SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

PhD Thesis Defense

Multiphysic Modeling of Second Generation Magnetoelectric Materials:

Application to Connected Objects

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Supervisor : Aurelie Gensbittel

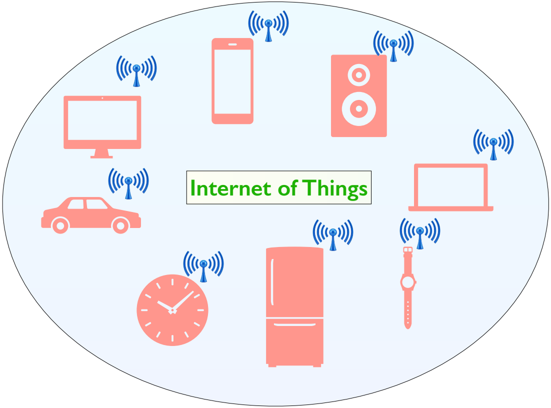
Plan

Outline

Motivation

Internet of Things

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

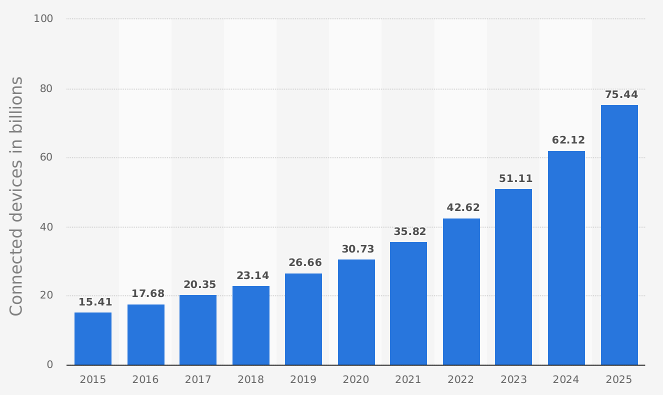


Envisaged applications

- Improved public safety
- Energy-efficient buildings
- Digitised healthcare system
- ...

Motivation

The evolution of IoTs



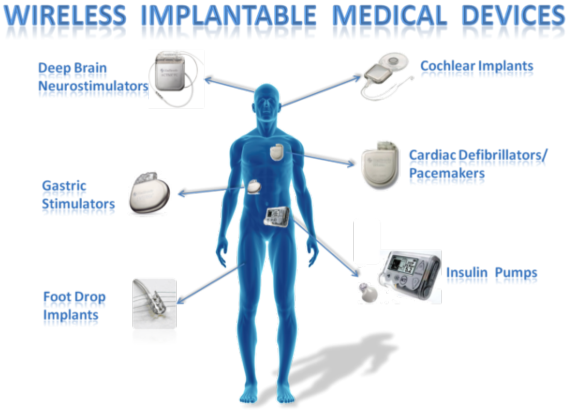
More devices

↓

More power requirement

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

Motivation



More devices

↓

More power requirement

infiniteinformation-technology.com *Internet of Things in the Medical Device Industry*

Battery as power

- ✗ Replacement difficulty
- ✗ Need cable for charging

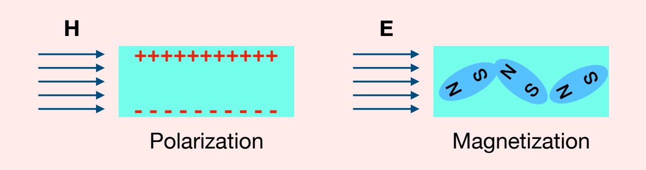
Magnetoelectric materials

- ✓ Wireless power transfer
- ✓ Magnetic energy → Electric energy

Magnetoelectric (ME) effect

Definition

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



Magnetoelectric (ME) effect

Definition

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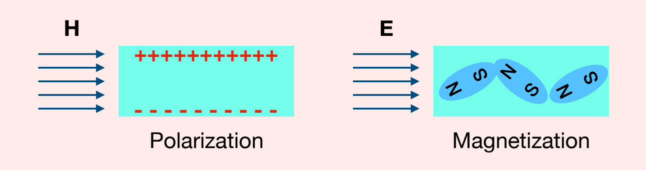
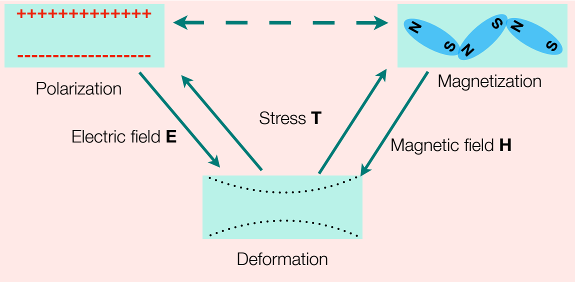




ME composite

Magnetostrictive material

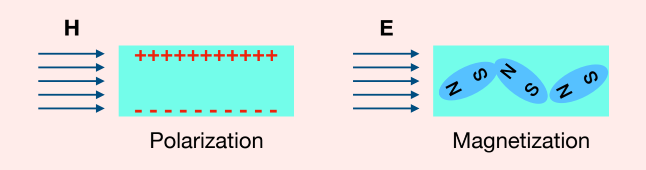
+

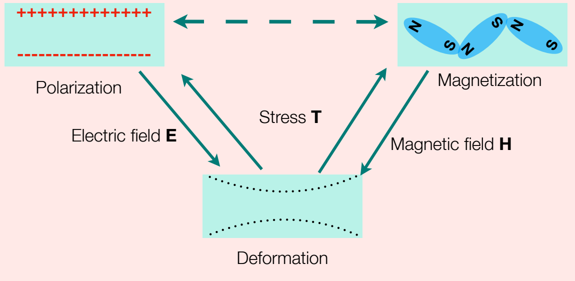
Piezoelectric material

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

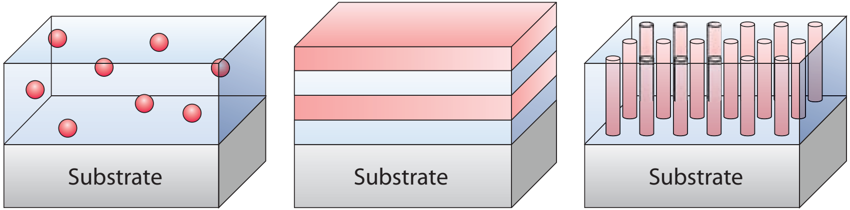
Magnetostrictive material

+

Piezoelectric material

ME composite

Three types of ME composite



0 - 3 type particulate composite

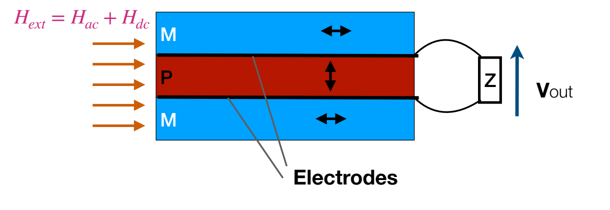
2 - 2 type laminate composite

1 - 3 type fiber composite

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

Wireless power transfer

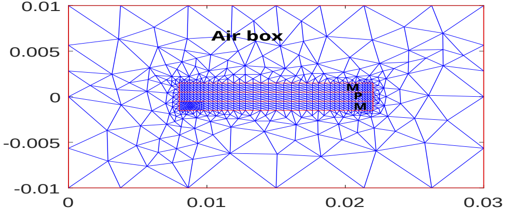
Working principle

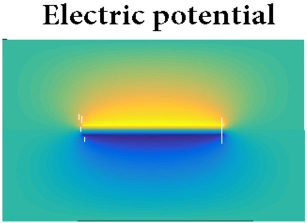


Potential examples healthcare:

- Cochlear implant
- Artificial pacemaker
- Insulin pump

2D model

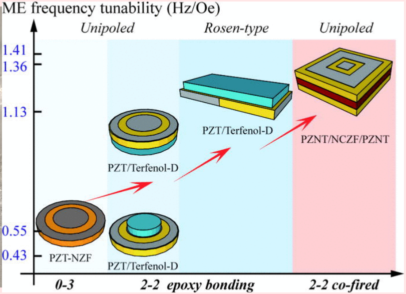




Condition: Laminate composites under the plane strain or stress state.

Context

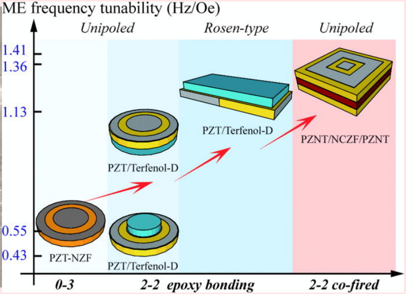
3D model is needed



Zhou, Y., Yan, Y., & Priya, S. (2014). *Co-fired magnetoelectric transformer.* Applied Physics Letters, 104(23), 232906.

Context

3D model is needed



Thesis works

- Develop a 3D FEM to consider complex structure.
- Analyze laminate composites (circular section, rectangular section), novel structures.
- Study different types: particulate composites and fiber composites.

Outline

Problem description

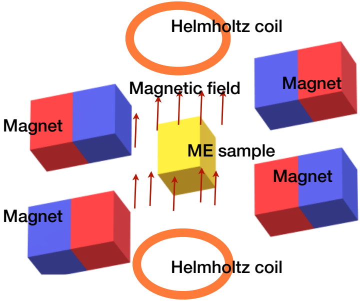
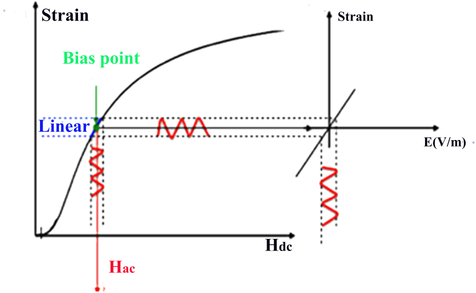


Illustration of ME measurement (L2E)



Bias point

Nonlinear static analysis $\longrightarrow$ Linear harmonic analysis

Outline

General multiphysic equations

Static regime

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

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

3D FEM formulation

Variational formulation

$$\begin{cases} \displaystyle\int_\Omega \mathfrak{D}\boldsymbol{u}'(c\mathfrak{D}\boldsymbol{u} + e^t \text{grad } V - h^t \text{curl } \boldsymbol{a})d\Omega = 0 \\ \displaystyle\int_\Omega \text{curl } \boldsymbol{a}'(-h\mathfrak{D}\boldsymbol{u} + \nu \text{curl } \boldsymbol{a})d\Omega = 0 \\ \displaystyle\int_\Omega \text{grad } V'.(e\mathfrak{D}\boldsymbol{u} - \varepsilon^S \text{grad } V)d\Omega = 0 \end{cases}$$

FE discretization

- Nodal element

$$\begin{cases} \boldsymbol{u}_h = w^n \boldsymbol{u}_h^k \\ V_h = w^n V_h^k \end{cases}$$

- Edge element

$$\boldsymbol{a}_h = \boldsymbol{w}^e \boldsymbol{a}_h^k$$

3D piezoelectric model

+

3D magnetostrictive model

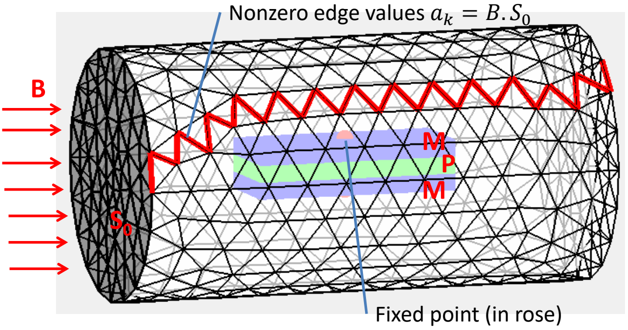
Zhi Qin. *Finite Element Modeling and PGD Based Model Reduction for Piezoelectric & Magnetostrictive Materials.* PhD Thesis 2016.

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 conditions



Nonlinear magnetostriction

Describe the nonlinear behavior by discrete energy averaged model (DEAM)

- Energy of a domain close to the easy axis $\boldsymbol{c}^k$

$$G^k = \frac{1}{2}K^k|\boldsymbol{m}^k - \boldsymbol{c}^k|^2 - \boldsymbol{S}_m^k \cdot \boldsymbol{T} - \mu_0 M_s \boldsymbol{m}^k \cdot \boldsymbol{H}$$

- The magnetization and the magnetostriction

$$\begin{cases} \boldsymbol{S}_m = \Sigma_{k=1}^6 \xi_{an}^k \boldsymbol{S}_m^k \\ \boldsymbol{M} = M_s \Sigma_{k=1}^6 \xi_{an}^k \boldsymbol{m}^k \end{cases}$$

- The magnetic induction and the strain

$$\begin{cases} \boldsymbol{S} = s\boldsymbol{T} + \boldsymbol{S}_m \\ \boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M}) \end{cases}$$

- 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., & Dapino, M. J. (2011). *Nonlinear finite element model for 3D Galfenol systems.* Smart Materials and Structures, 20(10), 105034.

DEAM

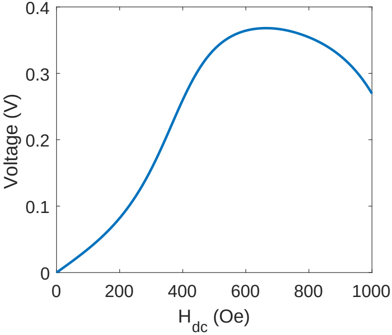
- ✓ Energy weighted summation of only six terms
- ✓ Compute material coefficients by analytic differential

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
$[\Delta \boldsymbol{U}, \Delta \boldsymbol{a}, \Delta V] = mat\_UAV \setminus \Delta \boldsymbol{F}$

↓

$[\Delta S, \Delta B, \Delta E] = state\_eq([\Delta \boldsymbol{U}, \Delta \boldsymbol{a}, \Delta V])$
$[\Delta H, \Delta T] = const.law(\Delta B, \Delta S)$

↓

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

✓ Preserve the spatial inhomogeneity in the material coefficients.

Outline

Dynamic analysis

- **Elastic equilibrium**

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

- **Ampere's theorem**

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

Introduce time primitive of electric potential (Faraday's law)

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

- **Gauss's law**

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

- **Electrical charge**

$$U = -Z\frac{dQ}{dt}$$

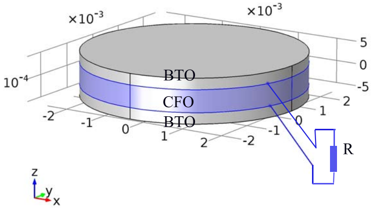
Linear harmonic analysis

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

with:

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

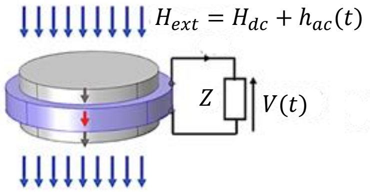
- Z : Electrical charge (R) connecting two electrodes.
- $\boldsymbol{C}_{uu} = \alpha \boldsymbol{M}_{uu} + \beta \boldsymbol{K}_{uu}$

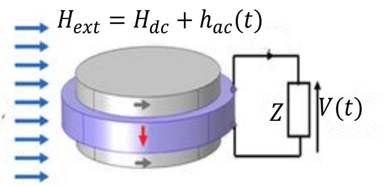


Outline

Geometry

Mode TT	Mode LT





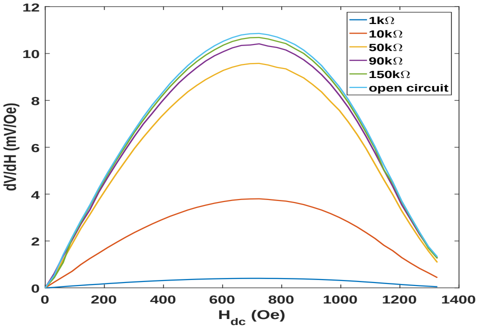
$BaTiO_3$ (gray layer): Thickness 1.5mm, diameter 12mm

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

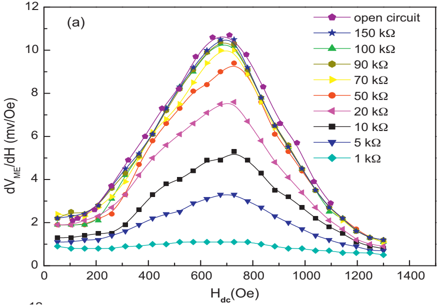
Wang, Lei, et al. *Effect of load resistance on magnetoelectric properties in FeGa/BaTiO3/FeGa laminate composites.* Journal of Alloys and Compounds 509.30 (2011): 7870-7873.

DC magnetic field dependence

Simulation results



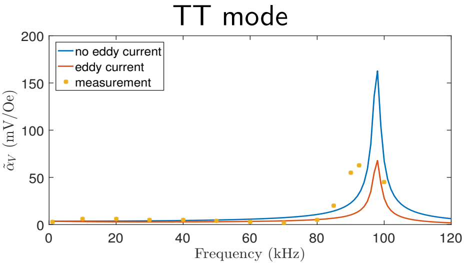
Measurement

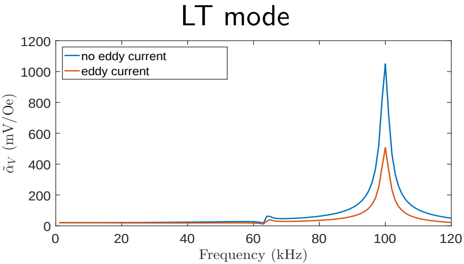


- ME voltage coefficient as a function of DC magnetic field under various electrical resistance load values and external magnetic field: $H_{ac} = 1$ (Oe), $f = 1$ (kHz)
- In concordance with

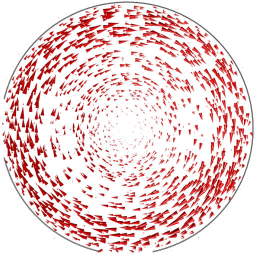
Wang, Lei, et al. 2011. *Effect of load resistance on magnetoelectric properties in FeGa/BaTiO3/FeGa laminate composites.* Journal of Alloys and Compounds

Eddy current effect

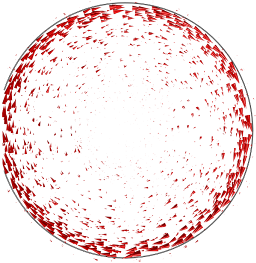




- The magnetic external field: $H_{ac} = 1$ (Oe)
- Eddy currents effect is observed.
- Skin effect is observed.

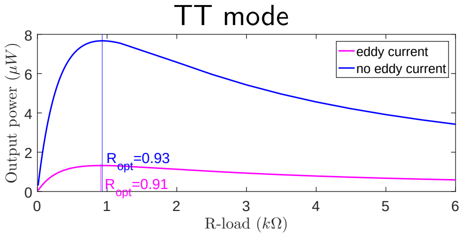


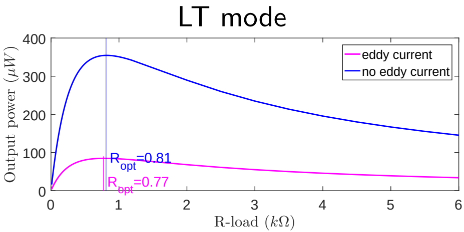
10 kHz



100 kHz

Performance





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

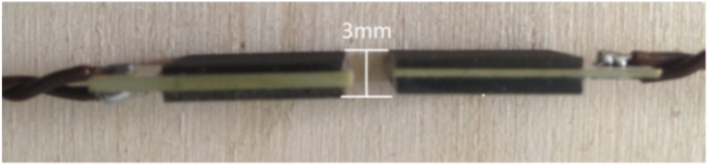
Conclusion

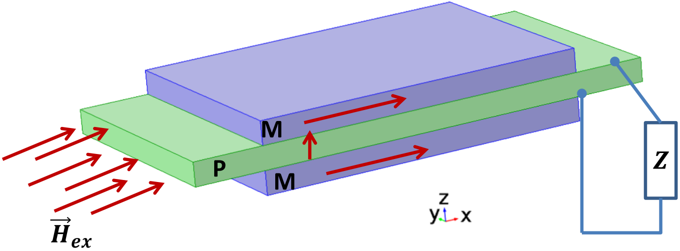
✓ Showing dependence of ME coefficient on static magnetic field, taking into account the eddy currents effect in dynamic regime.

✗ Damping effect, the influence of mechanical coupling.

Outline

Geometry



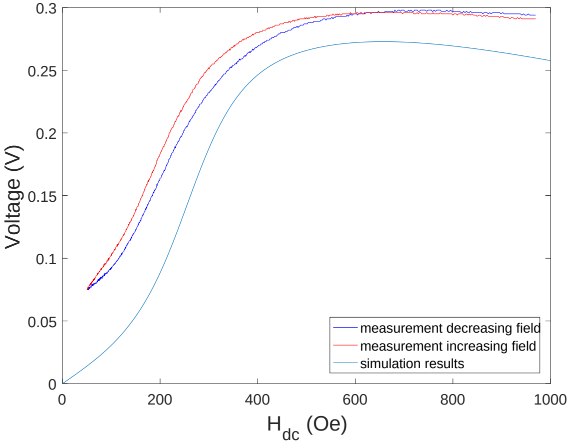


P51 (green layer): Thickness 1mm, surface 14x10 mmxmm

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

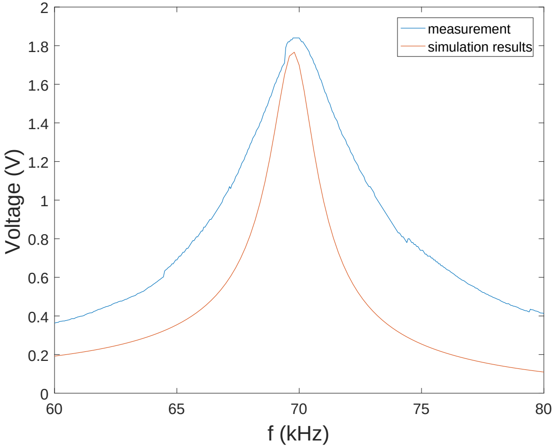
Kevin Malleron 2018. *Modelisation multiphysique, caracterisation et conception de transducteurs magnetoelectriques pour lalimentation de capteurs biomedicaux autonomes.* Phd Thesis.

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

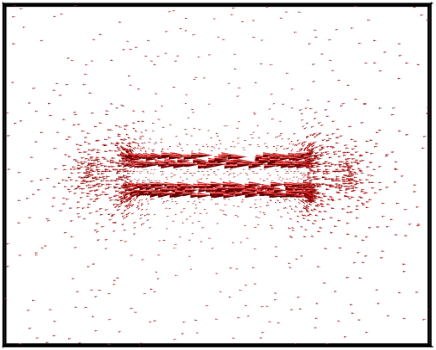
Frequency dependency



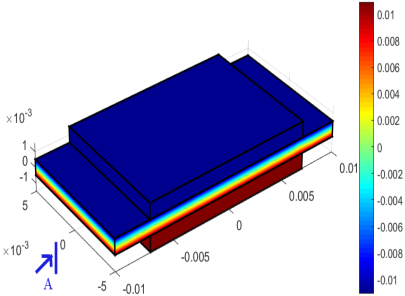
- Computed coefficients obtained at $H_{dc} = 650$ Oe are used for dynamic analysis $H_{ac} = 5$ Oe
- Frequency varies from 60 kHz to 80 kHz
- Maximum output voltage is obtained at resonance frequency $f = 70$ kHz

Field distribution

Magnetic induction distribution



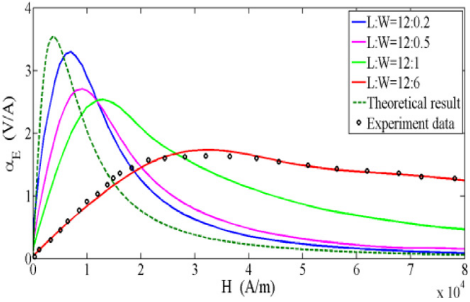
Electric potential distribution

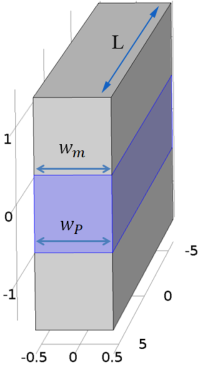


- High value of magnetic induction at magnetostrictive layer
- Polarization is observed at piezoelectric layer
- To increase the efficiency, the study of different ME structures is followed

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

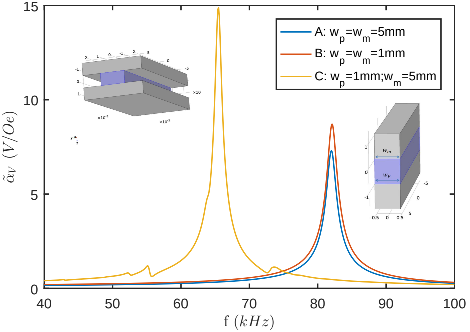
Performance

Three configurations are examined

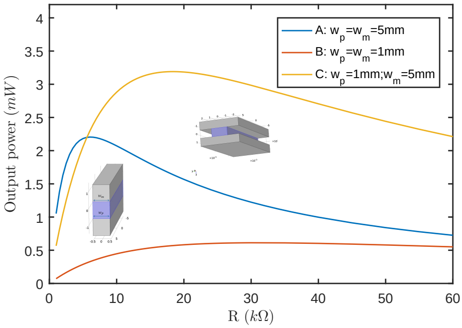
A. Width of 5mm for all layers. B. Width of 1mm for all layers.

C. Width of 5mm for m-layer and width of 1mm for p-layer.

Voltage

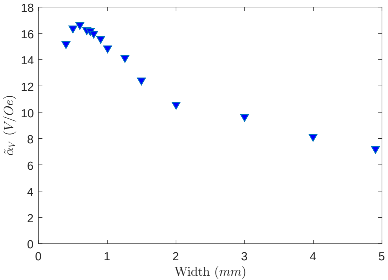


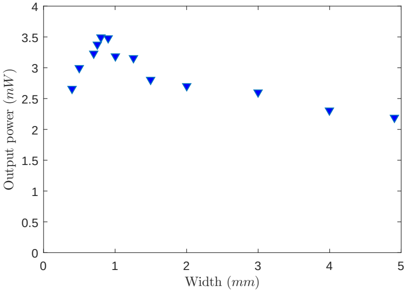
Output power

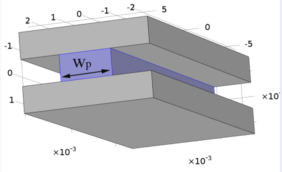


- Novel structure C generates higher output voltage power.
- Influence of width can be studied.

Parametric study



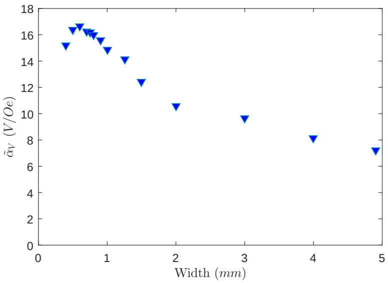


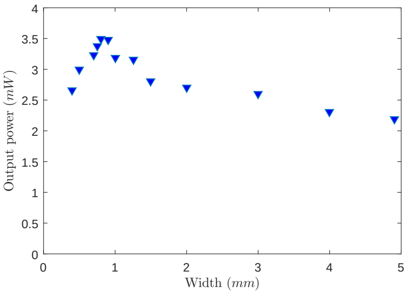


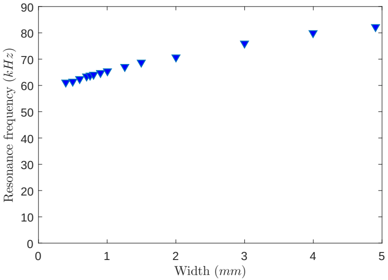
$w_p = 0.5 \rightarrow 5$ mm

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

Parametric study







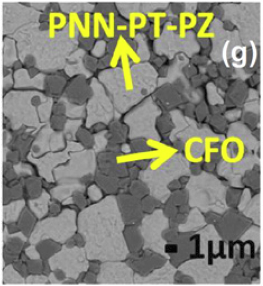
- Highest value of output voltage and power can be obtained at piezoelectric width of 0.8 mm.
- Resonance frequency increases when the width increases (the structure is more rigid).

Outline

0-3 type and 1-3 type ME composite

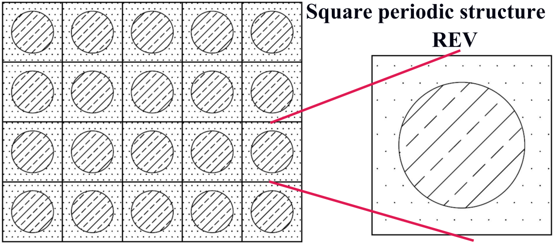
✓ 3D FEM is useful to study the behavior of ME laminate composite

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



→

- 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 magnetoelectroelastic behavior.* Physical Review B.

0-3 type and 1-3 type ME composite

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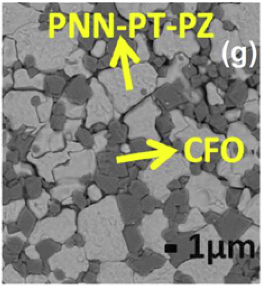

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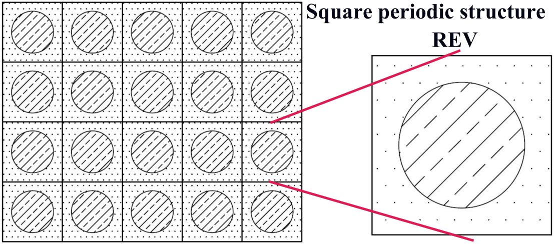
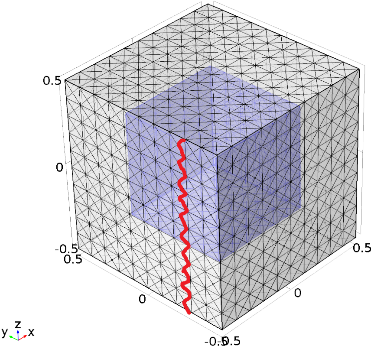


Vadla, S. et al. (2016) *Magnetoelectric coupling in 0.5 Pb (Ni1/3Nb2/3) O30.35 PbTiO30.15 PbZrO3 and CoFe2O4 based particulate composites.* Scripta Materialia

FEM analysis for REV → More complicated inclusion

Boundary condition

- Same mesh for opposite boundary surfaces.
- 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

Apply respectively $\bar{\boldsymbol{S}}, \bar{\boldsymbol{B}}, \bar{\boldsymbol{E}}$:

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

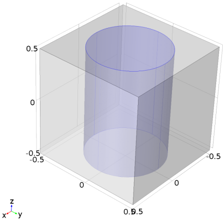
Local field $\boldsymbol{T}, \quad \boldsymbol{H}, \quad \boldsymbol{D}$

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

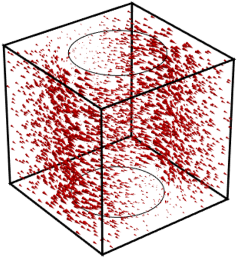
Outline

Fiber composite

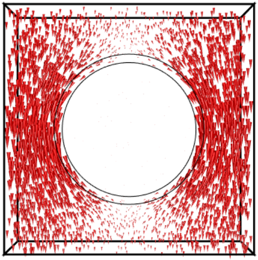


- Magnetostrictive matrix ($CoFe_2O_4$) reinforced by fiber piezoelectric ($BaTiO_3$).
- The volume fraction varies $f = 0$ to $f = 0.8$.

Example:
Magnetic field is applied
μ, q, α

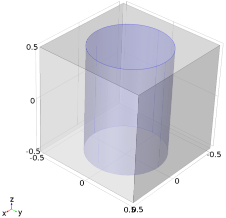


3D view



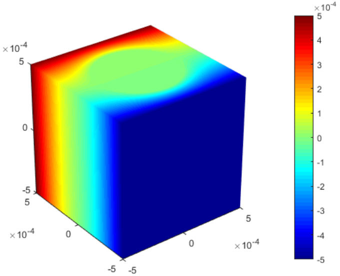
Top view

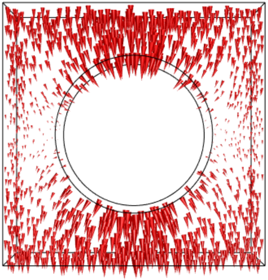
Fiber composite



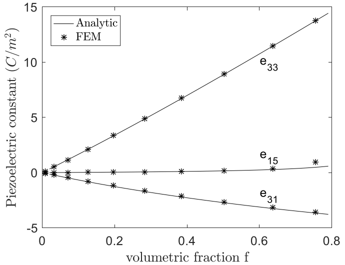
- Magnetostrictive matrix ($CoFe_2O_4$) reinforced by fiber piezoelectric ($BaTiO_3$).
- The volume fraction varies $f = 0$ to $f = 0.8$.

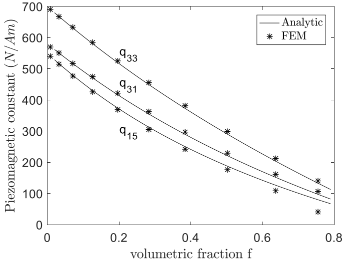
Example: Electric field is applied. ϵ, e, α

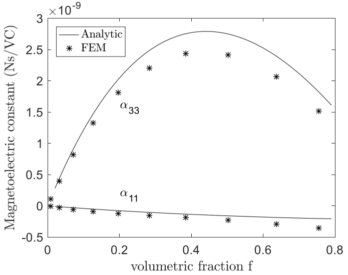




Effective coefficient





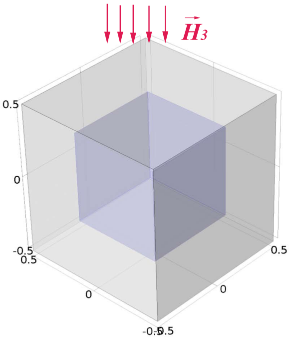


- Simulation results show good concordance with analytical results.
- Local ME coefficient is observed.

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

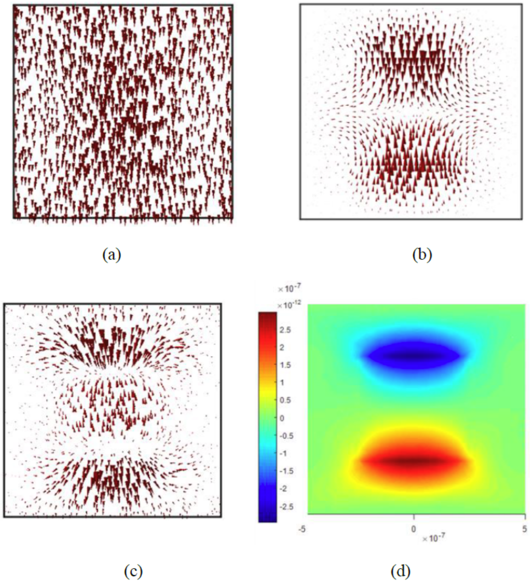
Outline

Field distribution

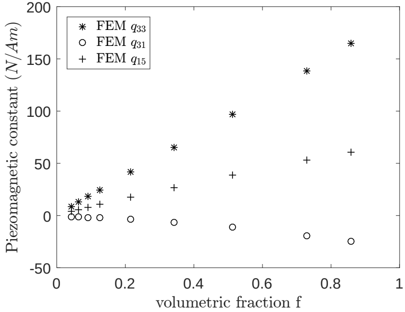


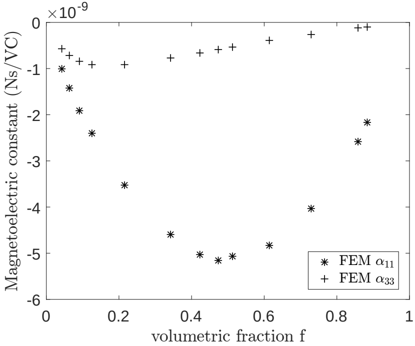
Magnetic field is applied

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



Effective coefficient

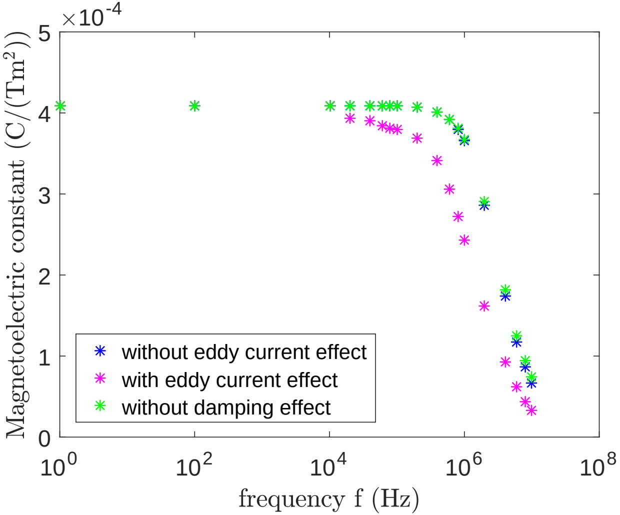




- Piezomagnetic coefficient increases when the magnetostrictive volume fraction increases.
- The optimal ME coefficient is (obtained @ $f = 0.5$) $5 * 10^{-9} Ns/VC$.

✓ Apply for more complicated inclusion, whatever the number of phases.

Dynamic analysis

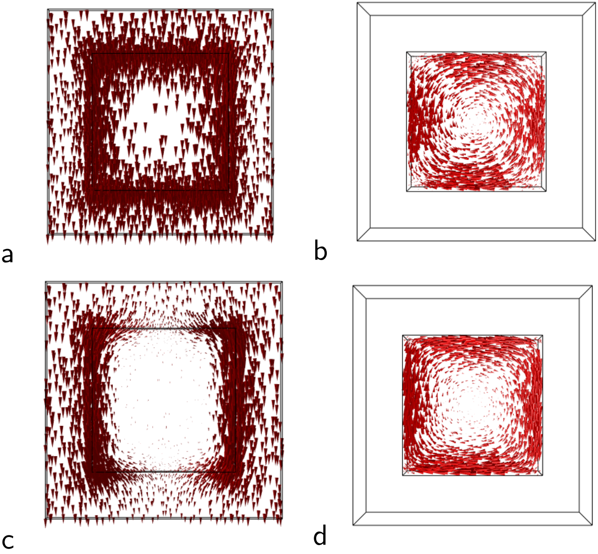


- REV of 1 mm dimension
- Particulate composite with magnetostrictive volume fraction = 0.6
- The frequency changes from 1 Hz to 10 MHz

Dynamic analysis

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

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



Skin effect is observed

Conclusion and perspectives

Conclusion

- A 3D FEM has been developed to analyze the behavior of ME materials.
- Non-linear magnetostrictive analysis and linear harmonic ME analysis have been performed for laminate composite.
- Novel laminate structure has been studied.
- Homogenization theory is applied for particulate composite and fiber composite.

Perspectives

- Other methods for analyzing nonlinear magnetostrictive can be tested.
- Analyze the behavior of particulate composite and fiber composite, REV with more complicated inclusion.
- Other structures 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

Appendix