CONTROL OF A NEW HYDRAZINE PUMP GENERATION IN PROPULSION SYSTEM

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Abstract: The aim of this paper is to emphasize the studies carried out for the new generation of hydrazine pumps, in terms of modeling, control and experiments in order to optimize the use of gas. It consists of an actuator conception for which it is possible to move the hydrazine pump leading to very short required displacements. It may be shown that the main advantage in using these new devices is the volume gain with respect to the existing satellites systems besides this will allow the system operates even if the gas reservoir pressure level is low, thus bringing great benefits. *Copyright © 2005 IFAC* .

Keywords: Hydrazine pump, Modelling, Propulsion systems, Satellite, Control design.
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1. INTRODUCTION

The satellites technology evolution is being of a great interest in aerospace engineering especially due to the constantly increasing number of launched space vehicles and the planned space missions in the near future all over the world. So then, developments are focused in new conceptions by means of for instance reducing satellite size, its weight as well as to enhance the ability to attain a very long lifetime, whilst more and more performance are required. That implies the intensification of the practical and theoretical investigations related to the space vehicles including planetary Landers which involve the development of specific propulsion systems. For more details on different propulsion systems, one may see for example (Griffin and French, 1991, Hill and Peterson, 1965).

We are interested in small satellites. The state of art in propulsion technology makes appear some limitations in gas consumption. As a matter of fact the gas reservoir cannot be totally blown off or used because the currently designed system has not the physical capability to operate for pressures below a given value, namely, it turns out that below a certain given pressure in the gas propulsion system reservoir, it is not possible to apply any impulse control even though the gas tank is far from to be empty. This is an important drawback in the sense that, besides the fact that the space vehicle cannot be controlled if a sudden external disturbance appears and induces satellite substantial deviation from its initial orbit, it is economically dramatic.

Therefore, the aim of this paper is to emphasize the studies carried out for the new generation of hydrazine pumps, in terms of modeling, control and experiments in order to optimize the use of gas. It consists of an actuator conception for which it is possible to move the hydrazine pump leading to very short required displacements. In previous work (Vannier et *al*., 2003), it has been described the technology of the actuator and some heuristic controllers but nevertheless very operating ones. However, some stabilization problems arise related to these controllers in some frequencies range that are difficult to handle because no analytic analysis is yet available. In particular, it has been shown that open loop controller may generate chocks that imply undesirable vibrations. So then, in order to elaborate advanced control strategies which will probably lead to the related solutions, a modelling of the system becomes necessary.

However, for the sake of implementation simplicity, classical controller has been first determined. It is known that, up to now, several industrial applications in different domain of activities use classical controllers. Simulation results show that the system met the desired operating frequency and the oscillating amplitude as well, in a steady state regime only while the transient is a little bit long.

The paper is organized as follows. Section 2 describes the basic principal of the system under consideration. Section 3 is dedicated to the proposed nonlinear modelling. Section 4 gives the first stage basic controller that one may apply to tune the thresholds and some other parameters. Section 5 gives the applied classical controller as a second stage and in order to enhance the performance, a nonlinear controller is described in Section 6. The paper ends with some concluding remarks.

2. DEVICE BASIC PRINCIPAL

Briefly, the actuator under consideration is composed of two parts: the first one is fixed and consists of an electromagnet, supplied through a coil of n turns, placed perpendicular to the magnetic field. Employing an electromagnet opens the possibility to have a magnet with a variable magnetic field. The second one is formed of a moving circular diaphragm, namely a disk of thickness a with a hole in its centre where the pump axis is rigidly fixed. In addition, the actuator structure exhibits a rotational symmetry. The axis of symmetry is displayed in dashed line as illustrated in Fig. 1.

i denotes the electrical current which flows in the coil. h is the height of the slot. e is the air gap thickness, r_1, r_4 are the actuator interior and exterior radius respectively while r_2, r_3 are the interior and exterior slot radius respectively.

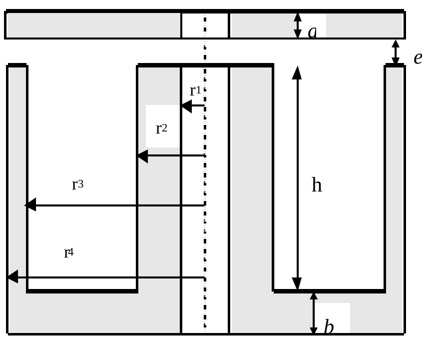

Fig. 1. Actuator scheme

The material of the actuator magnetic core has been chosen in such a way that the magnetic flux passes trough the coil with a sufficiently high frequency for the pump flow as well as a relative good amplitude level of the magnetic field, that is in order to provide the force capable to drive the axis pump.

All the studies concerning the materials, the calculation of the different forces involved in this system together with the physical constraints, the induced voltages and current levels have been carefully carried out and described in previous work (Dugué et *al*., 2001) where the reader may also find the explanation of the particular arrangement choice of the system. The resulting prototype of the pump is shown in Fig. 2.

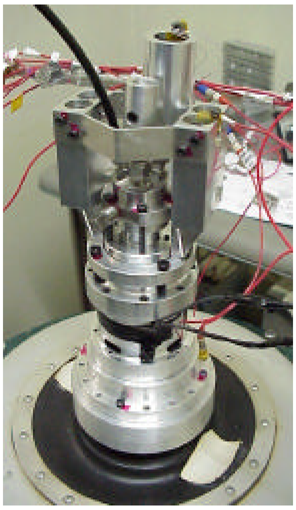

Fig. 2. Prototype of the pump

3. ACTUATOR MODELLING

In the perspective of elaborating advanced control strategy which satisfies the performance industrial demand, the modelling must be as simple as possible which nevertheless reflects the behaviour of the device. This is necessary in order to obtain a realisable controller by means of the implementation with respect to the required physical constraints and the additional electronic equipments. The experiments of an applied heuristic controller have shown a very high sensitivity with respect to some parameters.

Let us first consider the moving part of the device.

The magnetic force created through the area of the air gap S, which is in line with the pump axis, is given by the expression

$$F = \frac{B^2 S}{m_0} \qquad (1)$$

where m_0 denotes the magnetic permeability. Since the magnetic induction is

$$B = m_0 \frac{n i}{2 e} \qquad (2)$$

so then

$$F = \frac{m_0 n^2 S}{4 e^2} i^2 \qquad (3)$$

In order to elaborate a relatively simple modelling, we consider that the pump axis, let's call it a piston, acts like a mechanical spring with constant k, namely $F_s = F_0 + kx$, F_0 denotes the initial time applied force. The motion is axial, due to the particular symmetric arrangement of the system, there is no radial components of the acting forces.

The displacement of the pump piston results from these acting forces, namely the electromagnetic and spring forces but it is subject to a viscous frictions force proportional to the time derivative of the displacement x: $F_f = l\,\dot{x}$.

The reference frame is chosen such as $x = e$.

The piston pump weight is negligible so then from Newton's second law; it yields the following second order differential equation:

$$m\,\ddot{x} = \frac{a}{x^2} i^2 - kx - F_0 - l\dot{x} \tag{4}$$

where $a = \dfrac{m_0\, n^2 S}{4}$ and F_0 is being the initial force spring.

Moreover, the voltage across the windings is:

$$v = L\frac{di}{dt} + i\frac{dL}{dt} + R\,i \tag{5}$$

where R is the coil electrical resistance and its inductance L is a nonlinear function with respect to the displacement x, satisfying the following expression:

$$L(x) = L_0 + \frac{a}{x^2} \tag{6}$$

L_0 and a are constant.

Let $X = (x_1, x_2, x_3)^T = (x, \dot{x}, i)^T$ be the state vector, it then yields the state space representation:

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= -\frac{k}{m} x_1 - F_0 - \frac{l}{m} x_2 + \frac{a}{m\,x_1{}^2} x_3^2 \\
\dot{x}_3 &= \frac{x_1^2}{L_0 x_1^2 + a}(-R\,x_3 + 2a\frac{x_2 x_3}{x_1^3} + v)
\end{aligned} \tag{7}$$

The output of the system is the actuator position x, so $y = x_1$. The input control is the voltage across the coil, $u = v$.

In matrix notation, system (7) may be written as

$$\begin{aligned}
\dot{X} &= F(x_1, x_2, x_3, u) \\
y &= x_1
\end{aligned} \tag{8}$$

or in affine form :

$$\begin{aligned}
\dot{X} &= f(x) + g(x)\,u \\
y &= x_1
\end{aligned} \tag{9}$$

where

$$f(x) = \begin{pmatrix} x_2 \\ -\frac{k}{m} x_1 - F_0 - \frac{l}{m} x_2 + \frac{a}{m\,x_1{}^2} x_3^2 \\ \frac{x_1^2}{L_0 x_1^2 + a}(-R\,x_3 + 2a\frac{x_2 x_3}{x_1^3} + v) \end{pmatrix}$$

and $g(x) = \begin{pmatrix} 0 \\ 0 \\ \frac{x_1^2}{L_0 x_1^2 + a} \end{pmatrix}$.

From this system, one may derive the equilibrium point

$$x_{20} = 0\,,\ x_{30} = \frac{u_0}{R}$$

and the position satisfies the third order polynomial equation

$$-k\,x_{10}^3 - F_0 x_{10}^2 + a\ x_{30}^2 = 0 \tag{10.1}$$

namely

$$-k\,x_{10}^3 - F_0 x_{10}^2 + a\left(\frac{u_0}{R}\right)^2 = 0\,. \tag{10.2}$$

4. FIRST STAGE: BASIC CONTROLLER

The total displacement of the actuator is bounded such as its value is greater or equal to $1.2mm$. It may be however noticed, as already mentioned earlier, that the system is sensitive to some parameters variations which renders the control task not so easy particularly because of the very short displacement allowed so, the current signal over peak is to be reduced quite adequately. An open loop control design is shown to be not very efficient. An alternative has been thus proposed (Arzandé et *al.*) to overcome this difficulty by introducing a delay and shift back the instant of PWM control. Otherwise, the position goes to the upper thrust block that is not at all desirable because it may generate vibrations in the device.

A PWM controller using an air gap threshold in order to have the maximum permitted displacement of the actuator without reaching the threshold has been employed and lead to quite acceptable results, as illustrated in figure 3 in terms of the voltage and the current signals. The actuator experimental behaviour, namely of the prototype, is displayed in the following figure:

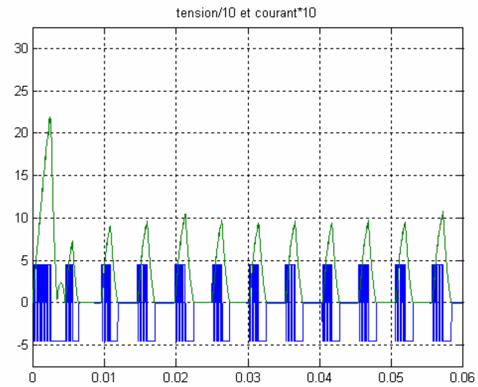

Fig. 3. Input voltage and current signal

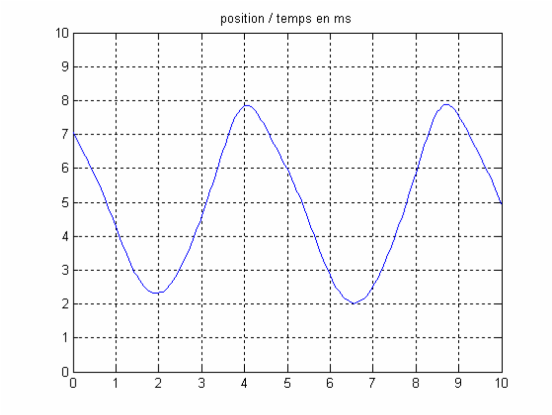

Fig. 4. Actuator position (in 0.1mm) vs time (in ms)

It has been observed that experimentally, when varying the frequency, the system passes through unstable regions.

So, a feedback loop controller is becoming necessary as well as defining the stable operation regions and clearly identifying the eventual unstable ones.

5. SECOND STAGE: CLASSICAL CONTROLLER

Considering first the local linearization of system (7) about an equilibrium point as defined in equation (10), the feedback loop response to a sinusoidal wave shape input voltage, of 40V amplitude (Fig. 5) and with frequency of 200 Hz, leads to the expected feedback loop motion of the actuator. Figure 6 displays the transient behavior and figure 7 the steady state behavior. For this purpose, a simple classical controller has been determined by means of PID controller. One may observe that the responses have the frequency of 200Hz which is indeed the desired frequency. Keep in mind the fact that it is not so easy to make the actuator oscillating with a frequency approximately around 200 Hz, besides this is the steady state regime.

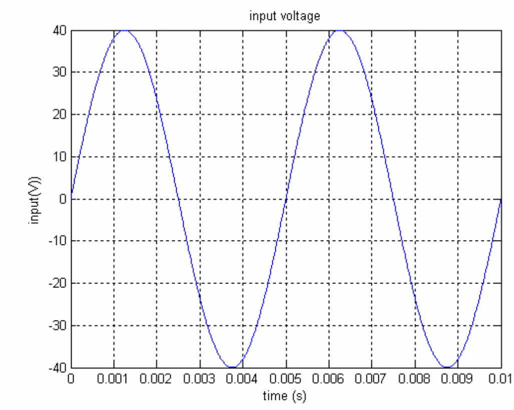

Fig. 5. Input voltage

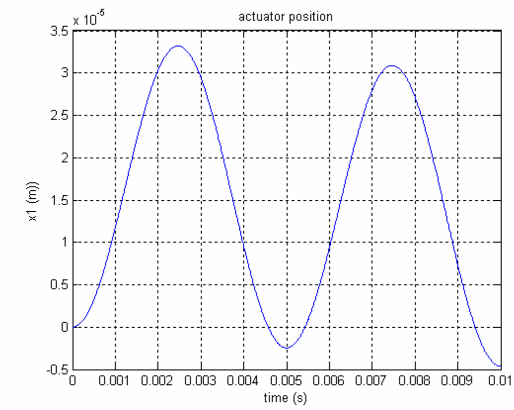

Fig. 6. Transient actuator position behavior

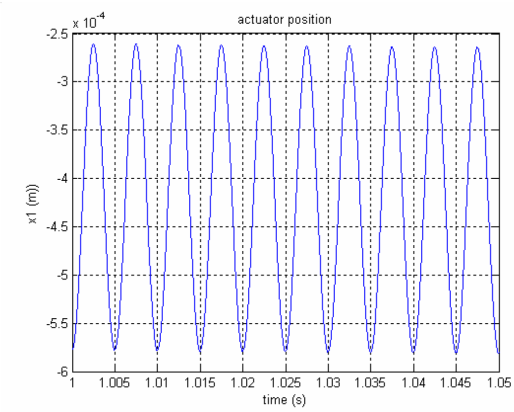

Fig. 7. Steady state actuator position behavior

One may also notice that the obtained actuator position is in concordance with the one resulting from the experimental tests (Fig. 4) that use a PWM input control signal (Arzandé et *al*.), in terms of the frequency and signal amplitude**.**

6. THIRD STAGE: NONLINEAR CONTROLLER

The above two first stages lead to some results by using quite simple controllers but drawbacks still remain. The nonlinear designed controller is then derived using the asymptotic output tracking based approach.

Let $x_R(t)$ be a prescribed reference output function differentiable at least n times with respect to the time t. The asymptotic output tracking problem consists in specifying a dynamic controller which depends on the reference output, a finite number of its time derivatives and the state variables and which forces the system output to asymptotically converge towards the reference desired one.

Define the tracking error $e(t)$ as the difference between the actual system output $x(t)$ and the reference output $x_R(t)$

$$e(t) = x_R(t) - x(t) \qquad (11)$$

Let us impose a dynamic equation to the error by forcing $e(t)$ to satisfy the third order differential equation

$$\dddot{e}(t) + b_2\ddot{e}(t) + b_1\dot{e}(t) + b_0 e(t) = 0 . \qquad (12)$$

From equation (12), using (7), it comes out the feedback control law

$$u = \left(\begin{array}{l} \dfrac{m(L_0 x_1^2 + a)}{2a\, x_3}\,(2\dfrac{a}{m}\dfrac{x_2 x_3^2}{x_1^3} + (\dfrac{k}{m} - b_1)x_2 + \\ (\dfrac{l}{m} - b_2)(\dfrac{a\, x_3^2}{m x_1^{2}} - \dfrac{F_0}{m} - \dfrac{k}{m}x_1 - \dfrac{l}{m}x_2) - b_0 x_1 \end{array} \right)$$

$$- (2a\frac{x_2 x_3}{x_1^3} - R\, x_3) + \frac{m(L_0 x_1^2 + a)}{2a\, x_3} b_0 y_R$$

The coefficients $b_i^{'}s$ are chosen in such away that the polynomial $s^3 + b_2 s^2 + b_1 s + b_0 = 0$ is Hurwitz.

Numerical simulations have been performed and as results Fig. 8 shows that the objective of having the desired behavior of the actuator position is reached despite the fact that it exhibits a shift phase with respect to the reference signal but one does not care about this existing shift phase, since the required frequency of 200Hz is met as long as the amplitude which is being less than 1.2mm. It may be observed that (Figs. 9 and 11) the actuator and the current are lying within the physical allowed values, while a saturation of 100V is put on the input voltage (Fig. 10). If this last one is of 70V (Fig. 12), it leads to the actuator position behavior of figure 13 which still satisfy the required performance.

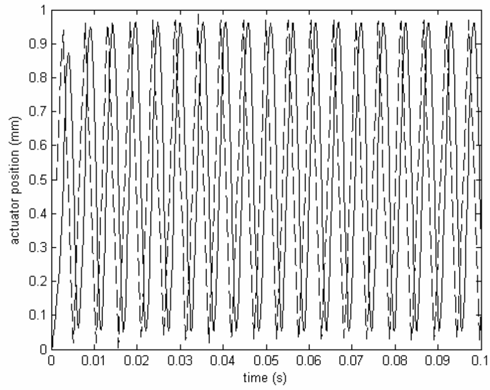

Fig. 8. Actuator position (in mm) vs time (s)

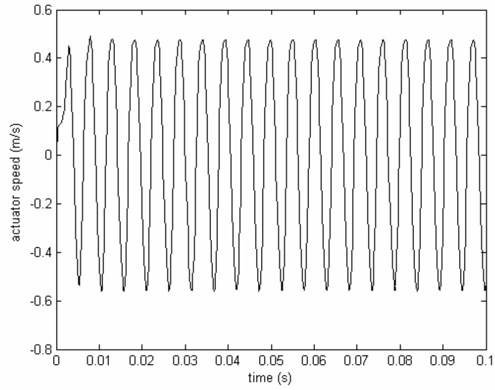

Fig. 9. Actuator speed behavior (in m/s) vs time (s)

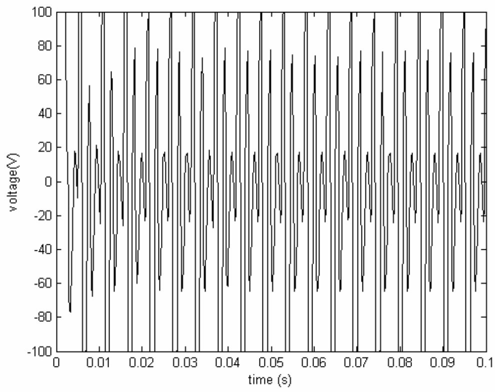

Fig. 10. Input voltage (in V) vs time (s)

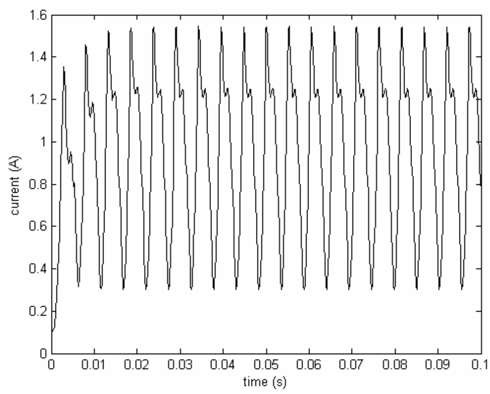

Fig. 11. Current (in A) vs time (s)

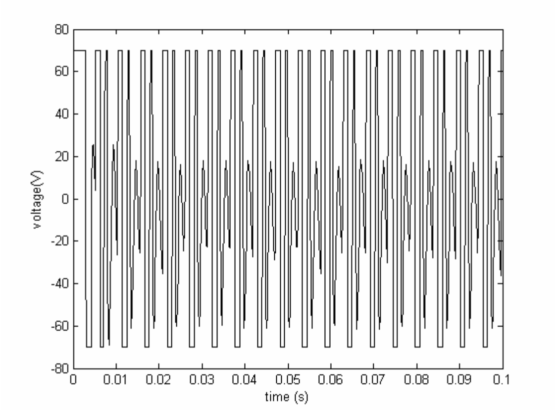

Fig. 12. Input voltage (in V) vs time (s)

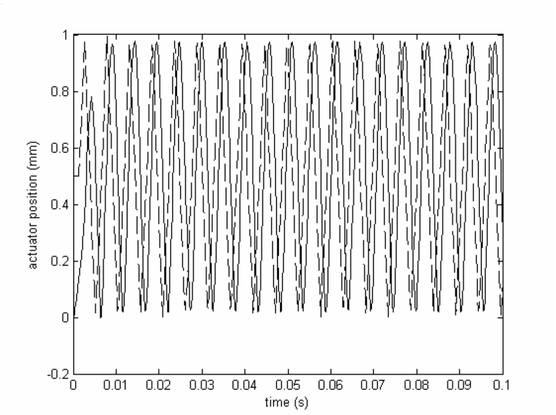

Fig. 13. Actuator position (in mm) vs time (s)

7. CONCLUSIONS

This paper presents the new technology of hydrazine pump for small satellites propulsion systems and it's mathematical modelling. It is shown that in order to elaborate a quite simple controller, for the sake of implementation simplicity, open loop PWM controller has been first investigated, it is pointed out that the drawback is that the actuator position goes to the upper thrust block, that is not at all desirable because it may generate vibrations of the device. Classical controller has been then determined. Simulation results show that the system met the desired operating frequency together with the oscillating amplitude but in steady state regime only. So then, it is possible to improve once more these results such as this oscillations amplitude reaches at least 1mm. This cannot be performed by the classical controller, besides the drawback mentioned above, because of the current and the voltage values that do not satisfy the physical constraints of the device. Then, finally a nonlinear controller has been investigated and show quite satisfactory results. The expression of the controller is relatively more complex and since digital controller is not possible for the present application, so analog implementation is being studied. The tests on the hydrazine prototype pump are also being carried out and will be presented in forthcoming near future work.

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AKNOWLEGMENTS

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NOMENCLATURE

a	Thickness of the moving diaphragm
B	Magnetic Induction
i	Current (A)
n	Number of turns coil
S	Area of core (m^2)
e	Thickness of the air gap (m)
f	Operating frequency (Hz)
L_0	Coil inductance (H)
m	Actuator mass (kg)
h	Height of the slot (m)
v	Voltage across the coil (V)
r_1, r_4	Interior and exterior radius of the actuator (m)
r_2, r_3	Interior and exterior radius of the slot (m)
x_1	Actuator position (m)
x_2	Actuator speed (m/s)
x_3	Electrical current in the coil (A)
v	Voltage across the windings