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LEARNING CONTROL OF A PUMP USED IN A LIQUID VENTILATOR

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Abstract: The liquid ventilator have a peristaltic pump to deliver oxygenated PFC liquid to and from lungs of newborn. This paper is about the learning control of the pump. The problem is to track a reference signal of N ramps in spite of large measurement noise. The presented algorithm slowly learns the initial conditions of the controller for each desired ramp. Thus, few information are memorized to track repetitive sequence. The implementation is based on the use of as many PI controllers as ramps. An analysis of the control scheme and experimental results with the prototype of a total liquid ventilation system are presented. *Copyright © 2002 IFAC*

Keywords: biomedical system, periodic motion, learning control, PI controller.

1. INTRODUCTION

There has been considerable research in total liquid ventilation (Sekins,1999; Heckman,1999) because it can be a potential therapy for injured lungs. In such ventilation, the lungs are completely liquid-filled with oxygenated perfluorochemical (PFC) liquid. A pump system is used to deliver oxygenated PFC liquid to and from lungs. The objective of this project was to develop and test a prototype of total liquid ventilator for newborn. The major problem was to control with high precision the volume of liquid to transfer in the lungs in spite of important measurement noises. Moreover, the speed of the pump must be slowly variable in spite of the noise, the pump disturbances and the possibility of collapse. This problem motivates the implementation of a learning controller in the sense that it learns the input needed for reproducing a given output trajectory for performing a cyclic sequence in a specified finite time.

It exists different forms of learning control for dynamic systems. The Repetitive Control, developed around the beginning of the 80's, stores a whole period of the signal. From a theoretical point of view, the repetitive controllers are applications of the *Internal Model Principle* according to Wonham (1976) : the reference-generating polynomial must be in the denominator of the open loop transfer. Hillerström (1994) applied it to control a peristaltic pump. However, even with really sophisticated filtering within the loop of the delay chain, the repetitive controller would not stabilize for full working range (Hillerström, 1996).

The cyclic controller executes cycles defined by a series of points in the product space of states and controls to be attained at given time instants, with the first and last points coincident (Lucibello and Panzieri, 1998).

The purpose of this paper is to present a control which learns the initial conditions of the controller for each desired ramp. Thus, with memorization of few information, it is able to learn a repetitive command of multiple ramps. Application to a peristaltic pump is based on the use of as many PI controllers as ramps. An analysis of the control scheme and experimental results with the prototype of a total liquid ventilation system are presented.

1. THE MODEL OF THE TOTAL LIQUID VENTILATOR

1.1 *Presentation of the prototype of total liquid ventilator*

The figure 1 presents the prototype liquid ventilation system. On the right, the peristaltic pump achieved the flow by compressing a plastic tube with three rotating rollers. The pump is driven by a DC shunt motor (115V,1.43A,1/8HP,1725rpm) with a gear (40:1,43 rpm). The motor is under the control of a servo-amplifier (series 25A of Advanced Motion Controls) configured in voltage mode. On the center, the flow direction is controlled by two electro-valves. On the left, the reservoir includes oxygenator and heated element on its bottom, and a condenser on the top.

Both the condenser and the heater are under control. Thus, a temperature sensor (AD590) is used to measure the liquid temperature in the reservoir. The objective is to keep it near 37°C. Moreover, another temperature sensor (AD590) is used to measure the air temperature of the outgoing air. The objective is to obtain an air temperature near 0°C. The liquid level is measured with a pressure sensor located on the bottom of the reservoir. The system is controlled by a micro-PLC (IC200UAL006).

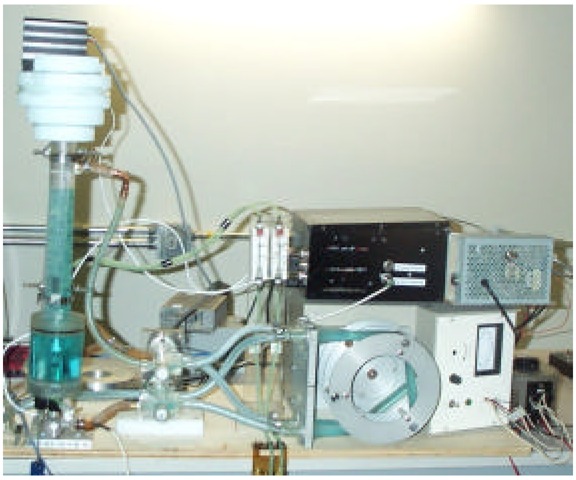

Fig. 1. The prototype of total liquid ventilator.

1.2 Control of the pump

The figure 2 presents the control of the pump. The therapist entries the tidal volume desired, the inspiration time and the expiration time. The signal generator builds the reference signal of the liquid level in the reservoir, $r(t)$. The figure 3 shows an example of a liquid level profile. In this example, there is four sequences: a gradual expiration sequence, a stop-flow to measure alveolar pressure, a gradual inspiration sequence, a stop-flow.

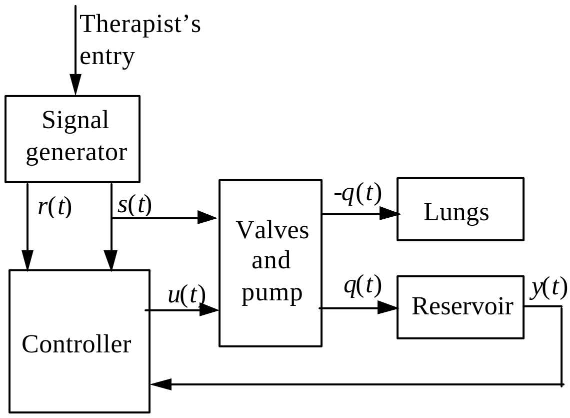

Fig. 2. Diagram of the functional blocks of the ventilator.

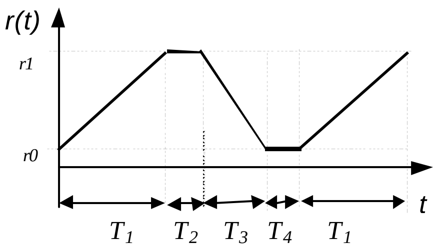

Fig. 3. Example of periodic reference.

In terms of control, the objective consists to find the command $u(t)$ such that $y(t) \rightarrow r(t)$. If the system is represented as a simple integrator model, the periodic command must be constant for the inspiration and expiration sequences. The figure 3 presents a example of periodic command of the pump. Classical feedback loop can be used to design this problem. However, there is many points which motivate the development of an original control system (Mazouzi,2001).

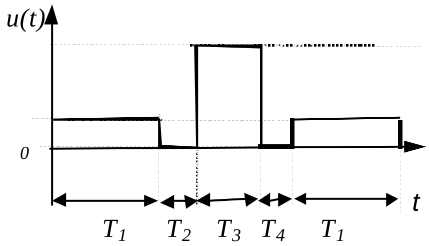

Fig. 3. Example of periodic command of the pump.

1.3 Model of the system

The electric signal $u(t)$ command the electric pump, thus the flow rate $q(t)$ in the reservoir is given by

$$q(t) = s(t)g(u(t),t) \tag{1}$$

where $s(t) = 1$ for expiration, $s(t) = -1$ for inspiration, and $g(u,t) \geq 0$ the nonlinear relation between the pump command and the flow rate. Due to the pump, the flow is pulsed which leads to a not constant flow rate. The command must respect the constraint : $0 \geq u(t) \geq u_{\max}$. Moreover, the alveolar could collapse during the expiration sequence. In this case, we can suppose that $g(u,t) \rightarrow 0$ very quickly.

The liquid volume in the reservoir is given by the following relation

$$\frac{dv}{dt} = q(t) \tag{2}$$

We assume that whole liquid coming from the reservoir goes into the lungs during the inspiration sequence. And vice-versa, during the expiration sequence, the liquid received in the reservoir comes from the lungs.

The volume of liquid in the reservoir is proportional to height of liquid in the reservoir: $y(t) = Kv(t)$. Moreover, there is many noise in the system. For example, the oxygenator generates many bubbles, or the valves generate pressure fluctuations when they move. Thus the output is written as :

$$y(t) = Kv(t) + b(t) \tag{3}$$

where $b(t)$ is a random noise signal.

2. THE CONTROL PROBLEM

2.1 Classical PI control law

For a cycle of N sequences, the reference signal can be described by the following model with n=1,2,…N :

$$\ddot{r}_n(t) = 0$$
$$\dot{r}_n(kT + t_n) \text{ and } r_n(kT + t_n) \text{ are given} \quad (4)$$

with k=0,1,2,…, $t_1 = 0$, $t_n = \sum_{i=1}^{n-1} T_n$ for n=2,3…,N and $T = \sum_{n=1}^{N} T_n$ the period of the cycle. For a periodic signal, the given values are constants for any k.

For the expiration sequence, the feedback control law is given by $u(s) = C(s)e(s)$ where $e(s) = r(s) - y(s)$ the error and $C(s)$ the controller. For the inspiration sequence, the control law must be $u(s) = -C(s)e(s)$ due to $s(t)$=-1 in the equation (1).

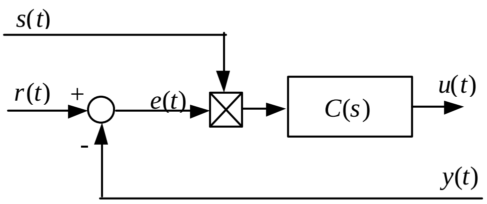

Fig. 4. The control scheme with a classical controller.

The *reference-generating polynomial* defined by the equation (4) is $\Gamma_i(s) = s^2$. It is the same for all sequences. According to the *Internal Model Principle* (Wonham, 1976) the reference-generating polynomial must be in the denominator of the open loop transfer : $C(s)G(s)$. From the equations (2) and (3), the system is $G(s) = K/s$; thus the controller can have the form of a PI controller :

$$C(s) = \frac{K_p s + K_i}{s} \quad (5)$$

with K_p the proportionnal gain and K_i the integral gain. The gains are chosen according to the pole placement method (Goodwin et. al, 2001).

In other words, a complete reference tracking is achieved with a PI controller, for an infinity time. However, the inspiration and expiration times are finite; thus, the error will not reaches the zero. A solution could be to assign rapid closed-loop poles. But, the trade-off inherent to a feedback loop leads to increase the noise sensitivity.

In other words, the speed of the pump must be slowly variable in spite of the noise, the pump disturbances and the possibility of collapse. The problem is to reach the perfect reference tracking without noise sensitivity.

2.2 The learning control of initial conditions

The solution proposed consists to memorize the value of the integrator at each end of each sequence. Thus, in this case, the system will learn cycle after cycle.

The figure 4 presents the controller for a ventilation cycle of 2 sequences. There is two PI controllers def ned by the equation (5). During the inspiration (s=1), the controller $C(s)$ in top of the figure 4 is connected. During the expiration sequence (s=-1), the controller $C(s)$ in bottom of the figure 4 is connected.

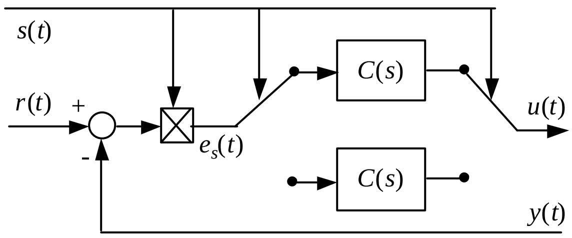

Fig. 4. The proposed scheme for a ventilation cycle of 2 sequences. The switches are driven by $s(t)$.

In the case of N different sequences, it is necessary to have N initial conditions for the N integrators of the N PI controllers.

Thus, for the sequence n=1,2,…,N, the control law is

$$u(t) = K_p e_s(t) + K_i z_n(t) \quad (6)$$

where $z_n(t)$ is the state variable of the integrator

$$\frac{dz_n}{dt} = e_s(t) \quad (7)$$

and $e_s(t)$ the output error multiplied by $s(t)$:

$$e_s(t) = s(t)\left(r(t) - y(t)\right) \quad (8)$$

2.3 Analysis for the simplest case

For the analysis, the simplest cycle with two sequences (N=2) is considered : the inspiration sequence, n=1, and the expiration sequence, n=2. We assume that there is no noise (b=0) and that $g(u(t),t) = g_0 u(t)$. The state variables of the system are the volume in the reservoir and the N memorized values :

$$x = \begin{pmatrix} v \\ z_1 \\ z_2 \end{pmatrix} \qquad (9)$$

For the inspiration sequence, n=1, the state form is

$$\dot{x} = A_1 x + B_1 r \qquad (10)$$

where $A_1 = \begin{bmatrix} -g_0 K_p K & g_0 K_i & 0 \\ -K & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$, $B_1 = \begin{pmatrix} g_0 K_p \\ 1 \\ 0 \end{pmatrix}$

For the expiration sequence, n=2, the state form is

$$\dot{x} = A_2 x + B_2 r \qquad (11)$$

where $A_2 = \begin{bmatrix} -g_0 K_p K & 0 & g_0 K_i \\ 0 & 0 & 0 \\ K & 0 & 0 \end{bmatrix}$, $B_2 = \begin{pmatrix} g_0 K_p \\ 0 \\ -1 \end{pmatrix}$

At the end of one cycle, at the time $t = T_1 + T_2 = T$, the final state is given by

$$x(T^-) = \ddot{O}_2 x(0^+) + \tilde{A}_2 \qquad (12)$$

with $\ddot{O}_2 = \exp(A_1 T_1 + A_2 T_2)$. The initial state is $x(0^+)$ when the inspiration start at $t=0^+$, the plus denotes the time just after zero. The final state is $x(T^-)$ when the expiration finishes at $t = T^-$, the minus denotes the time just before the end. Cycles after cycles, the vector $\tilde{A}_2$ is constant because :

$$\tilde{A}_2 = \int_{T_1}^{T_1+T_2} e^{A_2 t} B_2 r(T_2 + T_1 - t) dt + e^{A_2 T_2} \tilde{A}_1 \qquad (13)$$

and

$$\tilde{A}_1 = \int_0^{T_1} e^{A_1 t} B_1 r(T_1 - t) dt \qquad (14)$$

At the time $t=kT$ the state is completely defined by its state at the time $(k\text{-}1)T$. Thus the numeric equation is:

$$x[k+1] = \ddot{O}_2 x[k] + \tilde{A}_2 \qquad (15)$$

with $x[k] = x(kT)$ and k=0,1,2,…

The system will converge to the equilibrium point of the equation (15) : $x(\infty) = (I - \Phi_2)^{-1} \Gamma_2$ if and only if the modulus of all eigenvalues of $\ddot{O}_2$ are inferior than one.

3. RESULTS

3.1 *Configuration*

The sampling period is T_e=0.01s. The noise generated by the bubbles have been identified with the system identification toolbox of Matlab (Ljung, 1999). It is represented by a white noise of variance 6x10^{-5} filtered by a discrete IIR filter of order 5. The gain of the system is $g_0 K = 0.111$.

The cycle is T=9 seconds, with an inspiration during T_1=6 seconds, an expiration during T_2=3 seconds, and a stop-flow during T_2=2 seconds. The reference ramp shaped is in the range 3V to 5V.

3.2 *Results*

The figure 5 presents results of simulations. The gains of the controller are $K_p = 0.18$ and $K_i = 0.104$. The reference signal, the liquid level and the command signal are shown. In few cycles, the liquid level tracks the reference signal.

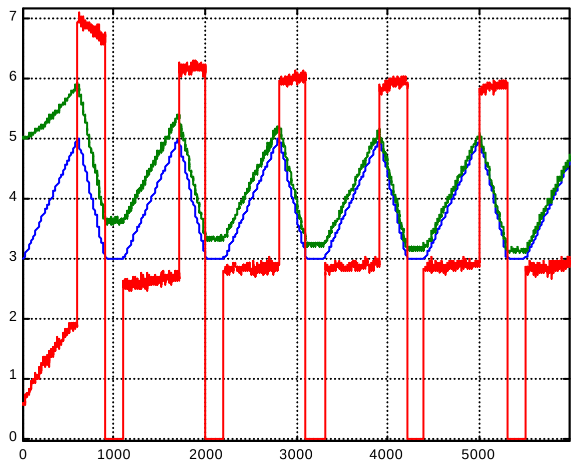

Fig. 5. Typical simulation results of liquid level (V) signal, reference signal (V) and command signal (V) versus the time in seconds.

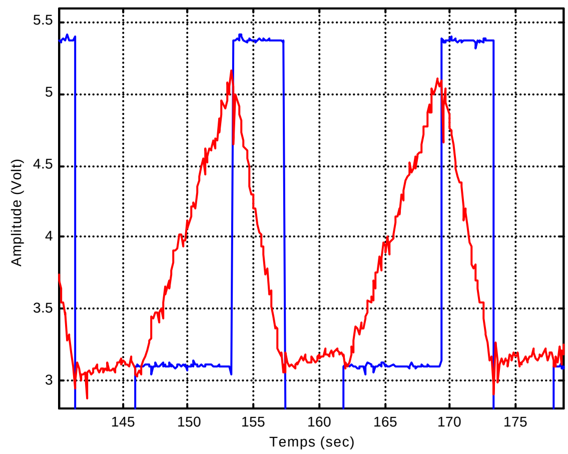

Fig. 6. Typical experimental results of pump command and pressure signal versus the time in seconds.

The figure 6 shows experimental results. The gains of the controller are $K_p = 9$ and $K_i = 0.52$. The liquid level in the reservoir perfectly track the reference objective. The pump command is well immunized from pulsation and noise (a death zone has been used in this case).

3. CONCLUSIONS

The control algorithm presented is able to learn a repetitive sequence with memorization of few information. Future works will be to improve the robustness of the feedback law.

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