

PhD Thesis Defense

Multiphysic Modeling of Second Generation Magnetolectric Materials: Application to Connected Objects

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1 Introduction

- Motivation

2 3D Multiphysic Modeling

- Configuration
- Static analysis
- Dynamic analysis

3 Laminate Composite

- Laminate composite with circular section
- Laminate composite with rectangular section

4 Homogenization

- Context
- Fiber composite
- Particulate composite

5 Conclusion

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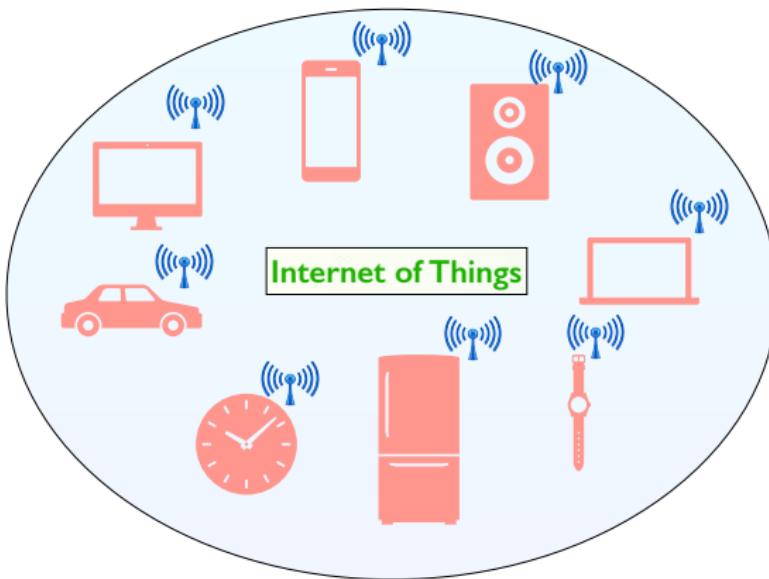
- Context
- Fiber composite
- Particulate composite

5 Conclusion

Motivation

Internet of Things

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

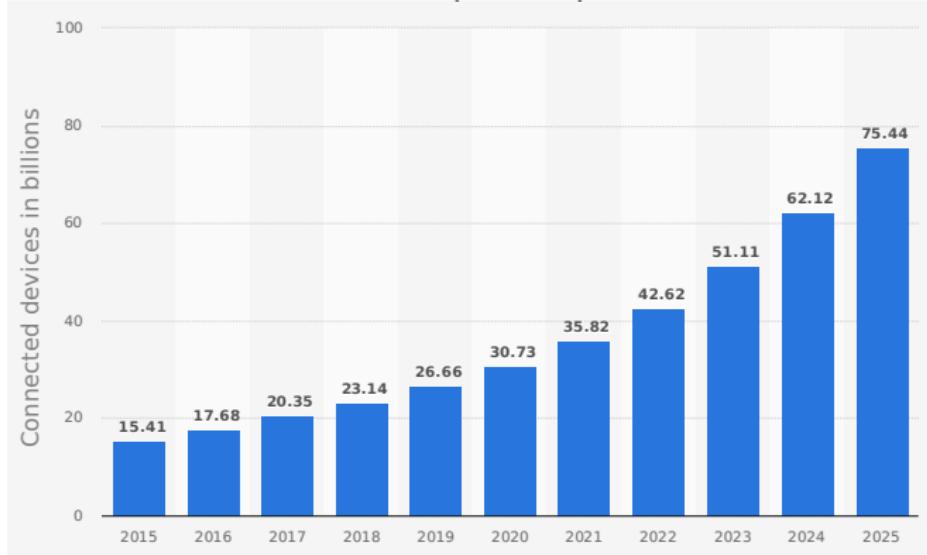


Envisaged applications

- 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.

Battery as power

- Replacement difficulty
- Need cable for charging

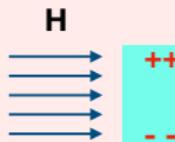
Magnetoelectric materials

- Wireless power transfer
- Magnetic energy → Electric energy

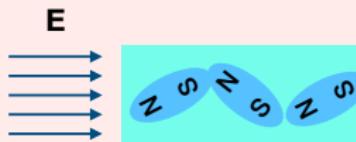
Magnetoelectric (ME) effect

Definition

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



Polarization

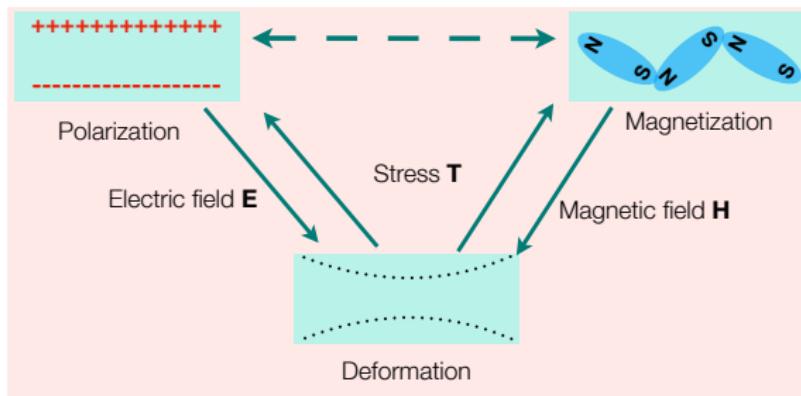


Magnetization

Magnetoelectric (ME) effect

Definition

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



ME composite

Magnetostrictive
material

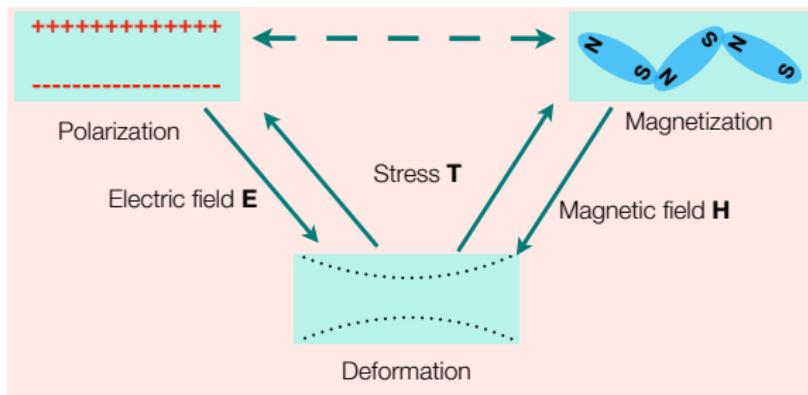


Piezoelectric material

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

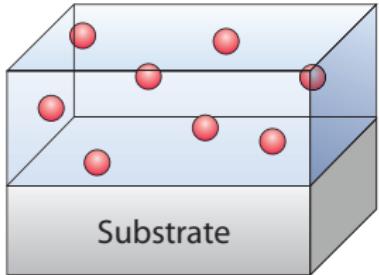
Magnetostrictive
material



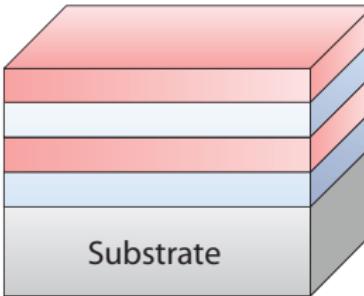
Piezoelectric material

ME composite

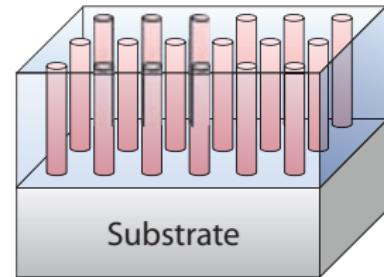
Three types of ME composite



0 - 3 type particulate composite



2 - 2 type laminate composite

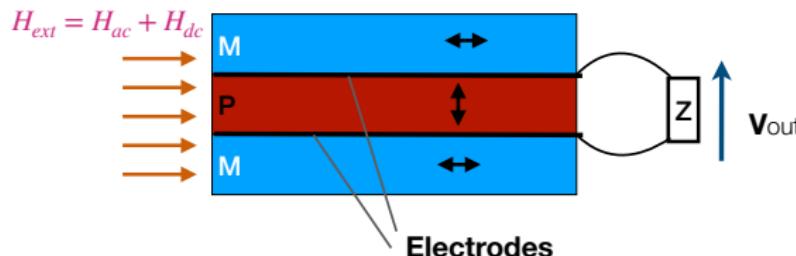


1 - 3 type fiber composite

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

Wireless power transfer

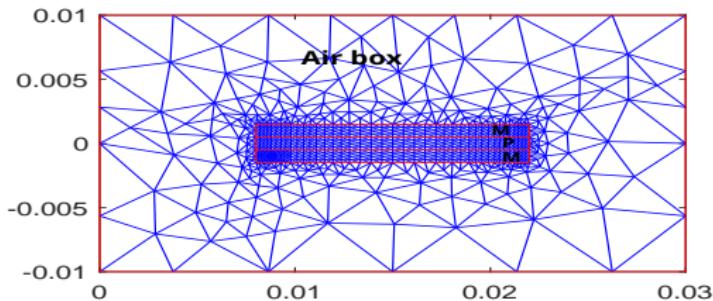
Working principle



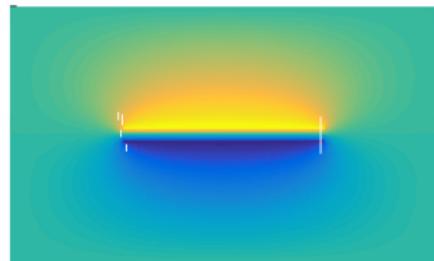
Potential examples
healthcare:

- Cochlear implant
- Artificial pacemaker
- Insulin pump

2D model

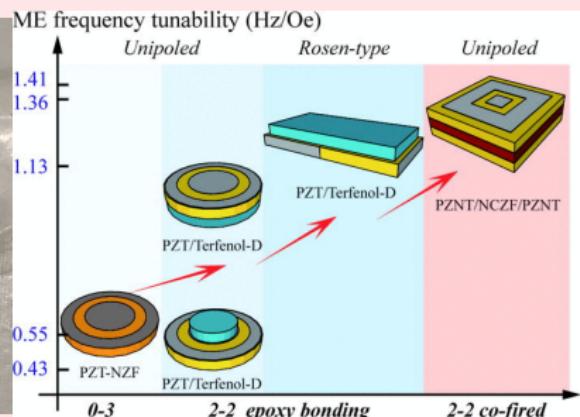


Electric potential



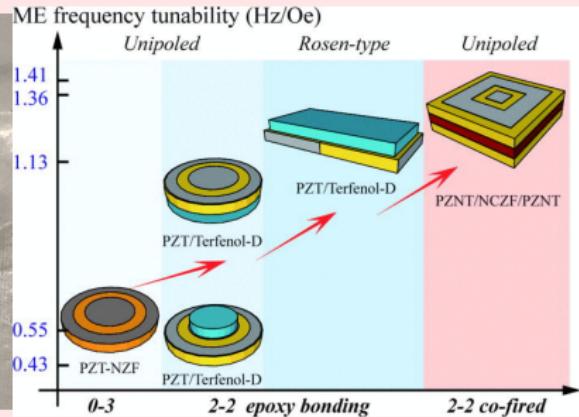
Condition: Laminate composites under the plane strain or stress state.

3D model is needed



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

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.

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Problem description

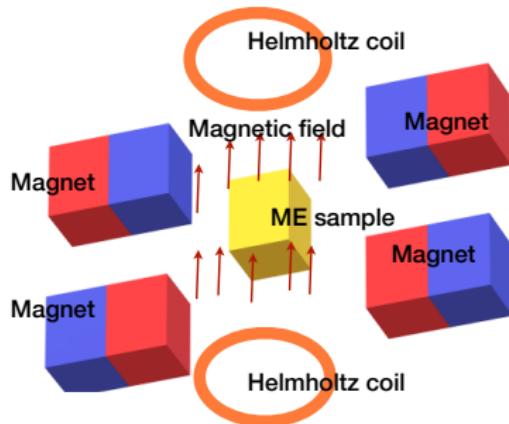
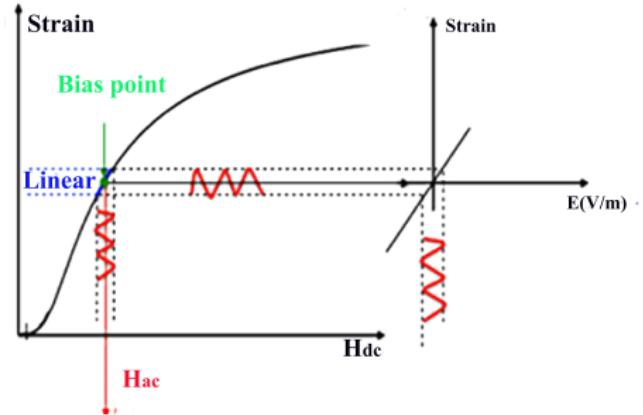


Illustration of ME measurement
(L2E)



Bias point

Nonlinear static analysis → Linear harmonic analysis

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- **Static analysis**
- Dynamic analysis

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General multiphysics equations

Static regime

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

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

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

$$\left\{ \begin{array}{l} \int_{\Omega} \mathfrak{D}\mathbf{u}'(c\mathfrak{D}\mathbf{u} + e^t \operatorname{grad} V - h^t \operatorname{curl} \mathbf{a}) d\Omega = 0 \\ \int_{\Omega} \operatorname{curl} \mathbf{a}'(-h\mathfrak{D}\mathbf{u} + \nu \operatorname{curl} \mathbf{a}) d\Omega = 0 \\ \int_{\Omega} \operatorname{grad} V' \cdot (e\mathfrak{D}\mathbf{u} - \varepsilon^S \operatorname{grad} V) d\Omega = 0 \end{array} \right.$$

FE discretization

- Nodal element

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

- Edge element

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

3D piezoelectric model



3D magnetostrictive model

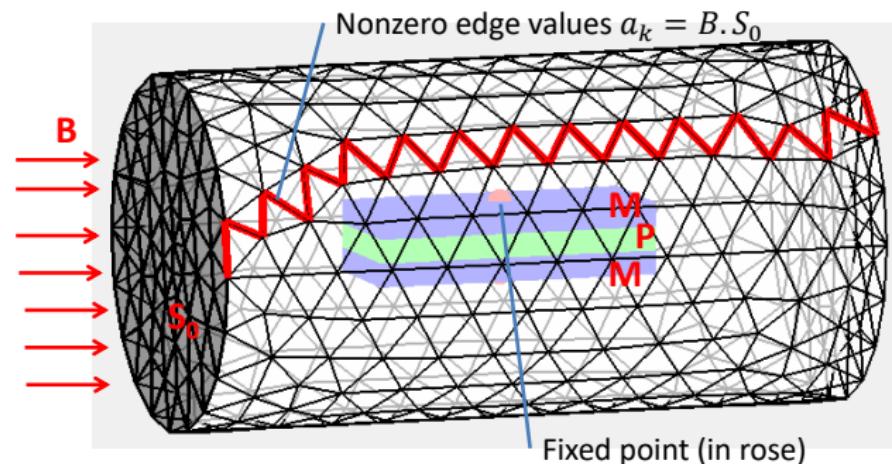
Zhi Qin. *Finite Element Modeling and PGD Based Model Reduction for Piezoelectric & Magnetostrictive Materials*. PhD Thesis 2016.

Static analysis

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

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

Boundary conditions



Nonlinear magnetostriction

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

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

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

- The magnetization and the magnetostriction

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

- The magnetic induction and the strain

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

- Compute material Jacobian

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

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

DEAM

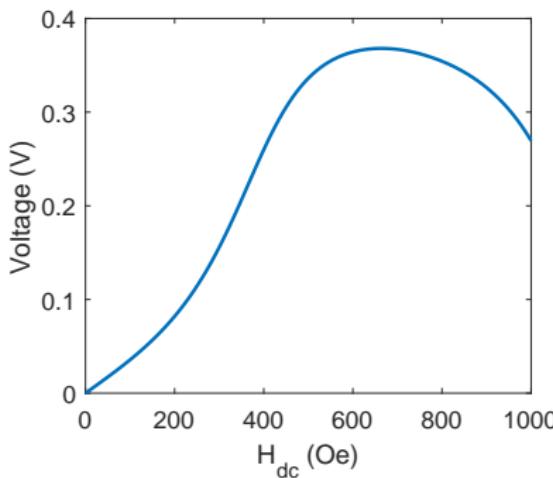
- Energy weighted summation of only six terms
- Compute material coefficients by analytic differential

Piesewise linear procedure

Under small deviations

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

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



Repeat N times

$[\mu, h, c] = DEAM_model(\mathbf{H}, \mathbf{T})$

Assemble matrix

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

Solve equation

$[\Delta \mathbf{U}, \Delta \mathbf{A}, \Delta \mathbf{V}] = mat_UAU \backslash \Delta \mathbf{F}$

$[\Delta S, \Delta B, \Delta E] = state_eq([\Delta \mathbf{U}, \Delta \mathbf{A}, \Delta \mathbf{V}])$

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

update \mathbf{H}, \mathbf{T}

Preserve the spatial inhomogeneity in the material coefficients.

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Dynamic analysis

- Elastic equilibrium

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

ρ : density kg/m³

- Ampere's theorem

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

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

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

- Gauss's law

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

- Electrical charge

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

Linear harmonic analysis

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

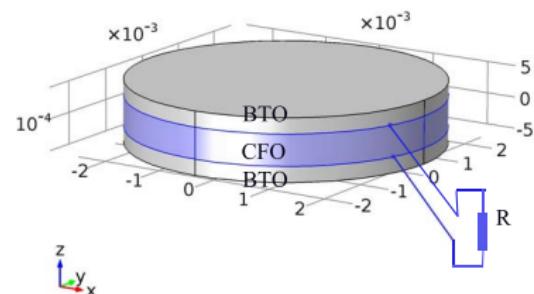
with:

-

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

- $\{X\} = \{u, \ a, \ \psi, \ Q\}^t.$

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



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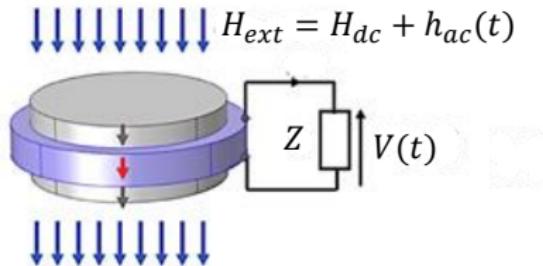
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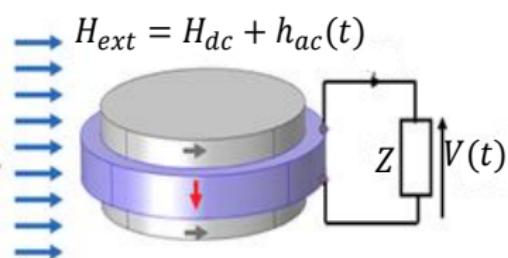
5 Conclusion

Geometry

Mode TT



Mode LT

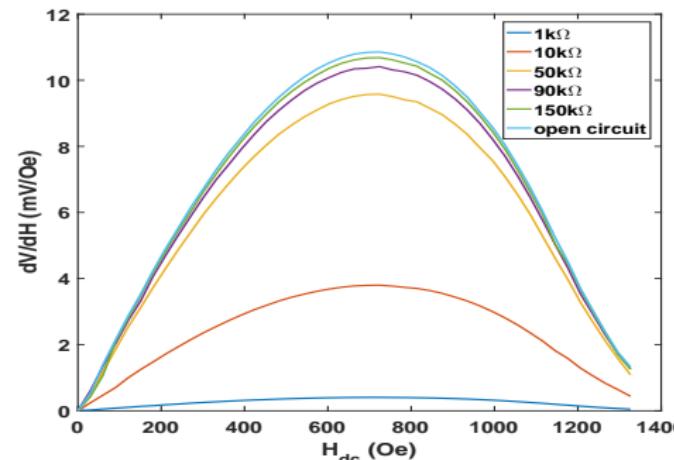


BaTiO₃ (gray layer): Thickness 1.5mm, diameter 12mm
FeGa (magenta layer): Thickness 1mm, diameter 10mm

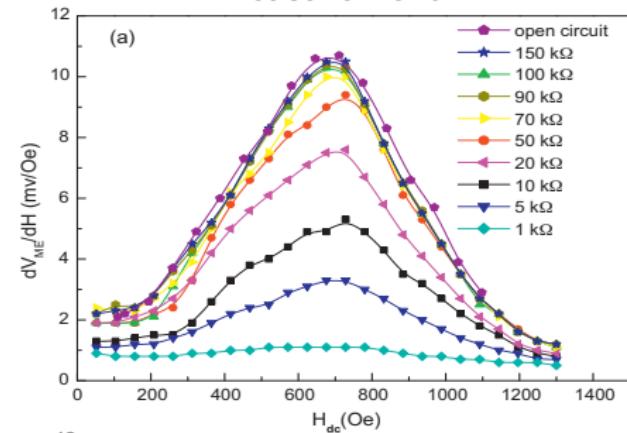
Wang, Lei, et al. *Effect of load resistance on magnetoelectric properties in FeGa/BaTiO₃/FeGa laminate composites*. Journal of Alloys and Compounds 509.30 (2011): 7870-7873.

DC magnetic field dependence

Simulation result



Measurement

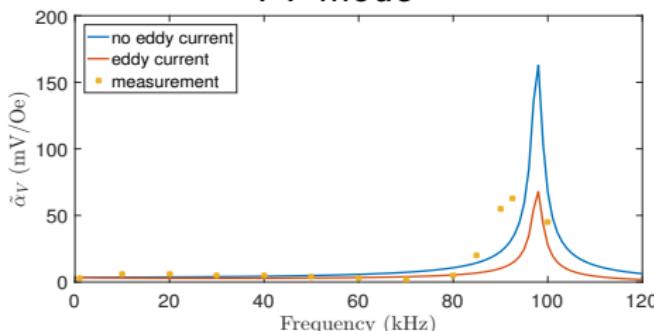


- ME voltage coefficient as a function of DC magnetic field under various electrical resistance load values and external magnetic field: $H_{ac} = 1$ (Oe), $f = 1$ (kHz)
- In concordance with

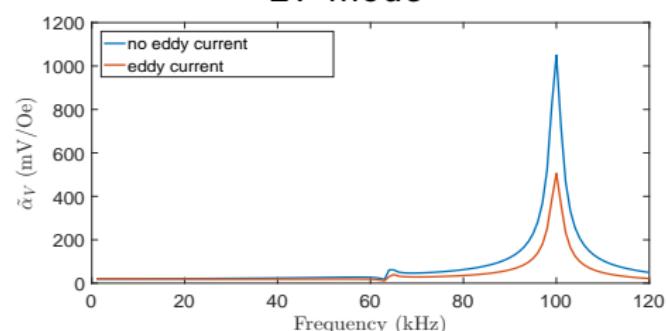
Wang, Lei, et al. 2011. *Effect of load resistance on magnetoelectric properties in FeGa/BaTiO₃/FeGa laminate composites*. Journal of Alloys and Compounds

Eddy current effect

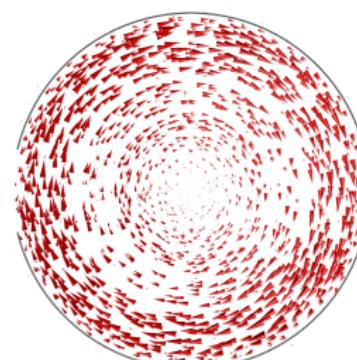
TT mode



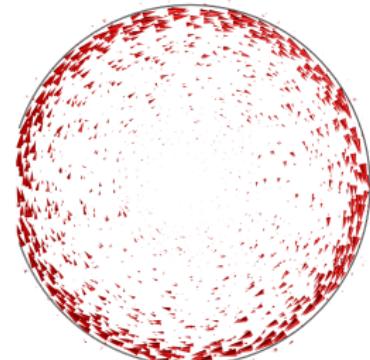
LT mode



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



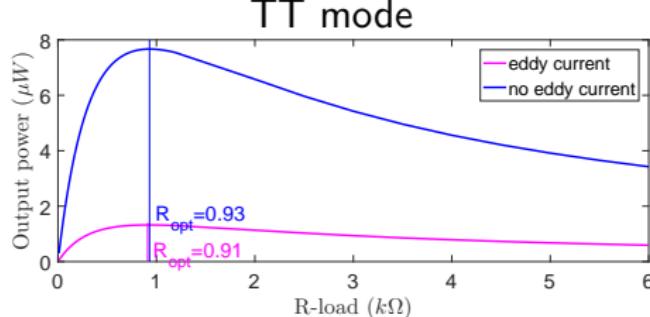
10 kHz



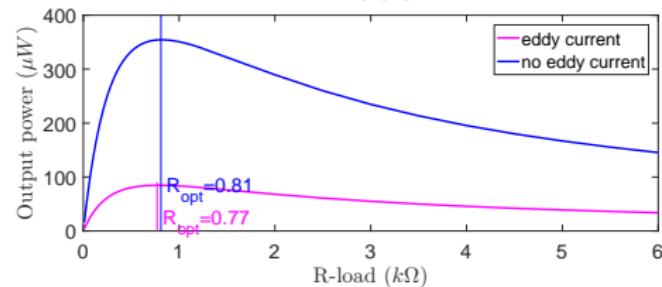
100 kHz

Performance

TT mode



LT mode



- 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.

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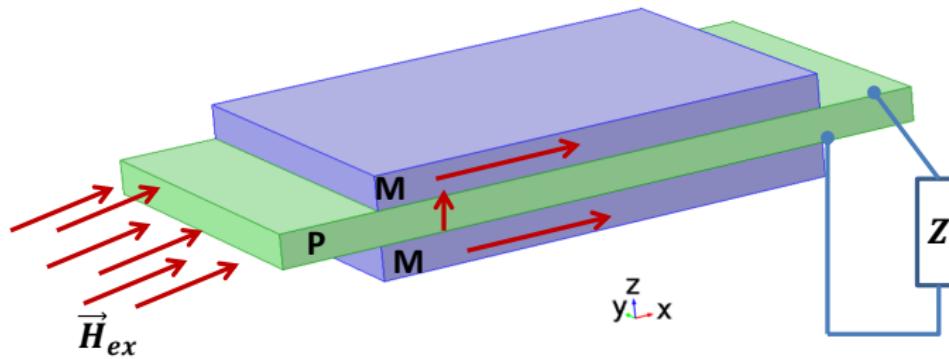
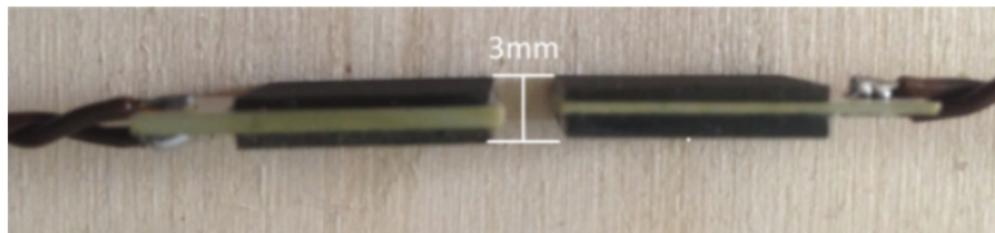
- Laminate composite with circular section
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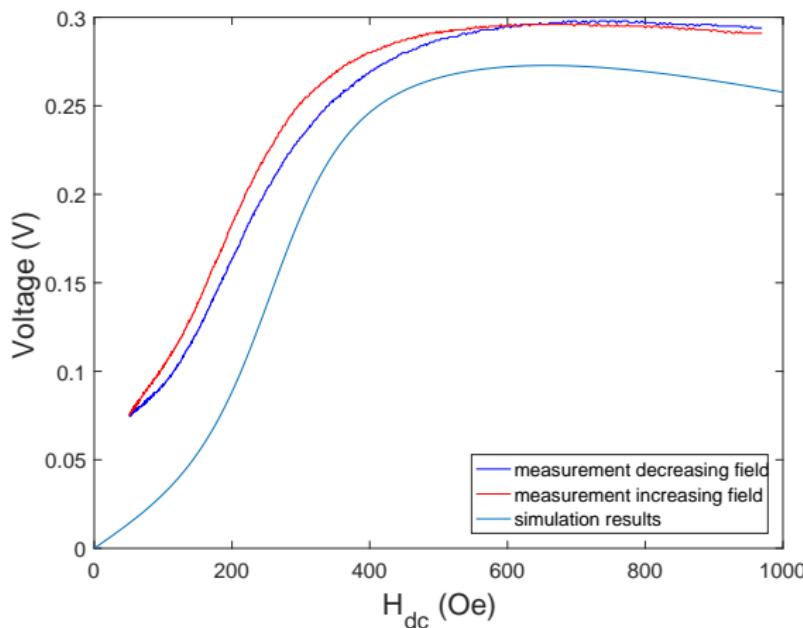


P51 (green layer): Thickness 1mm, surface 14x10 mm²

Terfenol-D (magenta layer): Thickness 1mm, surface 20x10 mm²

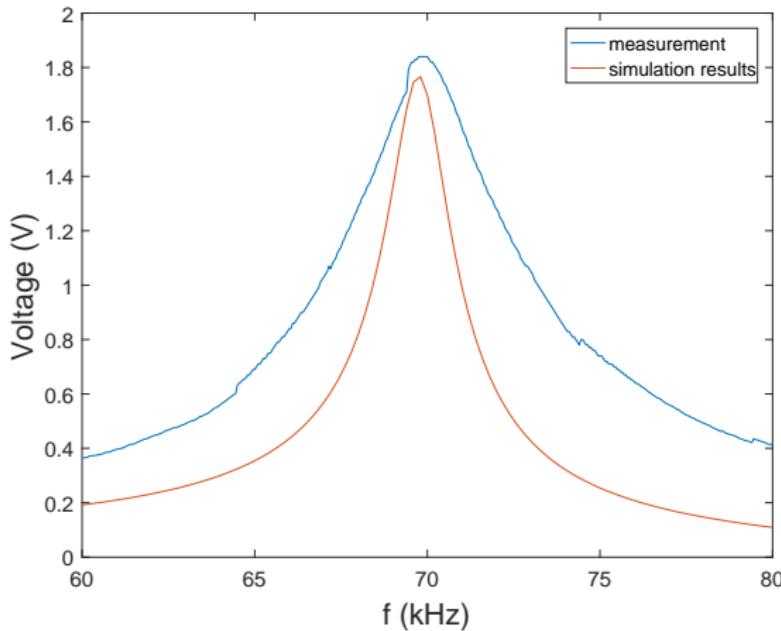
Kevin Malleron 2018. *Modélisation multiphylique, caractérisation et conception de transducteurs magnetoélectriques pour l'alimentation de capteurs biomédicaux autonomes*. Phd Thesis.

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

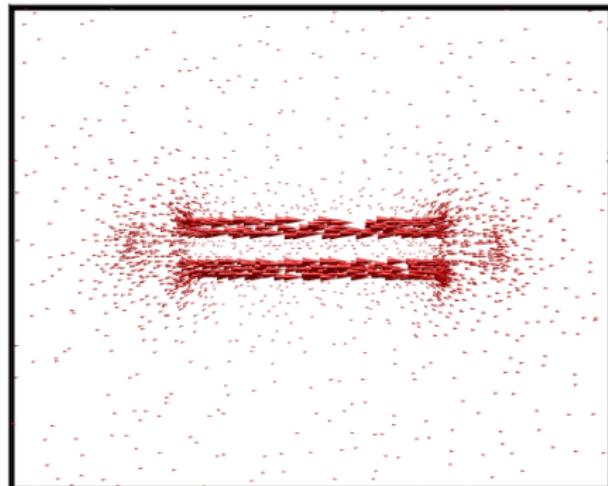
Frequency dependency



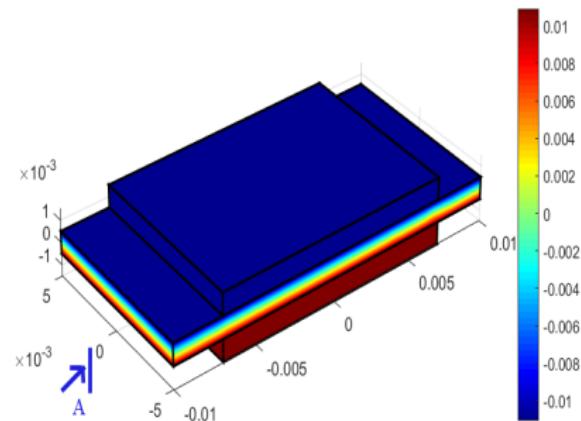
- Computed coefficients obtained at $H_{dc} = 650$ Oe are used for dynamic analysis $H_{ac} = 5$ Oe
- Frequency varies from 60 kHz to 80 kHz
- Maximum output voltage is obtained at resonance frequency $f = 70$ kHz

Field distribution

Magnetic induction distribution



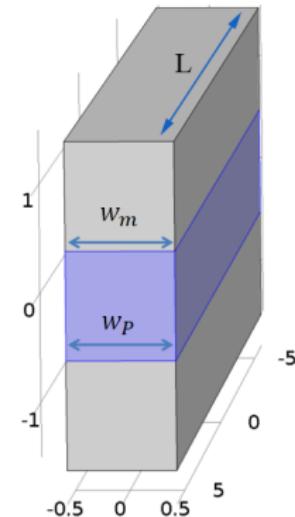
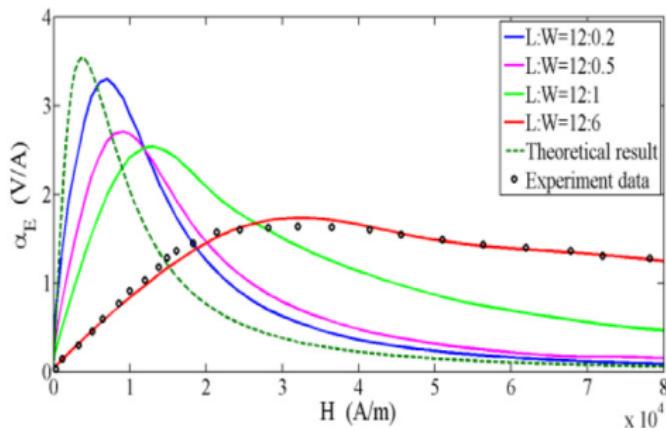
Electric potential distribution



- 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



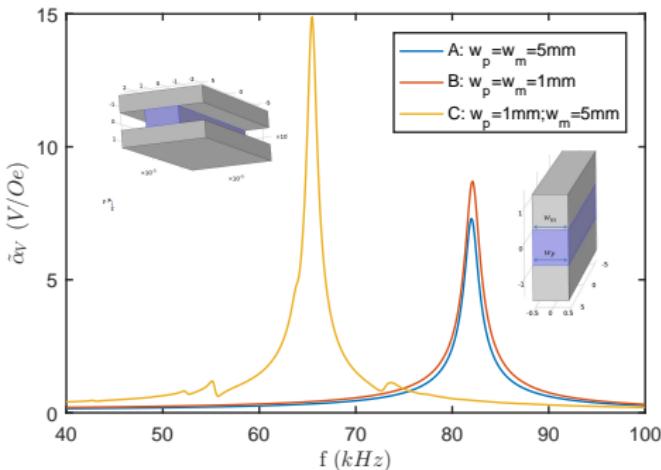
Wen, J. et al., 2008 *A coupling finite element model for analysis the nonlinear dynamic magnetoelectric response of tri-layer laminate composites*. Composite Structures

Performance

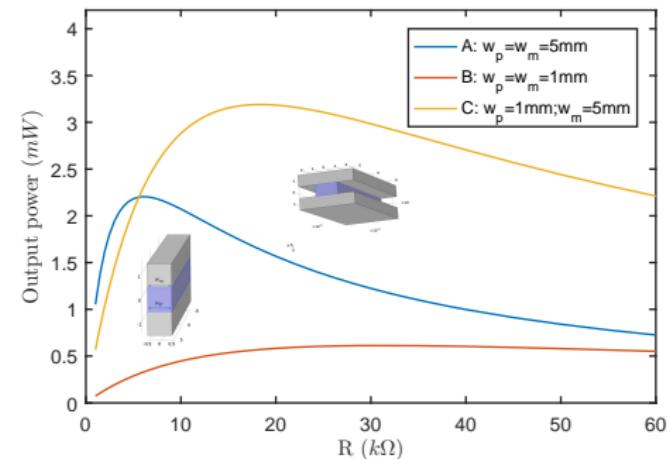
Three configurations are examined

- 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

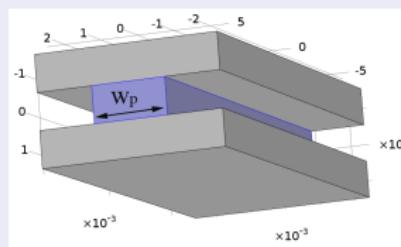
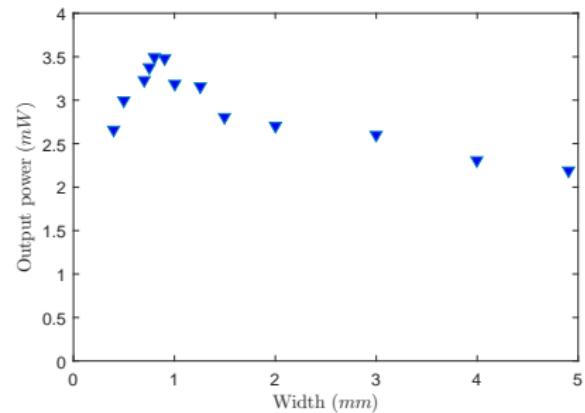
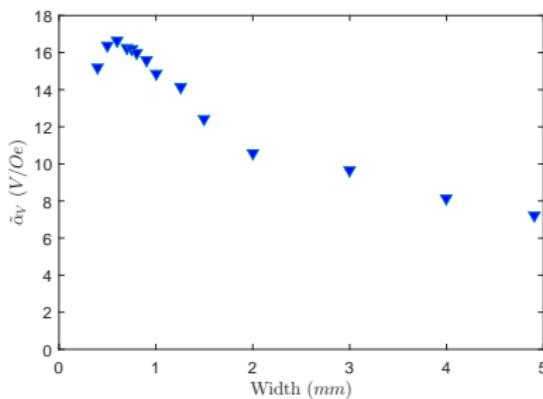


Output power



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

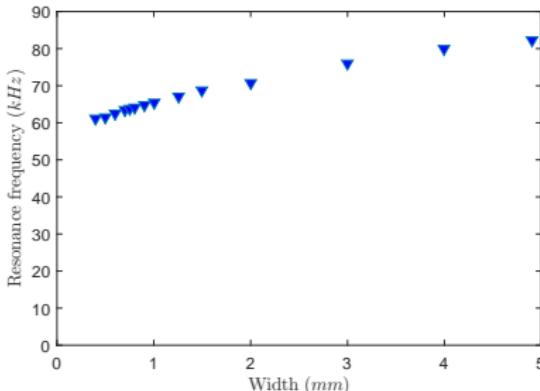
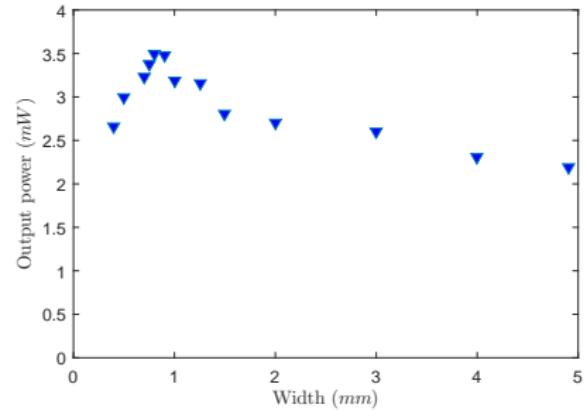
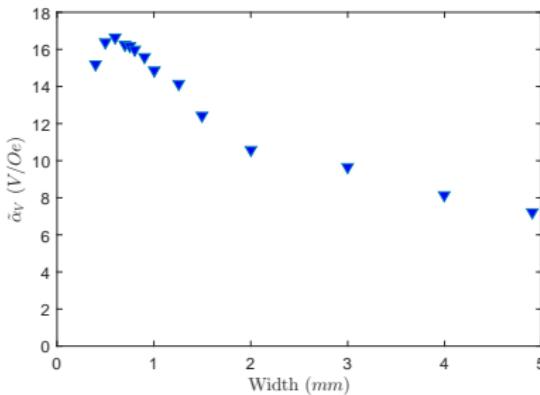
Parametric study



$$w_p = 0.5 \rightarrow 5 \text{ mm}$$

- 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).

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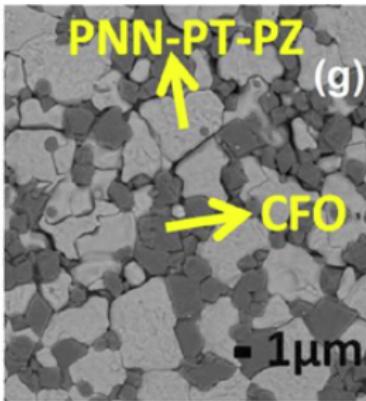
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- Particulate composite

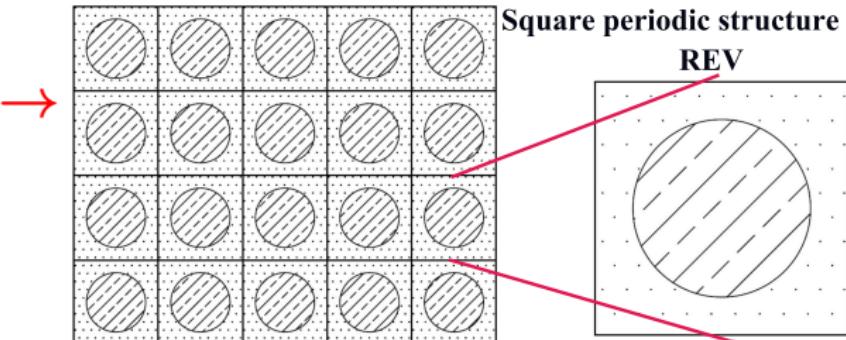
5 Conclusion

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.



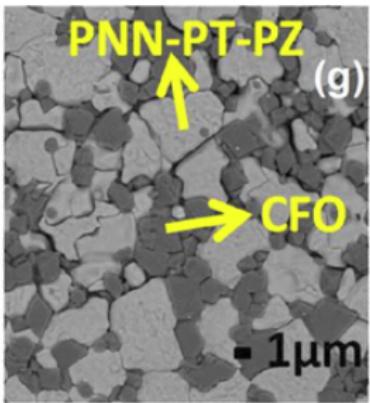
Vadla, S. et al. (2016)
Magnetoelectric coupling in 0.5 Pb (Ni_{1/3}Nb_{2/3}) O₃-0.35 PbTiO₃-0.15 PbZrO₃ and CoFe₂O₄ based particulate composites. Scripta Materialia

Analytical method → Simple structure
(Fiber composite)

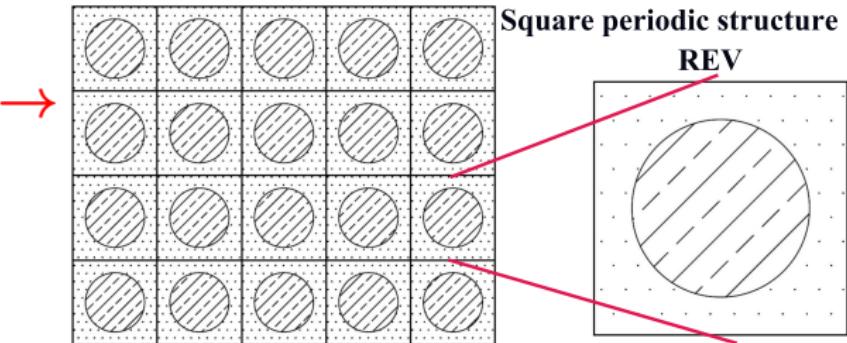
Corcolle, R. et al., 2008 *Generic formalism for homogenization of coupled behavior: Application to magneto-electroelastic behavior.* Physical Review B.

0-3 type and 1-3 type ME composite

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FEM analysis for REV → More complicated inclusion

Boundary condition

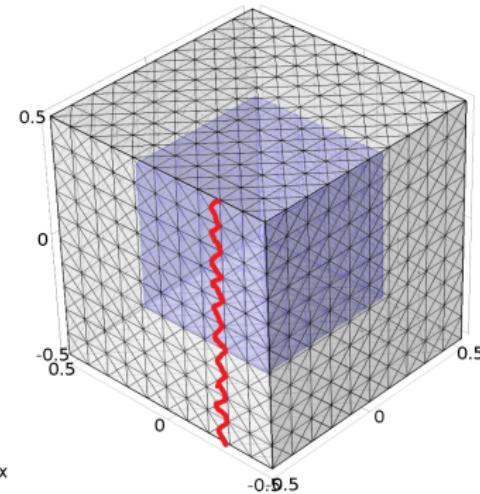
- Same mesh for opposite boundary surfaces.
- On the boundary surfaces:
Point: $k_i + d_i, k_i$
Edge: $(k_{i1} + d_i, k_{i2} + d_i), (k_{i1}, k_{i2})$

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

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

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

A : the perpendicular surface

Effective coefficients

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

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



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

$$\mathbf{S} = 1/2(\mathbf{grad} + \mathbf{grad}^t)u$$

$$\mathbf{B} = \mathbf{curl} \mathbf{a}$$

$$\mathbf{E} = -\mathbf{grad} V$$



Local field

$$\mathbf{S}, \quad \mathbf{B}, \quad \mathbf{E}$$

$$\mathbf{T} = c\mathbf{S} - e'E - h'B$$

$$\mathbf{H} = -h\mathbf{S} + \nu\mathbf{B}$$

$$\mathbf{D} = -e\mathbf{S} + \epsilon\mathbf{E}$$



Local field

$$\mathbf{T}, \quad \mathbf{H}, \quad \mathbf{D}$$

Local constitutive laws

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



Volume average

Material coefficients

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

1 Introduction

- Motivation

2 3D Multiphysic Modeling

- Configuration
- Static analysis
- Dynamic analysis

3 Laminate Composite

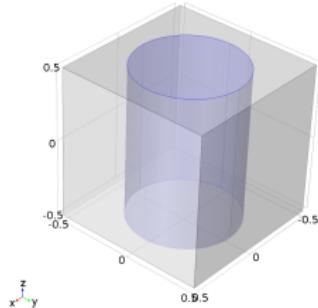
- Laminate composite with circular section
- Laminate composite with rectangular section

4 Homogenization

- Context
- **Fiber composite**
- Particulate composite

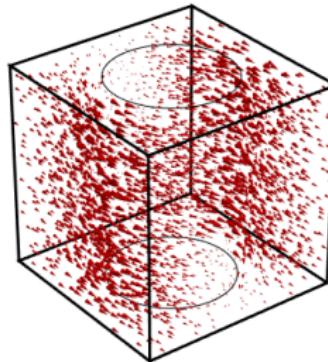
5 Conclusion

Fiber composite

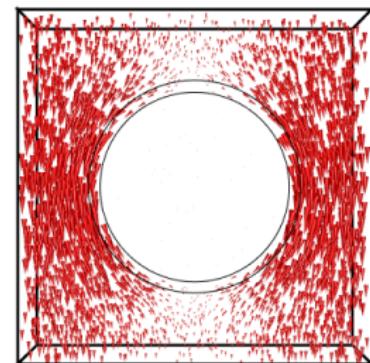


- Magnetostrictive matrix (CoFe_2O_4) reinforced by fiber piezoelectric (BaTiO_3).
- The volume fraction varies $f = 0$ to $f = 0.8$.

Example:
Magnetic field is
applied
 μ, q, α

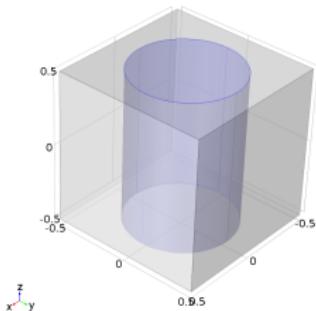


3D view



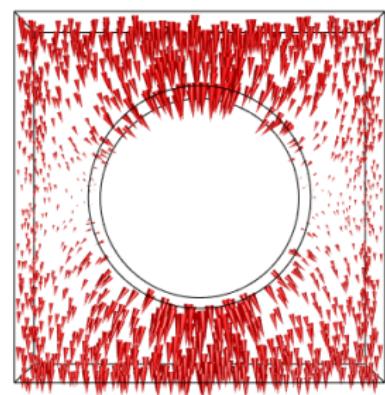
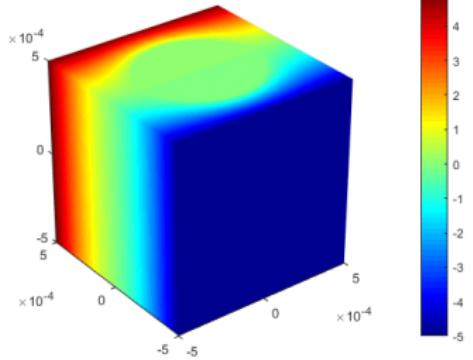
Top view

Fiber composite

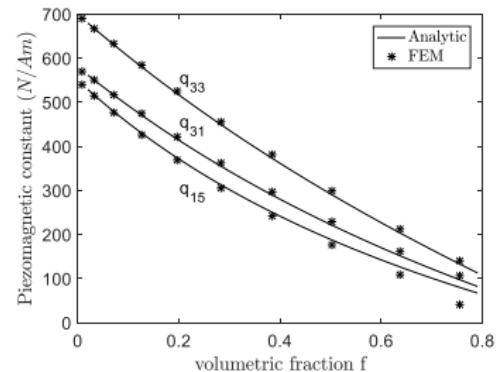
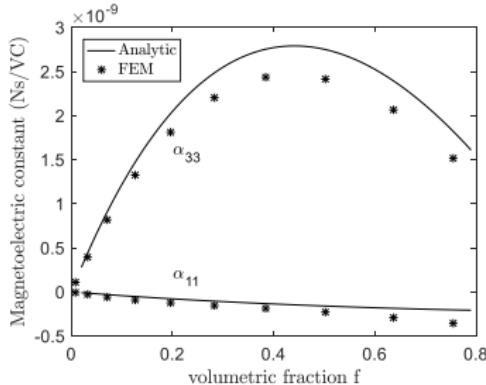
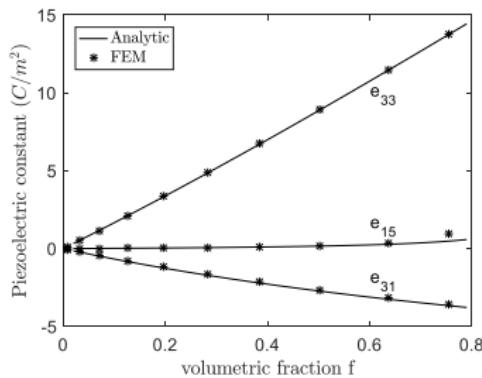


- Magnetostrictive matrix (CoFe_2O_4) reinforced by fiber piezoelectric (BaTiO_3).
- The volume fraction varies $f = 0$ to $f = 0.8$.

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.

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- Dynamic analysis

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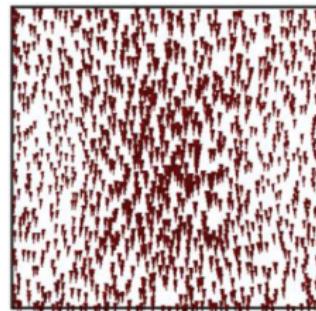
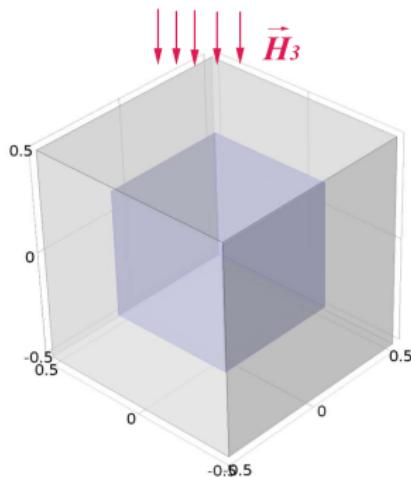
- Laminate composite with circular section
- Laminate composite with rectangular section

4 Homogenization

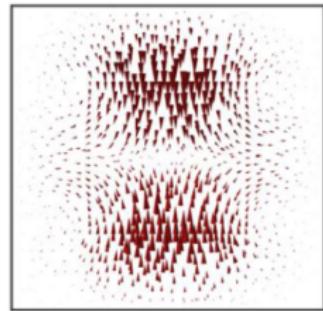
- Context
- Fiber composite
- Particulate composite

5 Conclusion

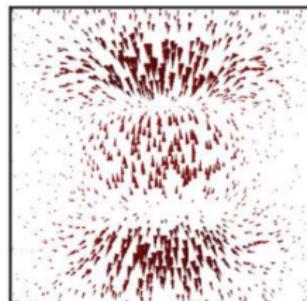
Field distribution



(a)



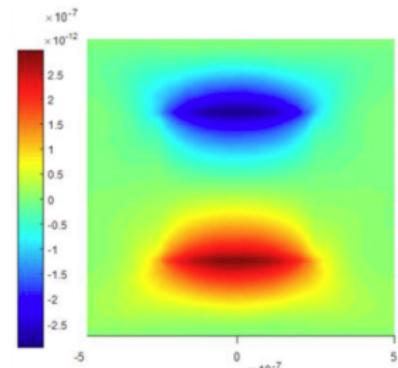
(b)



(c)

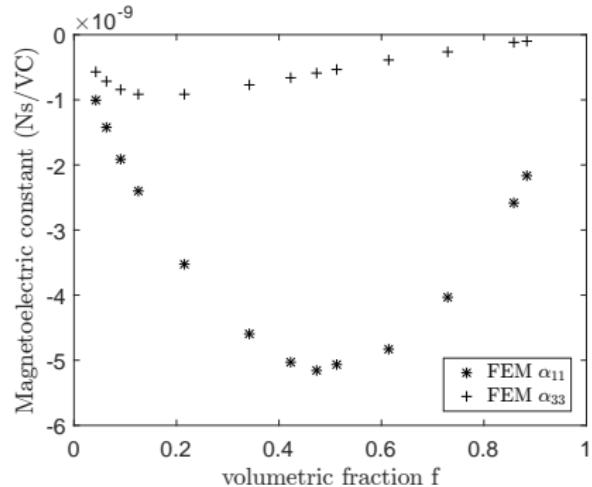
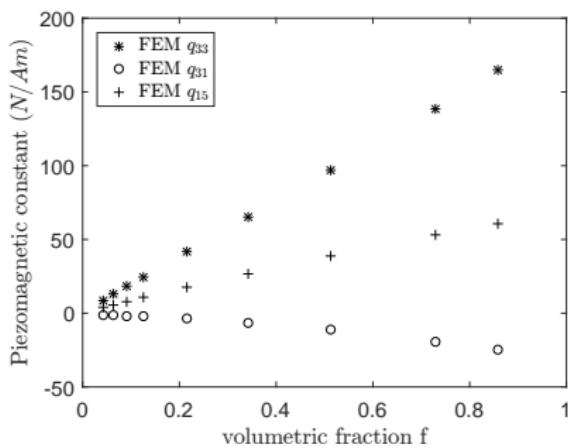
Magnetic field is applied

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



(d)

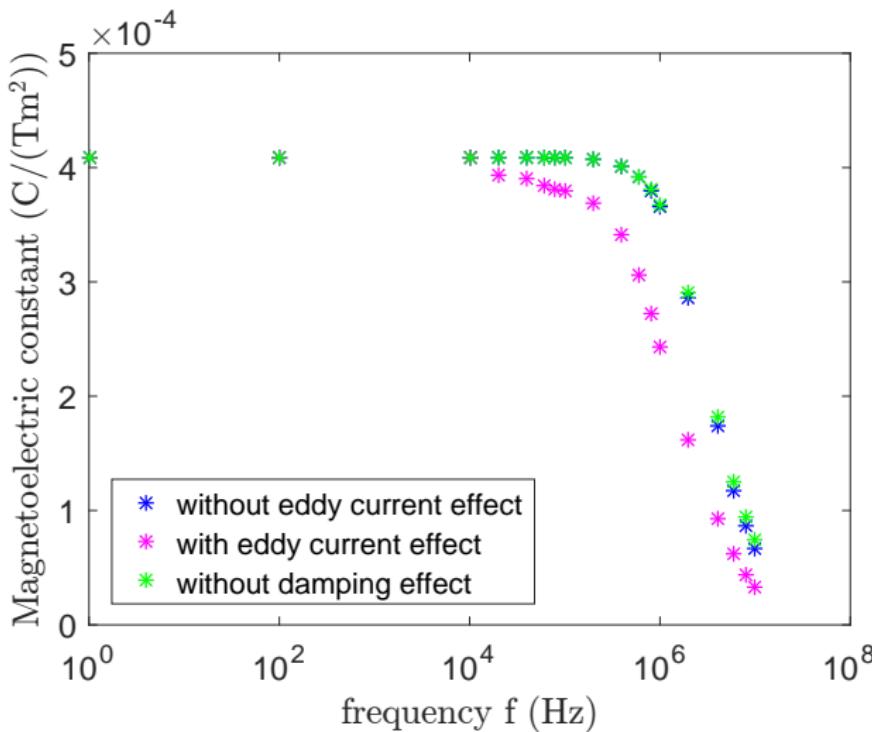
Effective coefficient



- 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

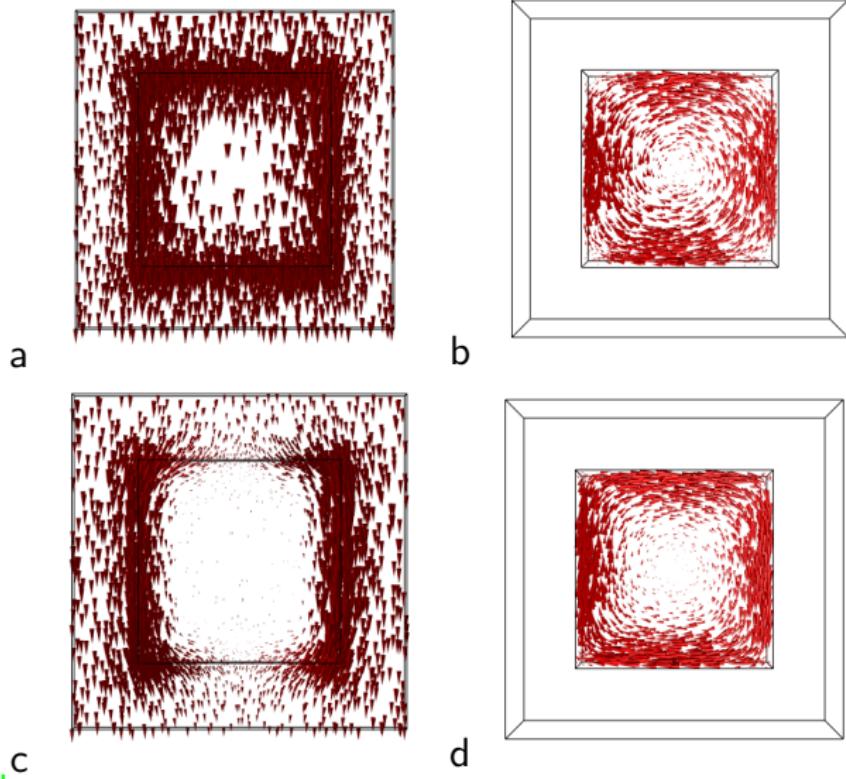


- REV of 1 mm dimension
- Particulate composite with magnetostrictive volume fraction = 0.6
- The frequency changes from 1 Hz to 10 MHz

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 using the coefficients effective obtained by homogenization procedure.
- Other structures can be considered to improve ME coefficient.

Publication

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

3-D Finite Element Analysis of Magnetolectric 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