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

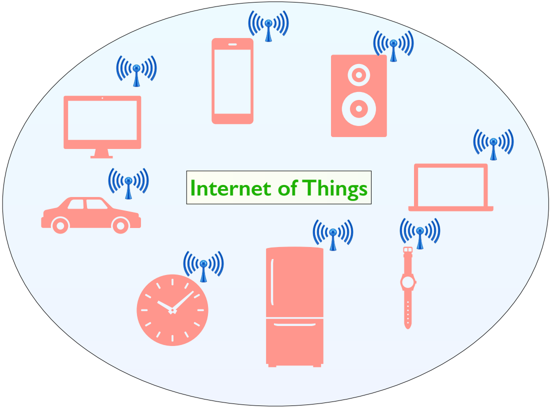
Plan

Outline

Motivation

Internet of Things

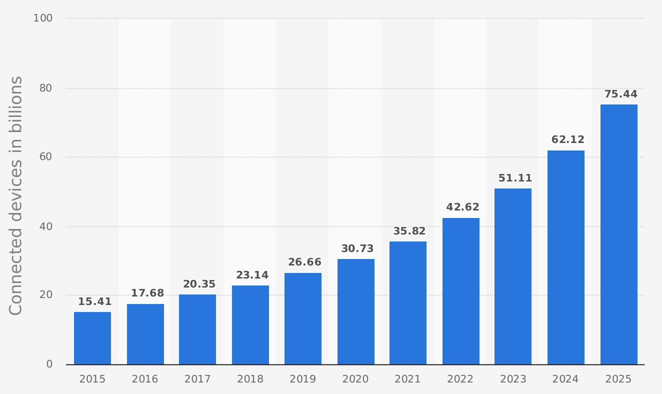
The internet doesn't just connect and distribute information, it can feel and intelligently respond.



- 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.

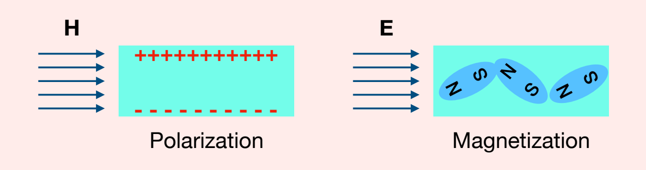
Magnetoelectric materials

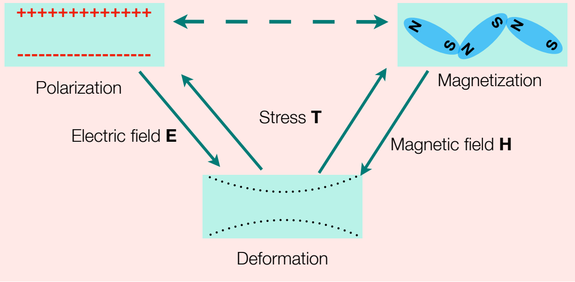
- ✓ Energy harvesting.
- ✓ Profit electromagnetic sources.

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

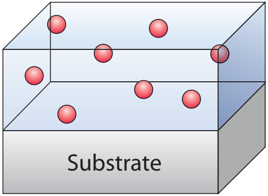
Magnetostrictive material

+

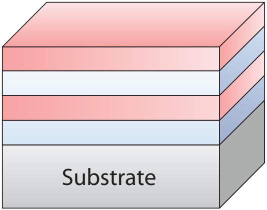
Piezoelectric material

ME composite

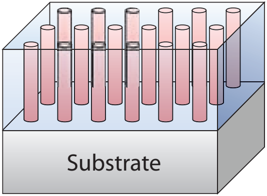
Three type of ME composite



0 - 3 type particulate composite



2 - 2 type laminate composite

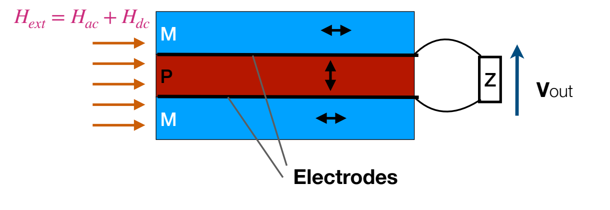


1 - 3 type fiber composite

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

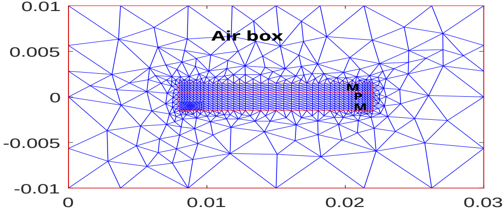
Energy harvesting

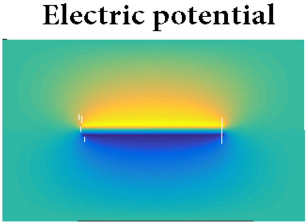
Working principle



- Cochlear implant
- Artificial pacemaker
- Insulin pump

2D model

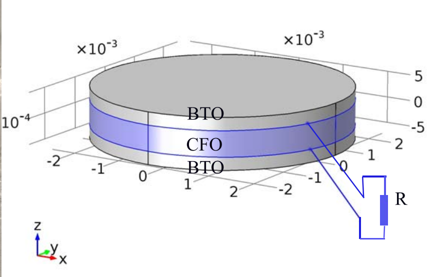




Condition: Laminate composites under the plane strain or stress state.

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

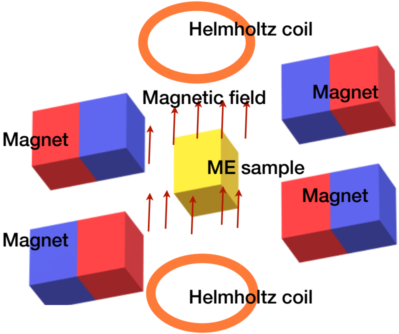
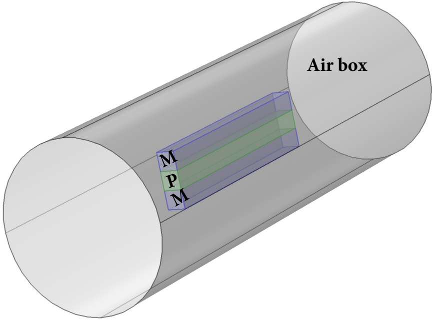


Illustration of ME measurement



3D model

Magnetic Field $\longrightarrow$ Electric potential distribution

General equations

Physical equations

- Elastic equilibrium

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

- Ampere's law

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

- Gauss's law

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

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

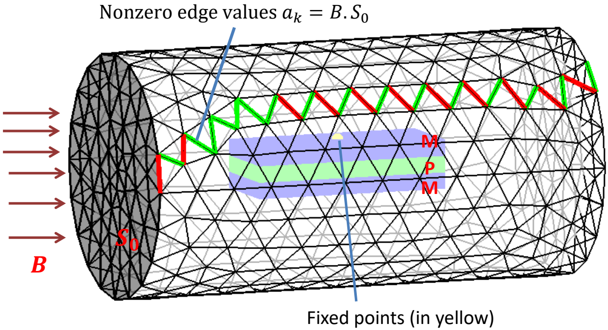
$$\begin{cases} \boldsymbol{S} = \frac{1}{2}(\nabla + \nabla^t)\boldsymbol{u} \\ \boldsymbol{B} = \nabla \times \boldsymbol{a} \\ \boldsymbol{E} = \nabla V \end{cases}$$

Static analysis

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

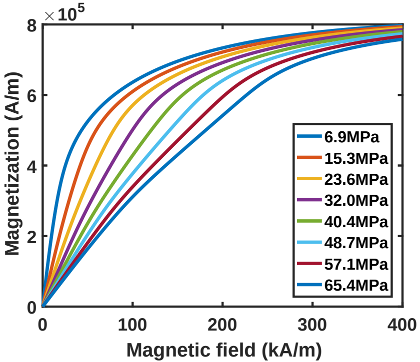
- $[\mathbb{K}] = \begin{bmatrix} \boldsymbol{K}_{uu} & -\boldsymbol{K}^t_{au} & \boldsymbol{K}^t_{vu} \\ -\boldsymbol{K}_{au} & \boldsymbol{K}_{aa} & 0 \\ \boldsymbol{K}_{vu} & 0 & -\boldsymbol{K}_{vv} \end{bmatrix}$
- $\{X\} = \{\boldsymbol{u}, \ \boldsymbol{a}, \ V\}^t$
- $[F] = \{0, \ \Sigma_k a_k, \ 0\}^t$

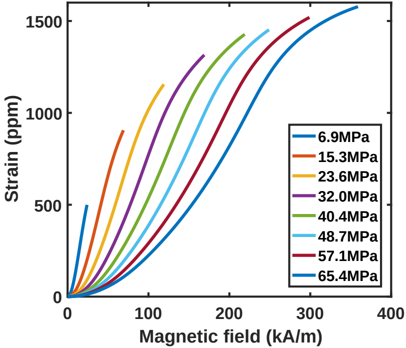
Boundary condition



Nonlinear magnetostriction

Decribe the nonlinear behavior by multiscale model





Compute material Jacobian

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

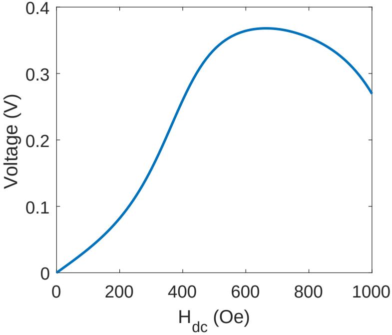
Chakrabarti, S. and Dapino, M. J. (2012). *Fully coupled discrete energy-averaged model for Terfenol-D* Journal of Applied Physics, 111(5), 054505.

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**

$$\text{div } \boldsymbol{T} + \boldsymbol{f} = \rho \frac{d^2 \boldsymbol{u}}{dt^2} \qquad \rho\text{: masse volumique kg/m}^3$$

- **Ampere's law**

$$\begin{cases} \text{curl } \boldsymbol{H} = \boldsymbol{J}_c \\ \text{div } \boldsymbol{J}_c = 0 \end{cases} \qquad \boldsymbol{J}_c = \sigma_c \boldsymbol{E}\text{: eddy currents}$$

Introduce time primitive of electric potential

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

- **Gauss's law**

$$\frac{d(\text{div } \boldsymbol{D})}{dt} = 0 \qquad \text{for the symetry of the system}$$

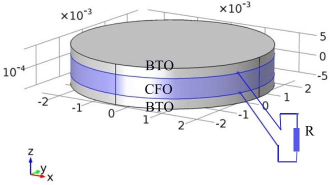
Linear harmonic analysis

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

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

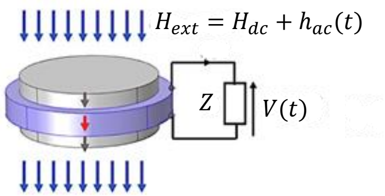
Geometry

Why laminate composite?

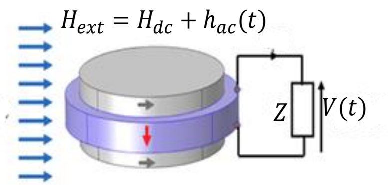
- ✓ Good coupling can be obtained at the ferroelectric and ferromagnetic interfaces.
- ✓ Higher resonance response in a wide frequency range

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

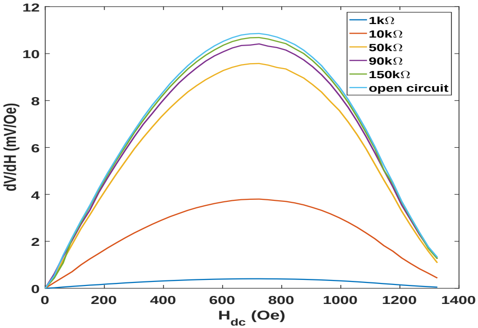


$BaTiO_3$ (gray layer): Thickness 1.5mm, diameter 12mm

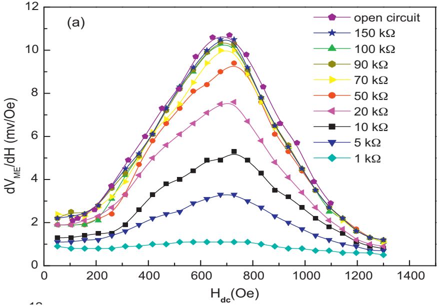
FeGa (magenta layer): Thickness 1mm, diameter 10mm

DC magnetic field dependence

Simulation result



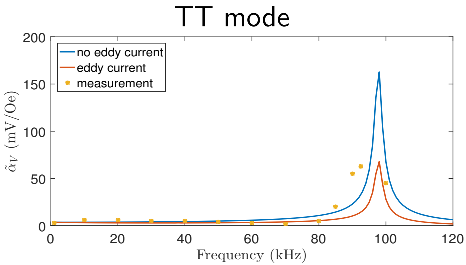
Measurement

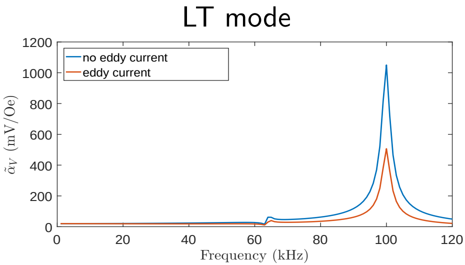


- ME voltage coefficient as a function of DC magnetic field under various electrical resistance load values and external magnetic field: $H_{ac} = 1$ (Oe), $f = 1$ (kHz)
- In concordance with

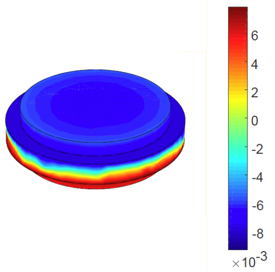
Wang, Lei, et al. 2011. *Effect of load resistance on magnetoelectric properties in FeGa/BaTiO3/FeGa laminate composites.* Journal of Alloys and Compounds

Eddy current effect



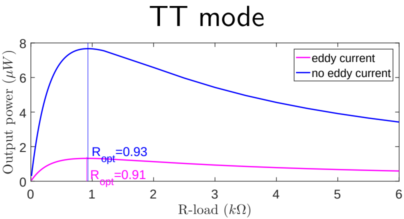


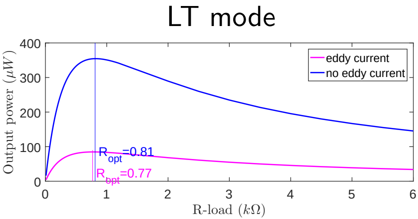
- The magnetic external field: $H_{ac} = 1$ (Oe)
- The result with effect of eddy current in TT mode in concordance with measurment
- The quality factor decrease under eddy current effect.



Electrical potential distribution

Performance

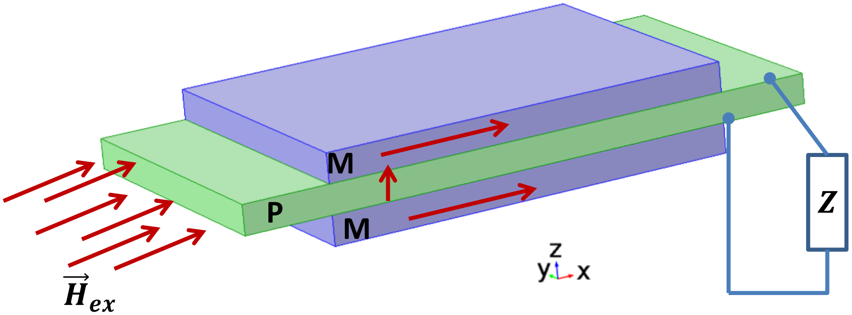




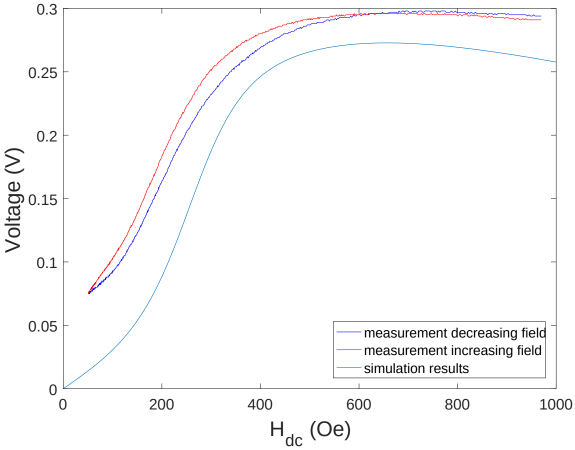
- Output power $P = V^2/R$ (post processing)
- The eddy current decrease the performance of material.
- Measurement with $P_{max} = 2.75(\mu W)$ $R_{opt} = 0.6k\Omega$

Outline

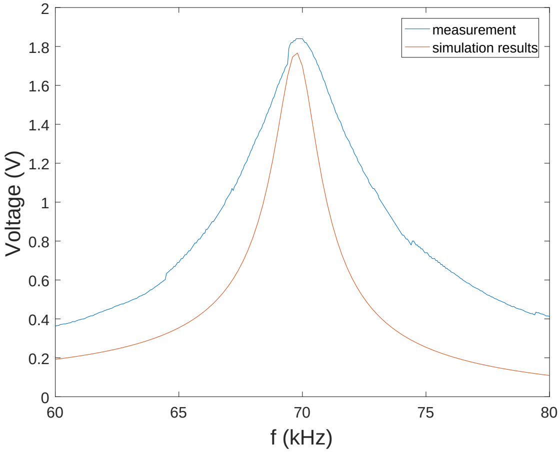
Geometry



DC magnetic field dependency

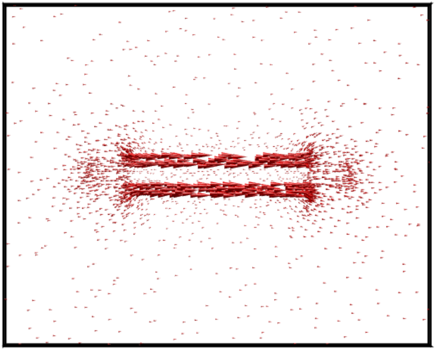


Frequency dependency

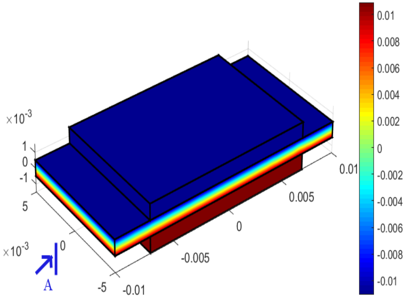


Field distribution

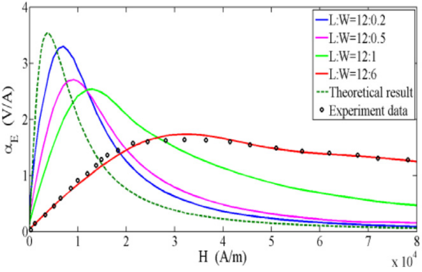
Magnetic induction distribution

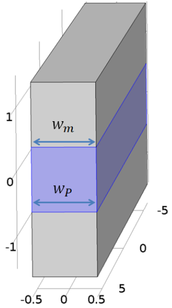


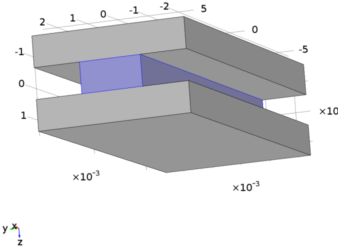
Electric potential distribution



Geometry







Three configurations are examined

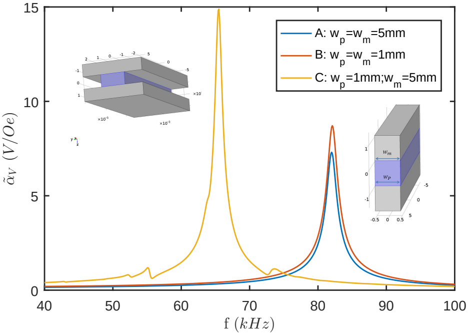
A. Width of 5mm for all layers.

B. Width of 1mm for all layers.

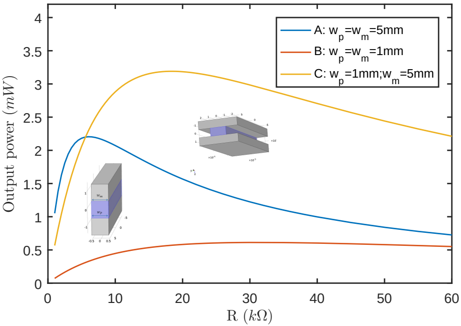
C. Width of 5mm for magnetostrictive layer and width of 1mm for piezoelectric layer.

Performance

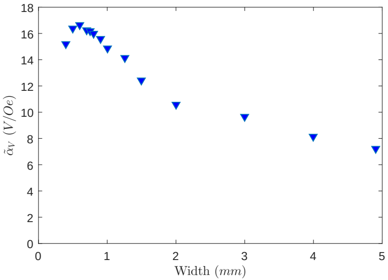
Voltage

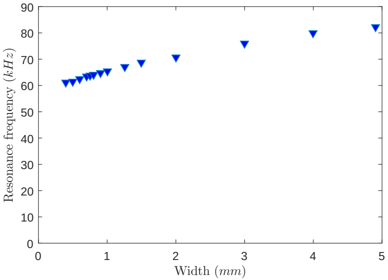


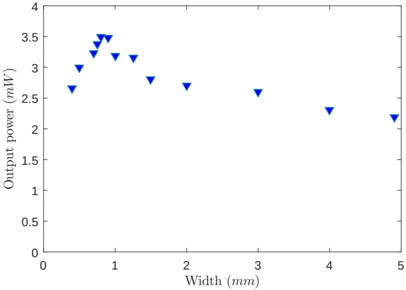
Output power



Parametric study







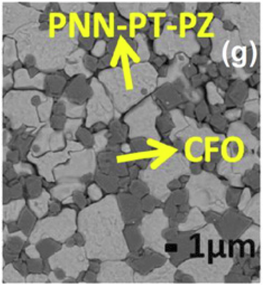
- a
- b
- c

Outline

0-3 type and 1-3 type ME composite

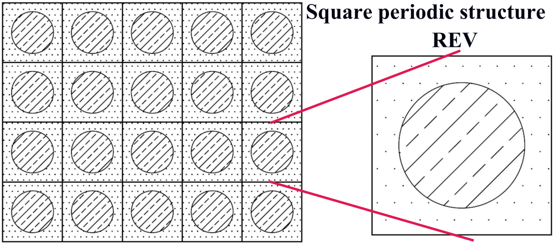
✓ 3D FEM is useful to study the behavior of ME laminate composite

✗ It is difficult to apply for fiber composite and particulate composite



→

- a
- b



Vadla, S. et al. (2016) *Magnetoelectric coupling in 0.5 Pb (Ni1/3Nb2/3) O3–0.35 PbTiO3–0.15 PbZrO3 and CoFe2O4 based particulate composites.* Scripta Materialia

Analytical method → Simple structure (Fiber composite)

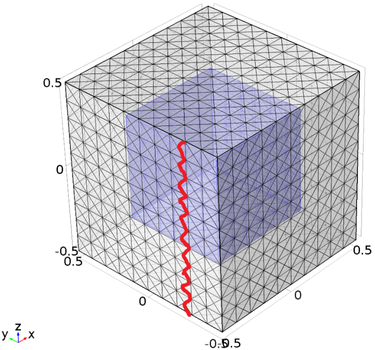
Corcolle, R. et al., 2008 *Generic formalism for homogenization of coupled behavior: Application to magnetoelectroelastic behavior.* Physical Review B.

Boundary condition

- a
- b

  Point: $k_i + d_i,\ k_i$

  Edge: $(k_{i1} + d_i, k_{i2} + d_i),\ (k_{i1}, k_{i2})$



Mechanics

$$u_j(k_i + d_i) = u_j(k_i) + \bar{S}_{ij} d_i$$

Electric

$$V(k_i + d_i) = V(k_i) + \bar{E}_i d_i$$

Magnetic

$$a(k_{i1} + d_i, k_{i2} + d_i) = a(k_{i1}, k_{i2}) + c_j \phi_j + c_k \phi_k$$

$$\begin{cases} c_j = 1/-1 & \text{for the red edges} \\ c_0 = 0 & \text{for the others} \end{cases}$$

$$\phi_j = \int \boldsymbol{B}_j dA$$

A : the perpendicular surface

Effective coefficients

Solve equation $[K]\{X\} = [F]$

State variable $\{X\} = \{\boldsymbol{u} \quad \boldsymbol{a} \quad V\}^t$

State equations
$$\boldsymbol{S} = 1/2(\textbf{grad} + \textbf{grad}^t)\boldsymbol{u}$$
$$\boldsymbol{B} = \textbf{curl}\ \boldsymbol{a}$$
$$\boldsymbol{E} = -\,\textbf{grad}\ V$$

Local field $\boldsymbol{S}, \quad \boldsymbol{B}, \quad \boldsymbol{E}$

Local constitutive laws
$$\boldsymbol{T} = c\boldsymbol{S} - e^t\boldsymbol{E} - h^t\boldsymbol{B}$$
$$\boldsymbol{H} = -\,h\boldsymbol{S} + \nu\boldsymbol{B}$$
$$\boldsymbol{D} = -\,e\boldsymbol{S} + \varepsilon\boldsymbol{E}$$

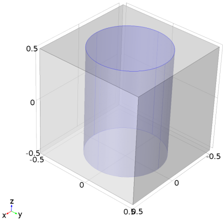
Local field $\boldsymbol{T}, \quad \boldsymbol{H}, \quad \boldsymbol{D}$

Volume average
$$\begin{cases} \bar{T} & = 1/V\int \boldsymbol{T}dV \\ \bar{H} & = 1/V\int \boldsymbol{H}dV \\ \bar{D} & = 1/V\int \boldsymbol{D}dV \end{cases}$$

Material coefficients
$$\begin{bmatrix} \bar{\boldsymbol{T}} \\ \bar{\boldsymbol{H}} \\ \bar{\boldsymbol{D}} \end{bmatrix} = \begin{bmatrix} \tilde{\boldsymbol{C}} & -\tilde{\boldsymbol{h}}^t & -\tilde{\boldsymbol{e}}^t \\ \tilde{\boldsymbol{h}} & \tilde{\boldsymbol{\nu}} & \tilde{\boldsymbol{\alpha}}_H^t \\ \tilde{\boldsymbol{e}} & \tilde{\boldsymbol{\alpha}}_H & \tilde{\boldsymbol{\varepsilon}} \end{bmatrix} \begin{bmatrix} \bar{\boldsymbol{S}} \\ \bar{\boldsymbol{B}} \\ \bar{\boldsymbol{E}} \end{bmatrix}$$

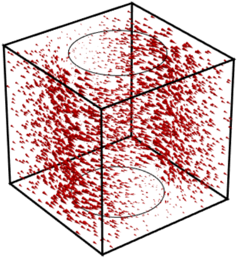
Outline

Apply of magnetic field

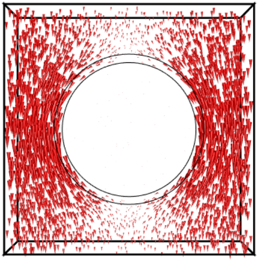


- Magnetostrictive matrix ($CoFe_2O_4$) reinforced by fiber piezoelectric ($BaTiO_3$).
- The volume fraction is $f = 0$ to $f = 0.8$.

Example:
Magnetic field is applied

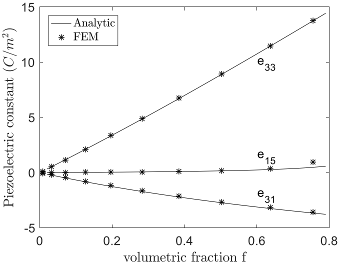


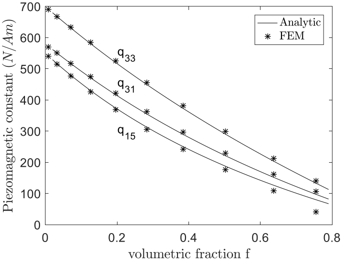
3D view

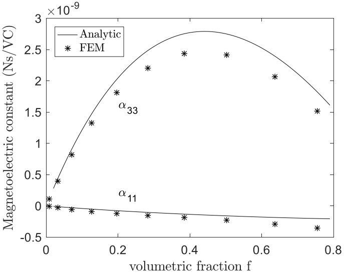


Top view

Effective coefficient

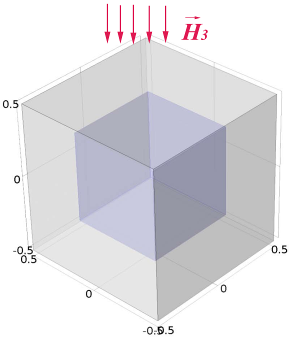






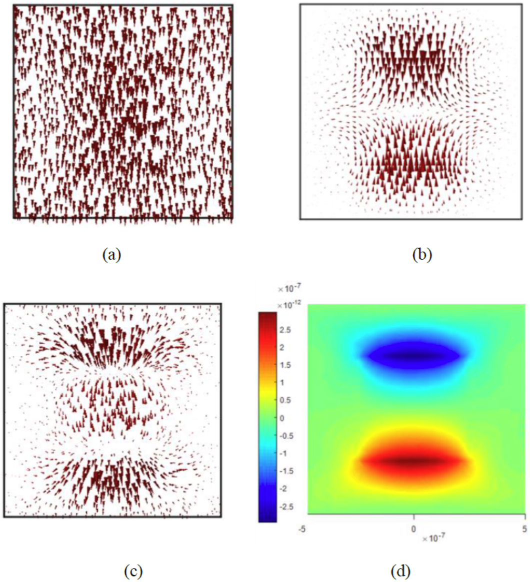
Outline

Field distribution

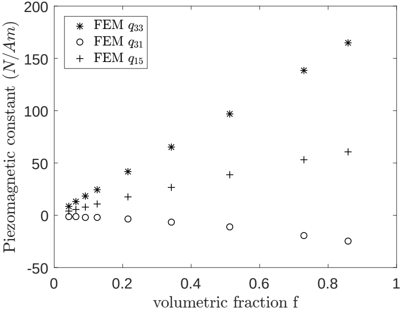


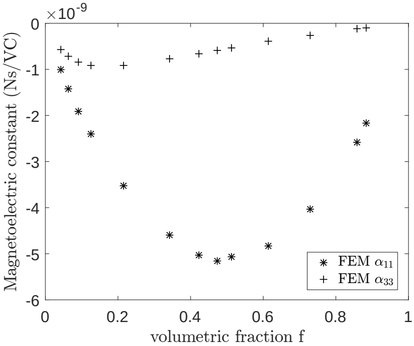
Magnetic field is applied

(a) Magnetic field
(b) Displacement field
(c) Electric field
(d) Electric potential

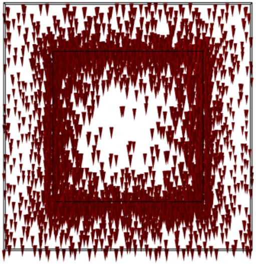


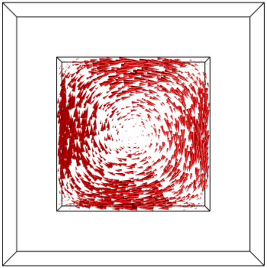
Effective coefficient

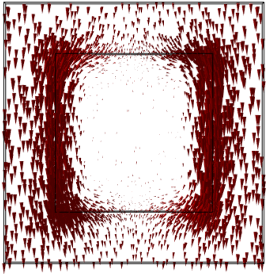


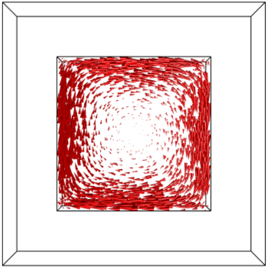


Dynamic analysis









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.

Publication

Homogenization of Magnetoelectric 0–3 Type Composites by 3-D Multiphysics Finite-Element Modeling. *IEEE Transactions on Magnetics* 2019.

3-D Finite Element Analysis of Magnetoelectric Composites Accounting for Material Non-linearity and Eddy Currents. *IEEE Transactions on Magnetics* 2019.

3D FEM modeling and study of novel structure of magnetoelectric composites. *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields* 2019.

THANK YOU FOR YOUR ATTENTION