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FF_Sim: A Simulation tool for ferrofluidic transducers

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Abstract: In this paper a simulation tool for ferrofluidic transducers is presented. The aim of the tool developed is twofold: to provide the designer with a useful tool which carries out both the behavioral analysis and the quantitative analysis of ferrofluidic devices and to support educational activity on the subject in advanced academicals courses.

Keywords: ferrofluids, transducers, modeling.

1. INTRODUCTION

Inertial sensors adopting a drop of magnetic fluid as active mass are of great interest due to their intrinsic robustness against inertial shocks and tuneable properties (operating range and responsivity). Moreover, such peculiarity is valuable also in view of a micro machined realization. To this aim non-conventional materials, such as Ferrofluids (synthetic compounds composed by colloidal suspensions of ultra-fine, 5-10 nm, particles) whose physical properties (like density and viscosity) can be controlled by applying a magnetic field, can be used. Ferrofluids are colloidal suspension of single domain magnetic nanoparticles (5-10 nm) in a carrier fluid (aqueous or non-aqueous) that can be controlled (in terms of viscosity and density) by the exploitation of a magnetic field [1-2]. The magnetic force acting on a ferrofluidic mass causes the alignment of the magnetic nanoparticles thus controlling the shape and the position of the mass.

Transducers using magnetic fluid in order to implement support actions such as dampers, valves, plungers and external mechanical devises are usually adopted to implement advanced fluid control [3-16]. In literature, several examples of sensors and transducers exploiting magnetic fluid have been proposed. An example of exploitation of magnetic field to change the mechanical characteristics of a cantilever beam dip in a magnetic fluid is proposed in [4] in order to measure micro accelerations; the device uses a capacitive readout strategy within a feedback compensation scheme. An interesting example of inclinometer is given in [5]. The device consists of a mobile magnetic core attached to two permanent magnets contained inside cylinder. Reduction of friction forces and sliding of the magnetic core induced by an external tilt is guaranteed by two ferrofluidic cushions. Repulsion forces between the supporting magnets and two magnets disposed outside the container imposes an equilibrium position at the core when the device is tilted. Two coils are used to detect the position of the magnetic core.

Actually, non-conventional materials such as ferrofluids are mainly used in order to implement actuator in microfluidic devices. In particular, micropipettes [6], alternating micropumps and valves [7, 8], rotating micropumps [9], electromagnetic micropumps [10], linear pump [11], microvalve [12] and an integrated MEMS ferrofluid pump [13] which use magnetic fluids to implement pumping operations are developed.

In [6] a micropipette exploiting the magnetic force generated by external electromagnets is proposed. The microfluidic device inlet and outlet has been implemented on the same side of the micropipette, thus requiring mechanical actions to move liquid samples from one tank to the other. In [7], an alternating micropump based on a ferrofluidic plunger and valves is presented. All components are controlled by external magnets moved by a DC motor and the valve is realized with a channel deformation. In [8], a ferrofluidic plunger is used to implement an alternating micropump where an external magnet actuated by a DC motor is used to move the plunger in the channel. In [9] a rotating micro pump using a ring tube with an inner and outer section is realized. Fluid sampling is accomplished through two ferrofluidic caps created by two external permanent magnets moved by a DC motor. In [10] a pump for magnetic particles is described. It consists of an array of electromagnets sequentially activated so as to move a volume of magnetic nanoparticles from an inner tank to a destination tank. In [11] magnetic fluid trapped in a elastic membrane is deformed exploiting the magnetic field generated by external electromagnets in order to realize a linear pump in a straight channel. In [12] a mass of ferrofluid is moved inside a micro channel by an external magnet in order to realize a micro valve in SOI technology. In [13] traveling wave excitations from integrated electrodes is used in order to obtain a continuous pumping of a magnetic liquids within a micro fluidic channel.

Therefore studies on dynamic phenomena on ferrofluidic device subjected to time varying magnetic fields are already present in literature [14-15].

In a recent paper the authors investigate the possibility to realize ferrofluidic transducers with nonmoving mechanical parts [17-25]. In particular, a study on the modeling of a ferrofluidic volume subjected to a magnetic force as a tunable non-linear equivalent mass-spring system [23-24]. The latter consideration highlights the possibility to adopt ferro fluids to develop valuable novel transducer architectures (such as accelerometers, inclinometers, gyroscopes and pumps) using the ferrofluid as active mass of the device. Such inertial transducers show interesting and valuable features, among which: high robustness against shocks, possibility to control the shape and the position of the ferrofluidic mass inside the device architecture by means of suitable magnetic fields and electro-magnetically tunable properties such as operating range, resolution and sensitivity [23].

The development of ferrofluidic transducers is affected by several factors, among them the device geometry, the ferrofluidic material adopted and the characteristics of the electro-magnetic driving systems. The investigation on such aspects will allow for a suitable design of the device fulfilling the required specifications.

In this paper a simulation environment, developed in Matlab® is presented (hereinafter FF_Sim). It provides the designer with a useful tool which carries out both the behavioral analysis and the quantitative one of the performances of the prototype. The aim of the tool developed is to provide an useful tool which accomplish behavioural and quantitative analysis of ferrofluidic devices and in particular to support the educational activity of students involved in advanced academicals courses.

2. SIMULATION TOOL

Figure 1 shows the schematization of the FF_Sim tool, which consists of the following environments:

- *device parameter setting*: to set the device specifications;
- *model definition block*: to implement the constitutive equations ruling the device behavior;
- *simulation parameter setting*: to set the type of the simulation and some specific parameters;
- *3D User interface*: to provide a behavioral evidence of the device operation; actually, the 3D interface exploits the Virtual Reality Toolbox in Matlab®, while the 3D prototype is implemented in VRML Language;
- *output section*: to provide the user with results of the performed simulation.

To the introduced environment a general structure applicable for the simulation of several architectures has been given: in this paper the first module of the FF_Sim tool (called FF_In_Sim) is described.

The module has been developed to simulate the behavior of the ferrofluidic inclinometer presented by the authors in static [23] and resonant configurations [24]. For the sake of convenience, in the following section a brief review of the operating principle of the ferrofluidic inclinometer in both static and resonant configuration is given.

3. THE FERROFLUIDIC INCLINOMETER

The working principle is summarized in this section and some considerations on models ruling the behavior of the device are presented (an extensive presentation can be found in [23-24]). The schematics of the proposed device in both static and resonant operating configurations are given in Figure 2. The sensors consist of a glass pipe filled with water where a drop of ferrofluid is injected. In order to control the ferrofluidic mass and to sense its position one primary coil and two sensing coils are wrapped around the glass channel. The magnetic force, induced by the primary coil through a DC current, I_{DC}, holds the ferrofluidic mass in an equilibrium position which depends on the device inclination (for a zero tilt the mass should be nominally maintained around the centre position of the primary coil). To sense the mass position an inductive readout strategy is implemented by realizing a coupling between the primary coil and the secondary coils through an AC current imposed to the primary coil. The differential voltage at the output of the two sensing coils is related to the ferrofluidic mass displacement and thus reflects the tilt to be measured [23].

The behavioral model for the static inclinometer can be expressed as [24]:

$$\rho_f V_f \ddot{z} = 6\cdot\pi\cdot\eta\cdot r_f\cdot\dot{z} + (\rho_f-\rho_l)\cdot V_f\cdot g\cdot\sin(\theta) + F_{m,ret} \quad (1)$$

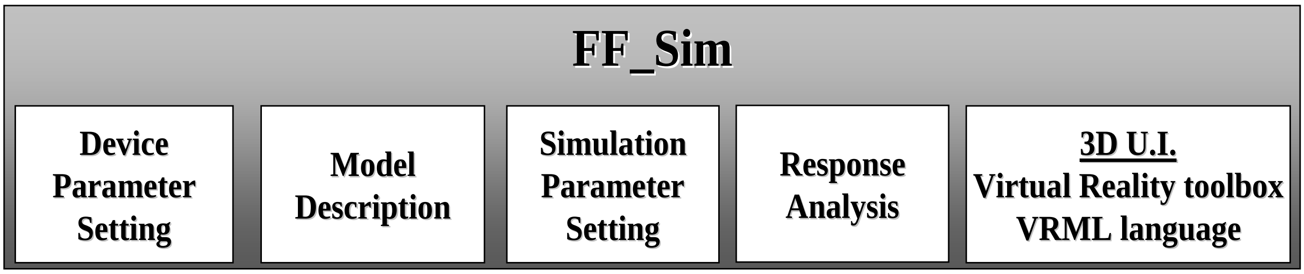

Figure 1. Schematics of the FF_Sim simulation tool.

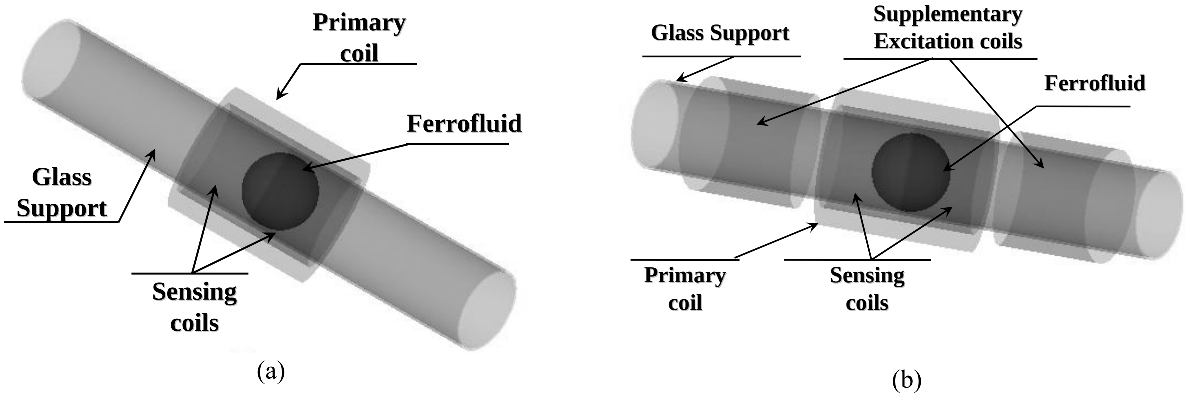

Figure 2. Schematics of the Ferrofluidic Inclinometer: (a) Static configuration (b) Resonant configuration.

where the first term on the right side represents the Hydrodynamic drag force (where η is the ferrofluid viscosity and r_f is the ferrofluidic sphere radius), the second term represents the gravitational and Archimede's forces (where ρ_f is the ferrofluid density, ρ_l is the water density, V_f is the ferrofluid volume, g is the gravitational acceleration and θ is the tilt applied to the device), while the last term represents the magnetic retention force induced by the primary coil. The expression of the magnetic force generated by the primary coil excited with the I_{DC} current is:

$$F_{m,ret}(z)=\frac{\mu_0 V\chi_m I_{DC}{}^2 N^2}{4L^2}\left[\frac{0.5L-z}{\sqrt{R^2+(z-0.5L)^2}}+\frac{0.5L+z}{\sqrt{R^2+(z+0.5L)^2}}\right] \quad (2)$$

$$\left[\frac{-R^2}{\left[R^2+(z-0.5L)^2\right]^{\frac{3}{2}}}+\frac{R^2}{\left[R^2+(z-0.5L)^2\right]^{\frac{3}{2}}}\right]$$

where: μ_0 is the vacuum permeability, V is the volume of ferrofluid, χ_m is the ferrofluid susceptibility, N is the number of turns of the coil, L is the coil length, R is the coil radius, I_{DC} is the DC current injected into the primary coil.

Although the magnetic force, $F_{m,\ ret}$, is a non-linearity for the device, under particular condition (a suitable L/R ratio) it is possible to show a wide operating range where a linear trend can be assumed [23].

In the resonant configuration, two supplementary excitation coils are used to put the ferrofluidic mass in movement around its equilibrium position. The aim of such approach is to prevent the adhesion of the ferrofluid to the glass pipe thus reducing the high static friction and improving the device resolution [24]. Actually, the supplementary coils are driven by two AC currents, I_a, with the same amplitude, 90º degrees of phase lag and frequency equal to the mechanical resonance frequency of the device observed for the specific I_{DC} current.

The model for the resonant configuration is obtained taking into account also the effect of the magnetic force induced by the supplementary excitation coils [13], thus leading to the following model:

$$\rho_f V_f \ddot{z}=6\cdot\pi\cdot\eta\cdot r_f\cdot\dot{z}+\left(\rho_f-\rho_l\right)\cdot V_f\cdot g\cdot\sin(\theta)+F_{m,ret}+F_{m,exc} \quad (3)$$

The last term of Eq.(3) represents the magnetic force induced by the supplementary excitation coils which must take into account the two contributions of the magnetic force due to the left coil and the right coil:

$$F_{m,exc}=F_{m,exc,R}\left(z+d,I_a\right)+F_{m,exc,L}\left(z-d,I_a\right) \quad (4)$$

These two forces have the same expression in Eq. (2), where d is the distance between the middle points of the primary coil and each supplementary excitation coil.

As already stated in [23, 24], once the ferrofluid characteristic and the device geometry have been fixed, the sensor characteristics such as the operative range, the resolution and the sensitivity, can be tuned by the I_{DC} current.

4. The FF_In_Sim User Interface

Figure 3 a) shows the user interface of the FF_In_Sim environment. In the following some details on the four sections of the interface will be given.

- *Device parameters setting.* Through this panel the user can set the geometrical parameters of primary, secondary and supplementary excitation coils (length, inner radius, number of turns, position and wire specifications), the amplitude of the I_{DC} current and the amplitude and the frequency of the I_a current, the properties of the magnetic fluid (volume, susceptibility, viscosity and density).
- *Simulation parameters setting*. This section is used to set the device operating mode (static/resonant), a number of simulation parameters such as the operating range of the device (which in the case considered means the initial tilt, the final tilt and the incremental tilt) and the simulation time. Moreover the user can define the aim of the simulation:

- to observe the device time response (such as the time evolution of the mass position) for well-defined stimuli (step, ramp);
- to observe the device operation such as the steady state mass position as a function of the tilt imposed;
- to observe the trend of other quantities such as the magnetic force inside the primary coil imposed by the I_{DC} current.

- *3D User Interface.* This graphic interface, shown in Figure 3.b, is used to provide the user with a graphic animation of the device behavior when forced with a mechanical stimulus (e.g. step, ramp or time varying tilt), in particular it is possible to understand how the ferrofluidic mass moves after a tilt variation.
- *Output section.* After the simulation has been performed, output information is made available in a graphic window (e.g. showing the time response of the device, as well as the device behavior as a function of the imposed tilt or the trend of the magnetic force). Figure 3 shows a typical mechanical step response for the static configuration. Results of the simulation are made also available in dedicated files for further elaboration and analysis.

A schematic of the simulation tool is presented in Figure 4.

Concerning models describing the magnetic and mechanic behaviour of the device, models introduced in Section II have been implemented and in particular a linear trend for the magnetic retention force can also be selected in the case of the static configuration (see [23]).

On the basis of the above consideration, the following tasks performable by the simulation tool are evincible:

- Definition of the model used to describe the behavior of the device under investigation.
- study of the mechanical response of the device (mass position as a function of the tilt imposed) and time response analysis (step response, ramp response) by analyzing the time evolution of the active mass;
- investigation of the device performances (as a function of geometrical and electrical parameters) such as operating range, mechanical sensitivity, resolution, time response and other specific analysis such as the investigation of the resonance frequency in the resonant configuration by exploiting graphic representation of such quantities as a function of device parameter
- simulations of the device behavior taking into account also the behavior of the inductive readout strategy. In this case the simulation output will be provided in terms of voltage rather than in terms of the mass position.

Actually, as largely discussed in [23], the geometrical and electrical parameters of the system deeply influence the device operation in terms of sensitivity, time response, operating range and linearity. Hence, the availability of the FF_In_Sim tool allows for a design of the device fitting the desired specifications and taking into account the geometric/electric parameters of the sensing architecture and the properties of the magnetic fluid adopted. The tool encourages students at the study of the ferrofluidic inclinometer and allows the understanding of the model of the devices.

Actually, the user is assisted in the analysis of the ferrofluidic inclinometer by message box explaining the meaning of the main device parameter and characteristics, in order to better understand the variation of transducers performances on the base of the defined parameters. In particular, attention on geometries of the primary coils is evidenced by the interface, through showing the magnetic force trend in the symmetry axis of the coil, in order to better understand how it is possible to modify the device characteristics (such as operative range, mechanical sensitivity, resolution) and in order to obtain a quasi linear trend of the magnetic force.

5. CONCLUSION

A simulation environment for the design and the analysis of ferrofluidic transducers has been presented. In particular, the module related to ferrofluidic inclinometers design and simulation is depicted.

This tool allows for an optimized prototyping of ferrofluidic transducers by defining the device layout, setting the device parameters, performing simulation in different domains and evaluating improvements coming from technical feedback obtained through experimental validation activities.

In the next future efforts will be dedicated to produce new releases of the simulation tool including also the following features:

- prototype optimization in terms of mechanical performance and power consumption;
- benchmark between different prototypes realizations;
- implementation of new sensing methodologies and new prototype configuration.
- The tool encourages students of advanced academicals courses the study of the ferrofluidic inclinometer allowing the understanding of the model of the devices and providing an useful tool which accomplish behavioural and quantitative analysis of ferrofluidic devices.

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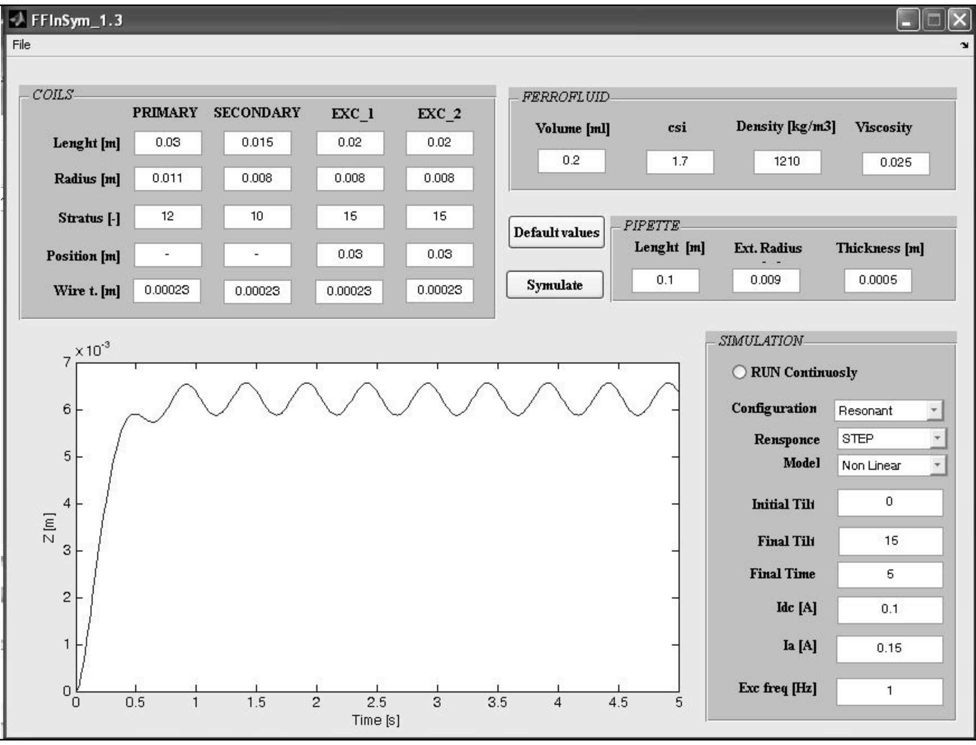
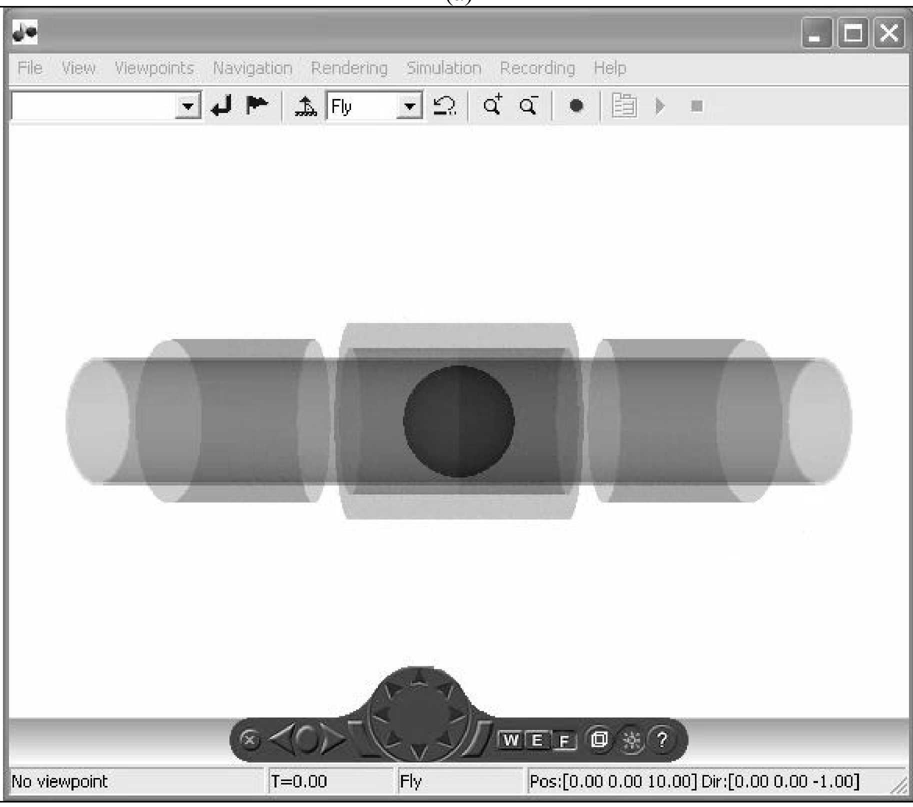


(a)



(b)

Figure 3. View of the FF_In_Sim user interface in a typical simulation of the step response of the resonant inclinometer (a) and the typical output of the 3D interface showing the mechanical simulated behavior of the device (b).

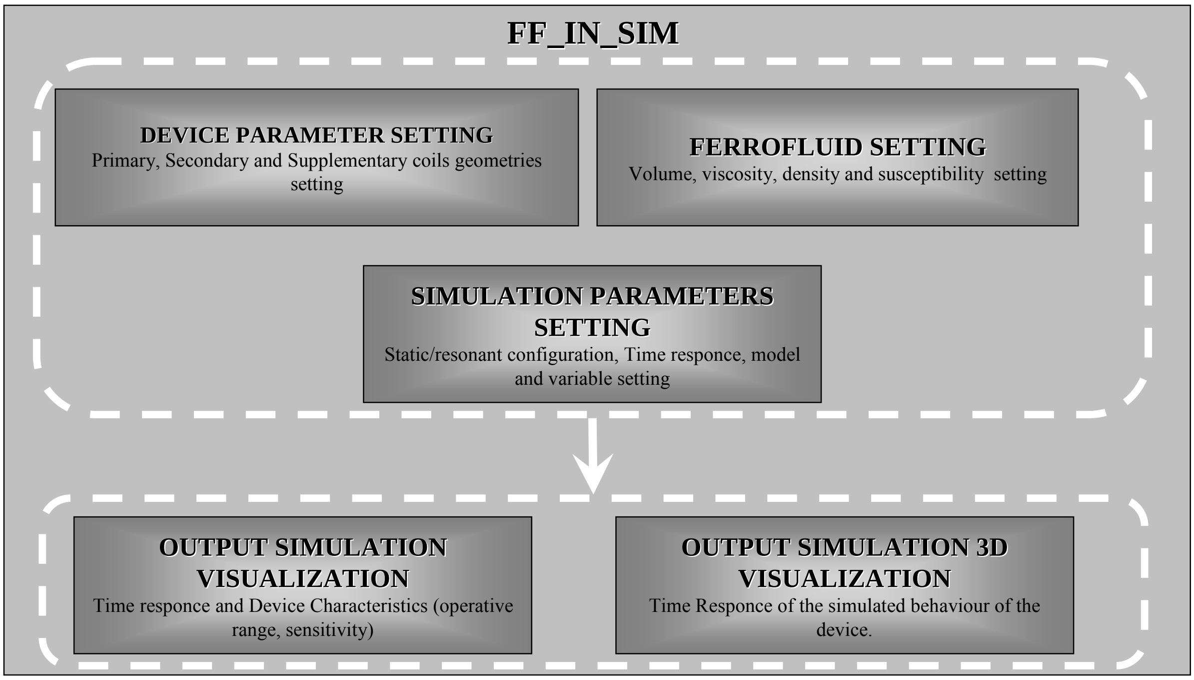


Figure 4. Schematic block of the simulation tool for the simulation of the ferrofluidic inclinometer behavior.

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