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Cascaded loops control of DC motor driven joint including an acceleration loop

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Abstract: The aim of this paper is to transform easily, a three cascaded loops controller toward a four cascaded loops controller which includes an acceleration loop. A state space analysis with pole placement is proposed for the gains calculation of the acceleration loop. The method is implemented on an experimental DC permanent magnet actuator. The position error and velocity are compared when torque disturbances are performed on the actual machine.

1. INTRODUCTION

Three cascaded closed loop position controller is widely used in controlled electrical drives (Leonhard.W,1985) (Robet P.Ph. et al. 1995), because of its simplicity. We find the position control loop, the speed control loop and the current control loop. The current control loop is also called torque control loop because of linear relation between the motor current and the generated torque.
To perform a random trajectory of position, a typical three cascaded closed loop system is often used in industrial application (Takesue N. et al. 1999) (Robet P.Ph. et al. 2001). It has been shown that introducing an acceleration loop improve stability, robustness against disturbances (Schmidt P.B. et al. 1992) (Godler I. et al. 2001). And, it has been found that disturbance cancelation is the main goal of the acceleration loop (Makkapati V.P et al. 2012) (Godler I. et al. 1999).
One of the constraints brought by the acceleration loop is the evaluation of the acceleration and this is the most important point (Hori, Y. 1988). Different methods are currently used (Ovaska S.J. et al. 1998). The observer technique needs good parameters identification and large base band (Schmidt P.B. et al. 1990) (Moatemri M.H. et al. 1991) . With an accelerometer sensor, the linearity, the noise and the limitation of the sensor base band has to be taken into account (Han J.D. et al. 2000). When a speed differentiation technique is used, the noise introducing has to be canceled with a low pass filter (Schmidt, P. et al. 2004). But now there are very high resolution sensors that have a very high bandwidth. This has the effect of obtaining a higher cutoff frequency of the low pass filter needed after differentiation. Consequently the bandwidth of the closed loop of acceleration does not decrease too much. This type of sensor will be use in our experiments to get acceleration.
The limits of acceleration loop with gain, sampling period, stability has been studied in (Deur J. et al. 2000) (Hashimoto K. et al. 2001). In our paper we consider the design of the acceleration loop in a continuous time by considering a high sampling frequency toward the base banded of the system (Robet P.Ph. et al. 2013).
Our method is based on pole placement. To adjust a possible interdependence of the three closed loops, a global state synthesis is done to have better results of gains correctors calculation. It means that the loop of current is not considered as a torque controller with a constant gain. Its dynamic which is linked to the acceleration loop is taken into account in our analysis.
An experimental validation of a position system with three cascaded closed loop is presented with and without acceleration loops. Errors of tracking position and velocity are compared when torque disturbances are applied to the *DC* machine.

2. A THREE CASCADED CONTROLLER

Let us consider a joint driven by a voltage source amplifier and a *DC* permanent magnet motor. Electrical and mechanical equations are the following:

$$U = R\,I + L\,\dot{I} + kt\,\dot{q} \tag{1}$$

$$\Gamma_m = kt\,I = J\,\ddot{q} + Fv\,\dot{q} + Fs\,sign(\dot{q}) + \delta\Gamma_m \tag{2}$$

where I, U, R, L, kt are respectively the armature current and voltage, the resistance, the inductance and the torque constant of the motor. For the mechanical dynamics, Γ_m, J, Fv, Fs, $\dot{q}$, $\ddot{q}$, are respectively the electromagnetic motor torque, the inertia moment, the viscous friction coefficient, the coulomb friction torque, the motor velocity and acceleration. A torque disturbances called $\delta\Gamma_m$ is introduced to test the errors tracking of position and speed of the system.

To control the position, a three cascaded-loops controller is used. The control law is realized with an *IP* controller for the current and the velocity loop and with a *P* controller for the position loop. This structure gives no tracking error on a step response of position.

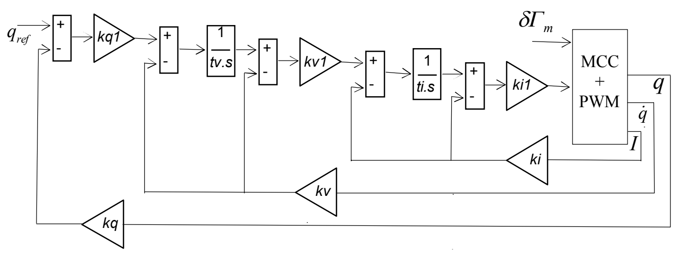

Fig. 1 Cascaded closed loop of current, of speed and position

The viscous friction coefficient $Fs\, sign(\dot{q})$ and $\delta\Gamma_m$ are considered as perturbations. The pulse width modulation amplifier (*PWM*) can be considered as gain *Go,* because of the high sampling frequency relative to the bandwidth of the current loops (Robet P.Ph. et al. 1998).

Different methods are available to place the poles (Umland J.W. et al. 1990) (Keviczky L. et al. 1995) (Datta S. et al. 2012). With electric drive an *IP* controller, experience leads us to choose second order polynomials for the dynamic of current:

$$P_{IGo}(s) = s^2 + 2\zeta_I w_I s + w_I^2 \qquad (3)$$

with a damping coefficient ζ_I and pulsation w_I in relation to the natural electrical dynamic $w_e = R/L$.

Typically $w_I \le w_e \le 10 w_I$ and $0.5 \le \zeta_I \le 0.707$ (4)

Second order polynomial is well adapted for a closed loop of speed including an *IP* controller.

$$P_{\dot{q}Go}(s) = s^2 + 2\zeta_{\dot{q}} w_{\dot{q}} s + w_{\dot{q}}^2 \qquad (5)$$

The pulsation $w_{\dot{q}}$ and the damping coefficient $\zeta_{\dot{q}}$ are currently given by:

$w_{\dot{q}} \le w_{em} \le 10 w_{\dot{q}}$ and $0.707 \le \zeta_{\dot{q}} \le 1$ (6)

where $w_{em} = kt^2/(RJ)$ is the electro-mechanical pulsation.

Usually the position loop is also equivalent to a second order with a damping greater than unity to avoid overspending. Here we keep only the dominant pole.

$$P_{qGo}(s) = s + w_q \quad \text{with} \quad w_q = w_{\dot{q}}/2 \qquad (7)$$

With the poles obtained, it is quite usual to do the synthesis of the electrical loop alone and then to perform the state synthesis of the speed and the position loop together. That is quite acceptable when the dynamics are far apart, a little less when dynamics are near each another. This is why we make a global state synthesis which has a goal to adjust the possible interdependence of the three nested loops. With the polynomials obtained with (3), (5), (7), the global polynomials equation is the following:

$$\begin{aligned} &P_{Go}(s) = P_{IGo}(s)\, P_{\dot{q}Go}(s)\, P_{qGo}(s) \\ &P_{Go}(s) = s^5 + a_{Go}s^4 + b_{Go}s^3 + c_{Go}s^2 + d_{Go}s + e_{Go} \end{aligned} \qquad (8)$$

Where coefficient $a_{Go}, b_{Go}, c_{Go}, d_{Go}, e_{Go}$ of $P_{Go}(s)$ are obtained by identification:

$$\begin{aligned} a_{Go} &= w_q + 2(w_{\dot{q}}\zeta_{\dot{q}} + w_I\zeta_I) \\ b_{Go} &= 2(w_{\dot{q}}\zeta_{\dot{q}} + w_I\zeta_I)w_q + w_{\dot{q}}^2 + w_I^2 + 4w_{\dot{q}}\zeta_{\dot{q}}w_I\zeta_I \\ c_{Go} &= (w_{\dot{q}}^2 + w_I^2 + 4w_{\dot{q}}\zeta_{\dot{q}}w_I\zeta_I)w_q + 2w_{\dot{q}}w_I(w_{\dot{q}}\zeta_I + w_I\zeta_{\dot{q}}) \\ d_{Go} &= 2w_{\dot{q}}w_I(w_{\dot{q}}\zeta_I + w_I\zeta_{\dot{q}})w_q + w_{\dot{q}}^2 w_I^2 \\ e_{Go} &= w_{\dot{q}}^2 w_I^2 w_q \end{aligned} \qquad (9)$$

To perform a global state synthesis on the system given by Fig. 1, it is easier to modify it as shown on Fig. 2. The state equation of the closed loop system is obtained as:

$$\dot{X} = \left(A_f - K_f\right) X + B_f \iint q_{ref}\, dt, \quad \text{with}$$
$$Y = C_f\, X$$

$$A_f = \begin{bmatrix} -R/L & -kt/L & 0 & 0 & 0 & 0 \\ kt/J & -Fv/J & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}, \quad B_f = \begin{bmatrix} K_{K3}/Lkq \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$K_f = \begin{bmatrix} 1/L \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} K_{K1} \\ 0 \\ K_{KI} \\ K_{K2} \\ K_{KV} \\ K_{K3} \end{bmatrix}^T, \quad C_f = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}^T, \quad X = \begin{bmatrix} I \\ \dot{q} \\ \int I\, dt \\ q \\ \int q\, dt \\ \iint q\, dt \end{bmatrix}$$

where

$$\begin{aligned} &K_{K1} = K1,\; K_{KI} = KI,\; K_{K2} = KI/ki*K2,\; K_{KV} = KI/ki*KV \\ &K_{K3} = KI/ki*KV/kv*K3 \end{aligned} \qquad (10)$$

and

$$\begin{aligned} &K1 = ki\; ki1\; Go, \quad KI = ki\; ki1\; Go/ti \\ &K2 = kv\; kv1, \quad KV = kv\; kv1/tv, \quad K3 = kq\; kq1 \end{aligned} \qquad (11)$$

The characteristic equation of $\left(A_f - K_f\right)$ is given by:

$$P_{Go}(s) = s\left(s^5 + a_{Go}s^4 + b_{Go}s^3 + c_{Go}s^2 + d_{Go}s + e_{Go}\right) \qquad (12)$$

with

$$\begin{aligned} &a_{Go} = \frac{JR + JK_{K1} + FvL}{JL}, \quad b_{Go} = \frac{FvR + FvK_{K1} + kt^2 + JK_{KI}}{JL} \\ &c_{Go} = \frac{K_{KI}Fv + K_{K2}kt}{JL}, \; d_{Go} = \frac{K_{KV}kt}{JL}, \; e_{Go} = \frac{K_{K3}kt}{JL} \end{aligned} \qquad (13)$$

With (10), (11), (13), It comes the correctors gains

$$\begin{aligned} &ki1 = \frac{J\,L\,a_{Go} - (L\,Fv + J\,R)}{J\;ki\;Go}, \quad ti = \frac{J\;ki1\;ki\;Go}{J\;L\;b_{Go} - (ki1\;ki\;Go\;Fv + Fv\;R + kt^2)} \\ &kv1 = \frac{J\;L\;ti\;c_{Go} - Fv\;ki1\;ki\;Go}{ki1\;Go\;kt\;kv}, \quad tv = \frac{ki1\;Go\;kt\;kv1\;kv}{J\;L\;ti\;d_{Go}} \\ &kq1 = \frac{J\;L\;ti\;tv\;e_{Go}}{kq\;kv1\;kt\;ki1\;Go} \end{aligned} \qquad (14)$$

where $a_{Go}, b_{Go}, c_{Go}, d_{Go}, e_{Go}$ are known value obtained by (9) with the poles placement.

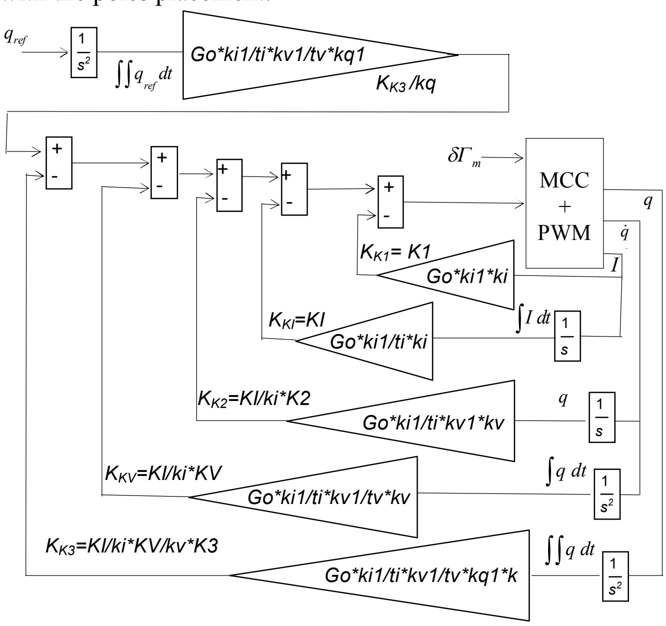

Fig. 2 Position control scheme

3. CASCADED CONTROLLER WITH AN ACCELERATION LOOP

On the controller of position given by Fig. 1, we include an acceleration loop between the current loop and the velocity loop.

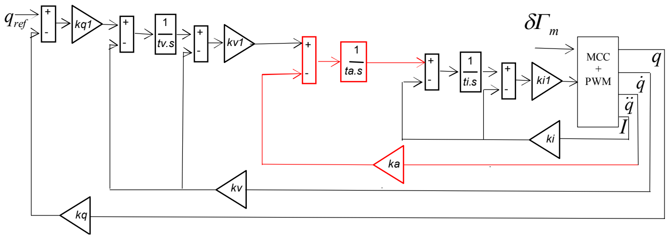

Fig. 3 Cascaded closed loop of current, of acceleration, of speed and position

One of the key points of the global state synthesis of the system is to find the new pole introduced by the acceleration loop. The solution comes straight forward looking the mechanical equation for very high dynamic. Equation (2) can be approached by:

$$kt\ I \simeq J\ \ddot{q} \tag{15}$$

It appears in (15) that driving the current is similar than driving the acceleration. That means, the dynamic of the acceleration loop has to be similar to the one of current loop. Consequently we add a pole such that:

$$P_{\ddot{q}acc}(s) = s + w_{\ddot{q}} \quad \text{with} \quad w_{\ddot{q}} = w_I \tag{16}$$

Taking into account the acceleration loop, with a similar synthesis method that previously, the characteristic equation (8) become:

$$P_{acc}(s) = P_{IGo}(s)\,P_{\dot{q}Go}(s)\,P_{qGo}(s)\,P_{\ddot{q}acc}(s)$$

$$P_{acc}(s) = \left(s^5 + a_{Go}s^4 + b_{Go}s^3 + c_{Go}s^2 + d_{Go}s + e_{Go}\right)(s + w_{\ddot{q}})$$

$$P_{acc}(s) = s^6 + a_{acc}s^5 + b_{acc}s^4 + c_{acc}s^3 + d_{acc}s^2 + e_{acc}s + f_{acc}$$

The coefficient can be expressed with those of (9):

$$\begin{aligned} &a_{acc} = a_{Go} + w_{\ddot{q}};\quad b_{acc} = b_{Go} + a_{Go}w_{\ddot{q}};\quad c_{acc} = c_{Go} + b_{Go}w_{\ddot{q}} \\ &d_{acc} = d_{Go} + c_{Go}w_{\ddot{q}};\quad e_{acc} = e_{Go} + d_{Go}w_{\ddot{q}};\quad f_{acc} = e_{Go}w_{\ddot{q}} \end{aligned} \tag{17}$$

With the poles obtained, we make a global state synthesis which has an aim to adjust the possible interdependence of the four nested loops. The system of Fig. 3 can be put in the following scheme shown on Fig. 4.

The state equation of the closed loop system is obtained as:

$$\dot{X} = \left(A_f - K_f\right)X + B_f \iiint q_{ref}dt$$

$$Y = C_f\ X$$

with

$$A_f = \begin{bmatrix} -R/L & -kt/L & 0 & 0 & 0 & 0 & 0 \\ kt/J & -Fv/J & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix},\quad B_f = \begin{bmatrix} K_{K3}/Lkq \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$K_f = \begin{bmatrix} 1/L \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}\begin{bmatrix} K_{K1} \\ K_{K4} \\ K_{KI} \\ K_{KA} \\ K_{K2} \\ K_{KV} \\ K_{K3} \end{bmatrix}^T,\quad C_f = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}^T,\quad X = \begin{bmatrix} I \\ \dot{q} \\ \int I\,dt \\ q \\ \int q\,dt \\ \iint q\,dt \\ \iiint q\,dt \end{bmatrix},\ \text{where}$$

$$\begin{aligned} &K_{K1} = K1,\ K_{KI} = KI,\ K_{KA} = KI/ki*KA \\ &K_{K2} = KI/ki*KA/ka*K2,\ K_{KV} = KI/ki*KA/ka*KV \\ &K_{K3} = KI/ki*KA/ka*KV/kv*K3 \end{aligned} \tag{18}$$

and

$$\begin{aligned} &K1 = ki\ ki1\ Go,\ KI = ki\ ki1\ Go/ti,\ K2 = kv\ kv1,\ KV = kv\ kv1/tv \\ &K3 = kq\ kq1,\ KA = ka/ta \end{aligned} \tag{19}$$

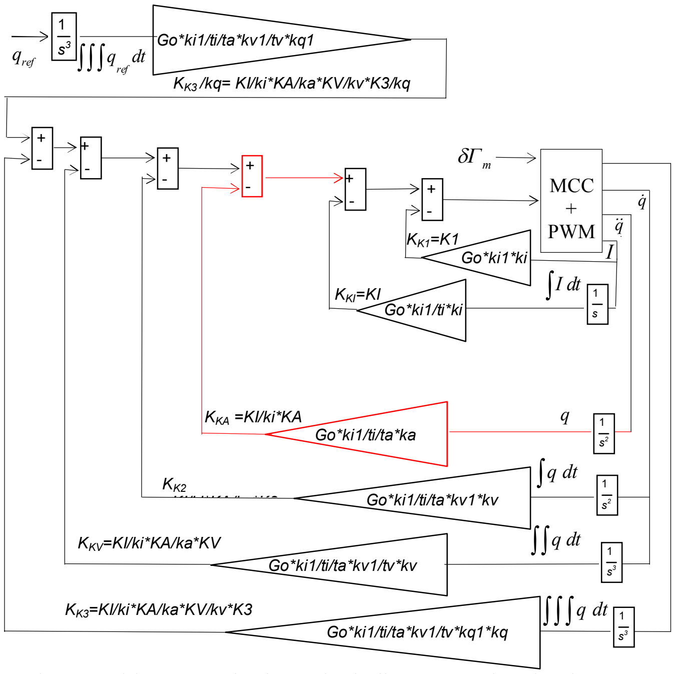

Fig. 4 Position control scheme including an acceleration loop

The characteristic equation of $\left(A_f - K_f\right)$ is given by:

$$P_{Go}(s) = s\left(s^6 + a_{acc}s^5 + b_{acc}s^4 + c_{acc}s^3 + d_{acc}s^2 + e_{acc}s + f_{acc}\right) \tag{20}$$

with

$$a_{acc} = \frac{JR + JK_{K1} + FvL}{JL},\quad b_{acc} = \frac{FvR + FvK_{K1} + kt^2 + JK_{KI}}{JL}$$

$$c_{acc} = \frac{K_{KI}Fv + K_{KA}kt}{JL},\quad d_{acc} = \frac{K_{K2}kt/JL}{JL},\quad e_{acc} = \frac{K_{KV}kt/JL}{JL}$$

$$f_{acc} = \frac{K_{K3}kt}{JL}$$

With (18), (19), (20), it comes :

$$\begin{aligned} &ki1 = \frac{J\,L\,a_{acc} - (Fv\,L + JR)}{J\ ki\ Go},\quad ti = \frac{J\ ki\ ki1\ Go}{J\,L\ b_{acc} - (Fv\ ki\ ki1\ Go + Fv\ R + kt^2)} \\ &kv1 = \frac{J\,L\ ti\ ta\ d_{acc}}{ki1\ Go\ kt\ kv},\quad tv = \frac{ki1\ Go\ kt\ kv\ kv1}{J\,L\ ti\ \ ta\ e_{acc}} \\ &kq1 = \frac{J\,L\ ti\ tv\ ta\ f_{acc}}{kq\ \ kv1\ kt\ ki1\ Go},\quad ta = \frac{ki1\ Go\ kt\ ka}{J\,L\ \ ti\ \ c_{acc} - Fv\ ki1\ Go\ ki} \end{aligned} \tag{21}$$

where a_{acc}, b_{acc}, c_{acc}, d_{acc}, e_{acc}, f_{acc} are known value obtained by (17) with the poles placement.

4. SIMULATION RESULTS

With the same data as section 5, but with no filter, a simulation is performed to validate the results of the previous paragraph that recommends taking as pulsation of the acceleration loop: $w_{\ddot{q}} = w_I$. We propose a comparison of the position error and speed error during a torque disturbance when the pulsation of the acceleration loop is smaller than w_I and equal to $w_{\ddot{q}} = w_{\dot{q}}$. Results are in SI units.

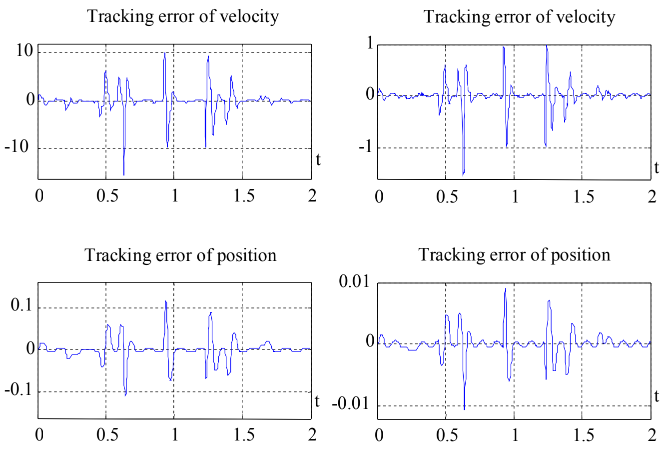

Fig. 5 Controller with acceleration loop ($w_{\ddot{q}} = w_{\dot{q}}$ and $w_{\ddot{q}} = w_I$)

In Fig. 5, it clearly appears an error ratio of 10 on the position and speed between the two simulations. So we can conclude; the highest the pulsation of the acceleration loop is, the lowest are errors. Consequently, the best is to have $w_{\ddot{q}} = w_I$ as pulsation.

Now let us do another simulation with a usual three cascade loops controller, where all the pulsations $w_{\ddot{q}}, w_{\dot{q}}, w_q$ are identical to the previous simulations.

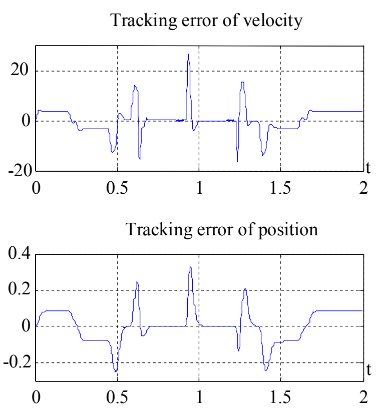

Fig. 6 Controller without acceleration loop

On Fig. 5 with $w_{\ddot{q}} = w_{\dot{q}}$ and Fig. 6, it appears an improvement by 2 on error if the pulsation of the acceleration loop is equal to the one of the speed loop. If $w_{\ddot{q}}$ is chosen such that $w_{\ddot{q}} >> w_{\dot{q}}$, the errors become smaller and can be divided by 20 as it is shown on Fig. 5 with $w_{\ddot{q}} = w_I$ and Fig. 6.

5. EXPERIMENTAL CASE STUDY

The linear positioning system EMPS300 connected to the control system from dSPACE™ are used. The control system is based on a TMS 320C31 Texas Instruments™ processor and Matlab-Simulink software, in order to get a high rate numerical control with a big computational capacity. The EMPS300 main components are a *DC* permanent magnet motor with *DC* tachometer and current controlled four quadrant *PWM* chopper, a ball screw drive positioning unit and an incremental encoder (dSPACE, 1995). All analog and digital signals are directly accessible between EMPS300 and Simulink using the C code generator RTW Matlab toolbox (The Mathworks, 2008) and the RTI program from dSPACE.

The proposed experimental identification is realized with a PWM gain equal to: *Go*=5.31 and with the following DC motor parameters: *L*=3.2E-3(H), *R*=2.2(Ω), *kt*=5.13E-2(V/rad/s), *J*=1.61E-5(kgm²), *Fv*=9.16E-5(Nm/rd/s), *Fs*=7.28E-3(Nm). The sampling frequency is 10kHz.
Damping coefficients ζ_I, $\zeta_{\dot{q}}$ and pulsations of the current, velocity and position loops are chosen with (4) ,(6) ,(7)

$$w_I = 3.9E3\ rad/s,\quad w_{\dot{q}} = 1.3E2\ rad/s,\quad w_q = 6.6E1\ rad/s$$

$$\zeta_I = 0.5,\quad \zeta_{\dot{q}} = 0.707$$

The corrector gains are obtained with (14):

$$ki1 = 0.64;\quad kv1 = 0.25;\quad kq1 = 38$$

$$ti = 2.2E-4,\quad tv = 8.4E-3$$

With the first experimentation, the reference position is set to $q_{ref} = 0$, while a torque perturbation $\delta\Gamma_m$ is applied in the controller of Fig. 1. Results, in SI units, are shown on Fig. 7.

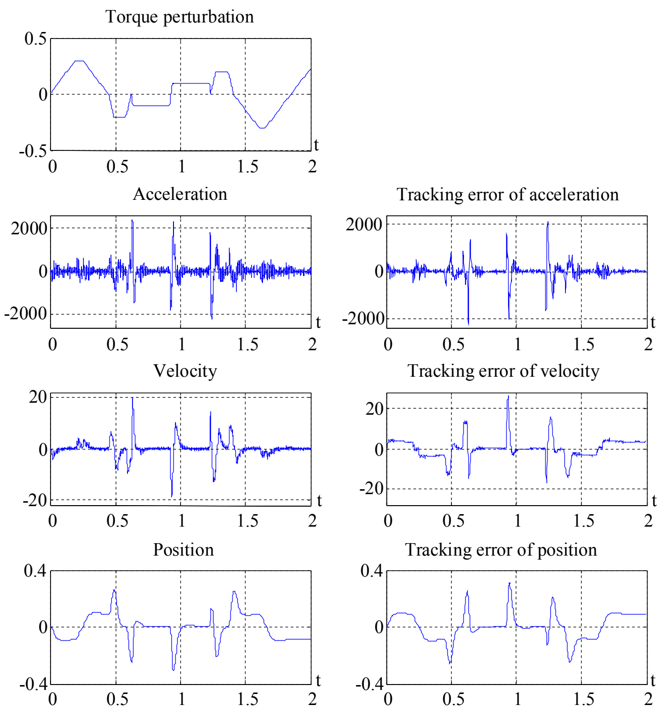

Fig. 7 Controller without acceleration loop

The second experimentation is done with the controller of Fig. 3, where a filter is added into the acceleration loop feedback. Introducing a first order filter with a cutoff frequency of w_f seems to validate the following options into experience:

-The speed differentiation to get acceleration requires a minimum bandwidth of the filter of $w_f = 3w_{\dot{q}}$. (22)

-The bandwidth of the acceleration loop is selected into the baseband of the filter, such as $w_{\ddot{q}} = w_f / 3$.

With these two findings, it is natural to establish the acceleration loop frequency as:

$$w_{\ddot{q}} = w_{\dot{q}} \quad (23)$$

As we can see, in practice the pulsation of the acceleration loop ($w_{\ddot{q}} = w_{\dot{q}}$) is smaller than w_I because of the filter. Consequently, referring to Fig. 5, the error improvement bring by the acceleration loop will not be so good than if $w_{\ddot{q}} = w_I$.

With (22), the first order filter place in the acceleration loop has a pulsation $w_f = 3.9E2\ rad/s$. The pulsation of the acceleration loop given by (23) is used to get the corrector gain obtain with (21).

$$\begin{array}{l} ki1 = 0.66;\ \ kv1 = 165E2;\ \ kq1 = 30 \\ ti = 2.2E-4,\ \ tv = 1.2E-2;\ \ ta = 2.6 \end{array} \quad (24)$$

With $q_{ref} = 0$ and with the same torque perturbation $\delta\Gamma_m$ that the first experimentation, we get the results shown on Fig. 8.

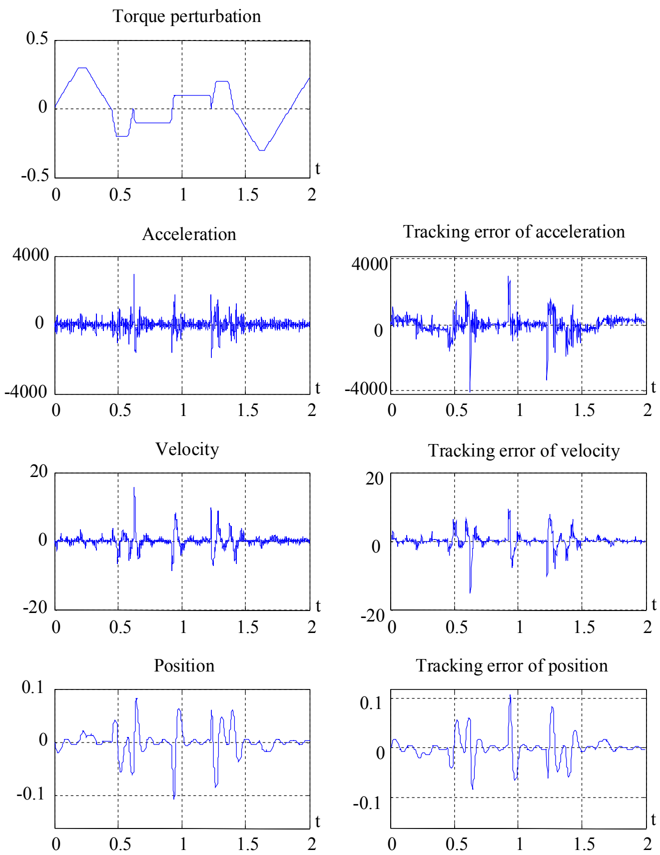

Fig. 8 Controller with acceleration loop

An interesting change appears with disturbances on the tracking errors of velocity and position; the errors are at least divided by two. This results is very interesting for example in haptic application, where the position move around a given q_{ref} . It shows a capability rejection of the natural non linear perturbation introduced by $Fs\ sign(\dot{q})$.

The filter introduced to calculate the acceleration on the actual experimentation gives us difficulty to increase $w_{\ddot{q}}$ bandwidth. We were limited to choose $w_{\ddot{q}} = w_{\dot{q}}$. To get a full advantage of the acceleration loop, the measurement of the acceleration on experimentation has to be improved. Such that the bandwidth can be increase up to $w_{\ddot{q}} = w_I$. This is a very important point of the design of an acceleration closed loop (Hori, Y. 1988). But this is not the purpose of this paper who is to derive a state space analysis with pole placement for the gains calculation of the acceleration loop.

It is interesting to notice that, by removing the integration into the velocity loop, and by keeping only the proportional controller into this loop, the errors tracking is similar. This result is obtained with the same gain corrector of (24), but without tv . By the way, the integration given by the acceleration loop introduced no tracking error on a step response of position. Consequently, the integration into the velocity loop is not necessary if there is one into the acceleration loop. As it is mentioned in (Schmidt P.B. et al. 1992) (Makkapati V.P.. et al. 2012), we also have seen that in tracking of position, the acceleration loop doesn't bring any improvement.

6. CONCLUSION

A state space analysis with pole placement has been proposed for the gains calculation of the acceleration loop. The main idea in this paper is to say that the pulsations of the current loop and the acceleration loop are of the same order of magnitude. This allows us to place the pole associated with the acceleration loop. Then an overall synthesis with the acceleration loop gives the correctors gains, which are calculated with (21).

The acceleration loop is mainly useful to reduce torque perturbations. The effect of the viscous friction coefficient, $Fs\ sign(\dot{q})$, brings a torque perturbation at the zero crossing position. This is why introducing an acceleration feedback control can be advantageously applied with robots in motion control into haptic.

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