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Positioning and Smoothing Movement Approaches of a Linear Actuator Dedicated to A Biomedical Application

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Abstract: The movement of linear stepper motors is characterized by a highly oscillatory translation, which is troublesome for the positional accuracy and the speed constant (often required by many industrial applications such as the syringe pump). These oscillations can lead to loss of synchronism and stall risk. Thus, in order to attenuate the amplitudes of these oscillations and to guarantee the positioning of the actuator without errors, solutions exploiting open-loop and closed-loop control techniques are proposed in this paper for the purpose of improve the performance of the actuator.

Keywords: Linear Actuator, Syringe Pump, Oscillations, Dynamic Response, Bang-Bang, Closed Loop Control and Precision.

1. Introduction

The syringe pump is a conventional biomedical system hospital emergency service. It is mainly used for intravenous, intra-arterial infusions, anesthetic infusions and chemotherapy. It is essential in the various departments of general surgery and the internal department of medicine for children, adults, pediatrics, the emergency department, gynecology, etc.

In the case of diseases affecting the patient's therapeutic area, such as renal insufficiency, the frequent administration of drugs leads according to the dose administered to two possible cases, [1]:

- If the dose is low, the drug becomes useless although there is a residual concentration maintained in the body. Thus, the mean value of the drug concentration is included in the ineffective zone, Figure.1.
- When the dose is too high, the average evolution of the concentration is carried in the toxic zone; the undesirable effects then become very important compared to the efficiency.

The pharmacokinetics of these two oral administration cases is illustrated in Figure.1.

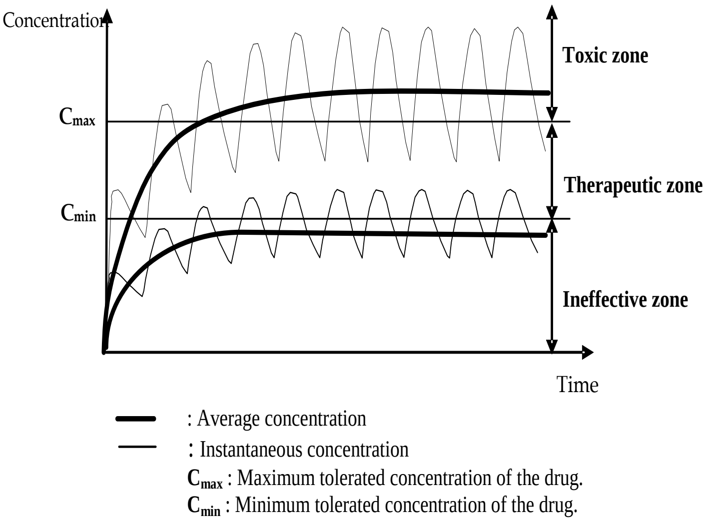


Fig.1- Pharmacokinetics of oral administration.

For such cases of diseases where the therapeutic zone is reduced, the maintenance of a concentration evolving without exceeding in this zone cannot be guaranteed by use of an oral administration. The use of an infusion is then a necessity.

Perfusion is a drug delivery method continuously over a constant rate. The plasma concentration increases until, for the same unit of time, the dissipated amount equates which is administered by infusion. This results in a plateau whose height at steady state depends on the rate of infusion and the concentration of the drug in the administered solution, Figure 2. Maintaining this equilibrium state is conditioned by the nature of the infusion solution, the infusion rate and duration of care. Moreover, they are in dependence on the patient's condition, age and weight, [2].

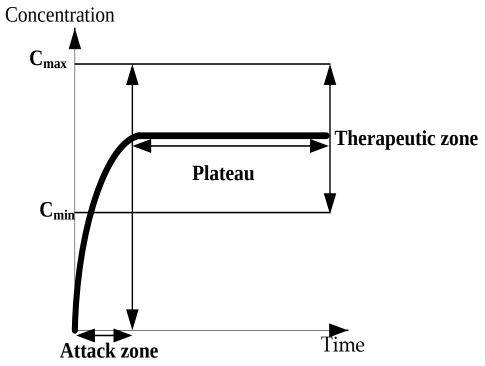


Fig.2- Pharmacokinetics of an infusion.

In the case of diseases with renal or cardiovascular insufficiency, the patient is subjected to treatment requiring infusions at high concentrations over a long period, with adjustable speed and precise rhythm, [1]. Therefore, it was necessary to set up the programmable automatic syringe (time, flow, period) whose technology is constantly evolving for the search for performance improvement. The block diagram of the all biomedical system (syringe pump), to be modelled, is illustrated by Figure 3 where all geometrical parameters are defined.

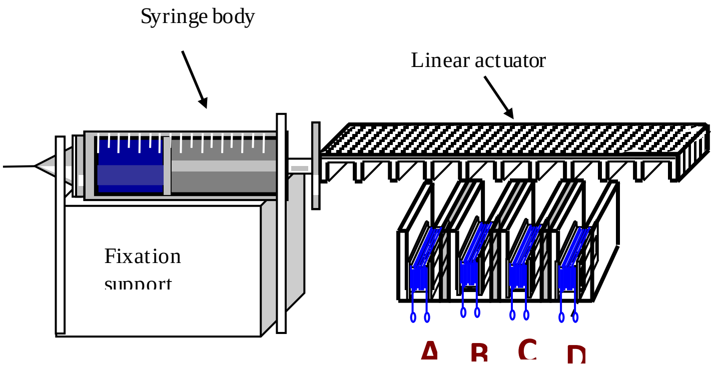


Fig.3- The proposed motorization solution.

Some significant characteristics of the actuator and syringe are given in table 1 and 2.

Table 1. Motor mechanical and electrical parameters

Number of modules	*4*
Tooth width	*3mm*
Slot width	*3mm*
Tooth pitch	*6mm*
Phase separation	*1.5mm*
Mover length	*135 mm*
stator length	*40.5 mm*
Air gap width	*0.1mm*
Height of the stator teeth	*17mm*
Height of the mover teeth	*4mm*
Depth of the actuator	*30mm*
Number of turns per phase	*520*

Table 2. Dimensions of the used syringe.

volume of the syringe	*60 ml*
Piston mass	15 g
Length of the cylinder	118 *mm*
External diameter of the cylinder	30.11 *mm*
Internal diameter of the cylinder	27.48 *mm*
Tube length	1600 *mm*
Inner diameter of the tube	3.7 *mm*
Needle length	69.7 *mm*
Needle diameter	0.8 *mm*
Required thrust force	*4N*
rated voltage	*14 V*
rated current	*1 A*

The movement of a stepper motor presents oscillations often generating vibrations and acoustic noise and can even, at certain operating frequencies, induce synchronism losses and chaotic operation cases. This unwanted operation is manifested by a start in jerky motion causing danger, a loss of synchronism leading to an eminent stall. These oscillations influence the evolution of the drug in the body. Therefore, the effectiveness of the drug that is on the patient's health.

Conventionally, when incremental displacement without vibrations or oscillations is required, two technological concepts are generally used for movement smoothing. The first involves improving the mechanical manufacture of the motor itself. The contributions in this case are often difficult, cumbersome and expensive. The second concept uses damping techniques ensured by the adaptation of laws and adequate control systems. Moreover, the research results obtained have shown that the characteristics of the thrust force developed by the linear actuator cannot be assimilated to sinusoids and that they are strongly influenced by the magnetic state and the geometries of the actuator.

The approach in this paper is to suggest control approaches taking into account the dynamic behavior ensuring precise positioning and without overshoot for different medication infusion rates.

2. Open loop control method (Bang Bang)

The oscillation damping of a stepping motor can be ensured by the successive excitation of two adjacent stator phases. Indeed, by exciting phase B until time t_1, the rotor is brought to a position close to its natural equilibrium, figure.4. At this time, a power supply switch is turned on to energize phase A and de-energize phase B. This power configuration where the coil of phase B is de-energized and the coil of phase A is energized remains locked until at time t_2. If the interval [t_1-t_2] is well adjusted, the amount of energy produced by phase A compensates exactly the kinetic energy accumulated during the movement. Then, to keep the rotor in the targeted position, the supply of phase B is restored at time t_2. Thus, the braking force imposed by the excitation of phase A attenuates the oscillations and allows the rotor to reach its equilibrium position without overtaking.

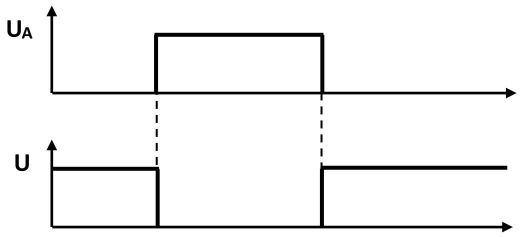
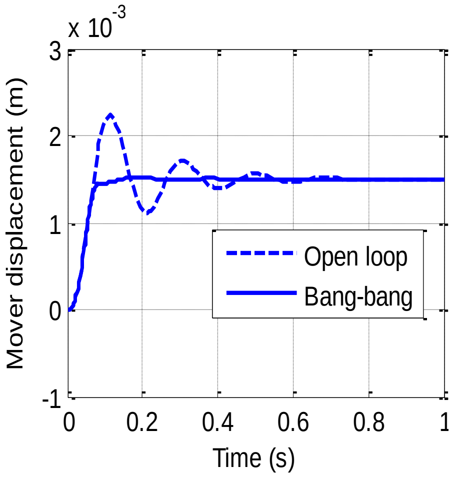


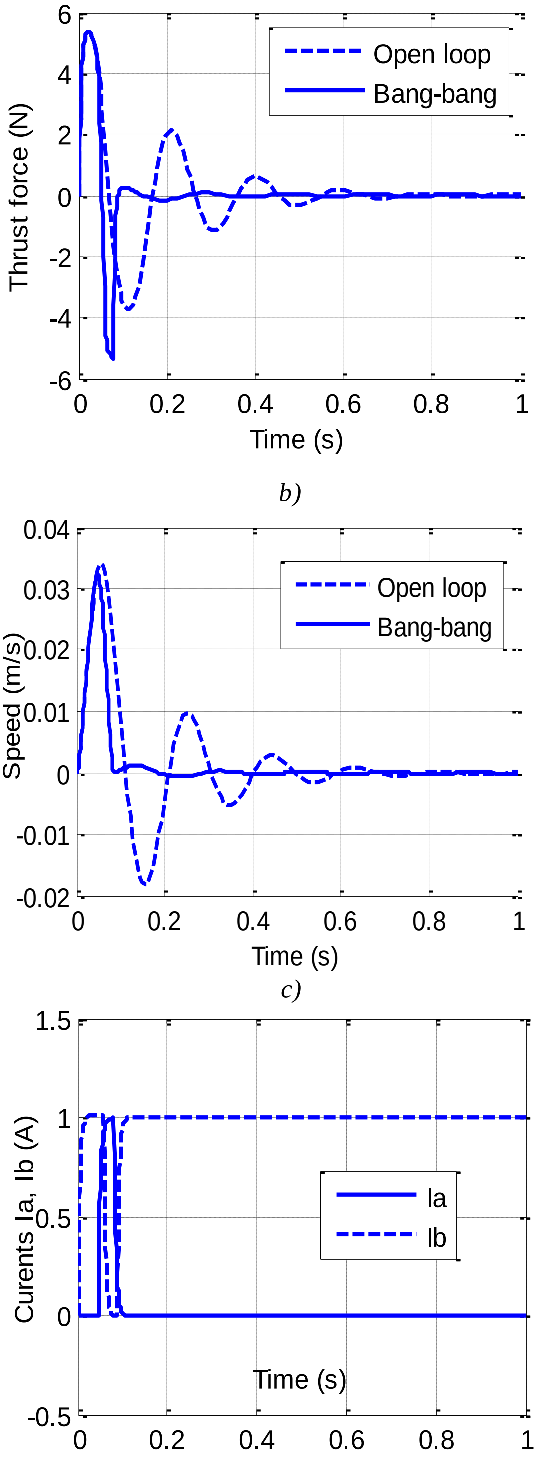
Fig.4-Applied voltage.

The determination of switching times t_1 and t_2 are strongly related to the stepper motor controlled, [4-5-6-7-8-9].

In the event of operation, phase B is considered as the driving phase and phase A is used for braking. The application by Bang-Bang control simulation, for switching times t_1 = 50 ms and t_2 = 80 ms and for a voltage of 18 V, allows the attenuation of the overruns observed at the position evolution. The determination of the appropriate switching times t_1 and t_2 has been adjusted several simulation tests. Figure.5 shows the evolution of the currents in the driving phase and in the braking phase. Consequently, the current generated in phase A allowed the motor braking and the damping observed on the position evolution.



a)



b)

c)

d)

Fig.5- Amortization of rotor oscillations by application of the "Bang-Bang" method.

(a) : Mover displacement (b) : Thrust force (c) : Speed (d) : Control current.

Comparing these results to those corresponding to full-step operation; it is remarkable that the "Bang-Bang" command provides indisputable improvements to the movement of the linear stepper machine. Indeed, the rotor has reached its target position virtually without oscillations.

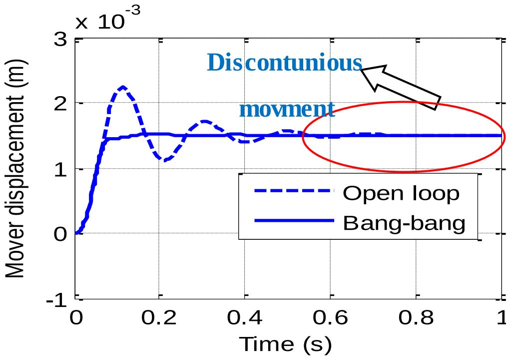


Fig.6- Waiting phase in open loop.

The control methods proposed in open loop, easy to implement, have greatly reduced oscillations and overruns and the mobile positioning accuracy. However, the mobile reaching its equilibrium position with a great delay, Figure.6, makes these control methods poorly suited for applications that require rapid positioning.

3. Improvement of the linear stepper motor positioning quality by the closed-loop control

The actuator-syringe assembly mechanical equation is of the form, [3-10-11-12]:

$$m_c \frac{dx^2}{dt^2} = F(i,x) - \xi \frac{dx}{dt} - F_0 signe\left(\frac{dx}{dt}\right) - F_c \quad (1)$$

With $F_c = m_s \frac{dx^2}{dt^2} + C_1 x \frac{dx}{dt} + C_2 (\frac{dx}{dt})^2 + C_3 \frac{dx}{dt}$ is the load force developed by the syringe, [13-14-15-16].

To synthesize the transfer function, it is considered that the machine operates at a vacuum $F_c = 0$ and the mobile movement is ahead where $sign(V) > 0$ and $F_0 = 0$. Equation (1) becomes:

$$m_c \frac{dx^2}{dt^2} = F(i,x) - \xi \frac{dx}{dt} \quad (2)$$

The transfer function between the position ***x*** and the thrust force ***F*** is given by, [4].

$$m_c s^2 x(s) + \xi s x(s) = F(s) \quad (3)$$

$$G(s) = \frac{x(s)}{F(s)} = \frac{1}{m_c s^2 + \xi s} \quad (4)$$

Moreover, the thrust force developed by one phase is expressed by:

$$F\left(i,x\right)=-ki^2\sin(\frac{2\pi}{\lambda}x) \quad (5)$$

Where $k=\frac{\pi L_1}{\lambda}$.

But for each movement sequence, the actuator is incremented by a step of, [10-12-17]:

$$x=\frac{\lambda}{4}+\Delta x \quad (6)$$

Whether:

$$\sin(\frac{2\pi}{\lambda}x)=\sin(\frac{2\pi}{\lambda}(\frac{\lambda}{4}+\Delta x))=\sin(\frac{\pi}{2}+\frac{2\pi}{\lambda}\Delta x)=\cos(\frac{2\pi}{\lambda}\Delta x) \quad (7)$$

Since Δx is weak then $\cos(\frac{2\pi}{\lambda}\Delta x)\ ;\ 1$

From where:

$$F\left(i,x\right)=-ki^2 \quad (8)$$

Following these developments, it is possible to deduce the block diagram given in Figure.7. This control configuration requires two regulators. A proportional regulator $R(1)$ of gain k_{p_1} for evaluating the reference speed V_{ref} and a proportional integral regulator $R(2)$ gains k_{p_2} and integral action T_i which serves to determine the reference force F_{ref}. According to the expression (8), the reference current i_{ref} can be calculated to control the converter. The load force F_c developed by the syringe is added to the system as a disturbance. Regulator gains are determined by the pole compensation method. Let $k_{p_1}=100$, $k_{p_2}=64.935$ and $T_i=0.0769$, [10-11-12-18-19-20-21-22]

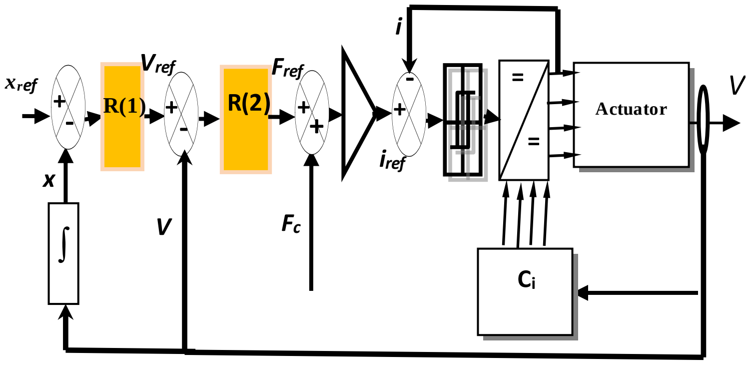
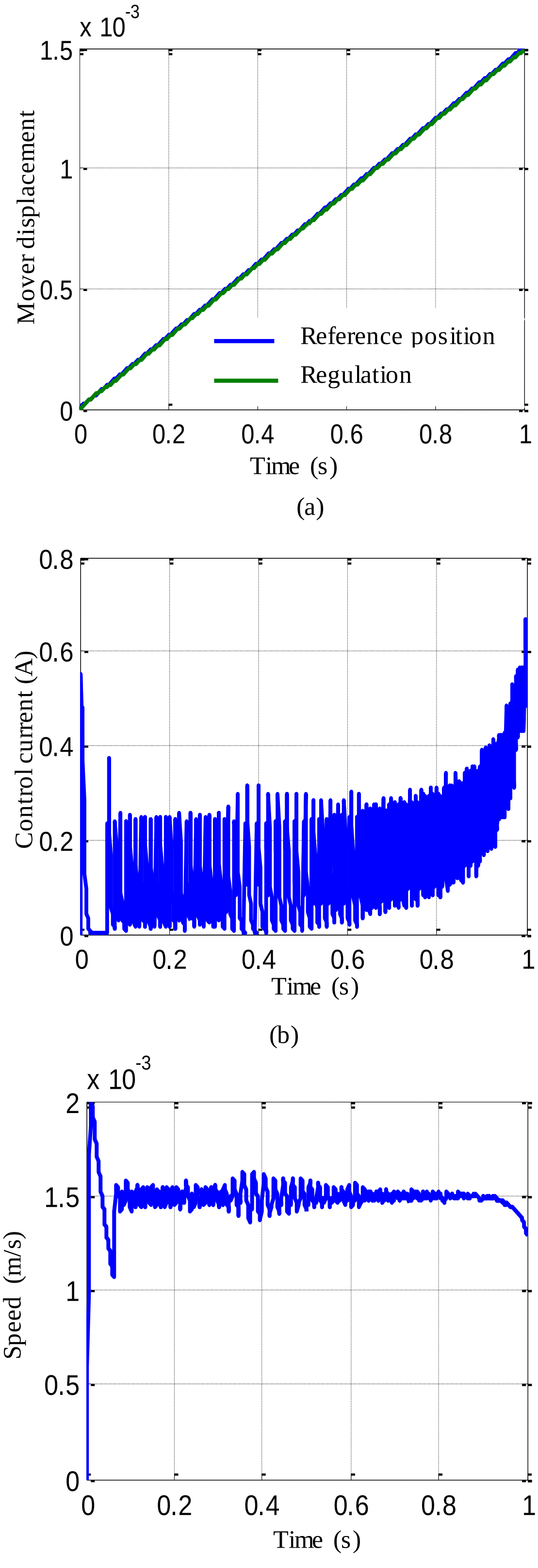


Fig.7- Control position architecture.

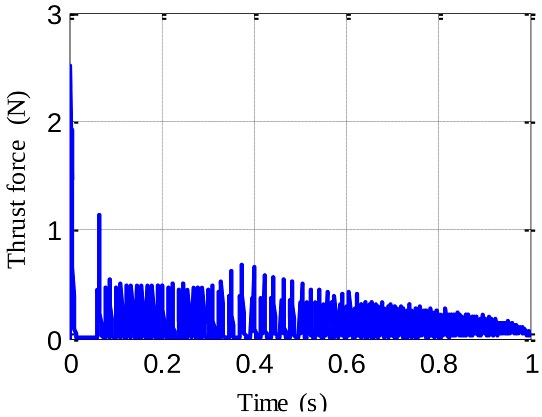
Simulation results for a time of the order of unity infusion, Figure.8 illustrates the dynamic behavior of the assembly from control current, position, speed and thrust force on a whole step.



(a)

(b)

(c)



(d)

Fig.8– Closed loop control: Dynamic performance of the actuator for 1s infusion time

(a) : Mover displacement (b) : Control current (c) : Speed (d) : Thrust force.

In the case of a linear reference, the rotor movement is also perfectly linear. It can be observed that the control law functions correctly with a trajectory tracking with a very good precision, figure 8 (a). As expected the current is chopped to satisfy the motion linearity, Figure.8 (b). The average speed remains constant around 1.510^{-3}m/s, figure.8 (c). As for the Thrust force, it remains positive average value canceling at the end of the step which is consistent with the principle of operation, Figure.8 (d). On the other hand, the excitation of the phase A allows the positioning of the actuator on the first equilibrium position corresponding to 1.5 millimeters. The successive excitation of the other phases is necessary for the next positions.

The closed-loop control has therefore brought undeniable improvements to the linear stepper movement and the control strategy has led to satisfactory results.

The dynamic performances of the all biomedical system during an infusion depend on the interaction of several parameters characterizing the volume of infusion $V_{infusion}$, the syringe geometry ($L_C = 118mm$ and $V_C = 60ml$) and the Tooth pitch of the actuator $\lambda = 6mm$. These parameters are related by the following expression:

$$V_{infusion} = \frac{\lambda}{L_c} V_c \quad (9)$$

Table 3. Infusion Volume versus infusion time and the number of cycles.

Number of power cycles	Infusion Volume (ml)	Infusion time (s)
1	1.5	4
2	3	8
3	4.5	12
4	6	16
….	….	…..
20	30	80

Table 3 shows that the infusion time is proportional to the volume of aqueous solution to be infused. For instance, an infusion volume of 1.5 ml of sodium chloride corresponds to an infusion time of four seconds which requires one power cycle of the actuator. According to the nature of the disease and the patient, the infusion volume is increased or decreased and consequently the infusion time. In this case, it is necessary to repeat or split the power cycle of the actuator according to the need.

4. Conclusion

The development of control methods for improved motion performance of LSRM is the purpose of this article. The first part is devoted to the study of conventional technique commonly used for the damping of rotor oscillations. However, this approach does not solve the problem of the movement regularity, an essential factor characterizing the medical application. To overcome the limitations and inadequacies of conventional control techniques, a control concept based on closed-loop control is developed in the second part. The application of this control strategy made it possible to enslave the system and force it to follow rigorously the linear reference without overshoots and without oscillations.

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