MODELING FERROFLUID SLOSHING VIBRATION ENERGY HARVESTING USING LEVEL-SET METHOD

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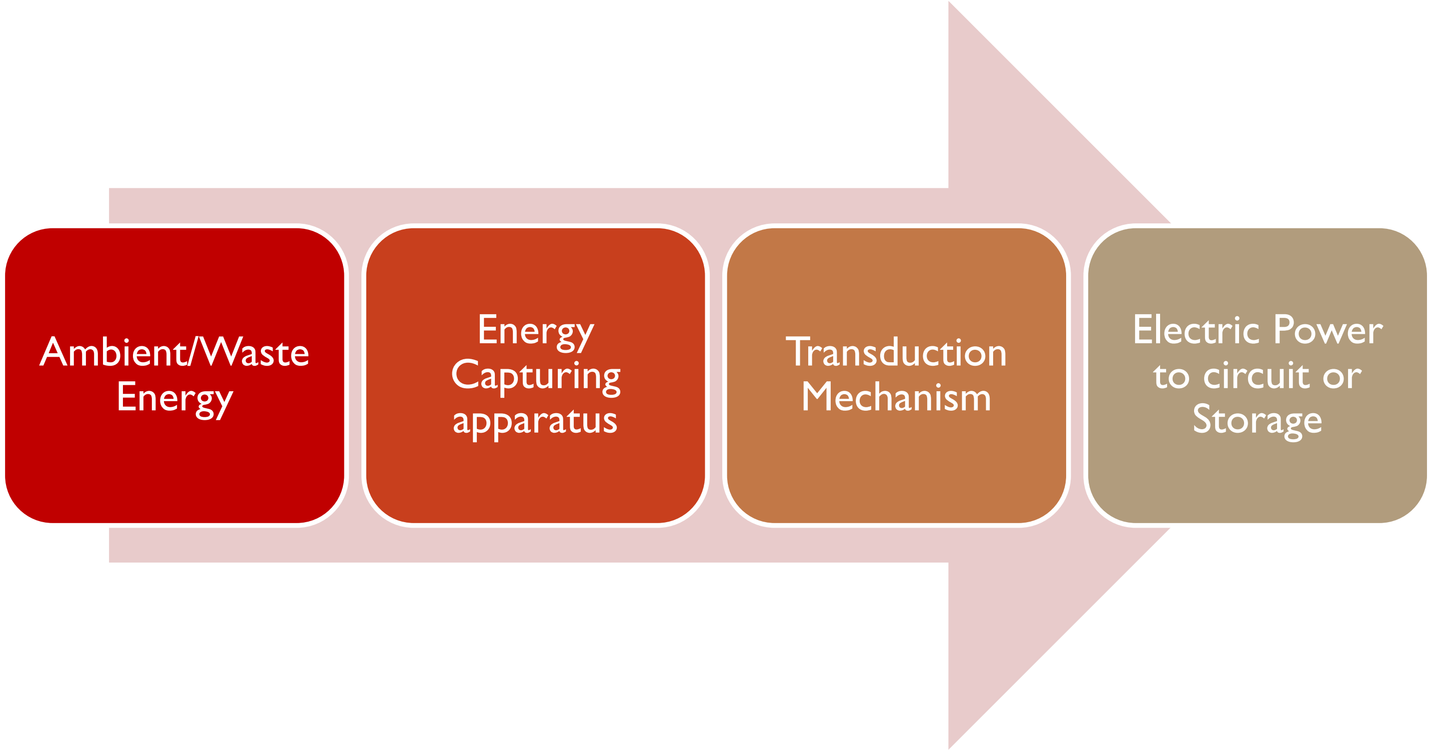
ENERGY HARVESTING & INTRODUCTION

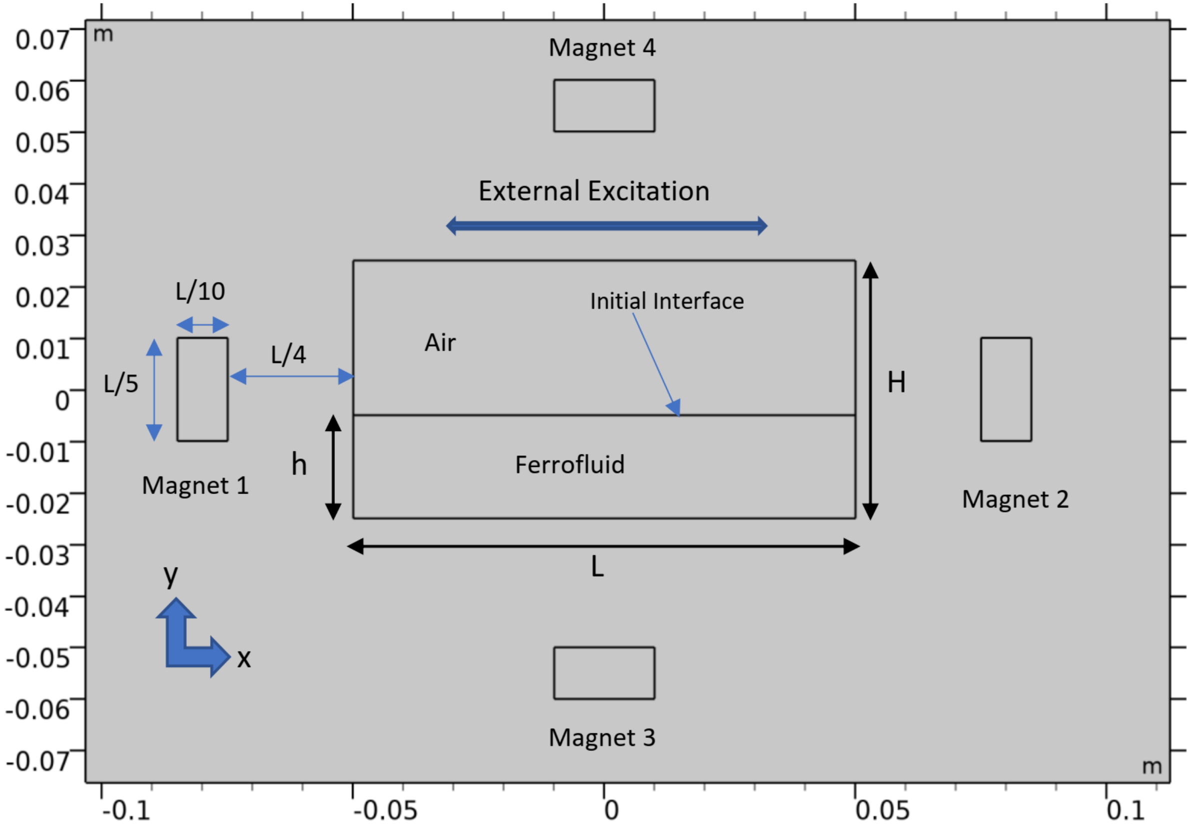
- Energy harvesting usually refers to the conversion of ambient energy into usable electric power through an energy capturing apparatus and transduction mechanism
- Usually the transduction mechanism is solid state and the ambient energy is either thermal or vibrational
- In recent years a liquid state transduction based energy harvester was introduced
- The harvester used Ferrofluid sloshing in an external magnetic field to harvest electricity from external oscillatory motion
- In this work a new symmetric ferrofluid sloshing vibration energy harvesting system is introduced and its characteristics analyzed.
- In this work a validation study is also produced which verifies COMSOL's capabilities in simulating such a system.

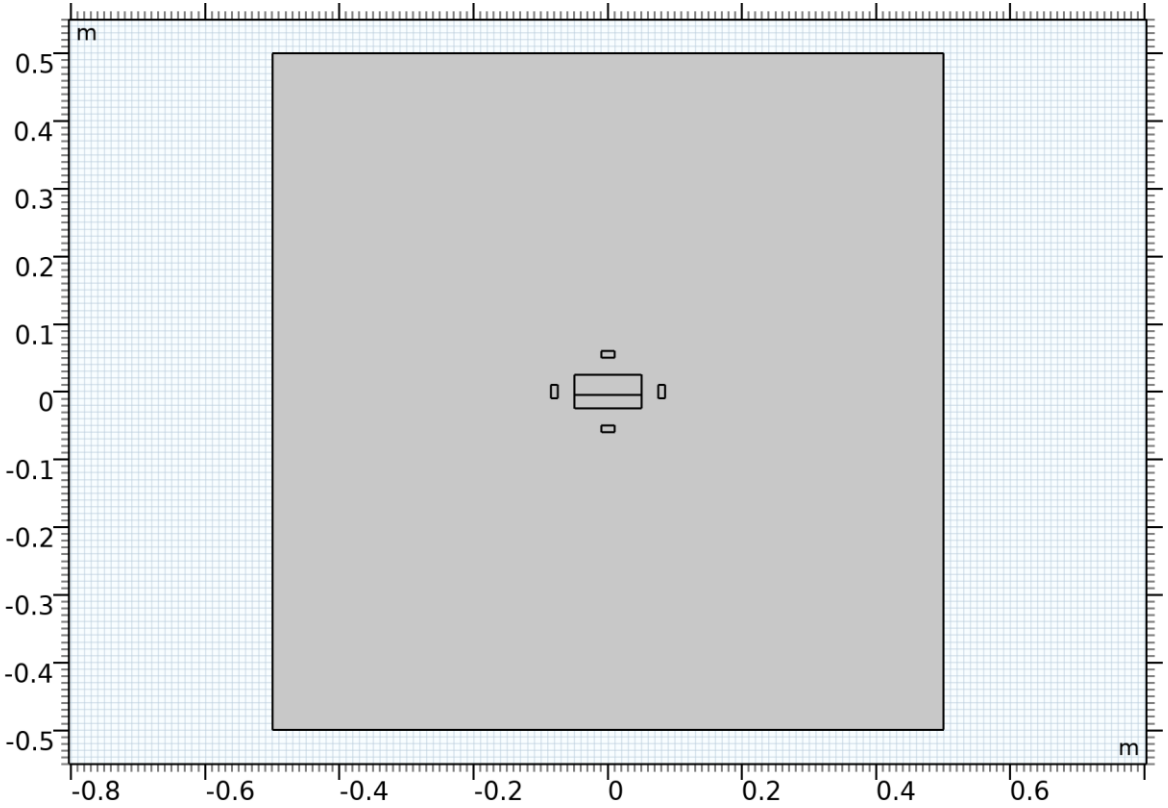


ANALYSIS OF A SYMMETRIC FERROFLUID SLOSHING VIBRATION ENERGY HARVESTER

- A unique configuration for a ferrofluid vibration energy harvester (VEH) is proposed, which exploits the two symmetry planes of the harvester and introduces 4 symmetrically placed powerful magnets to generate magnetic fields.
- The idea with symmetrical placement is that, it becomes easy to manufacture if the structures are symmetric. This can also make it a wearable energy harvester, which can cater the needs of growing power supply to the Internet of Things or other wearable devices.
- Finally, the level-set method is introduced to capture the movement of the free surface.
- Although level-set method has been used to perform numerical studies on ferrofluid droplets but for ferrofluid sloshing this is the first endeavor with level-set method

SYSTEM CONFIGURATION





GOVERNING EQUATIONS

- Continuity:

$$\rho\nabla.\vec{V} = 0 \quad (1)$$

- Momentum:

$$\rho\frac{\partial\vec{V}}{\partial t} + \rho(\vec{V}.\nabla)\vec{V} = -\nabla p + \mu\nabla^2\vec{V} + \vec{F_m} + \rho\vec{g} + \vec{F_{st}} \quad (2)$$

- Where, $\vec{V}$ is the velocity vector, $\vec{F_m}$ is the magnetic force, $\vec{g}$ is the external acceleration on the system including the external excitation, $\vec{F_{st}}$ is the force of the surface tension.
- Here the external excitation is given as:

$$x = X_0 Sin(\omega t) \quad (3)$$

- Where X_0 is the amplitude of external excitation and ω the angular frequency, which is related to the excitation frequency f as, $2\pi f$. This makes the acceleration to be:

$$a_0 = -X_0\omega^2 Sin(\omega t) \quad (4)$$

- Level-set equations for interface tracking:

$$\frac{\partial\phi}{\partial t} + \vec{V}.\nabla\phi = \gamma\,\nabla.\left(\epsilon_{ls}\nabla\phi - \phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right) \quad (5)$$

Where, ϕ is the level set variable, γ is the re-initialization parameter and ϵ_{ls} is the parameter which controls the thickness of the fluid-air interface

- For the fluid domain inside the tank the properties must be expressed in terms of the level set variable. Density is given as:

$$\rho = \rho_1 + (\rho_2 - \rho_1)\phi \quad (6)$$

- Viscosity is given as:

$$\mu = \mu_1 + (\mu_2 - \mu_1)\phi \quad (7)$$

- Where the indices 1 and 2 denotes fluid 1 and fluid 2, which in our case is the ferrofluid and air, respectively.

$$\vec{F_m} = \vec{M}.\nabla\vec{H} \quad (8)$$

- Where, $\vec{H}$ is the magnetic field, and the magnetization $\vec{M}$ is given by the constitutive relation:

$$\vec{M} = \chi_m\vec{H} \quad (9)$$

- Where, χ_m is the magnetic susceptibility and is obtained from the level set function for the whole domain as:

$$\chi_m = \chi_{m1} + (\chi_{m2} - \chi_{m1})\phi \quad (10)$$

- The Maxwell's conservation laws for the system are[11]:

$$\nabla.\vec{B} = 0 \quad (11)$$

$$\nabla\times\vec{H} = 0 \quad (12)$$

$$\nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t} \quad (13)$$

- The magnetic field can be written as:

$$\vec{H} = -\nabla V_m \quad (14)$$

- Where, V_m is the magnetic scalar potential.
- The following are the constitutive relations for different regions:

$$\vec{B} = \mu_0\vec{H}\ \ (for\ air)\ ;\ \vec{B} = \mu_0(\vec{H} + \vec{M_s})\ (for\ the\ magnets)\ \&\ \vec{B} = (1+\chi_m)\vec{H}\ for\ sloshing$$

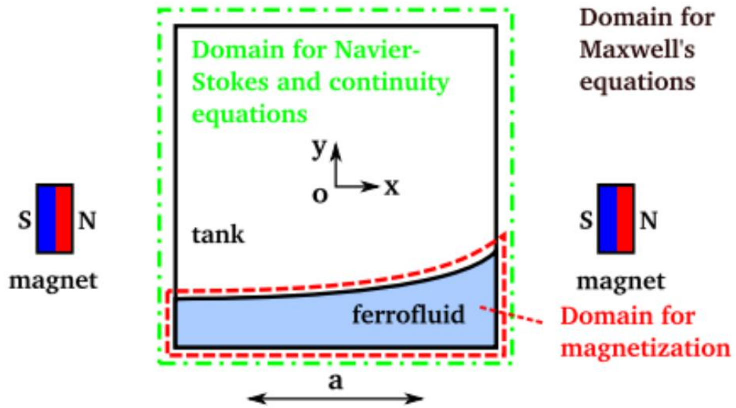
- The electromotive force from sloshing is picked up by an external coil with 2000 turns (N). The electromotive force is given as:

$$\epsilon = -N\frac{d\Phi}{dt} \quad (15)$$

- Where, Φ is the magnetic flux, obtained by integrating the magnetic flux density over the area. The electromotive force due to the changing magnetic field inside the harvester is picked up

NUMERICAL MODELING & VALIDATION

- The Numerical modeling was performed in COMSOL Multiphysics
- Implicit adaptive time stepping is used to advance the solution in time
- Segregated step solver is used to solve the solution at each time step
- The groups solved for are:
  - Level set variable
  - Velocity and pressure
  - Magnetic scalar potential
- In adaptive time stepping maximum time step constraint is used as 5 ms
- The BDF of order 2 and 1 are used for time stepping



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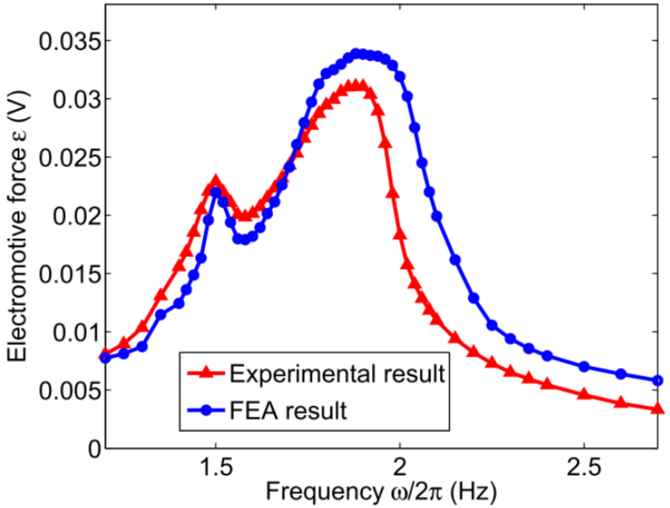

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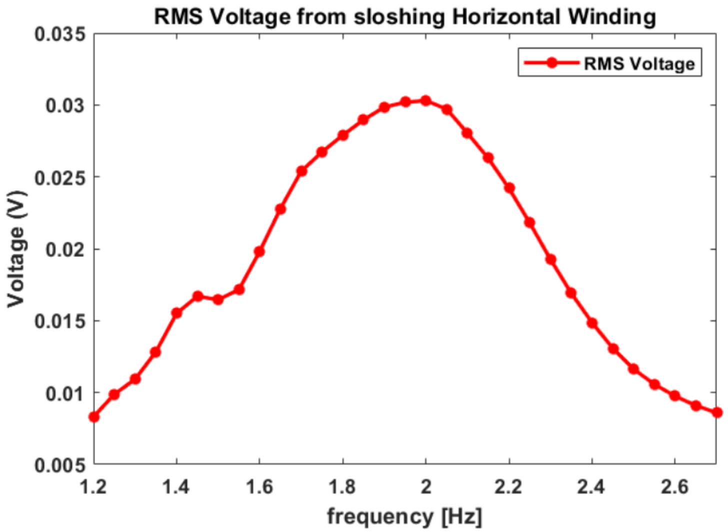
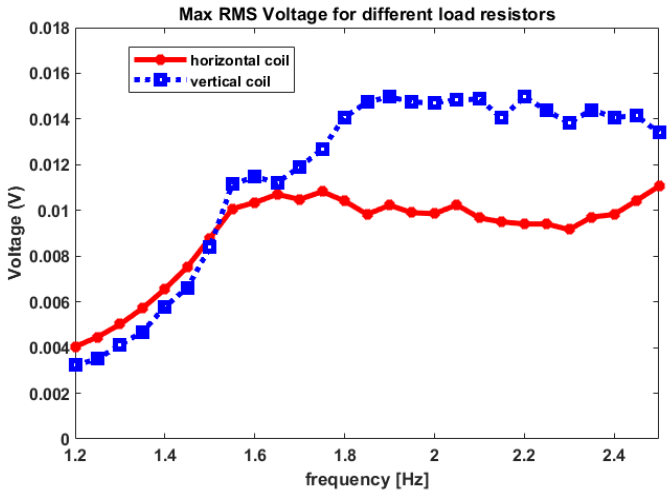
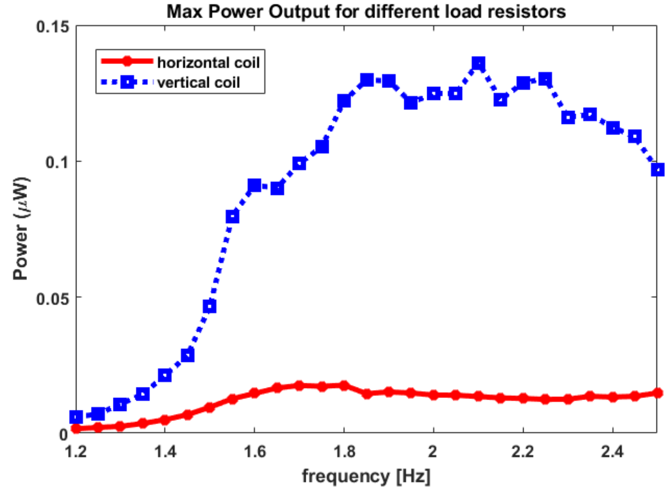
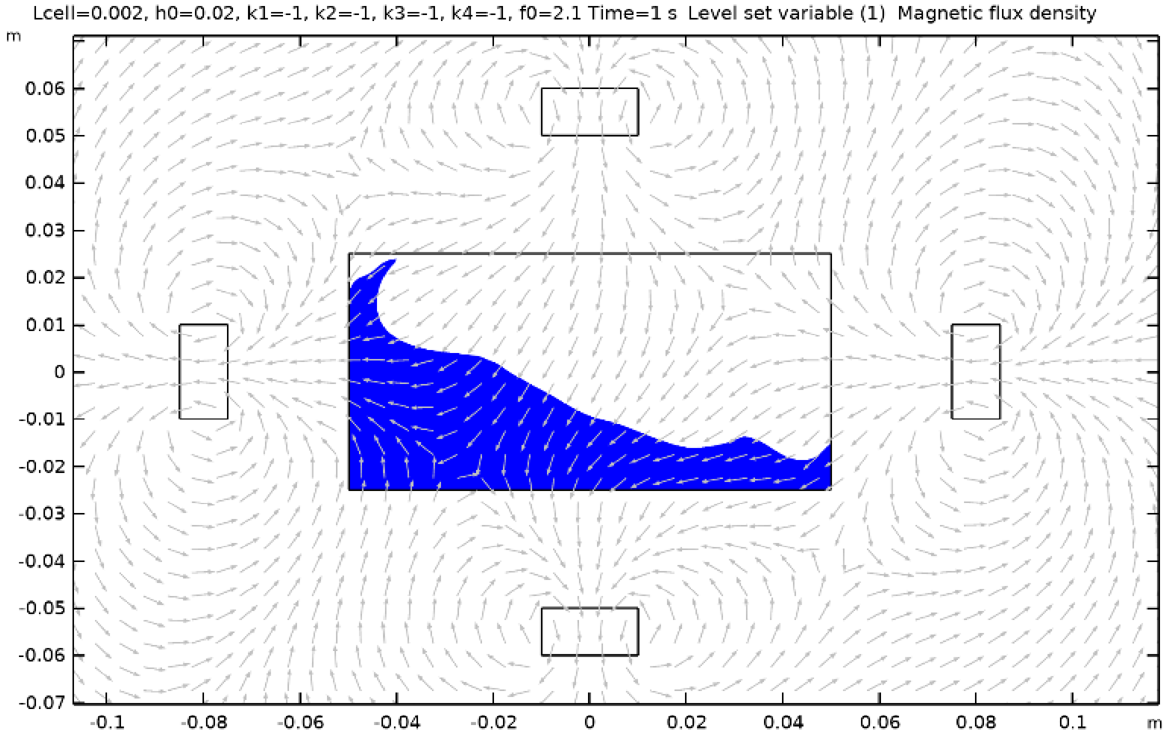


RESULTS

- It is assumed that the tank is wound with 1000 turns coil either in horizontal or vertical direction. This gives different coil resistances and inductances
- Four strong permanent magnets of magnetization 400 kA/m are used. The magnets are placed in such a way that for magnet 1 the south pole faces the tank wall, for magnet 2 the north pole faces the magnet wall, for magnet 3 the south pole faces the nearest tank wall and for magnet 3 the north pole faces the nearest tank wall.
- A frequency sweep from 1.2 Hz to 2.5 Hz is performed to obtain how the harvester behaves at different frequencies.
- To perform impedance matching load resistors from 1 ohms to 1e5 ohms are used incrementally.
- The highest Voltage obtained is around 0.015 V for the vertically wound coil
- The highest Power is obtained from the Vertically wound coil, which is 0.14 micro-watts







CONCLUSIONS

- COMSOL Is very efficient in simulating Ferrofluid Vibration Energy Harvesting Phenomena
- The symmetric ferrofluid VEH is simulated with four strong magnets kept at the symmetry planes of the sloshing tank.
- The energy harvester was subjected to a frequency sweep with an external acceleration fixed at 1 m/s^2
- This resulted in the highest output power of around 0.14 micro watts, from the vertically wound coil
- The system can be optimized further especially by adjusting the polarity of the magnets, so that the fluid becomes more free to move inside the tank and cuts the magnetic field lines in a way that generates higher variation of magnetic flux with time (i.e. Emf)