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A multi-physics-based methodology for electro-magneto-mechanical co-simulation in dynamic applications: A case study

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ABSTRACT

Multibody-based design methodologies are techniques that have seen an increasing use, both in industry and science, in the last few decades. Normally the analysis of large and complex mechanical systems tends to be decoupled to isolate the main macro phenomena and thus allow the models to be simulated by different techniques, tools, and algorithms. All these aspects highlight the difficulties of analysis of coupled heterogeneous systems. The strict interdependence between the different physical domains or different scales of analysis has clearly increased the difficulties in multibody prediction capabilities. An interesting new approach is represented by the multi-physics co-simulations technique where the global model of a coupled system is solved through the inter-exchange of effort and flow variables coming from events of different natures. The paper intends to propose a novel co-simulation architecture for the integration of the magnetic and analog electronic domains into the mechanic one through the implementation among the others of a Matlab-Python based bi-directional communication routine for the interexchange of effort and flow independent variables between the master model (multibody-based) and the equivalent circuit model developed through Spice® as well as the possibility to integrate the dynamic analysis of the 3D electro-magnetic field through the open package ESRF Radia®. To highlight the potentiality of the multi-domain architecture and to validate the results obtained from the co-simulation a comparison with the experimental results of a micro electro-magnetic actuated drive [1] are proposed.

Keywords: Multibody, Multiphysics, Spice-Simulink, ESRF Radia-Simulink, Spice-electronics.

1 INTRODUCTION

Multibody dynamics methodologies represent an indispensable tool for the kinematic and dynamic description of mechanical interaction among rigid and flexible bodies. However, when such interactions come from events of different physical nature, the estimation of the whole phenomena can be extremely complicated. The field of mechatronics certainly represents one of the target areas for this type of research, in fact in such applications it is frequent to interface structures/systems of mechanical nature with devices, sensors and actuators characterized by different physical domains, such as electronics, electrostatics, electro-magnetism, magneto-

statics/dynamics, hydraulics, pneumatics and many others. A common approach toward these arising aspects is to narrow the complexity of the numerical modeling through the isolation of the main macro-domains, and thus solving the different phenomena through dedicated languages, tools, and algorithms [2]. However, in applications where the strict interdependence between the different physical domains and scales cannot be decoupled the introduction of a complete multidomain co-simulation architecture is required necessary [3]–[5]. Matlab/Simulink® certainly represents the most advanced graphical programming environment for the simulation of dynamic systems, being developed for the analysis of multipurpose and general nature problems. The proposed co-simulation algorithm exploits the capabilities of a system-level environment in order to integrate under a single dynamic model, whose core is designed into the multibody ambient, several device-level simulators implemented respectively for the electronic and magnetostatic analysis through the equivalent circuit methodology (ECM) and the 3D finite volume modeling (3DFVM). To test and validate the proposed methodology, a micro-electromagnetic actuator is taken under analysis, the numerical results obtained by the multi-physics model are compared with the experimental relatives reported by Kim et al. in [1], further numerical dynamic evaluation are proposed as explanatory examples to highlight the improved potentiality of the so-implemented multibody-based co-simulation architecture.
In the following: Section 2 addresses the formalism behind the integration of the proposed architecture into a general multibody formulation. Section 3 introduces the whole co-simulation architecture, highlighting the execution frequency control structure. Importance is given to the two novel bi-directional co-simulation algorithms for the integration of the analog electronic and magneto-static domain through PySpice-Simulink and ESRF Radia-Simulink routines, faced in Section 4 and Section 5 respectively. Section 6 highlights the potentiality of the proposed multibody-based architecture through a validation process based on the experimental results obtained onto a micro electromagnetic actuator, together with detailed and purely numerical dynamic evaluations and finally, appropriate conclusions are drawn in Section 7.

2 MULTIBODY DYNAMICS FORMULATION

The multibody dynamics allows to fully describe the purely mechanical nature of a system under its kinematic and dynamic aspects. A multibody model can be essentially schematized as a collection of rigid and/or flexible bodies actuated through forces and torques and constrained in their relative motion through ideal kinematic joints [6], [7]. The general kinematic formulation passes through the generalized coordinates vector.

$$\boldsymbol{q} = \{q_1, q_2, q_3, \dots, q_n\}^T \tag{1}$$

To fully describe the relative dependencies among the set of coordinates previously reported, it is mandatory to define the constraint vector $\boldsymbol{\Phi}(\boldsymbol{q}, t)$. Mathematically its geometry and times reliance are described according to Equation (2).

$$\boldsymbol{\Phi}^{u,v}(\boldsymbol{q}, t) = \boldsymbol{v}^T\boldsymbol{u} - |\boldsymbol{v}||\boldsymbol{u}|\cos(\angle\mathbf{v}, \mathbf{u}(\mathrm{t})) = 0 \tag{2}$$

Where $\boldsymbol{v}$ and $\boldsymbol{u}$ are two generic vectors used in the definition of the rigid bodies, $|\boldsymbol{v}|$ and $|\boldsymbol{u}|$ are the respective norms and $(\angle\mathbf{v}, \mathbf{u}(\mathrm{t}))$ is the relative angle among them. The equation of motion (EOM) characteristic of a general multibody system, is thus given by:

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{\Phi}_{\mathrm{q}}^T\boldsymbol{\lambda} = \boldsymbol{f} \tag{3}$$

Where $\boldsymbol{M}$ is the global mass matrix of the system, $\ddot{\boldsymbol{q}}$ the vector of natural accelerations, $\boldsymbol{\lambda}$ the vector of Lagrange multipliers and finally $\boldsymbol{f}$ is the generalized force vector.
Fig. 1. outlines a possible configuration of a generic multibody model, in which a series of flexible and non-flexible bodies (Flexible Body 1, Body 1, Body 2, Body 3,…) are interconnected through ideal kinematic joints as hinges , ball joints, prismatic joints, fixed joints, etc. Under the dynamic aspects instead, it is possible to note how these bodies could interact by means of two main different categories of forces: purely mechanic forces such as springs, dampers, ideal actuators, contact forces, etc. and forces coming from phenomena of a different physical nature. The proposed approach essentially integrates the generalized force vector $\boldsymbol{f}$ according to Equation (4)

$$\boldsymbol{f} = \left\{\boldsymbol{f}_{\boldsymbol{mech}}, F_{mag1}, F_{el,mag2}, F_{el3}, \dots\right\}^T \tag{4}$$

Where $\boldsymbol{f}_{\boldsymbol{mech}}$ is the purely mechanic generalized force vector, instead F_{mag1}, $F_{el,mag2}$, F_{el3} represent general force elements coming from the electro-magneto-mechanic interactions.

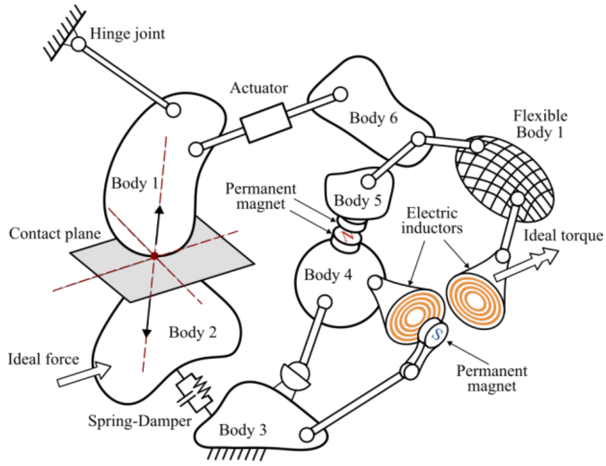

Figure 1. A general representation of a multibody model.

3 THE PROPOSED MULTI-PHYSICS ARCHITECTURE

3.1 The logic

The proposed co-simulation multi-scale and multi-physics implementation logic is reported in Fig. 2. through a block diagram schematization.

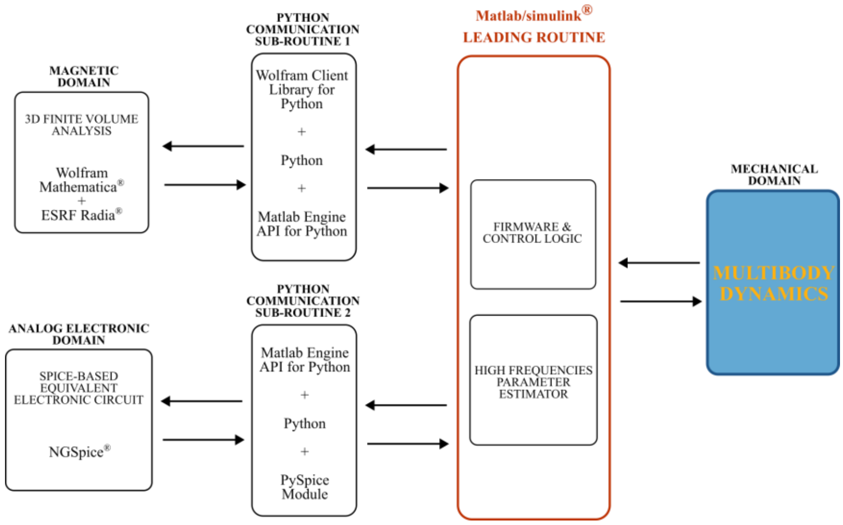

Figure 2. The proposed multi-domain co-simulation architecture.

The core of the model developed in Matlab\Simulink, discretizes the time of the simulation interfacing the different physical domains. This discretization process represents one of the key aspects of the co-simulation algorithm. It takes place independently for each physical domain treated. Inside the MATLAB/Simulink master routine, two other main functions are also implemented: the high-frequency parameter estimator that computes the induced variation in parameters and variables affected by the interaction with different physical domains, and the firmware and control logic routine, that allows to embed a firmware control loop in the case that the studied device is governed by a microprocessor or a microcontroller. In detail the mechanic nature and the relative kinematics and dynamics interactions are taken into account through a complete multibody model of the full device assembly under analysis, the Mathematica open-source package ESRF Radia solves the static and dynamic electro-magnetic fields through a 3D FVM algorithm, and finally the equivalent circuit properties are integrated and solved through the Spice engine. The whole dynamics behavior is integrated at every time step and updated, the resulting sets of PDE/ODE of each domain are settled taking effort of the dedicated platform solver, and finally the bi-directional communication is taken in charge by two novel implemented and dedicated Matlab/Python routines fully described in Section 4 and Section 5.

3.2 The time-line discretization

As reported in Fig. 3. during the entire time line each physical domain has its own simulation time window and a characteristic sampling frequency reported in the image with t and $f = 1/T$ respectively. The Matlab/Simulink leading ambient defines the maximum temporal length for the entire simulation ($t_{Matlab/Simulink}$) and discretizes it through a variable step integrator, the length of these time steps represents the maximum length of the instantaneous simulation window of the individual physical domains ($t_{ESRF-Radia}$, t_{Spice} and $t_{Multibody}$), which are called independently according to their respective calling frequencies, which are necessarily lower or equal than the minimum leading one ($1/T_{Matlab/Simulink}$), in fact as reported not all the Matlab/Simulink time steps present a call to the other domains.
In case the characteristic phenomenon of a particular domain occurs at higher frequencies, the algorithm is able to adapt to the event and follow the changes according to a dedicated sampling frequency ($1/T_{ESRF-Radia}$, $1/T_{Spice}$ and $1/T_{Multibody}$), as in the case of the electronic domain call, in fact, the Spice integrator further discretizes the relative timeline, with frequencies in the order of 10^9Hz, returning at the end of the co-simulation process, for the considered Matlab/Simulink time instant the results obtained from the last Spice discretization interval. This aspect firstly allows to independently integrate the three standard tools for the dedicated analysis as well as to sample/call the different domains at an optimal frequency thus optimizing the computational effort of the CPU and preventing the aliasing phenomenon.

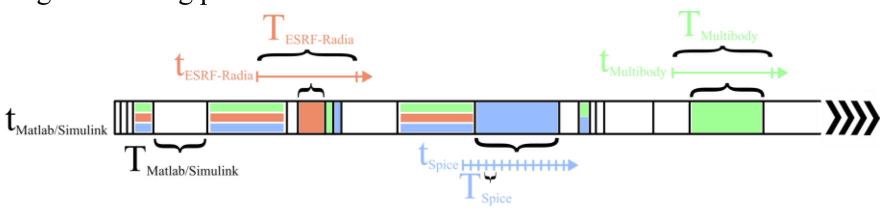

Figure 3. *Representative example of a time line discretization.*

4 INTEGRATION OF THE ANALOG ELECTRONIC DOMAIN

4.1 Introduction

Currently, device-level circuit simulators represent the standard solution in complex electronic simulations. Their strengths is based on the conformity to fundamental physical principles [3], which in turns introduces long-time simulation, losses in computing performances and difficulty in multi-domain integration. On the other side, system-level like ambient such Matlab/Simulink can guarantee high computational performances and multipurpose analysis at the expense of a reduced range of possible simulations, due to lack of transient, AC/DC or sweeps analysis capabilities and a limited availability of complete components libraries [8].
The proposed work therefore introduces and defines a new co-simulation methodology between a device-level ambient and a system-level circuit simulator. Respectively, Spice which over the years has consolidated as the standard tool for the simulation of analog electronic both for industry and science and Matlab/Simulink, so as to ensure high fidelity in the simulation of the related physical phenomena and to broad the range of events that can be studied.
In literature few attempts were made toward this direction, among the others a work was proposed by Madbouly et al. in [9] in which are presented a set of simulation tool called MATSPICE, that introduce a preliminary step for the optimization of parameters and the rapid iteration of circuit resolutions through a SPICE-based solver engine. Another significant implementation is proposed in [10] where authors describe an innovative and interesting approach to the problem, through a Simulink-based S-function implemented as a Level-2 M-file capable of coupling NGSpice engine with a Matlab/Simulink model. The proposed architecture instead aims to integrate the analog electronic domain through a completely different approach. A dedicated Simulink Matlab-based function execute through the Matlab Engine API for Python the implemented Python-based routine, that merge the open source module PySpice [11], which in turn executes the NGSpice/Xyce simulator and allows the bi-directional communication of the effort and flow variables among the co-simulated ambient.

4.2 The algorithm

Fig. 4.(a). depicts the logic behind the algorithm of co-simulation between the Spice-based circuit integrator and Matlab/Simulink.

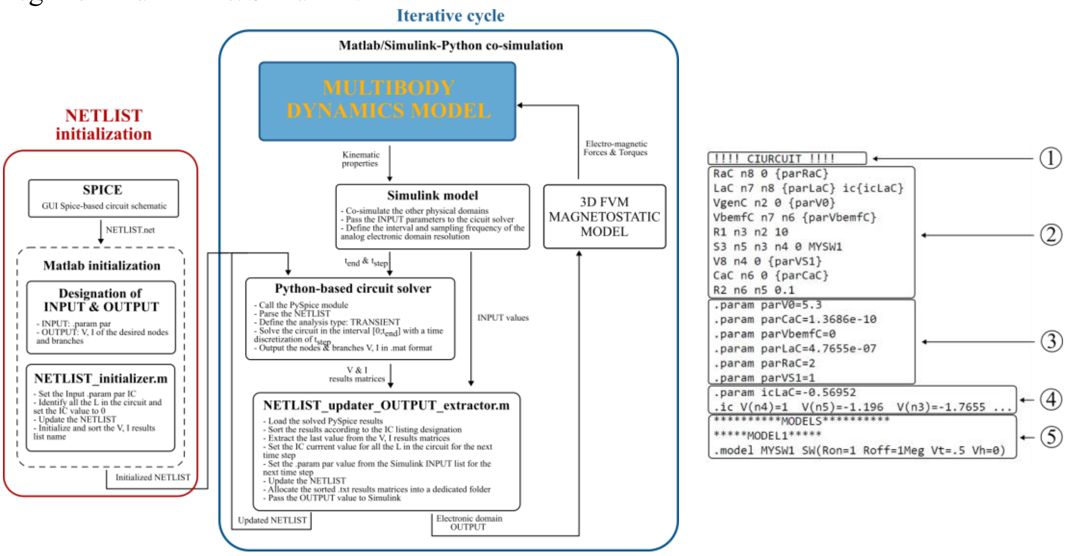

Figure 4. *(a) Flowchart of the analog electronic integration algorithm, (b) Modified Netlist for the co-simulation execution.*

This analog electronic coupling architecture is defined over two main different steps: the Netlist initialization and the proper iterative cycle. The initialization process starts with a fast implementation of the circuit schematics through a Graphic User Interface (GUI) editor. The components network is then grouped inside the so called ".net" file NETLIST, that passes through a manual dedicated process that aligns the NETLIST structure according to the co-simulation algorithm requirements, as reported in Fig. 4.(b). In detail, can be distinguished five main different parts: The title (1), (2) highlights the core structure of the NETLIST where all the components' networks are defined on the basis of the circuit nodes connections. The key part of the Netlist is enclosed under (3) that defines the INPUT values that are passed from Simulink to Spice during the co-simulation exchange and allow a continuous modification of the circuit caused by the interaction with the other physical domains. During each Simulink call and according to what described in Section 3.2 and Fig. 3. during each Simulink call, the Spice integrator generates a new independent timeline, that needs to be temporally relocated in the main macro timeline and initialized on the basis of the previously obtained results. These initial conditions parameterization is listed in (4). Finally (5) defines and lists all the equivalent NGSpice/Xyce-based models of the real electronic components.

Now that the constitutive circuit NETLIST has been initialized the analog electronic model is ready to be co-simulated on the basis of the following steps: I) The multibody solver settles the kinematic parameters that are passed to the communication routine, II) Simulink calls off the communication routine framework through the Matlab Engine API for Python that execute the Spice solver based on the open source PySpice module, III) NGSpice/Xyce solves the circuit NETLIST, IV) the routine extracts the last V/I Spice discretization results, as Spice samples the electronic phenomena at higher frequency (i.e. 10^9Hz) compared to the Simulink leading routine call, V) a Matlab function re-initialize the circuit NETLIST updated on the last extracted Spice results and on the solved and updates INPUT parameters coming from the interaction with the other domains (e.g. mechanical, magnetic…), VI) these analog electronic voltages and currents are passed to the magnetostatic domain and VII) the loop is closed transferring the resulting effort and flow variables to the multibody model in the form of electromagnetic forces and torques.

5 INTEGRATION OF THE MAGNETO-STATIC DOMAIN

5.1 Introduction

The other main routine presented in the paper cover the integration of the magneto-static domain. In the literature several interesting case studies are reported mainly focused in the field of motor drives or magneto-strictive actuators, the effects of the magnetic domain onto the functional behavior of these apparatus is mainly taken under analysis through a finite element methodology (FEM) approach [12]. In our study, we propose an alternative perspective with respect to this classic FEM-based approach, taking efforts of the potentiality of the finite volume modeling (FVM). In fact as validated in [13] the method used in ESRF Radia belongs to the category of boundary integral methodologies and differs strongly from the Finite Element Methods. Once the 3D volume objects are created, the materials are applied and the interaction matrix is obtained, and once the relaxation procedure is executed all the magnetization vectors are extracted by the single tiny volume. During this procedure one applies some kind of segmentation to the field-producing objects (typically iron) but, contrary to the FEM approach, one does not need to mesh the vacuum. This has a number of important consequences: I) geometries opened to infinity are more easily simulated, II) the number of elements required for a given precision on the prediction is typically twenty times smaller compared with a FEM code as well as the CPU time required, III) once the relaxation is done, the magnetic field and field integrals can be computed anywhere in space whatever the distance to the field-producing objects, and finally IV) field integrals can be computed using analytical formulas.

5.2 The algorithm

The presented algorithm logic is similar to the one reported for the Spice-based analog electronic integration. Fig. 5. depicts through a flow chart the main implementation and execution steps of the routine. It starts with the initialization of the magnetostatic model. The 3D Finite Volume Model (3DFVM) is first implemented in Wolfram Mathematica® language and preliminary tested for the further dynamic co-simulation, once verified is imported under a Python module and interpreted by the Mathematica-Python API. The completely set model is passed to the iterative cycle according to the presented closed loop logic, characterized by the following steps: I) The multibody solver settles the kinematic parameters that are passed to the communication routine, II) the leading Simulink routine calls off and update through the Matlab Engine API for Python the 3D FVM model implemented in Mathematica language and integrated in the Py-module, that is iteratively interpreted through the Wolfram Client Library for Python, III) the ESRF Radia engine solves the model based onto the achieved configuration, IV) the routine extracts the obtained results (e.g. magnetic fields intensity, magnetic forces/torques…) and finally V) These results are integrated with the information passed by the analog electronic domains and finally VI) the loop is closed transferring the resulting effort and flow variables to the multibody model in the form of electromagnetic forces and torques.

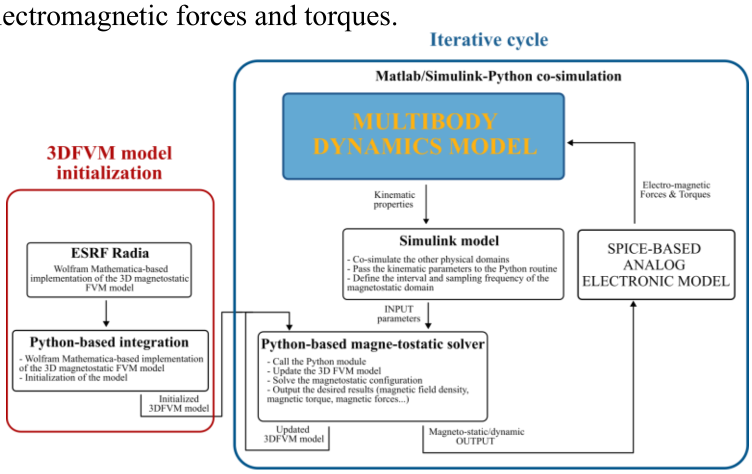

Figure 5. *Flowchart of the 3D FVM magnetostatic integration algorithm.*

6 THE CASE STUDY

6.1 The device

The structure of the micro electromagnetic actuator is depicted in Fig. 6. As reported in [1] the actuator is composed of three actuation chambers for the peristaltic drives. The motion is obtained through a synchronous oscillation of the three main parylene membranes, whose characteristic dimensions are: $4.5mm\ x\ 4.5mm$ and a thickness of $3.5\mu m$. These membranes are bonded over a $330\mu m$ n-type silicon substrate that is glued over a Fe-core frame. The Fe-based frame is added by designers to improve the performances of the device acting onto the guidance of the magnetic field lines generated by three NdFeB magnets, characterized by $3.2mm$ in diameter and $1.6mm$ in height. These permanent magnets present one of their faces at $330\mu m$ from the oscillating membranes and interact with three planar spiral electroplated micro copper coils mounted over the parylene layer.

The authors propose two main different devices based onto different geometries and characteristics, the proposed experimental-numerical comparison is based onto the results obtained from the device that has developed the most effective performances, thus the one constitutes of a corrugated borders membrane. Further and deeper constitutive information can be found under the related article [1].

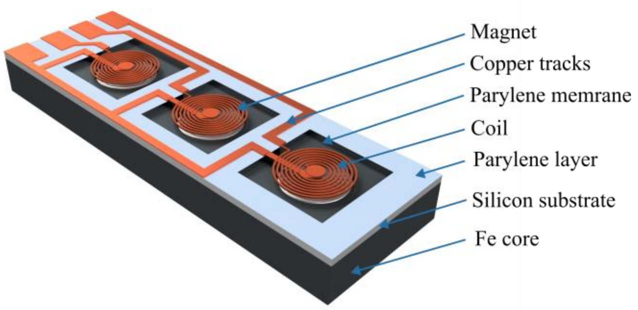

Figure 6. *3D graphical representation of the micro electromagnetic actuator.*

6.2 The numerical model

The core of the numeric model structure is implemented through the multibody analysis, where the kinematics properties of the device are settled by the mechanic solver and passed at every time step of the simulation to update the magnetic and analog electronic models, that in turn restitute the resulting electromagnetic forces and torques back to the MBD model, for the actuation of the coupled moving parts.

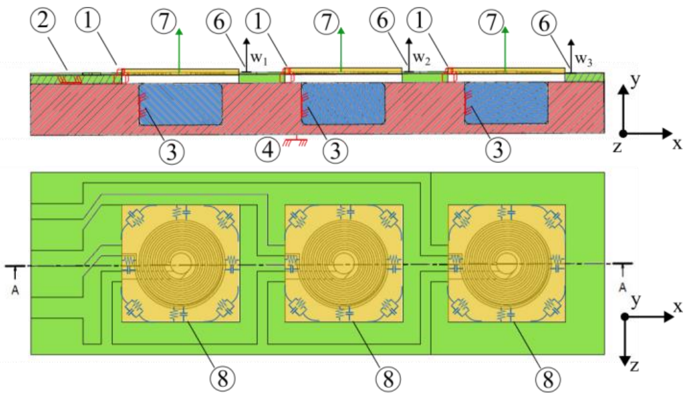

Figure 7. *Explicative view of the multibody model.*

In detail as depicted in Fig. 7. the MBD model can be subdivided over four main different constitutive parts (marked through four different colors).

- The parylene membrane with the electroplated micro coil (yellow bodies)
- The silicon substrate (green body)
- The Fe-based core (red body)
- The NdFeB permanent magnets (blue bodies)

In the following are described the modelling choices adopted for the replication of the kinematic and dynamic properties characteristic of the micro electromagnetic actuator.

- The NdFeB magnets, the silicon substrate and the Fe core are ideally bonded together through a fix joint (2) and (3) and settled to the ground in (4).
- The kinematic deformation properties of the membrane are modelled through a prismatic joint (1) between the fictitious diaphragm-coil subassembly and the silicon substrate.
- The kinematic measures w and dw (6) of the equivalent deflection are gauged between

the Si substrate and the lower face of the membrane and is passed back to the leading routine as presented in Fig. 2. to compute the induced e.m.f. for the analog electronic model and the updated relative position between the coils and the permanent magnets.

- Under the dynamic aspects, the electromagnetic interactions are integrated under the mechanic model through a classical force element (7), it is applied between the magnet and the membrane, and its absolute value and the verse of application are estimated according to the Lorentz's formulation of force and computed through the results extracted by the other two domains.
- A dynamic bushing element (8) is added to replicate the elastic and dissipative properties of the corrugated parylene diaphragm, this kind of dynamic joint introduces spring-damper equivalent forces between the two parts both under the translational and rotational directions. For the application under analysis only the component of forces acting along y-axis is taken under consideration.

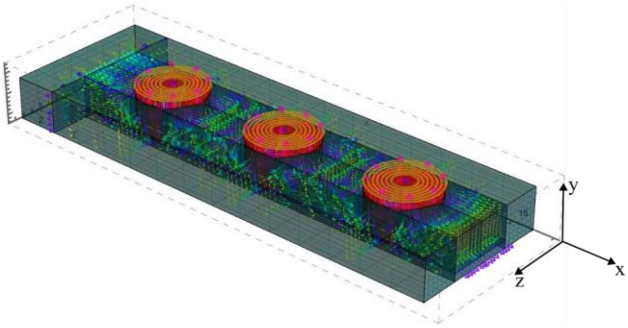

Figure 8. *3D magneto-static finite volume model.*

The magnetic interaction terms, previously reported during the multibody model implementation description, are here taken under analysis through the 3D finite volume methodology. In detail, the model is implemented through the Wolfram Mathematica-based language and interpreted by the ESRF Radia engine. Fig.8. depicts the implemented framework, with the characteristic field lines distribution obtained during a frame of the full co-simulation process.
Since most of the constitutive parts do not have any ferromagnetic properties and consequently would not interact during the simulation, the system is modelled through a reduced number of components: the planar micro-coils, the NdFeB permanent magnets and the Fe core.
The iron-based frame together with the three permanent magnets are maintained steady for the entire simulation time window, while the micro coils are continuously updated in position to have a correspondence between the magnetic model and the MBD model.
Finally, the electric coupling phenomena are here taken under analysis through a Spice-based analog electronic model. Fig. 9 shows the GUI circuit schematic of the Spice-based equivalent model.

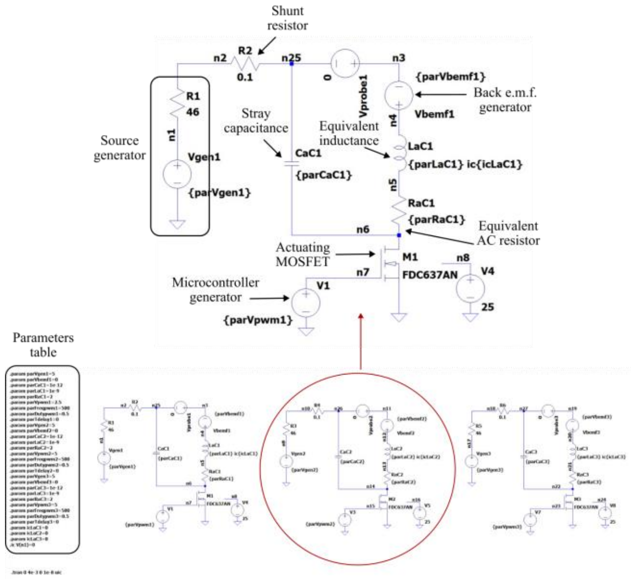

Figure 9. *GUI Spice-based circuit schemtics model.*

The model is constituted by the same circuit repeated three times to replicate the three different electroplated micro-coils. In the upper part of the picture is reported a magnification of one of the subcircuits, the considerations made in the following lines are to be considered valid also for the two remaining ones. The schematic is implemented for the NGSpice engine simulator, the planar micro-coil is here modeled through a parallel between the stray capacitance and the series of the AC resistance, the equivalent inductance, and the back e.m.f. generator, that allows to introduce in the full model the back induction phenomena due to the coil motion inside the permanent magnet field. The circuit is fed by a 46 Ω source generator. In order to replicate a real case application and to enhance the potentiality of the proposed architecture, an active actuation control is introduced, this microcontroller replica is implemented through an equivalent generator and a MOSFET. The circulating current is measured through the voltage drop across the shunt resistor terminals. Finally, is highlighted also the parameters list that represent the core of the co-simulation process, as described in Section 4.2.

6.3 Numerical-experimental comparison and architecture validation

In this section we propose a validation of the implemented multi-domain architecture, comparing the obtained numerical results with the experimental measurements reported in the referred article [1].

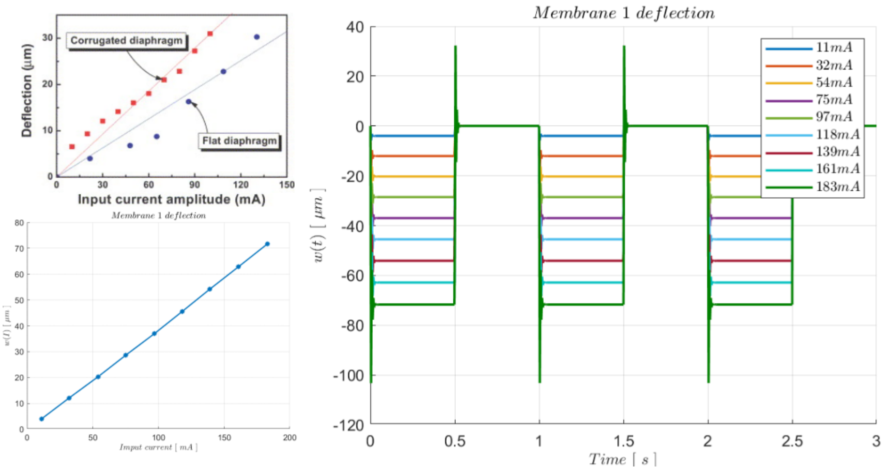

Figure 10. *(a) Experimental-numerical comparison of a single membrane deflection, (b) 1Hz deflection amplitude, due to a variable amplitude feeding current.*

The test was performed imposing a variable amplitude square wave input current with a frequency of 1Hz and a characteristic duty equal to 50%. During our validation champaign we replicated this feeding and testing apparatus under the analog electronic equivalent model. Fig. 10.(b). shows the oscillating deflection at the imposed frequency of 1Hz, the different waveforms are obtained from the model imposing different levels of feeding current, from 11mA up to 183mA with a step of about 20mA. Extracting the maximum steady results of these oscillations is obtained the curve reported in the lower part of Fig. 10.(a). This result confirms that the model guarantee a high fidelity in dynamic response prediction, in fact, comparing this curve with the one reported in the upper image (Fig. 10.(a).) concerning the corrugated diaphragm, can be noticed how close are this numerical and experimental outcomes.

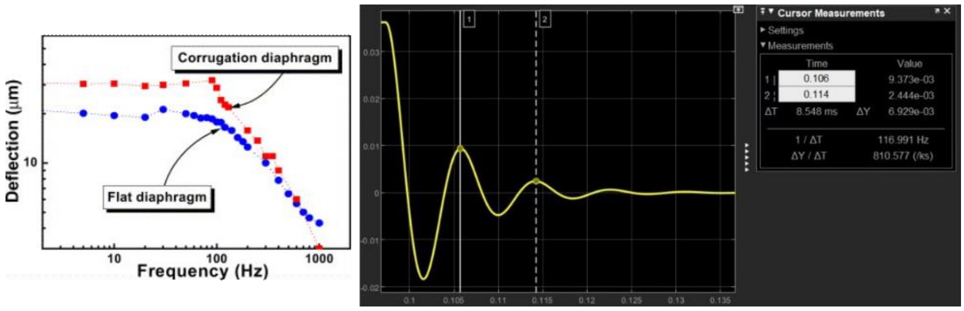

Figure 11. *Frequency response function and free-dumped oscilating behaviour.*

Another important dynamic result concerns the validation of the model under the frequency response area. Fig. 11. depicts under the left side the frequency response function of the diaphragm amplitude of oscillation, in which is highlighted that the cut-off frequency of the device is around 100Hz. In fact imposing to the model a membrane deformation and a consequent free dumped oscillation the resulting natural frequency of the response is equal to 116.9Hz.

7 CONCLUSIONS

The work introduces an improvement in the simulation capabilities of complex and strongly coupled devices, with particular emphasis on the coupled analysis between multibody dynamics, analog electronics, and magneto static/dynamic phenomena. A very important area of interest for such application is certainly represented by the field of mechatronics, where complex mechanical structures/systems are interfaced with devices, sensors and actuators characterized by different physical natures, such as electronics, electrostatics, electro-magnetism, magneto-statics/dynamics, hydraulics, pneumatics and many others.

In details, in the presented paper a novel time-based multi-domain architecture is taken under analysis, and its capabilities and accuracy are verified. The study focuses onto the integration under a general multibody formulation of a classical element of force and torques, which does not introduce state variables and algebraic constraints, and allows to integrate the electro-magnetic coupled dependencies. The method uses a multi-physics approach, where two novel Python-Matlab based bi-directional communication routines integrate two consolidated simulation tools and languages for the electronic and magnetic domains: the Spice-based analysis and the 3D Radia-based finite volume methodology, respectively.

The presented multi-domain co-simulation algorithm is finally validated through a complete comparison of the experimental measurements obtained from a micro electromagnetic actuator [1]. The numeric results are compared both under the quasi-static and dynamic analysis, highlighting how the model is able to predict with a quite good level of accuracy the tested trends.

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