

Design of a set-up for Measuring Magnetostrictive Materials without Strain Gauges to assess the magnitude of Villari Effect

Wojciech Pałka, Karolina Laszczyk*

Wrocław University of Science and Technology, Poland, Wrocław, Wybrzeże Stanisława
Wyspiańskiego 27,

*Corresponding Author's e-mail address: karolina.laszczyk@pwr.edu.pl

Summary:

This paper presents the set-up design for measuring the properties of magnetostrictive materials to assess the magnitude of the Villari effect. For this, the method to do measurements was developed and described, further the set-up was designed. A significant advantage of this method is the elimination of the need for additional consumable materials, such as strain gauges.

Keywords: Magnetostrictive materials, Villari effect, energy harvesting, strain gauges

Background, Motivation and Objective

Magnetostriction refers to the ability of a material to undergo mechanical strain in response to the magnetic field. It is the phenomenon observed in almost all ferromagnetic materials. It couples elastic, electric, magnetic, and in some situations also thermal fields [1]. The magnetostrictive phenomenon is reversible, i.e. a mechanical impact on these materials results in their magnetic properties modification. This is a direct analogy to the piezoelectric case, where the elastic and dielectric properties are involved as well as the piezoelectric. In the magnetostrictive case a reverse phenomenon is known as the Villari effect [1]. Therefore, it is considered to be used for sensors, actuators or power scavenging, where electric power could be harvested due to a vibrated structure with magnetostrictive properties, e.g. piezomagnetic coefficient. Such a typical vibration energy harvester (EH) set-up then consists of a cantilever that produces an oscillating magnetic field wound with a coil. The cantilever experiences a time-varying compressive mechanical stress, inducing the current in the coil that is connected to a resistive load.

Low level vibrations are ubiquitous: they are present in buildings, automobiles, aircraft, ships, trains, industrial and home machines. A combination of theory and experiment shows that from vibrations about $300 \mu\text{Wcm}^{-3}$ could be generated [2]. This makes it a potential reliable remote energy source to replace batteries for low power demand components, e.g. for IoT

sensors [2]. Today, the magnetostrictive materials are present in a form of solid blocks, fibers, powders [3]. To make the use of such forms of magnetostrictive materials for small type energy harvesters, it must be possible to adapt them to fabrication techniques available for a micro- or meso-scale, including 3D printing. This is achievable by developing new composite materials possessing magnetostrictive properties [4]. However, a new issue is arising, how to check their properties in order to confirm their utility and further to improve these composites to achieve higher conversion efficiency [5]. In the magnetostrictive EHs, output energy depends on the coupling of magnetic susceptibility, mechanical stresses, strains and magnetic field strength. Additionally, the output power is not uniform across the frequency spectrum [8, 9]. Although, there are a lot of challenges and parameters to be confirmed, the magnetoelastic coupling coefficient is the primary to be investigated. Commonly, the magnetostrictive materials are characterized by static measurements; the sample is placed in the tuned DC magnetic field, meanwhile the compressive stresses of a sample are obtained using the strain gauge [8]. However, aside from the nonlinearity, the issue is the thermal effect that is inevitable when the investigated materials are combined with the strain gauges; in [9] it was reported that the reduction of the temperature effect of the substrate on the measurements is of high importance and can be achieved by the integration of microfabricated strain gauges directly on the sample. This raises challenges

about the additional time to spend on the design, fabrication and measurement calibration.

The objective of this work was to design a setup for measuring the coupling between excitation from the impact on the sample r and the generated magnetic field in an alternative way, i.e. dynamic, based on the Villari effect, without the necessity to use the strain gauges.

The set-up design

The set-up design implementations encompassed following assumptions:

1) to create an impact to transform stress to magnetic field, 2) to measure the magnitude of the generated magnetic field in a simple way and 3) to minimize measurement errors between different samples. These requirements were achieved respectively by: ad 1. including a dedicated vibrating electromechanically controlled carrier for the measured samples, ad 2. a magnetometer, whose magnetic bias is negligible, and ad. 3 to use of the carrier's holder that enables in the ease and repeatable manner to mount samples.

On the other hand, it is necessary to establish the method, based on the theory, how to transition the obtained data to make them useful to estimate the magnitude of the Villari effect from the investigated samples. In the context of energy scavenging, precise knowledge of the piezomagnetic coupling is not required: the energy harvesters are matched to the frequency spectrum associated with the presence of mechanical vibrations [2]. Therefore, it is more important to know the function of the generated magnetic field for the selected frequencies. This can be achieved by measuring the magnetic field of a sample in regards to the sample's position, specifically described as a function of displacement in time.

In the proposed set-up the sample vibrates in one direction. Hence, the displacement of the sample is considered as a 1D wave vector ($\psi(r,t)$; Eq. 1) for a selected frequency, in the form of a wave number k , amplitude a and wave position r . Consequently, the magneto-mechanical coupling becomes the conversion of a wave vector ($\psi(r,t)$) into the corresponding magnetic field.

$$\psi(\mathbf{r}, t) = A \cos(\mathbf{k} \cdot \mathbf{r}) \quad (\text{Eq. 1.})$$

Based on the present assumptions and relations a dedicated experimental set-up was designed (Fig. 1). It comprises a vibration table as a carrier with a sample holder. All this serves as the excitation base. Additionally the set-up has a magnetometer AK09918 (AKM, JP) and an accelerometer ICM20600 (InvenSense, US). The vibration table is driven by a DC motor Pololu 2214 (Wagney, PL). The whole set-up is controlled by an ESP-32 microcontroller (Espressif, PRC). The motor speed controller was created using the regulator LM2596 (Texas Instruments, US) with a digital potentiometer connected to its feedback loop and the microcontroller.

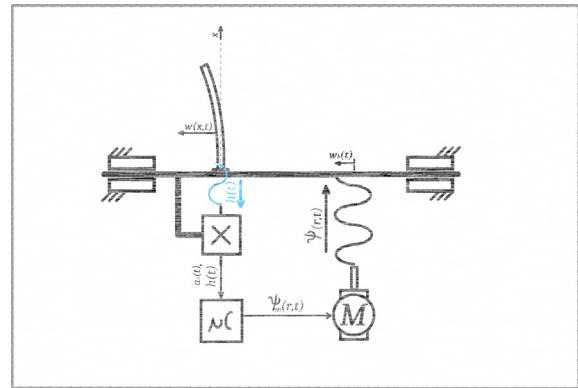


Fig. 1. Schematic picture of a proposed measurement set-up.

When the sample is mounted to the vibration table, the displacement at $w(0,t)$, remains identical to the displacement of $w_b(t)$ - at the base. . The displacement at $w_b(t)$ is controlled by a microcontroller. a frequency and amplitude sweep are obtained from... and contribute to the frequency-based characteristics. As the result, in a mapping of a 2d plane of frequencies and magnitudes (wave vectors) into a generated magnetic field by the sample. To minimize noise, the data gathered from an accelerometer are useful to further post into the wave vector. Additionally, the corresponding values of the generated magnetic field are recorded. . The acquired data are processed in real time using algorithms designed to filter out external noises (e.g. mechanical disturbance).

Conclusions

The proposed set-up can be utilized in the initial iteration phase of designing magnetostrictive samples. For example, by comparing the results of each iteration it is possible to determine the highest magnetic field output. t This enables a basic optimization process for samples intended for micro-scale energy harvesting applications. Furthermore, based on the frequency response of a given sample, a more

suitable load circuit can be subsequently designed.

Based on the change in output power concerning the resistive load and Faraday's coupling, a new measuring setup was developed to minimize measurement errors between different samples. This was achieved by replacing the pickup coil with a magnetometer, whose magnetic bias is negligible. In addition the developed setup eliminates the need for specialized laboratory equipment and consumables, making the measurement process more efficient and accessible..

- [1] "IEEE standard on magnetostrictive materials: Piezomagnetic nomenclature," IEEE Std 319-1990, pp. 1–, 1991, doi: 10.1109/IEEESTD.1991.101048
- [2] S. Roundy, P. K. Wright, and J. M. Rabaey, Energy Scavenging for Wireless Sensor Networks. Springer Book Archive, Springer New York, NY, 1 ed., 2003, doi: 10.1007/978-1-4615-0485-6
- [3] L.A. Dobrzański, A. Tomiczek, B. Tomiczek, A. Ślawska-Waniewska, O. Iesenchuk, "Polymer matrix composite materials reinforced by Tb_{0.3}Dy_{0.7}Fe_{1.9} magnetostrictive particles", Journal of Achievements in Materials and Manufacturing Engineering, vol. 37 no. 1, 16--23, 11 2009,
- [4] A. A. Paul, Q. H. Nguyen, W. Shen, "3D printed magnetostrictive polymer composites (MPCs) for wireless stress sensing," Materials & Design, vol. 247, 2024, doi: 10.1016/j.matdes.2024.113402
- [5] L. Wei, H. Liu, L. Shu, L. Zhao, Z. Liu, and Y. Chang, "Study of a magnetostrictive energy harvester for harvesting transient shock vibration," Sensors and Actuators A: Physical, vol. 361, p. 114577, 2023, doi: 10.1016/j.sna.2023.114577
- [6] D. Davino, A. Giustiniani, and C. Visone, "Effects of hysteresis and eddy currents in magnetostrictive harvesting devices," Physica B: Condensed Matter, vol. 407, no. 9, pp. 1433–1437, 2012, doi: 10.1016/j.physb.2011.07.038
- [7] L. Wang and F. G. Yuan, "Vibration energy harvesting by magnetostrictive material," Smart Materials and Structures, vol. 17, p. 045009, jun 2008, doi: 10.1088/0964-1726/17/4/045009
- [8] A. Bieńkowski, R. Szewczyk, and R. Kolano, "Influence of thermal treatment on magnetoelastic villari effect in fe78si13b9 amorphous alloy," Materials Science and Engineering: A, vol. 375-377, pp. 1024–1026, 2004, doi: 10.1016/j.msea.2003.10.045
- [9] M. Li, Z. Hu, B. Yan, J. Wang, H. Zhang, F. Ye, B. Sun, J. Liu, Y. Li, G. Ding, F. Zang, and Z. Yang, "A flexible resistive strain gauge with reduced temperature effect via thermal expansion anisotropic composite substrate," Microsystems nanoengineering, vol. 10,p. 129, 09 2024, doi: 10.1038/s41378-024-00762-w

Acknowledgment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101007429.



Project co-financed by the Polish Ministry of Education and Science under the program titled International Co-financed Projects.