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Implementing Modified Command Filtering to Eliminate Multiple Modes of Vibration

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Abstract

The requirements for large robots in waste management and space applications necessitate active vibration control algorithms. The use of long, flexible links provides the needed range of motion but their inherent flexibility can generate undesirable vibrations making both control and endpoint positioning difficult. This paper presents two shaping algorithms, the impulse shaping method and the modified command filtering technique, to eliminate the first two modes of vibration in a flexible manipulator. The vibration suppression capabilities are demonstrated using a large elliptic trajectory that produces a significant change in the system properties of the two-link robot. The acceleration response of the tip of the manipulator provides a means of comparison for the different shaping algorithms.

Introduction

To obtain the required high positioning accuracy from large, flexible manipulators, the unwanted residual vibration must be removed from the tip motion. This can be achieved using a variety of active and passive control techniques. Passive methods are not able to control the distribution of energy and usually involve constraining the motion of a given system. Some common passive methods involve the application of a thin layer of visco-elastic film that absorbs kinetic energy or using piezo-resistive films to resist beam deflection. Active control techniques are able to distribute quantities of energy and usually involve the measurement of system states and the resulting control efforts based on them. This research will discuss active shaping techniques to prevent residual vibration from occurring in a two-link, flexible manipulator.

The first shaping algorithm called impulse shaping was developed by Singer and Seering [7,8]. Their method utilizes linear superposition of second-order system impulse responses to prevent residual vibration in the system. They developed a set of nonlinear, trigonometric constraint equations that must be solved to yield the appropriate amplitudes and starting times of the impulses that eliminate the vibration. Their method is actually a time-domain realization of a notch filter that places multiple zeros at the pole locations of the second-order system.

Singhose, Seering and Singer [9] extended the impulse shaping idea with a vector diagram approach. Using vector addition, many different impulse combinations are possible to eliminate the residual vibration in the system. The sensitivity of the method to errors in natural frequency was also discussed and can be adjusted by moving the impulse vectors. Hyde and Seering [2] extended the impulse method to solve the nonlinear constraint equations for three modes of vibration. Their work showed the difficulty in solving the set of equations and demonstrated ways to optimize the problem.

Other researchers have since used the active control algorithm for a variety of flexible arm control applications. Hillsley and Yurkovich [1] applied the shaping technique for the vibration control in large angle slewing maneuvers of a two-link flexible robot. However, they found that endpoint acceleration feedback was also required to fully damp the vibration in a system with varying parameters. Zuo and Wang [10] used the impulse shaping method in a PD feedback control system with good success. The shaping algorithm was able to reduce the vibration in the flexible link while the PD routine positioned the tip of the manipulator.

Variations of the impulse shaping technique have recently appeared for controlling multiple modes of vibration and for adapting to changes in system frequencies within the workspace. Rappole [6] investigated an extrapolation method to accommodate changes in system parameters. By splitting each impulse into two impulses placed at adjacent discrete-time locations of the control system, impulse sequences can vary continuously with changes in frequency. Magee and Book [3,4] developed a modified command filtering method that in effect double filters the desired sample to allow time variations of the system parameters. Using the modified filtering method in a feedback manner, the first mode of vibration in a two-link, flexible manipulator named RALF (Robotic Arm, Large and Flexible) was eliminated. The method was extended to eliminate two modes of vibration using the same manipulator for small variations in system parameters [5]. The current work will demonstrate the vibration suppression abilities of the modified filtering method over a large portion of the manipulator's workspace and compare the method to the impulse shaping algorithm of Singer and Seering.

Impulse Shaping

To understand the modified command filtering method, a short description of the impulse method is needed. Since the method involves the impulse response of a second-order system, the first term in the filter is an impulse. Using the definition of the logarithmic decrement, the next impulse is placed at one-half the damped natural period of the system with a reduced amplitude corresponding to the logarithmic decrement. The two-term filter takes the form

$$\hat{H}_2(s) = 1 + e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}} e^{-s\frac{\pi}{\omega_n\sqrt{1-\zeta^2}}} \tag{1}$$

which can then be normalized so that the coefficients sum to one. This normalization ensures that the output of the filter is not larger than the input. The normalized filter can be written as

$$H_2(s) = \frac{1}{1+M} + \frac{M}{1+M} e^{-s\frac{T_d}{2}} \tag{2}$$

where M is the logarithmic decrement and T_d is the damped period of the system.

To improve the robustness to uncertainty in system parameters, the order of the filter can be increased. According to Singer and Seering, this involves solving a larger set of nonlinear equations. However, this difficult solution process is not required. Careful study of the method reveals that this shaping algorithm places zeros of the filter at the pole locations of the system. Therefore, to increase the robustness of the filter, multiple zeros are placed at the poles. The shaping filter takes an iterative form and can be written as

$$H_N = (H_2)^{N-1} \tag{3}$$

where N is the number of terms in the filter. The number of terms in the filter is determined by the amount of residual vibration error that can be tolerated by the application and is discussed in [3]. In general, the N term filter can be written as

$$H_N(s) = \sum_{i=0}^{N-1} A_i e^{-i\cdot s\frac{T_d}{2}} \tag{4}$$

with the A_i corresponding to the coefficients of the delay terms in the filter. The filter can now be transformed into the discrete-time domain

$$h_N[n] = \sum_{i=0}^{N-1} A_i \delta[n - i \cdot deln[n]] \tag{5}$$

where $deln[n]$ is the discrete-time period of the flexible system. The discrete-time period can be calculated from the damped period of the system using the following transformation

$$deln[n] = int\left(\frac{T_d}{2} \cdot f_s\right) \tag{6}$$

where f_s is the sampling rate of the control system and the $int(\cdot)$ function truncates the argument to an integer. Notice that the discrete-time period is a function of time which generates a problem for the impulse shaping method.

Modified Command Filtering

The modified command filtering technique is a time-varying filter that allows for variations in the system parameters. The discrete-time form of this new filter is

$$h_N[n] = \sum_{i=0}^{N-1} A_i \langle \delta[n - i \cdot deln[n]] + (deln[n] - deln[n-i]) \cdot \delta[n - i \cdot delns[n]] \rangle \tag{7}$$

where the minimum discrete-time period over the finite sum of terms is defined as

$$delns[n] = \min(deln[n], \ldots, deln[n-N+1]). \tag{8}$$

For this filtering scheme to work properly, the change in discrete-time period is limited to ± 1 over this short range of values. This filter ensures that each discrete-time sample of the steady-state output contains the correct sum of index coefficients and produces a continuous output as the system parameters vary with time. A more detailed discussion can be found in [3].

The modified command filtering idea can be expanded to filter two modes of vibration in a time-varying system. The N^2 term, two mode modified command filter can be written as

$$\begin{aligned} h_{2N}[n] = \sum_{j=0}^{N-1}\sum_{k=0}^{N-1} A_{1j} A_{2k} \cdot \\ \langle \delta[n - j \cdot deln_1[n] - k \cdot deln_2[n]] + \\ (deln_1[n] - deln_1[n-j] + deln_2[n] - deln_2[n-k]) \cdot \\ \delta[n - j \cdot delns_1[n] - k \cdot delns_2[n]] \rangle \end{aligned} \tag{9}$$

where the subscripts '1' and '2' denote the corresponding mode numbers. The limitation on the amount that each discrete-time period can change still holds and an additional constraint that only one discrete-time period can change over the finite sum of terms is also imposed. This constraint is not as demanding as it might appear since the filter makes a complete transition in just $N - 1$ samples of the filter which is a very short duration in time for control systems with reasonably fast sampling rates.

Now that the two mode modified command filter has been presented, it can be implemented in a feedback control structure to eliminate the residual vibration of the two-link, flexible manipulator called RALF.

Feedback Control Structure

To eliminate the vibration and allow accurate endpoint positioning, the shaping algorithms are applied to the error term in a feedback control system. Figure 1 shows a block diagram of the overall controller that provides active vibration suppression in RALF.

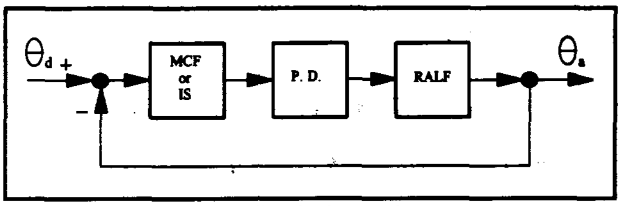

Figure 1. Shaping-Feedback Control System

This application of the shaping filters differs from the one originally proposed by Singer and Seering. Their implementation filtered only the desired trajectory signal with the addition of a feedback control system after the shaping filter. This method requires knowledge of the effective damping ratio and damped natural frequency because of the feedback system.

The new implementation allows for direct use of experimental data taken with a digital Fourier analyzer. The damped natural frequency and damping ratio were parameterized as a function of joint configuration for accurate calculations of system parameters for the shaping algorithms. As the manipulator tracks the desired trajectory, the parameters can be calculated for each new configuration. The maximum error in the parametrization is nearly 20% for the calculation of damped natural frequency which results in a four-term filter used for each mode of vibration.

Desired Trajectory

To compare the shaping algorithms and allow for a fair comparison, a test trajectory containing specific frequency components was generated. The desired trajectory is an ellipse with a major axis length of nearly 16 ft. and a minor axis length of nearly 6 ft. so that a large variation in system parameters occurs. The variation is from 3.27 Hz to 5.95 Hz in the first damped natural frequency and from 8.88 Hz to 10.83 Hz in the second damped natural frequency. The percent deviation from the average values of frequency is about 30% for the first mode and about 10% for the second mode. This information will prove valuable when evaluating the experimental results in this paper. For completeness, a variation in damping ratio was also observed but the unreliability of the measuring technique used by the analyzer makes this data suspect.

To artificially excite the manipulator, two sinusoidal components with frequencies near the average of the first two modes are added to the normal component of the ellipse. The desired trajectory is shown in Figure 2 and the added sinusoidal components are very apparent. This test trajectory is obviously a worst case scenario and is used only to demonstrate the effectiveness of the shaping algorithms.

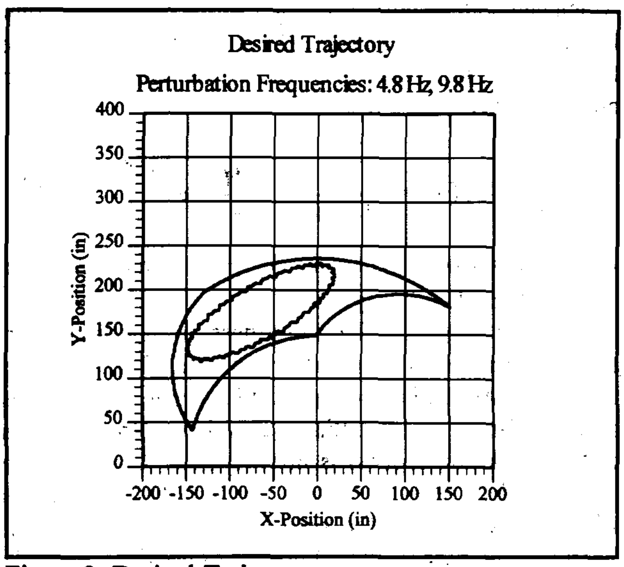

Figure 2. Desired Trajectory

Experimental Results

The first experiment shows the acceleration response at the tip of the manipulator when just the PD control routine is used to follow the desired trajectory. Figure 3 shows the frequency response of an accelerometer mounted at the tip of RALF. The spectrum of the vibration was calculated based on 10 averages of the acceleration response taken over one cycle of the ellipse. Notice the first two major peaks that occur at the first and second damped natural frequencies of the system. They are very broad signifying a large change in natural frequency due to the configuration changes of the manipulator. The results using the modified command filtering technique are also shown to give a relative measure of the acceleration response.

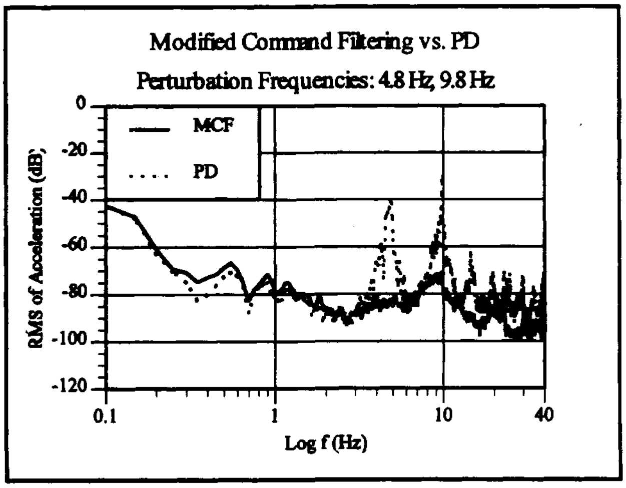

Figure 3. PD Comparison

The next comparison shows the problem with the impulse shaping method if the discrete-time period is allowed to vary with time. The impulse method will actually induce a vibration into the system because each sample of the filtered trajectory does not contain all the indexed terms. Gaps are produced in the filter output and have been verified in [3]. Figure 4 shows this frequency response comparison. Notice that two vibrations are also induced at 20 Hz and 40 Hz that are beyond the control bandwidth of the actuators.

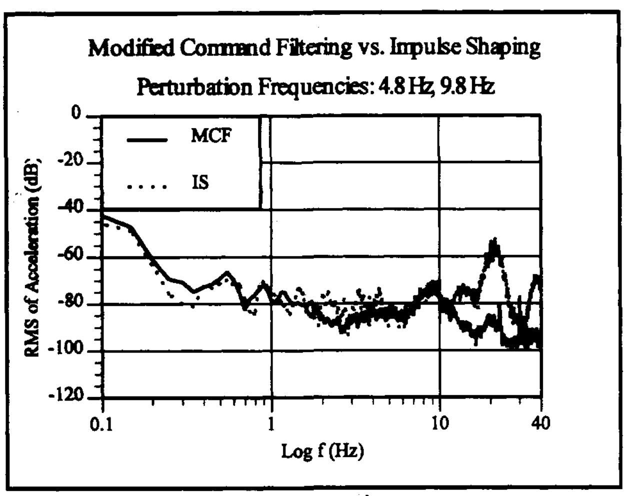

Figure 4. Time-Varying Comparison

For practical applications, the impulse method should not be implemented using time-varying parameters. A more realizable approach is to use some fixed value of damped natural frequency. The first comparison uses the lower frequency bound for each mode of vibration (3.27 Hz, 8.88 Hz) and average values for the damping ratio. Figure 5 contains this frequency response comparison. The results are not too surprising

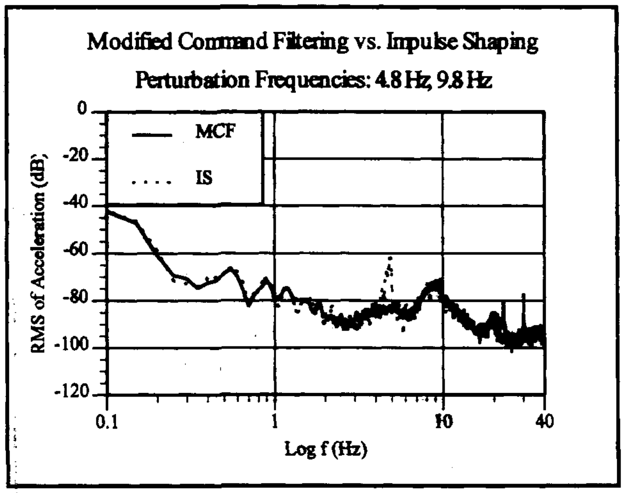

Figure 5. Lower Frequency Comparison

since there is nearly 47% error in the first mode. At the frequency range of the first natural frequency, a vibration occurs at a frequency corresponding to the first sinusoid added to the ellipse. There is no vibration in the second frequency range because the error in the second mode is within an allowable range specified by the vibration error curves [7,8]. However, notice that no vibration results when the modified command filtering technique is used because it can adapt to any variation in natural frequency.

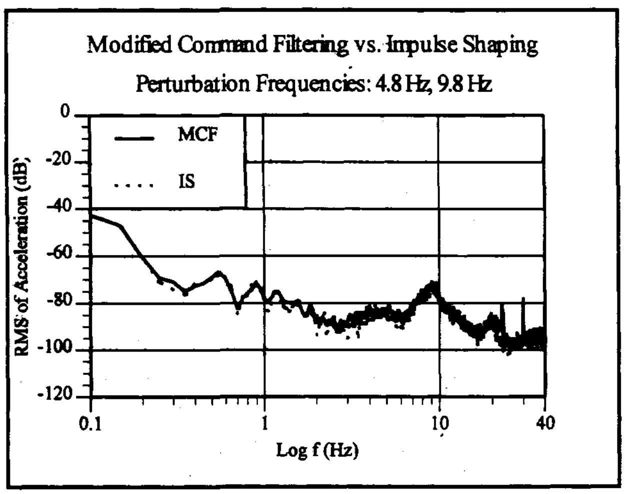

Figure 6. Average Frequency Comparison

The impulse shaping method can produce results comparable to the modified command filtering technique when average values of the damped natural frequencies are used (4.61 Hz, 9.855 Hz). Figure 6 compares the two shaping algorithms for this scenario. The results are the same since the error in system parameters is within tolerable ranges specified by the amount of acceptable vibration error.

The last comparison between the two shaping methods is shown in Figure 7 using the upper frequency bound for each mode of vibration (5.95 Hz, 10.83 Hz). Again, a low frequency vibration results when using the impulse shaping method due to the error in the design frequency for the method (20%). However, the amplitude of the peak in the frequency response is not as large as before since the error is smaller. Again, the modified command filtering method can adjust to changes in system configuration and prevent the residual vibration.

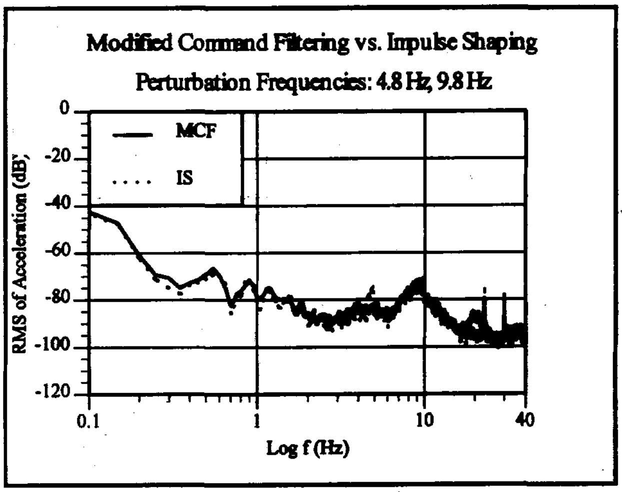

Figure 7. Upper Frequency Comparison

Conclusions

The suppression of the first two modes of vibration in a two-link, flexible manipulator was presented using two different shaping algorithms. The impulse shaping method was shown to induce vibration in the flexible system if the discrete-time period was permitted to vary with time. However, it produced more favorable results when fixed values for the system parameters were used. The method is still limited in applicability for time-varying systems because the variation in system parameters is limited to about 10%. The modified command filtering technique, on the other hand, could adapt to the large variations in parameters and prevent any residual vibration.

Future work will include development of a more universal filtering technique without restrictions on the number of or amount in which the discrete-time periods can change. The filtering technique will also be more robust to variations in payload that can produce large variations in system parameters.

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