Two Degrees of Freedom Electromechanical Energy Harvesting

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ABSTRACT -Energy harvesting from vibration sources is typically performed by means of single degree of freedom approach with the consequence of having a narrow resonance bandwidth that has to perfectly match the vibrational input frequency to provide good recovery performance. In addition, broad frequency band inputs result poorly coupled with the transducer, or single frequency input may loose their frequency matching due to alteration in the input itself or in the transducer during time. In this paper, starting from the experience of the authors in different applications and using magneto-inductive electromechanical oscillators, a two-degree-of-freedom energy harvester is designed employing the Firestone electromechanical analogy with the aim of obtaining a wide and quasi-constant frequency response as consequence of the non-linear magnetic spring coupling the oscillating magnets. Simulations show that the non-linearities of the magnetic forces and fluxes can represent an effective advantage.

Keywords — energy harvesting, nonlinear magnetic coupling, multi-degree-of-freedom, aeroelastic vibrations.

1. INTRODUCTION

One of the main limitations of the magneto-inductive EHs is that, being single-degree-of-freedom (S-DOF) systems, they present very narrow resonance bandwidth that, in order to make the energy recovery effective, must perfectly match the vibrational input frequency. During the device lifetime, theoretically endless, constitutive materials proprieties may alter for example due to friction deteriorations or temperature changes, shifting the transducer natural frequency. Moreover, also the vibrational input characteristics may vary during time shifting its main frequency. It follows that operating condition may lose the frequencies matching making performance very poor. In order to widen the EH device frequency bandwidth, many solutions have been proposed mainly exploiting systems constituted by several SDOF oscillators. The limitation of this solution is that it consist of several EHs of which only one or few provide good performance. In addition, the overall frequency band of the system is characterised by narrow consecutive peaks instead of a constant band.

The aim of the present works is to show how a 2-DOFs magneto-inductive EH, by exploiting the magnetic nonlinear stiffness coupling the oscillating magnets, may broaden its frequency response to a large quasi-constant frequency bandwidth. The working principle can be further extended to M-DOFs analogous systems.

In order to better match the mechanical and electrical systems descriptions, the developed model employs Firestone's analogy as it allows traducing the first one in an electrical circuit having the same architecture and hence easier to understand and extend.

2. EH 2-DOFS ARCHITECTURE

The considered EH device is a magneto-inductive linear generator. Two floating permanent magnets opposite oriented can slide into a guide suspended between two springs. Around the guide, coils are wound, see Fig. 1. Due to input vibrations, each floating magnet moves with respect to the guide causing flux linkage variation in the coils and inducing voltage at their ends. This architecture allows exploiting for the energy recovery two vibrational modes and tune their frequency in order to optimise the device performance.

Transducer system can be represented as two S-DOF systems coupled by means of a magnetic spring that introduces peculiar and very attractive aspects in the overall behaviour.

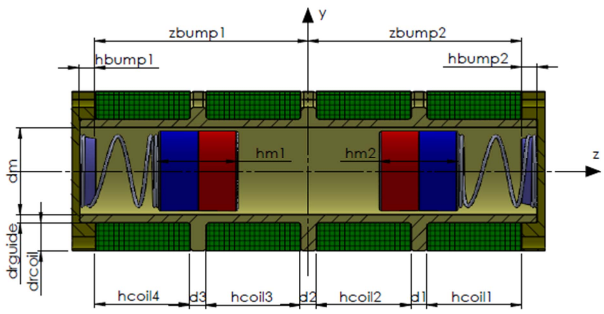


Fig.1 EH 2-DOFs architecture

3. DEVICE MODELLING

Employing the Firestone's electromechanical analogy, based on the equivalence of the state variables velocity-voltage and force-current, the transducer mechanical system has been represented as an electrical circuit where masses, springs, dampers, "imposed kinematics' and external forces are respectively capacitors, inductors, resistors, voltage generators and current generators connected between the same physical nodes (Fig.s 2, 3, 4). The main advantage of this analogous representation is that it maintains unvaried the mechanical system's architecture making the understanding and the extension to more complicated architectures easier.

In order to evaluate the behaviour of the system, a multi-physics integrated simulation tool based on a block-oriented logic has been developed in Matlab/Simulink environment. Electro-mechanical coupling parameters are derived by means of an electromagnetic FEM simulation implemented in FEMM environment and allow describing the influence that each domain has on the other. Such a tool represents a very effective and versatile design platform easily adaptable to various design needs and harvester architecture changes.

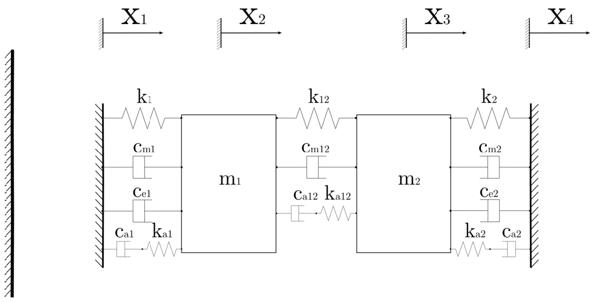


Fig.2 Mechanical representation of the 2-DOF transducer.

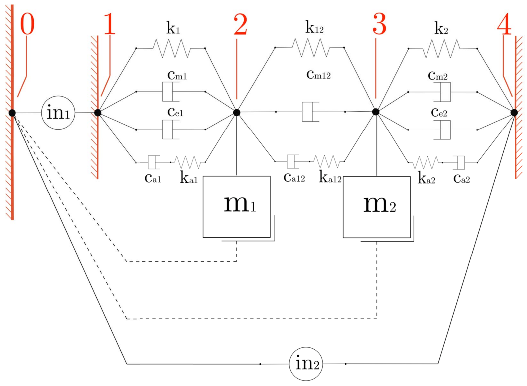


Fig.3 Intermediate representation of the 2-DOF transducer

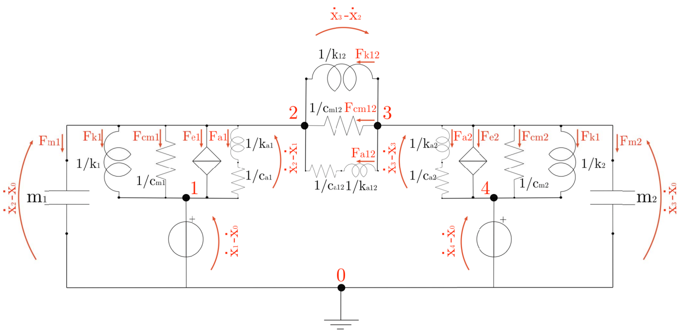
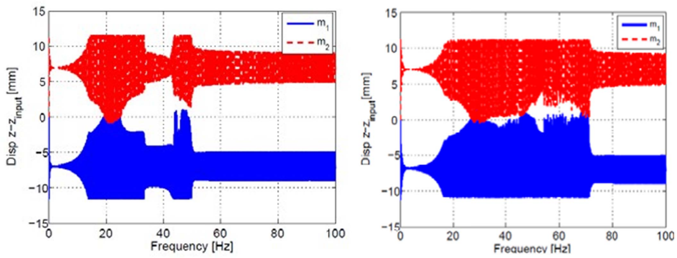


Fig.4 Electric representation of the 2-DOF transducer

4. RESULTS

The comparison between the sweep response in the case of ideal linear and in the case of magnetic non-linear middle spring, Fig 5, shows that in the first case two well distinct peaks of the response are highlighted, while in the second the non-linearity introduced in the system makes the two natural frequencies a wide resonant band. This behaviour allows effectively exploiting wider the operative conditions.

Another very interesting aspect regards the choice of the floating masses and linear springs stiffness during the design phase as a symmetric configuration presenting equal masses and equal springs leads to the cancellation phenomenon of the second mode, the anti-phase oscillation, due to the fact that the same kinematic law is simultaneously imposed to the two constraints. This undesirable effect can be avoided by considering slightly asymmetric parameters.



a) b)

Fig.5 2-DOFs EH sweep response: (a) ideal linear springs and (b) non-linear magnetic spring between the floating elements

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

The potentiality of adopting a 2-DOFs EH to recover energy from a wide band input have been proven demonstrating the possibility of obtaining a quasi-constant broadband frequency response. Prototypes have been manufactured in order to experimentally validate and test the proposed solution, Fig. 6.

Fig.6 Prototype of the 2-DOF transducer

6. REFERENCES

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