Energy Harvesters and their modeling under magnetic excitation

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MOTIVATION AND INTRODUCTION

In recent years, a large increase is observed in the use of low power electronic circuits

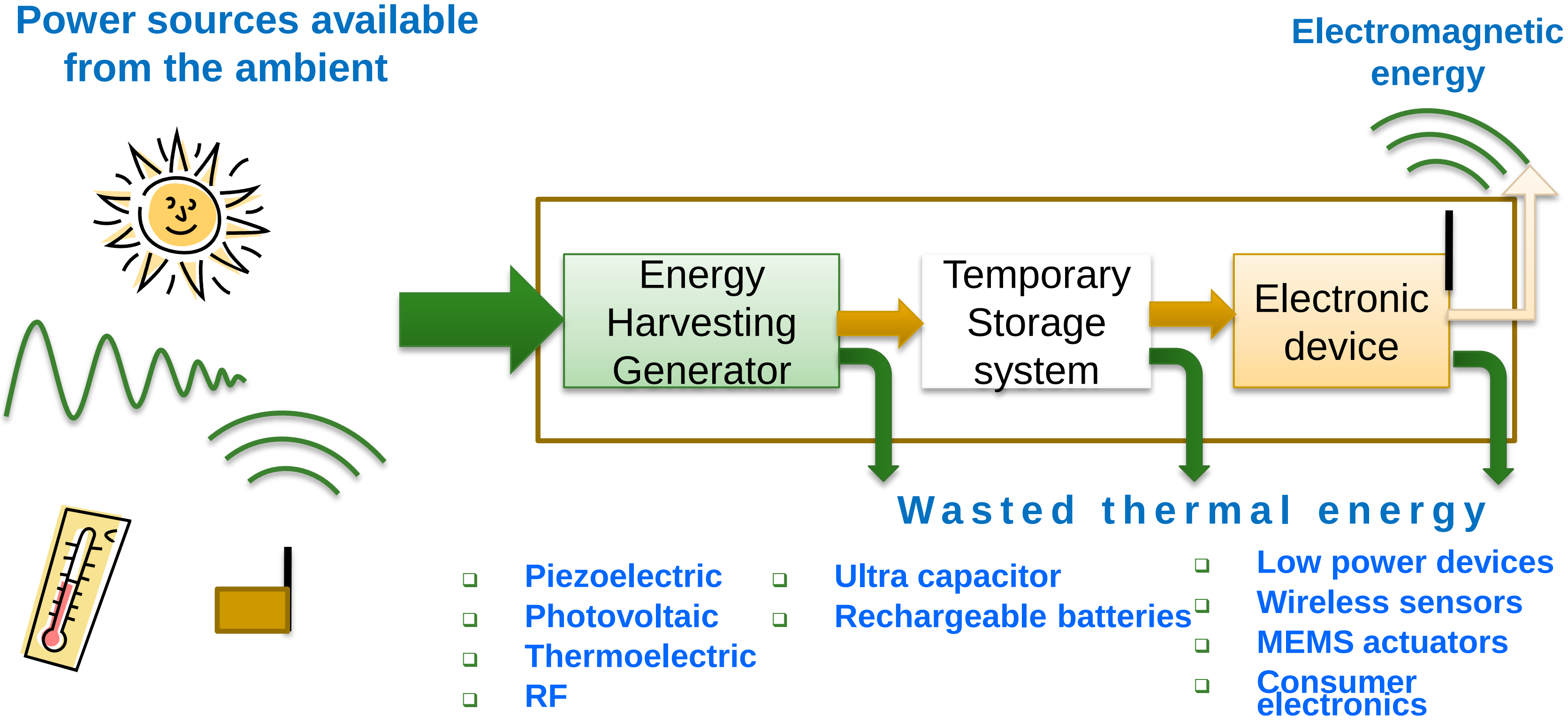
The power requirements of these circuits are provided by chemical batteries generally.

These batteries have some drawbacks such as causing environmental pollution and requiring replacement after a certain period of time because of their limited lifetime.

Energy harvesting systems, which can produce energy at a low level, are used in order to overcome these problems.

These systems can provide a part or all of energy requirement of the electronic devices with low power consumption.

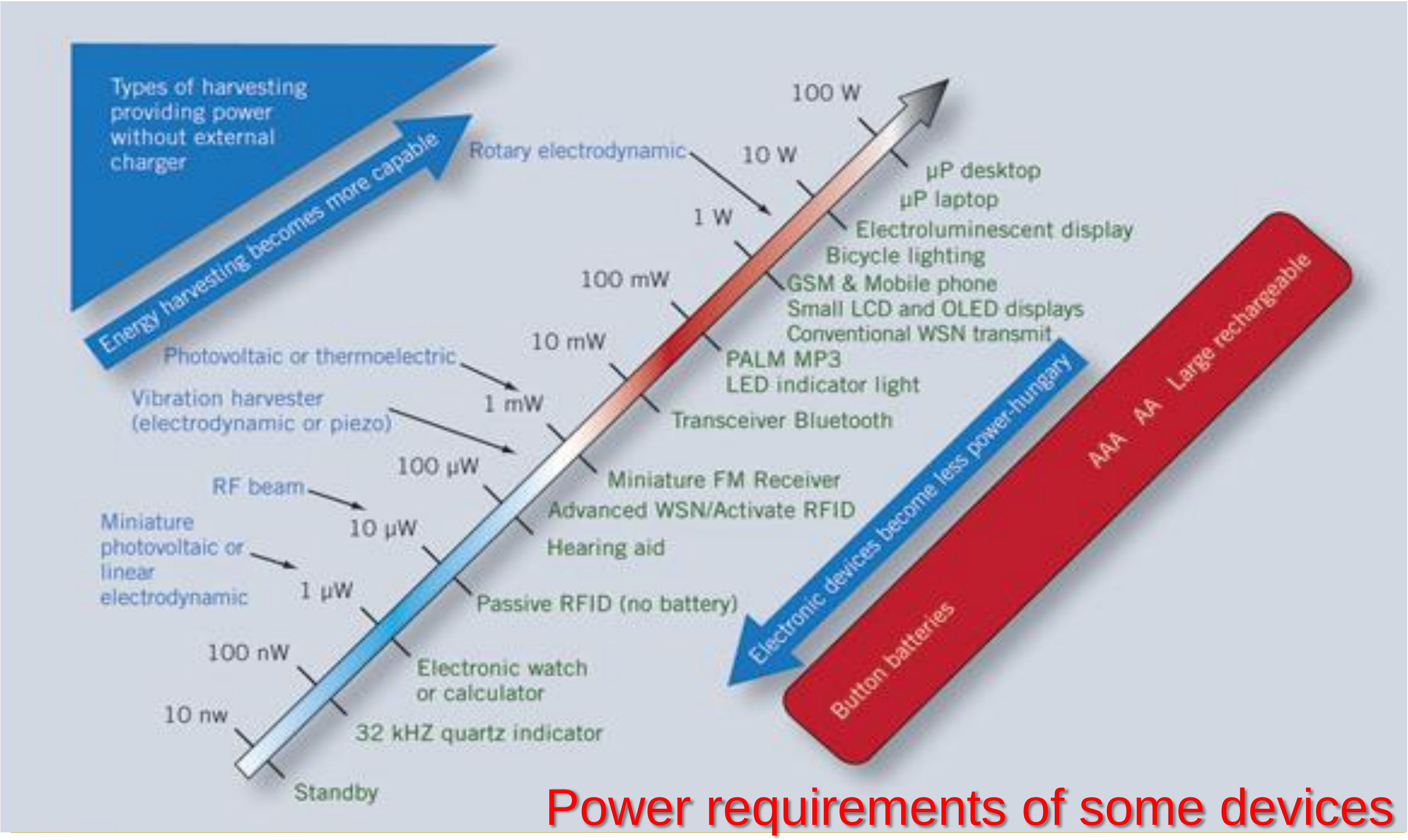
Energy harvesting: An alternative to batteries



- Piezoelectric
- Photovoltaic
- Thermoelectric
- RF

- Ultra capacitor
- Rechargeable batteries

- Low power devices
- Wireless sensors
- MEMS actuators
- Consumer electronics

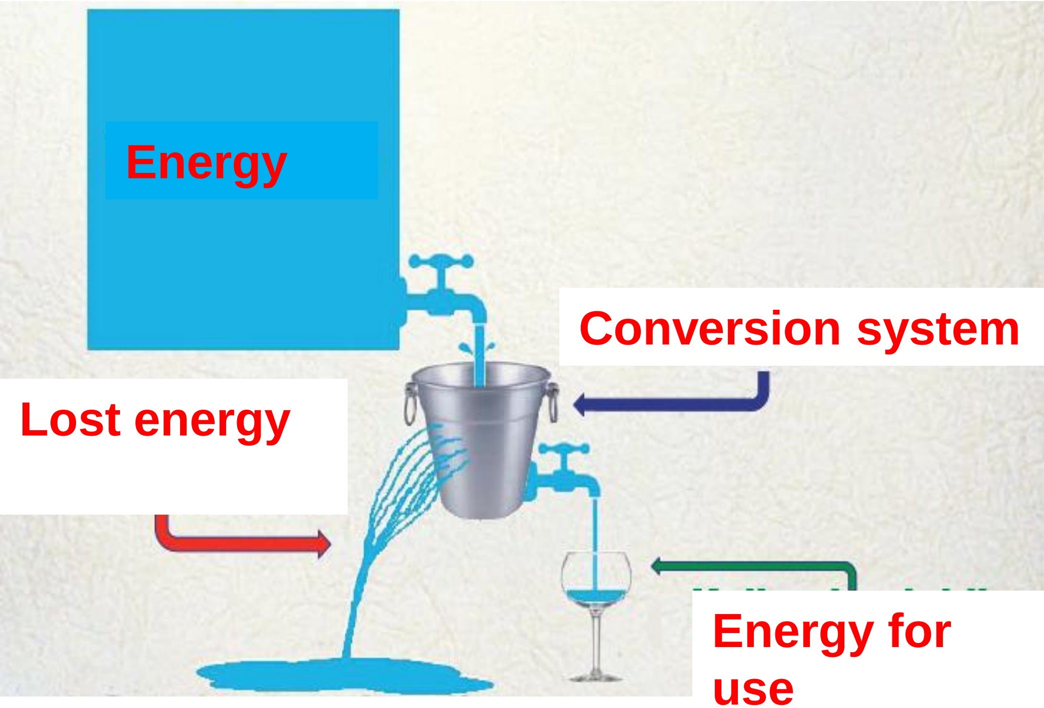


Power requirements of some devices

Power Characteristics of a New Contactless Piezoelectric Harvester - E.Kurt - Y. Uzun, C. Durmus 4th Int. Conf. Electric Power and Energy Conversion Syst. (EPECS 2015), Sharjah, UAE

- **Among the energy harvester systems, the most popular one is the piezoelectric harvesters, since the energy density of the piezoelectric harvester is higher.**
- **In addition, this type of harvester gives a chance to make optimization for a certain excitation frequency range, thereby increases the energy harvesting efficiency.**
- **There exist many vibration sources in the nature: Seismic, tidal, wind flow, thermal, electrical and magnetic effects…**
- **The harvesters can get efficient energy, if the external vibration sources have the vibration frequency equal to the harvester natural frequency.**
- **If the external vibration has another frequency different than f_0, one needs MPPT circuits or additional vibration equipments.**
- **In the nature, nearly all vibrations have broad band frequencies, which include many frequencies. Thus, the construction of an efficient harvester for the broad band excitations is very vital task for the harvester technology.**

Clean and alternative energy



Energy

Conversion system

Lost energy

Energy for use

By using alternative energy, mechanical vibrations in nature and industrial areas can provide small but continuous energy.

Questions

- Can nonlinearity help to enhance the power output of piezo-system?
- What is the nature of nonlinearity for magnetic effects in piezosystems?
- Can one enable to use the energy in ambient media?
- Can magnetic field exert better power in piezosystems?
- What are the parametrical dependencies of piezosystems

Introduction

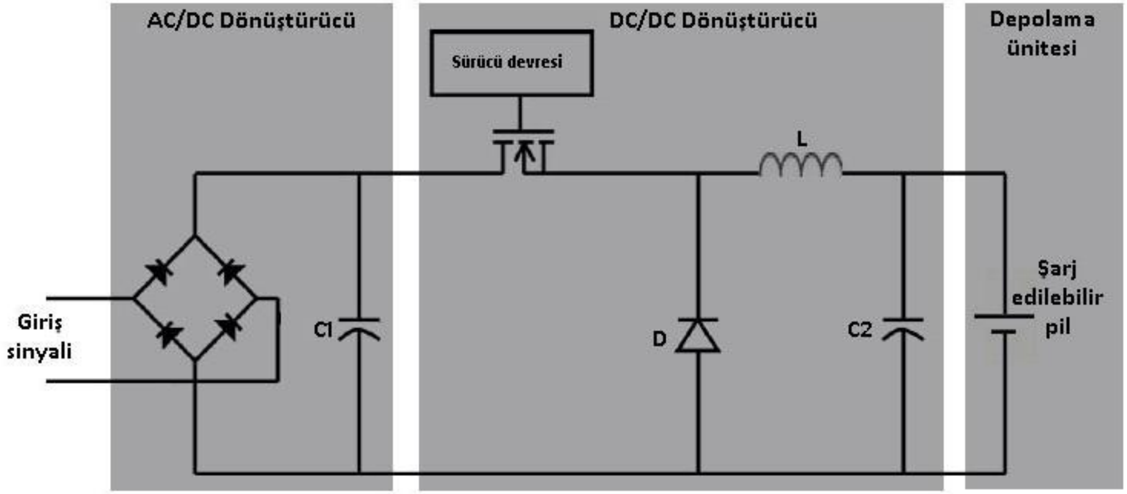
- Presently, energy requirements of large amount of mobil devices are provided by batteries. But the recharging processes, prices and refulfillments in hard nature conditions motivate the researchers to seek other ways.
- Natural or man-made vibrations, thermal exertation, light energy can be counted among the alternative resources.
- Energy needs of mobil devices show varieties depending on the operation type and duration. For instance, power requirement of a watch is about 5 μW.

Device Name	Power spended
Mobil phone	1W
MP3 player	50mW
Hearing device	1mW
Wireless sensor node	100uW
Heart Batery	50uW
Quarz watch	5uW

Vibration Source	Acceleration (m/s^2)	Frequency (Hz)	Vibration Source	Acceleration (m/s^2)	Frequency (Hz)
Auto engine	12	200	Refrigerator	0.1	240
Blender	6.4	121	Washing Machine	0.5	109
Clima	0.2-1.5	60			
Window near traffic	0.7	100			
Laptop (when CD inserted)	0.6	75			
Ofis ground	0.2	100			
Bread production machine	1.03	121			

How to do?

- Irregular vibrations: Hard to store them. Rectification needed.
- Maximal operation point estimation for optimal gain. Piezos have strong dependence on the load ressitance such as 1 MΩ. Empedance is vital.
- DC-DC convertor is needed for empedance balance.



Storage and rectifier for generated energy

Literature

- Piezoelastic (PZT) layers take much attention recently for their applications in engineering systems. Among them, the reputable fields can be counted as *energy harvesting* for the renewable energy technologies and *sensor-actuator productions*.
- In 1881; Gabriel Lippman invented inverse-piezoelectric effect. Curies also convince about it.
- In 1910; Woldemar Voigt has published his book "Lerburch der Kristallphysic" about natural piezo-crystals about 20.
- First application of piezos is ultrasonic deep-sea detector.
- A piezoelastic inverted pendulum including four permanent magnets in a homogeneously exerted magnetic field is introduced to the literature by Cottone et al.

- Jung et al have developed an energy harvesting system using the wind vibration for wireless sensor node.
- Ferrari et al [3] improved energy harvesting from wide-band vibrations by nonlinear piezoelectric converters applying permanent magnets.
- In 1935; Busch ve Scherrer has invented piezo-effect in potasyum dihidrogen phosphat.
- In 1940s; baryum titanate (BaTiO3), in 1950 lead metaniobat (PbNb2O6) and lead zirkonat titanat (Pb[Ti,Zr]O3) are invented.
- At the middle 1960s; some Japannesse companies worked for piezo-circuits and their commercial applications.

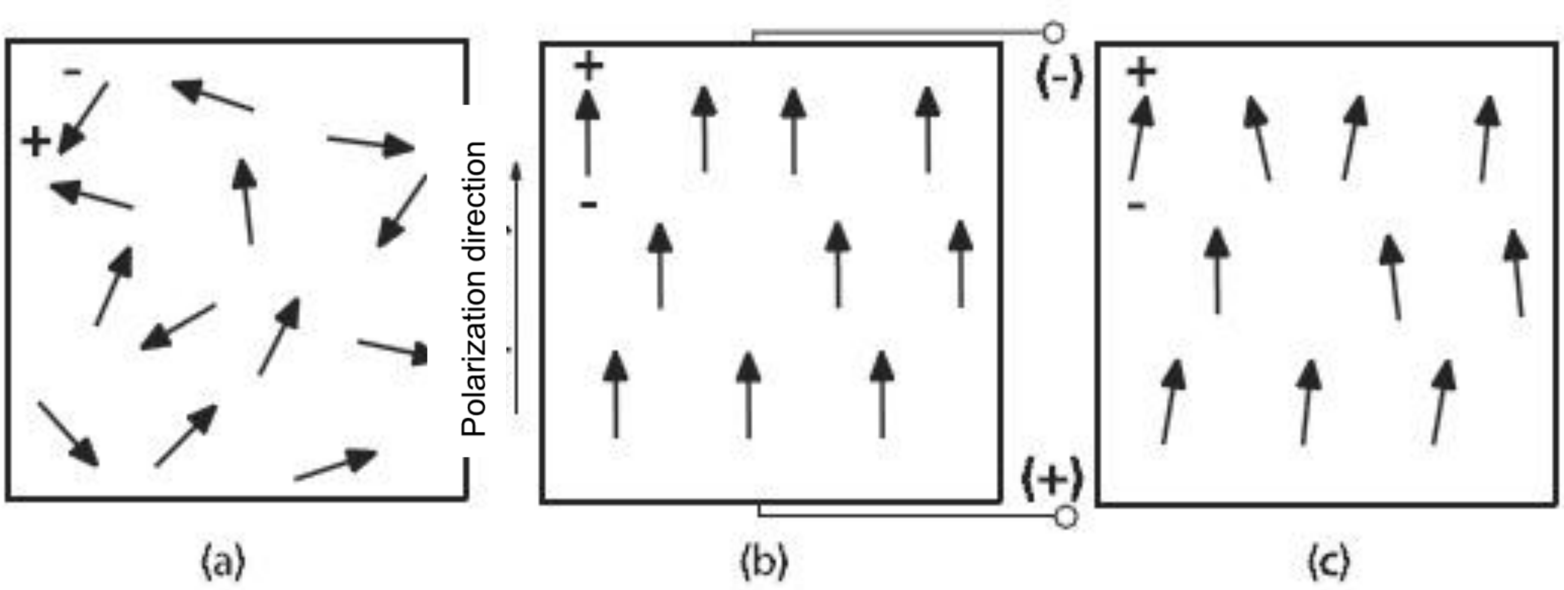
Features of Piezoelectric Materials

- If certain crystals were subjected to *mechanical strain*, they became electrically polarized and the degree of polarization was proportional to the applied strain.
- The Curies also discovered that these same materials deformed when they were exposed to an electric field. This has become known as the inverse piezoelectric effect.
- Piezoelectrics lose their features when the temperature of specimen exceeds the Curie's temperature.

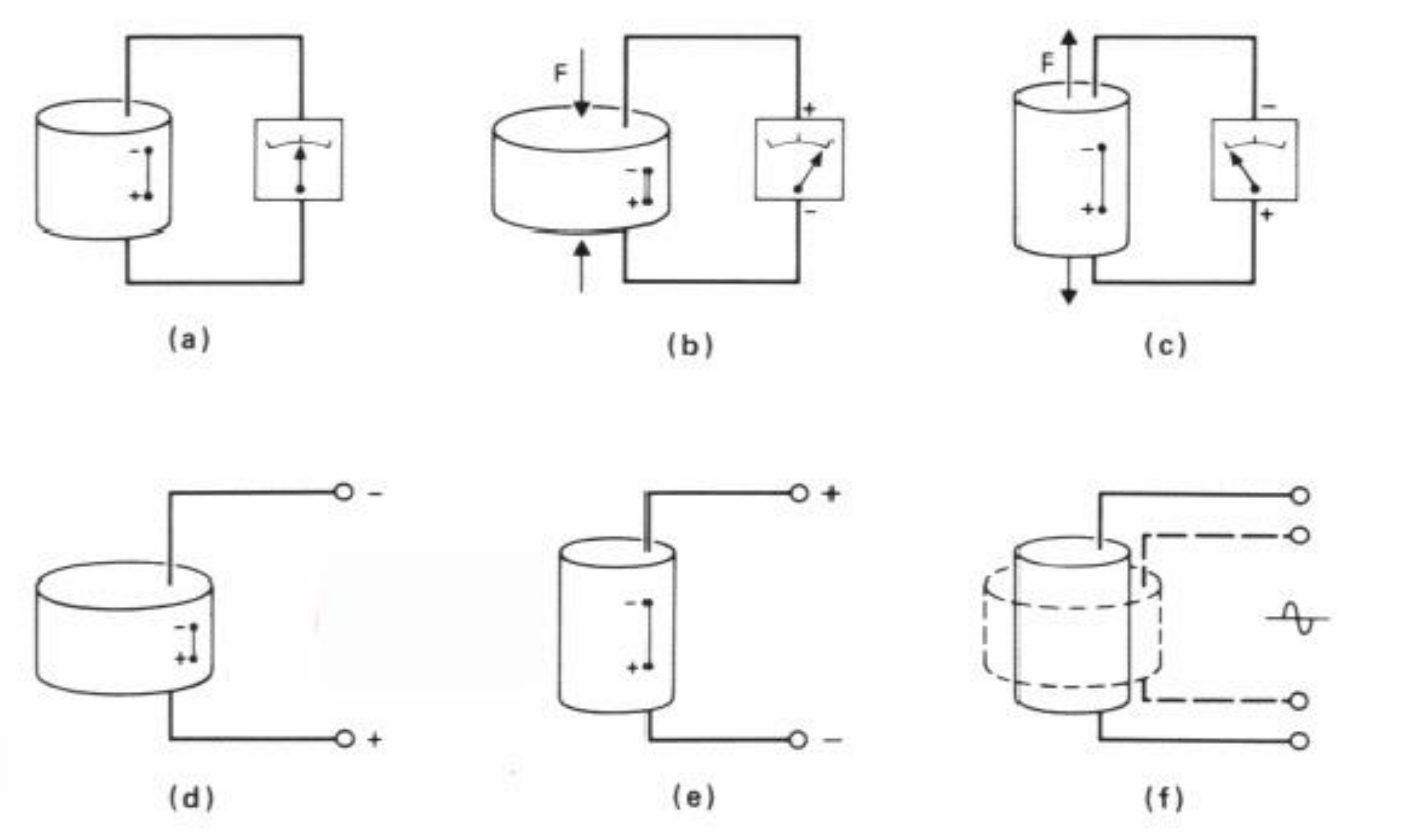
Polarizing Operation

- Randomly distributed domains exist in specimens. It means no polarization. Domains are directed when applying a DC field to the crystal under a certain temperature below the Curie's temperature.
- After the polarization, nearly all domains are directed towards the field and the lenght is increased along the field. Whem the dc-effect is cut off, some domains change its direction.

Polarization Operation

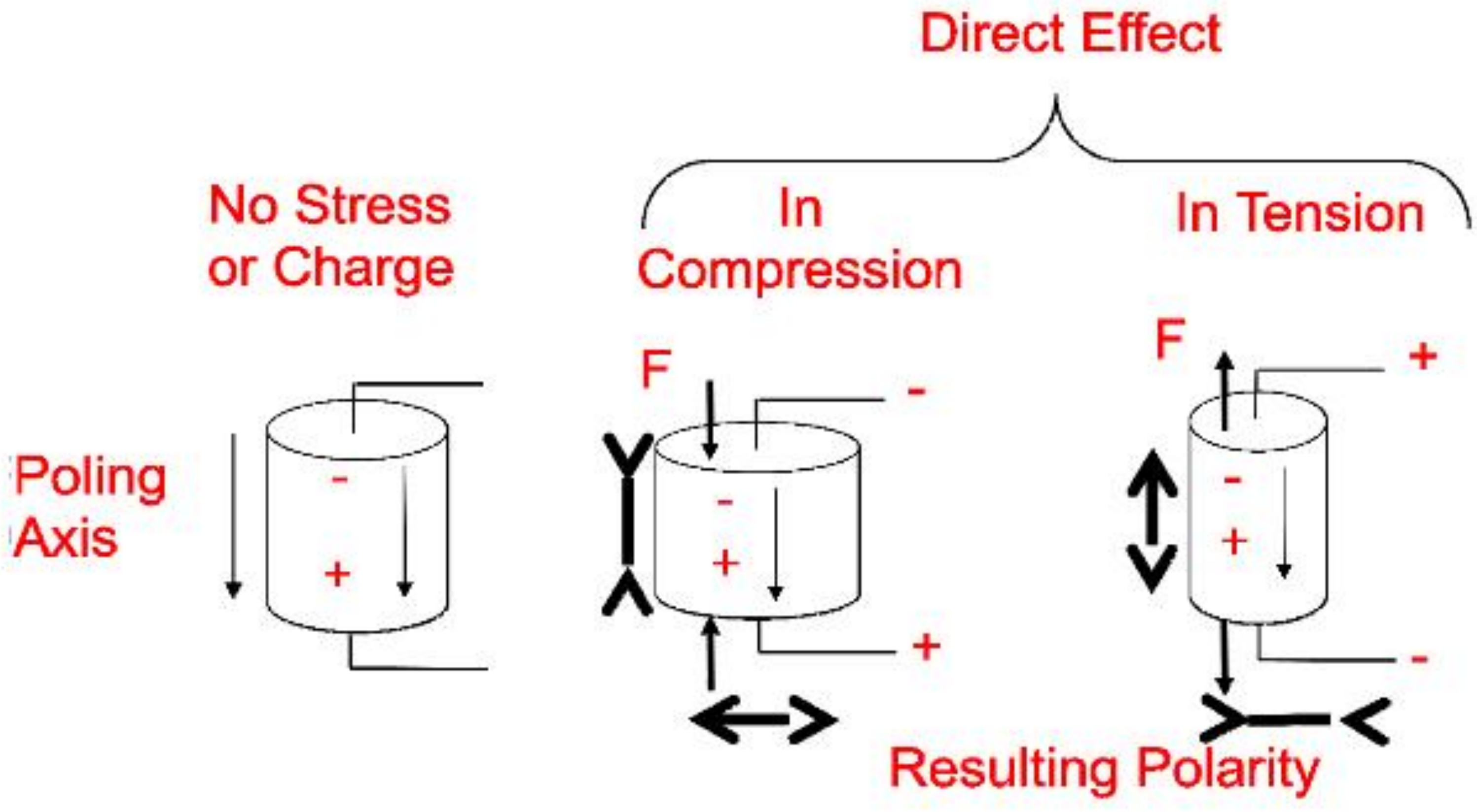


Piezoelectric and inverse-piezoelectric effect



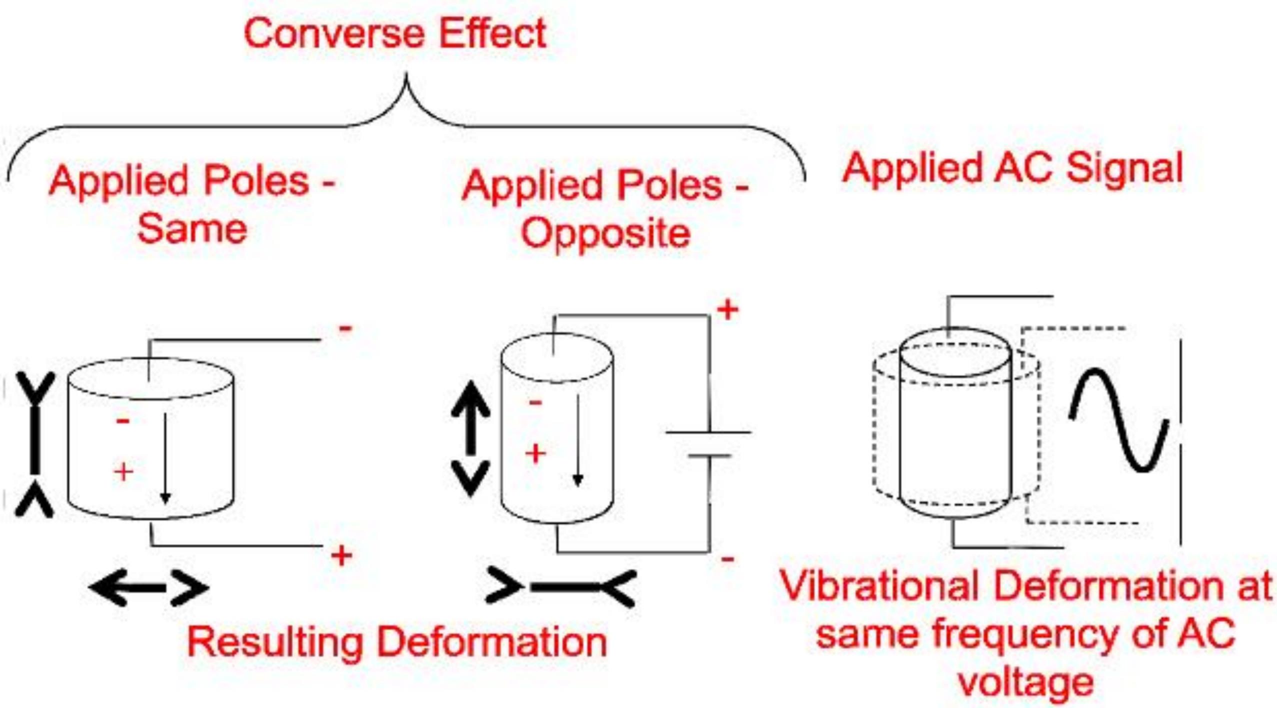
Direct piezoelectric effect

- Deformation of the piezoelectric material causes an electrical charge on certain opposite faces of the piezoelectric material.

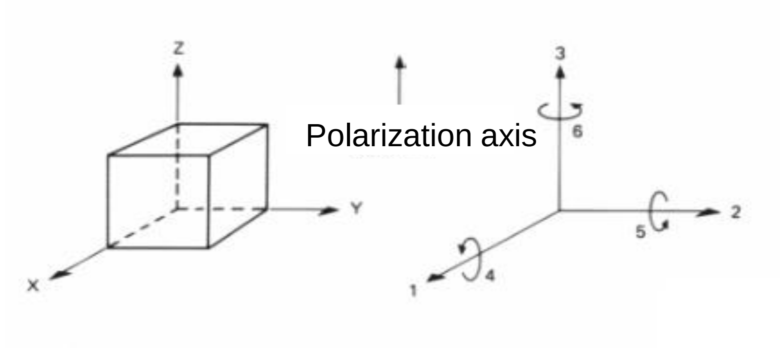


Converse piezoelectric effect

Application of an electric field (potential difference) across certain opposite faces of the piezoelectric material causes the material to be deformed.



Piezoelectric constants



Voltage constant: It identifies the electric field or voltage upon the material when a mechanical stress is applied.

g_{33} In 3-direction when a stress is applied; in 3-direction an electric field obtained. In 3-direction unit electric voltage is applied and in 3-direction a mechanical stress occurs. In our case g_{33}= $24,0x10^{-3}Vm/N$

g_{31} When the stress in 1-direction is applied the voltage in 3-direction occurs. Or vice versa. In our case; g31= $-11,6x10^{-3}Vm/N$

Elektromechanic coupling factor

Elektromechanic coupling factor k, indicates the conversion ability of the stress to voltage. In our case;

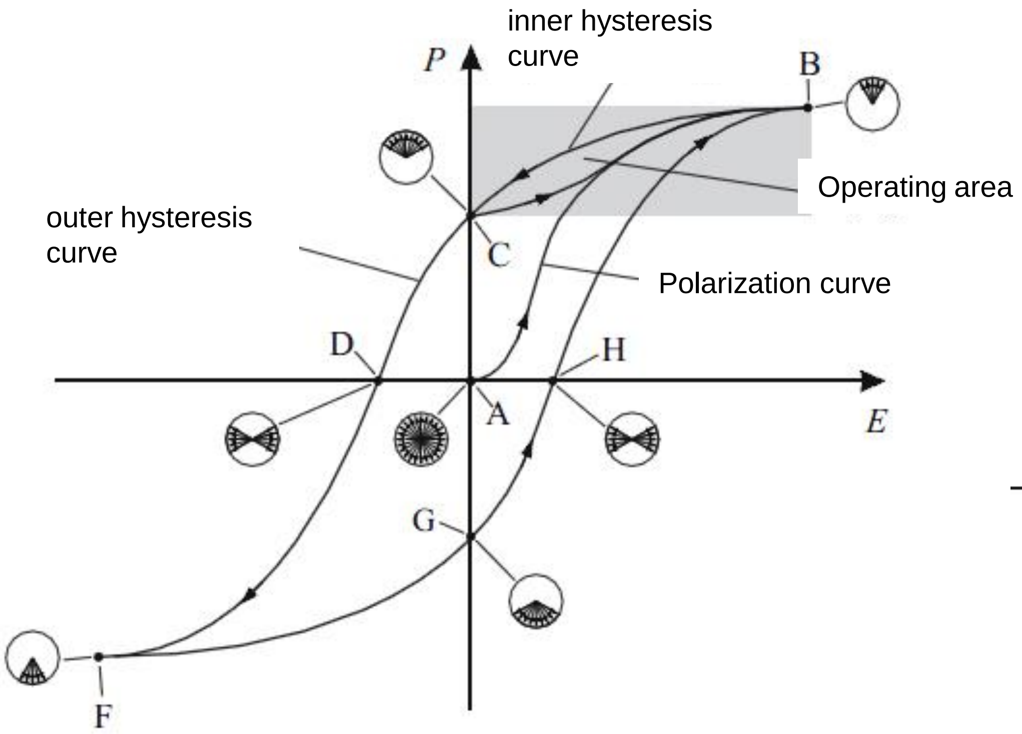
$$k_{33} = 0,72 \ ve \ k_{31} = 0,35$$

Elasticity (Young) module

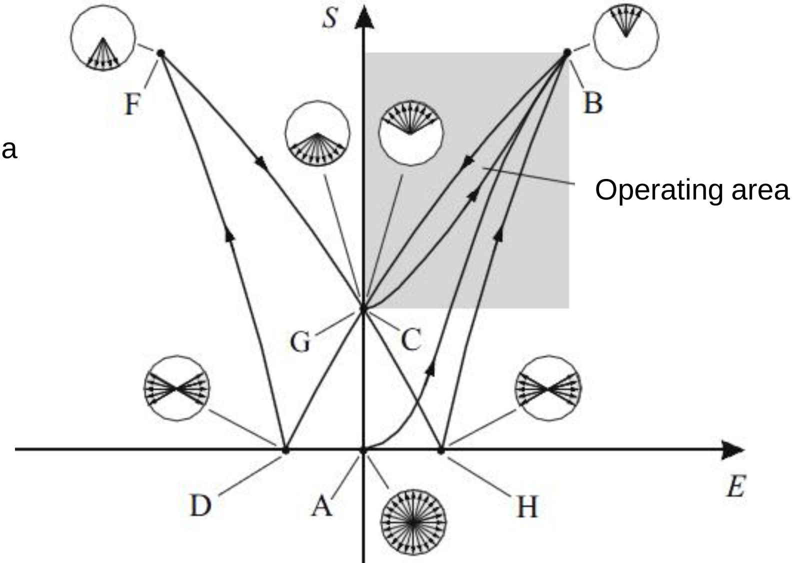
Young module identifies the hardness order of the material. It is found by the ratio of pressure and stress for a certain direction. In our case $Y_{33}^{E} = 5,2x10^{10} \ ve \ Y_{11}^{E} = 6,6x10^{10}$

Electromechanic behavior of piezoelectrics

Piezos behavior shows similarity with the ferromagnetic materials.



Polarization curve as function of electric field



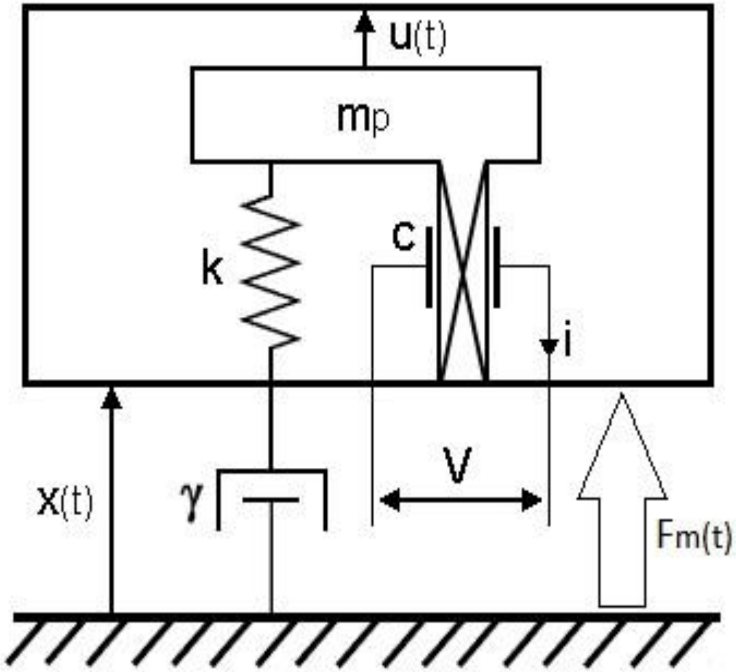
Alongation of lenght of material as function of field

Modeling of the system

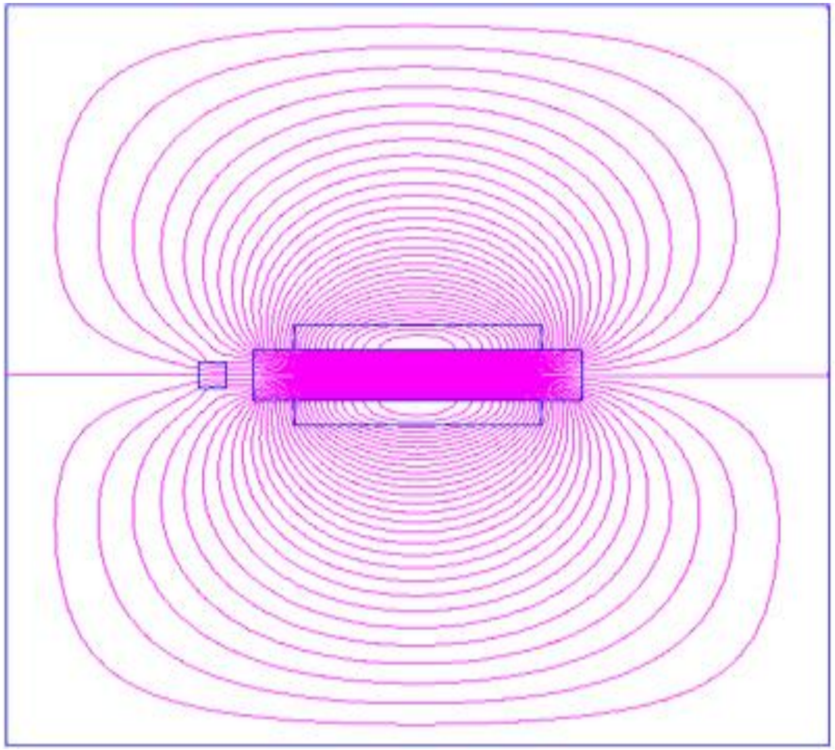
The model includes these aspects:

- *a mass-spring*,
- *a damper*,
- *a capacitor*.

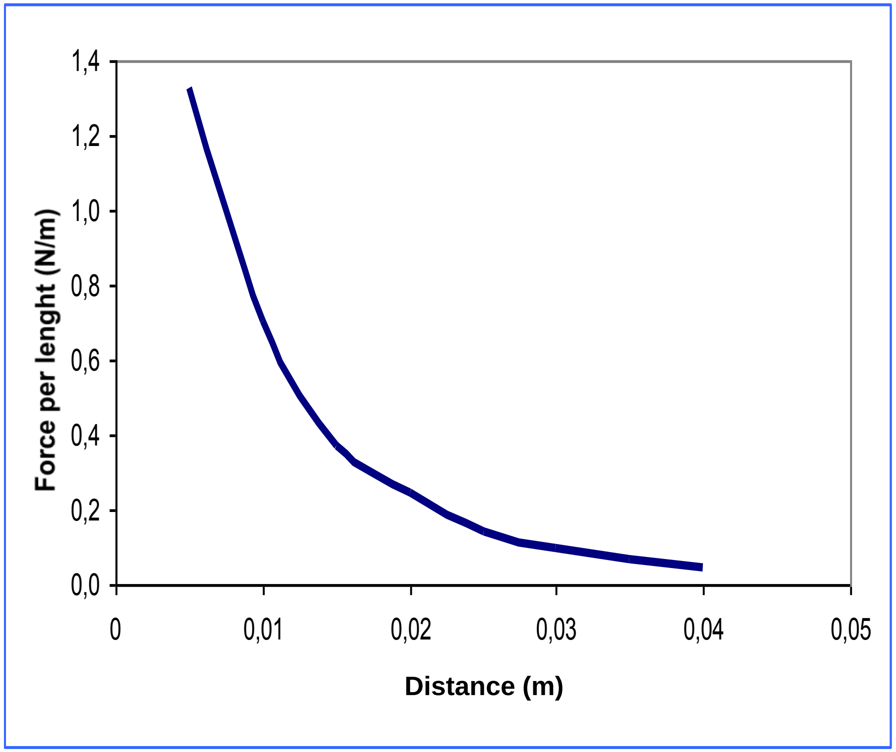
Here the rigid mass m_p and the stiffness constant k determine the mechanical structure under a damper γ which gives the mechanical losses in the overall system.



Design of electromagnet



Superfish programme simulation result



Force deviation as function of distance to elecrromagnet

Modeling of the system…

$$F_{total} = ku + \alpha V + F_m,$$

$$i = \alpha \frac{du}{dt} - C\frac{dV}{dt}.$$

$$(m + m_p)\frac{d^2x'}{dt'^2} = -\gamma \frac{du'}{dt'} - m_p \frac{d^2u'}{dt'^2} - ku' - \alpha V - F_m(t),$$

$$\frac{d^2x'}{dt'^2} = -\frac{\gamma}{(m+m_p)}\frac{du'}{dt'} - \frac{m_p}{(m+m_p)}\frac{d^2u'}{dt'^2} - \frac{k}{(m+m_p)}u' - \frac{\alpha}{(m+m_p)}V - \frac{1}{(m+m_p)}F_m(t),$$

$$\frac{dV'}{dt'} = \frac{\alpha}{C}\frac{du'}{dt'} - \frac{i}{C},$$

$$\frac{d^2u'}{dt'^2} = -\frac{\gamma}{3m+4m_p}\frac{du'}{dt'} - \frac{k}{3m+4m_p}u' - \frac{\alpha}{3m+4m_p}V - \frac{1}{3m+4m_p}F_m(t),$$

$$\frac{dV'}{dt'} = \frac{\alpha}{C}\frac{du'}{dt'} - \frac{i}{C},$$

Identification of system parameters

All forces upon the pendulum type piezosystem as follows:

$$m\frac{d^2x}{dt^2}=-b\frac{dx}{dt}-kx-f(x) \qquad f(x)=\begin{cases} 0 & \text{No Magnetic field} \\ -10^{-6}x^3+28028x^2+0{,}0623x+0{,}7056 & \text{Magnetic field} \end{cases}$$

Here m mass in kg, b is damping coefficient in kg/s, k is force coefficient (N/m), x distance in m. $f(x)$ is nonlinear magnetic force. When all terms are divided into m;

$$\frac{d^2x}{dt^2}=\frac{b}{m}\frac{dx}{dt}-\frac{k}{m}x-\frac{f(x)}{m}$$

Damping ratio ⟹ $\gamma=\frac{b}{m}$ and $\omega_0^2=\frac{k}{m}$ is written.

Natural frequency of piezo-layer

Equation is defined as follows:

$$\frac{d^2x}{dt^2} = -\gamma \frac{dx}{dt} - \omega_0^2 x - \frac{f(x)}{m}$$

In place of velocity $y = \frac{dx}{dt}$ is taken.

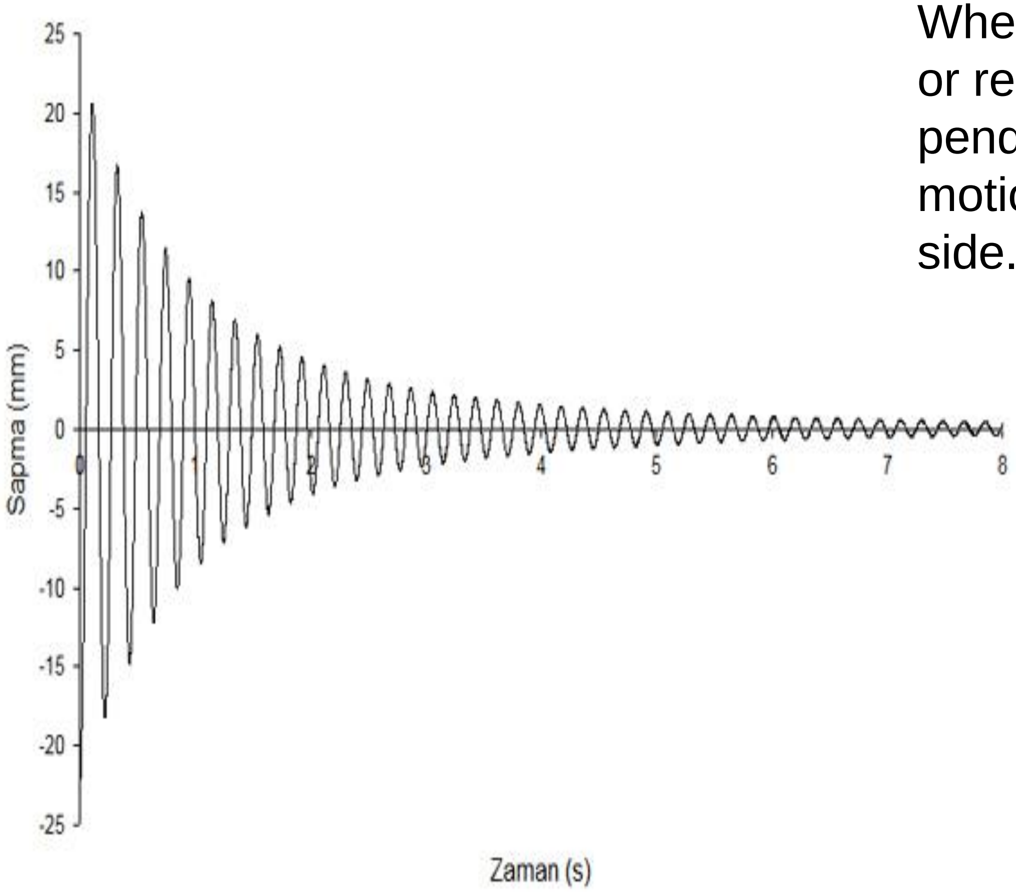
$$\ddot{x} = \dot{y} = -\gamma y - \omega_0^2 x - \frac{f(x)}{m}$$

Frequency is found as;

$$\omega = \sqrt{\omega_0^2 - \left(\frac{\gamma}{2}\right)^2} \quad , \quad f = \frac{1}{2\pi}\sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}$$

↓

Frequency for a damped motion



Distance variation as function of time

When there exist no applied force or restoring force upon the piezo-pendulum, a damped harmonic motion occurs as at the left hand side.

In this case position is given by

$$x = Ae^{-(b/2m)t}\cos(2\pi ft + \theta)$$

Experimental system parameters

From the graph the period has been measured as T= 0.198 s. Tn that case, The natural frequency is calculated as f=1/T= 5.05 Hz.

Elde edilen grafikte periyodun T = 0,198 sn olduğu görülmüştür

Bu durumda sistemin doğal frekansı $f = \frac{1}{T} = 5{,}05\,\mathrm{Hz}$ olacaktır.

Yine yapılan çalışmada grafiğin üstel sınırı şu şekilde bulunmuştur;

$$x = 20e^{-0{,}74t}$$

Hesaplamalar sonucunda $\frac{b}{m} = 1{,}48$ ve $\frac{k}{m} = 1009$ olduğu görülmüştür.

Cismin kütlesi $37{,}4\mathrm{x}10^{-3}$ kg olarak ölçüldü.

Modeling of the system…

$$F_m(t)=\left\{(1\text{-}0.7056/d)+0.0623(1\text{-}3u)+28026d(1-3u)^2-10^6d^2(1-3u)^3\right\}\left\{8\times10^{-8}i_c(t)^2-10^{-9}i_c(t)\right\}$$

$$i_c(t)=\left\{\begin{array}{ll}\dfrac{V_c}{R_c}(1-e^{-R_ct/L}) & 0<t\le\dfrac{T}{2}\\ \dfrac{V_c}{R_c}e^{-R_ct/L} & \dfrac{T}{2}<t\le T\end{array}\right\}$$

$$\frac{du}{dt}=y,$$

$$\frac{dy}{dt}=-\frac{\gamma\tau}{3m+4m_p}y-\frac{k\tau^2}{3m+4m_p}u-\frac{(m+m_p)\tau^2F_m(t)}{(3m+4m_p)d}-V\frac{\alpha\tau^2V_0}{(3m+4m_p)d},$$

$$\frac{dV}{dt}=\frac{\alpha d}{CV_0}\frac{du}{dt}-\frac{\tau V}{V_0CR_L}$$

$$V=\frac{uR_L\alpha j\omega_m\{(m+m_p)\omega_m^2-F_0<I_c^2>+F_1<I_c>\}}{(-\gamma j\omega_m-m_p\omega_m^2-k)(1+R_LCj\omega_m)-\alpha^2R_Lj\omega_m}+h.o.t.,\qquad V=\frac{jR_L\alpha\omega_m u}{1+jCR_L\omega_m},$$

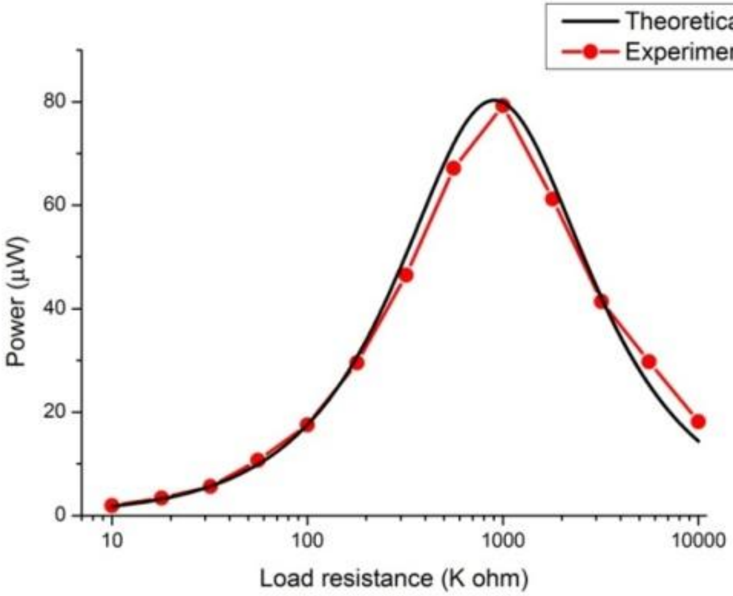
Modeling of the system

$$< I_c >= \frac{V_c}{2R_c} + \frac{V_c L\omega_m}{2\pi R_c^2}\left(2e^{-\frac{R_c\pi}{L\omega_m}} - 1 - e^{-\frac{R_c 2\pi}{L\omega_m}}\right),$$

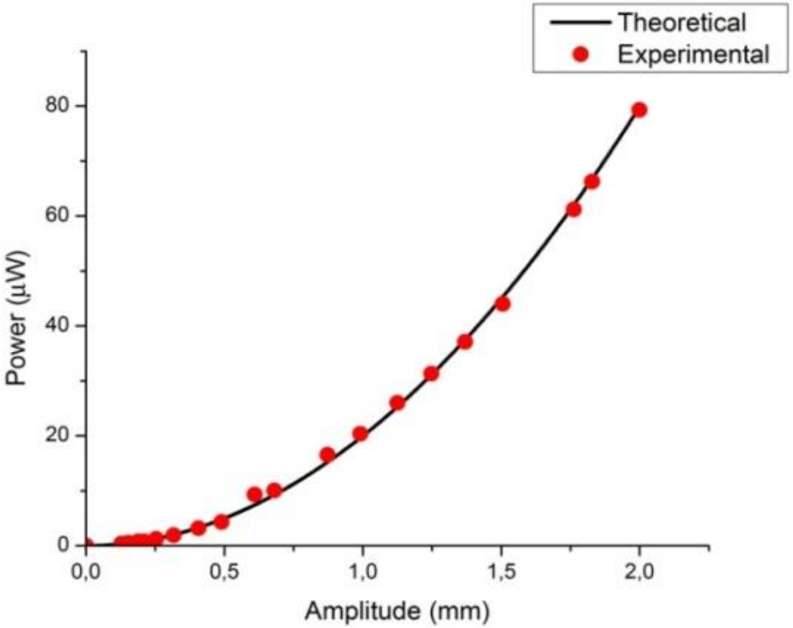
$$< I_c^2 >= \frac{V_c^2}{2R_c^2} + \frac{V_c^2 L\omega_m}{4\pi R_c^3}\left(1 - e^{-\frac{R_c 4\pi}{L\omega_m}}\right) + \frac{L\omega_m}{\pi R_c}\left(e^{-\frac{R_c\pi}{L\omega_m}} - 1\right),$$

$$\boxed{< \mathrm{P} >= \frac{\mathrm{u}^2 \mathrm{R}_\mathrm{L} \alpha^2 \omega_\mathrm{m}^2 \{(\mathrm{m} + \mathrm{m}_\mathrm{p})\omega_\mathrm{m}^2 - \mathrm{F}_0 < \mathrm{I}_\mathrm{c}^2 > + \mathrm{F}_1 < \mathrm{I}_\mathrm{c} >\}^2}{\mathrm{k}^2(1 + \mathrm{C}^2\mathrm{R}_\mathrm{L}^2\omega_\mathrm{m}^2) + 2\mathrm{k}\omega_\mathrm{m}^2(\mathrm{m}_\mathrm{p} + \alpha^2\mathrm{C}\mathrm{R}_\mathrm{L}^2 + \mathrm{C}^2\mathrm{m}_\mathrm{p}\mathrm{R}_\mathrm{L}^2\omega_\mathrm{m}^2) + \omega_\mathrm{m}^2 \mathrm{A}}}$$

$$\mathrm{A} = \{2\alpha^2\gamma\mathrm{R}_\mathrm{L} + \alpha^4\mathrm{R}_\mathrm{L}^2 + 2\alpha^2\mathrm{C}\mathrm{m}_\mathrm{p}\mathrm{R}_\mathrm{L}^2\omega_\mathrm{m}^2 + \gamma^2(1 + \mathrm{C}^2\mathrm{R}_\mathrm{L}^2\omega_\mathrm{m}^2) + \mathrm{m}_\mathrm{p}^2\omega_\mathrm{m}^2(1 + \mathrm{C}^2\mathrm{R}_\mathrm{L}^2\omega_\mathrm{m}^2)\}$$



The experimental and theoretical output powers as functions of load resistance *R*. The distance *d* from the equilibrium point to the tip of electromagnet is 2 cm and the voltage over the electromagnet is 8V.



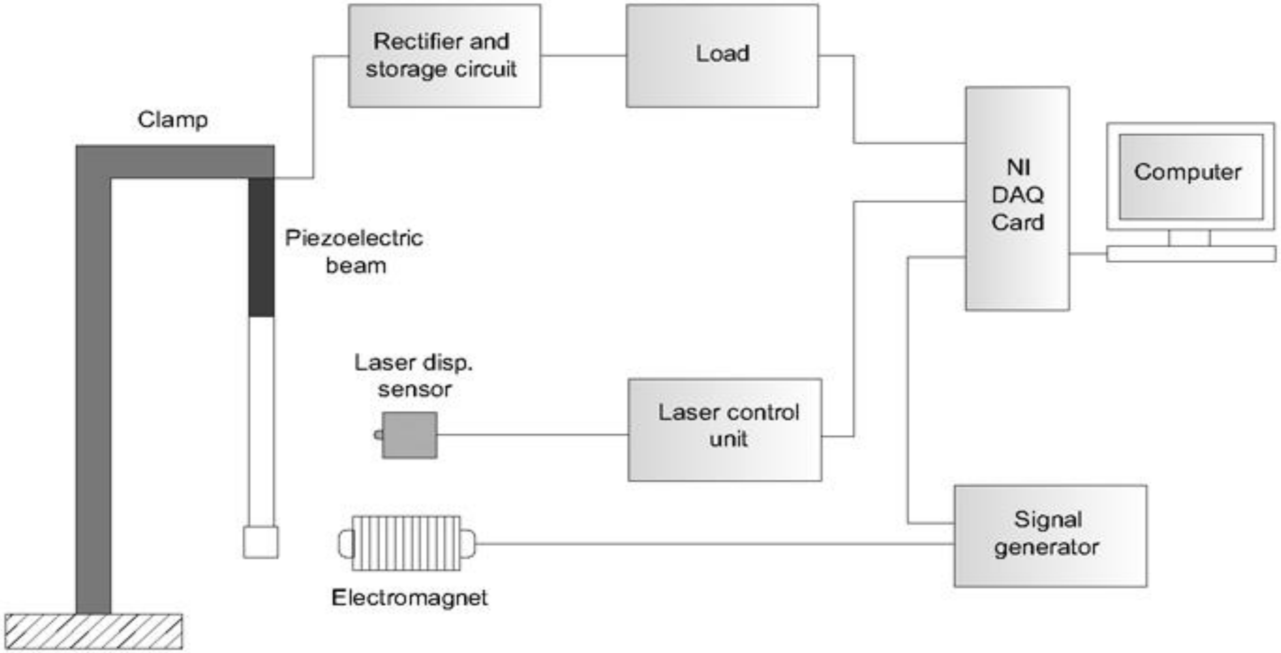
The experimental and theoretical output powers as functions of PZT tip amplitude *u* . The load across the PZT is adjusted as 1 MΩ.

Break


HOLLYWOOD
PRODUCTION
DIRECTOR
CAMERA
DATE
SCENE
TAKE
Popcorn

Experimental

The experimental setup for the exploration of piezoelectic harvester response is sketched following figure.



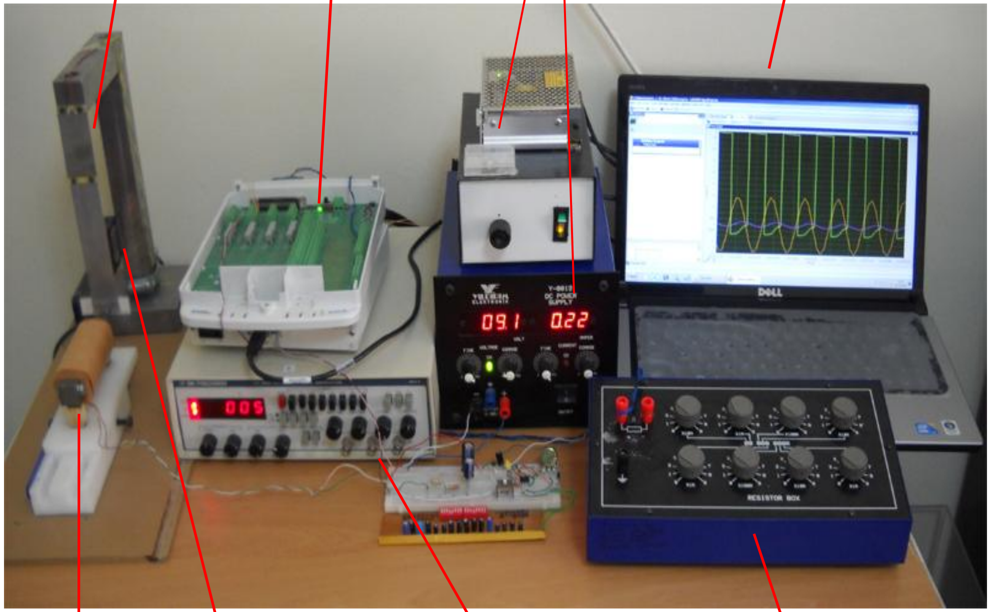
Experimental

electromagnet and LDS feeding sources

piezoelectric layer

laptop

DAQ card

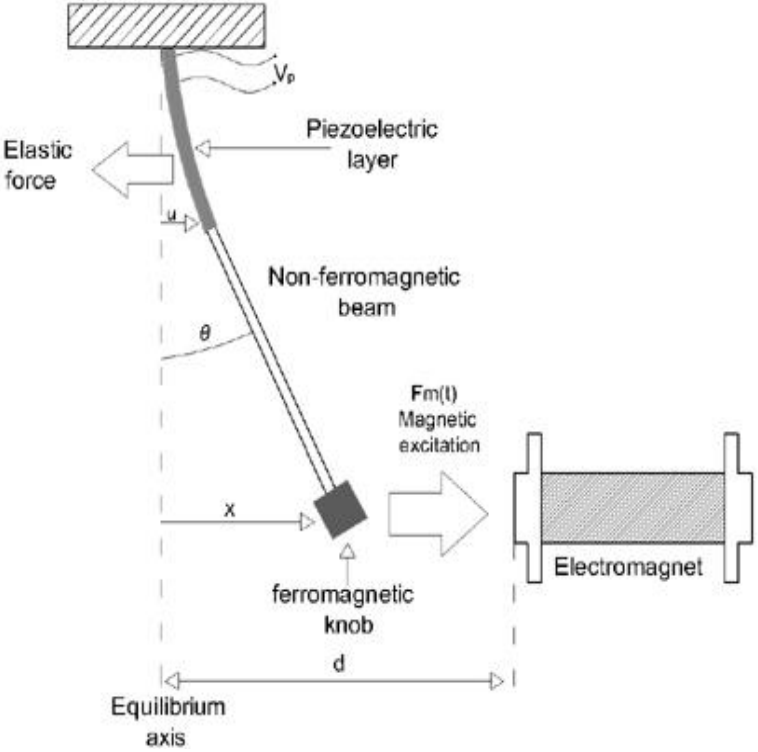


LDS

signal generator

electromagnet

variable resistive load



Experimental materials

Piezoelectric layer

Electromagnet

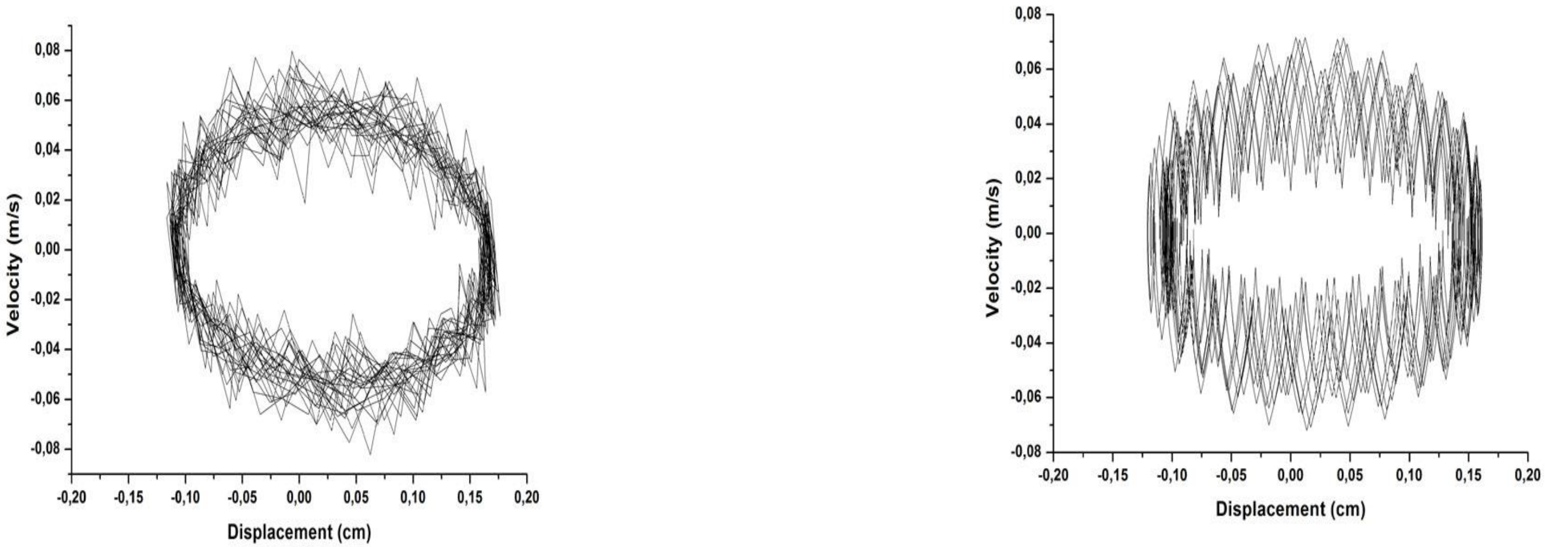
Laser sensor head

Power source

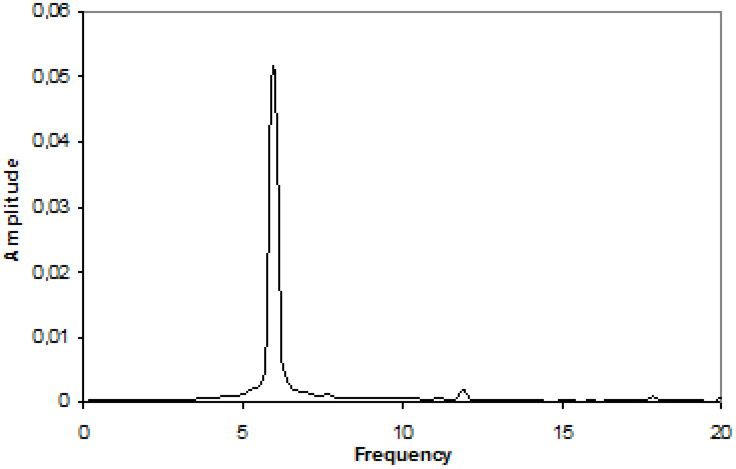
DAQ card

Laser control unit

Experimental Discussion



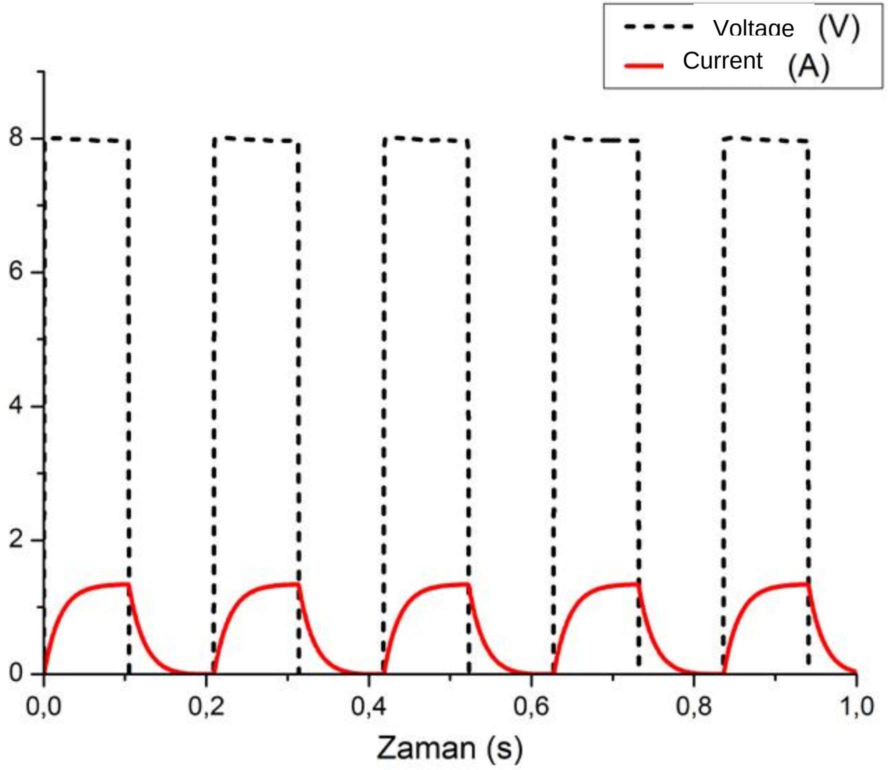
Phase space constructions from the experiment (left) and theory (right).



FFT diagram

Figure was plotted while the excitation frequency f=6.02 Hz, distance between elcectromagnet and pendulum d=2 cm, the voltage which applied to electomagnet V=8 V.

Experimental parameters



When voltage is on current is given by :

$$i(t) = 1,345 - 1,345e^{-47,6t}$$

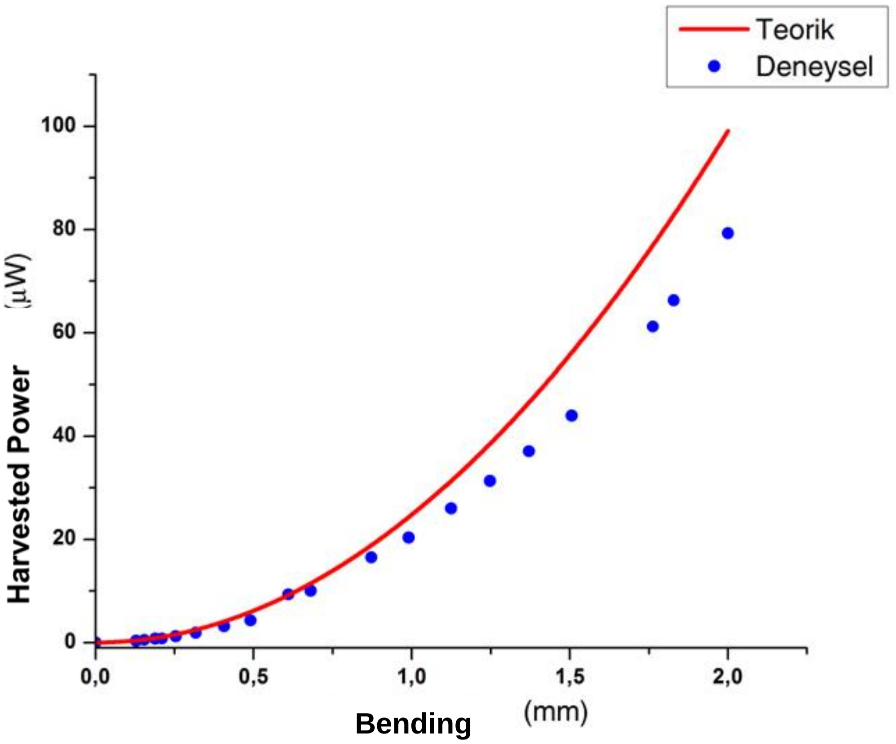
Frequency is about 4,76 Hz. When the voltage applied on electromagnet is off, current is given by

$$i(t) = 1,335e^{-47,6t}$$

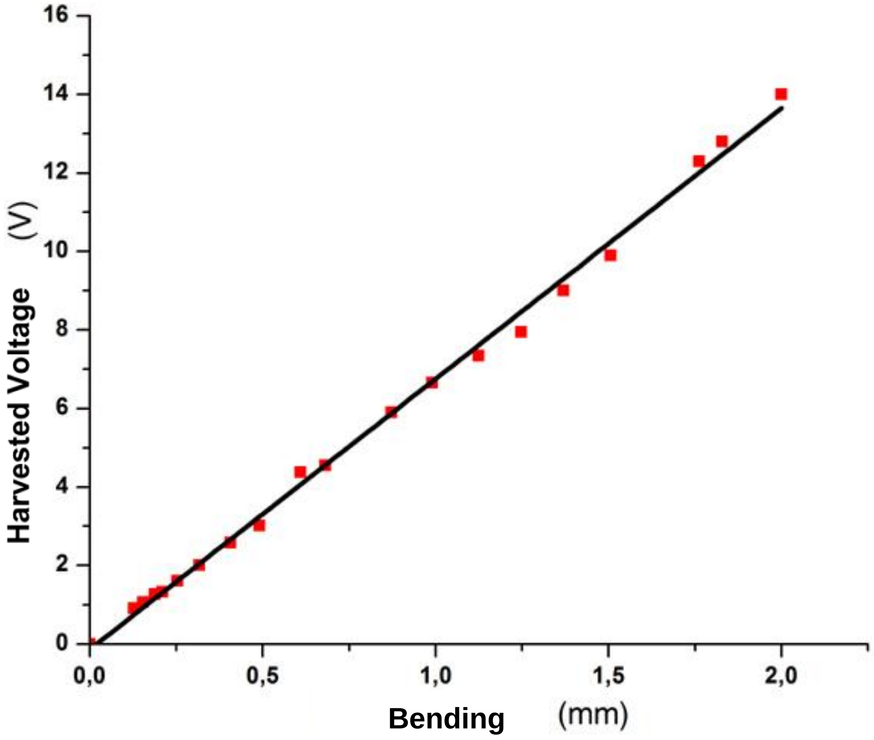
Under 8 volts square voltage is applied, current in red.

Harvested power

There exist a relation between the bending amount and harvested energy. According to experiments, that relation is a parabolic curve.



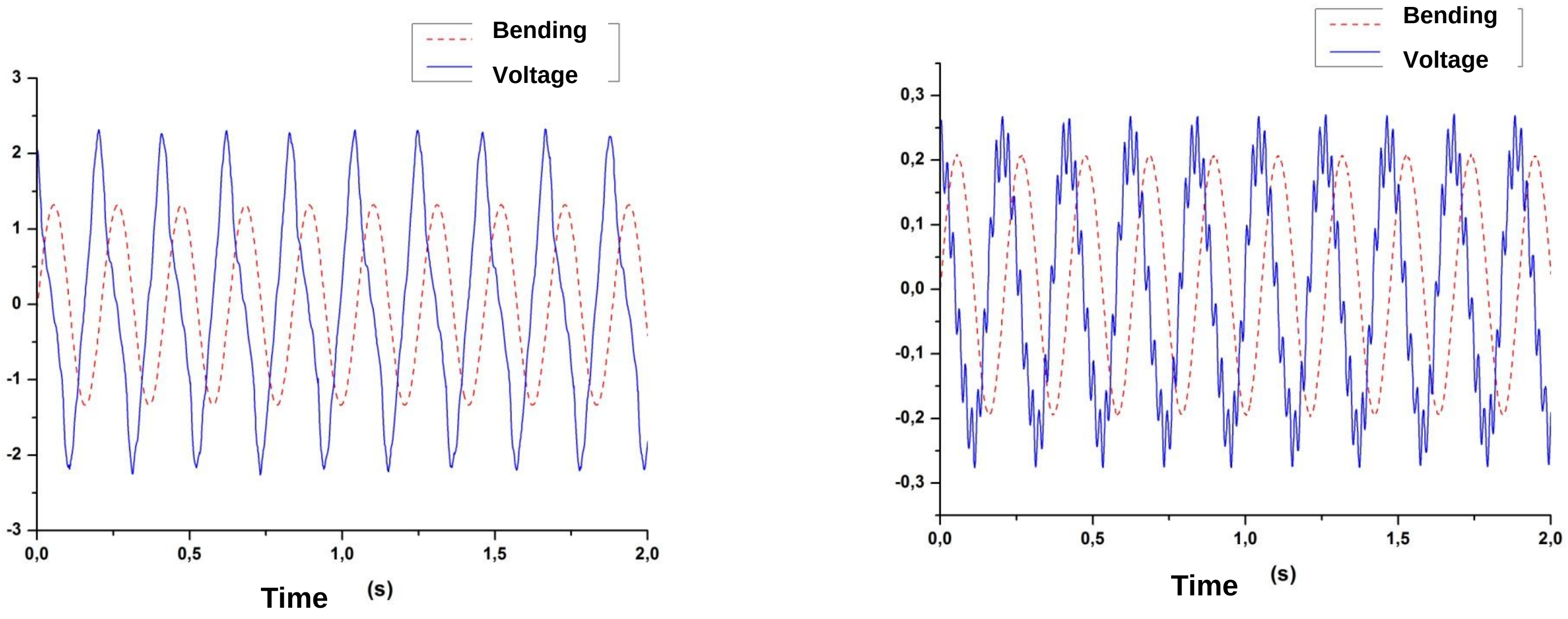
Bending-power relation



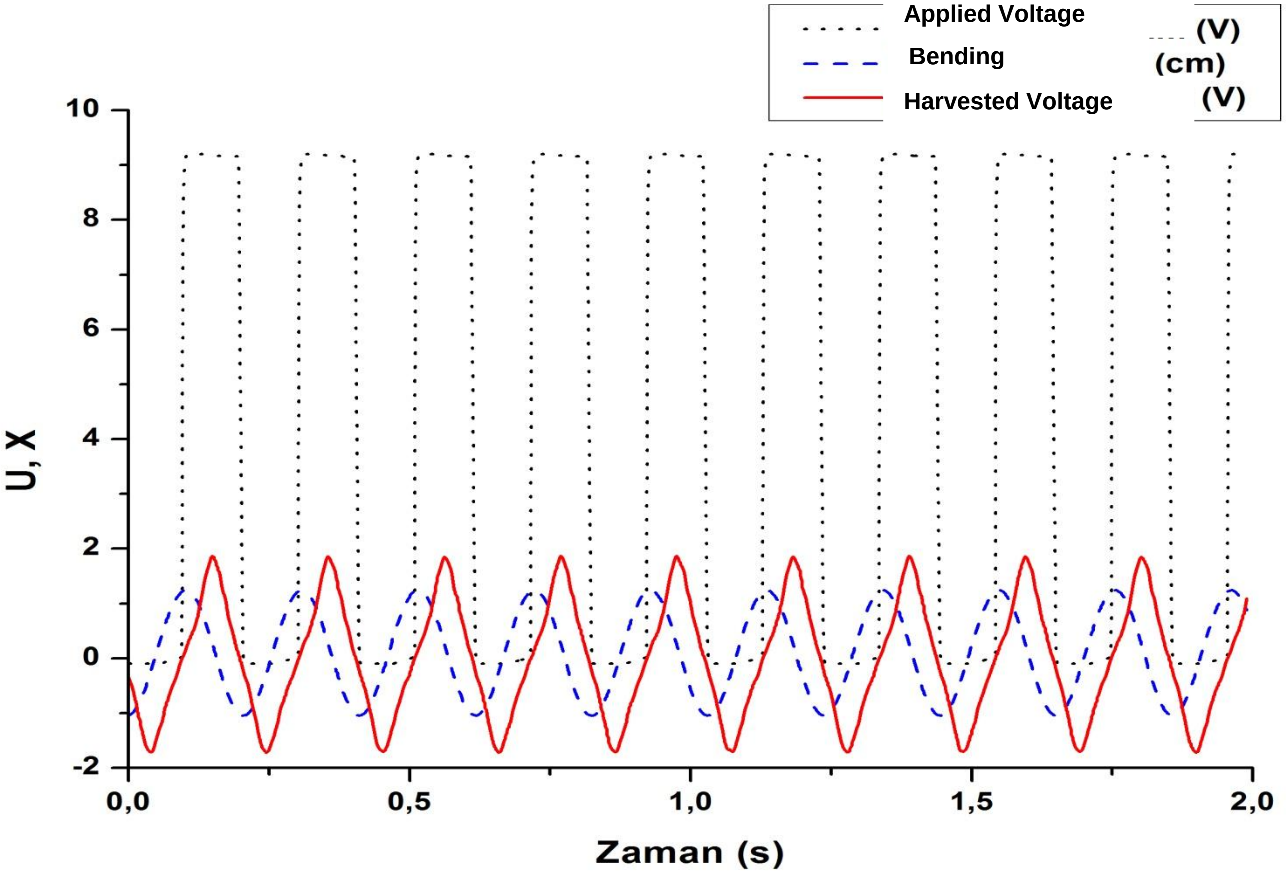
Bending-voltage relation

Experimental results

Bending Amount changes drastically by the distance to the electromagnet. The magnetic force increases rapidly by decreasing distance.



***f*=4,76 Hz, *R*$_L$=100 KΩ , *d*=20 mm (left), *d*=22 mm (right): bending and voltage plots**



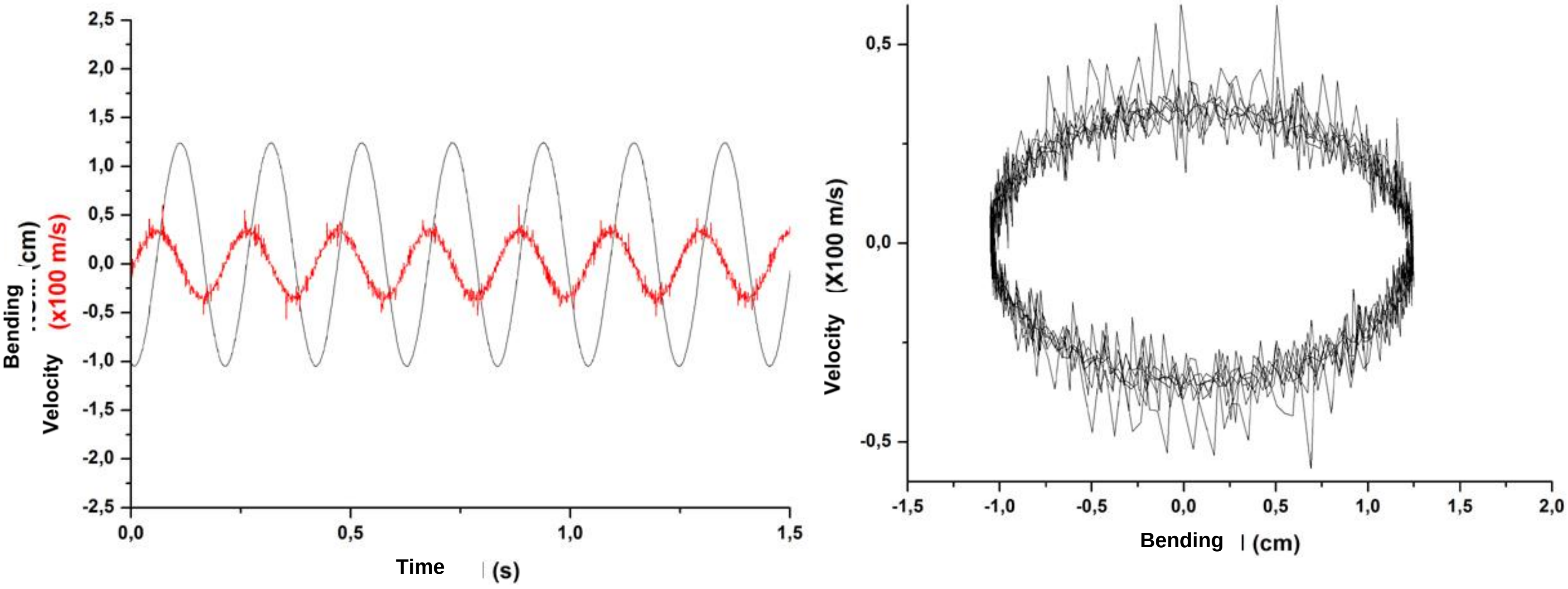
Resistive load is 100KΩ. Distance to beam tip d=2 cm, Applied frequency f=4,83 Hz.

Power Measurements

$$P = U(t)^2 / R_L$$

For every pieozo-layer, there exists an inner resistiveity.
That effects the harvested power with the terminated electrical load R_L.
That is the maximal power extraction from the piezo-layer.

Nonlinear Analysis



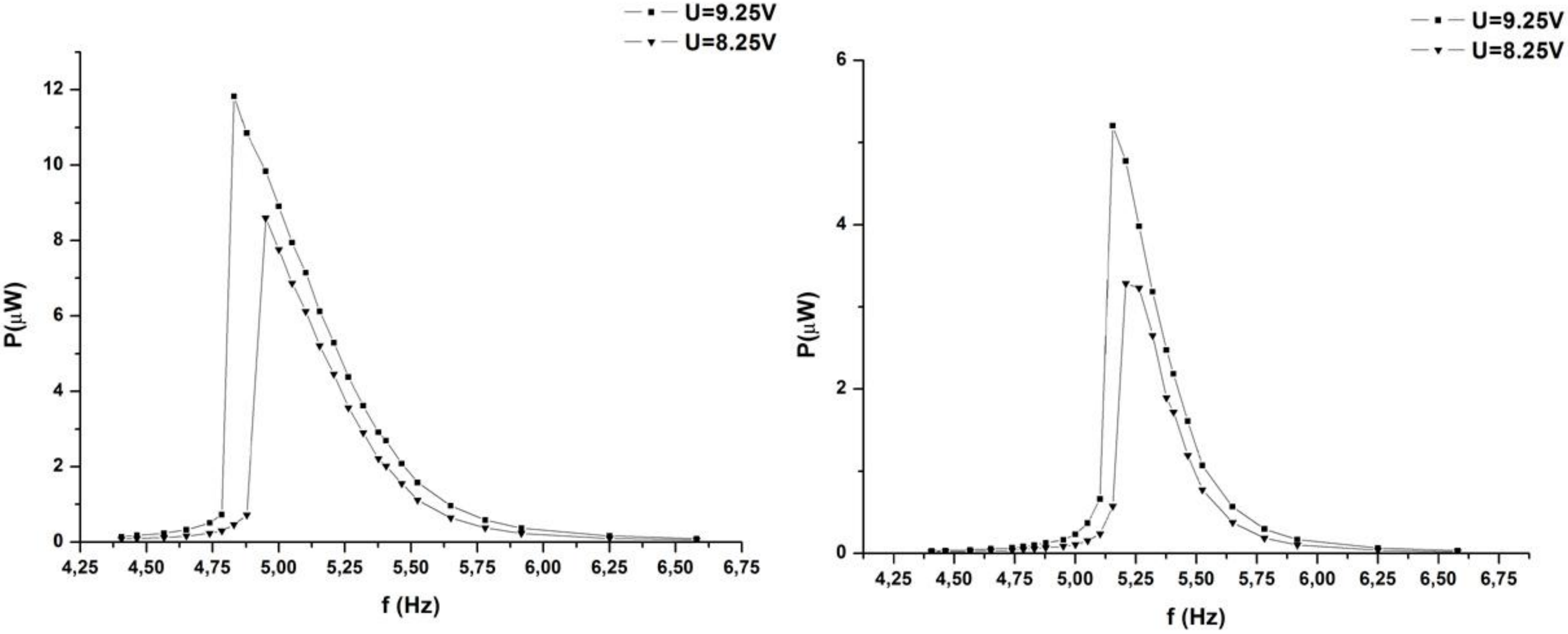
a)

b)

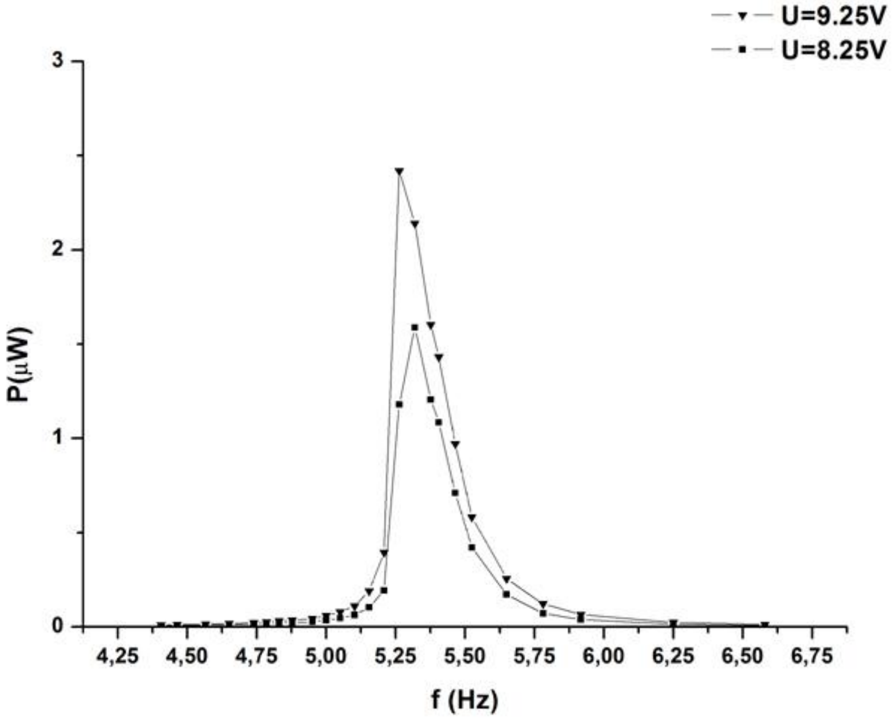
In the case *d=2 cm*, *U_e=9.25 V,*

a) Position and velocity as function of time

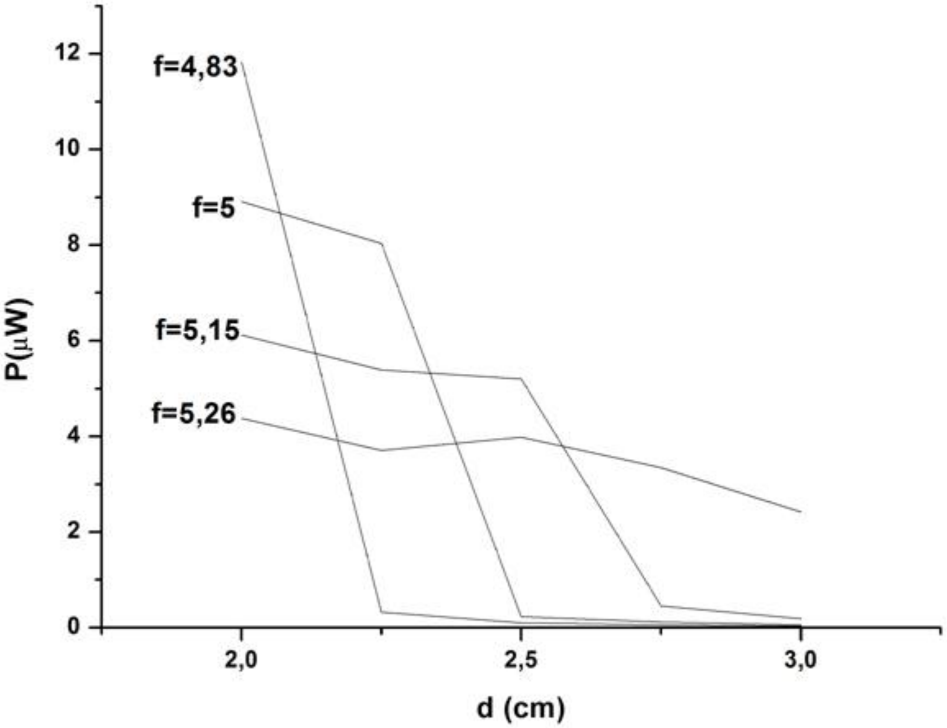
b) Attractor



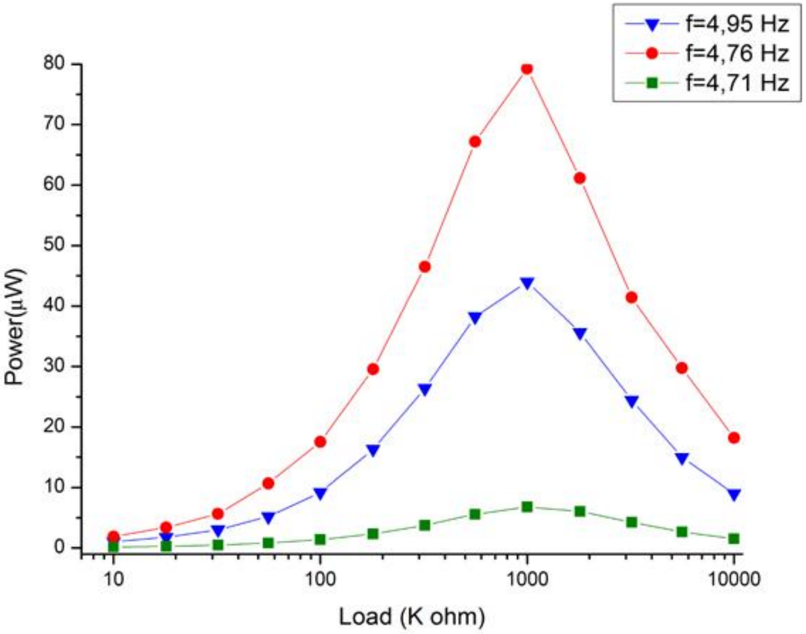
Frequency-power plot for *d=2 cm* and *d=2.5cm*



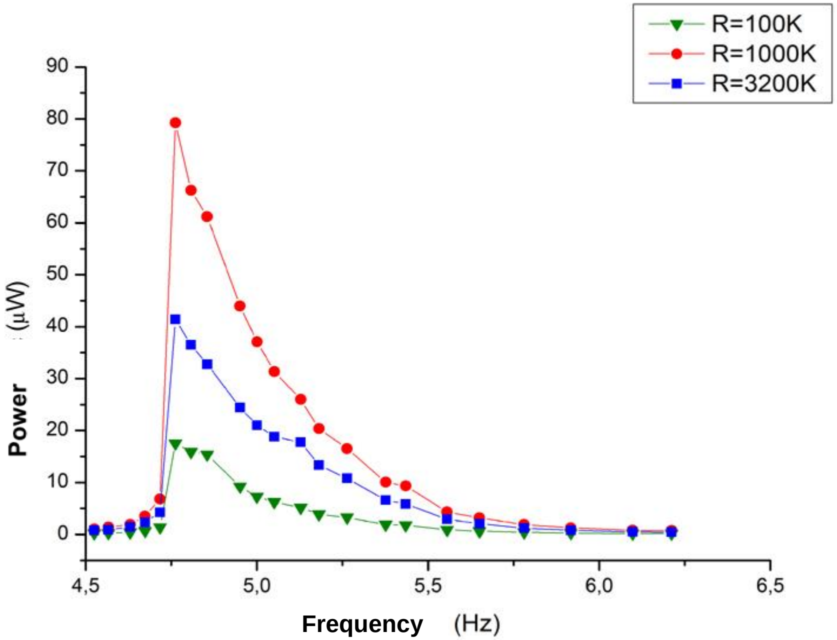
Frequency- power graph at d=3 cm.



Distance to electromagnet and power



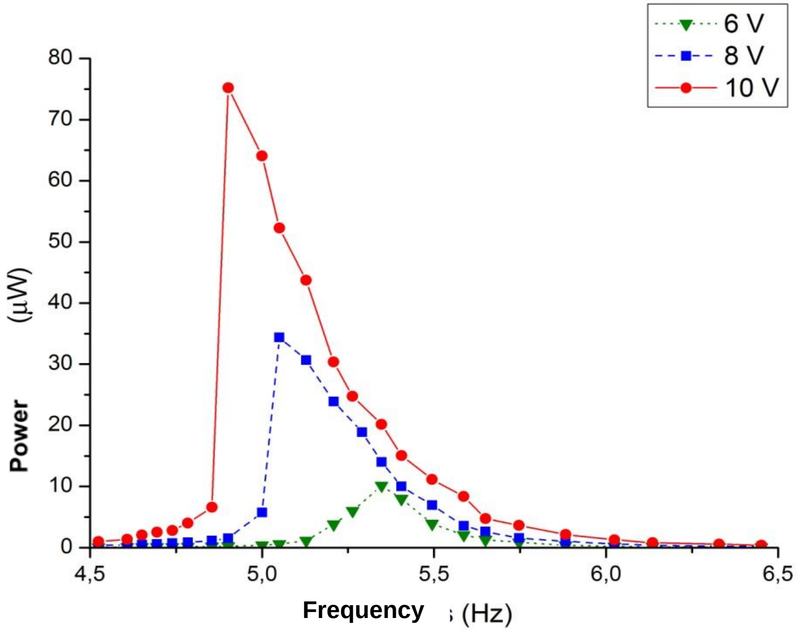
Generated power as function of resistive loads in the case of different excitation frequencies.
The parameters are *d= 2 cm* and the square voltage over electromagnet V_c=*8V.*

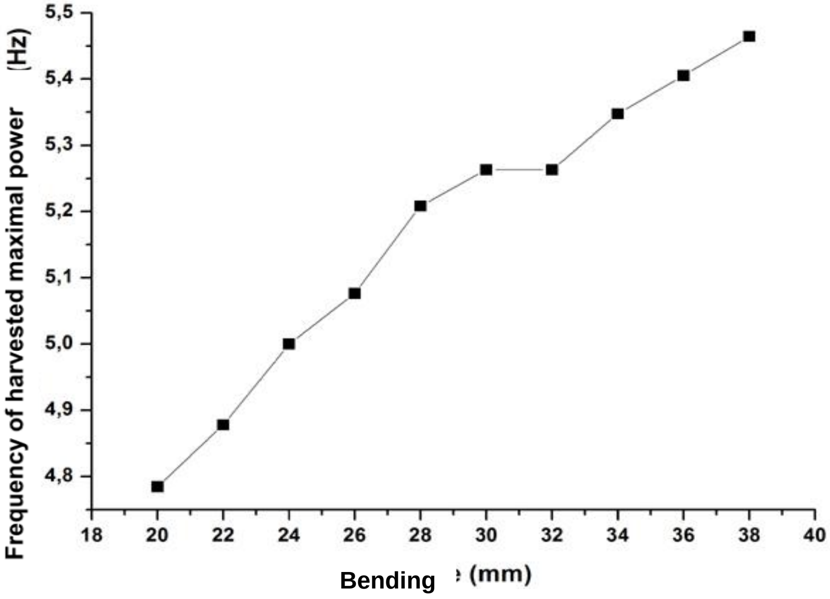


Peak voltage as function of the excitation frequency f_m.
Softening effect is observed for the sweep up/down cases.
The parameters are *d= 2 cm*, the load resistance R_L= *820kΩ* and the square voltage over electromagnet V_c=*8V.*

Right figure shows the softening effect of the magnetic field frequency ω_m. It is obvious that the generated voltage strictly depends on the excitation frequency. While ω_m decreases from its high value (i.e. 6 *Hz*), voltage values increase upto 11 V; however if one sweeps up excitation frequency ω_m, voltage initially increases smooth till one reaches ω_m=4.25 *Hz*, then a jump to 5 V is observed and the curve starts to decrease for high excitation frequencies.

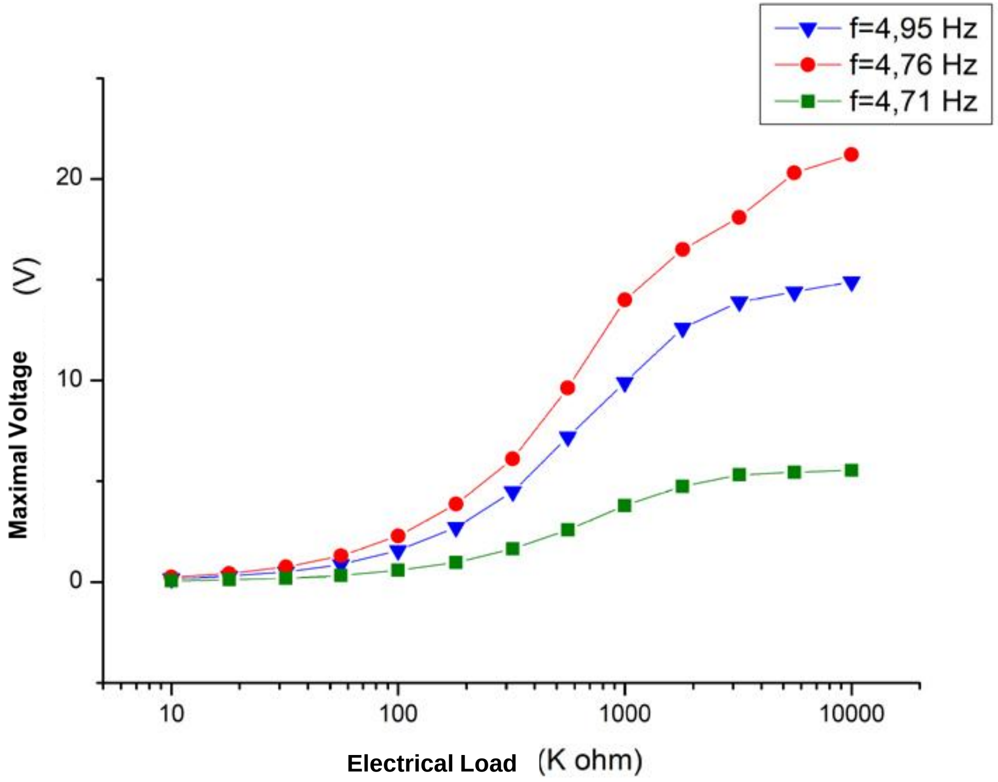
Piezoelectrics can be classiffied as soft and hard structured piezoelectrics. In our experiments, for instance, we used soft materials. These two types materials exhibit different nonlinear features towards the applied force and its frequency. In the left graph, according to various magnetic forces, the curve tends to direct left hand-side. Thus taht gives softening effect.

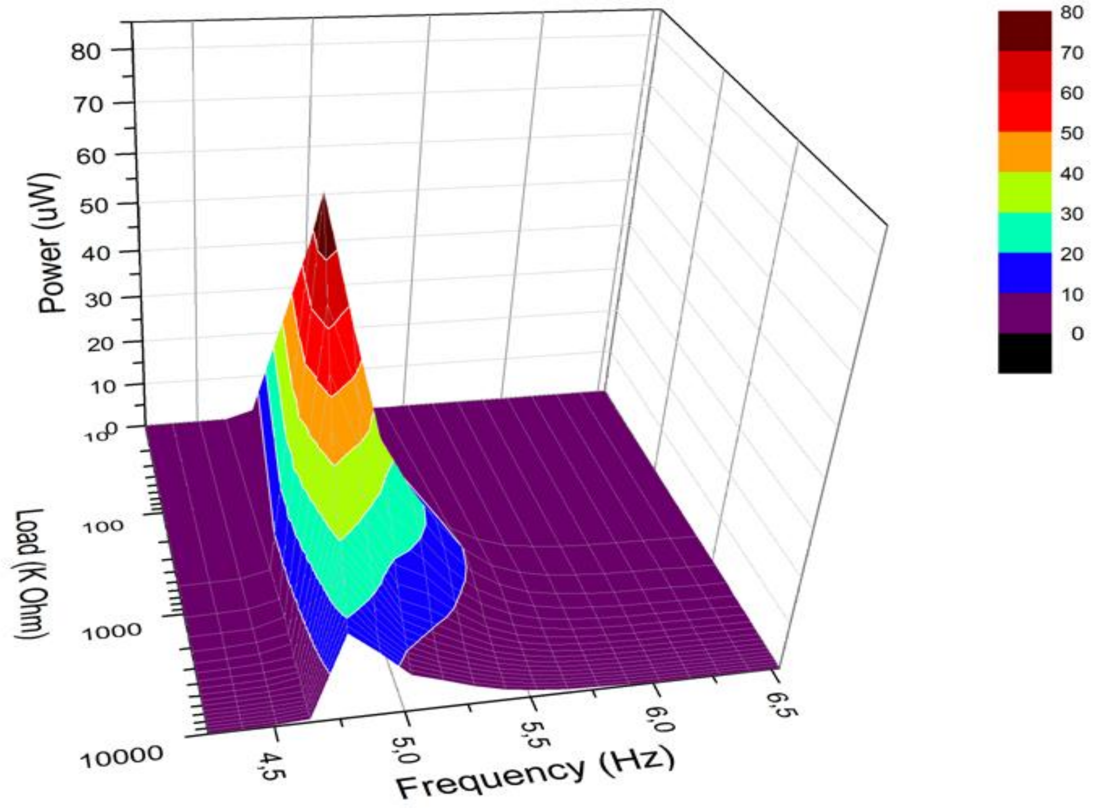




Power v.s. Frequency for softening effect

Elektromıknatısın sisteme olan uzaklığına bağlı olarak maksimum gücün elde edildiği frekans değerleri

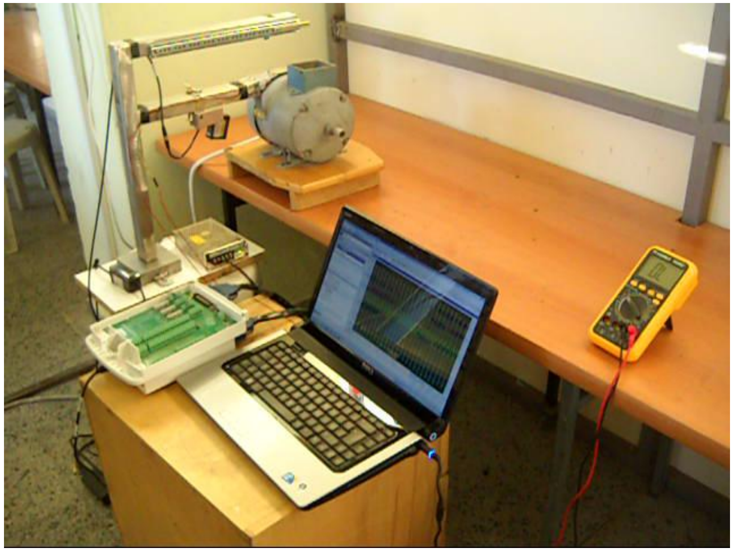

f=4,95 Hz
f=4,76 Hz
f=4,71 Hz
Maximal Voltage (V)
20
10
0
10
100
1000
10000
Electrical Load (K ohm)

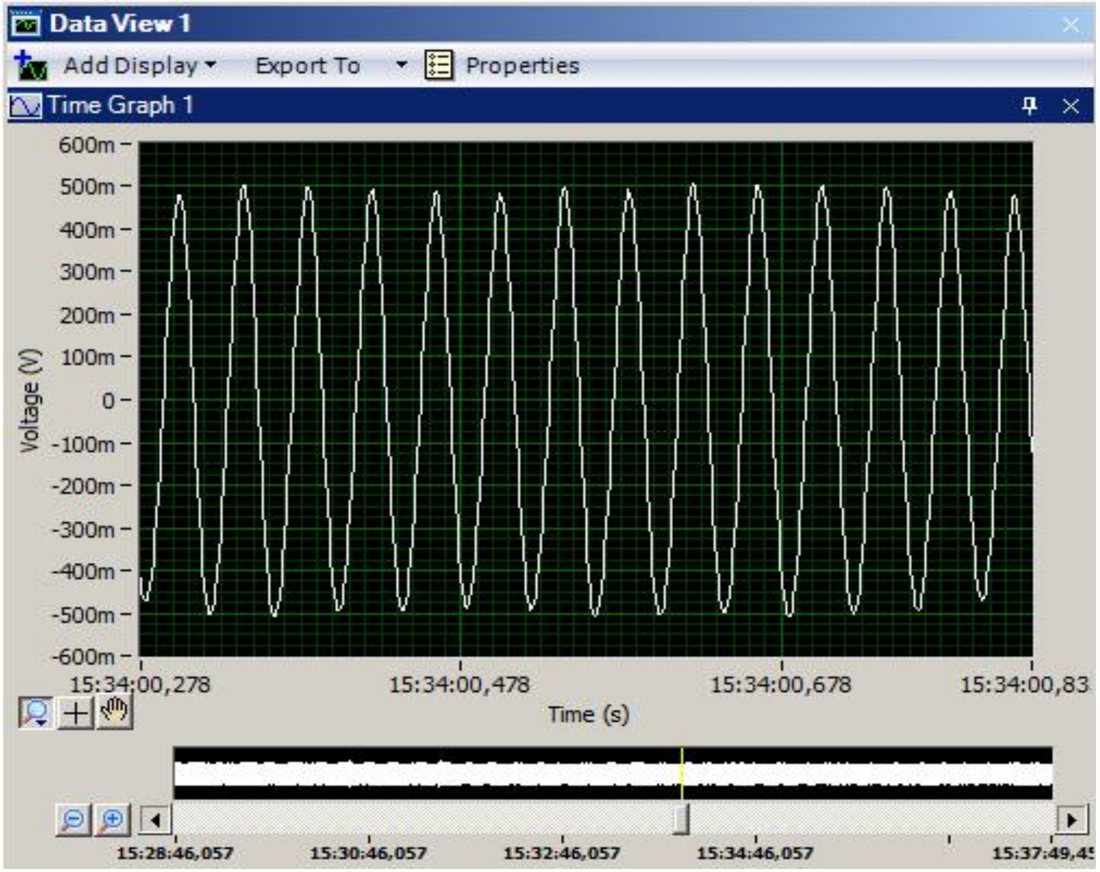


Generated power on the plane of resistive load and excitation frequency ω_m. The parameters are $d = 2\ cm$ and the square voltage over electromagnet $V_c = 8V$.

Apply of PZT Pendulumun to induction motor

Results & Discussion …

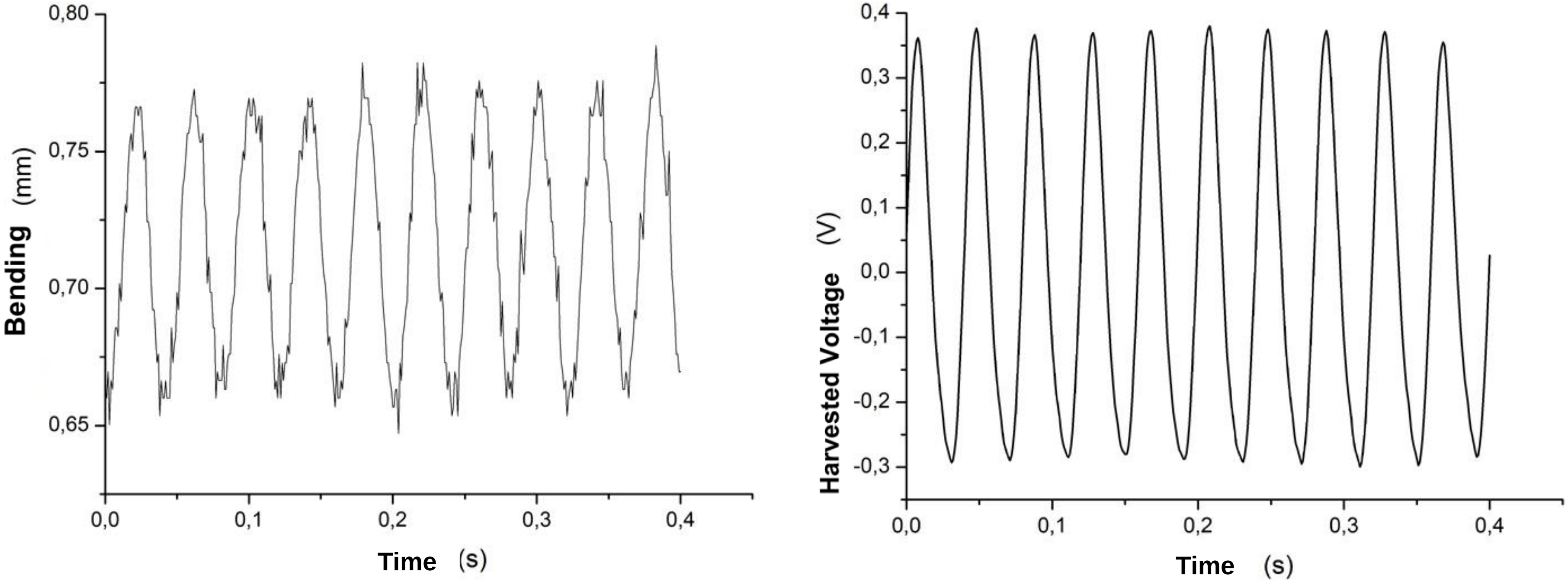




Generated voltage from PZT near to 3-phase induction motor

Harvesting energy from an asynchronous motor

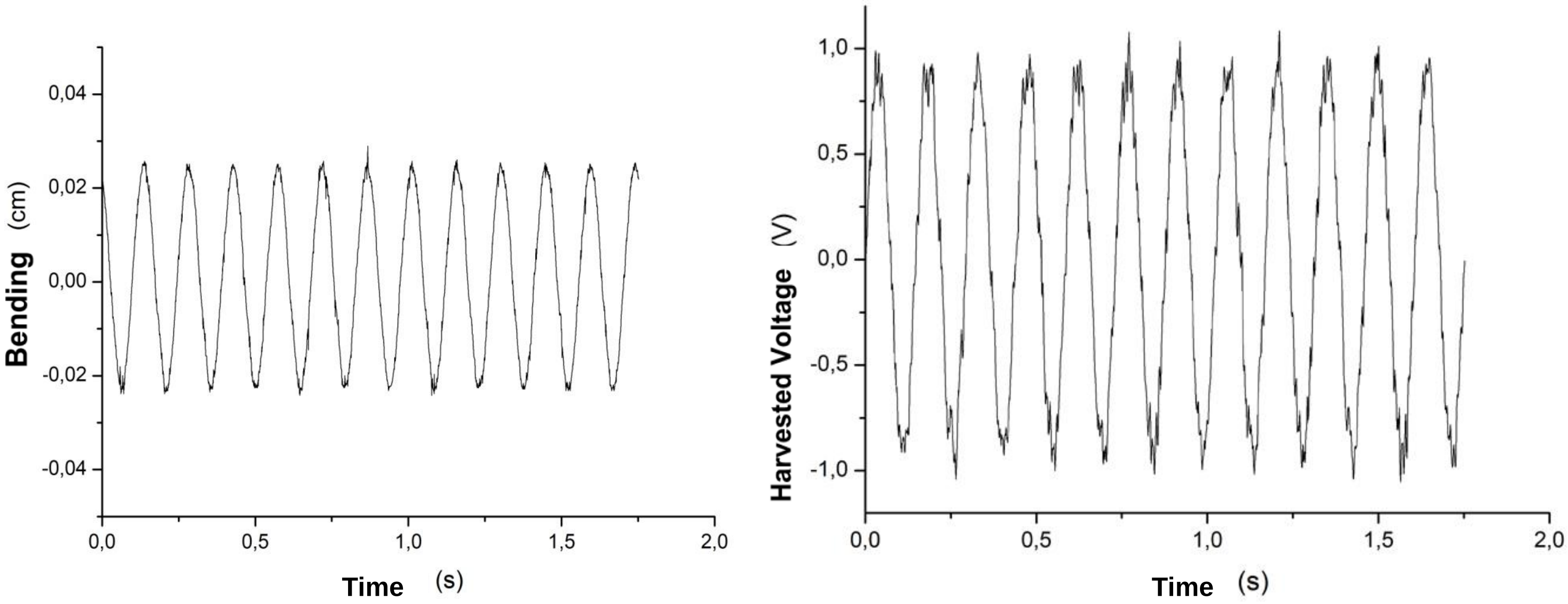
The lost magnetic flux surrounding the motor can be caught and a small amount of energy can be obtained. Since the motor in this experiment has 4 poles, the buckling and voltage have the frequencies of 25 Hz.



Bending and harvested voltage v.s. time

Harvesting energy from a washing machine

Here the mechanical vibrations of the washing machine produces the harvested energy.



Bending and harvested voltage v.s. time

Conclusions

- The bending increases when the electromagnet comes near to the piezo-beam tip. That yields to higher powers due to incrasing bending amount.
- The most important thing is the maximal power. If the applied frequency is nearby the natural frequency of the system, the power enhances drastically.
- When the distance to electromagnet is increased to 3 cmm from 2 cm, the maximal power is obtained for the skipped value of frequency from 4.83 Hz to 5.37 Hz. Therefore it is important to determine the exact location of the magnetic field.
- The dynamics is found to be rich from the regular phase portraits to the chaotic ones depending on the system parameters of electromagnet voltage V, distance d from the electromagnet and the excitation frequency f.
- The experimental and theoretical results are in good agreement in terms of phase portraits.
- Softening effect has been observed in the power output of *PZT* layer.
- There exists a strong dependence on the load resistance in terms of electrical power generation in the system.
- A theoretical expression on power formulation has been identified.
- The maximal power changes by the frequency, load resistance and the magnetic excitation amplitude.

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Thank you!