USE OF THE COG REPRESENTATION TO CONTROL A ROBOT WITH ACCELERATION FEEDBACK

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Abstract: A controller using acceleration feedback has been applied to a flexible robot for which the position and velocity of the load are not measured. It is shown by using the Causal Ordering Graph (COG), that the motor can be controlled by using acceleration feedback and that it allows an exact tracking of the motor position, irrespective of the non-linear flexibilities of the axis and of the measurement disturbances. This easy-to-tune algorithm, in which main control parameters are the modal masses of the motor and load part and only consists of a positive acceleration feedback plus a PD controller, has been validated on an industrial 3-axis robot.

1 INTRODUCTION

The demands for smaller operation times, low-energy consumption and lower robot costs are the main motivations for the use of lightweight high-speed robots. However, high speed and accelerations supported by such flexible robots lead to undesirable vibrations. Since vibrations deteriorate the equipment and affect the precision of the positioning device, their damping should be considered as a prerequisite to any further increase of performances. As will be explained below, the combination of this underdamped behaviour and the lack of measures on the end-point makes it impossible for the current industrial control structures to perform rapid and robust closed-loop dynamics.

Obtaining accurate control-oriented models of complicated flexible structures is not an easy task. Whereas finite element method (FEM) allows the different modes of deformation of a structure to be understood, they are not suitable for control purposes. A simpler model can be obtained when decomposing the structure in a set of rigid bodies linked by spring elements using Assumed Modes Methods (AMM). Meirovich have proven to be able to represent the dynamic structure of a CNC axis drive (Meirovich, 1994). In such a complex structure as a flexible Cartesian robot, it has been found experimentally that the springs' stiffness exhibit large variations whereas modal masses remain nearly constant. Moreover, it is impossible to measure the load position and velocity in the industrial context, since the cost of measurement devices (e.g. a laser or a camera) is prohibitive. As a consequence, only the motor part is controlled in closed loop whereas the load is controlled in open-loop, and this fundamental aspect is not often accounted for in the literature (Béarée, 2004). It has been shown (Béarée, 2004) that the combination of low damping and the lack of measures on the load results in poor control performances. As an alternative to load position measurements, the use of an accelerometer mounted on the effector's end can provide additional information at a reasonable price. Since it is impossible in practice to derive the velocity and position of the load from an integration of the acceleration signal owing to the important measurement noise, the acceleration feedback should be directly embedded in the controller.

Acceleration feedback has been be expressed in the framework of optimal control (Luo and Saridis, 1985) for which a compensation of non-linear terms enforces the tracking error to converge asymptotically to zero. This method, however, needs to measure the torques at the motor shafts and the

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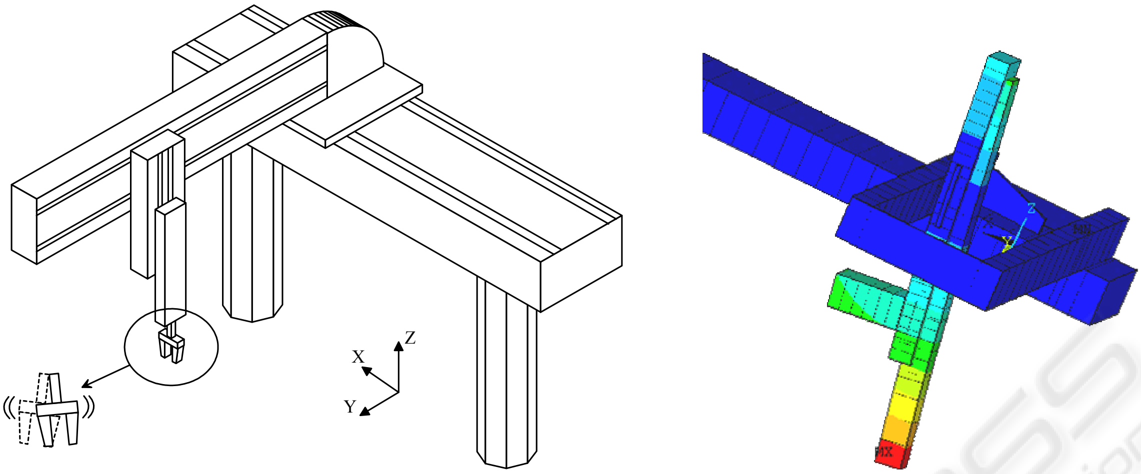


Figure 1: Identification of the main deformation mode (Horizontal motion X axis: Bending of Z) with ANSYS

joint accelerations, and is not easily applicable in an industrial context, where such complete and accurate measurement is not available. Indeed, the tuning and the practical implementation of this algorithm (Mc Inroy and Saridis, 1990) meets many difficulties such as the obtaining of angular accelerations and torque measurements which require further computations or approximations. It has been shown experimentally that an increase of the sampling frequency or the feedback gains leads to instability. In summary, there have been few experimental results actually based on the measured acceleration information.

In this paper, the same acceleration feedback algorithm of (Luo and Saridis, 1985) is deduced by using the Causal Ordering Graph (COG introduced by Hautier, 2004) on a robot modelled by a two mass model with a spring with lumped stiffness parameters. The COGs consist in a graphical language for describing the dynamics of physical systems and provide general methodology to determine their control structures.

Contrary to Luo and Saridis algorithm, the developed controller just needs the value of the modal masses and is thus easier to tune. Two figure cases will be tackled, corresponding to the industrial context: the tracking of a reference trajectory of the motor, and the tracking of a reference trajectory of the load for which the motor reference motion is computed off-line.

The paper is organized as follows: the modelling approach of the robot is described in the first part. The acceleration feedback algorithms are developed next section. Finally, real-time validations are presented for an industrial pick-and-place robot.

2 A LUMPED MASS-SPRING MODEL OF AN INDUSTRIAL ROBOT

The robot which is considered in this study is an industrial Cartesian robot, which exhibits an average cycle time of 3 *s*, a mass of 750*kg* and accelerations up to $4 m.s^{-2}$. The robot cycle time is a key parameter in the overall process optimisation. The vibrations due to the robot flexibilities (in particular that of the vertical axis) are quite underdamped, and become critical when exceeding more than 2*mm* (or 0.3*mm* on the motor reference trajectory), which restrains the performances and limits the cycle time.

In this part, it will be recalled how classical modelling methods allow to design a control-oriented model which respects the physics of the structure of such a flexible robot and allows the damping of vibrations. A presentation of such methods can be found in more details in (Meirovich,

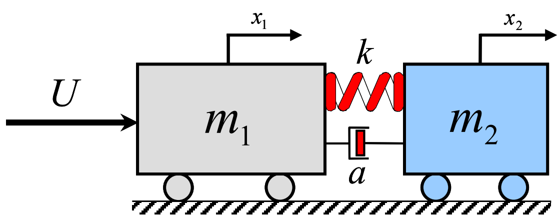


Figure 2: Two-mass-spring model of a Cartesian robot (X axis)

1994), (Ellis, 2000).

The Finite Elements Method is a classical tool which enables an accurate modelling of the dynamical behaviour of a flexible system, using a polynomial approximation of the deformations of elements such as beams, plates, etc... Figure 1 shows the first deformation mode due to the bending of the vertical Z-axis during the horizontal motion of the robot. The evolution of the other deformation modes during the motion of the robot in its working space is not intuitive.

Whereas this method allows the behaviour of the robot to be understood, its complexity prevents its use for control purposes. An alternative method to the modelling of small deformation consists of decomposing the structure in a set of rigid bodies which are linked by spring elements using the method of Assumed Modes. A model with lumped parameters for which the stiffness of the spring depends on the position of the load mass in the working space allows the first deformation modes to be represented (Meirovich, 1994). This study will be limited to the modelling and control of the first deformation mode, i.e. projection of the bending of the vertical axis on the horizontal plane during the motion of the X axis. The dynamical model of the motion can be represented by a two-mass model with a spring of variable stiffness.

Modal analysis can be carried experimentally using an impulse response obtained when exciting the effector's end with an impact hammer (Barre, 96). The signal is recorded using a spectrum analyser. The variation of the modal parameters for an horizontal displacement (axis X) is moderate but becomes very important because of torsional coupling when both the axis X and Y are moving. All these parameters are lumped through the value of the Z position. According to Figure 2, the equations of model are:

$$m_1\ddot{x}_1 = k\left(x_2 - x_1\right) + a\left(\dot{x}_2 - \dot{x}_1\right) + u \qquad (1)$$

$$m_2\ddot{x}_2 = k\left(x_1 - x_2\right) + a\left(\dot{x}_1 - \dot{x}_2\right) \qquad (2)$$

$$k = k_0 + g\left(y_2\right) \qquad (3)$$

where u is the driving effort, x_1 and x_2 are respectively the positions of the motor and the load for the horizontal X axis, y_2 is the position of the load for the transverse Y axis, m_1 and m_2 are respectively the modal masses of the motor and the load part, k is the modal stiffness. Experimental results show that $g(y_2)=a.y_2+b$.

Consider an horizontal displacement, for which $y_2-y_{20}=\alpha(x_2-x_{20})$. The stiffness k is now a linear function of the load position x_2, with $k=k_0+a\alpha(x_2-x_{20})+b+ay_{20}$.

The frequency of the main deformation mode and the corresponding damping ratio are given:

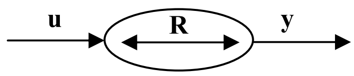
$$F_n = \frac{1}{2\pi}\sqrt{\frac{k}{M_{eq}}}, \varsigma = \frac{A}{2\sqrt{kM_{eq}}}, \frac{1}{M_{eq}} = \frac{1}{m_1} + \frac{1}{m_2} \qquad (4)$$

3 ACCELERATION FEEDBACK

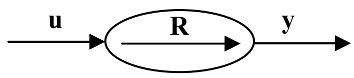
As discussed previously, the motor part can be controlled in closed-loop whereas the load is controlled in open-loop. Two control methods can be employed, depending on the specifications that are required by the user. As an example, one may want to improve the cycle time while others want to reduce the load's vibrations to an acceptable level.

3.1 Tracking of the Motor Reference Position

Since the concept of causality is important in the comprehension of the physical phenomena, we used a tool called the Causal Ordering Graph and introduced by Hautier (Hautier, 2004). It allows us to represent a system with elementary objects defined using energetic considerations. When an object does not store any information, the causality will be defined as external and the output will be derived directly as a function of the input. The relation (R) is then called rigid:



If an object stores information, the causality is internal and the output is a function of the energetic state of the system. In this case, the relation (R) is called causal, both the time and initial state are the implicit inputs:



When the model of the process is established, the control structure is deduced by inversion of the COG. This model being made up of causal and rigid relations, two different solutions for the inversion result:

In a Rigid Relation, a bijective relation C determines a control law using direct causal inversion.

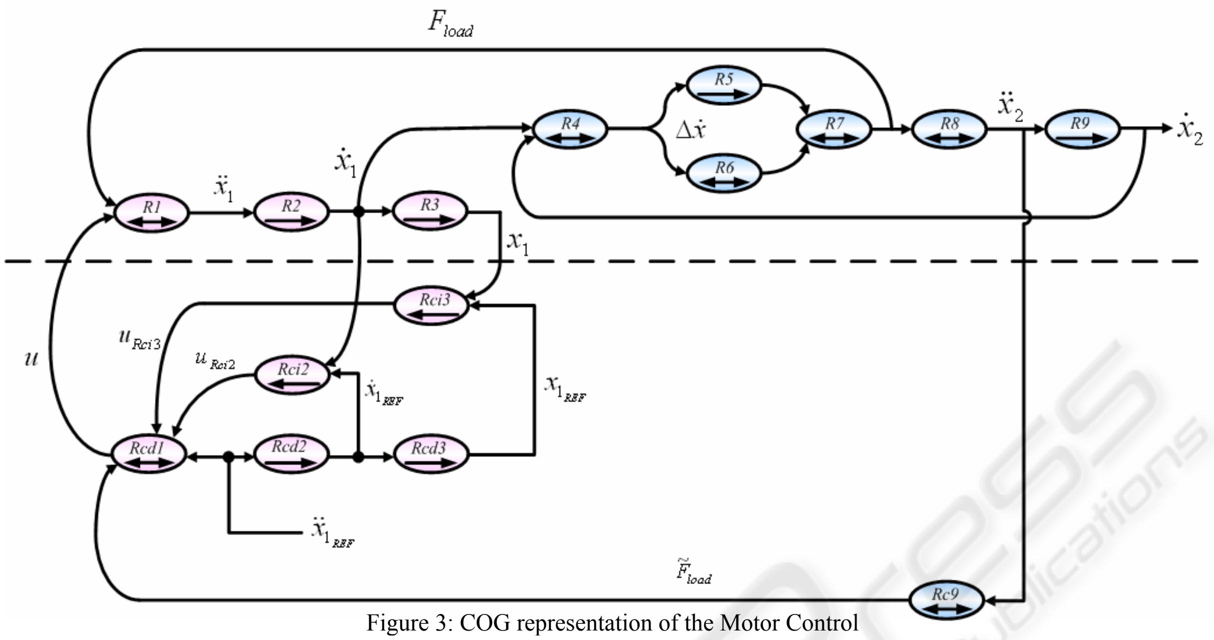
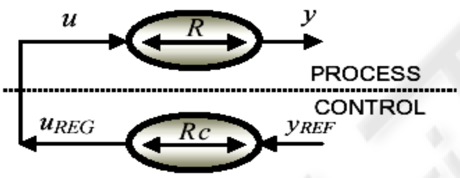


Figure 3: COG representation of the Motor Control

$$R \rightarrow y = f(u) \Rightarrow \quad Rc \rightarrow u_{REG} = C(y_{REF})$$

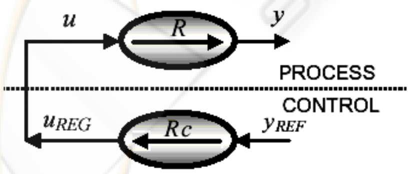
If $C = f^{-1}$ and $u = u_{REG}$ then $y \rightarrow y_{REF}$



In a Causal Relation, time acts implicitly so that the accumulation effect induces an initial value and the relation is not bijective any more. Thus, the tuning value u_{reg} is elaborated while taking into account, at any moment, the value of y according to its reference y_{ref}. This inversion principle is nothing but the measurement feedback principle.

$$R \rightarrow y = f(u,t) \Rightarrow \quad Rc \rightarrow u_{REG} = C(y_{REF} - y)$$

If $C \rightarrow \infty$ and $u = u_{REG}$ then $y \rightarrow y_{REF}$



Applying these rules, we obtain the COG representation of the Motor Control which is shown in Figure 3. The different relations are summarized in Table 1. The overall control u is obtained by using the model inversion principle and choosing C_2 and C_3 as simple gain k_1 and k_2:

$$u = m_2\ddot{x}_{2_{MES}} + m_1\ddot{x}_{1_{REF}} + k_1\left(\dot{x}_{1_{REF}} - \dot{x}_{1_{MES}}\right) + k_2\left(x_{1_{REF}} - x_{1_{MES}}\right) \quad (5)$$

It allows a perfect tracking of the motor irrespective of the non-linear flexibilities of the axis and of the measurement disturbances. One can recognize the simplified version of the acceleration feedback algorithm of (Luo and Saridis, 1985). This is the main advantage to use the COG formalism. Indeed, the motor control algorithm is derived easily by using this tool.

Table 1: Relations of the COG representation of the Motor Control

Two-Mass-Spring Model	Motor Control
$R_1 \rightarrow m_1\ddot{x}_1 = u(t) - F_{load}$	$R_{ci1} \rightarrow u(t)_{reg} =$ $m_1\ddot{x}_{1_{REF}} + \tilde{F}_{load} + C_2\Delta\dot{x}_1 + C_3\Delta x_1$
$R_2 \rightarrow \frac{d}{dt}(\dot{x}_1) = \ddot{x}_1$	$R_{cd2} \rightarrow \frac{d}{dt}\left(\dot{x}_{1_{REF}}\right) = \ddot{x}_{1_{REF}}$
$R_3 \rightarrow \frac{d}{dt}(x_1) = \dot{x}_1$	$R_{cd3} \rightarrow \frac{d}{dt}\left(x_{1_{REF}}\right) = \dot{x}_{1_{REF}}$
$R_4 \rightarrow \Delta\dot{x} = \dot{x}_1 - \dot{x}_2$	$R_{ci2} \rightarrow u_{ci2_{REG}} = C_2\left(\dot{x}_{1_{REF}} - \dot{x}_{1_{MES}}\right)$
$R_5 \rightarrow \frac{d}{dt}\left(F_{spring}\right) = k\,\Delta\dot{x}$	$R_{ci3} \rightarrow u_{ci3_{REG}} = C_3\left(x_{1_{REF}} - x_{1_{MES}}\right)$
$R_6 \rightarrow F_{viscous} = a\,\Delta\dot{x}$	$R_{c9} \rightarrow \tilde{F}_{load} = m_2\ddot{x}_{2_{MES}}$
$R_7 \rightarrow F_{load} = F_{spring} + F_{viscous}$	
$R_8 \rightarrow \ddot{x}_2 = \frac{F_{load}}{m_2}$	
$R_9 \rightarrow \frac{d}{dt}(\dot{x}_2) = \ddot{x}_2$	

Figure 4: Overview of the test-setup prototype (stroke [mm]: X-1000 Y-400 Z-800, maximum speed: 120*m/min*, maximum acceleration: 4$m.s^{-2}$).

3.2 Load's Vibrations control

The former method of control consists of enforcing the motor to follow a prescribed trajectory. Conventional controllers for Cartesian robot use a reference trajectory for the motor position, which does not guarantee performances for the dynamics of the load. An alternative method consists of defining a reference trajectory for the load (e.g. a trajectory with no vibrations). The corresponding motor reference trajectory is determined using model inversion by differentiating relation (2):

$$\begin{aligned} a\ddot{x}_{1_{REF}} &= -\left[k_0 + g\left(x_2\right)\right]\dot{x}_{1_{REF}} - \left[g'\left(x_{2_{REF}}\right)\dot{x}_{2_{REF}}\right]x_{1_{REF}} \\ &+ a\ddot{x}_{2_{REF}} + m_2\ddot{x}_{2_{REF}} \\ &+ \left[k_0 + g\left(x_{2_{REF}}\right)\right]\dot{x}_{2_{REF}} + \left[g'\left(x_{2_{REF}}\right)\dot{x}_{2_{REF}}\right]x_{2_{REF}} \end{aligned} \quad (6)$$

Where $x_{2_{REF}}$ is the desired load trajectory

Equation (6) underlines that the third derivative of the load position (the jerk) should be continuous in order to avoid peaks on the motor acceleration (and thus on the control). Indeed, the jerk value is known to be a key tuning parameter (Barre, 2004).

4 EXPERIMENTAL VALIDATION

The main objective of the validation part is to show that the acceleration feedback allows the cycle time to be increased and the vibrations on the motor and the load to be reduced. The experimental section is organized as follows: the robot is moving diagonally and results are compared for the tracking of a prescribed motor trajectory, and for a load reference trajectory with small and high jerk.

4.1 Material

The experimental validations are carried out on a Cartesian 3-axis robot (figure 4). It was equipped with a real-time "dSPACE 1103" control card. The available measurements on the motor part come from the actuator encoders of axis and an

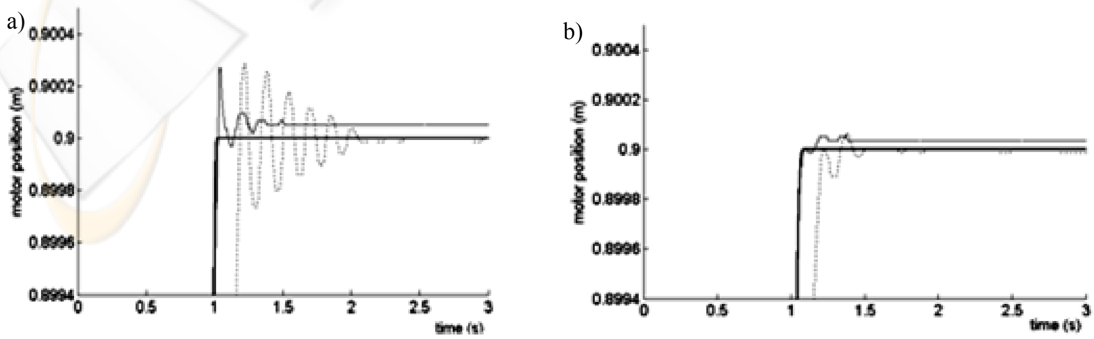


Figure 5: Diagonal displacement, motor position - a) $Je = 500\ \mathrm{ms}^{-3}$, b) $Je = 50\ \mathrm{ms}^{-3}$, Strong Full Line: Reference Trajectory, Full line: Acc. Feedback, Dotted: Industrial loop.

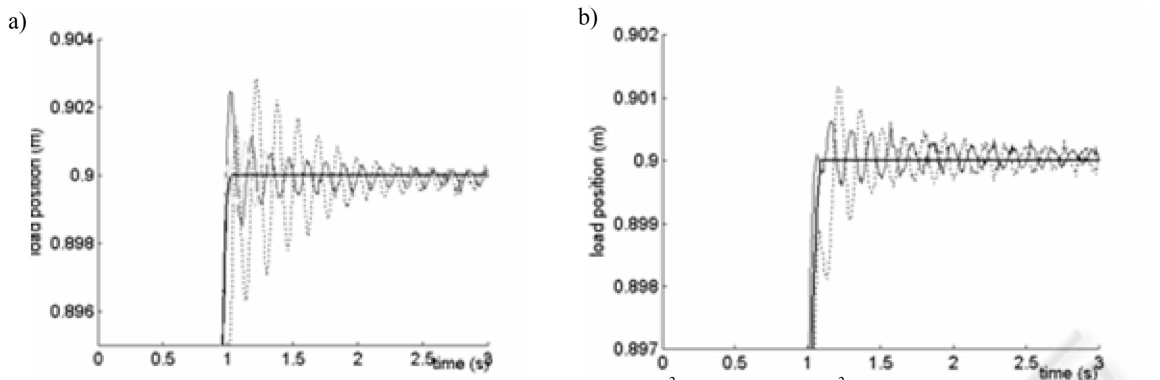


Figure 6: Diagonal displacement, load position - a) $Je = 500$ ms^{-3}, b) $Je = 50$ ms^{-3}, Strong Full Line: Reference Trajectory, Full line: Acc. Feedback, Dotted: Industrial loop

accelerometer located on the effector's end gives the load acceleration. A laser sensor (measuring distance: 50*mm* / measuring range: 20*mm*) directly gives the load position and is only used for experimental verification.

The validations are undertaken for a displacement y_2-y_{20}=α(x_2-x_{20}), where x_2 varies from x_{20}=0 to x_2=900*mm* as before, and y_2 varies from y_{20}=0 to y_2=400*mm*, with a height z=315*mm*. The transverse Y-axis is controlled with a classical PI controller, it has been checked that the actual trajectory is nearly a straight line.

4.2 Tracking of a Motor Position Reference Trajectory

The reference trajectory profile is a classical jerk-limited bang-bang, i.e. the acceleration exhibits a trapezoidal profile. The average modal masses taken in the model and used for control (5) and simulations are m_1=350*kg* and m_2=46*kg* (mean value), according to that determined experimentally. The stiffness in equations (1-3), according to the X-axis, is:

$$k = k_0 + a\alpha\left(x_2 - x_{2_0}\right) + b + ay_{2_0} \tag{7}$$

where k_0=1.27 10^5*N.m*, α=0.444, a=-1.56 10^5*N*. The error on the stiffness correlation ranges from ±15%, the mean uncertainties on modal masses are about ±25%. k varies from 1.27 10^5*N.m* to 0.66 10^5*N.m*, i.e. about 100% during the whole course. In the case considered, there exists an optimal value of the jerk which limits the amplitude of vibrations (Béarée, 2004) (Barre, 2004), which is of 50*ms*$^{-3}$.

One can see that the combination of the acceleration feedback and an appropriate jerk allows the rise time to be greatly improved while vibrations almost vanish (Figure 5). In any case, the acceleration feedback outperforms the conventional loop (tuned at its best). The rise time is about 1.05*s* when the robot is controlled with acceleration feedback with a high jerk value, (1.15*s* with a jerk of 50*ms*$^{-3}$) versus respectively 1.25*s* and 1.39*s* for the conventional feedback with high and low jerk values. The tracking performances of the acceleration feedback algorithm allow to compensate for the lag resulting from the use of a low jerk value.

In theory, residual oscillations on the motor position should not occur. Unperfect trajectory following and oscillations can be due to non-linear effects in axis coupling that where not taken into account in the model, Coulomb friction effects and effective variations of the modal masses. The results on the load position show that high-amplitude oscillations still occur whereas the cycle time is improved.

4.3 Tracking of a Load Position Reference Trajectory

An appropriate acceleration profile of the load is now considered, for which the jerk is limited either to 50*ms*$^{-3}$ or to 500*ms*$^{-3}$. The trajectory will be chosen to be the same as the reference trajectory of the motor which was chosen in the previous validation scheme. The motor reference trajectory is thus derived using equation (6).

One can find that the damping is quite better with acceleration feedback (one significant peak), while the cycle time (obtaining of a near-steady state value) reduces to 1*s* versus 1.15*s* for the conventional algorithm. The results with an appropriate jerk show that the load can be damped very quickly (the oscillations are not even visible by the operator, and with an amplitude under 0.2*mm*) with far better performances than the conventional algorithms (with or without jerk). Simulation results are good enough, considering that the true variation of modal masses was not taken into account.

Figure 6 shows the robustness of the acceleration feedback with respect to modelling errors and nonlinearities (considering that modelling errors are quite important, more than 20% for each parameter). The conventional controller is unable to compensate the variations of stiffness as shown in figure 7 (oscillations are up to 3*mm* which is far too much for the application considered). Oscillations are quite underdamped with a low jerk. Nevertheless, the gain on the cycle time is quite important (more than 0.15*s*), the amplitude of the oscillations do not exceed ±0.5*mm*, which is quite satisfactory for our application.

5 CONCLUSION

An acceleration feedback algorithm has been determined by using the COG methodology. It allows, in theory, an exact tracking of the motor position. Moreover, model inversion allows an appropriate motor reference to be derived to control the load. This algorithm has been successfully applied to an Industrial Robot which dynamics is modelled by a two-mass spring with lumped parameters and in the case of the load's vibration control, the Acceleration Feedback Controller nearly eliminates the vibrations on the load. This may allow to increase the performances of such manipulators and to improve greatly the cycle time.

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