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Towards System-Level Simulation of a Miniature Electromagnetic Energy Harvester

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Background

Since 2015, 'Industry 4.0' has evoked the growth of 'Internet of Things', which uses battery-powered wireless devices and sensors to monitor environmental phenomena and exchange data. The main challenge here is the periodic replacement of drained batteries.

In recent years, energy harvesting has emerged as a solution to provide a lifetime power supply to wireless devices or sensors. In this work, we present the electromagnetic energy harvester model (see Fig.1), which is reproduced in ANSYS Maxwell 3D [1]. On the basis of this model, we present the standard industrial workflow of exporting a compact model from Maxwell 3D into ANSYS Twin Builder for system-level simulations. Furthermore, in order to improve the generation of the compact model and to enable an efficient geometry optimization of the electromagnetic energy harvester, we adapt two alternative parametric model order reduction (pMOR) methods for effective parametric studies.

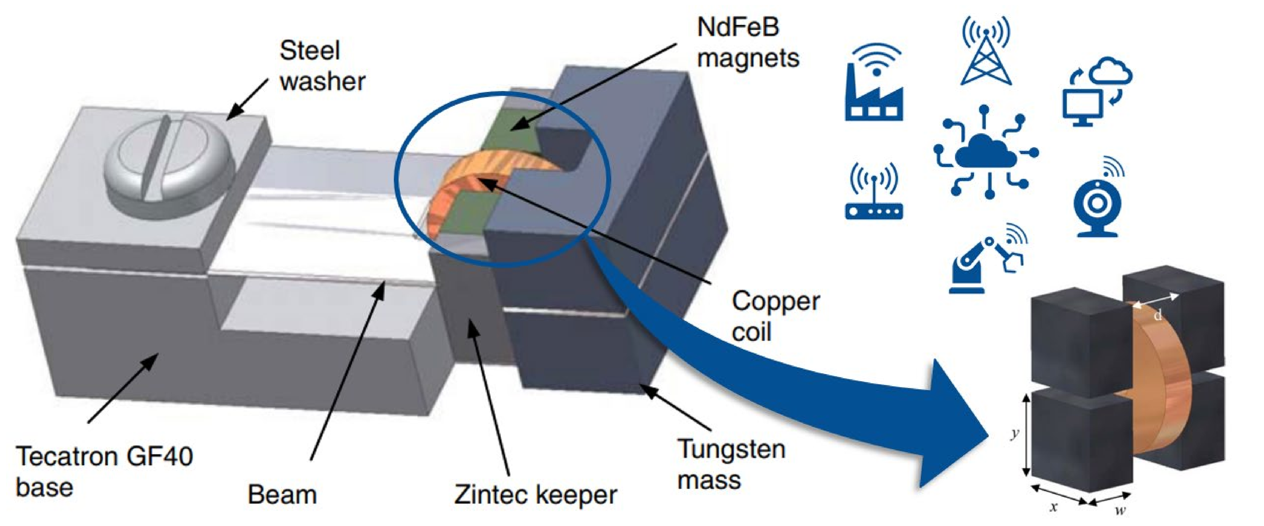

Fig. 1: To overcome the drawback of battery-powered wireless systems, energy harvesting has emerged as a solution. This figure shows a drawing of the assembled electromagnetic energy harvester model introduced by Beeby et al. [1] and the schematic of the magnets and the coil.

Equivalent Circuit Extraction (ECE)

In this work, a magnetic finite element (FE) model is built in ANSYS Maxwell 3D (see Fig. 2 and Fig. 3) on the basis of the model setup introduced by Beeby et al. [2]. The structure of the electromagnetic energy harvester model consists of a copper coil and two pairs of magnets. The inside and outside radius of the coil volume is 0.3 and 1.2 mm. Its thickness is 0.5 mm. It is configured with 600 turns of 25 µm diameter copper wire. The magnets are 1×1×1.5 mm³ in size and polarized along the long edge. Furthermore, they are surrounded by motion bands, which enable their displacement in ANSYS Maxwell 3D in a transient analysis.

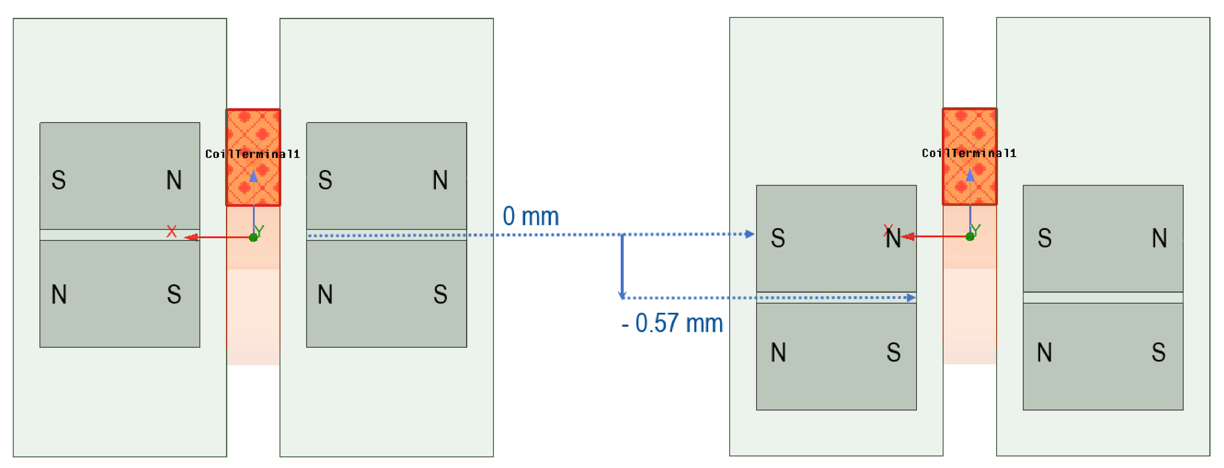

Fig. 2: The positions of the four magnets in the z-direction. The magnets are at the reference position when the center line of the two pairs of magnets is at 0 mm (left) and the initial resting position of the two pairs of magnets in the z direction is at -0.57 mm (right).

It is shown in Fig. 3 that, the two magnets on each side of the coil are grouped and moved in a motion band in the z-direction. In order to establish the harmonic motion of the magnets in transient analysis, a time-dependent force is applied to each group of magnets:

$$F(t) = m \cdot \omega^2 \cdot x_0 \cdot \cos(\omega t)$$

where m = 22.2 µg is the mass of two magnets. $\omega = 2\pi f$ with f = 60 Hz is the excitation frequency and x_0 = 0.57 mm is the designated oscillation amplitude.

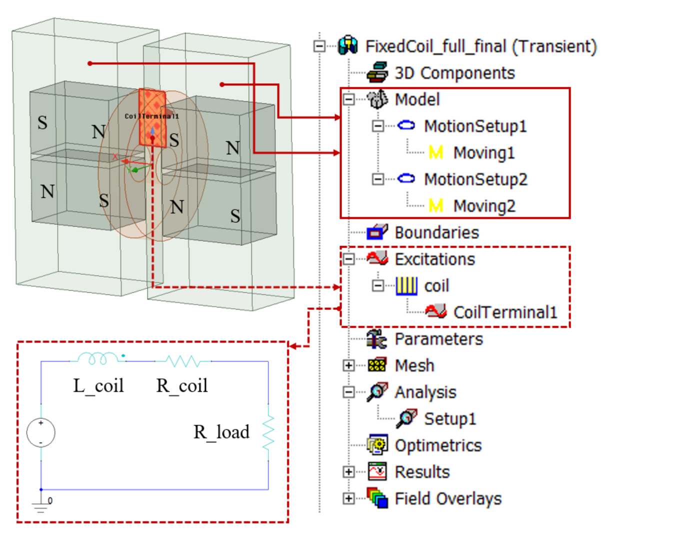

Fig. 3: Model setups in ANSYS Maxwell 3D. The oscillation of the magnets is modeled via the motion setups in two motion bands. The coil terminals are connected to an external circuit.

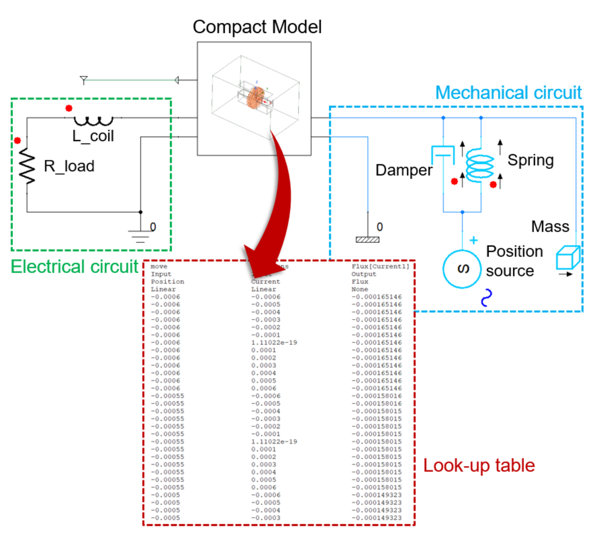

Fig. 4: The compact model is constructed based on the look-up table of the parametric simulation results and is connected to both electrical and mechanical circuits.

However, the computational cost of the transient simulation of the full-scale FE model is relatively high. In order to reduce the computational cost, we apply the ECE technique in ANSYS Maxwell 3D to generate a compact model for fast simulations at the system level (see Fig. 4).

Parametric Model Order Reduction

Although the look-up table-based compact model enables efficient system-level simulation, it is still time-consuming to generate it, as it is constructed based on a large number of parametric simulations of the full-scale FE model in ANSYS Maxwell 3D. Hence, in this work, we suggest using two different mathematical pMOR methods to speed up the computational time of doing the parametric studies and improve the accuracy.

- Matrix interpolation-based pMOR [3]: generate the local reduced-order models (ROMs) at selected values of the geometrical parameter. The global parametric reduced-order model (pROM) is constructed by interpolating the local ROMs.
- Algebraic parameterization-based pMOR method [4]: extract the geometrical parameter in front of the system matrices during the finite element discretization and then apply multivariate moment-matching-based pMOR [5] method to generate a pROM.

Fig. 5 shows that both methods are applied to a 2D single magnet model. To parameterize the position and size of the magnet, the mesh topology of the model is fully controlled by scaling elements. APDL command 'ARSCALE' is used.

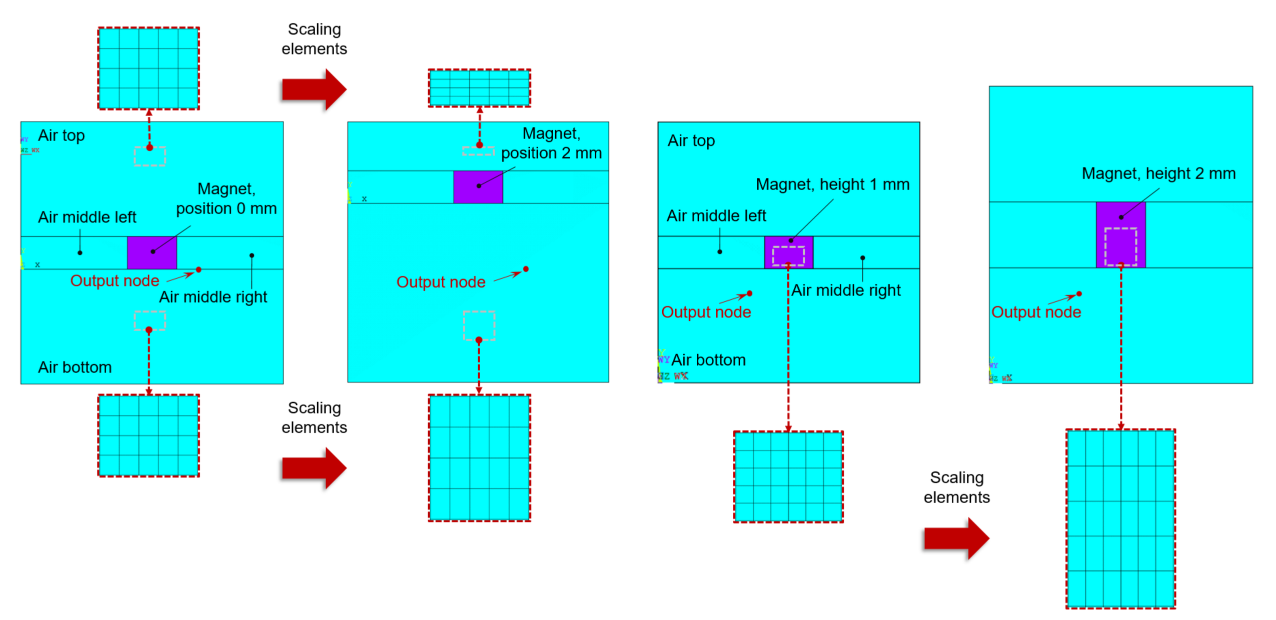

Fig. 5: Preserve the mesh topology of the 2D permanent magnet model while changing the position of the magnet via scaling the mesh in the top and bottom air regions (left); Parameterize the height of the magnet via scaling the mesh in the magnet (right).

Results

The simulations are carried out with an excitation frequency f = 60 Hz and an acceleration amplitude of a_0 = 0.59 m/s². The spring rate is calculated as $k = \omega^2\ m$ = 3.16 N/m. A displacement amplitude of 0.57 mm is expected. Therefore, the excitation amplitude can be calculated as follows:

$$x_0 = \frac{a_0}{\omega^2} = \frac{a_0}{(2\pi f)^2} = 4.15\ \mu\mathrm{m}$$

The induced voltage from the compact model is shown in Fig. 6 left. A parameter study of the load resistance gives the results presented in Fig. 6 right. The maximum power output is 4.28 µW. In Fig. 7 shows an excellent match between the different pROMs and the full order model.

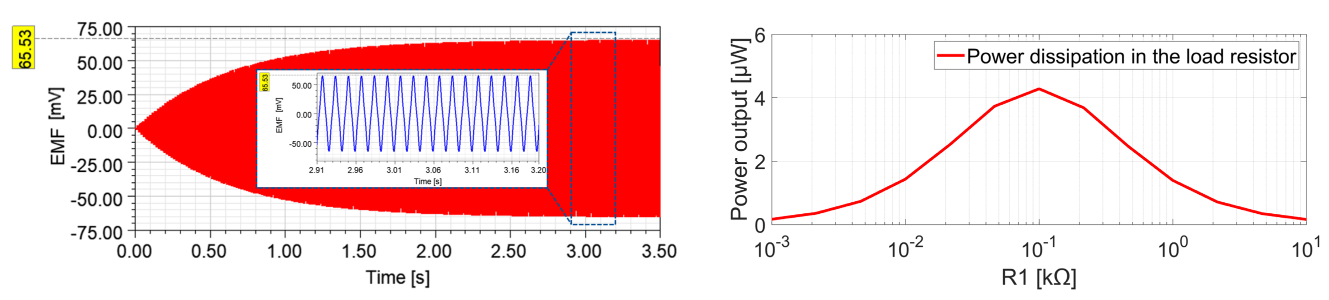

Fig. 6. Voltage output from the compact model in an open circuit condition with the load resistor of 10 GΩ (left); Power dissipation in the load resistor with the varying load resistance (right).

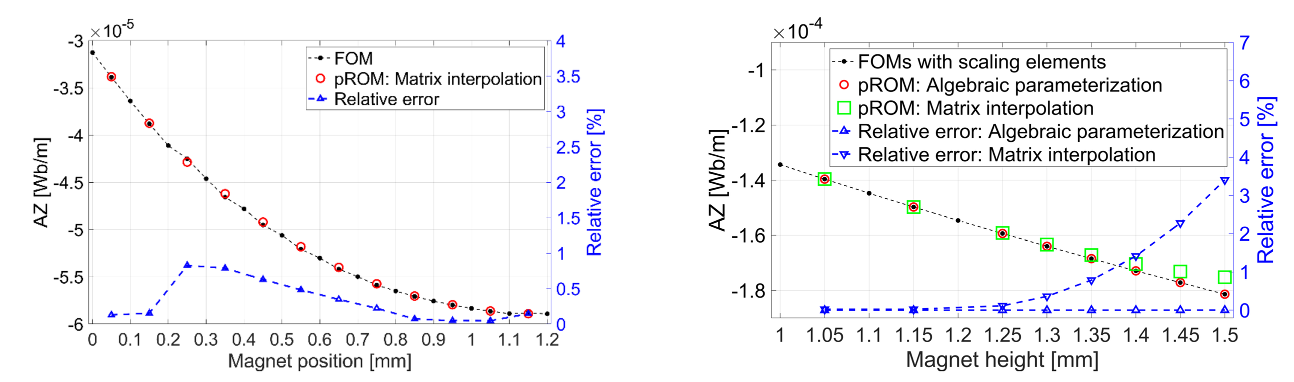

Fig. 7. Magnetic vector potential (AZ) results from the pROM obtained via matrix interpolation-based pMOR method. Change the position of the 2D magnet between 0 and 1.2 mm (left); Comparison of the results from the pROMs obtained via matrix interpolation and algebraic parameterization to the full order model (FOM). Change the height of the magnet between 1 and 1.5 mm (right).

References

[1] ANSYS®. Electronics Desktop, Maxwell 3D, Release 2023 R1. ANSYS, Inc.

[2] S. P. Beeby, et al., "A micro electromagnetic generator for vibration energy harvesting", *J. Micromech. Microeng.* vol. 17, pp. 1257-1265, 2007.

[3] H. Panzer et al., "Parametric model order reduction by matrix interpolation", *Automatisierungstechnik*, vol. 58, pp. 475-484, 2010.

[4] C. Moosmann. "ParaMOR – Model Order Reduction for parameterized MEMS applications", PhD Thesis, University of Freiburg, 2007.

[5] P. Gunupudi et al. "Multi-Dimensional Model Reduction of VLSI Interconnects", In Proceedings of the IEEE 2000 Custom Integrated Circuits Conference, Orlando, USA, May 2000.

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