ENOC 2017, June 25-30, 2017, Budapest, Hungary

Energy recovery from a pendulum vibration absorber with a maglev harvester

Krzysztof Kecik*, Andrzej Mitura*, Piotr Brzeski** and Przemyslaw Perlikowski**
*Department of Applied Mechanics, Lublin University of Technology, Lublin, Poland
**Division of Dynamics, Lodz University of Technology, Lodz, Poland

Summary. The paper proposes a novel concept of the dynamic vibration absorber with possibility of energy recovery. The pendulum - oscillator system applied in vibration mitigation is modified by adding the maglev (magnetic levitation) harvester device inside the pendulum construction. This concept allows energy recovery, for a semi - trivial (no active pendulum) as well as no - trivial (active pendulum) solutions. The influence and optimization of the maglev harvester parameters on the recovered energy has been done. Additionally, the numerical and experimental results have been compared.

Introduction

Energy harvesting (called energy scavenging or ambient power) is one of the most promising research area as demands for renewable energy sources. There are many methods of harvesting energy. Three of the most common are: Variable Capacitance Systems (VCS), Piezoelectric Material Systems (PMS), and Magnetic (Electromagnetic) Induction Systems (MIS). The electromagnetic energy harvesters depends on many factors, including the size and configurations of the induction system (magnets and coil), the magnetic flux density of the magnets and the excitation frequency [1, 2].
A promising solution for low frequency excitation energy harvesting are the magnetic levitation (maglev) devices. There are electromechanical systems that suspend ferromagnetic materials using electromagnetism, and are characterized by non-linear dynamics, instability and are described by highly nonlinear differential equations [2]. Their non-complex design is effective in many engineering applications (trains, bearings, etc.).

Pendulum Vibration Absorber with a Maglev Harvester

An energy harvester prototype with a maglev inductor is presented in Fig, 1(a) and 1(b), and studied in [1]. The design consists of two identical fixed permanent cylindrical magnets mounted at the top and bottom tube. A third cylindrical permanent magnet (moving) is free to levitate in the axial r direction. The polarity of the magnets is so arranged such that causes levitation effect of the middle magnet ($NS - SN - NS$). The tube of pendulum is made from the non−magnetic plexiglas material. In the tube the special hole (air exits) in order to air cushion reduction are done. A coil of wire is wrapped around the outside of the pendulum tube (Fig.1(b)). While, the moving magnet oscillate, the electromotive force is induced. This harvester system is mounted in the pendulum-oscillator system, which is designed to vibration mitigation (pendulum mass damper), Fig.1(d).

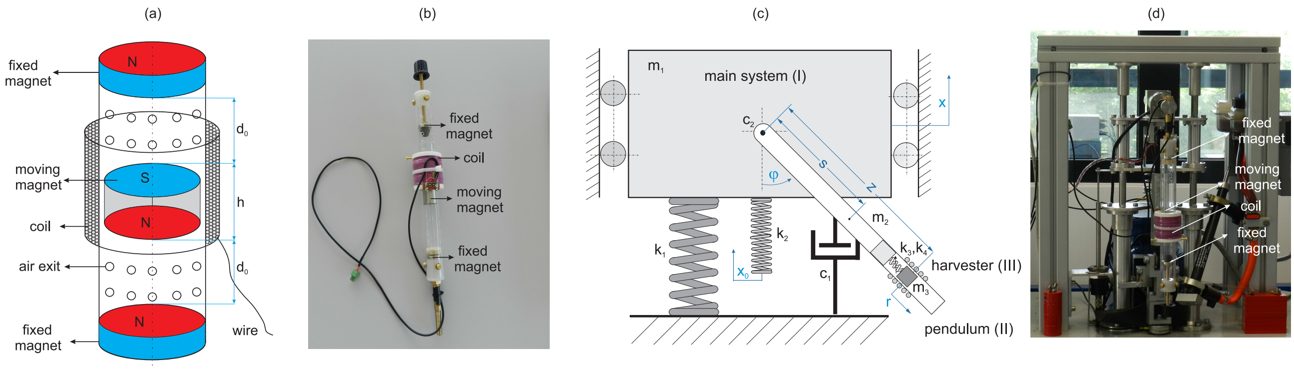

Figure 1: Scheme (a) and laboratory (b) maglev harvester, mounted in the laboratory rig (d). The physical model of the laboratory rig in (c) is shown.

A schematic diagram of the harvester−absorber system is shown in Fig.1(c). This is a coupled three mechanical and one electrical degrees of freedom system. The maglev force, given by the sum of the repulsive forces acting on the top and bottom magnets, leads to the form of the magnetic spring describing by the hardening Duffing′s characteristics [2, 3]. Therefore, the maglev suspension can be modelled as mechanical suspension having non-linear spring (linear k_3 and non−linear k_4 stiffness).
The main system (I) is the oscillator with mass m_1, linear spring k_1 and linear damping component c_1, connected to the base. The pendulum m_2 with the moving magnet m_3 (I_0 means mass inertia momentum) creates the dynamic vibration absorber. The absorber−harvester system is kinematically excited by the linear spring k_2 in the vertical direction. The parameter z denotes position of the moving magnet, the parameter s means gravitation centre of the pendulum (with harvester device). The changes in the magnets separation distance (parameter d_0 in Fig. 1(a)) cause alter stiffness leading to resonance [2]. For small values of relative displacements r of the moving magnet, the levitation suspension can be treated as linear problem. However, for higher magnet′s displacement, the magnetic suspension is strongly non−linear.

The governing equations of the non-linear harvester-absorber system derived from the Lagrange′s equations of the second kind have the form:

$$(m_1+m_2+m_3)\ddot{x}+(m_2s+m_3(z+r))[\ddot{\varphi}sin\varphi+\dot{\varphi}^2cos\varphi]+m_3(2\dot{r}\dot{\varphi}sin\varphi-\ddot{r}cos\varphi)+c_1\dot{x}+(k_1+k_2)x=k_2x_0, \quad (1)$$

$$(I_0+m_3(z+r)^2)\ddot{\varphi}+(\ddot{x}+g)[m_2s+m_3(z+r)]sin\varphi+2m_3\dot{\varphi}\dot{r}(z+r)+c_2\dot{\varphi}=0, \quad (2)$$

$$m_3\ddot{r}-m_3[\ddot{x}cos\varphi+\dot{\varphi}^2(z+r)]-m_3gcos\varphi+k_3r+k_4r^3+\alpha(r)i=0, \quad (3)$$

$$L\dot{i}+R_ti-\alpha(r)\dot{r}=0, \quad (4)$$

$$\alpha(r)=a_1r+a_2r^3+a_3r^5+a_4r^7+a_5r^9+a_6r^{11}+a_7r^{13}. \quad (5)$$

Eqs. (1)-(3) describe the mechanical components: $x-$ oscillator, $\varphi-$ pendulum, $r-$ moving magnet, while Eq. (4) describes the current flow (i) in the electrical circuit ($L-$ is the inductance of the coil, $R-$ is the sum of coil and load resistances). Eq.(5) presents model of the coupling coefficient $\alpha(r)$ which describes the magnet position versus the coil, and it is proposed in the paper [4] (a_1-a_7 are the coefficients determined experimentally). Note that this system is strongly non−linear, coupled by the inertial and velocity terms. Therefore, different dynamics from periodic, quasi−periodic to chaotic is possible.

Results and Discussion

The exemplary resonance curves for the oscillator, the pendulum and the moving magnet versus frequency of excitation (ω) are shown in Figs. 2(a)−(d), respectively. The black line corresponds to the case where the linear levitation stiffness equals to $k_3=35[N/m]$, the green line to $k_3=200[N/m]$, and the blue line to $k_3=500[N/m]$. The unstable solutions are marked by dash−dotted lines, while the solid lines denote the stable solutions. In the literature, this type of systems characterized by the instability region observed near the main parametric resonance [4]. In this case instability zone causes by Neimark−Sacker (NS) bifurcations and is located for frequency $\omega\approx 38-45[rad/s]$.

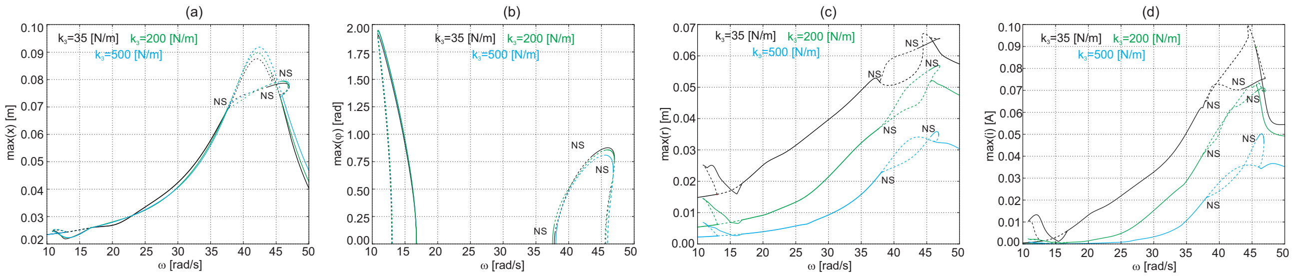

Figure 2: Exemplary resonance response curves: main system(a), pendulum (b), moving magnet (c) and recovered current (d). The simulation data: $x_0=0.04[m], m_1=0.4[kg], m_2=0.45[kg], m_3=0.09[kg], k_1=800[N/m], k_2=1000[N/m], k_4=180000[N/m^3], c_1=10[Ns/m], c_2=0.0125[Nms/rad], z=0.17[m], R_t=3.1[k\Omega], L=1.463[H]$.

Note, that increase in the linear levitation stiffness practically does not influence on dynamic vibration effect, but strongly influence on the magnet dynamics (Fig. (2c)) and reduced recovered current (Fig. 2(d)). The resonance zone is slightly shifts to the right side. Additionally, for higher frequency ($\omega>40[rad/s]$), a small increase in the oscillator and pendulum amplitude vibration is observed.

Conclusions

The paper proposes a novel type of a pendulum vibration absorber with the device for energy recovery (absorber−harvester system). The system is dedicated generally for the pendulum swinging as well as semi−trivial solution (pendulum fixed). The obtained results show that application of the harvester device and change in levitation suspension can increase of energy recovery without loss of vibration mitigation effect. However, near main parametric resonance the instability region can be detected.

Acknowledgements: This work was financially supported under the project of National Science Centre according to decision no. DEC-2013/11/D/ST8/03311.

References

[1] Kecik K., Brzeski P., Perlikowski P. (2017) Non-linear Dynamics and Optimization of a Harvester-Absorber System. *I. J. Struc. Stab. Dynam.* **17(9)**:1-15.

[2] Mann B.P., Sims N. (2009) Energy harvesting from the nonlinear oscillations of magnetic levitation. *I. J. Soun. Vib.* **319(1-2)**:515-530.

[3] Kecik K., Mitura A., Warminski J., Lenci S. (2016) Non-linear Dynamics od a Pendulum Vibration Absorber with a Maglev Harvester. *Proc. XXIV ICTAM, Montreal, Canada, 2016*:186-187.

[4] Warminski J., Kecik K. (2009) Instabilities in the main parametric resonance area of mechanical system with a pendulum. *J. Soun. Vib.* **332**:612-628.