VIBRATION CONTROL OF MULTI-LINK ROBOT MANIPULATORS; PART I WITH RIGID LINKAGES

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ABSTRACT

Joint resilience is inherent in all mechanical structures with working joints. In case of multi-link robotic manipulators, joint resilience may cause undesirable oscillations of the end effector. These oscillations may persist for extended durations resulting in long idle periods between performing different tasks.

Numerical predictions are presented in this paper to demonstrate the effectiveness of a control technique in quickly attenuating excessive transient oscillations of a two-link arm. The technique is based on actively manipulating the joint resilience. It is effective. It is suitable to be implemented as an add-on controller and it requires minimal hardware. It is a stable control technique due to its being dissipative in nature.

1. INTRODUCTION

Industrial automation has significantly raised the expectations from the new generation robots in terms of both speed and accuracy. Most of the robots are powered at joints by electro-mechanical drives, consisting of DC or AC motors in series with other units such as harmonic drives, couplings and belt drives. Flexibility, which is always inherent in these units, produces oscillations. These oscillations may be caused either by interacting with surrounding objects or by stopping abruptly once a new positioning is completed. The result of such disturbances is to produce large amplitude transient oscillations. If not controlled effectively, these oscillations not only lead to end point positioning and tracking inaccuracies but also cause long idle waiting periods between tasks. Hence, controlling the vibrations of industrial robots with flexible joints is a problem of practical significance.

Over the past ten years, many methods have been proposed including joint torque feedback control, acceleration feedback control, adaptive control. Zhang et al. [1] described a basic method of disturbance rejection, and friction compensation in robots with flexible drive systems. The position control system consisted of a conventional semiclosed -loop proportional, derivative (PD) control plus joint torque feedback. While it is shown that joint torque negative feedback is effective on vibration suppression, the property of disturbance rejection deteriorates easily when a high gain joint torque feedback is used. Ider et al. [2] has shown that, in a flexible-joint robot, the acceleration level inverse dynamic equations are singular because the control torques do not have instantaneous effect on the end-effector accelerations due to flexibility. The drawback of the technique is the presence of jump changes in all states of the desired trajectory. Xi [3] also studied the trajectory control technique, this time with redundant flexible-joint manipulators. This method utilizes joint redundancy to minimize the change in the manipulator inertia so that a simple gain-fixed control law can be used. The technique requires two different control methods depending on whether the joint inertia is predominant increasing the complexity of control method. Adaptive control techniques can be helpful by tuning the controller gains to changing parameters where system parameters change significantly during the operations. Lim et al. [4] presented an adaptive partial state-feedback controller for a rigid-link flexible-joint robot. The controller compensates for parametric uncertainty while only requiring measurement of link position and actuator position. Ge [5] suggested another adaptive control technique based on singular perturbation theory and using only position and velocity feedback by modelling the motor tracking error (instead of the joint elastic force). Both the computational requirements and the number of feedback parameters can make adaptive control technique impractical.

One of the disadvantages of a full state feedback controller is requiring additional sensors for implementation. The inclusion of additional sensors to measure actuator
velocity, link position, and link velocity would certainly add to the cost and physical complexity of robotic systems. Performance of most of the vibration control techniques in literature for flexible-joint robot arms rely on a proper structural model. This need may cause difficulties since there is unavoidable simplifications in models. In addition, dynamics of a robot could change significantly by an operation such as picking up a payload or changing relative orientation of linkages. Therefore, it is very important to use a vibration control technique whose performance is relatively independent from the system parameters.

In this paper the “Variable Stiffness Control” technique has been used to attenuate the vibrations of two link robot arm with flexible joints. The technique is based on manipulating the joint resilience (which is inherent to a certain degree) in the structure. Its performance is relatively independent of system parameters. It is a stable control technique due to its being dissipative in nature [6-g]. The technique is suitable to be implemented as an add-on controller and it requires minimal hardware.

The proposed controller was used in an earlier study [9] using only one actuator at the elbow. The primary concern of this paper is to extend the earlier application to two actuators and to present new performance data.

2. NUMERICAL MODEL

2.1 Variable Stiffness Control Technique

Only a brief description of the Variable Stiffness Control technique (VSC) will be presented here. More detailed information may be found in Reference [7].

![Figure 1: Undamped oscillator with Variable Stiffness Control.](image)

The undamped oscillator shown in Figure 1, has two parallel springs, a passive spring with a stiffness of K-ΔK and an active spring with ΔK. Effective stiffness of the system is K when the clamp of the active spring is applied, and K-ΔK when the clamp is released. The Variable Stiffness Control technique is based on changing the stiffness of the system between these two states at instances when it is most beneficial for control. In Figure 1, M represents the mass of the oscillator, coordinate x indicates the absolute displacement.

Initially, the active spring is clamped producing the full stiffness K. After applying a transient disturbance to start oscillations of the system, the active spring is kept clamped until the instant of peak displacement X₀. At the instant of peak displacement, the active spring is unclamped. This unclamping causes the active spring to assume its undeformed position instantly since it has no inertia. Therefore, all the potential energy stored in the active spring is dissipated by this actuation. If the clamp is applied back before the system has a chance to move from its maximum displacement position, the original full stiffness of K is recovered. But, now the total energy of the system is reduced by the amount dissipated through the actuation of the clamp.

Along with this dissipated energy, the active spring is now in an undeformed state when the clamp is re-applied while the oscillator is still displaced by X₀ from its original equilibrium position. Hence, the control action produces a second effect with its shifted equilibrium of the active spring. The shifted equilibrium position imposes a constant restoring force of amplitude ΔKX₀ to oppose the velocity of oscillations, similar to a case of Coulomb friction.

![Figure 2: Force-displacement graph of the system in Figure 1.](image)

The effect of the control action may be shown clearly in the force-displacement diagram in Figure 2. Oscillations start at the origin when the external disturbance is imposed and follow State 1 with full stiffness K until the maximum displacement X₀. At X₀, the active spring is unclamped and the system jumps from “a” to “b”, into State 2 with an effective stiffness of K-ΔK. When the active spring recovers, the effective stiffness again becomes K and oscillations resume in State 3. Potential energy dissipated by the control action is represented by the area of the trapezoid bounded by States a, b and the two parallel lines representing the full stiffness K (States 1 and 3) in the first quadrant. The equilibrium shift that produces the constant restoring force is the result of shift in the state of the system from State 1 to State 3. The shifted equilibrium position will be at a smaller displacement amplitude for the second and following actuations of the control, eventually leading to zero displacement offset when oscillations cease.
diminish. Also, it may be shown that the most effective control of transient oscillations are obtained when the stiffness ratio between the active and the full stiffness, \( \Delta K/K \), is 0.5. \( \Delta K/K=0.5 \) leads to elimination of oscillations within half a cycle and with only two actuations [7].

It is important to note that the Variable Stiffness Control is always dissipative. An actuation never results in addition of energy to the system. Therefore, the control technique is unconditionally stable for a lumped parameter oscillator.

2.2 Model

Figure 3 shows the model investigated in this paper. The arm consists of two rigid beams. Link-2 is attached to Link-1 at elbow, and Link-1 is attached to base with pin joints. Two parallel torsional springs at elbow and base represent active and passive springs similar to the single degree-of-freedom model explained in Section 2.1.

![Figure 3: Model of a two-link flexible arm when the linkages are (a) aligned and (b) bent by \( \alpha \).](image)

The passive springs, \( K_{\text{base}}-\Delta K_{\text{base}} \) and \( K_{\text{base}} \), represent a compliant elbow and base joints while the second torsional springs, \( \Delta K_{\text{elbow}} \) and \( K_{\text{base}} \), model the active springs of the controller. Torsional viscous dampers provide a model for frictional dissipation at joints which are not shown in the figure for clarity. Structural damping of 0.5% critical damping for the first two modes is also included in the model to represent inherent energy dissipation[10]. The arm is assumed to move in horizontal plane. Lumped masses located at the tip, \( M_{\text{tip}} \), and at the elbow, \( M_{\text{motor}} \), model the payload and motor mass. Rotary inertia effects of these masses are neglected. Mass of the base actuator is assumed to be a part of the fixed base.

2.3 Numerical simulations

Several simplifying assumptions have been made in the numerical model. First, only small oscillations are assumed. Secondly, to avoid the time varying system matrices, elbow angle is set to a specific value before the system is excited. Finally, initial conditions are assumed to be zero. The results for the numerical simulations have been obtained using MATLAB [11].

First, the program produces the global matrices using the standard finite element method with the parameters shown in Table 1 [12]. These parameters have been selected similar to those in an earlier study [9]. Then the numerical integration is performed using the Newmark-\( \beta \) scheme summarised in Craig [13].

Each actuation at elbow and/or base, depending on performing single or dual control action, is performed similar to the single degree freedom system explained in Section 2.1. Actuation points are determined by monitoring relative angular velocity at joints. An actuation is performed in the time step immediately following a sign change in the relative angular velocity. The effect of an actuation in the numerical process, is to apply a constant resisting torque at the elbow and/or the base, after a peak relative angular displacement. This constant torque is kept until the next sign change occurs in relative angular velocity. The magnitude of the torque in each actuation is determined from the product of the relative angular displacement at that instant and the active stiffness coefficient, \( \Delta K \).

<table>
<thead>
<tr>
<th>Table 1. Two link-arm parameters used for simulation.</th>
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<tbody>
<tr>
<td><strong>Arm parameters (same for both links)</strong></td>
</tr>
<tr>
<td>LENGTH, L</td>
</tr>
<tr>
<td>WIDTH OF BEAM, b</td>
</tr>
<tr>
<td>THICKNESS OF BEAM, h</td>
</tr>
<tr>
<td>BENDING STIFFNESS OF BEAM, E</td>
</tr>
<tr>
<td>MASS/LENGTH OF BEAM, m</td>
</tr>
<tr>
<td>NUMBER OF FINITE ELEMENTS SELECTED FOR EACH LINK</td>
</tr>
<tr>
<td><strong>Other parameters</strong></td>
</tr>
<tr>
<td>TIP MASS, ( M_{\text{tip}} )</td>
</tr>
<tr>
<td>ACTUATOR MASS, ( M_{\text{motor}} )</td>
</tr>
<tr>
<td>PASSIVE ELBOW STIFFNESS, ( K_{\text{elbow}}-\Delta K_{\text{elbow}} )</td>
</tr>
<tr>
<td>ACTIVE ELBOW STIFFNESS, ( \Delta K_{\text{elbow}} )</td>
</tr>
<tr>
<td>PASSIVE BASE STIFFNESS, ( K_{\text{base}}-\Delta K_{\text{base}} )</td>
</tr>
<tr>
<td>ACTIVE BASE STIFFNESS, ( \Delta K_{\text{base}} )</td>
</tr>
<tr>
<td>EQUIVALENT VISCOUS DAMPING RATIO-STRUCTURAL</td>
</tr>
<tr>
<td>ELBOW VISCOUS DAMPING COEFFICIENT</td>
</tr>
<tr>
<td>BASE VISCOUS DAMPING COEFFICIENT</td>
</tr>
</tbody>
</table>

Simulations start with a tip disturbance of \( 5\sin(\omega t) \) that represents an impact of the arm with its environment. This impact is a half sinusoid which is always perpendicular to the tip of the link-2. \( \omega \) is the fundamental frequency of the
Since the very first peak of relative elbow and/or base angle has the largest absolute value, the very first actuation will have the highest corrective torque applied in the numerical simulations. Therefore, the first actuation has a high significance over the effectiveness of the control. For this reason, a delay is implemented in the numerical process to avoid premature first actuation. If there is a sign change in angular velocity they are ignored until a quarter of fundamental period is reached. All the simulations run for two seconds which is, in most cases, sufficient to observe a settling time. Setting time is assumed when the tip displacement amplitudes decay below 0.001 m.

2.4 Results

The numerical simulations have been performed for different elbow angles, \( \alpha \), of 0°, 30°, 60°, 90°, 120° and 150° but not all could be included in this paper because of the space limitations. Histories of the tip displacement for uncontrolled (---), only-elbow (-----) and only-base controlled (- - - - - -) cases are shown in Figure 4(a) and 4(b) for elbow angles, \( \alpha \), of 0° and 90°. In Figure 4(a) and 4(b), x-axis represents the time and, y-axis the tip displacement. All the tip displacements presented in graphs are in the local co-ordinates, along the axis perpendicular to the tip of link-2.

As the arm folds in, the maximum displacement amplitudes decrease from around 0.03 m for 0° to around 0.01 m for 150°. In addition, the fundamental frequency of oscillations increase, as presented in Table 2, from 18.44 rad/s to 35.26 rad/s for the same angles. The reason for this behaviour, of course, is the increase in the apparent stiffness of the arm when it changes from a straight open arm to a folded one. Nevertheless, in this frequency range, the integration step of 0.00125 has been found to be small enough to perform the numerical simulations.

Table 2. Natural frequencies of the system for different elbow angles.

<table>
<thead>
<tr>
<th>Elbow angle</th>
<th>( \omega_1 ) (rad/s)</th>
<th>( \omega_2 ) (rad/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>18.44</td>
<td>86.97</td>
</tr>
<tr>
<td>30°</td>
<td>19.00</td>
<td>75.47</td>
</tr>
<tr>
<td>60°</td>
<td>20.66</td>
<td>58.28</td>
</tr>
<tr>
<td>90°</td>
<td>24.11</td>
<td>49.91</td>
</tr>
<tr>
<td>120°</td>
<td>29.80</td>
<td>40.55</td>
</tr>
<tr>
<td>150°</td>
<td>35.26</td>
<td>40.64</td>
</tr>
<tr>
<td>180°</td>
<td>35.04</td>
<td>45.74</td>
</tr>
</tbody>
</table>

In a wide range of elbow angles, base controller cases show more effectiveness over the elbow controller cases. But, as the arm folds in, the effectiveness of the elbow control over the base control becomes clearer. Especially for 150° elbow angle, only-base control becomes ineffective by giving almost same performance of the uncontrolled case. This is not surprising, considering the fact that as the arm folds in, most of the energy will be stored between the elbow and the tip of the arm after the tip impact occurs. As a result, the deflections between the elbow and the tip will be higher than those between the elbow and base. Higher amplitude means higher corrective torque, which will result in more effective control.

In an identical format to that in Figure 4, results of the simulations with a dual controller (-------) are presented in Figure 5. Improvement is clear in almost all cases, especially at higher elbow angles around 150°. The settling time is less than 0.6 sec. at almost all the elbow angles. As mentioned before, settling time is assumed when the tip oscillations' amplitudes decay below 0.001 m. With this definition, uncontrolled settling time is about 13 seconds at 0° elbow angle due to the poor inherent energy dissipation. Hence, dual control action at this angle shows about 22 times (95%) faster attenuation than the uncontrolled case.

Earlier results in Figures 4 5 were run with 0.5 stiffness ratio for both base (\( \Delta K_{base}/K_{base} \)) and elbow (\( \Delta K_{elbow}/K_{elbow} \)). To investigate if this assumption is a good compromise for dual control, simulations have been performed and presented in surface graphs in Figures 6 and 7. In all simulations, same parameters have been used from Table 1. Firstly, in Figure 6, simulation results are given to investigate the best stiffness ratio for the elbow at different elbow angles by keeping the base stiffness ratio, \( \Delta K_{base}/K_{base} \), at 0.5. The horizontal axis (x-axis) represents the time, the depth (y-axis) represents the elbow stiffness ratio, and the vertical axis (z-axis) represents the tip displacement. With dual control, effectiveness of control becomes almost insensitive to the change of elbow stiffness ratio which was not the case for single-elbow controller. Any elbow stiffness ratio between 0.1 and 0.9, with the constant base stiffness ratio of 0.5 can produce effective control. Effectiveness of control is at its best between around 0.4 and 0.6. When the elbow stiffness ratio approaches 0.9, number of cycles decreases but settling time increases due to too significant stiffness changes at each actuation.

Similarly, simulations have been performed to investigate the best stiffness ratio for the base, for different elbow angles, this time by keeping the elbow stiffness ratio, \( \Delta K_{elbow}/K_{elbow} \), at 0.5. These simulations are presented in Figure 7 in an identical format to that in Figure 6. It can be concluded that around 0.5 elbow stiffness ratio, along with 0.5 base stiffness ratio, will be a good compromise.

The results show that dual control is more effective than single controller in a wide range of stiffness ratio combinations making it insensitive to stiffness ratio variations. Still it can be noted that best stiffness ratios are around 0.5.
Figure 4: Tip displacement histories of uncontrolled (---), only-base controlled (.-.-.-.) cases for different elbow angles of (a) $\alpha = 0°$, (b) $\alpha = 90°$.

Figure 5: Same as in Figure 4 but for dual control.
Figure 6: Tip displacement histories for varying $\Delta K_{\text{elbow}}/K_{\text{elbow}}$ but for constant $\Delta K_{\text{base}}/K_{\text{base}} = 0.5$ and for different elbow angles of (a) $\alpha = 0^\circ$, (b) $\alpha = 90^\circ$.

Figure 7: Same as in Figure 6 but for variable $\Delta K_{\text{base}}/K_{\text{base}}$ and constant $\Delta K_{\text{elbow}}/K_{\text{elbow}} = 0.5$. 


3. CONCLUSIONS

Performance of most of the vibration control techniques for robots with flexible-joints, rely on a proper dynamic model. This need may cause difficulties since there is unavoidable simplifications in models. In addition, dynamics of a robot could change significantly by an operation such as picking up a payload or changing relative orientation of linkages. Therefore, it is very important to use a vibration control technique whose performance is relatively independent from the system parameters. In this study, the variable stiffness control (VSC) is suggested to be such a technique. Numerical simulations suggest that the control is effective and relatively insensitive to parameter variations. The next stage of this investigation is to implement the control experimentally.

REFERENCES


