EXTENDED FREQUENCY BANDWIDTH THROUGH MULTI-DEGREE-OF-FREEDOM NONLINEAR MAGNETO-MECHANICAL ENERGY HARVESTING

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SUMMARY: Energy harvesting from different vibration sources is typically designed by means of a single degree of freedom approach and implementing both linear and nonlinear principles and techniques. In this paper, starting from the experience of the authors in different applications and using linear magneto-inductive electromechanical oscillators, a two-degree-of-freedom energy harvester is designed with the aim of supplying sensors in a wing typical section. The energy harvester can be modelled as a system of two masses with linear springs or nonlinear elastic interactions due to magneto-static forces. The equivalent mechanical dampers of the same device are four coils that can be connected to the electric interface and then to the electric load circuit. The strong improvement of this simple extension of a linear generator with two degrees of freedom relies on the dynamic improvements of the coupling to the source that can be tuned in order to increase the frequency bandwidth of the device. The simulations show that, although the limited stroke of the magnets and the undesired mechanical friction can reduce the energy harvested, the nonlinearities of the magnetic forces and fluxes can represent an effective advantage, in particular, in a multi-degree of freedom system subject to a large frequency bandwidth input or random excitations. Potential perspectives could be also implemented through semi-active or active strategies obtained through the electric interface.

KEYWORDS: energy harvesting, nonlinear magnetic coupling, multi-degree-of-freedom, aeroelastic vibrations.

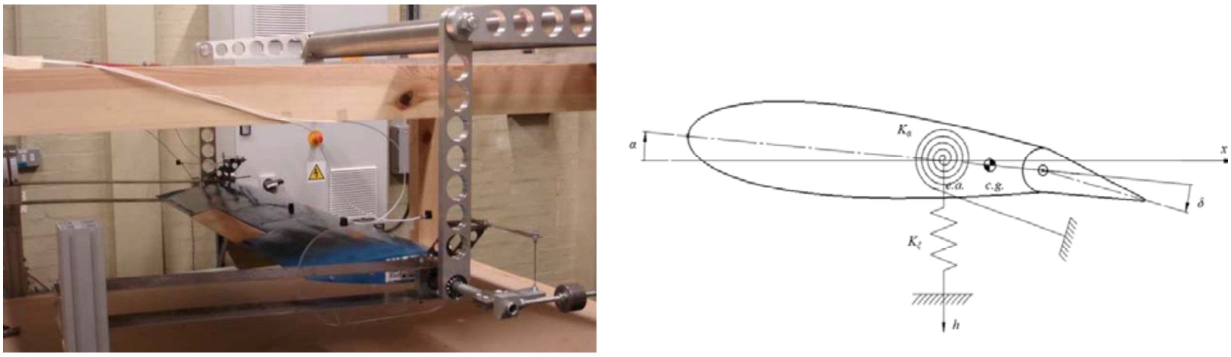
1. INTRODUCTION

Structural integrity systems require the adoption of control systems to monitor the state of health and guarantee the correct operating conditions. Control system is made of a control unit and a series of sensors nodes placed in different points on the controlled system structure. The control unit processes the sensors information in order to perform optimal corrective actions. Traditional batteries supplying the sensors often represent a critical problem as their life cycle in many cases is too short if compared to the operating life of the sensors or their replacement is unsafe, expensive or impossible. In these cases, employing energy harvesting techniques represent a possible solution.

The basic idea of the considered application case study is to investigate the possibility to make the wireless sensor networks [1] for structural health monitoring on unmanned aerial vehicles electrically autonomous by exploiting the energy that can be harvested by the wing aeroelastic oscillations in response to atmospheric gust and turbulence [2]. For this purpose, a single-degree of freedom (SDOF) and two-degree of freedom (2-DOFs) linear magneto-inductive energy harvesters (EH) have been designed and their behaviour simulated. As the vibrating input presents two fundamental harmonics depending on the operating conditions, the aim of the study is to evaluate the benefits deriving the exploitation of a wide resonant bandwidth.

2. INPUT CHARACTERISATION AND CONSTRAINT DEFINITION

For harvesting vibration energy due to atmospheric gust and turbulence, an aeroelastic model representative of a wing typical section is used [3]. The system has two structural degrees of freedom, consisting of bending and torsional modes. The numerical model setup [4] has been created to simulate the behaviour of a wind tunnel model at the University of Liverpool (Fig. 1a). The representative wing chord is 0.35 m. Predicted aeroelastic accelerations in response to external gusts are used as input data for the energy harvester performance simulation. Fig. 1b illustrates a schematics of the wing typical section, equipped with a trailing-edge control surface for aeroelastic control. Discrete deterministic gusts and stochastic turbulence excite the vibrations of the wing typical section, and the acceleration data are used as energy source for the recovery. As all the aeroelastic systems, the dynamic response is function of the operating conditions involved. The eigenvalues migration with the aerofoil free stream velocity is shown in Fig. 2.
Geometric constraints have been imposed to the energy harvester design according to the device positioning in the wing, Fig. 3, and the influence that this additional mass has on the aerofoil dynamics. To evaluate this aspect, the two-dimensional model with two degrees of freedom in the pitch and plunge motions with natural frequencies function of aircraft free-stream velocity and plunge displacements amplitudes (nonlinear plunge stiffness) have been implemented. The simulation results reported in Fig. 4 show negligible influence on the response of the linear aerofoil system.



(a) (b)

Figure 1. (a) experimental wind tunnel model and (b) schematic representation

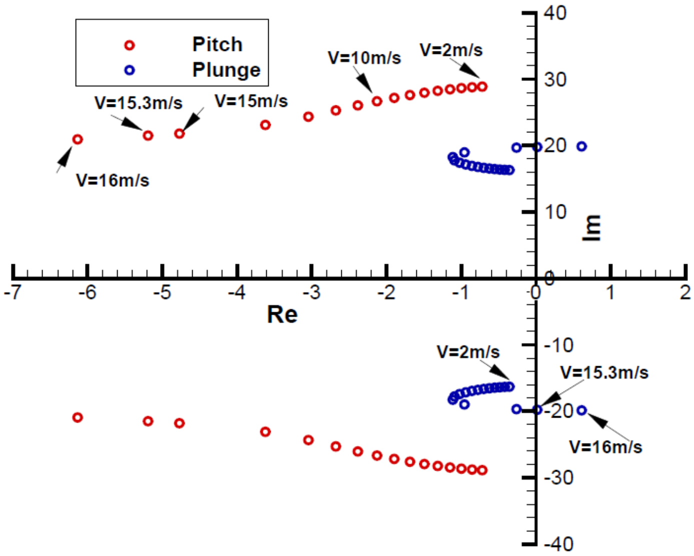


Figure 2. Eigenvalue analysis of linear two-degree of freedom aerofoil system

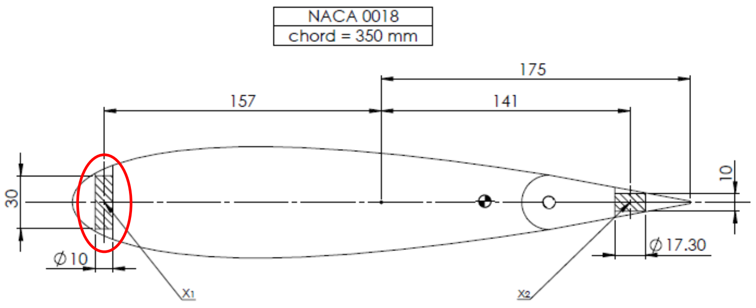


Figure 3. EH constraints and positioning in the wing

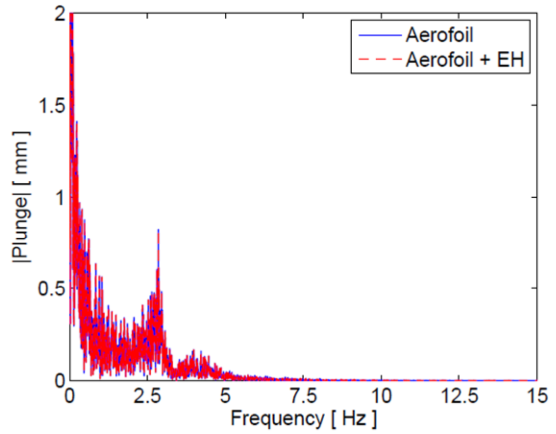


Figure 4. Energy harvester mass influence on the wing dynamics.

3. ENERGY HARVESTING SOLUTIONS

3.1. Transducer description and developed design tool

As anticipated, the considered EH device is a magneto-inductive linear generator [5, 6]. One or more floating permanent magnets can slide into a guide suspended between two springs (Fig. 5). Around the guide two coils connected in series are wound in opposite direction. Due to the wing vibrations, each floating magnet moves with respect to the guide causing flux linkage variation in the coils and inducing voltage at their ends. To better exploit the vibrational input, the EH axes is aligned to the main oscillation direction, e.g. out-of-plane bending vibrations [7-9].

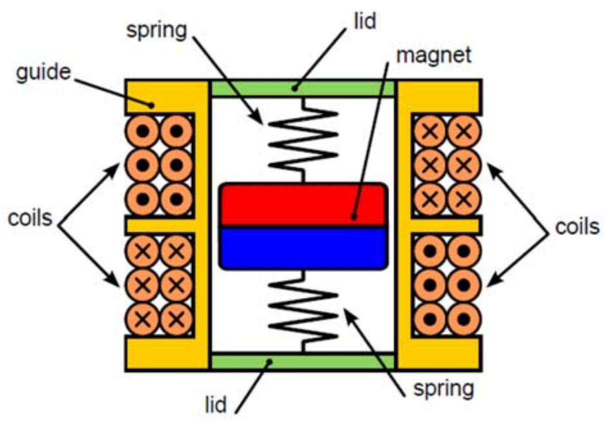


Figure 5. Magneto-mechanical energy harvester representation

It is possible to represent the device as a single/multi degree of freedom base-excited mass-spring-damper system where the transducer is considered as an inertial device, so that the forces act on its base and the masses freely vibrate. In the following, the two differential equations, for the mechanical and for the electrical domain, describing the SDOF system are reported in case of a generic electric load:

$$\begin{cases} \dfrac{d^2 z_r}{dt^2} = -\dfrac{d^2 z_{inp}}{dt^2} - \dfrac{c}{m}\dfrac{dz_r}{dt} - \dfrac{k}{m} z_r + \dfrac{\lambda'}{m} i \\ \dfrac{di}{dt} = -\dfrac{R}{L} i + \dfrac{V_L}{L} + \dfrac{\lambda'}{L}\dfrac{dz_r}{dt} \end{cases} \quad (1)$$

where m is the mass of the moving magnet, k is the sum of the stiffness of the two springs, c is a generic dissipative viscous mechanical damping, z_{inp} is the base motion, z_r the relative position between magnet and base, λ' is the derivative of the magnetic flux linkage with respect to the relative displacement, R and L are respectively the resistance and inductance of the transducer coils, $V_L(i)$ is the voltage on the load, and i is the current [10, 11]. An accurate modelling of the system usually requires considering non-linearity of k and λ' that are function of the relative displacement [12, 13].
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. 6 shows the developed model architecture for the SDOF configuration.

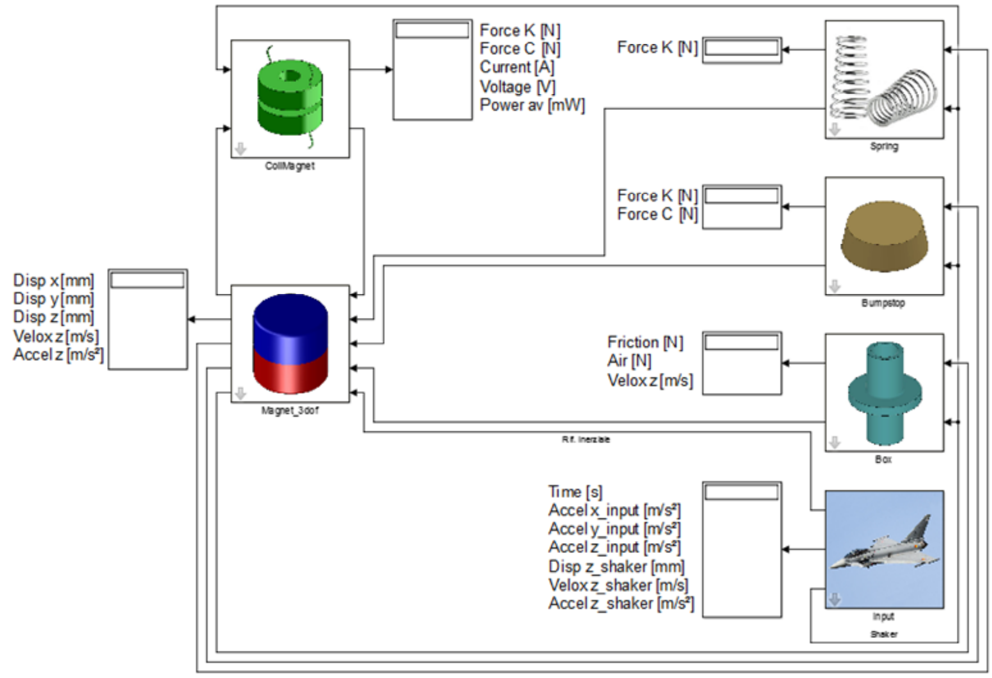


Figure 6. Block-oriented model of the SDOF energy harvester

3.2. SDOF energy harvester

The SDOF configuration of the energy harvester has been firstly investigated. Many configurations of the design parameters, namely the geometric characteristics of the components influencing the electro-mechanical coupling and the dynamic response of the magnet, have been considered and simulated. In Fig. 7 the functional model of the SDOF EH device is presented.
However this kind of solution allows aligning the EH frequency response only to one of the operative conditions making the device ineffective in the others. This reflects in low power recovery as shown in Fig. 8.

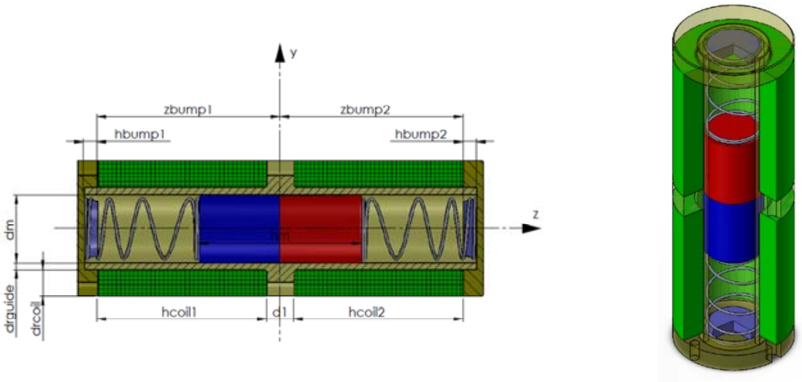


Figure 7. Functional model and design geometric parameters

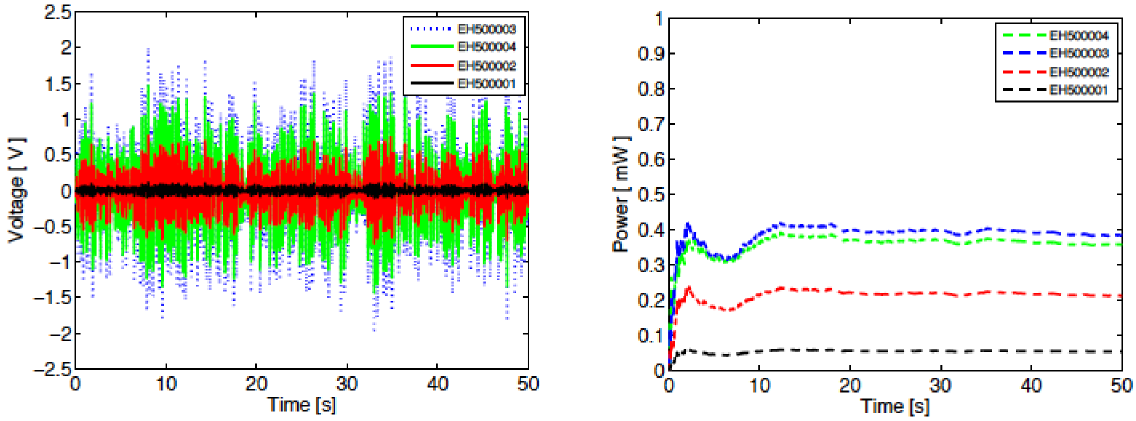
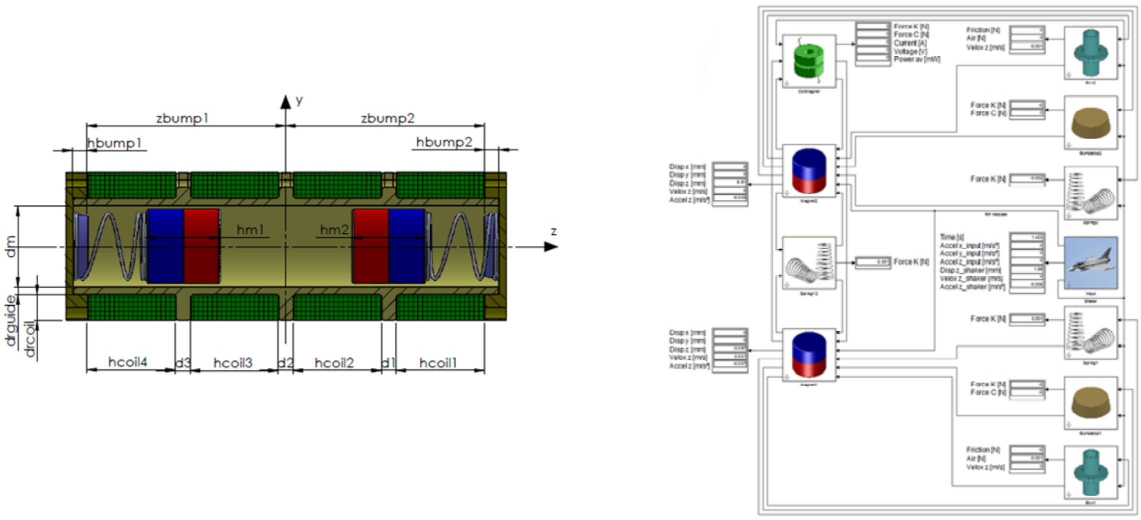


Figure 8. Electrical performance of different configuration of SDOF EH

3.3. Extension to 2-DOFs energy harvester

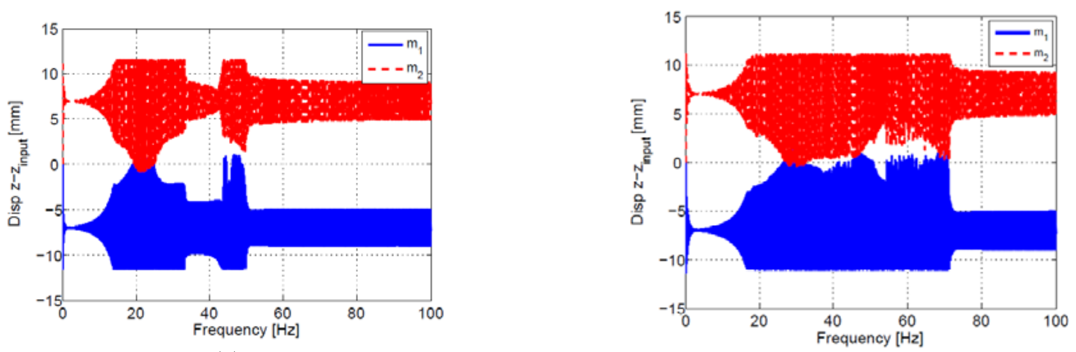
The need of effectively exploit the frequency content of all the operative conditions, make useful adopting a 2-DOFs configuration of the energy harvester. Such configuration can be obtained by splitting the floating magnet of the SDOF configuration in two magnetic elements opposite oriented, Fig. 9a. In this way it is possible to exploit for the energy recovery two vibrational modes and tune their frequency in order to match the input characteristics. To better exploit the magnetic flux variation, also the coils are split in two smaller elements. The result is a harvester configuration that can be represented as two SDOF systems coupled by mean of a magnetic spring that introduces peculiar and very attractive aspects in the system behaviour. Fig. 9b reports the evolution of the block-oriented simulation model.
As shown in Fig. 10a, consider applying a constant acceleration amplitude frequency sweep to the ideal case where the middle spring characteristic is linear, two well distinct peaks of the response are highlighted. Instead, when considering the magnetic spring, Fig. 10b, the non-linearity introduced in the system makes the two natural frequencies a wide resonant band. This behaviour allows effectively exploiting all the operative conditions.
Another very interesting aspect regards the choice of the floating masses and linear springs stiffness during the design phase. As it can be seen in Fig. 11a, a symmetric configuration presenting equal masses and equal linear 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 two slightly different masses, Fig. 11b.
The weak points of this solution are mainly two aspects related one to the mechanical and one to the electrical side. By maintaining constant the length of the guide with respect to the SDOF configuration, in the 2-DOF case each magnet has shorter available stroke; in addition the smaller magnets and coils dimension involve more problematic design aspects. Moreover, the exploitation of two vibrating modes reflects in a more difficult

management of the voltage inducted at the ends of the coils. Considering the in-phase and the anti-phase oscillation it can be easily understood as maintaining the same coils connections leads to the addition or the subtraction of the electrical effects. Also active control strategies are suitable for conveying energy from the transducer to the electric load [14, 15].



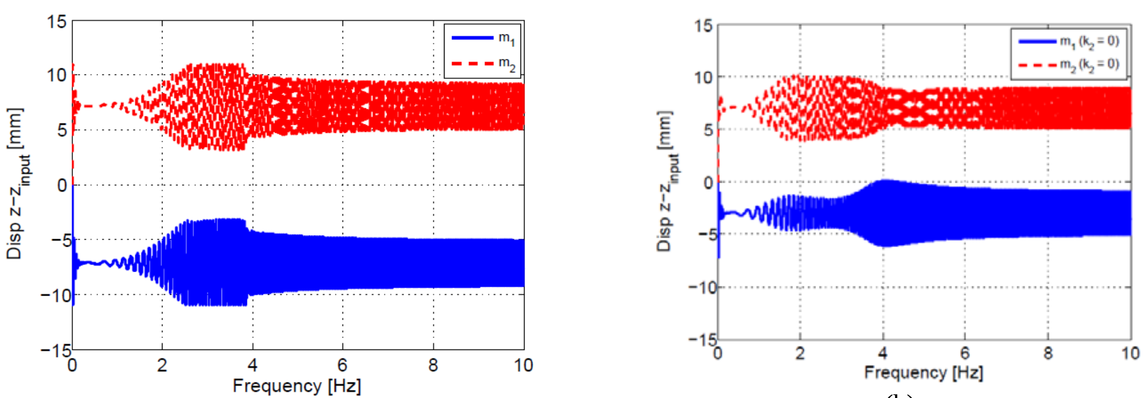
(a) (b)

Figure 9. (a) 2-DOFs EH functional model with design geometric parameters and (b) block-oriented simulation model



(a) (b)

Figure 10. 2-DOFs EH sweep response: (a) ideal linear springs and (b) non-linear magnetic spring between the floating elements



(a) (b)

Figure 11. 2-DOFs EH sweep response: (a) symmetric and (b) asymmetric configurations

CONCLUSIONS AND FUTURE DEVELOPMENTS

This work aims at making some progress in harvesting aeroelastic vibrations of a wing typical section, and some practical solutions are suggested.
With the aim of exploiting for the energy harvesting a vibrating input that depending on the operative condition presents different main frequencies, two magneto-inductive linear energy harvesting devices have been considered: a SDOF and a 2-DOFs configuration, presenting respectively one and two floating magnets, two and four coils and two and three springs, one of them magnetic.
An integrated multi-physics simulation model has been developed in Matlab/Simulink environment and used to evaluate the dynamics of the floating elements and the performance of the device.
The possibility of effectively exploit only one fundamental frequency of the input, or no more than a very narrow bandwidth, makes the SDOF solution useless for this purpose. The 2-DOFs solution, exploiting the non-linearity introduced by the magnetic springs that couple the behaviour of the two floating masses, allows obtaining a wide resonant bandwidth. It implies the possibility of well exploiting all the operative conditions that can occur considering different flight speed. Another peculiar aspect highlighted by this solution is the phenomenon of the cancellation of the modes that must be avoided by making the system non-symmetric, for example introducing two slightly different magnetic masses. Weak points of this second configuration are the more problematic design aspects due to the shorter available stroke that each magnet has, and to the smaller magnets and coils dimensions. Moreover, the more complicated management of the induced voltage makes the developed simulation model appropriate only to evaluate the dynamics of the system and not to derive the 2-DOFs EH performance.
In conclusion, the potentiality of adopting a 2-DOFs magneto-inductive linear EH to recover energy from a multi-frequency input have been proven. However, important improvements on the electrical side of the simulation model have to be done in order to evaluate the performance of such solution and determine the practical feasibility. Prototypes shown in Fig. 12 have been made in order to experimentally test the proposed device.
Future work includes testing the prototypes on a flexible high-aspect ratio wing which is undergoing preliminary wind tunnel tests at the University of Southampton.

Figure 12. Prototypes of 2-DOFs EH

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