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PREFILTERS IN THE CONTROL OF MECHATRONICS SYSTEMS

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Abstract: *Many mechanical applications need a way to reduce or eliminate the mechanical vibrations that may appear if the reference signal modifies suddenly. Due to the tuning of the controller, the new reference can be obtained by an aggressive control, which leads to vibrations or a slow response, which leads to the increase of the response time. A solution that allows both vibration elimination and a fast response time is using pre-filters. The area of applications is large: cranes, manipulators, automated machinery etc.*

Key words: *Mechatronics systems, prefilter, input shaping, trajectory generation, optimization.*

1. INTRODUCTION

Mechatronic systems [1], [2] are systems that bound actuators, sensors, mechanical and control system design. By bonding all these aspects in the design process, superior control performances can be obtained than if we take each aspect individually. This definition of mechatronic systems engulfs a vast area, such as robots, linear motors, airplanes, vehicles etc. By linear approximation of nonlinear dynamics (e.g. friction) many of these systems can be represented through linear time invariant models (LTI), models with linear system dynamics.

For these systems three control problems can be defined. First we highlight the tracking control, which defines the trajectory in state space, coordinates of the trajectory in time and performance criteria for the accuracy of the trajectory. Another situation is tracking the trajectory in state space, but not having restricts regarding coordinates of the trajectory in time. These controllers can be optimized in terms of parameters such as: minimum time trajectories, energy consumption, achieved accuracy. Another situation is based on getting to and keeping a reference without specifying trajectory path conditions (classical adjustment problem). In this case the controller can be optimized in set time, overshot, consumed energy or other constraints.

Many of these mechatronic systems are still controlled using traditional closed loop control methods such as PID (Proportional Integral Derivative control) tuned with empirical techniques such as Ziegler-Nichols. The main disadvantage of these linear controllers is that they cannot take into consideration easily the constraints on inputs, outputs, states. However, regarding the tuning problems where minimization of the set time has to be achieved in terms of constraint on the input signal, these systems don't work well. To obtain optimal performances regarding the time there are numerous approaches: pre-filters for filtering the reference signal to eliminate the oscillations induced by the eigenvalues of the system, trajectory generators which replaces the reference signal (if there's a jump) with a smoothly variation signal that leads to highly reduced vibrations (oscillations).

2. INPUT SHAPING APPROACH

The "Input sharping" pre-filters [3] allows the implementation of a filtering technique that transforms a step reference signal in a smooth linear trajectory of the reference, so that it can be obtained without having residual oscillations, minimizing the set time. The original filter in a time continuous filter performing a combination of a step signal and a finite impulse response filter, where pulse amplitude and position are determined analytically based on the equation of oscillations of a 2nd order system. The impulses are chosen so that the dominant poles of the 2nd order system are compensated (which eventually approximates the mechatronic system). To obtain the shortest set time, the length of the pre-filter is minimized, meaning the position of the last impulse in FIR filter is placed as early as possible. In the original design only positive impulses are allowed, thus guaranteeing the input constraint satisfaction if the unfiltered reference signal satisfies the input constraints. However, this basic approach is sensitive in modeling errors and has the disadvantage of a long filter length.

To reduce the set time of the filters, many variants allow negative impulses [4]. This significantly reduces the filter length (meaning the last impulse position) thus the set time. However, in contrast with the design based only on positive pulses, the input constraints satisfaction is not guaranteed for all step signals which for unfiltered signal do not lead to saturation. Also, robustness decreases compared with the use of only positive impulses. Therefore the effect of saturation and other nonlinearities is analyzed and can be shown that these effects can be diminished [5], [6] by limiting the allowed region or reference signal preconditioning. These introduce conservative effects and non-saturation preconditioned references as well. Other extensions lead to improving the set time by incorporating knowledge on step signal reference amplitude, by designing a closed loop controller that takes into account the filter, by solving an analytical extended problem for all the modes simultaneously. However the optimization problem increases exponentially and is non-convex.

Concerning the robustness, the pre-filters are highly sensitive on the eigenvalues of the system, which means that if the eigenvalue of the system is slightly different from the nominal eigenvalue used in the filter design, then the system still has vibrations if the ζ amortization coefficient is small even if reference signal is pre-filtered. Usually, robustness in terms of parameter uncertainty is expressed through sensitivity curves. These curves show the residual vibration system level for a pre-filtered step signal depending on a normalized parameter.

Concerning the pre-filters, this sensitivity is expressed usually based on the natural frequency of the system function. To introduce robustness, the sensitivity curve has to have small values for the whole set of natural frequencies. This robustness can be obtained by imposing supplementary local and global constraints for the sensitivity curve. Locally, designing the pre-filter may impose the derivative curve of sensitivity (not only the constraints on the sensitivity curve values) which can locally reduce the curve sensitivity, technique implemented in ZVD pre-filter (zero vibration derivative)[7].

3. TRAJECTORY GENERATION

Because applying a pure step jump to the reference signal leads to residual vibrations, these jumps can be replaced by slow modification of the reference trajectory which reduce or even eliminate these vibrations. It must be specified that the purpose of a control system is to get the system to the wanted reference. Therefore often the followed trajectory is not important, which leads to a certain degree of freedom in choosing the path. So, a trajectory generator can replace a step jump with a signal that has same start and end values but which avoids jumps by imposing constraints on the derivate.

One of the reference trajectory frequently used is using a trapezoidal profile for speeds, meaning accelerating linearly to the top speed and in the final phase decelerating to zero speed. These profiles generate residual vibrations dough, due to discontinuities [8].

Therefore, more advanced approaches were proposed, where the so called S curves are used, applying trajectories based on superior polynomial functions, e.g. a ramp profile is imposed to the acceleration, not to the speed profile. The residual vibrations can be minimized by selecting an optimal growing ramp, based on the assumption that the system can be represented as a dual spring-mass system. Asymmetrical trajectories may be used with a more fast acceleration and a slower deceleration which can short the set time [9].

Instead of using polynomial functions, in [10] they used a reference trajectory based on sine functions tuned to the natural system frequency. Thus more robust trajectories are generated useful in non-linear resonance frequency change systems. This technique limits only the speed, acceleration and possibly the high derivate of the reference trajectory. Constraints on input cannot be taken into consideration directly. Moreover, minimizing the set time is just approximated by using line trajectories leading to reduced vibration and overshot.

Note that advanced off-line design approach permit imposing of some constraints on the input and can generate truly time optimal trajectories. In [11] a reference trajectory is designed, defined by a polynomial function. The polynomial coefficients are optimized by solving a linear matrix inequality (LMI). Growing the polynomial degree, constraints on the inputs and outputs can be imposed.

A disadvantage on each approach is the fact that none can take into consideration directly the constraints on the input. Moreover, minimizing the set time is not imposed directly; these approaches are usually based on the smoothness of the reference trajectory and at most can guarantee the time optimal in several low order systems such as a series of pure integrators.

4. SIMULATION EXAMPLE

Considering a linear system described by the following equation:

$$\begin{gathered} y(t)=-a_1y(t-1)-a_2y(t-2)-a_3y(t-3)+ \\ b_1u(t-1-d)+b_2u(t-2-d)+b_3u(t-3-d) \end{gathered} \tag{2.2}$$

Where: y[.] is the output and y_r is the reference signal;

-u[.] is the control system, 0≤ u[.] ≤ 250;

-A[.]=[1 -2.43492 1.97629 -0.53468];

-B[.]=[0.000948 0.00443818 0.001296496];

- gain factor is 1 and dead time is d=1

A solution to avoid the oscillations in step reference signal is to replace the reference signal by a variable reference signal like:

$$y_{r1}(t)=y_r(t)-k\_ref\cdot\left(y_r(t)-y(t)\right) \tag{1}$$

where y_{r1} is the new reference to be followed, *k_ref* is a weighting factor. In other words, it is intended that at every sampling step, if possible, to reduce at least a fraction proportional to *k_ref* from setting error. Increasing *k_ref* leads to low oscillations, high robustness but a high response time.

In fig. 1 the *k_ref* parameter effect is revealed. If the parameter rises the system response is slower but the overshot and oscillations are low. Moreover, in fig. 2 a zoom from figure 1 is presented, to better revealed the effect on the measured signal.

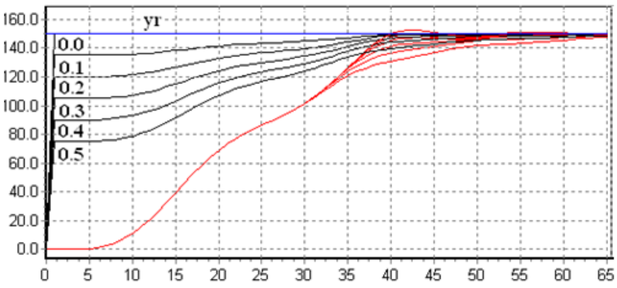

Fig. 1 Step response

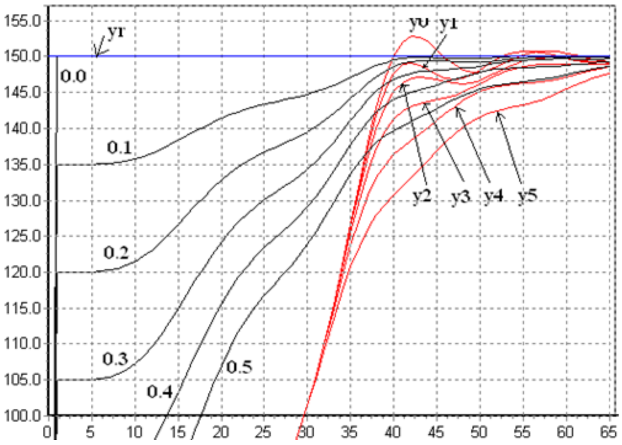

Fig. 2 – Step response - zoom

5. CONCLUSION

This paper presents aspects regarding using pre-filters in mechatronic control systems. Optimal designing of such pre-filter may lead to a minimum time response and no oscillations.

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Prefiltrele în controlul sistemelor mecatronice

Rezumat: *In multe aplicații din domeniul mecanic este necesară reducerea si pe cat posibil eliminarea vibrațiilor mecanice ce pot apare atunci când semnalul de referință se modifică brusc. Funcție de modul în care este acordat controlerul, noua referință se poate atinge printr-un control agresiv, ceea ce dă naştere vibrațiilor sau cu un răspuns lent ceea ce conduce la creşterea timpului de răspuns. O soluție ce permite atât eliminarea vibrațiilor cat si un răspuns suficient de rapid este utilizarea prefiltrelor. Aria de aplicații este destul de vasta:cranes, manipulators, automated machinery etc. Lucrarea prezintă şi exemple de aplicații.*

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