Quantities Affecting the Behavior of Vibrational Magnetostrictive Transducers

Quantities affecting the behavior of vibrational magnetostrictive transducers

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Through the conversion from mechanical to electrical energy it is possible to monitor a vibrating machine of any kind, by exploiting the mechanical energy produced by the vibration. To this end, one can use direct force devices inserted in the supports or in the kinematic chain of the vibrating contrivance, or cantilever devices with seismic masses. Regarding the devices of the first type, the maximization of the electrical output depends on various parameters. This work, through a combined experimental and modeling approach, analyzes the behavior of a transducer based on a rod of Terfenol-D. Many parameters are analyzed, such as the frequency of the vibration, the amplitude of the force transmitted by the vibration, the characteristics of the coupled electrical circuit, the magnetic and mechanical bias. It is shown how the output power and electrical current are strongly influenced by the mechanical and magnetic bias. In addition, avoiding tensile stresses, the work shows how the maximum output power is obtained when the mechanical bias is close to the amplitude of the dynamic force imposed by the vibration.

Index Terms – **Electromagnetic measurements, Electromagnetic modeling, Energy harvesting, Magnetic devices, Magnetostriction.**

I. Introduction

The ability of magnetostrictive materials in converting mechanical time variant stress into electrical signal is of interest in the field of energy harvesting. Harvesters use wasted energy from the environment, and the energy they produce is often used for supplying wireless transmission systems. These latter, as a zigbee node, requires a supply power from some milliwatts to some tens of milliwatts and currents from some millamperes to some tens of milliamperes [1]. Various types of devices have been studied using shape memory alloys or piezoelectric materials or electrodynamic contrivances with permanent magnets [2]. Some of them have a cantilever structure, other exploit directly the force exerted by the vibration.

A general overview of all vibration-based energy harvesting technologies can be found in [3], but comparisons with experiments are restricted to piezoelectric generators. Magnetoelastic harmonic oscillators are widely studied in [4], making reference to Galfenol alloy, while the effectiveness of direct force transducers is faced in [5-9]. In particular, papers [5, 6] focuses on high-stress harvesters, suitable for structural applications, while in [9] a Galfenol harvester for very low frequency (less than 1 Hz) applications is considered. In all these papers, the influence of some parameters on the harvester effectiveness is analyzed by experiments and modeling, but limiting the attention to range of values that are typical of high force applications. In this work, a specific focus is posed on direct force MST devices able to exploit energy vibrations similar to those generated in industrial environment (e.g. by a machine tool). This means paying attention to harvesters working with frequencies and forces in the 10^2 range.

The considered device consists of a bulk $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ rod provided by Etrema Inc. having two NdFeB permanent magnets (PM) at both ends, which is excited by the force generated by a vibration. A pick up coil wrapped around the material harvests the electric energy produced by the Villari effect. A measurement system is built around the transducer, including a laser vibrometer, a force sensor and a DAQ system for all the mechanical and electrical quantities. The system has been built being traceable to SI units and includes a full controlled piezoelectric actuator able to produce a vibration excitation having a nearly sinusoidal force profile.

Through the above mentioned setup, authors realized the analysis of many parameters of influence such as: frequency, preload (prestress), dynamic force amplitude, electric load and PM magnetization. It must be remarked how this paper deals with the device behavior and not actually on the whole characterization of the material itself, as for example in [10-11].

The combined effect of the prestress and of the dynamic stress has been found of particular interest. The results show how the maximum output power is obtained when the force excitation peak is close to preload. In the experiments, a power equal to 82.8 mW at 300 Hz has been generated by the setup, corresponding to a specific power of 5.2 mW/cm^3. At any rate, the setup is able to generate higher power density by increasing the energy and the frequency of the vibration input. The limit is given solely by the accuracy of the setup and by the thermal stability of the force generation system.

II. Experimental setup

An experimental setup has been developed for the purpose and is shown in Fig. 1. It consists of a non magnetic frame (gantry structure) embedding the mechanical excitation and the transducer. The device core is a 60 mm long $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ (TerfenolD by Etrema Inc.) rod, with a 12 mm diameter, topped by a Nd-Fe-B permanent magnet at both ends. The transducer is bounded by a coil and is excited by a vibrating force applied through a full controlled piezoelectric actuator, able to impose a force sinusoidal profile in the frequency range up to 1 kHz. Between the actuator and the transducer a small disk, target for a laser doppler vibrometer,

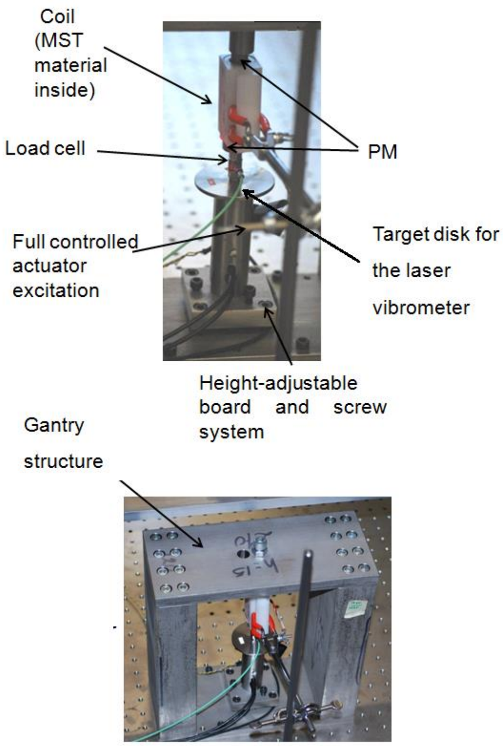

Fig. 1 – Detail and full view of the transducer and experimental setup.

and a piezoelectric load cell are interposed. These latter transducers measure the time behaviour of the force and of the velocity of the vibration. The magnetostrictive material is prestressed by a screw system.

The active electric power load is directly measured through a multimeter (Yokogawa WT 3000) on a resistive load. The total expanded uncertainty concerning the electrical measurement is ~0.2 %, performing measurements always above the 70% of the current range, whilst the one related to mechanical measurements is ~ 5%.

III. ANALYSIS

The analysis described in the following was carried out experimentally, but also by modeling, especially for what concern the magnetization bias effect. To this end, we used therefore the validated modeling approach proposed in [7], based on a finite element simulation of the device coupled with a Preisach-based magnetoelastic model of the MST material.

A. Coupled circuit and frequency effect

The impedance of the load circuit, coupled to the harvester, is one of the parameters of the generation. The latter is function of the coil turn number and of the wire section and should be chosen as a function of the current and voltage levels desired as output. An extended analysis of the influence of load characteristics is out of the scope of the present paper, being the subject of already published papers (see for example [8, 12]).

Table 1 shows, for some types of coils coupled to the transducer, the calculated parameters of the generation at 300

TABLE I

COIL PERFORMANCE AT 300 Hz, PRELOAD σ_0 = 6 MPa, $\delta\sigma_{PK}$=0.84 MPa

Coil	Turn number	P [mW]	I_{rms} [mA]	R_M [Ω]	Wire diam [mm]
1	288	2.2	33.2	2.0	1.0
2	540	3.0	20.7	7.0	0.5
3	990	3.8	11.3	30.0	0.5
4	24300	4.2	0.53	15000	0.1

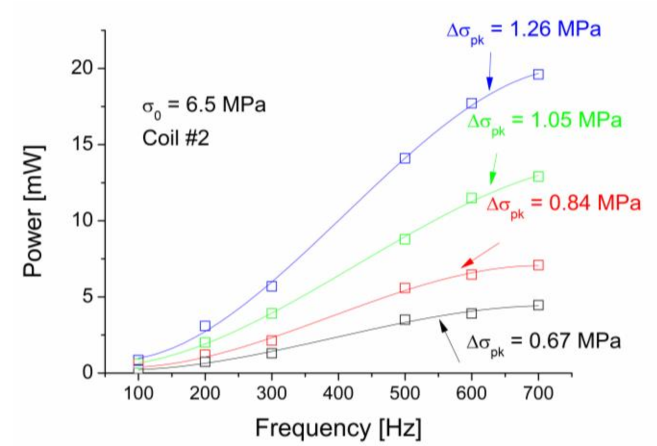

Fig. 2 – Effect of the vibration frequency on the measured electrical output power, at four different dynamic stress amplitudes, fixing the prestress at 6.5 MPa. Results refer to configuration with coil #2.

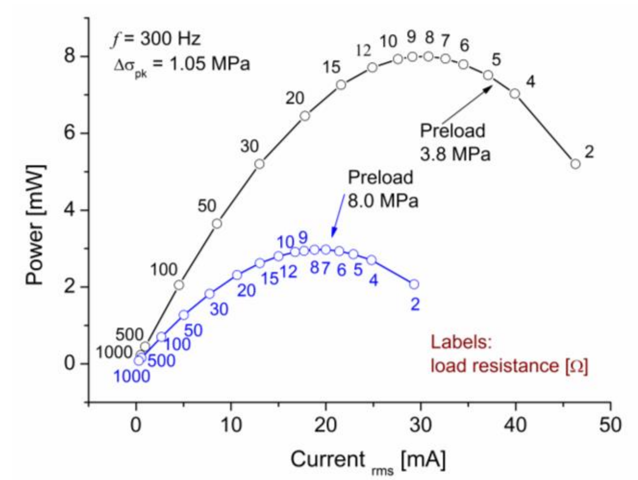

Fig. 3 – Effect of the mechanical prestress and load resistance on the measured electrical output power, at constant excitation force amplitude. Results refer to configuration with coil #2.

Hz. They are: the maximum generated power and the correspondent current, which has been calculated in case of resistive load R_M matching the coil impedance.

In the following, coil #2 and coil #1, specified in Table I, have been chosen for the experimental measurements.

Fig. 2 shows the output power versus frequency, measured being constant the preload applied to the magnetostrictive material. Four amplitudes of the time varying vibrational stress were considered. The output power increases with frequency and tends to saturate at higher frequencies, as a consequence of the eddy current effects, which limits the flux penetration in the rod.

Fig. 3 illustrates the effect of the electric load on the output power and current, in the case of coil #2. As shown in the figure, the load that provides maximum power is slightly influenced by the mechanical preload, while the output power undergoes major changes. A deep insight on the effect of mechanical prestress is discussed in the next section.

B. Preload effect

The giant magnetostrictive materials, when not prepared under induced anisotropies [11], need a suitable mechanical prestress to optimize their performances. This is well known for actuators and studies can be found in literature concerning this topic [13, 14]. Less known is the effect of the mechanical preload for transducers. To study this effect, the magnetostrictive sample was placed in the test-rig and constrained by the only compression between the surrounding parts. To this reason, in order to ensure mechanical stability of the system, the maximum sinusoidal excitation force peak must not be higher than the preload.

Fig. 4 shows the behavior of the electrical power output versus the preload applied to the magnetostrictive material. Four curves are presented, each one corresponding to a different amplitude of the sinusoidal dynamic stress. As expected and also seen in Fig. 2, making constant the preload and increasing the excitation force amplitude, the energy of the vibration increases and the output power rises. When the preload value is close to the excitation force peak, the device produces the maximum output power. By approaching this limit the system becomes unstable, since the rod remains without constraints for a part of the period. This is the reason why the curves do not reach preload values lower than the excitation amplitude. Defining the ratio *r as*

$$r = \frac{\Delta\sigma_{pk}}{\sigma_0}$$

that is the peak magnitude of the dynamic force on the preload, one can say that the maximum power is obtained when $r \approx 1$ and the output power is as low as the ratio r is lower than 1.

Fig. 5 shows the trend of the generated electric power as a function of the preload, for three different values of the dynamic stress amplitude. Even in this case, the power increases when the preload decreases towards the value of the dynamic load. In the testing at 300 Hz, a dynamic load of 2.75 MPa has been reached, corresponding to a peak force of ~325 N. In this case prestress has not been set below 4.55 MPa for mechanical stability and measurements repeatability reasons.

C. Effect of the magnetization bias

The effect due to a variation of the remanence of the PM utilized in the device is important, even if not easy to be evaluated experimentally. Therefore, we used the aforementioned model approach. In the present case, for the maximum bias considered in the simulations, we refer to commercial NdFeB magnets having a maximum remanence of 1.2 T. In the previous experiments the magnets utilized have a measured remanence equal to 1.10 T.

Fig. 6 shows the stress induced hysteresis loops, calculated at 300 Hz, for different remanence values of the permanent magnet. The loops refer to the local sample magnetization and

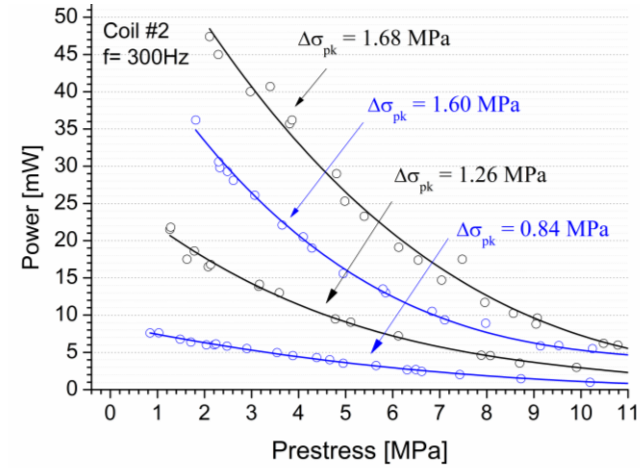

Fig. 4 – Curve family measured at 300Hz. Output power versus the applied preload, measured for four different vibration stress amplitudes. Results refer to configuration with coil #2. The measured values are represented by circles. The solid lines interpolate the measured values.

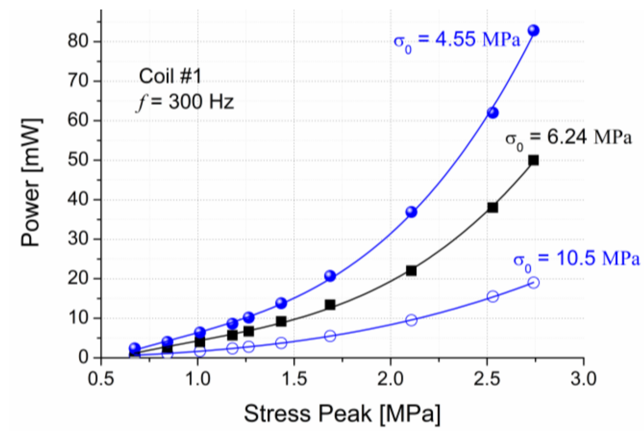

Fig. 5 – Measured power vs the dynamic stress peak amplitude of the vibration, for three different preload values. Results refer to config. with coil #1.

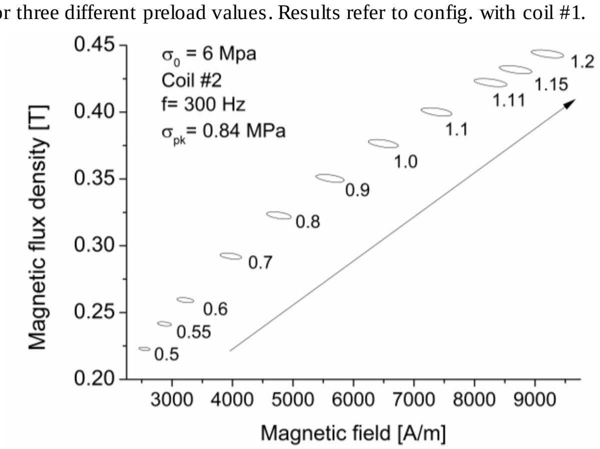

Fig. 6 – Vibration induced hysteresis loops, calculated as a function of the remanence of the permanent magnet. The horizontal axis represents the total field applied to the magnetostrictive material. Each remanence value, expressed in tesla, is shown close to the corresponding cycle.

magnetic field in the rod center. In fact, the magnetization of the sample varies according to the permanent magnet remanence. The loop area rises increasing the magnets remanence up to around 1 T, then remain nearly constant. The width of the loop has been experimentally verified in terms of ΔH_{max} and ΔB_{max}, even if the experimental values cannot be superposed in the diagrams because the magnetization bias of the sample cannot be measured.

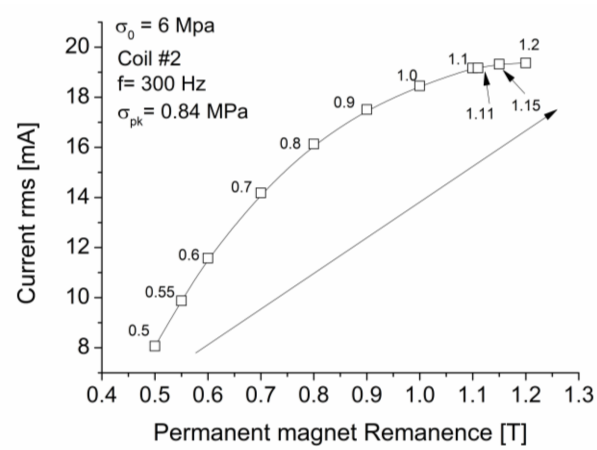

Fig. 7 – Calculated electrical current produced by the harvester as a function of the remanence of the permanent magnets. The remanence of the PM, expressed in tesla, is reported near each simulated point.

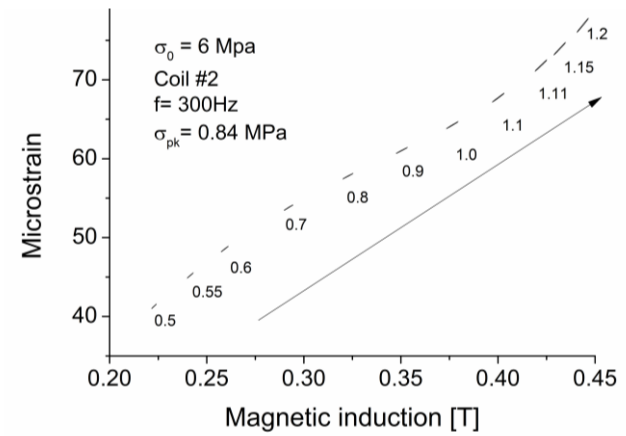

Fig. 8 – Simulated vibration-induced magneto-mechanical paths. The correspondent remanence of the PM, in tesla, is reported near each path.

The bias level provided by magnets has a direct effect on the output current, as shown by Fig. 7. The maximum current from the transducer is obtained in presence of the greatest magnetic remanence of the magnets. This outcome is not a foregone conclusion. As evidenced in [6,15], in the case of similar transducers, the current and power produced by the transducers have a maximum for a specific optimum magnetic bias.

The mechanical vibration induces magneto-mechanical cycles, in terms of strain of the sample versus the applied magnetic field or versus the magnetic flux density. These cycles, in the second case, are shown in Fig. 8. The diagram illustrates how the vibration induces a deformation of the sample, which corresponds to a magnetic flux density variation, which is the one that generates the emf. The deformation takes place around a mechanical bias which is determined by both, the magnetic bias and the mechanical preload. It is noted that the sample magnetization variation ΔB increases with the magnetic bias as well as the emf and current.

IV. Conclusions

This work provides an analysis of the quantities that influence the performance of a direct force transducer based on Tefernol-D. The study shows that the generated electrical current and power have a complex dependence on several quantities, namely the coil characteristics, the type of permanent magnets and the characteristics of the mechanical excitation. In particular, the magnetic bias and mechanical bias are of great importance in terms of power generated. This study underlines that, in the case of terfenol-D, one need to use magnets with high remanence (1.1 -1.2 T) and to provide a preload close to the peak amplitude of the dynamic mechanical stress provided by the vibration. To obtain optimized and especially repeatable results the parameters which should be carefully checked, in addition to those mentioned, are the frequency, the amplitude of the dynamic stress and the electrical load.

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