Vibration energy harvesting using Galfenol based transducer

Viktor Berbyuk*
Division of Dynamics, Department of Applied Mechanics
Chalmers University of Technology, SE-412 96, Gothenburg, Sweden

ABSTRACT

In this paper the novel design of Galfenol based vibration energy harvester is presented. The device uses Galfenol rod diameter 6.35 mm and length 50mm, polycrystalline, production grade, manufactured by FSZM process by ETREMA Product Inc. For experimental study of the harvester, the test rig was developed. It was found by experiment that for given frequency of external excitation there exist optimal values of bias and pre-stress which maximize generated voltage and harvested power. Under optimized operational conditions and external excitations with frequency 50Hz the designed transducer generates about 10 V and harvests about 0,45 W power. Within the running conditions, the Galfenol rod power density was estimated to 340mW/cm3. The obtained results show high practical potential of Galfenol based sensors for vibration-to-electrical energy conversion, structural health monitoring, etc.

Keywords: Magnetostrictive material, Galfenol-based sensors, vibration energy harvesting

1. INTRODUCTION

With increasing demand for wireless sensor nodes in automobiles, aircrafts, railway vehicles, wind turbines and other engineering systems, the need for vibration energy harvesters as well as for health monitoring has been growing. In many applications energy harvesters already provide a more robust and inexpensive power solution than batteries. In order to enhance the efficiency and power density of existing vibration energy harvesters, different techniques and materials have been proposed. For instance, vibration energy harvesters explore the ability of some active materials, e.g. piezoelectric, magnetostrictive, ferroelectric, etc., to generate an electric potential in response to external mechanical stresses. As a result, these materials can be effectively utilized to transform mechanical strains into electrical power. The later can be stored or used to directly run and maintain low-power devices.

Traditionally the development of compact energy scavenging devices was based on the use of the electro-mechanical coupling attributes of piezoelectric materials to converge mechanical energy to electrical[1-2]. A great attention, however, is paid now days to magnetostrictive alternatives for this application, see e.g.[3-10]. The promise of magnetostrictive alternatives in a host of applications was greatly increased since the development of a new class of magnetostrictive compound – an Iron-Gallium alloy (Galfenol)[10-15,19,23]. This alloy exhibits moderate magnetostriction (~350 ppm) under very low magnetic field (~100 Oe), have negligible hysteresis, demonstrate high tensile strength (~500 MPa) and limited variation in magnetomechanical properties for temperatures between -20 and 80 °C. This material is machinable, ductile and can be welded. Thus this kind of materials can be easily threaded, attached to existing structures and can be used as load bearing members. They have a high Curie temperature (675°C), are corrosion resistant and their properties do not degrade over time. The raw material cost to produce FeGa is about \$0.08/g compared to \$0.50/g for Terfenol-D. All these factors demonstrate that FeGa has great promise as an engineering material for actuation and sensing applications.

In this paper a brief review of characteristics of two magnetostrictive materials, Terfenol-D and Galfenol, is given from perspective of their applications in sensing and actuation. In continuation of the previous results obtained at the division of Dynamics at Chalmers University of Technology on designing and evaluation of Terfenol-D based vibration energy transducers[4-7], the novel design of Galfenol based vibration energy harvester is presented.

* viktor.berbyuk@chalmers.se; www.chalmers.se

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2. MAGNETOSTRICTION, GALFENOL AND TERFENOL-D

Magnetostrictive materials are a class of compounds which deform when exposed to magnetic field. Magnetostrictive effect or Joule effect pertains to the case when deformation is induced along the applied magnetic field direction. Such effect is often employed in actuators design, see for instance[16-18]. Due to the reciprocal nature of magnetoelastic coupling, magnetostrictive material responds with a change in their magnetic state when subjected to deformation. This phenomenon, referred to as Villari effect or inverse magnetostrictive effect, provides a mechanism for sensing and potential for energy harvesting. In summary, the bi-directional coupling between the magnetic and mechanical states of magnetostrictive material provides a transduction mechanism that is used in both sensing and actuation. Most magnetostrictive materials such as cobalt, iron, nickel, ferrite, and etc. exhibit Villari effect, but their magnitudes are too low to be of consequence in sensing and energy harvesting. Magnetostrictive effects, including Joule and Villari effects, are inherent material properties of all ferromagnetic materials. Direct and inverse magnetostrictive effects applicable to actuator and sensor modes of operation are summarized in Table 1.

Table 1. Summary of magnetostrictive effects

Direct Effects	**Inverse Effects**
Joule Effect Change in sample dimensions in the direction of the applied field	*Villari Effect* Change in magnetization due to applied stress
ΔE effect Magnetoelastic contribution to magnetocrystilline anisotropy	Magnetically induced changes in the elasticity
Wiedemann effect Torque induced by helical anisotropy	*Matteuci effect* Helical anisotropy and emf induced by a torque
Barret effect (Magnetovolume effect) Volume change due to magnetization (most evident near the Curie temperature)	*Nagaoka-Honda effect* Change in the magnetic state due to a change in the volume

Table 2. Comparison of Galfenol and Terfenol-D characteristics[3-27]

Parameters and Properties		Units	**Galfenol** $Fe_{1-x}Ga_x$ $0.14<x<0.3$	**Terfenol-D** $Tb_xD_{1-x}Fe_y$ $0.27<x<0.3$ $1.9<y<2$
Free strain / magnetostriction	λ	ppm	300-400	1600-2400
Density	ρ	kg/m^3	7870	9210-9250
Curie temperature	$\mathbf{T_C}$	^{0}C	675	375
Young's modulus	$\mathbf{E}^S$	GPa	30-80	10-90
Tensile strength		MPa	515 (ductile)	28-40 (brittle)
Compress. strength		MPa		305-880
Elastic compliance	$\mathbf{s_{33}^H}$	m^2/N	$17*10^{-12}$	$42*10^{-12}$
Effective MS constant	$\mathbf{d_{33}}$	nm/A	18	8-20
Relative Magnetic Permeability	μ_{33}^s / μ_0	---	70	2-10
Actuation field (bias)		Oe	~100	~1000
Strain-Voltage hysteresis			Very low	Moderate~10%
Coupling coefficient	$\boldsymbol{k}_{33}$		0.38-0.78	0.6-0.85
Material Resistivity		μΩm		0.6
Sound Propagation speed		m/s		1650-1950
Energy Density		kJm^{-3}	2.0-3.1	4.9-25

Thanks to the development of giant magnetostrictive materials, at least three commercially available magnetostrictive materials make energy harvesting possible: crystalline alloys from ETREMA Products, Inc.[19] – Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_{1.9-2}$) and Galfenol ($Fe_{1-x}Ga_x$, $0.14<x<0.3$) – and Metglas 2605SC ($Fe_{81}B_{13.5}Si_{3.5}C_2$), amorphous alloy, from Metglas[20]. Below a brief overview of Galfenol and Terfenol-D characteristics and properties are presented and some of the characteristic parameters of Terfenol-D and Galfenol are given in the Table 2. Note that the magnetic properties of Galfenol and Terfenol-D depend crucially on their composition, production method and structure.

The comparative energy harvesting tests has shown[3] that for certain range of mechanical vibrational input (40-70 Hz), research grade Galfenol (single crystal structure + special production conditions) consistently outperformed Terfenol-D by at least 20 percent when all other variables (pre-stress, mechanical input), except magnetic bias were the same. However, this performance advantage for research grade is true if the input strain to the material is less than its saturation value. In the paper[21] Galfenol was investigated for use in stress based magnetic force control. Comparison with Terfenol-D clarified Galfenol with high saturation enlarges force variation and its inverse magnetostrictive property seems most utilized in series circuit. In practical applications, the magnetic circuit should be modified so as to apply an appropriate bias field to reduce the compressive stress. The force variation of 20N obtained here shows the great potential of Galfenol in handling high density magnetic energy. Authors concluded that applications include composites with piezoelectric materials for zero power magnetic force control device, energy harvesting, and stress sensors[21]. Authors of the paper[22] also concluded that there may be specific applications where Galfenol provides a clear advantage over Terfenol-D. These applications may include those that require extreme space efficiency, active structures, low drive fields, or no permanent magnets.

It has been found[13] that saturation magnetostriction (λ_s) of Galfenol varies significantly with Ga content and it can be expected that the magnetomechanical behavior also varies strongly with Ga content. A wide range of FeGa compositions was studied, see for instance[3,10-13,23]. The highest values of coupling factor and gage factor were observed for operating compressive stresses lower than 20MPa and below magnetic field of 5kA/m. It was found that the highest energy density, magnetomechanical coupling and sensing gage factor were exhibited by Galfenol alloys having composition in the range of 16 to 19 at% Ga thereby making them ideal for both actuation and sensing applications. Note that it is also extremely important to have information about conditions and techniques of preparations of the Galfenol in order to be able to evaluate obtained result correctly. A comprehensive comparative study of the different preparation techniques has been performed by Kellogg[13].

Galfenol, iron-gallium alloy, is newest promising magnetostrictive. The studies performed on directionally cast Fe-Ga alloys showed about seven times increase in magnetostriction compared to polycrystalline iron. Although Galfenol offers only one-third the strain of commercial Terfenol-D, it requires less than one-tenth the magnetic field required to saturate Terfenol-D. This attribute can be useful for design of compact and low-weight devices by reducing the amount of coil and high power electronics which are usually required to obtain high drive current in Terfenol-D transducers. Moreover, it has been found that $Fe_{81}Ga_{19}$ shows only minor variations in its saturation magnetostriction value between -21 ^{0}C to +80 ^{0}C and hence can be used for a large range of temperature without significant loss of magnetostriction.

3. GALFENOL BASED TRANSDUCER AND EXPERIMENTAL SETUP

3.1 Transducer design

Galfenol can be easily machined and hence can be obtained in different shapes and sizes which might be useful for innovative devices. Hence it is a structural magnetostrictive material; it can be used to design devices which use its structural properties as well as magnetostrictive actuation and sensing capabilities. Several researchers have designed innovative proof-of-concept devices using the special attributes of Galfenol: bending sensor; strain sensor; tactile sensor; torque sensor; a tuning fork-based gyro sensor; nanowire-based broadband acoustic sensor; positioning actuator for cryogenic environment; linear actuator; wobbler; and vibrator. Now days the FSZM (Free Stand Zone Melting)[19] method is used to produce two types of Galfenol: research grade (with magnetostriction 220ppm ±25 ppm), and production grade (168 ppm ±18 ppm). Magnetization for both grades: 1.3 Tesla to 1.5 Tesla.

In Fig.1 the schematic representation of *Villari effect* is depicted. In this way the magnetostrictive material based transducers that utilize vibrations to produce electricity can be designed. Following this concept several transducers have been developed and studied at the division of Dynamics, department of Applied Mechanics, Chalmers University of Technology[4-7]. Below the focus is put on several results obtained for Galfenol based transducer.

General view of assembled transducer as well as its components is given in Fig. 2, (A– fully assembled transducer; B – component parts of transducer: 1 – Galfenol rod, 2 – bobbin with pick-up coil, 3 – Teflon body with magnet magazine, 4 – permanent magnets; 5 – permedyn plates; all dimensions in mm). The magnetostrictive rod 1 is tightly seating inside the Teflon bobbin 2 with pick-up coil. The bobbin is placed inside transducers body 3. Transducer functional components and their parameters are as follow.

Magnetostrictive element: Galfenol rod from ETREMA products Inc., polycrystalline, production grade, manufactured by FSZM process with 18.4 at% gallium. Rod is laminated to 0.024" thickness via wire EDM. The critical eddy current frequency is of ~8000 Hz.

Final machined geometry: diameter 6.35 mm, length 50 mm, mass 12.6 g, density 7.954 g / cm^3.

Collecting coil: 4000 turns of Cu wire, l = 42 mm, d_{in} = 7 mm, d_{out} = 23 mm, R = 76 Ohm.

Magnetic bias: Bar-type neodymium magnets (diam. 6 mm, length 10 mm), flux density 1.17T – 1.27 T.

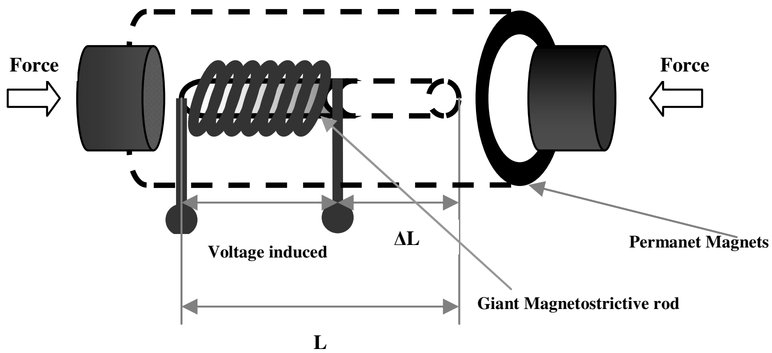


Figure. 1 Schematic of Villari effect.

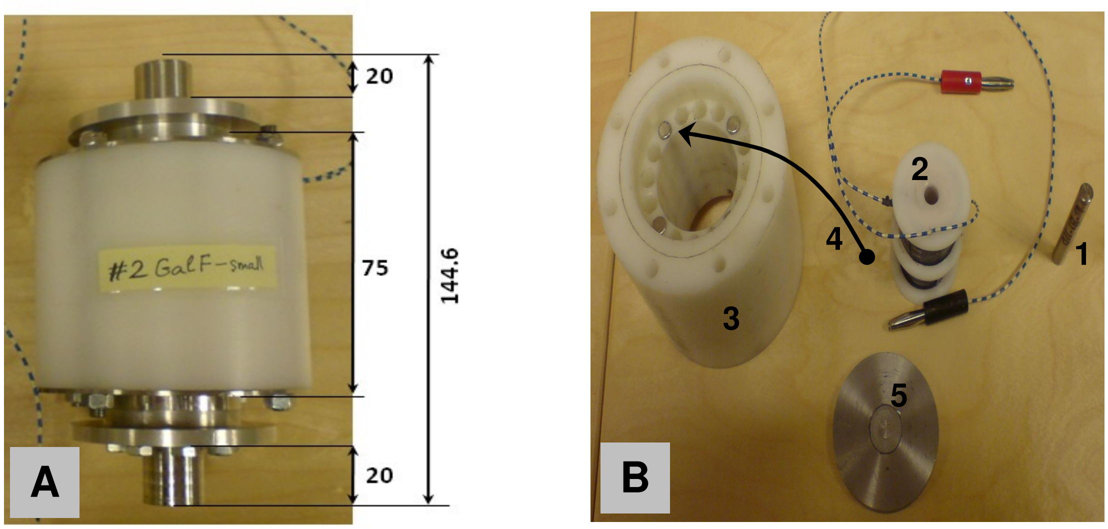


Figure 2. Galfenol based transducer and its components.

3.2 Experimental setup

The general overview of the experimental setup is depicted in Figure 3. It consists of VIBEL (VIBrations to ELectricity) machine, measurement system, computer and Labview based interface. VIBEL machine has been designed and manufactured to produce harmonic mechanical load with controlled frequency and amplitude. This machine is supposed to be utilized for various experiments in the field of smart materials based transducers, primary – in the research on energy harvesting from mechanical vibrations. Closed view of the VIBEL machine with Galfenol based transducer is shown in Figure 4.

The VIBEL machine works as follows (Fig. 4). The rotation of the shaft of motor 1 is transformed into harmonic vibrations by eccentric 2, pusher 3 and vibrating plate 4. Through the crossbar 5 these vibrations are transmitted to upper plunger 6. The frequency of vibrations is controlled by regulator 7. The distance between upper (6) and lower (8) plungers may be varied by pre-stress unit 9, which is also used to create mechanical pre-load on magnetostrictive rod, if necessary. The force applied to the input and output shafts of the Galfenol based transducer 10 are controlled by the pair of strain gauges 11 mounted on both plungers. The electric signal of strain gauges is measured with multimeters (model HP 34401 and Agilent Tech. 34401). The axial shift of plungers 6 and 8 regarding their initial positions is monitored by optical laser sensors 12 (Baumer Electric AG, model OADM 12I6430/S35A).

Figure 3. Experimental setup with VIBEL machine.

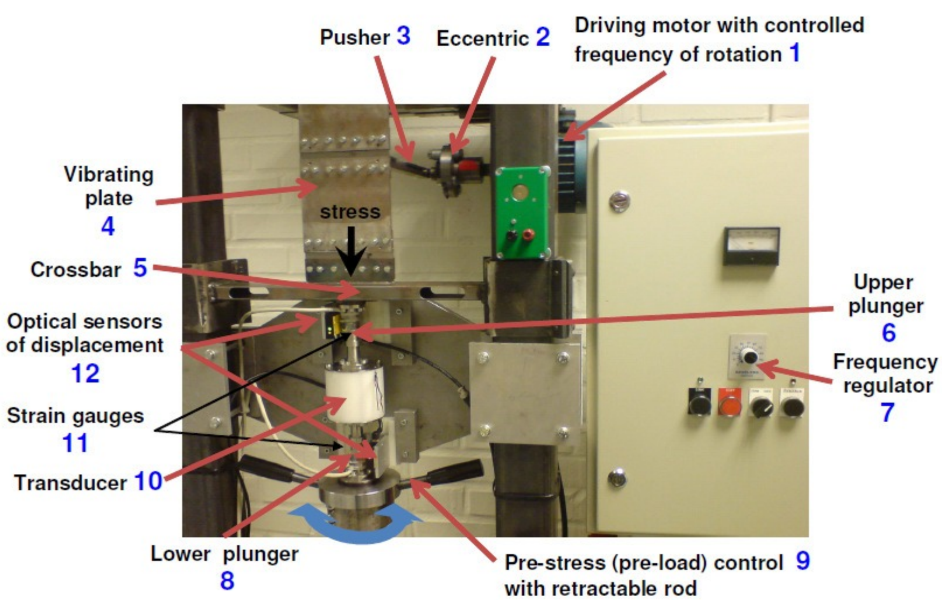


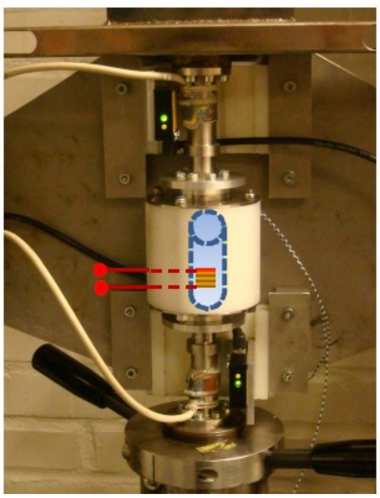
Figure 4. Closed view of VIBEL machine.

A video showing designed Galfenol based transducer in its real-time operation as power harvesting device at the VIBEL machine can be found via web link http://www.am.chalmers.se/~berbyuk/dynamicsofVibeltestrig2.mpg .

4. MEASUREMETS, ANALYSIS AND DISCUSSION

4.1 Measurement of Galfenol rod compression inside the transducer body

To determine precisely the relation between the externally applied force and the real compression of the Galfenol rod inside the transducer, specially designed test measurement was performed. Strain measurements were taken in parallel from the strain gauges located on the upper plunger (applied load) (see Fig. 4) and on the Galfenol rod which are located directly under the sense coil (real rod compression). Such approach is schematically shown in Fig. 5 (left). Special calibration utility has been created (Fig. 5 right). Four strain gauges were mounted in the center ¾ portion of the Galfenol rod to measure longitudinal strains. Two sets of two gauges each were positioned on opposing sides of the rod with all gauges wired in series to cancel out any induced bending moments. A large gauge area was also desired for an averaging effect since magnetostriction in Galfenol is not necessarily uniform.



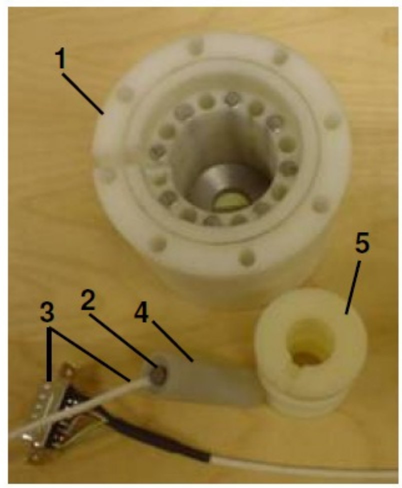


Figure 5. Left – The scheme of experiment with the strain gauge inside the transducer. Right – Special utility for direct measurement of Galfenol rod compression: 1 – Transducer's body; 2 – Galfenol rod; 3 – Strain gauges connector; 4 – Teflon guide bushing; 5 – Coil bobbin.

The whole assembly was fitted to the standard transducer body by means of Teflon bushing and coil bobbin of appropriate size. First, the calibration of the strain gauges mounted on the Galfenol rod has been performed. Five independent sets of measurements have been performed, and quite good reproducibility of obtained data was observed. After that, the Galfenol rod was placed into transducer and whole transducer was then placed in the VIBEL, (see Fig. 5 left). Now, comparing the calibrated signals from two strain gauges – on the upper plunger (see Fig. 4) and on the Galfenol rod – it is possible to estimate the transmission coefficient of the externally applied force from VIBEL machine to the magnetostrictive rod.

After averaging of all independent data sets we obtain perfect linear relationship between two signals which gives us the ratio between applied stress and real strain of the rod inside transducer. The transmission coefficient was found to be 71%. The loss of about 30% of force may be explained by different bending (non-axial) deformations appearing in the VIBEL machine structure and in the transducer. Note, that such calibration is only possible in the static mode, because under cyclic periodic stress (dynamic conditions) the magnetic field generated by Galfenol rod may significantly distort the electric response of the strain gauges.

4.2 Experimental study of power harvesting by Galfenol based transducer

The main aim of the present experiments with Galfenol based transducer is threefold. Primary task is to determine optimal condition for the operation of the designed transducer, namely magnetic bias, mechanical pre-stress and operation frequency. At second, it is important to estimate the efficiency of the developed transducer as a power harvester. Third question was to estimate the power density of Galfenol material with the aim of usage for electric current generation as well as for other applications.

First task was accomplished by carrying out the series of experiments with varying external parameters – magnetic bias, pre-stress, operation frequency, load resistance, etc. Then, comparing the obtained results, the range of optimal operation conditions has been determined. The overall efficiency of the harvester (efficiency factor, χ) is determined as a degree of conversion of mechanical energy into electric energy. This value will be a characteristic of a given transducer only. It includes both magneto-mechanical properties of the magnetostrictive element and specific parameters of transducer's construction. The efficiency factor χ is calculated as a ratio of electric power output P_{el} and mechanical power input P_{mech} , i.e. $\chi = P_{el} / P_{mech}$. Generated electric power P_{el} may be easily found from measurement results and calculated as: $P_{el} = V_{rms}^2 / R_{load}$, where V_{rms} is the measured root-mean-square value of generated voltage, and R_{load} is the load resistance. Applied mechanical power is calculated as a mechanical work expended for compression of Galfenol rod during 1 sec, i.e. $P_{mech} = F * \Delta l * f$, where F is applied force, Δl is compression of Galfenol road, and f is frequency of applied force. Power density of magnetostrictive element may be calculated as collected electric power per unit of material volume.

Electric voltage output of the transducer was recorded from the pick-up coil with or without load resistor. Three load resistances were used in present experiments: **150 Ohm** – quasi-optimal power transfer at moderate efficiency, **10 kOhm** – high efficiency at low power transfer and **0 Ohm** – (open circuit) taken as reference.

The measurements were performed with the help of oscilloscope (Agilent Technologies DSO 1014A). The root-mean-square value of generated voltage, V_{rms}, was measured as a most appropriative for further calculations. To reduce scattering of data, the averaging of 64 measurements was used as "experimental value". The frequency of applied mechanical load was set by frequency regulator of the electric motor in VIBEL setup. Applied mechanical load was calculated from the response of lower strain gauge (See Fig. 4).

The output voltage of the transducer in the open circuit regime (R_{load}= 0) is shown in Fig. 6. First of all we note that generated voltage linearly increases with frequency in all range of investigation. Second, the magnitude of generated voltage is severely affected by both pre-stress and bias that agrees well with known theoretical and experimental data. Thus, it is important to stress that when bias is absent ("NO magnets" plot), no voltage is generated by transducer.

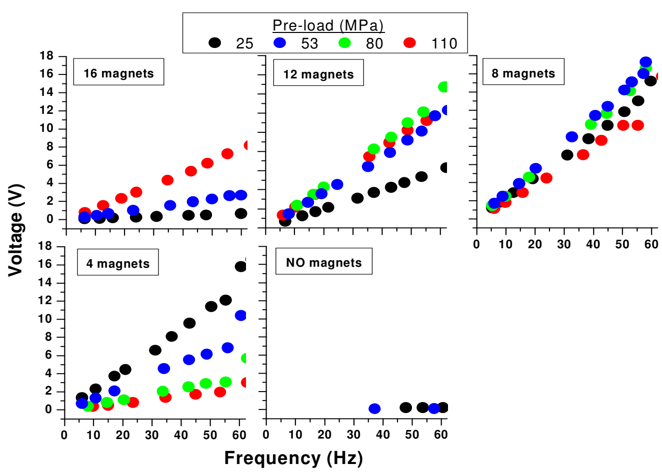


Figure 6. Voltage generated by Galfenol harvester (open circuit mode; R_{load}= 0) as a function of frequency, pre-stress and bias. The Y-axis is scaled identically in all plots for better comparison.

The similar tendencies are observed for non-zero load resistance (see Fig. 7). The growth of output voltage with frequency, bias and pre-load dependence remain practically unchanged. The nearly linear growth of the output voltage with frequency may be easily understood. Indeed, the transducer works as *electric current* generator. It means that than higher frequency of applied mechanical load than higher specific current is inducted in the pick-up coil. Taking into account that $\mathbf{U} = \mathbf{I} \times \mathbf{R}$ and $R = const$, it becomes clear that registered voltage should increase as frequency goes up. At the same time, the "specific" voltage or so-called Volt-per-Hertz ratio must remain constant, that is clearly demonstrated in Figure 8.

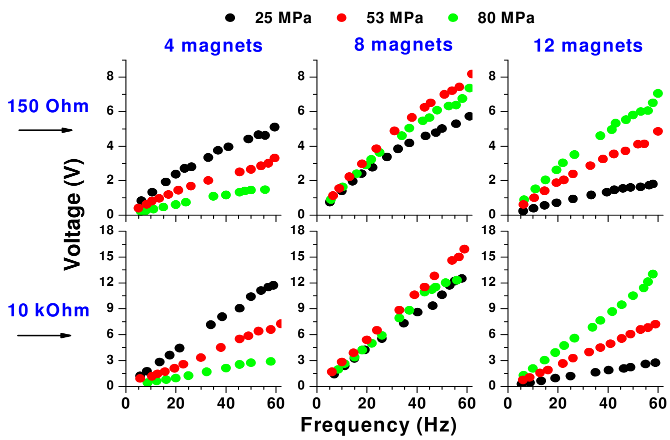


Figure 7. Voltage V_{rms} registered at different load resistance as a function of frequency, pre-stress and magnetic bias.

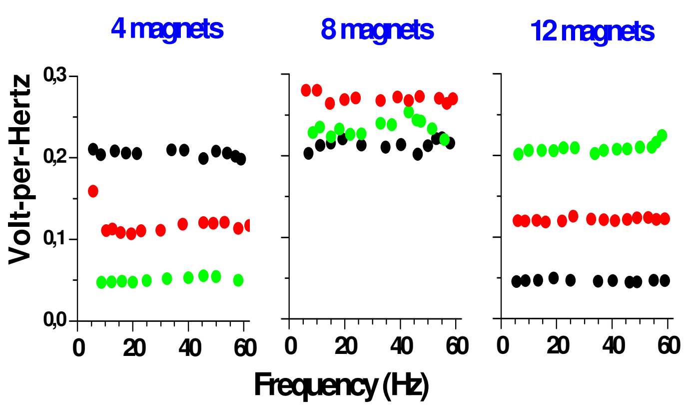


Figure 8. Volt-per-Hertz ratio as a function of frequency, pre-stress and magnetic bias (load resistance – 10 kOhm).

Another important observation from Figures 6 and 7 is clear dependence of generated voltage on both pre-stress and bias. Moreover the magnitude of generated voltage depends not directly on the pre-stress or bias, but rather on combination of both parameters. Thus at low magnetic bias the voltage decreases with applied pre-stress ("*4 magnets*" plots in Fig.6), while it increases with pre-stress at high bias ("*12 magnets*" plots in Fig.6). At moderate bias ("*8 magnets*" plots in Fig.6) no significant dependence of voltage on the pre-stress is observed. Such behaviour agrees well with theoretical considerations, which show that the effects of mechanical pre-stress and magnetic bias are interconnected.

To analyse in more details the dependence of generated voltage on the magnetic bias and applied pre-load, it is useful to consider the variation of this value at certain fixed frequency of applied mechanical stress. Such approach is quite reliable since voltage-frequency dependence is nearly linear in the whole region under investigation. Figure 9 shows the dependence of generated voltage (left plot) and harvested electric power (right plot) on the external conditions at 50 Hz excitation. First of all, it is immediately seen that there is an optimal value of magnetic bias which corresponds in our case to 8 magnets (in fact, 8 columns with 5 single magnets each). In addition, at this bias the optimal pre-stress appears to be of about 50 MPa. It is also seen from Fig. 9 that despite the magnitude of generated voltage is about twice higher for 10 kOhm load than for 150 Ohm one, the generated power is 10 times higher for smaller load. This result is in agreement with the theoretical consideration on the effect of load resistance. Indeed, the 150 Ohm resistance is optimal for power transfer, while 10 kOhm load provides higher voltage output.

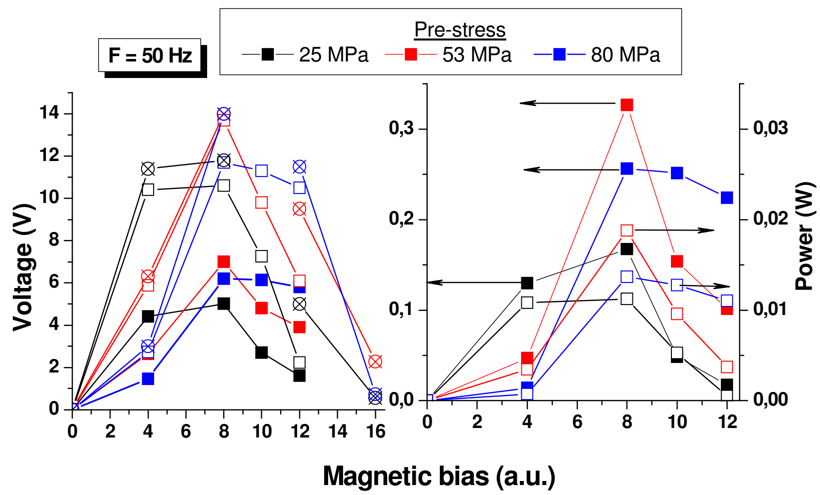


Figure 9. Generated voltage V_{rms} (left) and harvested electric power (right) for different experimental conditions (stress frequency – 50 Hz). Bold symbols –for 150 Ohm; open symbols – for 10 kOhm; crossed circles – open circuit.

It is clear that resulting transducer efficiency factor χ value will be strongly dependent on experimental conditions. Figure 10 shows several examples of transducer's efficiency determined for different frequency of external excitations. Figure 11 presents frequency dependences of the harvested electric power and corresponding efficiency factor under optimal experimental conditions for considered transducer. It appears that maximal efficiency of the transducer (within the range of tested parameters) is about 6 %.

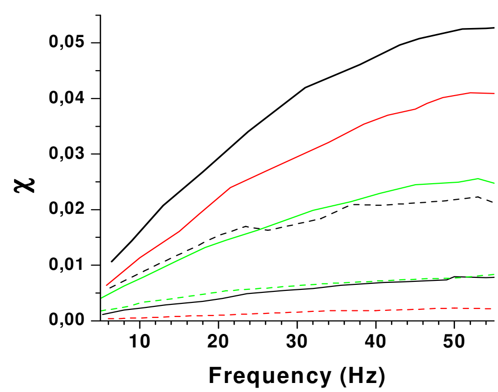


Figure 10. Several typical examples of χ values under various experimental conditions.

Considering quite low efficiency of the whole setup, important note should be made. The displacement of upper plunger in VIBEL machine is nearly constant in all cases (depends on pre-stress) that means that applied mechanical force is not regulated. Thus for pre-stresses 0 – 50 MPa applied stress is 110 MPa. On the other hand, the saturation stress for $Fe_{81.6}Ga_{18.4}$ rod, after which the magnetisation of the material remains unchanged so that no electric current is generated by pick-up coil, is about 63 MPa. It means that large part of mechanical energy applied to transducer does not contribute in electric energy production. In addition, there are significant mechanical energy losses due to bending (non-axial) deformation in the transducer itself that reduces really applied mechanical power in comparison with calculated value. Therefore the real efficiency coefficient of vibration-to-electricity energy conversion by using considered Galfenol based transducer will be quite higher that "gross" coefficient calculated above.

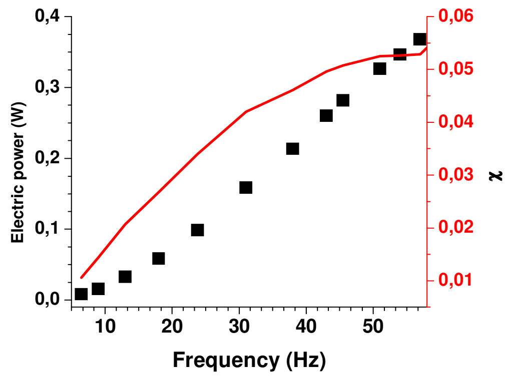


Figure 11. Frequency dependence of harvested electric power (symbols) and corresponding efficiency factor (line) in the case of quasi-optimal conditions: pre-stress – 50 MPa, magnetic bias – 8 magnets, load resistance – 150 Ohm.

On the basis of experimentally obtained data, it is possible to estimate the power density of the Galfenol rod. In our experiments we have: the maximal harvested power – 0.45 W (at 150 Ohm load, 50 MPa pre-stress, 8 magnets bias, and 60 Hz frequency); the volume of the Galfenol rod – 1.584 cm^3; the length of pick-up solenoid – 84% of the rod length. From this it follows that in the present experiments the Galfenol rod power density is P = 338 mW / cm^3. It should be noted that obtained power density is quite high comparing to the highest value of power density for Galfenol reported for the small Galfenol rod operating in bending mode[14].

5. CONCLUSIONS

In this paper a brief review of parameter values and characteristics of two magnetostrictive materials, Terfenol-D and Galfenol, is given from perspective of their applications in sensing and actuation. In continuation of the previous results obtained at the division of Dynamics at CHALMERS the novel design of Galfenol based vibration energy harvester has been presented. The device uses Galfenol rod diameter 6.35 mm and length 50mm, polycrystalline, production grade, manufactured by FSZM process by ETREMA Product Inc. The test rig with VIBEL machine has been developed and calibrated to be used for experimental study of performance of the Galfenol based sensors and actuators. The actual working frequency range for VIBEL machine has been found to be between 5 and 60 Hz. It was also found that the machine possesses strong internal resonant vibration at about 30 Hz.

It was found that for given frequency of external excitation there exist optimal values of bias and pre-stress which maximize generated voltage and harvested electric power. Under optimized operational conditions and external excitations with frequency 50Hz the designed transducer generates about 10 V and harvests about 0,45 W electric power. Within the running conditions of experiments, the Galfenol rod power density has been estimated to be about 340mW/cm^3.

The obtained results show high practical potential of Galfenol based sensors which can be used for different applications (power harvesting from vibrations, structural health monitoring of engineering systems, others.). It should be noted, however, that for better investigation of fundamental properties of magnetostrictive materials like Galfenol and

Terfenol-D and their potential for sensing and actuation applications, optimisation of both VIBEL machine and transducer design are advisable.

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