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MODELING AND EXPERIMENTAL VERIFICATION OF MAGNETO-MECHANICAL ENERGY HARVESTING CONCEPT BASED ON CONSTRUCTION STEEL

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Summary. Modeling and design of a prototype device for testing a magnetostrictive energy harvesting concept are presented. The working principle of the device and the device design are explained briefly. A reluctance network model is used to identify the magnetization curves of the test sample under static stress based on measurements. Results for the induced secondary voltage under dynamic stressing are given. Possible applications, future work, advantages and limitations of proposed device are discussed.

INTRODUCTION

The concept of energy harvesting through ambient vibrations has seen significant rise in academic interest as it allows wireless or portable systems to be autonomous and self-sufficient in terms of energy requirement[1]. Ambient sources of vibration involve vibrations from bridges, skyscrapers, rail tracks, machines, motors, shafts and body of cars or ships etc. Thus, the harvested energy depends on the nature and amplitude of vibration available.

Vibrational energy harvesting techniques typically encompass either piezoelectric or magnetostrictive phenomena. The concept in discussion focuses on magnetostrictive energy harvesting technique due to its higher energy density as compared to piezoelectric[2,3]. The project aims at the development of a stress dependent reluctance network model to determine the effect of mechanical stress on magnetization curves and for simulating the energy conversion process, as well as measurement of the power density obtainable from the test material.

DEVICE DESIGN AND WORKING PRINCIPLE

2.1 Mechanical design

The mechanical design of the energy harvesting device is shown is Figure 1. Two sets of steel grips are designed to hold the test sample. Stress is applied using a hydraulic press machine. Complete setup of the designed device is shown in Figure 1. The test sample is made up of construction steel sheets stacked together in the form of a rectangular bar. The length of the test sample is 345 mm with the cross-sectional area of 400 mm^2.

The working principle of the energy harvesting device is shown in Figure 2 where the test sample is first externally magnetized parallel to the applied stress using two sets of coils and a u-core. A time-varying mechanical stress is applied parallel to the test sample indicated by the arrows in Figure 2 and the open circuit voltage is measured from the secondary coil wound around the test sample.

2.2 Proposed model

The proposed model can be utilized to determine the magnetization curves in the externally magnetized test sample based on the measured magnetization current and secondary voltage under AC excitation and static stress. Integration of Ampere's law (1) around the flux path gives

$$NI(B,s) = H_{\mathrm{bar}}(B,s)L_{\mathrm{bar}} + H_{\mathrm{core}}(B)L_{\mathrm{core}}\,, \tag{1}$$

where B is the magnetic flux density, s is the stress, I refers to magnetization current which depends on B and s, N is the number of turns in the magnetization coils. H_{bar} and H_{core} are the magnetic field strength in the test sample and u-core, respectively, whereas L_{bar} and L_{core} are the corresponding magnetic circuit lengths. The flux density has been calculated by integrating the secondary voltage, and the excitation voltage has been iterated so as to obtain a sinusoidal flux density into the test sample. Single-valued $I(B, s)$ curves have been determined by tracing the tips of hysteresis loops obtained with different flux-density amplitudes. The $H_{\mathrm{core}}(B)$ curves are known from previous measurements and thus the magnetization curves for the test sample can be obtained as

$$H_{\mathrm{bar}}(B,s) = \frac{NI(B,s) - H_{\mathrm{core}}(B)L_{\mathrm{core}}}{L_{\mathrm{bar}}}\,. \tag{2}$$

Results from the model are then utilized to analyze how deformation can affect the magnetic properties of materials by comparing magnetization curves when the material is stressed.

1. RESULTS

Magnetization curves have been determined using AC magnetization where static stress is applied and the behavior of magnetization curve in the test sample is analyzed for different values of stress. The magnetization curves for tensile and compressive stress values are plotted in Figure 3a. The results are compared with the magnetization curve under zero stress. The plotted results show that compressive stress decreases the permeability of the material causing decrease in the value of magnetic flux density B at given magnetic field intensity H, whereas tension improves the permeability of the material and an increase in magnetic flux density can be seen at the same value of magnetic field intensity.

The energy harvesting concept is tested using DC magnetization and the test sample is stressed dynamically. Figure 3b shows the plot for the measured DC magnetization current versus the RMS voltage measured from the secondary coil wound around the test sample under sinusoidal stress at 12 Hz with the amplitude of -15 to 15 MPa. A voltage drop can be seen when the material reaches saturation.

2. DISCUSSION AND CONCLUSION

The concept of energy harvesting through magnetostrictive phenomenon under ambient vibration has been discussed in this document. A stress dependent reluctance network model has been proposed to analyze the behavior of magnetic field intensity under mechanical stress. Experimental results showed that under compressive stress, the magnetic flux density decreases whereas tensile stress improves the magnetic flux density. The proposed model can be utilized to determine the appropriate value of magnetizing current at which maximum power can be obtained. In the real application, the excitation would be replaced by permanent magnets. The model can also be utilized to test different ferromagnetic materials to determine the power density for the material under test. Possible applications may include development of a structural condition monitoring system, powering devices located in remote areas or wireless sensors, actuators, and measuring instruments etc. An energy harvesting device will allow battery free application for low power sensors and actuators. Structural condition monitoring can help to take precautionary measures in advance before structure collapse or any real damage occurs to the structure.

The experiments were performed at three different values of compressive and tensile stresses. It was observed that there is a small change in the magnetization curve for higher values of tensile stress. For higher compressive stress values, a supporting mechanism must be devised to prevent the sample from buckling. The energy harvested from ambient vibrational sources depends strongly on the nature and strength of vibrations which may act as a limiting factor. Possible future work may include development of energy efficient circuitry and structural optimization of the devices. Magneto-mechanical energy harvesting has a great potential in the field of energy and eco-efficiency.

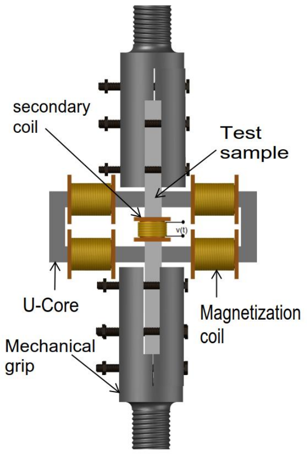

Figure 1: Mechanical design of energy harvesting device

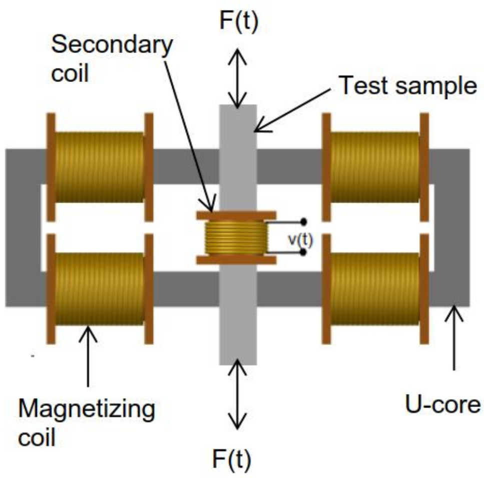

Figure 2: Working principle of the energy harvesting device.

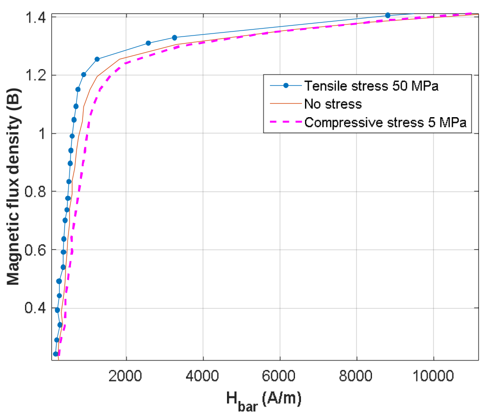

Figure 3a: Measured magnetization curves under different stress values.

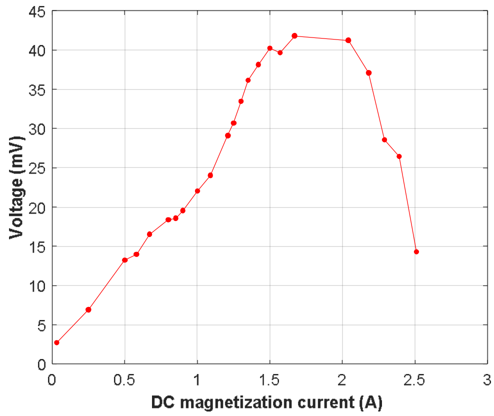

Figure 3b: Measured open circuit voltage vs DC magnetization current.

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