PhD Thesis Defense

Multiphysic Modeling of Second Generation Magnetoelectric Materials:

Application to Connected Objects

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Plan

1. Introduction
   - Motivation
2. Modeling
   - Static analysis
   - Dynamic analysis
3. Laminate
   - Laminate composite with circular section
   - Laminate composite with rectangular section
4. Homogenization
   - Context
   - Fiber composite
   - Particulate composite
5. Conclusion

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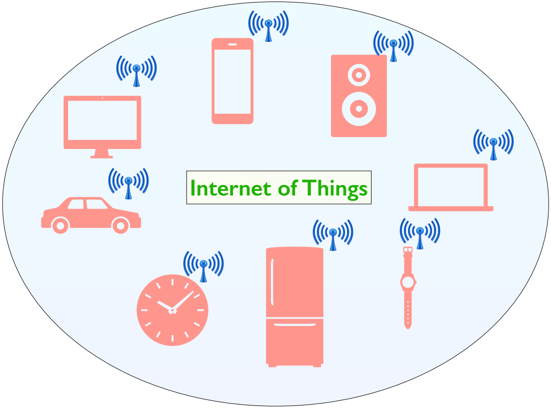
Motivation

Internet of Things

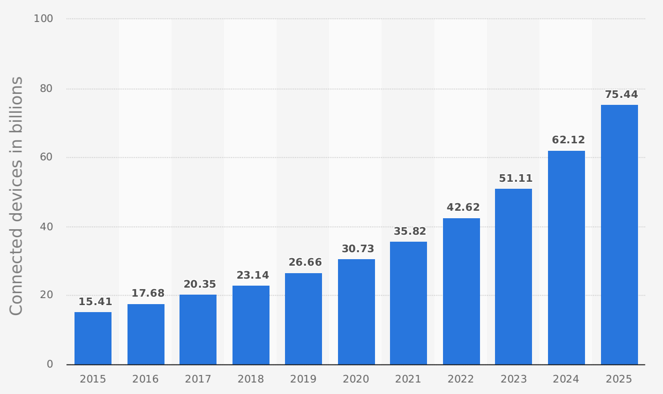
The internet doesn't just connect and distribute information, it can feel and intelligently respond.



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

Motivation

The evolution of IoTs



More devices

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More power requirement

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

Battery as power

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

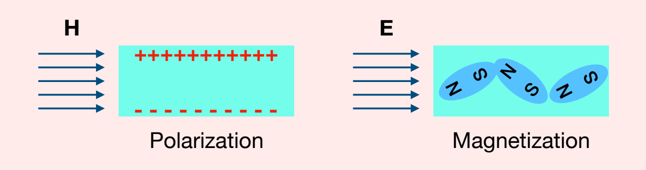
Magnetoelectric materials

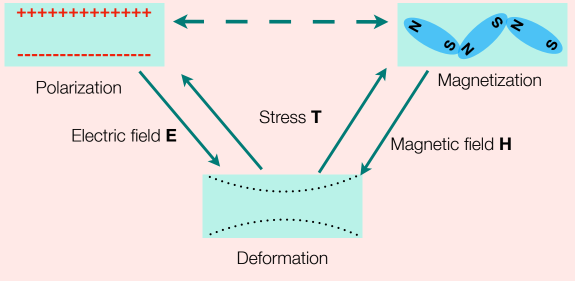
- ✓ Energy harvesting.
- ✓ Profit electromagnetic sources.

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

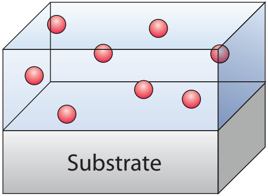
Magnetostrictive material

$+$

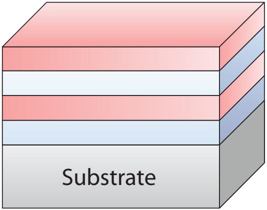
Piezoelectric material

ME composite

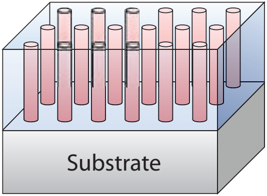
Three types of ME composite



0 - 3 type particulate composite



2 - 2 type laminate composite

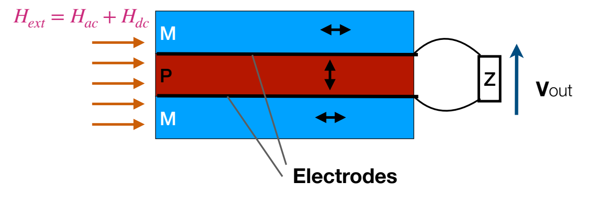


1 - 3 type fiber composite

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

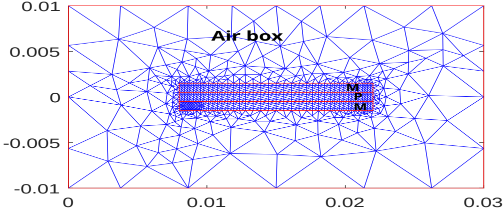
Energy harvesting

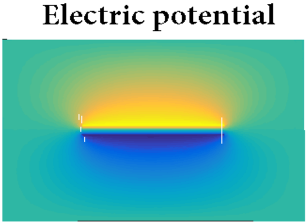
Working principle



- Cochlear implant
- Artificial pacemaker
- Insulin pump

2D model

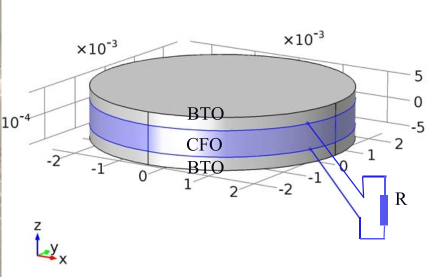




Condition: Laminate composites under the plane strain or stress state.

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 types: particulate composite and fiber composite.

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Problem description

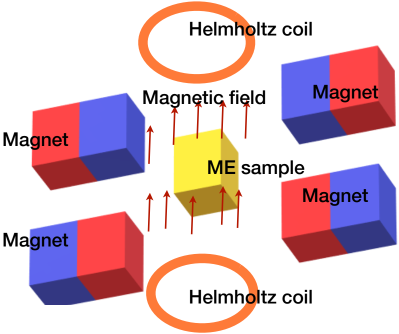
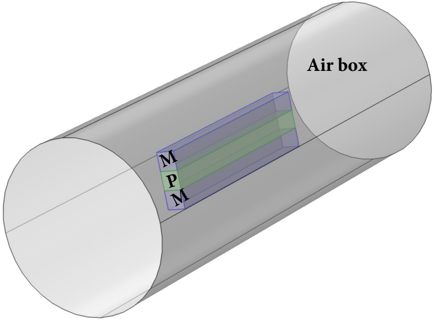


Illustration of ME measurement



3D model

Magnetic Field $\longrightarrow$ Output voltage

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

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

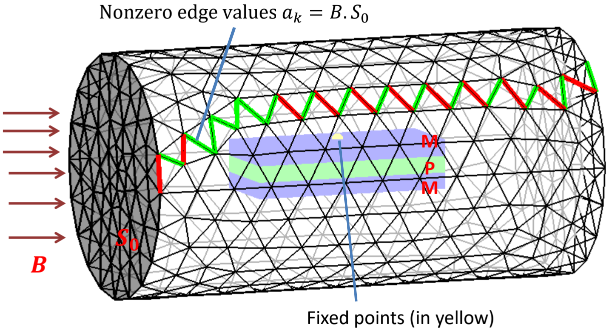
Static analysis

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

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

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

Boundary condition



Static analysis

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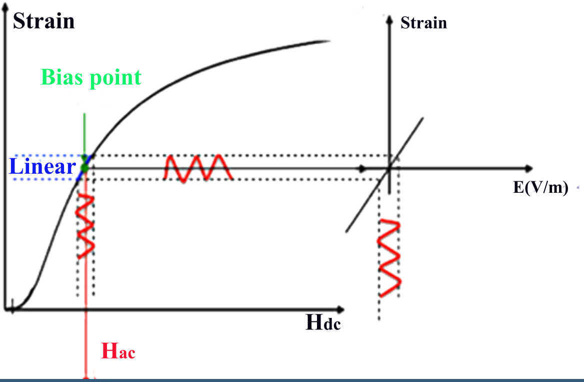
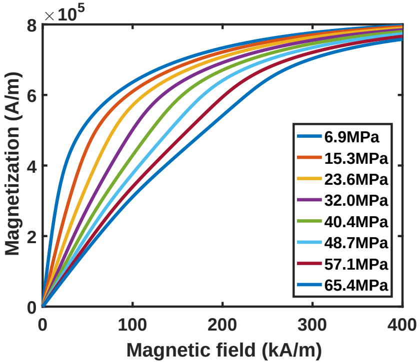
- $\{X\} = \{\boldsymbol{u}, \ \boldsymbol{a}, \ V\}^t$
- $[F] = \{0, \ \Sigma_k a_k, \ 0\}^t$

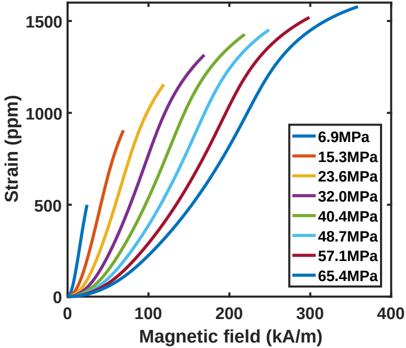
Nonlinear magnetostriction



Nonlinear magnetostriction

Describe the nonlinear behavior by multiscale model





Compute material Jacobian

$$\zeta = \begin{bmatrix} \mu^S = \frac{\partial \boldsymbol{B}}{\partial \boldsymbol{H}}(\boldsymbol{H_0}, \boldsymbol{T_0}) & d = \frac{\partial \boldsymbol{B}}{\partial \boldsymbol{T}}(\boldsymbol{H_0}, \boldsymbol{T_0}) \\ d^t = \frac{\partial \boldsymbol{S}}{\partial \boldsymbol{H}}(\boldsymbol{H_0}, \boldsymbol{T_0}) & s^H = \frac{\partial \boldsymbol{S}}{\partial \boldsymbol{T}}(\boldsymbol{H_0}, \boldsymbol{T_0}) \end{bmatrix}$$

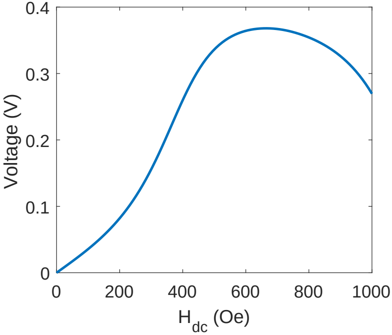
Chakrabarti, S. and Dapino, M. J. (2012). *Fully coupled discrete energy-averaged model for Terfenol-D* Journal of Applied Physics, 111(5), 054505.

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

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Dynamic analysis

- **Elastic equilibrium**

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

- **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**

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

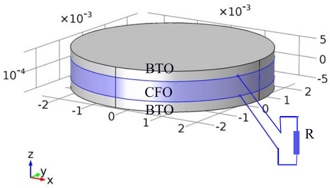
Linear harmonic analysis

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

with:

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

Z : Electrical charge connecting two electrodes.



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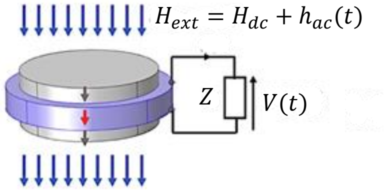
Geometry

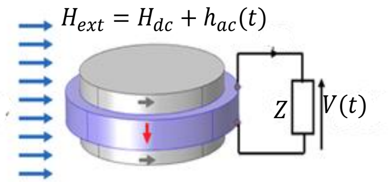
Why laminate composite?

- ✓ 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



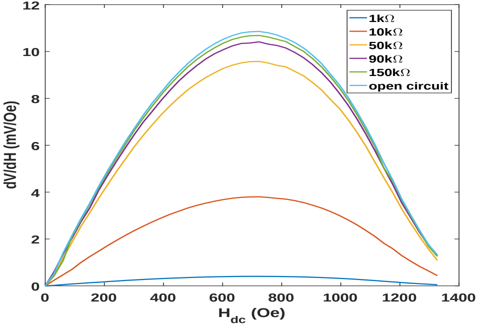


$BaTiO_3$ (gray layer): Thickness 1.5mm, diameter 12mm

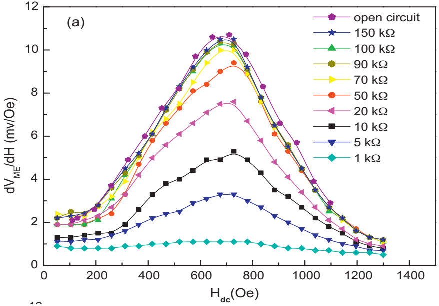
FeGa (magenta layer): Thickness 1mm, diameter 10mm

DC magnetic field dependence

Simulation result



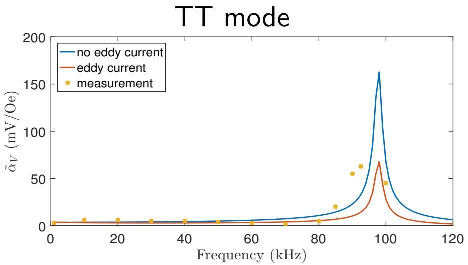
Measurement

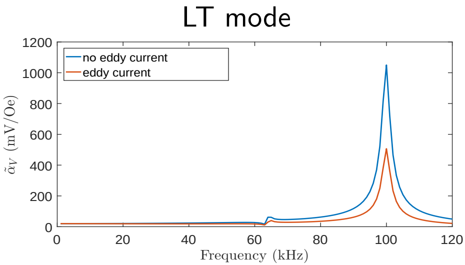


- ME voltage coefficient as a function of DC magnetic field under various electrical resistance load values and external magnetic field: $H_{ac} = 1$ (Oe), $f = 1$ (kHz)
- In concordance with

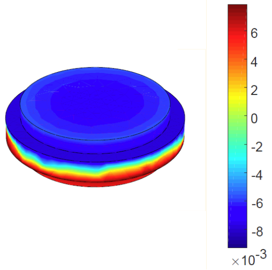
Wang, Lei, et al. 2011. *Effect of load resistance on magnetoelectric properties in FeGa/BaTiO3/FeGa laminate composites.* Journal of Alloys and Compounds

Eddy current effect



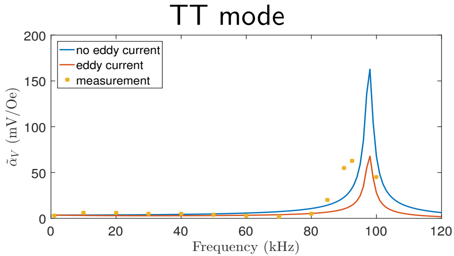


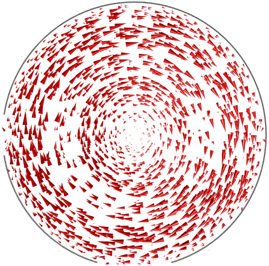
- The magnetic external field: $H_{ac} = 1$ (Oe)
- The result with effect of eddy current in TT mode in concordance with measurment
- The quality factor decreases under eddy current effect.



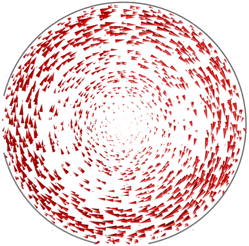
Electrical potential distribution

Skin effect

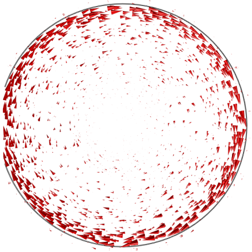




1 kHz

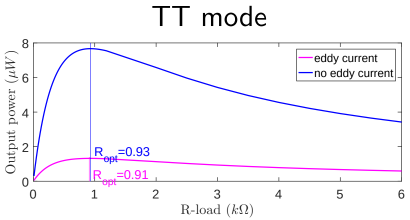


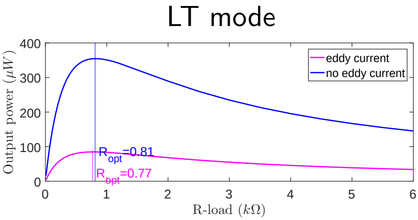
10 kHz



100 kHz

Performance





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

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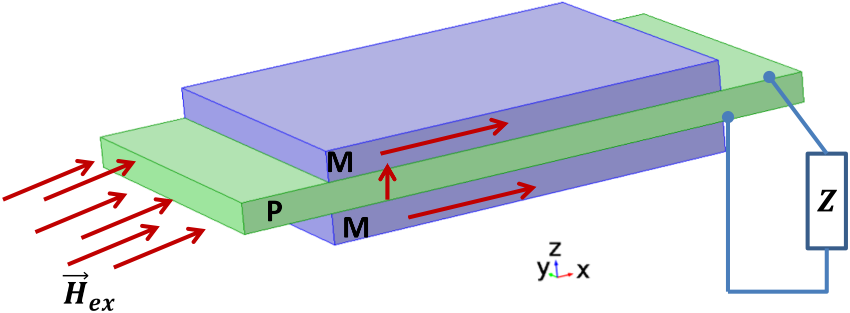
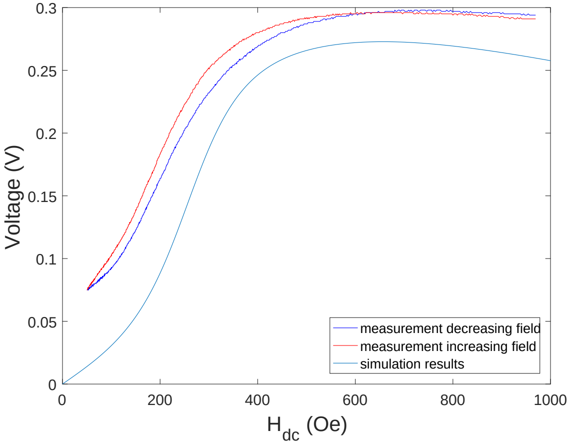
Geometry



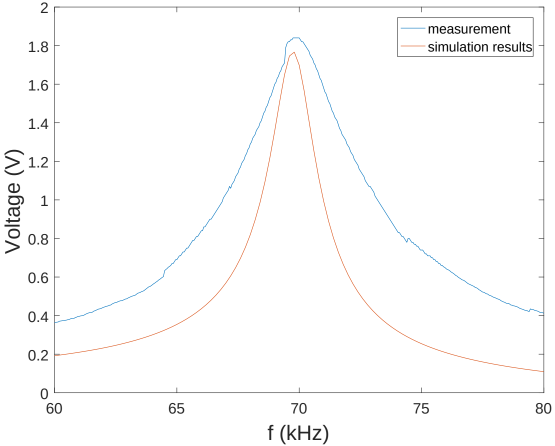
P51 (green layer): Thickness 1mm, surface 14x10 mmxmm
Terfenol-D (magenta layer): Thickness 1mm, surface 20x10 mmxmm

DC magnetic field dependency



- H_{dc} increases step by step from 0 Oe to 1000 Oe.
- Output voltage at dynamic field $H_{ac} = 5$ Oe @ 1 kHz
- Maximum output voltage is obtained at $H_{dc} = 650$ Oe

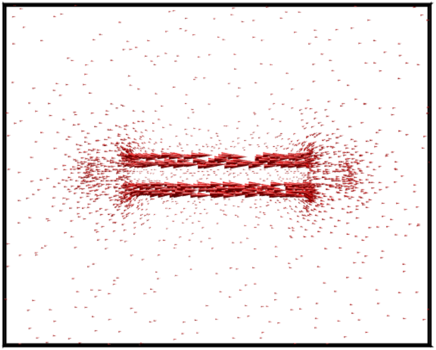
Frequency dependency



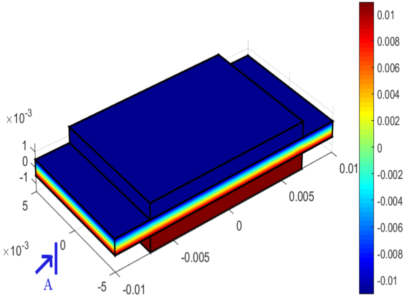
- Computed coefficients obtained at $H_{dc} = 650$ Oe are used for dynamic analysis $H_{ac} = 5$ Oe
- Frequency varies from 60 Oe to 80 Oe
- Maximum output voltage is obtained at resonance frequency $f = 70$ kHz

Field distribution

Magnetic induction distribution



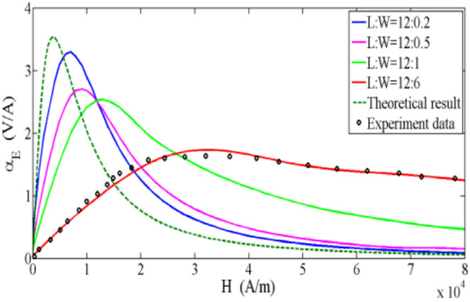
Electric potential distribution

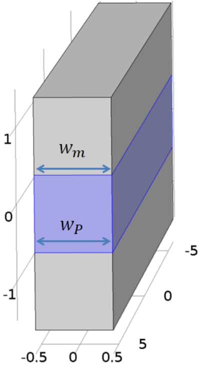


- High value of magnetic induction at magnetostrictive layer
- Polarization is observed at piezoelectric layer
- To increase the efficiency, the study of different ME structures is followed

Geometry

Decreasing of the width can generate higher output voltage

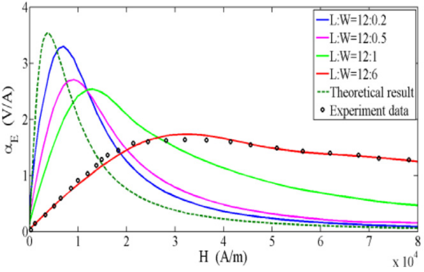


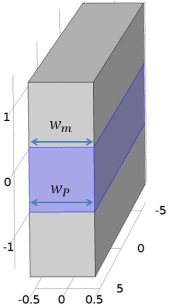


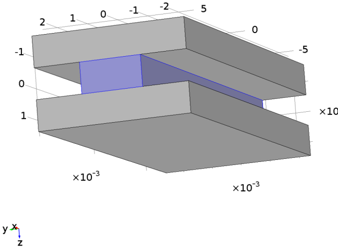
Wen, J. et al., 2008 *A coupling finite element model for analysis the nonlinear dynamic magnetoelectric response of tri-layer laminate composites.* Composite Structures

Geometry

Decreasing of the width can generate higher output voltage



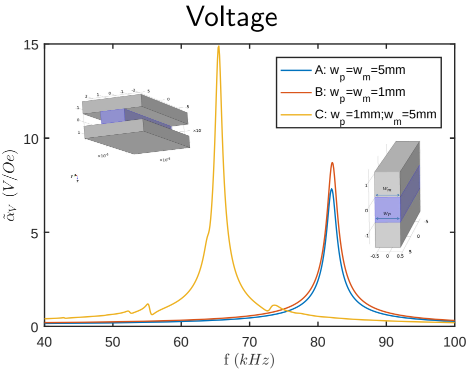


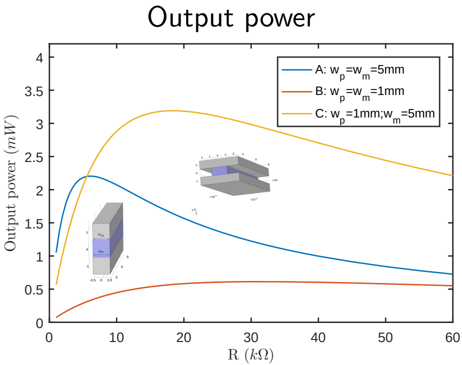


Three configurations are examined

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.

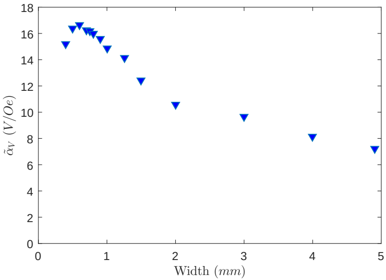
Performance

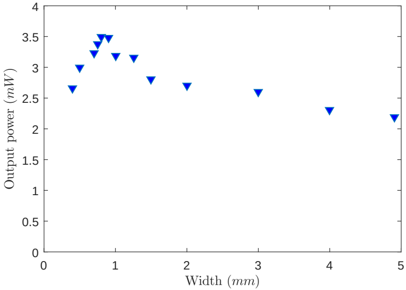


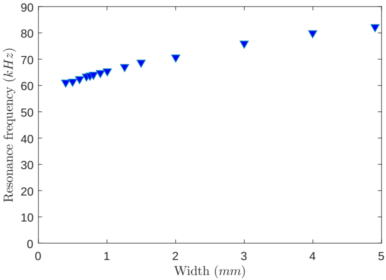


- Novel structure can generate higher output voltage and more output power.
- Influence of width can be studied.

Parametric study







- Highest value of output voltage and power can be obtained at piezoelectric width of 0.8 mm
- Resonance frequency decreases when the width increases (the structure is more rigid).

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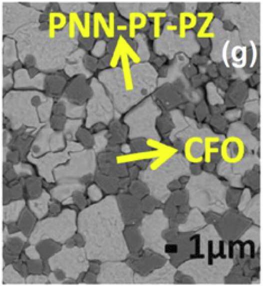
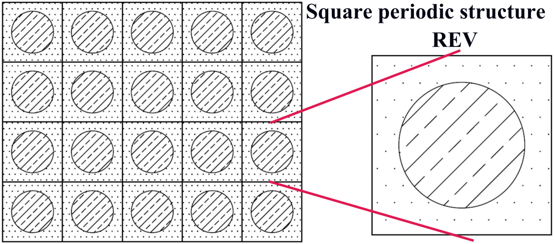
0-3 type and 1-3 type ME composite

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

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



- The size of the particles is very small.
- The mesh is heavy.



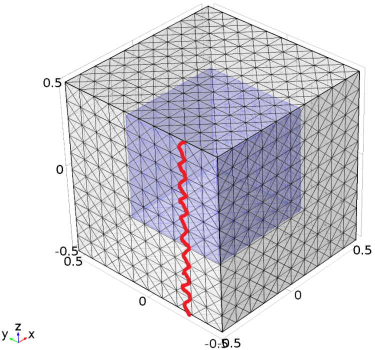
Vadla, S. et al. (2016) *Magnetoelectric coupling in 0.5 Pb (Ni1/3Nb2/3) O30.35 PbTiO30.15 PbZrO3 and CoFe2O4 based particulate composites.* Scripta Materialia

Analytical method → Simple structure (Fiber composite)

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

Boundary condition

- Boundary surfaces must be similar.
- On the boundary surfaces:
  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

$$a(k_{i1} + d_i, k_{i2} + d_i) = a(k_{i1}, k_{i2}) + c_j \phi_j + c_k \phi_k \qquad \phi_j = \int \boldsymbol{B}_j dA$$

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

A : the perpendicular surface

Effective coefficients

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

$\downarrow$

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

$\downarrow$ 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 $\boldsymbol{S}, \quad \boldsymbol{B}, \quad \boldsymbol{E}$

$\downarrow$ 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 $\boldsymbol{T}, \quad \boldsymbol{H}, \quad \boldsymbol{D}$

$\downarrow$ Volume average

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

$\downarrow$

Material coefficients

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

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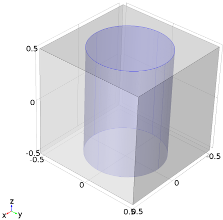
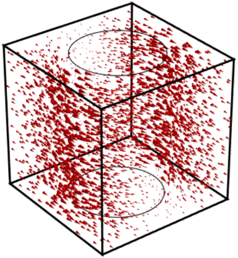
Apply of magnetic field

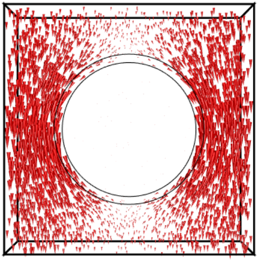


- Magnetostrictive matrix ($CoFe_2O_4$) reinforced by fiber piezoelectric ($BaTiO_3$).
- The volume fraction varies $f = 0$ to $f = 0.8$.

Example: Magnetic field is applied

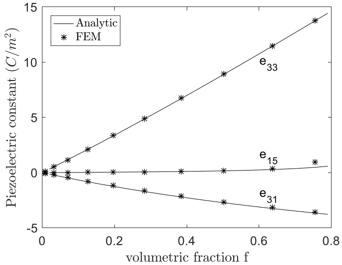


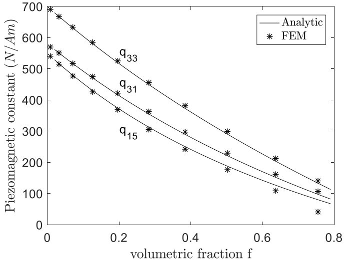
3D view

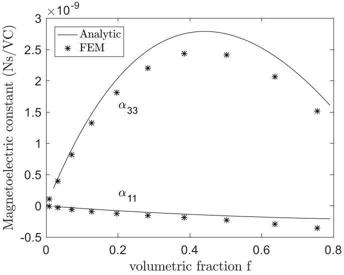


Top view

Effective coefficient







- Simulation results show good concordance with analytical results.
- Local ME coefficient is observed.

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

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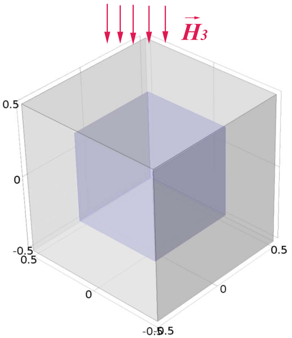
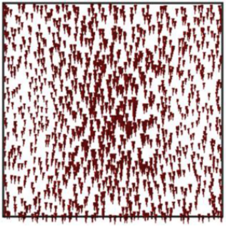
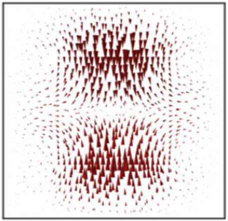
Field distribution

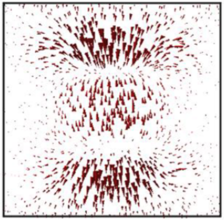




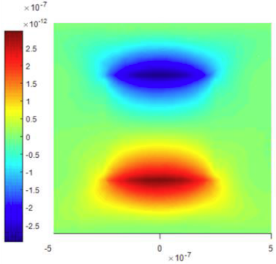
(a)



(b)



(c)

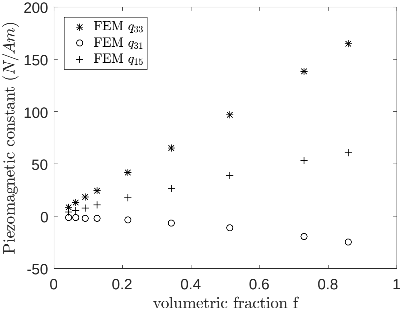


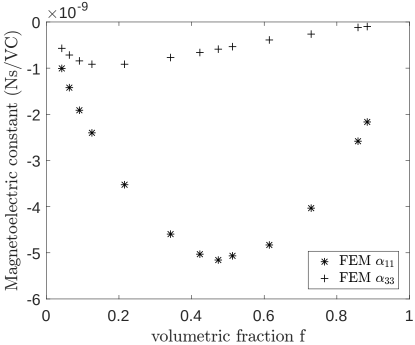
(d)

Magnetic field is applied

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

Effective coefficient

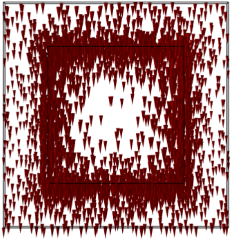




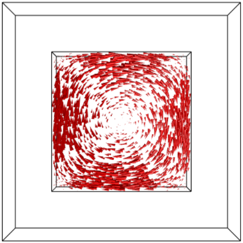
- Piezomagnetic coefficient increases when the magnetostrictive volume fraction increases.
- The optimal ME coefficient is observed ($f = 0.5$).

Dynamic analysis

Distribution of:
(a) Magnetic induction
(b) Eddy currents
at 300 kHz

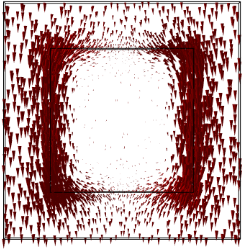


a

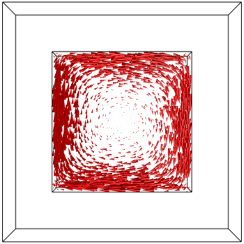


b

Distribution of:
(c) Magnetic induction
(d) Eddy currents
at 3 MHz



c



d

Skin effect is observed

Conclusion and perspectives

Conclusion

- A 3D FEM has been developed for analyze the behavior of ME materials.
- Linear harmonic ME analysis and non-linear magnetostrictive analysis have been performed for laminate composite. The 3D analysis provides a useful tool to study ME composite of various geometries for energy transducer. Novel laminate structure has been studied.
- For particulate composite and fiber composite, the homogenization theory is applied.

Perspectives

- Other formulations for analyzing nonlinear magnetostrictive can be tested.
- A more efficient method for solving large matrix equations is needed.
- Other structure can be considered to improve ME coefficient.

Publication

Homogenization of Magnetoelectric 03 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