows the BA evolution of the resonant solution (2^1) calculated for $\omega = 60(rad/s)$. The red (or orange) color - high energy output, the yellow - low energy output.

The solution (1) in Fig.4 corresponds to the lower branch, while $(2^1$ and $2^2)$ to the top branch in Figs.2 and 3. The solution (2) is much better for the energy harvesting. One can easily notice that the BA represents by yellow colour is dominant. However, the situation changes when frequency of excitation is increased, as the BA of the solution expands and become more and more important.

4. Conclusions

The paper presents numerical analysis of the maglev harvester system. The change of the load resistance can introduce a new solution and then the coexistence of periodic solutions is possible. Moreover, the stability loss by a period doubling bifurcation can be observed. The most promising energy recovery appears nearly the coil resistance $R_l = 1.2(k\Omega)$. Then, the maximal recovered current equals about $i = 0.09(A)$ $(P = 10.4(W))$. Higher value of ω are better in terms of recovered energy. However, the magnet's vibration amplitude is also greater which threatens to leave the coil.

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