DOI 10.5162/SMSI2023/C6.3

Theoretical Model and Simulation of a 3D Printed Multi-Material Vibration Harvester

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Summary:

In this contribution, we present a novel 3D printed multi-material, electromagnetic vibration harvester. The harvester is based on a cantilever design and utilizes an embedded constantan wire within a matrix of polyethylene terephthalate glycol (PETG). A prototype has been manufactured with a combination of a fused filament fabrication (FFF) printer and a robot with a custom-made tool.

Keywords: energy harvesting; vibration; 3D printing; multi-material; cantilever

Introduction

Energy harvesting provides a sustainable way to power wireless sensor nodes (WSN) [1]. 3D printed energy harvesters offer the possibility to manufacture application specific harvester geometries and sizes [2]. Printing multiple materials has been utilized in the field of triboelectric harvesters [3]. 3D printing multiple materials has not been researched regarding electromagnetic vibration harvesters yet [2]. In this contribution, we propose a 3D printed cantilever made of PETG and an embedded constantan wire for electromagnetic energy harvesting.

Methods and Materials

A cantilever-geometry (clamped-free) was applied for the harvester. The dimensions are shown in Fig. 1. The red area was clamped while the green area was the free tip. The cantilever was analytically modelled as a layered Euler-Bernoulli-beam with tip mass (green area = tip) and external excitation.

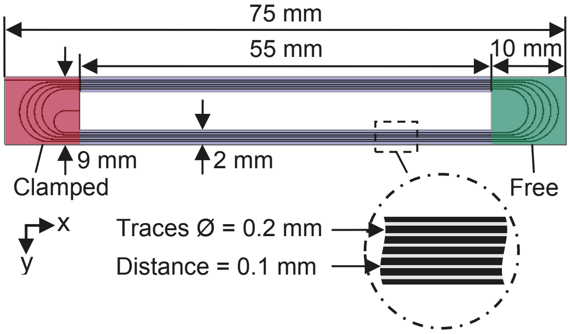

Fig. 1. Geometry and dimensions of the cantilever with embedded wire.

The equation of motion can be expressed as [4], [5]:

$$\sum_{j=1}^{s} E_j I_j \, w^{IV} + \sum_{j=1}^{s} \rho_j A_j \, \ddot{w} = W_0 \sin(\Omega t) \qquad (1)$$

With layer j, number of total layers s, Young's modulus E, deflection w, density ρ, area A, ambient amplitude W_0, excitation angular frequency Ω and time t, respectively. The moment of inertia I can be calculated with the parallel axis theorem [4]:

$$I_j = I_{y_j} + z_{s_j}^2 A_j \qquad (2)$$

The cantilever features a height of 1 mm and was printed via FFF with PETG. A constantan-wire (Ø 0.2 mm, 0.1 mm distance between traces, 5 turns) was embedded during the print with a custom-made tool and a KUKA Agilus KR 6 R900-2. A height of 1 mm was chosen in order to achieve a low resonance frequency, while still allowing the wire-embedment. Low frequencies offer more energy [6]. The composite layer was simplified for calculation and assumed as a homogenous layer as shown in Fig. 2.

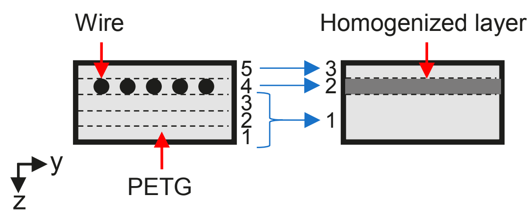

Fig. 2. Cross section of cantilever, (left) printed layers, (right) analytical layer-numbers with homogenized layer.

We combined the Young's modulus and density of the wire and PETG-matrix by the corresponding volume fraction in the layer. The displacement $w(x,t)$ in z-direction is given [5]:

$$w(x,t) = [A \cdot \cos(\kappa x) + B \cdot \sin(\kappa x) + C \cdot \cosh(\kappa x) + D \cdot \sinh(\kappa x)] \cdot W_0 \sin(\Omega t) \quad (3)$$

With the boundary conditions and (3), the linear system of equations can be solved. For non-trivial solutions the determinant of the system has to be zero [5]:

$$1 + \cos(\kappa_i l)\cosh(\kappa_i l) + \varepsilon\kappa_i l[\cos(\kappa_i l)\sinh(\kappa_i l) - \sin(\kappa_i l)\cosh(\kappa_i l)] = 0 \quad (4)$$

with the length l, the mass-ratio ε between tip mass and cantilever and the variable κ [4], [5]:

$$\kappa^4 = \omega^2 \frac{\sum_{j=1}^{s} \rho_j A_j}{\sum_{j=1}^{s} E_j I_j} \quad (5)$$

From (4), the eigenvalues can be derived by searching for zero points as shown in Fig. 3. The resulting angular frequency can be calculated with [4], [5]:

$$\omega_i = \frac{\kappa_i^2}{l^2} \sqrt{\frac{\sum_{j=1}^{s} E_j I_j}{\sum_{j=1}^{s} \rho_j A_j}} \quad (6)$$

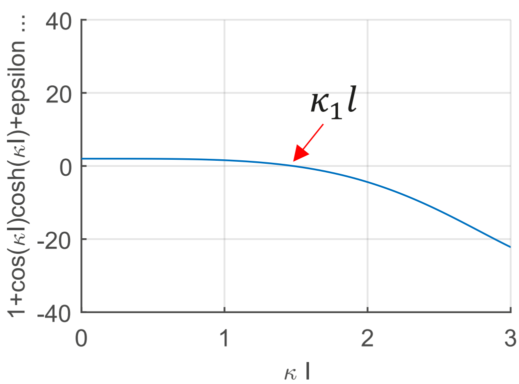

Fig. 3. Frist eigenvalue of the cantilever with tip-mass

Results and Discussion

Utilizing equation (6) an angular frequency of 248.9 s^{-1} and a resonance frequency of 39.6 Hz was calculated for the first resonance frequency. The simulated resonance frequency in COMSOL with the embedded wire-structure was 37.7 Hz. Fig. 4 depicts the specimen after embedding the wire during the printing-process. The finished specimen showed a warping effect towards the side with the embedded wire. This is expected due to the nonsymmetric layer-order as shown in Fig. 2. Magnets will be added around the moving area of the cantilever as shown in Fig. 5 in order to electromagnetically harvest energy from mechanical vibrations.

Fig. 4. Cantilever during printing-process after embedding the wire in layer 4.

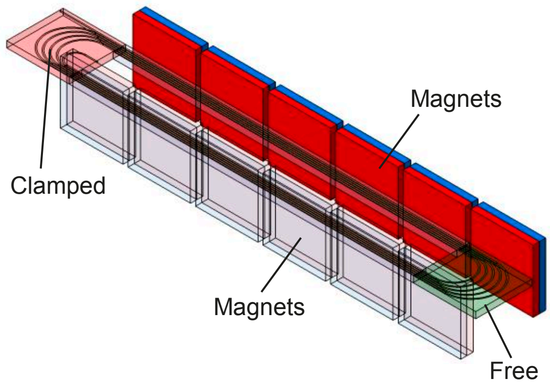

Fig. 5. Cantilever with embedded wire and magnets.

Conclusion

A theoretical model, simulation results and the fabrication of a multi-material 3D printed cantilever have been shown. Future work will focus on the characterization of the harvester and the electrical energy output.

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