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A method and a tool for fast transient simulation of electromechanical devices: application to linear actuators

Bertrand du Peloux, Laurent Gerbaud, Frédéric Wurtz, E. Morin

***Abstract*— The paper deals with a tool for the fast simulation and pre-sizing of electromechanical actuators: Reluctool. The modeling of the electromagnetical parts is carried out with reluctant network [2]. The paper presents an approach of automatic coupling of a reluctant network with any kind of basic electrical circuit, and the dynamics of a mechanical moving part. The proposed method allows to simulate devices to get response times. So, devices could be quickly pre-sized taking into account all geometrical, electrical and mechanical parameters.**

***Index Terms*— Reluctance network, actuators, modeling, simulation, ordinary differential equations**

I. INTRODUCTION

Nowadays, pre-design and simulation have taken a significant weight within manufacturing process and allows to reduce design time and to optimize manufacturing costs.

A good solution for the pre-sizing of an electromagnetic device where numerous parameters are constrained (sizes, criteria, etc) is to use reluctant networks that are a fast means to get the main characteristics of a device operating [1].

Usually, during the pre-sizing step, in order to reduce the trip response time of a device, the designer tries to maximize the electromagnetic force on a static reluctant model. However, what he really needs is a transient model in which the response time appears directly as a problem variable. For this purpose, the paper presents a method to couple any reluctant model with its control electrical circuit and the mechanical equations of its moving part. This method allows very fast simulation times that are compatible with optimization, and has been improved in a dedicated tool.

The paper first explains how the 3 physical parts of the dynamic model are generated: it recalls that the magnetic part of the device model can be automatically generated thanks to the tool Reluctool [2], it presents how electrical equations are set, and it gives a description of the mechanical ones. Then, it shows the way these three models are coupled in order to obtain the resulting dynamic. Finally, it shows some results and opens some perspectives.

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II. MAGNETIC MODEL

In this approach, the magnetic model is obtained from a graphical description of the reluctance network topology [2]. It allows to compute all the magnetic fluxes from geometric parameters and amp-turns sources characteristics. Besides, considering an energy-based approach of electromagnetism [3], the force is computed from the virtual works principle. This model gives the flux in the magnetic circuit from the coil current.

The nonlinearities are taken into account by using the expression of the induction magnetic B according to the magnetic field H (see Fig 1).

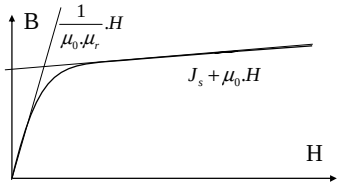


Fig. 1: General shape of the curve B(H) used for the ferromagnetic materials

In this way, the ferromagnetic materials are characterized by using the expression (1):

$$H(B) = \frac{(\mu_r - 2.a + 1).B - \mu_r.J_s - J_s.\sqrt{\left(\frac{(\mu_r - 1).B}{J_s}\right)^2 - 4.a.(a - \mu_r)}}{2.\mu_0.(\mu_r - a)} \quad (1)$$

where: μ_0 magnetic permitivity of the air

μ_r magnetic permitivity of the ferromagnetic material

J_s the magnetic polarisation at the saturation

a a parameter to adjust the camber between the two linear zones of curve B(H) of Fig 1.

This expression is identified by experimental results, for each ferromagnetic material.

The magnetic model is obtained from the method described in [8] (Fig 2). The equations of the circuit fundamental meshes gives the mesh fluxes φ_{Mj}. Those equations are implicit and non linear and solved by a Newton Raphson method. Then, the

reluctance fluxes φ_i are obtained by the law of flux conservation that gives explicit equations.

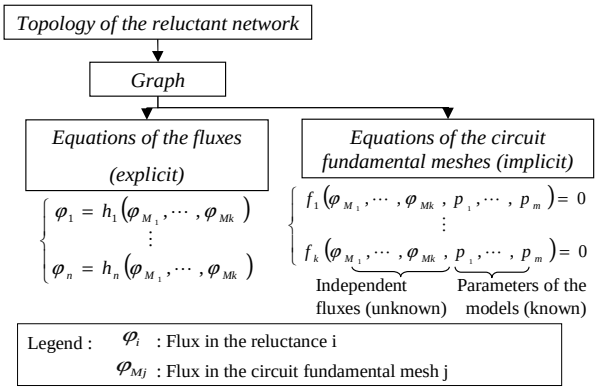


Fig. 2: Implicit equations of the magnetic model

The magnetic energy useful for the connection with the other part of the device, is modeled by using the expression of the energy and co-energy of the magnetic reluctances [3].

$$W = \int_0^B H.dB \tag{2}$$

$$W_{co} = \int_0^H B.dH \tag{3}$$

For example, for a reluctance defined by a rectilinear flux tube which section is S and a linear material, the energy is given by :

$$W = W_{co} = \frac{1}{2}.B.H = \frac{1}{2}.\frac{\varphi^2}{\mu_0.\mu_r.S^2} \tag{4}$$

By summing all the energy and using the virtual works, the magnetic force applied on the moving element of the device is defined by :

$$F = \frac{\partial W_{co}}{\partial x} \tag{5}$$

for a linear or angular movement x

III. ELECTRICAL MODEL

For the electrical part, the paper proposes to treat circuit with resistor, inductor, capacitor, diodes and controlled switches. The semiconductors are modeled with a binary resistance model (Ron/Roff) [4][6]. A state-variable method approach has been chosen to automatically formulate the circuit behavior [4, 7].

Furthermore, to couple coils to the control circuit, those coils may be seen as current sources (see equation (6)) or voltage sources (see equation (7)) [5].

$$\begin{cases} \dot{X} = A.X + B.U - B_c.N.\dot{\varphi}_c + E.\dot{U} \\ \dot{\varphi}_c = \dfrac{\partial \varphi_c}{\partial I_c}(F.X + G.U, x).(F.\dot{X} + G.\dot{U}) + \dfrac{\partial \varphi_c}{\partial \theta}(F.X + G.U, x).\dot{x} \end{cases} \tag{6}$$

$$\begin{cases} \dot{X} = A.X + B.U + B_c.I_c + E.\dot{U} + E_c.\dot{I}_c \\ \dot{\varphi}_c = \dfrac{-1}{N}(F.X + G.U + G_c.I_c + H.\dot{U} + H_c.\dot{I}_c) \end{cases} \tag{7}$$

where index “c” indicates the parts concerning the coils, X is the electrical state vector containing the capacitor tree branch voltages and the inductor link currents [4][6], I_c the coupling coil currents, U the vector of sources, x the postion variable of the mobile part of the actuator; A, B, E, F, G, H matrices depend on the electrical circuit topology [4].

Second expression is easier to solve due to the fact that there are less coupling and so less use of implicit solving. By considering that there are not pure inductive nodes at the coil electrical terminals, E_c and H_c are null and the final system can be expressed as the state system (8).

$$\begin{cases} \dfrac{\partial}{\partial t}(X) = A.X + B.U + B_c.I_c + E.\dfrac{\partial}{\partial t}(U) \\ \dfrac{\partial}{\partial t}(\varphi) = F.X + G.U + G_c.I_c + H.\dfrac{\partial}{\partial t}(U) \end{cases} \tag{8}$$

IV. COUPLING

In the paper, the following assumptions are carried out: the behaviour is quasi static and there are not Foucault currents.

As seen above, I_c appears as an input of the electrical part of the model. For the magnetic part the corresponding state variable is the magnetic flux. Hence, I_c has to be obtained from the flux, by inverting the magnetic part of the model.

As the electrical and magnetic models, the mechanical one is generated from a simple equation description.

The magnetic force is obtained from the derivative of the co-energy of the magnetic device according to the position variable of the actuator mobile part: x, as said before.

The coupling for a 1D movement can be illustrated by the example of Fig 3.

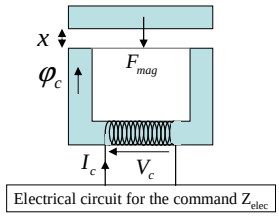


Fig. 3: basic example of linear actuator

In this way, the coupling equations of the three models are:

$$\begin{cases} m.\dfrac{\partial^2 x}{\partial t^2} = F_{mag}(x, \varphi_c) + \sum F_{ext} \\ V_{bob} = -N.\dfrac{\partial \varphi_c}{\partial t} \\ V_c = V_c(Z_{elec}, I_c) \end{cases} \tag{9}$$

where F_{ext} represents any force on the mobile part, i.e. the friction force or any mechanical force.

V. DYNAMIC SOLVING OF THE MODEL

Then, these three models are linked according to fig. 4, in order to be integrated by an ODE solver (Runge Kutta 44).

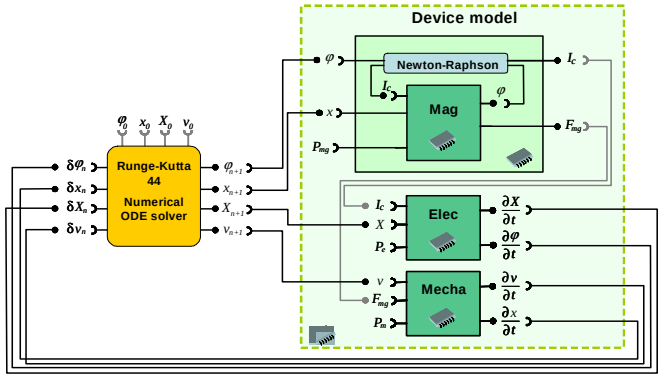


Fig. 4. State variables coupling and integration schema

The time step is variable or not.

A. *Initialisation of the time step*

To initialize the value of the time step, the magnetic model is linearised:

$$F_{mag_{(\varphi_c,x)}} \approx F_{mag}(\varphi_c, x) + \frac{\partial F_{mag}}{\partial \varphi_c}.\varphi_c + \frac{\partial F_{mag}}{\partial x}.x \tag{10}$$

The complete state equation to solve becomes :

$$\begin{cases} \frac{\partial}{\partial t}(X) = A.X + B.U + B_c.I_c + E.\frac{\partial}{\partial t}(U) \\ \frac{\partial}{\partial t}(\varphi) = F.X + G.U + G_c.I_c + H.\frac{\partial}{\partial t}(U) \\ \frac{\partial x}{\partial t} = v \\ \frac{\partial v}{\partial t} = m_0 + m_1.x + m_2.v + m_3.(F_{mag}(\varphi_c, x) + \frac{\partial F_{mag}}{\partial \varphi_c}.\varphi_c + \frac{\partial F_{mag}}{\partial x}.x) \end{cases} \tag{11}$$

that gives the following linear shape:

$$\begin{bmatrix} \frac{\partial X}{\partial t} \\ \frac{\partial \varphi_c}{\partial t} \\ \frac{\partial x}{\partial t} \\ \frac{\partial v}{\partial t} \end{bmatrix} = \begin{bmatrix} A & \frac{B_c}{L} & 0 & 0 \\ -\frac{1}{N}.F & -\frac{1}{N}.\frac{G_c}{L} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & m_3.\frac{\partial F_{mag}}{\partial \varphi_c} & m_1 + m_3.\frac{\partial F_{mag}}{\partial x} & m_2 \end{bmatrix} . \begin{bmatrix} X \\ \varphi_c \\ x \\ v \end{bmatrix} \tag{12}$$

$$+ \begin{bmatrix} B & 0 & 0 & 0 \\ -\frac{1}{N}.G & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} . \begin{bmatrix} U \\ 0 \\ 0 \\ m_1 + m_3.F_{mag}(\varphi_c, x) \end{bmatrix} + \begin{bmatrix} E & 0 & 0 & 0 \\ -\frac{1}{N}.H & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} . \begin{bmatrix} \frac{\partial U}{\partial t} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

In this way, the state matrix becomes linear, its eigenvalues can be valued and a time step can be deduced.

However, the use of (12) assumes that $\frac{\partial F_{mag}}{\partial \varphi_c}$ and $\frac{\partial F_{mag}}{\partial x}$ can be calculated.

For that, let's consider the equations of the magnetic fluxes that are created by n coils:

$$\begin{cases} \varphi_1(p_1,...,p_m,I_1,...,I_n) - \tilde{\varphi}_1 = 0 \\ ..... \\ \varphi_n(p_1,...,p_m,I_1,...,I_n) - \tilde{\varphi}_n = 0 \end{cases} \tag{13}$$

The φ_i are the functions allowing to estimate the fluxes according to the model input parameters and the excitation currents I_j of the coils. The $\tilde{\varphi}_i$ are the fluxes allowing to obtain the I_j

The derivatives of the current according to the fluxes give:

$$\begin{bmatrix} \frac{\partial I_1}{\partial p_1} & \cdots & \frac{\partial I_1}{\partial p_m} & \frac{\partial I_1}{\partial \tilde{\varphi}_1} & \cdots & \frac{\partial I_1}{\partial \tilde{\varphi}_n} \\ \vdots & & \vdots & \vdots & & \vdots \\ \frac{\partial I_n}{\partial p_1} & \cdots & \frac{\partial I_n}{\partial p_m} & \frac{\partial I_n}{\partial \tilde{\varphi}_1} & \cdots & \frac{\partial I_n}{\partial \tilde{\varphi}_n} \end{bmatrix} = \tag{14}$$

$$-\begin{bmatrix} \frac{\partial \varphi_1}{\partial I_1} & \cdots & \frac{\partial \varphi_1}{\partial I_n} \\ \vdots & & \vdots \\ \frac{\partial \varphi_n}{\partial I_1} & \cdots & \frac{\partial \varphi_n}{\partial I_n} \end{bmatrix}^{-1} . \begin{bmatrix} \frac{\partial \varphi_1}{\partial p_1} & \frac{\partial \varphi_1}{\partial p_m} & -1 & 0 & \cdots & 0 \\ & & 0 & \ddots & \ddots & \vdots \\ & & \vdots & \ddots & \ddots & 0 \\ \frac{\partial \varphi_n}{\partial p_1} & \frac{\partial \varphi_n}{\partial p_m} & 0 & \cdots & 0 & -1 \end{bmatrix}$$

So, by composition, any model output is given by

$$\frac{\partial S_j}{\partial \tilde{\varphi}_i} = \sum_{k=1}^{n} \frac{\partial S_j}{\partial I_k} . \frac{\partial I_k}{\partial \tilde{\varphi}_i} \tag{15}$$

Specifically:

$$\frac{\partial F_{mag}}{\partial \varphi_{bob}} = \frac{\partial F_{mag}}{\partial I_{bob}} . \frac{\partial I_{bob}}{\partial \varphi_{bob}} \tag{16}$$

where $\frac{\partial I_{bob}}{\partial \varphi_{bob}}$ is computed with (14) and $\frac{\partial F_{mag}}{\partial I_{bob}}$ can be formulated by a similar way, with the equation of the reluctance network from section II [2].

B. *Change of the time step*

The simulation may be carried out with a fixed step given by the Reluctool user.

At every time step, the simulation time step may also change. The time step is inititialised by the method described in the previous section. Then, it can change according an error given by an integration with Runge Kutta 44 and an integration with a fifth order Runge Kutta [9]. The over calculation cost of the fifth order method is 6/4 because it uses the four state derivative calculation for Runge Kutta 44, at each time step. According to the error between the two methods, the time step changes according to a factor depending of the error, but no more than 5 [9].

VI. Implementation: Reluctool

A tool, we have developed, supports all these aspects: Reluctool. From a reluctance representation of the magnetic circuit (Fig. 5), a description of the control electrical circuit feeding the coil (Fig. 6), and a symbolic parameterization of the mechanical part that is linear or rotational (see fig. 7); Reluctool gives automatically a dedicate application for simulation and pre-sizing.

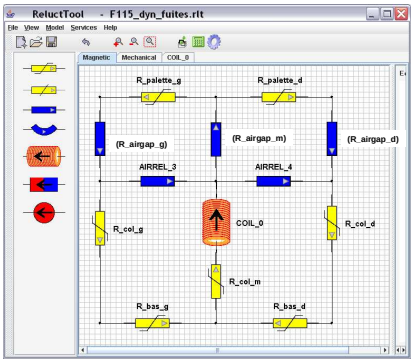


Fig. 5. Magnetic description of the actuator.

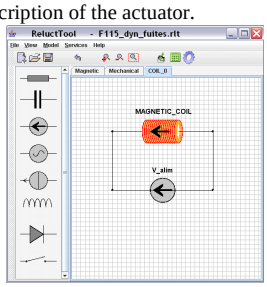


Fig. 6. Description of the control circuit of every coils (one description window per coil).

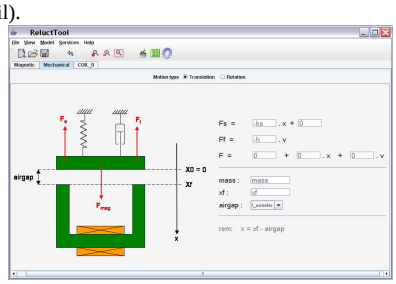


Fig. 7. Value setting of the symbolic parameter of the mechanical part (linear case)

VII. Application

Several applications have been treated among them the application of fig. 8.

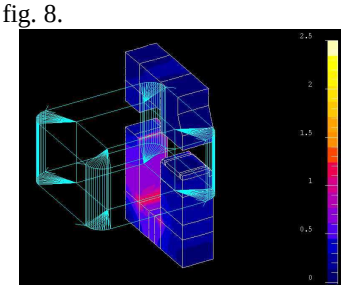


Fig. 8. Flux in the simulated actuator (result from Flux tool)

This device has been dynamically simulated by using FEM simulation (by using Flux software) and Reluctool (see Fig. 9).

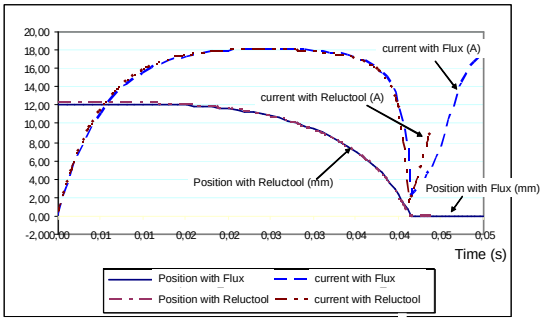


Fig. 9. Dynamic simulation: comparison of Flux and Reluctool simulation

Note that the presence of the reluclance AIRREL_3 and AIRREL_4 in fig. 5 represent losses are very important to obtain a good result. They concern the linkage reluctances in the air between the airgaps. Without these reluctances, the simulation is wrong, as shown on Fig 10.

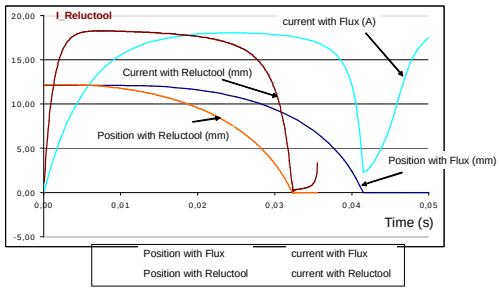


Fig. 10. Dynamic simulation: comparison of Flux and Reluctool simulation withour the reluctances AIRREL_3 and AIRREL_4

The dynamic simulation with Reluctool is very faster than with finite element software (Flux) and the dedicated software application can be used in several contexts to do such simulations.

The time simulation duration with Reluctool is about some minutes compared to a time simulation with Flux3D that needs many hours.

VIII. Conclusion

This approach for fast simulation, useful in the first steps of the design, has been used to generate a tool for actuator design. In the future, it will give the designers an energy balance analysis that will help them to create devices with high energy efficiency by introducing expressions of the losses in the materials.

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