

COB-2023-2232

Design and Optimization of an Electromagnetic Energy Harvester for Wireless Sensors Applications

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Abstract. *In the last few decades, Vibration Energy Harvesting (VEH) techniques have become promising alternatives for supplying low-power equipment, such as wireless sensors and vibration monitoring devices. Nowadays, most VEH technologies can be easily integrated into Internet of Things (IoT) systems and are capable of providing real-time monitoring of assets and health indicators of a machine. Moreover, the autonomy of wireless sensors has been significantly increased with VEHs, in contrast to the usage of conventional batteries, which can provide no more than 5 years of autonomy in general. The vast majority of existing VEHs can be classified into four main categories, according to the transduction principle behind their operation: Piezoelectric; electromagnetic; electrostatic and magnetostrictive harvesters. This work presents the design and optimization of a commercial vibration transducer. Such a device contains in its interior a resonant-type electromagnetic generator that can be modeled as a 1 DoF (Degree of Freedom) system, the latter composed by a seismic mass and a mechanical spring, as well as other components. The complete set weighs about 90 g and occupies a total volume of approximately 50.97 cm³, being able to generate up to 45 mW at its resonance frequency of 60 Hz, with a bandwidth of 2.5 Hz. Furthermore, the linear generator presented in this article reaches a maximum Normalized Power Density (NPD) of 1.8018 mW/cm³/g² at an acceleration amplitude of 0.7 g (~ 6.67 m/s²). A numerical model was developed via commercial software Comsol Multiphysics, in order to model the electromechanical system and to proceed with further optimization, from which it was possible to optimize its geometry and maximize its NPD and power output. A Surrogate optimization algorithm was then implemented in MATLAB, in which both volume and mechanical stress were considered as project constraints. The optimized geometry is under prototyping and its performance is compared in terms of NPD with the commercial transducer.*

Keywords: *Vibration Energy Harvesting, Electromagnetic Generator; Numerical Modeling; Optimization; Normalized Power Density*

1. INTRODUCTION

In the realm of predictive maintenance strategies, Condition Based Monitoring (CBM) has emerged as a powerful approach, continuously extracting vital data such as vibration and temperature from operational machinery in real-time, enabling the timely detection of potential failures and relevant changes. Presently, CBM predominantly relies on wireless sensors powered by batteries, boasting an autonomy of approximately 5 years. (Briand, 2015)

However, as the demand for sensors with extended autonomy and reduced reliance on battery replacements grows, there is a compelling need to explore alternative technologies based on energy scavenging from the environment. Notably, piezoelectric and electromagnetic transducers have garnered considerable attention as VEHs, capable of converting linear mechanical vibrations into electricity in the order of mW, each offering its unique set of characteristics, advantages, and disadvantages. (Beeby, 2006)

Piezoelectric devices exploit the unique properties of specific materials, commonly crystals, which exhibit the phenomenon of piezoelectricity. When these materials undergo deformation caused by an external load, they accumulate electric charges and generate a potential difference within their interior. This electrical potential is a direct result of the applied mechanical stress and deformation. On the other hand, electromagnetic transducers operate on the principle of electromagnetic induction. These devices can generate electrical energy through the relative movement between a magnet and a coil. As the magnet moves in proximity to the coil, a changing magnetic field induces an electromotive force (EMF) in the coil. This EMF creates an electrical current in the circuit connected to the coil, enabling the charging of batteries or small capacitors. This process allows electromagnetic transducers to efficiently convert mechanical energy from the

relative motion into electrical energy, making them valuable in various energy harvesting applications.

In this article, the study of a commercial Electromagnetic Energy Harvester (EMVEH) is presented, the latter being designed to generate electrical energy at the frequency of 60 Hz. This frequency aligns with that of the electrical network, making it relevant for the vast array of small and large equipment operating within this standard.

2. LITERATURE REVIEW

Electromagnetic generators can be classified into two main categories: Magnetic and mechanical spring devices. The main difference between them lies in the nature of the restoring force that acts on the seismic mass. Magnetic spring EMVEHs, for example, are constructed in a way that the magnetic repulsion between the seismic mass and fixed permanent magnets is responsible for the restoring force in the system, which is non-linear with the displacement. Such configuration allows for a wider bandwidth in which the harvester operates and eliminates the effect of fatigue between components. Figure 1 illustrates an example of a magnetically levitated block that oscillates inside a multi-turn coil and can generate up to $410 \mu\text{W}$ at the resonance frequency of 6.7 Hz and an acceleration of 0.1 g. The maximum NPD, in this case, reaches up to $7 \text{ mW}/(\text{cm}^3 \text{g}^2)$, as presented in (Berdy *et al.*, 2014).

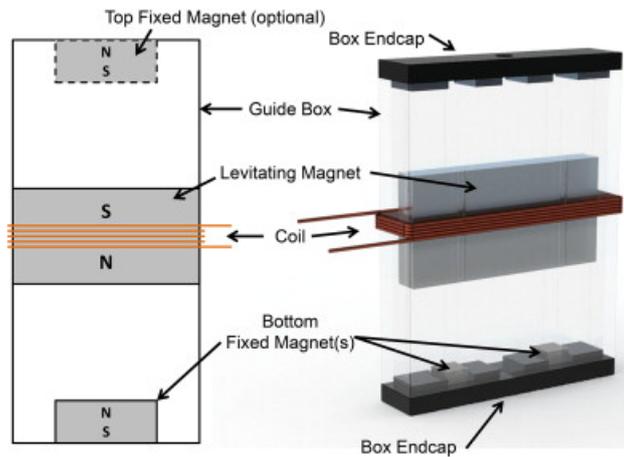


Figure 1. Example of an EMVEH with magnetic spring.
Obtained from (Berdy *et al.*, 2014).

Although magnetic sprung generators are interesting in powering small scale sensors, their non-linear nature makes it difficult to operate such devices for larger acceleration amplitudes, especially when tuning the ambient excitation frequency with their resonance frequency.

2.1 EMVEHs with Mechanical Spring

Linear generators with mechanical springs, in turn, are characterized by the storage of the system's potential energy in, as the name suggests, mechanical springs or stiffness elements that generate restoring forces directly proportional to the displacement of the seismic mass. Such elements can be designed and built in different configurations, of which the so-called helical springs and deformable beams stand out.

In Figure 2, a hybrid harvester is composed by a set of two different spring systems: Oblique mechanical springs and a magnetic spring. Such combination broadens the frequency–response through additional nonlinear behavior while simultaneously reducing energy losses, as evidenced in (Nammari *et al.*, 2017). Their proposed design was capable of generating a voltage amplitude of approximately 2.95 V, with a maximum NPD of $0.136 \text{ mW}/(\text{cm}^3 \text{g}^2)$ at a base excitation of 0.75 g. Even though the final prototype is not completely optimized in terms of NPD, the work in (Nammari *et al.*, 2017) provides an example of the usage of helical springs to improve the response of the harvester in lower frequencies while maintaining the resonance at a larger frequency.

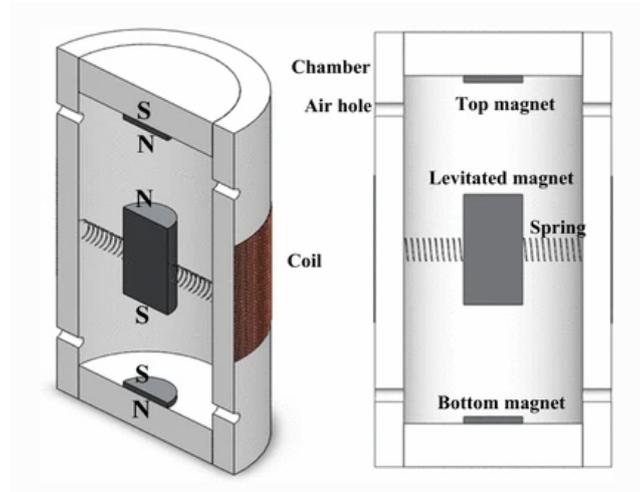


Figure 2. Hybrid EMVEH with oblique mechanical springs.
Obtained from (Nammari *et al.*, 2017).

In general, linear electromagnetic devices built with mechanical springs can operate with greater acceleration amplitudes due to the absence of non-linearities in their dynamic behavior. Moreover, the miniaturization of its components involves less complexity and greater ease of tuning the natural frequency of the equivalent system, hence the interest in modeling a harvester with mechanical springs.

3. MATERIALS AND METHODS

As presented in the next subsections, both the design and optimization of an electromagnetic transducer are performed using commercial software. The numerical analysis of such EMVEH is conducted via COMSOL Multiphysics, which allows the integration of different physics modules such as *Structural Mechanics* and *Magnetic Fields* interfaces. Thus, it is possible to determine the transducer's electromechanical behavior in the frequency domain. The numerical results are then validated with experimental data, provided in terms of output power per acceleration. Finally, a numerical optimization routine is implemented in MATLAB and integrated with the COMSOL interface at each iteration of the algorithm, the latter applied to the original transducer design. (Schmitt *et al.*, 2022)

3.1 Electromechanical Modeling

Figure 3 illustrates the 3D model of a commercial EMVEH. Its geometry is composed by a seismic mass mounted on a mechanical spring, the latter consisting of six thin, curved beams connected to a pair of internal and external metallic rings. In addition to the mechanical structure, a multi-turn cylindrical coil is positioned around the magnet and attached to the rings, thus being responsible of converting the external vibration into electrical energy via Faraday's Law of induction.

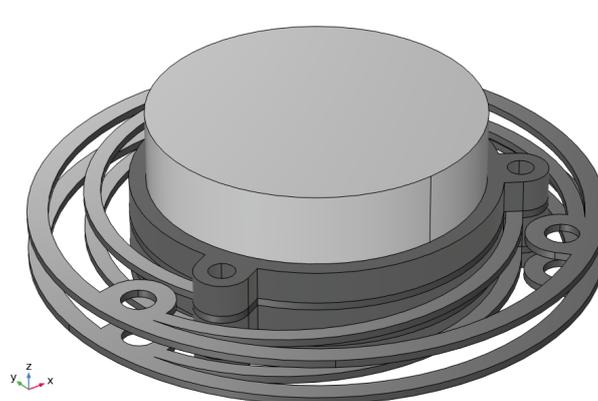


Figure 3. 3D geometry of a commercial EMVEH.

A simplified axisymmetric model can be built from the original geometry in order to reduce the computational cost in the numerical optimization step. Such geometry can be modeled by replacing the mechanical springs with metallic disks of equivalent stiffness, as shown in Figure 4.

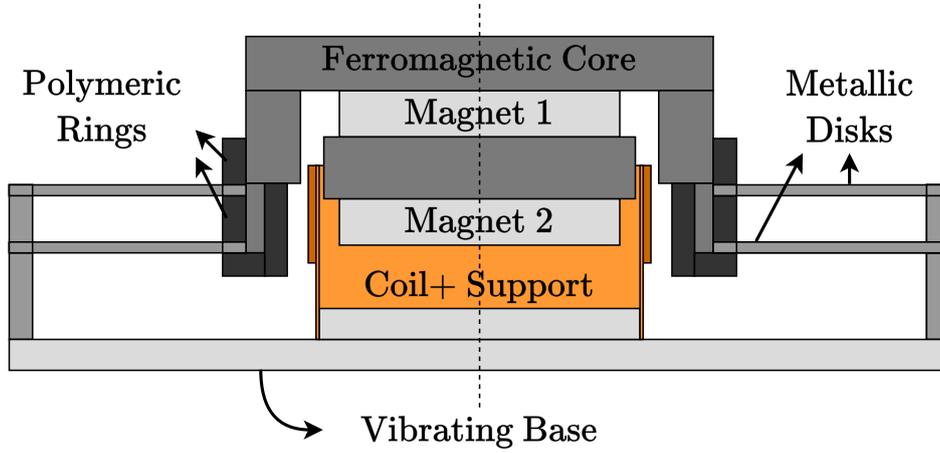


Figure 4. Equivalent axisymmetric geometry.

The materials that constitute the main components of the EMVEH are shown in Table 1. The seismic mass, in this case, is assembled from three main components: Two flat cylindrical magnets made of neodymium-ferrite (NdFeB, grade N52); a 409 ferritic stainless steel core / armature and *High Density Polyethylene* (HDPE) rings connecting the core to the mechanical springs, which are composed of low carbon steel.

Table 1. Constituent materials of the EMVEH components and its properties.

Components	Materials	Mechanical Properties		
		E [GPa]	ρ [kg/m ³]	ν
Permanent Magnet	NdFeB N52	160	7500	0.24
Ferromagnetic Core	409 Stainless Steel	195	7610	0.28
Polymeric Rings	HDPE	1.86	950	0.46
Metallic Rings	Low Carbon Steel	210	7840	0.30

3.2 Numerical Optimization

Once the electromechanical simulation via Finite Elements Method (FEM) has been validated with experimental data in terms of output power per acceleration, the equivalent axisymmetric design is then miniaturized by applying a Surrogate Optimization (SO) algorithm. Similar to other numerical optimization routines, the SO algorithm is based on the definition of an objective function f_{obj} that one seeks to minimize. However, SO is best suited to time-consuming objective functions, as in the case of the numerical model presented in the previous subsection.

Since the mechanical spring for the optimized geometry must remain with the same characteristics as the original design, the optimization routine is performed in two main phases. In the first step, only the seismic mass is miniaturized. Therefore, the objective function for the first phase is simply defined as $f_{obj} = -NPD$. The second stage, in turn, focuses on the optimization of the mechanical spring considering its occupied volume and the maximum von Mises stress in its domain. As input variables, all of the coil and seismic mass dimensions are considered as optimization parameters, the latter being defined in between pre-established upper and lower bounds (see Figure 5).

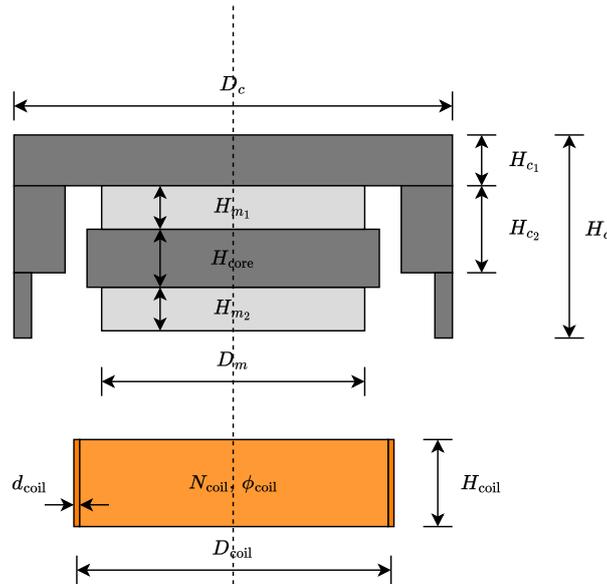


Figure 5. Optimization parameters of the seismic mass and the coil.

4. RESULTS AND DISCUSSION

The results obtained from electromechanical modeling via FEM followed by the application of a SO optimization algorithm to miniaturize the equivalent axisymmetric geometry are detailed in the following subsections. The final design is then compared to the original transducer in terms of occupied volume and maximum NPD.

4.1 Electromechanical Simulation

The first mode of vibration of the 3D geometry was numerically determined via modal analysis:

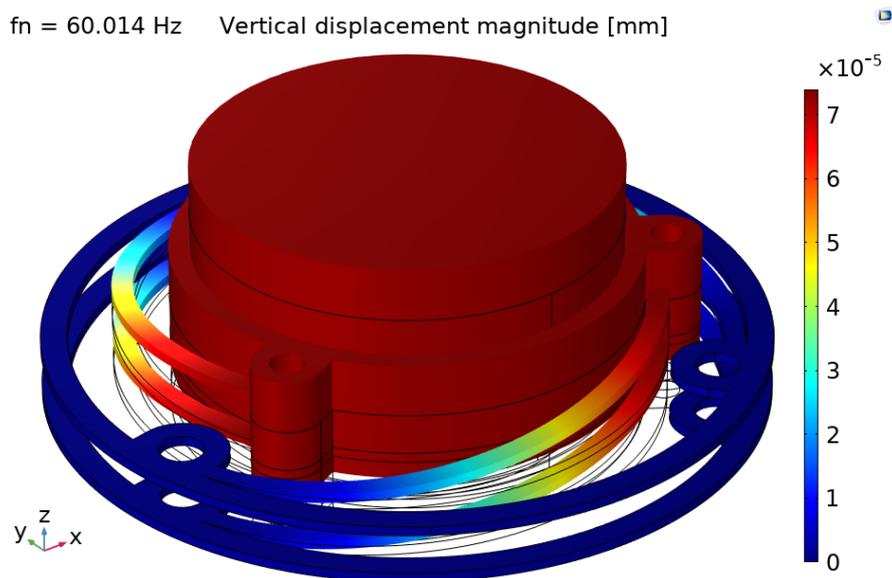


Figure 6. First mode shape of the 3D geometry.

Figure 6 shows the first mode shape at the resonance frequency of $f_n = 60.014$ Hz. As expected, the seismic mass movement occurred exclusively in the vertical direction, thus constituting a transversal mode shape. As a result of a *Stationary Study* performed via FEM, it was possible to numerically determine the flux density norm for the axisymmetric geometry, as illustrated in Figure 7:

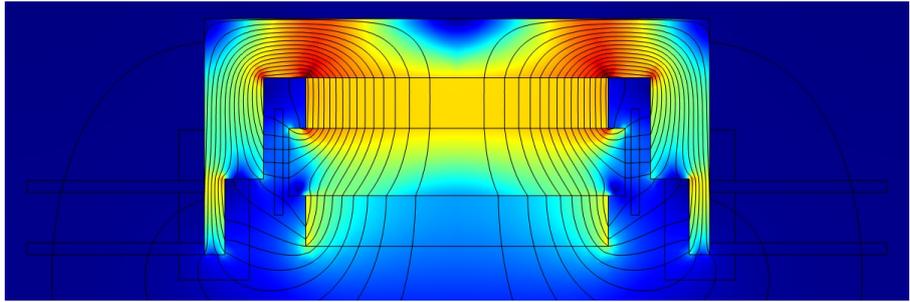


Figure 7. Magnetic flux density norm in the axisymmetric domain.

Observe that the ferromagnetic core concentrates the magnetic flux lines around the coil, so that the flux gradient is maximized in the region enclosed by the coil's geometry. The axisymmetric model generated up to 45 mW at its resonance frequency of 60 Hz, with a bandwidth of 2.5 Hz, reaching a maximum NPD of $1.8018 \text{ mW}/(\text{cm}^3 \text{g}^2)$ at an acceleration amplitude of 0.7 g ($\sim 6.67 \text{ m/s}^2$)

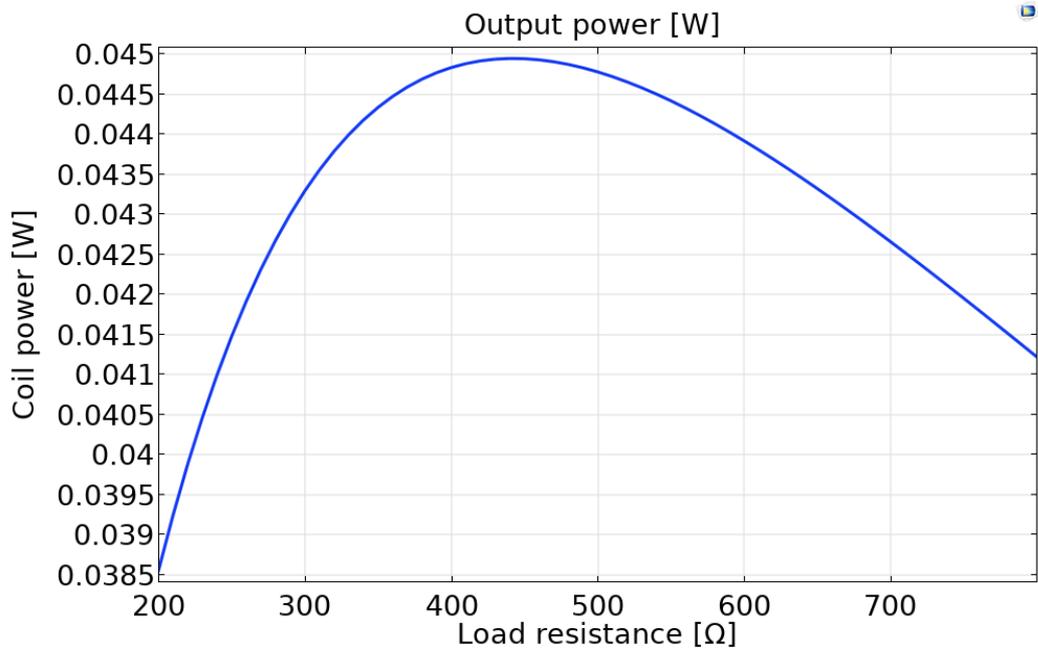


Figure 8. Output power \times Load resistance R_L .

In terms of normalized power, the results from the numerical model agreed with experimental data, reaching about $1.2 \text{ mW}/\text{g}^2$ at an acceleration of 0.1 g .

4.2 Optimized Design

The optimized design obtained from the SO algorithm occupies a volume of approximately 2.18 cm^3 and can generate up to $291.43 \text{ mW}/(\text{cm}^3 \text{g}^2)$ at an optimal acceleration amplitude of 2.25 m/s^2 . Its final NPD resulted in $2.54 \text{ mW}/(\text{cm}^3 \text{g}^2)$ and the bandwidth remained the same as the original geometry.

Figure 10 shows the optimized geometry and highlights the mechanical spring generated after optimizing both seismic mass and coil parameters.

Although the original design occupies a volume of approximately 50.97 cm^3 , the optimized design showed that it is possible to maintain the transducer performance in terms of NPD even after miniaturizing its geometry. Such results were obtained by allowing all the geometry and coil parameters to vary in between pre-established bounds. The final concept maximizes the number of coil turns, in order to generate the maximum induced voltage at the coil terminals. It is important to note that the bandwidth remained the same because the same materials were considered for the mechanical spring.

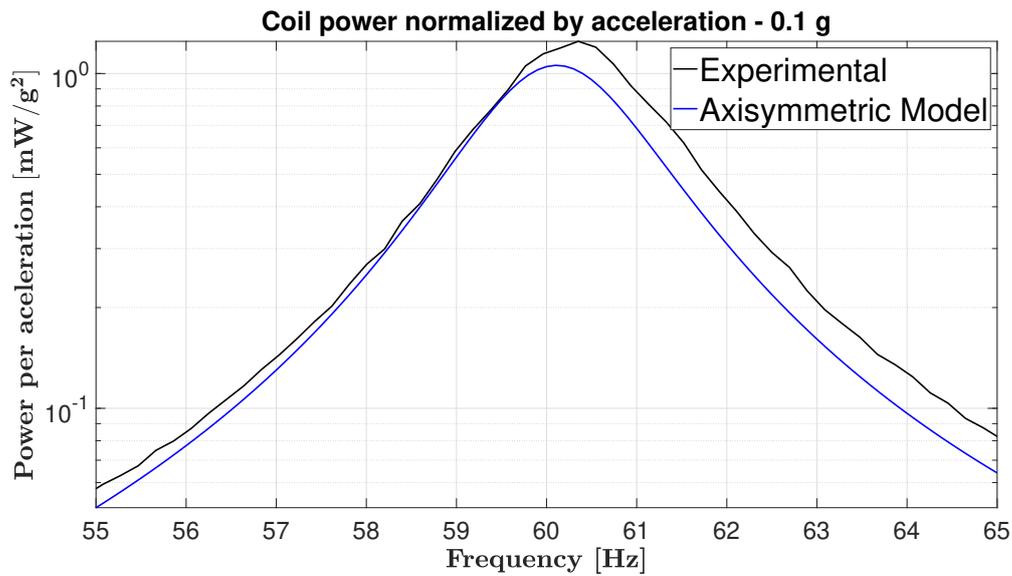


Figure 9. Output normalized power – Numerical model × Experimental data.

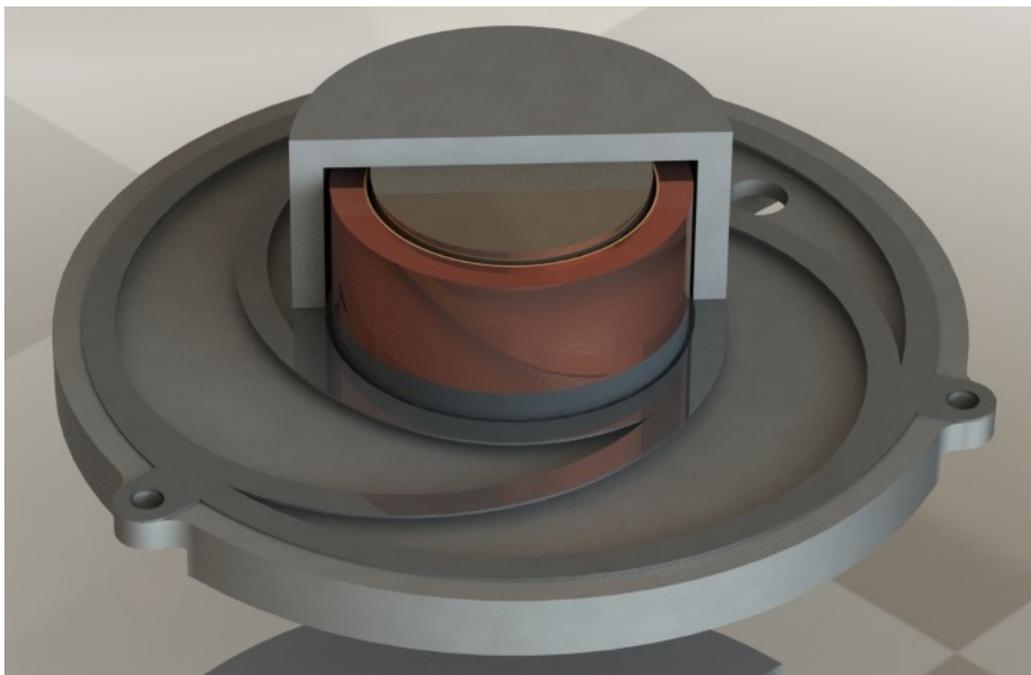


Figure 10. Optimized geometry obtained from SO algorithm.

5. FINAL CONSIDERATIONS

Linear EMVEHs stand out for their robustness and performance when there are no restrictions in terms of volume or material. In fact, the NPD of most linear electromagnetic generators become generally higher than other transduction mechanisms when such restrictions are ignored. (Saha *et al.*, 2008) (Cho and Kim, 2017). However, the opposite is observed after miniaturizing them. In fact, the output power of EMVEHs significantly reduces by restricting its dimensions. Since the efficiency of an EMVEH is closely related to the relative velocity between its magnets and coil, an optimized design usually requires higher values of height/width ratio.

Finally, as in the case of the commercial transducer presented in this work, it is common to use ferromagnetic materials in EMVEHs to concentrate the magnetic field around the coil and increase its induced voltage.

6. ACKNOWLEDGEMENTS

We thank Dynamox S/A and the Laboratory of Vibrations and Acoustics at UFSC, supported by FEESC, for making this work possible through the project "Development of vibration energy harvesting systems for vibration monitoring sensors."

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