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APPLICATION OF DIGITAL FILTER BASED MOTION COMMAND PRECONDITIONING METHODS FOR VIBRATION SUPPRESSION OF A FLEXIBLE TRUSS WITH DENSELY SPACED MODES

George N. Glossiotis and Ioannis A. Antoniadis*

National Technical University of Athens, Department of Mechanical Engineering,
Mechanical Design and Control Systems Division,
9 Heroon Polytechniou Str., 15773 Athens, Greece.
antogian@central.ntua.gr

Abstract

The motion of flexible structures excites transient and residual vibrations and for this reason numerous command preconditioning techniques have been developed, with various degrees of effectiveness concerning vibration suppression. The basic aspect that these methods have to confront is the contradicting requirements between the speed of response of the system and the robustness to variations of its natural frequencies. Among those command-preconditioning methods, Finite Impulse Response (FIR) filters can present an extremely robust behavior, combined with the introduction of the minimum possible delay. This optimal combination renders FIR filters applicable in a wide range of engineering applications, where wide bands of structural resonances are excited. Such a typical flexible truss is considered, characterized by wide bands of dense clusters of eigenfrequencies. The constructed truss is attached to the end point of a hydraulic Cartesian manipulator, by the use of which the motion commands are generated. A FIR filter based preconditioning scheme is implemented for the motion control of the system. The corresponding experimental results demonstrate that the filtered commands effectively suppress the excited vibrations, covering in the best possible way all the excited modes of the structure.

INTRODUCTION

Due to the inherent flexibility of engineering structures, transient and residual vibrations occur when a motion command is applied, raising thus several practical restrictions concerning their fast, accurate and safe motion. The traditional approaches to minimize the effect of this type of vibrations are focused either on passive vibration techniques, or on active vibration suppression methods. An alternative approach for suppressing vibrations generated due to a motion command is the proper conditioning of the pre-specified motion pattern (which is called "Command" or "Control Input" or "Input"), so that the system moves to the desired position with the minimum level of vibrations. Preconditioning methods can be either used individually as stand alone motion control schemes or supplement the afore-mentioned traditional methods.

Among them, “Input Shapers” have drawn special attention, since they can be applied to convolve any arbitrary input to the system with a series of impulses. Input shapers have been proposed, either for single-degree-of-freedom systems using a limited number of impulses [9,11], or for multi-degree-of-freedom systems, further convolving or delaying in time the above basic impulse pattern [6, 9]. Alternative approaches have been described for the design of input shapers in the discrete domain [10, 12], by appropriately placing zeros at the poles of the flexible system on the z-plane. Although input shaping methods suppress effectively vibration in a variety of systems and applications [1, 2, 6, 8, 12], their robustness (or insensitivity) is limited in narrow local areas around the estimated system natural frequencies. This robustness can be increased only by increasing the total duration of the pulse sequence and as a result, longer delays in the system motion are introduced. This fact prevents input shapers to perform effectively, especially in cases where a broad band of structural resonances are excited.

Since convolution with input shapers is mathematically equivalent to the application of Finite Impulse Response (FIR) filters, the various forms of the input shapers can be considered as specific cases of digital notch FIR filters. Recently, Economou et al. [3, 4] considered the application of conventional digital filters for motion command preconditioning as an alternative for input shapers. After a systematic consideration of several types of conventional FIR filters it has been demonstrated that three types of them can present substantially increased robustness to variations of the system natural frequencies, while simultaneously introducing the minimum possible delay and vibration error [4].

In this paper the digital filter based motion preconditioning method is applied to lightweight flexible structures, were multiple and densely packed modes are simultaneously excited by the motion commands. Such structures generally posse high modal densities, with clusters of densely packed modes, existing even at relatively low frequencies [5, 7, 13, 14]. Initially the necessary framework for the application of digital filters in vibration suppression is summarized. The method is verified in a relevant experimental application, for the motion preconditioning of a flexible truss that has more than 20 dense modes in a range from 0.4 to 80Hz.

INPUT PRECONDITIONING USING FIR FILTERS

A Finite Impulse Response (FIR) filter is a series of constants $\{c_n\}$ (the filter coefficients) of length N+1, where N is called the "filter order". The corresponding frequency response function of a FIR filter, with sampling frequency f_s, is given by:

$$F(jw) = F(j2pf) = \sum_{n=0}^{N} c_n e^{-jn2p\frac{f}{f_S}} \tag{1}$$

According to the proposed preconditioning approach, instead of the direct implementation of the original input to a system, a conditioned guidance function can be alternatively used, obtained by appropriately digital filtering the original guidance function, using a common filter with a transfer function of the form of Eq. (1).

Provided that the Frequency Response Function $F(j\omega)$ of Eq (1) of the filter is zero at frequencies coinciding with the expected natural frequencies of the dynamic system, this filter is capable of completely eliminating the residual vibrations effect. Considering further the requirement for robust residual vibration suppression, the robustness properties for the preconditioning procedure can be directly met, by extending the requirement for zero frequency response of the filter not only for individual frequencies coinciding with the expected natural frequencies of the system, but also for extended areas (stop-band areas) of the filter FRF $F(j\omega)$, in order to cover additionally the possible variations of the system natural frequencies. In addition, the response for zero frequency of this filter should be kept equal to one, in order to ensure the proper motion of the mechanical system as a rigid body.

Thus, an appropriate extra insensitive filter capable to suppress the transient and residual vibrations a flexible system, should be of low pass type, covering the following requirements [4]:

R.a) Cut-off frequency equal to the system's lowest natural frequency.

R.b) Stop-band quite wide in frequency in order to suppress the vibrations from all the excited natural frequencies.

R.c) Response for zero frequency equal to one.

R.d) Ripples on the stop-band lower than a pre-specified value, which defines the maximum permissible residual vibration error.

R.e) Minimum possible delay, introduced by the application of the filter.

Based on the above requirements, the Delay-Error-Order (DEO) Curves concept, a tool for the optimum filter design has been proposed [4]. DEO curves have been generated for ten FIR filters and three IIR filters [3]. From these curves it is concluded that three FIR filters (the Parks-McClellan filter, the Constraints Least Square filter and the filter designed using a Chebyshev window) introduce the shortest delays while they present extremely extended robustness.

Once the DEO curves are obtained, the filter design parameters can be easily calculated [4] for every specific physical system, using the following procedure. First, the system's lowest expected natural frequency f_0 is calculated. This is the only information necessary from the dynamic system and can be calculated either from experimental data or using a system model. According to requirement R.a, the filter cut-off frequency f_C is set equal to the system's lowest damped natural frequency. Then, according to the task specifications and constraints for the filter time delay and/or for the maximum permissible vibration error, a specific DEO curve is selected. The order N of the filter order is selected as high as necessary, since the robustness of the filter increases almost proportionally to the filter order N [4], without any adverse effect to the total delay introduced by the filter. This leads to a specific point on the selected DEO curve, from which the optimal filter parameters can be defined.

EXPERIMENTAL SETUP

In order to evaluate the FIR preconditioning method, experiments were conducted for the motion command preconditioning of an aluminium truss. As shown in Fig. 1, the truss is fixed at the end point of the vertical arm of a 3-dof hydraulic manipulator. The manipulator used is of Cartesian type, constructed by three independent linear axes of motion, perpendicular to each other. Each axis uses a hydraulic radial piston motor and the rotational motion is converted to linear one through a toothed ruler.

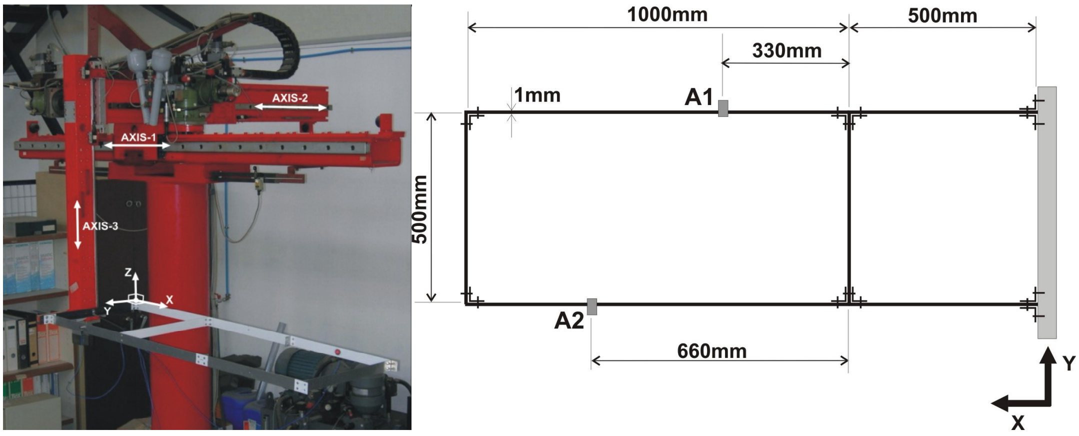

Figure 1 - View of the hydraulic manipulator with the flexible truss, and a drawing indicating the measuring points on the truss.

The structure examined (Fig. 1) is an aluminium-made truss consisting of 2 sets (bays) connected by properly designed clamped joints. The assembled truss is fixed at a rigid iron-made mounting, which in turn is properly attached at the end point of the vertical arm of the manipulator. The entire structure is positioned parallel to the horizontal plane.

The truss follows the motion of the manipulator and the conducted experiments involved linear motions along the axis-2. During and after the completion of each motion, the coupled beams of each of the two sets undergo axial and bending vibrations. The joints connecting the beams transmit longitudinal (axial) and transverse forces, as well as bending moments. Some indicative material properties and geometric parameters of the truss elements are: (a) $A=4\cdot10^{-5}$ m^2, (cross-section of a beam member), (b) $\bar{m}=0.0844$ Kg/m, (mass per unit length), (c) $E=206800\cdot10^6$ Pa, (modulus of elasticity) and (e) $\rho=2700$ Kg/m^3, (Aluminium density).

Measurement System

The measurement system is built based on an industrial PXI-1010 chassis of National Instruments. The core of the system is the embedded controller NI PXI-8145 RT that operates in real time. A Motion Controller card (PXI-7344), and a Data Acquisition card (PXI-6040E Multifunction I/O) are mounted into slots adjacent to the controller.

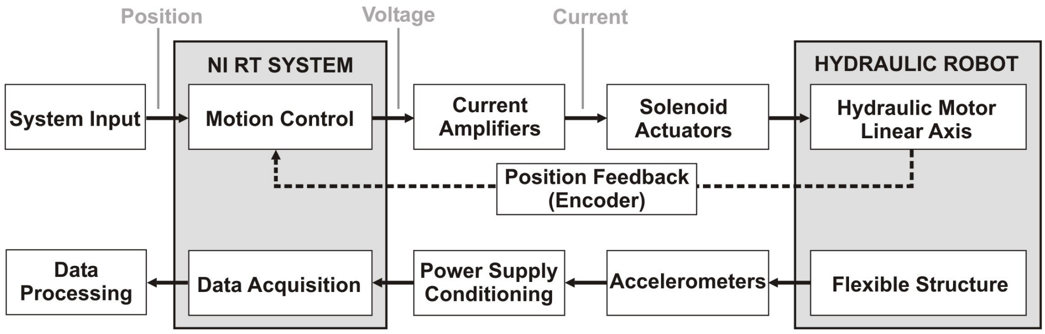

Figure 2: Block diagram of the experimental set-up.

A block diagram of the experimental set-up is shown in Fig. 2. The input to the system is the desired motion profile to be followed by the manipulator. The input is properly scaled in the motion controller, and the resulting voltage signal (±10 Volt) is fed to the current amplifier (Rexroth VT-SR1-1X) of the servo-valve. The command signal from the drive is fed to the solenoid actuator (Rexroth Model 4 WS 2 EE 10-4X), and the corresponding reference motion is obtained. The precise position of the axis is obtained by an incremental angle encoder (Heidenhain ROD 420), which is also used for feedback of the closed-loop control system. Finally, two ICP accelerometers of PCB Piezotronics (Model 352C33) are used for the measurement of the excited vibrations of the truss during and after its motion.

EXPERIMENTAL RESULTS

Original rigid body motion profiles

A specific motion profile is applied to the second axis of the manipulator, and correspondingly to the truss. The time profile motion, indicated in Fig. 4, corresponds to a classical trapezoidal point-to-point motion command, typically used in the case of rigid bodies. It consists first from a constant acceleration phase, with duration of 0.08 sec, a constant velocity phase of 0.375 m/sec with duration of 0.84 sec, and a constant deceleration phase with duration of 0.08sec.

The system response is evaluated by the data collected from the two accelerometers. The corresponding spectra of the accelerations of the two accelerometers are presented in Fig. 3. As it can be observed, the motion profiles introduce a significant amount of vibrations. We note that resonances in this system occur in dense clusters extending in a very wide frequency band (0Hz - ~75Hz), in both spectra estimated. The magnified view of the acceleration spectrum for the accelerometer at position A2 (Fig. 3) shows characteristically this aspect. However, the only element needed from the above dynamic analysis for the proper implementation of the filtering procedure, is just an estimate of the lowest natural frequency of the system, which is approximately 0.4Hz.

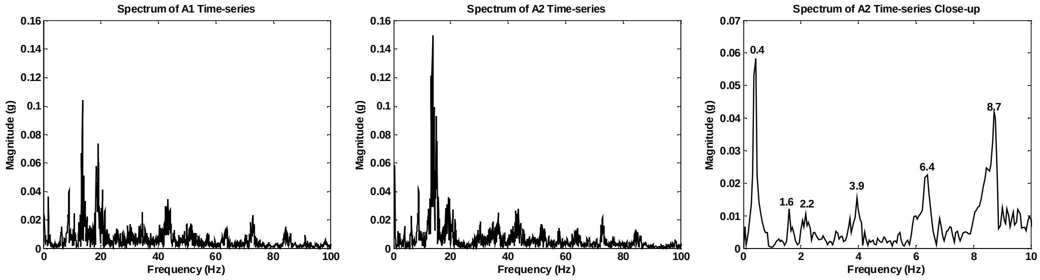

Figure 3 - Spectra of the accelerations at two individual points (A1 and A2) of the truss in the case of rigid body motion and a magnified view (0-10Hz) at position A2.

Input preconditioning procedure: FIR filter design

A Parks McClellan type FIR filter will be used for the preconditioning of the motion commands. The basic requirements needed from the dynamic system for the application of the filter is an estimation of the cut-off frequency, which is selected equal to the lowest expected natural frequency of the system (0.4 Hz) and the selection of the permissible vibration error, which is set to 5%. The stop-band of the filter should cover a region between 0.4Hz and 80Hz, which results to a relative robustness or approximately r_R=198. From Figure 4 in [4] it is concluded that a filter with an order of 240 would be in principle satisfactory for the application. The selected filter presents an almost maximally robust behavior, with a relative robustness equal to 99%. From Figure 3 in [4] the relative delay introduced by the filter results to approximately 1.2 times the highest natural period of the system, which leads to a total time delay of the filtering process equal to approximately 3 sec.

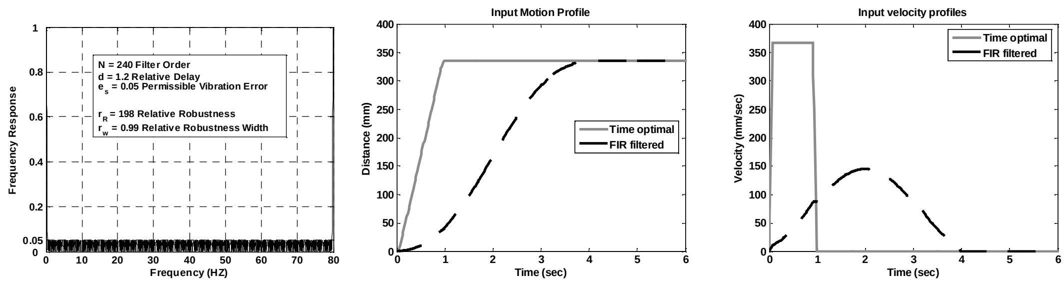

Figure 4 - The FRF of the filter type and the resulting motion profiles and velocity profiles

The rest of the filter design parameters are retrieved from the DEO curves and the look-up tables corresponding to the specific filter [4]. The filter transfer function is shown in Figure 4. The stop band of the filter covers frequencies from 0.4Hz up to approximately 80Hz.

Effects of the preconditioned inputs

The designed filter is then used to precondition the commanded inputs. The resulting inputs are shown in Fig. 4, in comparison to the original time-optimal inputs.

The resulting acceleration time series along y-direction, at the point A2 of the truss are illustrated in Fig. 5a for the FIR filtered inputs, together with the original vibrations. It can be easily observed, that the fluctuations and the magnitudes of the vibration are notably diminished, both during the transient and the residual states of the motion. Further details on the performance of the filtering method can be revealed in Fig. 5b, where the spectra of the corresponding accelerations are presented. The presence of characteristic lobes in the FRF of the FIR filter prevent the perfect elimination of the vibrations, while an additional source of the remaining vibrations is attributed to excitations from the components of the hydraulic circuit.

(a)

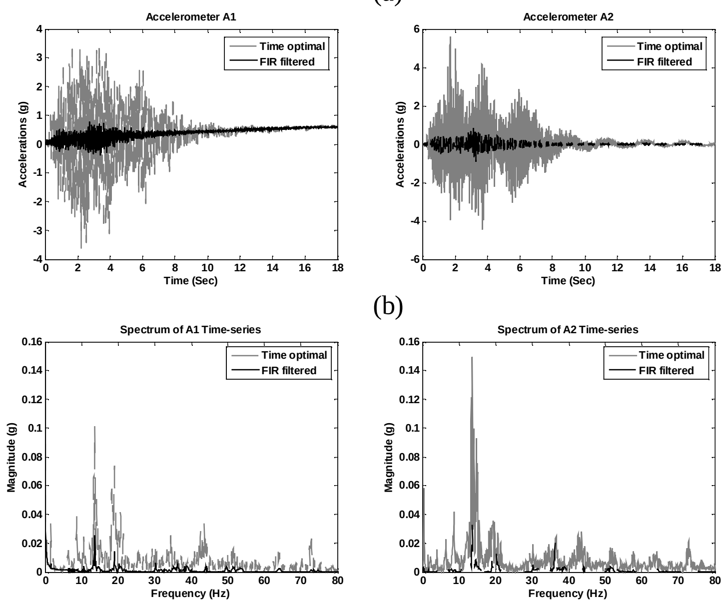

Figure 5 - Acceleration time series at the points A1 and A2 for the time-optimal and the FIR filtered command inputs and the respective spectra.

The results indicate that the traditional practice of "instantly" applying all the available power of the system in the form of a "bang-bang" motion type, although it can lead to time minimal motion profiles, it produces vibrations, which in turn may result to other undesirable side effects. Contrary, the application of the filter results to an optimally distributed supply of power to the system, preventing the generation of vibrations from the beginning of the motion.

CONCLUSION

Transient and residual vibrations of structures with densely packed modes can be drastically reduced, when FIR filters are used to precondition the motion inputs prior to their application to the system.

The cost anticipated, is a time delay for the motion, which is of the order of magnitude of the largest expected natural period of the system. However, this drawback can be compensated by the fact that the vibration suppression capabilities of the proposed method omit the long rest times introduced by lightly damped systems. Additional side benefits are gained due to the reduced stress levels of the equipment and the smooth way, in which the power is now supplied to the system.

Since the practical implementation of the method requires just the application of an already pre-designed digital filter, and an estimate of the lowest expected natural frequency of the system, the method is simple to implement in actual configurations, it is efficient and does not require special sensors or other equipment.

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