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Modelling and simulation of a remote controlled mechatronic device

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ABSTRACT

The paper introduces the design, modelling and simulation of an electromechanical actuator device able to produce periodical translation movement. The parameters characterizing this movement (stroke length, force, speed profile) are considered to be remotely programmable via a wireless interface.

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1. Introduction

The device investigated in this paper should provide an autonomous operation (powered from included battery). The basic components of this mechatronic device are indicated in Fig. 1.

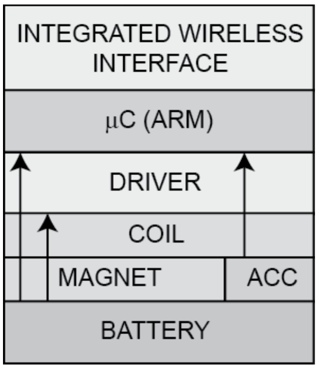


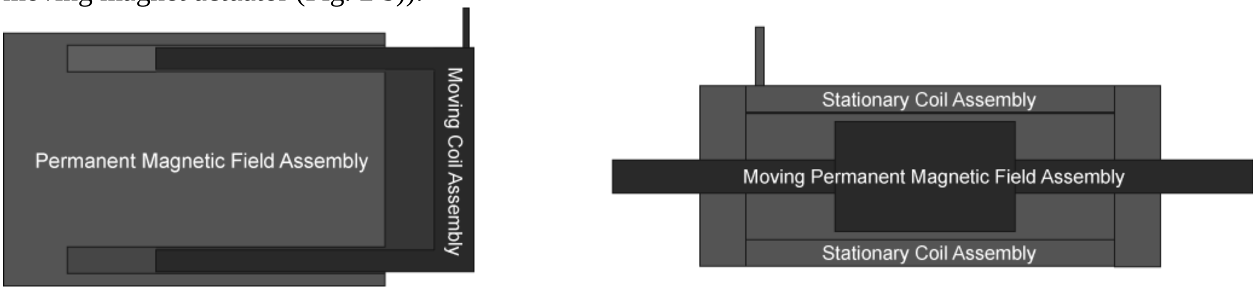
Figure 1. Basic components of the mechatronic device

The setups generally considered for fast and ultrafast linear motion generation are the voice coil type (VC), the double sided coil type (DSC) and the Thomson coil type (TC).

The voice coil setup has several proven advantages:

- brushless construction offers higher reliability,
- fast acceleration / deceleration and high speed operation can be achieved by direct coupling of the motor to the load,
- easy change of the movement direction by reversing the polarity of the applied voltage,
- the force generated by the actuator is proportional to the current flowing through the coil.

Its construction falls generally into one of the following categories: moving coil actuator (Fig. 2 a)) and moving magnet actuator (Fig. 2 b)).



a) NCC Type Moving Coil Actuator b) NCM Type Moving Magnet Actuator

Figure 2. Voice coil actuators

The fast sampling of the acceleration signal can be used in order to provide the characterization of the movement. The driving of the coil can be done either with simple switching topologies, either with more complex prescribed current profiles. The later allows the implementation of more complex speed profiles. All programmable parameters used in the control of the driver operation should be prescribed via the wireless interface.

The simulation of electromechanical actuators is done mainly using lumped parameter models and using FEM based simulation environments. For the first approach, providing the possibility of measuring coil current profile as well as the acceleration profile is important in the identification of the system parameters. The second approach involves two phases: accurate modelling of the geometry for every system component and the simulation of the system behaviour in a multiphysics simulation environment. While the first approach may lead to simpler lumped parameter model that can be used for the designs of the control algorithms, the second approach may offer a valuable validation tool as well as the possibilities for comparing the performance/efficiency of different geometries. The analogue/equivalent models are frequently used in optimization studies.

2. Modelling of the actuator

There are different geometries and different manufacturing technologies ([1-5]) associated with voice coil type actuators, providing linear or rotary motion. The geometry of cylinder shaped coil is considered in what follows, in a setup conforming to Fig. 2a).

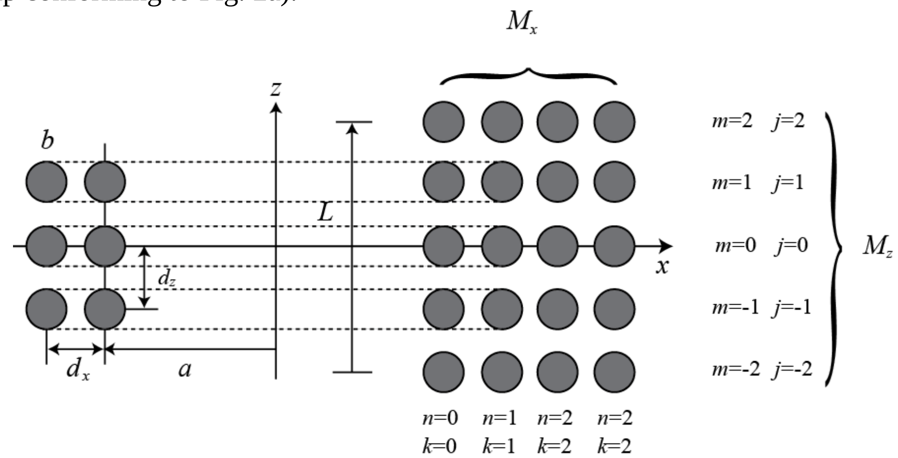


Figure 3. Solenoid model for general induction calculation ([6])

The wire thickness, the internal radius, the external radius and the height of the winding are the main parameters in modelling the coil geometry, as they determine the values for the parameters indicated in Fig. 3. The total inductance of the air core coil can be estimated using:

$$L = a\mu_0 \left[\ln\left(\frac{8a}{b}\right) - \frac{7}{4}\right] \tag{1}$$

L – total inductance of a single circuit current loop, a – loop radius, b – wire cross-section radius

$$L = \frac{\pi\mu_0 a^2 M^2}{\sqrt{4a^2+(M-1)^2 d^2}} \tag{2}$$

$$L = \frac{\pi\mu_0 r_0^3 (M_x M_z)^2}{r_0 l + 0.9 r_0^2 + 0.32 l t + 0.84 r_0 t} \tag{3}$$

$$l \equiv (M_z - 1)d_z \tag{4}$$

$$t \equiv 2M_x b \tag{5}$$

$$r_0 \equiv a + (M_x - 1)b \tag{6}$$

More precise values can be obtained using the discrete summation methods using the magnetic vector potential are indicated in [6]. Other approaches based on the numerical estimation of elliptic integrals are considered in [7] and [8].

The equations which describe the mathematical model of the electromechanical actuator dynamics, are presented in what follows. The forces balance equation is:

$$m_e \frac{d^2x}{dt} = F_m - F_f - (xk_0 + k(x - x_{Lim})), \tag{7}$$

where m_e is the total mass of the coil and of the control electronic circuit, $x(t)$ is the coil movement in relation to the initial position (the initial position corresponds to the situation in which the coil is totally under the influence of the permanent magnetic field; t represents the variable time), $F_m(t)$ is the moving Lorentz force and the constant of the spring k together with the friction force F_f are considered to be 0 outside the endpoints intervals.

Equation (7) can be rewritten under the following form:

$$\frac{d^2x}{dt} = \frac{1}{m_e}\left(F_m - F_f - (xk_0 + k(x - x_{Lim}))\right) \tag{8}$$

The force F_m is given by:

$$F_m = B\frac{h-x}{h}T_L i \tag{9}$$

where B is the magnetic field generated by the permanent magnet, h is the coil height, T_L represents the number of the coil winding and $i(t)$ is the current which passes through the coil. By applying the Kirchhoff theorem for the electrical circuit in which the coil is connected, the following equation results:

$$V - BT_L\frac{h-x}{h}\frac{dx}{dt} = i\frac{dL}{dt} + L\frac{di}{dt} + Ri \tag{10}$$

where $V(t)$ is the circuit supplying voltage under the form of an impulse sequence, R is the coil equivalent resistance and $L(x(t))$ is the coil inductance which is a function dependent on the coil movement and implicitly on time. The coil inductance is given by:

$$L = L_{int} + L_{ext}, \quad L_{int} = \mu_r\frac{h-x}{h}L_0, \quad L_{ext} = \frac{x}{h}L_0 \tag{11}$$

where $L_{int}(x)$ is the inductance associated to the part of the coil which is influenced by the permanent magnet magnetic field and $L_{ext}(x)$ is the inductance associated to the part of the coil which operates independently by the permanent magnet influence. L_0 is the coil inductance for $x(t) = h$ and μ_r is the magnetic permeability of the coil. By replacing (11) in (10), the following equation is obtained:

$$V - BT_L\frac{h-x}{h}\frac{dx}{dt} = i\frac{L_0}{h}(1-\mu_r)\frac{dx}{dt} + \frac{L_0}{h}(\mu_r(h-x)+x)\frac{di}{dt} + Ri \tag{12}$$

which can be written in the form:

$$V\frac{h}{L_0} - BT_L\frac{h-x}{L_0}\frac{dx}{dt} = i(1-\mu_r)\frac{dx}{dt} + (\mu_r(h-x)+x)\frac{di}{dt} + \frac{h}{L_0}Ri \quad (13)$$

From (13), it results the equation of the current derivative in relation to time, form which is the final mathematical model of the electromechanical actuator:

$$\frac{di}{dt} = \frac{1}{\mu_r(h-x)+x}\left(V\frac{h}{L_0} - BT_L\frac{h-x}{L_0}\frac{dx}{dt} - \left(\frac{h}{L_0}R + (1-\mu_r)\frac{dx}{dt}\right)i\right) \quad (14)$$

By implementing in MATLAB/Simulink equations (8)-(13), the functional structure of the electromechanical actuator mathematical model results, structure which offers the possibility of the proposed model simulation.
One of the main problems associated with the modelling of the actuator is its experimental validation. The setup indicated in Fig. 4 is proposed for sampling the relevant variables of the model (current and acceleration).

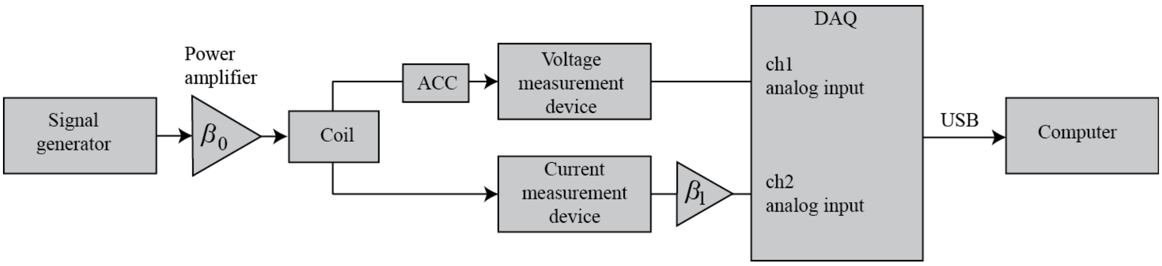


Figure 4. A modified setup that follows the one in [12], augmented with acceleration measurement

3. Simulation results

The following values of the model parameters were used in the simulation: m_e = 8.34·10^{-3} kg, B = 0.5 T, μ_r=1.05 H/m, T_L = 3.38 m, h = 2·10^{-3} m, L_0 = 0.14563 H, R = 5ohm, k_0 = 0, α = 0.01, k_{sup} = k_{inf} = 1000, $xlim_{sup}$=1.9·10^{3}m, $xlim_{inf}$ = 0.1·10^{-3}m , h = 2·10^{-3}m.
The mathematical model presented in Section 2 is augmented in order to have a more realistic approach for the alternating linear motion scenario: at both endpoints of the travelling, the coil assembly will exhibit collision with the encapsulation. That is modelled by considering a partly elastic behavior and a partly dissipative behavior, by defining two neighborhoods of the endpoints in which an elastic force and a friction force occur. If x exceeds its upper/lower limit defining these neighborhoods, the value of the spring constant k is set to *ksup*/*kinf* and the *xlim* parameter is initialized with the appropriate value (*xlimsup*/*xliminf*). If x lies within the allowed range, the elastic force is set to zero.

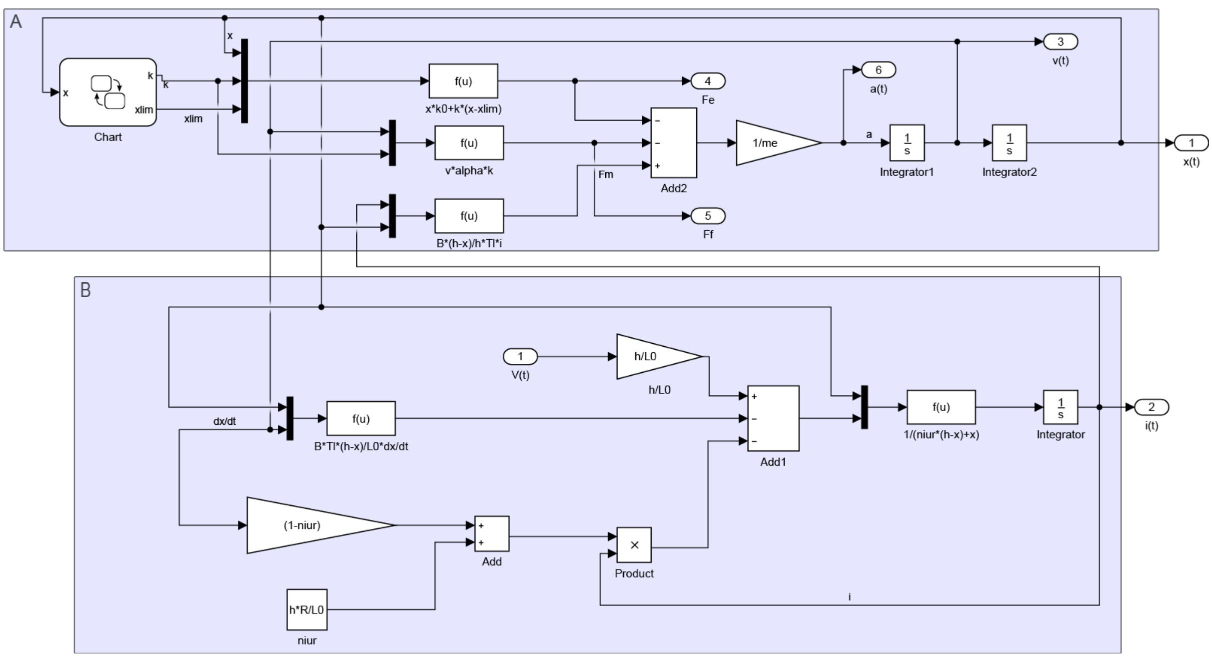


Figure 5. Matlab Simulink hybrid model

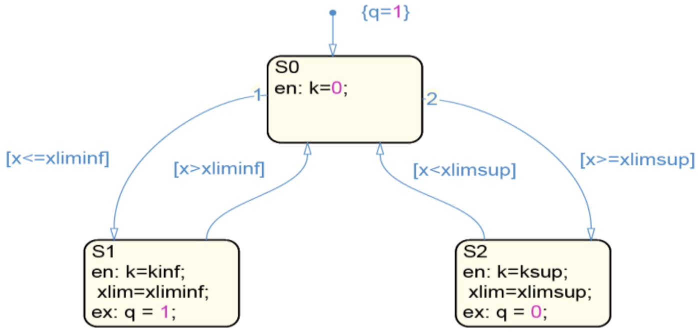


Figure 6. Stateflow diagram for the discrete part of the system

Fig. 5 presents the model developed in Matlab Simulink for simulating the behavior of the system. The block marked with B in the figure is implementing equation (14), while the block denoted with A is based on equation (8). The Stateflow block (fig. 6) included in the model, initializes some parameters of the model according to the current value of the displacement *x*.

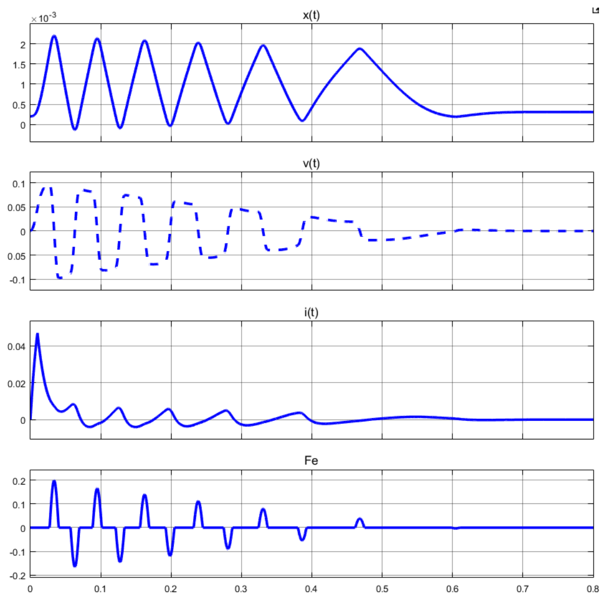


Figure 7. Response to a pulse signal ($F_f = 0$)

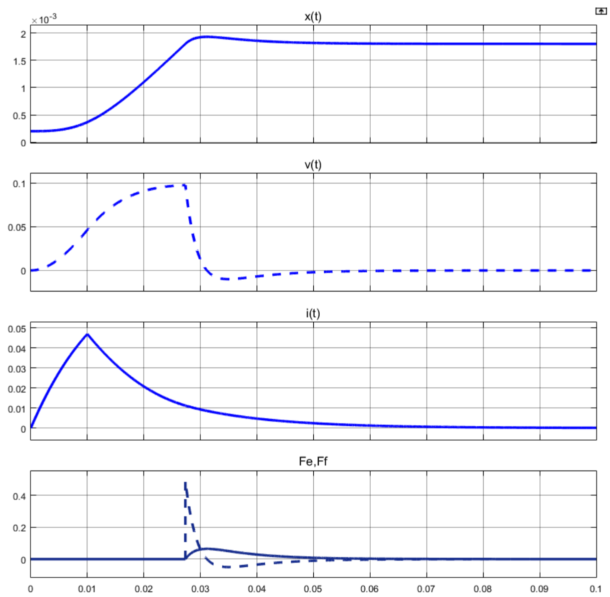


Figure 8. Response to a pulse signal when F_f is considered

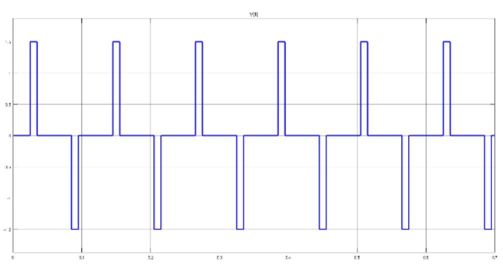


Figure 9. Input signal

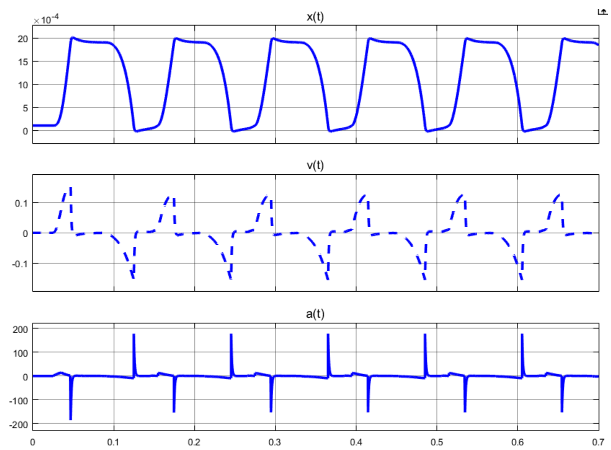


Figure 10. Alternating linear motion

Fig. 7 presents the simulation results obtained by applying a single pulse at the input, and considering just the spring elements at the endpoints (pure elastic collision), while Fig. 8 indicates the results obtained when the additional dissipative force F_f, is considered. The displacement x, the velocity v and the acceleration a presented in Fig. 10 were obtained for the waveform V shown in Fig. 9.

4. Conclusions

The design, modelling and simulation of an electromechanical actuator device able to produce periodical translation movement was presented. The mathematical model is based on the equations which describe the physical behavior of the actuator. The simulation results prove the model validity.

A more complex hybrid system with four discrete states will be considered for a more accurate modelling. Future work is dedicated to finalizing the implementation of a validation platform conforming to the proposed setup.

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