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Vibration reduction using a two-step braking profile

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Abstract— **In this paper, a new stopping approach used for residual vibration reduction of slightly flexible robot arms is presented. This technique, using two steps braking, is proposed for a wide class of mechantronic applications with structural flexibilities that demand high dynamic performance. This new method was validated experimentally on a slightly flexible robot used for medical imaging.**

I. INTRODUCTION

Vibration control in robotic applications is still an open topic that requires more R&D efforts to achieve convenient solutions for industrial applications [1]. Control of flexible structures was usually addressed for industrial applications demonstrating very slow vibrating modes such as flexible arms on space robots [2]. Yet, these solutions are only effective for slow dynamics control.

For industrial applications, the problem of vibration is solved using a notch filter to remove the undesired frequencies from the input reference. This technique gives conclusive results. Nevertheless, it is not very robust to parametric uncertainties. In this paper, we present a two steps braking approach that uses the *a priori* known vibrating behavior of the system to generate a braking profile so as to reduce the residual vibration. This approach was easy to implement, since it does not require additional sensors or actuators and implies minor software modifications. The "two steps braking" method was validated experimentally on the Innova robot used for medical imaging [3].

II. DESCRIPTION OF THE APPLICATION

The Innova cardiovascular robot (Fig. 1) is used for medical X-ray imaging. It is a 4 DOF open-chain robot composed of the following links: an L-arm: rotational joint, Pivot: a rotational joint, a C-arc: rotational joint and a Lift: prismatic joint.

In this paper, the pivot joint is used to illustrate the study. The flexibility observed on the pivot structure is modeled as a two-mass spring plant representing one vibrating mode. The plant dynamic is given by the flowing equation:

$$J_{PVT} \cdot \ddot{\theta} + d \cdot \dot{\theta} + k(\theta - \theta_m) + \Gamma_l(\theta) = 0 \qquad \textbf{(1)}$$

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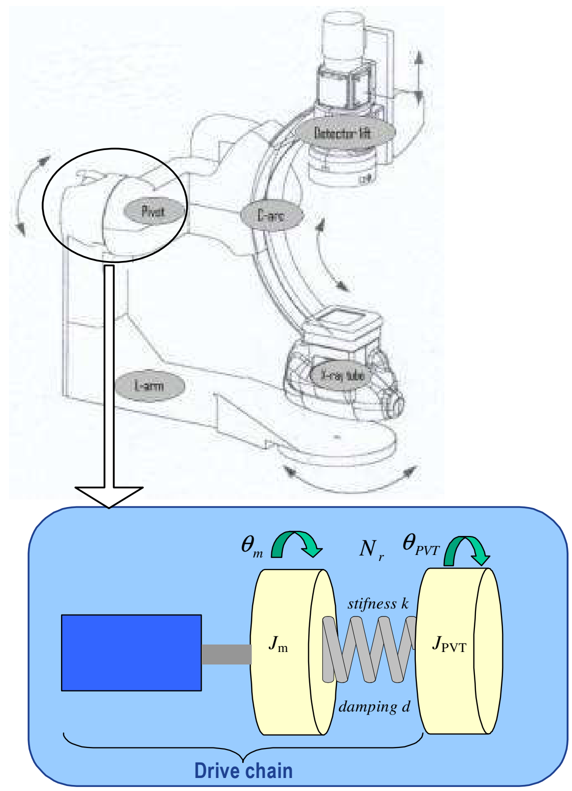

Fig. 1: Two-mass spring pivot model of the Innova Robot

where J_{pvt} the pivot inertia, k the joint stiffness, d the joint damping, θ the joint position, θ_m the motor position and Γ_l the load torque.

The variation of the load torque is very small during the stopping process. Thus, we can assume that it is a constant and thereby, it does not have an impact on the dynamic of the vibration. Consequently, the dynamic behavior of the plant can be expressed without load torque, as:

$$\frac{\theta}{\theta_m} = \frac{\omega_0^2}{s^2 + 2 \cdot \zeta \cdot \omega_0 \cdot s + \omega_0^2} \qquad \textbf{(2)}$$

where the identified parameters of this plant are:
$\omega_0 = 24.32\ rad/s = 3.87\ Hz$ and $\zeta = 0.02$

III. TWO STEPS STOPPING PROFILE

When stopping, the mechanism always vibrates at the same frequency regardless of the operating point:

$$f = f_0 \cdot \sqrt{1-\zeta^2} \approx f_0 \qquad \textbf{(3)}$$

In fact, the vibration is maintained due to the potential energy stored in the spring, given by:

$$U_0 = \frac{1}{2} k(\theta - \theta_m)^2 \qquad \textbf{(4)}$$

Therefore, the vibration can be considerably reduced when U_0 is minimized i.e. minimizing the difference between θ and θ_m. Actually, the two steps braking profile consists of generating a profile that minimize $(\theta - \theta_m)$ using the *a priori* known vibrating behavior of the system (2).

Hence, the braking of the joint motion is achieved through two actions. The first one is the classical braking while the second one is to minimize $(\theta - \theta_m)$ (Fig. 2).

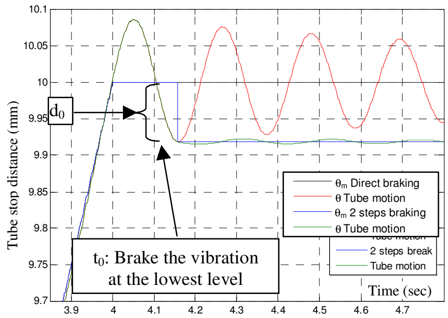

Fig. 2: Two steps braking strategy

The profile is tuned using the parameters "d_0" and "t_0" that will define the velocity profile. These parameters are optimized to get the best residual vibration reduction. The cost function of optimization algorithm was defined as the vibration amplitude one second after "t_0". The optimization algorithm is initialized at: d_0: the amplitude of the 2nd peak and t_0 : the moment of the 2nd peak.

The system requirements impose a stopping distance less than 10 mm measured at the tube tip. The best result was obtained using: $d_0 = 4.5$ mm and $t_0 = 0.1$ s.

IV. Simulation Resluts

The two steps braking profile showed a very good residual vibration reduction. Fig. 3 shows the trajectory of the tube tip when braking the pivot from 20°/s revolute motion.

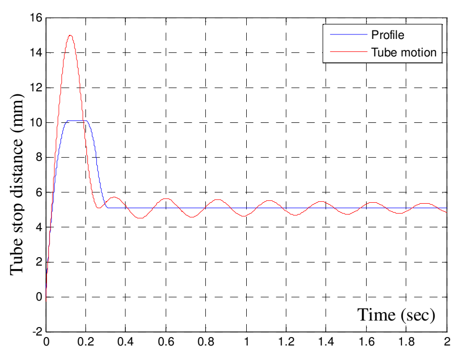

Fig. 3: Tube stopping trajectory, V_pvt : 20°/s, Stop distance : 10mm.

V. Robustness to Parameter Uncertainty

The two steps profile presented so far is optimized according to the identified vibrating mode. Figure 4 shows a comparison of the two steps braking profile along with a classic notch filtering of the input. It can be observed that the combination of both actions gives a very interesting result enhancing both the vibration reduction as well as the parametric robustness.

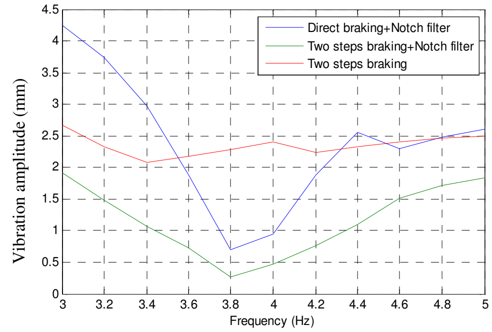

Fig. 4: Robustness to f_0 uncertainty, V_pvt : 20°/s, Stop distance : 10mm.

VI. Experimental Validation

The two steps braking profile was implemented on the Innova robot motion controller. The experimental results showed a significant reduction of the residual vibration after stopping. Figure 5 shows the impact of the residual vibration on the pixels shift of an X-Ray image.

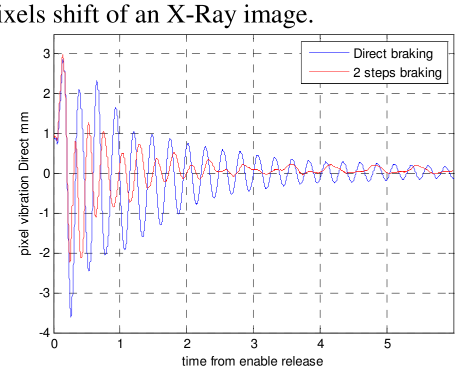

Fig. 5: X-Ray image pixel shift, V_pvt : 20°/s, Stop distance : 10mm.

VII. Conclusion

In this paper, we presented a braking approach aiming to reduce the residual vibrations on a flexible manipulator robot. This approach consists of braking the motion in two steps so as to dissipate the potential energy that maintains the vibration. This approach was validated in simulations as well as experimentally. Moreover, the robustness of this approach has been verified.

VIII. References

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