SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

L2e

PhD Thesis Defense

Multiphysic Modeling of Second Generation Magnetoelectric Materials:

Application to Connected Objects

Tuan Anh DO

November 04, 2019

Thesis directors:	Zhuoxiang Ren
	Hakeim Talleb
Supervisor :	Aurélie Gensbittel

Plan

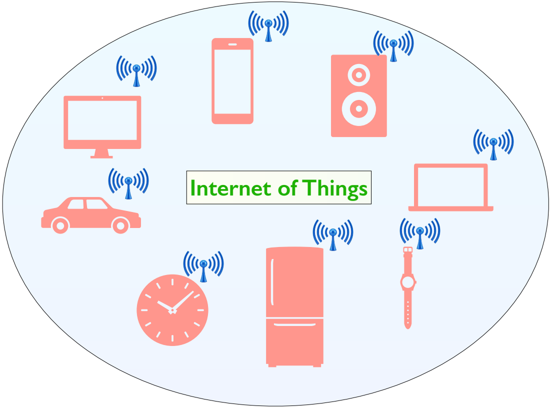
Outline

1. Introduction
   - Motivation
2. Modeling
   - Static analysis
   - Dynamic analysis
3. Laminate
   - Laminate composite with circular section
4. Conclusion

Motivation

Internet of Things

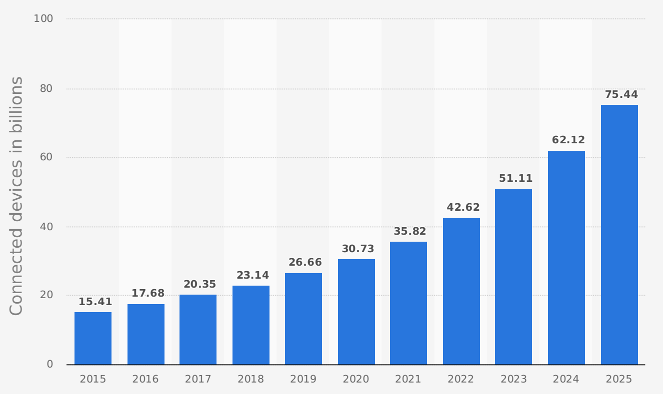
The internet doesn't just connect and distribute information, it can feel and intelligently respond.



- More efficient water supply
- Improved public safety
- Energy-efficient buildings
- Digitised healthcare system

Motivation

The evolution of IoTs



More devices

↓

More power requirement

IHS forecast. *IoT platforms: enabling the Internet of Things.* March 2016.

Battery as power

- ✗ Replacement difficulty.
- ✗ Need cable for charging.

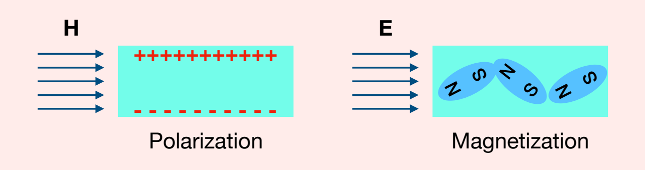
Magnetoelectric materials

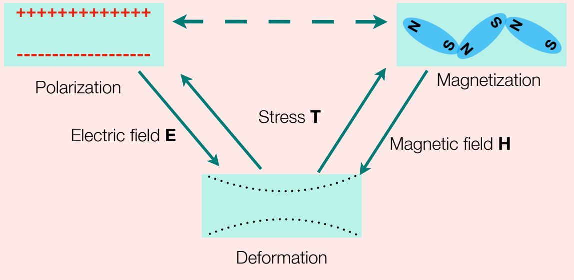
- ✓ Energy harvesting.
- ✓ Profit electromagnetic sources.

Magnetoelectric (ME) effect

Definition

Magnetization induced by an electric field or polarization induced by a magnetic field.





ME coefficient

Static regime:

$$\alpha_V = \frac{V}{H}$$

Dynamic regime:

$$\tilde{\alpha}_V = \frac{\Delta V}{\Delta H}$$

ME composite

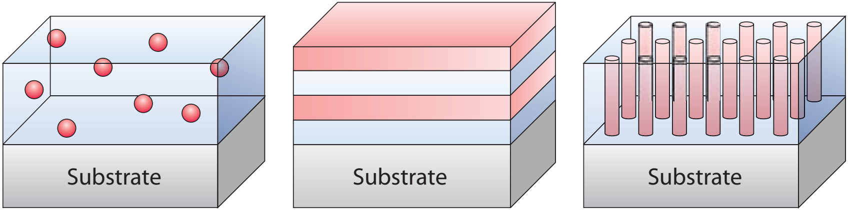
Magnetostrictive material

$+$

Piezoelectric material

ME composite

Three type of ME composite

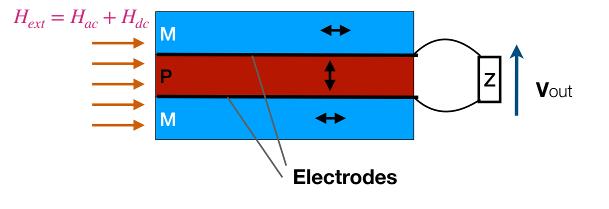


0 - 3 type particulate composite | 2 - 2 type laminate composite | 1 - 3 type fiber composite

Wang, Yao, et al. *Multiferroic magnetoelectric composite nanostructures.* NPG Asia Materials 2.2 (2010): 61.

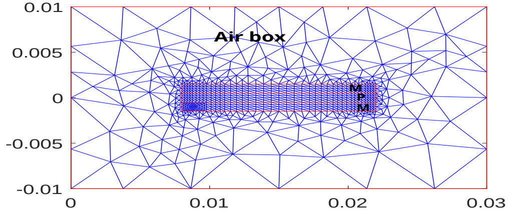
Energy harvesting

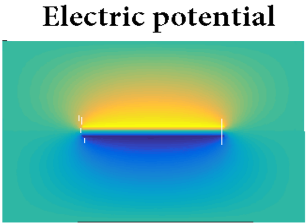
Working principle



- Cochlear implant
- Artificial pacemaker
- Insulin pump

2D model

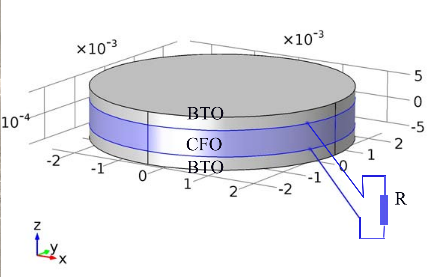




Condition: Laminate composites under the plane strain or stress state.

Context

3D model is needed



Thesis works

- Develop a 3D FEM to consider complex structure.
- Analyze laminate composite(circular section, rectangular section), novel structure.
- Investigate different type: particulate composite and fiber composite.

Outline

Problem description

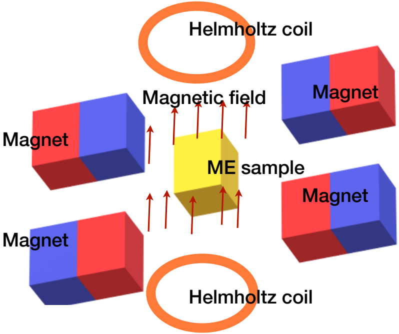
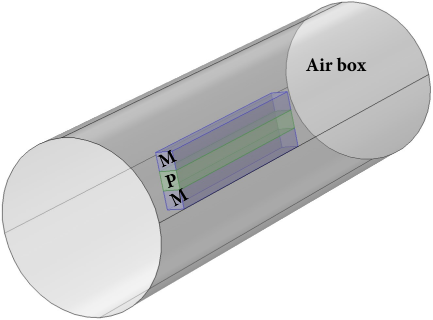


Illustration of ME measurement



3D model

Magnetic Field $\longrightarrow$ Electric potential distribution

General equations

Physical equations

- Elastic equilibrium

$$\operatorname{div} \boldsymbol{T} + \boldsymbol{f} = 0$$

- Ampere's law

$$\operatorname{curl} \boldsymbol{H} = \boldsymbol{J}$$

- Gauss's law

$$\operatorname{div} \boldsymbol{D} = \rho_V$$

Constitutive laws

$$\begin{cases} \mathbf{T} = c\boldsymbol{S} - e^t\boldsymbol{E} - h^t\boldsymbol{B} \\ \boldsymbol{H} = -h\boldsymbol{S} + \nu\boldsymbol{B} \\ \boldsymbol{D} = -e\boldsymbol{S} + \epsilon\boldsymbol{E} \end{cases}$$

Introduce state variables

$$\begin{cases} \boldsymbol{S} = \frac{1}{2}(\nabla + \nabla^t)\boldsymbol{u} \\ \boldsymbol{B} = \nabla \times \boldsymbol{a} \\ \boldsymbol{E} = \nabla V \end{cases}$$

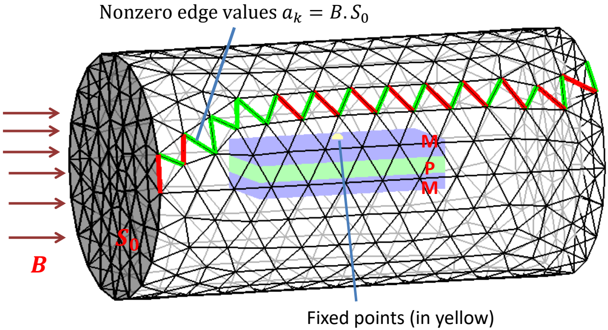
Static analysis

$$[\mathbb{K}]\{X\} = [F]$$

- $[\mathbb{K}] = \begin{bmatrix} \boldsymbol{K}_{uu} & -\boldsymbol{K}_{au}^{t} & \boldsymbol{K}_{vu}^{t} \\ -\boldsymbol{K}_{au} & \boldsymbol{K}_{aa} & 0 \\ \boldsymbol{K}_{vu} & 0 & -\boldsymbol{K}_{vv} \end{bmatrix}$

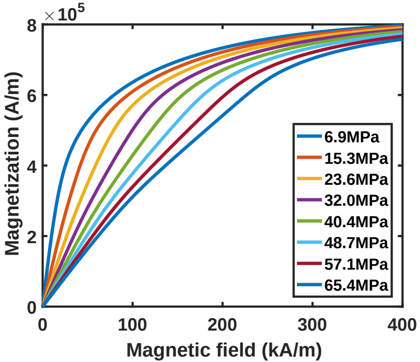
- $\{X\} = \{\boldsymbol{u},\ \ \boldsymbol{a},\ \ V\}^t$
- $[F] = \{0,\ \ \Sigma_k a_k,\ \ 0\}^t$

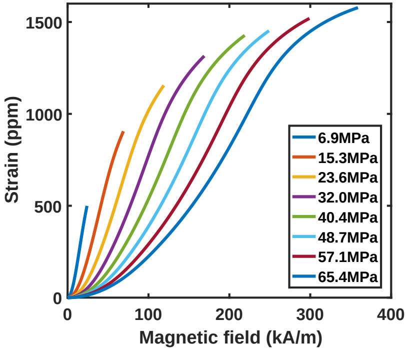
Boundary condition



Nonlinear magnetostriction

Decribe the nonlinear behavior by multiscale model





Compute material Jacobian

$$\zeta = \begin{bmatrix} \mu^S = \frac{\partial \boldsymbol{B}}{\partial \boldsymbol{H}}(\boldsymbol{H}_0, \boldsymbol{T}_0) & d = \frac{\partial \boldsymbol{B}}{\partial \boldsymbol{T}}(\boldsymbol{H}_0, \boldsymbol{T}_0) \\ d^t = \frac{\partial \boldsymbol{S}}{\partial \boldsymbol{H}}(\boldsymbol{H}_0, \boldsymbol{T}_0) & s^H = \frac{\partial \boldsymbol{S}}{\partial \boldsymbol{T}}(\boldsymbol{H}_0, \boldsymbol{T}_0) \end{bmatrix}$$

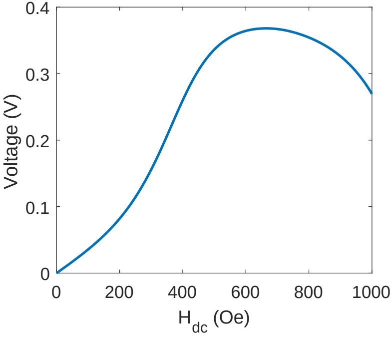
Chakrabarti, S. and Dapino, M. J. (2012). *Fully coupled discrete energy-averaged model for Terfenol-D* Journal of Applied Physics, 111(5), 054505.

Piesewise linear procedure

Under small deviations

$$\begin{bmatrix} \Delta \boldsymbol{H} \\ \Delta \boldsymbol{T} \end{bmatrix} = \zeta^{-1} \begin{bmatrix} \Delta \boldsymbol{B} \\ \Delta \boldsymbol{S} \end{bmatrix}$$

Choose ΔH, $N = \frac{H_{max}}{\Delta H}$



Repeat N times

$[\mu, h, c] = DEAM\_model(\boldsymbol{H}, \boldsymbol{T})$

↓

Assemble matrix

$\boldsymbol{K}_{uu}, \boldsymbol{K}_{ua}, \boldsymbol{K}_{aa}, \Delta \boldsymbol{F}$

↓

Solve equation

$[\Delta \boldsymbol{U}, \Delta \boldsymbol{A}, \Delta V] = mat\_UAV \backslash \Delta \boldsymbol{F}$

↓

$[\Delta S, \Delta B, \Delta E] = state\_eq([\Delta \boldsymbol{U}, \Delta \boldsymbol{A}, \Delta V])$

$[\Delta H, \Delta T] = const.law(\Delta B, \Delta S)$

↓

update $\boldsymbol{H}, \boldsymbol{T}$

Outline

Dynamic analysis

- **Elastic equilibrium**

$$\text{div } \boldsymbol{T} + \boldsymbol{f} = \rho \frac{d^2 \boldsymbol{u}}{dt^2}$$

ρ: masse volumique kg/m^3

- **Ampere's law**

$$\begin{cases} \text{curl } \boldsymbol{H} = \boldsymbol{J}_c \\ \text{div } \boldsymbol{J}_c = 0 \end{cases}$$

$\boldsymbol{J}_c = \sigma_c \boldsymbol{E}$: eddy currents

Introduce time primitive of electric potential

$$\boldsymbol{E} = -\frac{d(\boldsymbol{a} + \text{grad } \psi)}{dt}$$

with $V = \frac{d\psi}{dt}$

- **Gauss's law**

$$\frac{d(\text{div } \boldsymbol{D})}{dt} = 0$$

for the symetry of the system

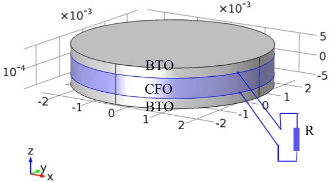
Linear harmonic analysis

$$[\mathbb{K}]\{X\} = [F]$$

with:

- $$[\mathbb{K}] = \begin{bmatrix} -\omega^2 \boldsymbol{M}_{uu} + j\omega \boldsymbol{C}_{uu} + \boldsymbol{K}_{uu} & -\boldsymbol{K}_{ua} & j\omega \boldsymbol{K}_{u\psi} & 0 \\ -\boldsymbol{K}_{ua}^t & j\omega \boldsymbol{C}_{aa} + \boldsymbol{K}_{aa} & j\omega \boldsymbol{C}_{a\psi} & 0 \\ j\omega \boldsymbol{K}_{u\psi}^t & j\omega \boldsymbol{C}_{a\psi}^t & j\omega \boldsymbol{C}_{\psi\psi} + \omega^2 \boldsymbol{K}_{\psi\psi} & -j\omega \boldsymbol{K}_{\psi q} \\ 0 & 0 & -j\omega \boldsymbol{K}_{\psi q}^t & j\omega Z \end{bmatrix}$$
- $\{X\} = \{\boldsymbol{u},\ \boldsymbol{a},\ \psi,\ Z\}^t$.

Z : Electrical charge connecting two electrodes.



Outline

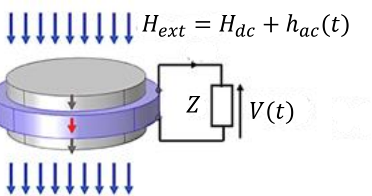
Geometry

Why laminate composite?

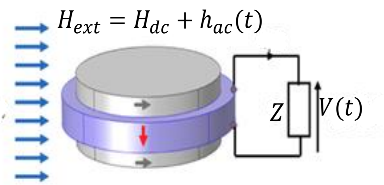
- ✓ Good coupling can be obtained at the ferroelectric and ferromagnetic interfaces.
- ✓ Higher resonance response in a wide frequency range

Wang, Lei, et al. *Effect of load resistance on magnetoelectric properties in FeGa/BaTiO3/FeGa laminate composites.* Journal of Alloys and Compounds 509.30 (2011): 7870-7873.

Mode TT



Mode LT

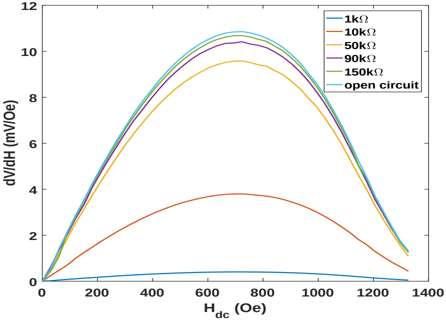


$BaTiO_3$ (gray layer): Thickness 1.5mm, diameter 12mm

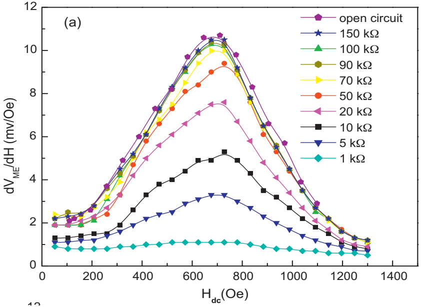
FeGa (magenta layer): Thickness 1mm, diameter 10mm

DC magnetic field dependence

Simulation result



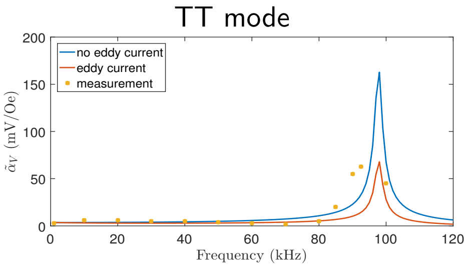
Measurement

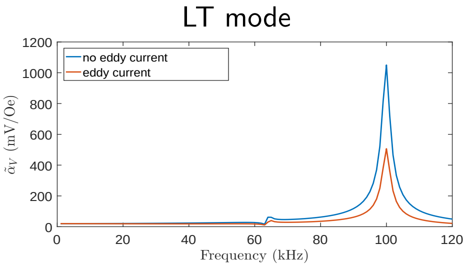


- ME voltage coefficient as a function of DC magnetic field under various electrical resistance load values and external magnetic field: $H_{ac} = 1$ (Oe), $f = 1$ (kHz)
- In concordance with

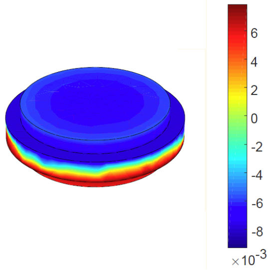
Wang, Lei, et al. 2011. *Effect of load resistance on magnetoelectric properties in FeGa/BaTiO3/FeGa laminate composites.* Journal of Alloys and Compounds

Eddy current effect





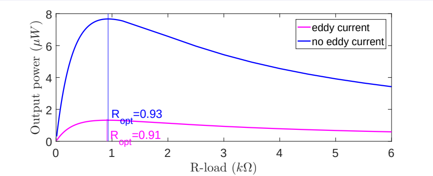
- The magnetic external field: $H_{ac} = 1$ (Oe)
- The result with effect of eddy current in TT mode in concordance with measurment
- The quality factor decrease under eddy current effect.



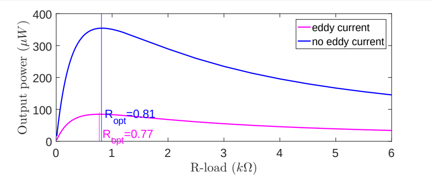
Electrical potential distribution

Performance

TT mode



LT mode



Output power $P = V^2/R$ (post processing)

The eddy current decrease the performance of material.

Measurement with $P_{max} = 2.75(\mu W)$ $R_{opt} = 0.6k\Omega$

Geometry

Conclusion and perspectives

Conclusion

- Completed FEM of circular tri-laminated ME composite has been presented.
- The effect of eddy current is included.
- The 3D analysis provides a useful tool to study ME composite of various geometries for energy transducer.

Perspectives

- Optimization geometry can be performed by this model.
- Investigation under large signal of magnetic field
- Time reduction for computation is needed.

THANK YOU FOR YOUR ATTENTION