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Analysis of active vibration control of multi-degree-of-freedom flexible systems by Newmark method

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ABSTRACT

A flexible robot arm can be modeled as a lumped-parameter multi-degree-of-freedom mass–spring system. The actuator at one end positions the payload at the other end. The flexibility causes the vibration of the payload at the end point. This paper considers a 4-degree-of-freedom mass–spring system. A closed loop active vibration control system is analyzed to suppress the end-point vibrations. The mathematical model of the system is established by using the Lagrange equations. The average of the displacements of the masses is used for the feedback. A PID control is applied. The numerical solution is obtained by integrating the control action into the Newmark method. The instantaneous average displacement is subtracted from the reference input to find the error signal value at a time step in the Newmark solution. The PID control action is applied to find the actuator signal value in the time step. This input value is used to find the displacements for the subsequent time step. The process is continued until the steady-state value is approximately reached. The analytical solution is given by using the Laplace transform method to check the validity of the Newmark solution. It is observed that the numerical and analytical results are in good agreement. The integration of the control action into Newmark solution as presented in this study can be extended to finite element solutions to simulate the control of complex mechanical systems.

1. Introduction

Flexible and light mechanical systems are more advantageous than rigid and heavy ones. The most current examples of flexible mechanical systems are robot manipulators. Flexible manipulators have smaller driving actuators and consume lower energy. However, residual vibrations occur due to the flexibility. This affects the settling time and accuracy at the end point while operating with high speeds. Elimination or suppression of these vibrations by using different control strategies is a challenging problem for researchers.

The mathematical model of manipulators can be constructed by the finite element method or analytical methods [1]. The governing differential equations of dynamic systems can be solved by using numerical methods [2–5] or commercial engineering programs [6].

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One link flexible robot arm can be modeled with linear models, and multi-link manipulators can be modeled with non-linear models. Basic spring–mass discrete models, linear Euler–Bernoulli partial differential equations, generalized Newton–Euler algorithms, Lagrangian equations, associated to a Rayleigh–Ritz elastic field decomposition method and finite element decomposition or modal decomposition have been used to analyze multi-body flexible manipulators [1]. Fung presented a sub-stepping procedure to construct unconditionally stable higher-order accurate algorithms based on the Newmark method [2]. Owren and Simonsen used Runge–Kutta Method for the time integration of the equations of motion in structural dynamics [3]. Zang et al. developed a stochastic Newmark algorithm which was appropriate for earthquakes and sea waves [4]. Haidao et al. used an Implicit Newmark with corrector–predictor algorithm for time integration solution of the equation of the motion for slab structures [5]. Karagulle and Malgaca studied on the effect of the flexibility on the trajectory of a planar two-link manipulator using integrated computer-aided design/analysis (CAD/CAE) procedures [6]. They also analyzed active vibration control in smart structures by ANSYS [7].

Residual vibration amplitudes of flexible robot manipulators can be suppressed by using passive or active control. Passive control, which deals with the open loop system, can be achieved by motion commands [8–12]. Active control requires the closed loop model and an external actuator. Piezoelectric elements are widely used for the vibration control of flexible structures [13–17].

A brief summary of the vibration control strategies of flexible systems is given here. Meck and Seering [8] investigated open loop control of such systems by using “bang bang” control function and another control function to avoid resonance. They also examined the performance of a control function for a ramp input. This study was expanded by Singhose and *et al.* by using input shaping with impulse series. They showed that negative input shapers yielded much faster rise time than positive input shapers [9]. Jayasuriya and Choura developed an open loop force function which demolished the residual vibrations due to minimum energy law while reducing the system response time [10]. Shan, Liu and Sun developed the modified input shaping method for multimode vibration suppression. The method was applied on a single link flexible manipulator and the researchers proposed the modified input shaping to get much better performance than the traditional input shaping method [11]. On the other hand, Shin and Brennan considered a cantilever beam and suggested two methods for suppressing the residual vibration of a single degree of freedom system without any control. They proved that the second method which was similar to the input shaping method can control both position and time simultaneously [12].

Numerical simulations were carried out for active control of a 4-bar linkage mechanism with piezoelectric actuators and sensors using the reduced modal controller, the classical and the robust H_∞ controller [13]. Simulation and experimental studies were conducted for vibration suppression of a flexible one-link manipulator using piezoceramic actuators with model-based predictive controller [14]. Gaudenzi et al. studied on the vibration reduction for an active cantilever beam by using piezo-patches. They used a single-input single-output feedback closed loop control system for control strategy [15]. Rahman and Alam presented vibration suppression of smart beams using piezoelectric patch structure. The researchers developed a state space model characterizing the dynamics of the physical system from experimental system using PID approach [16]. Khot et al. studied on the active vibration control of cantilever beam by using PID control theory with output feedback [17].

The dynamic model of robot manipulators can be considered as a lumped multi degree of freedom system [18,19]. A position control algorithm using mechanical waves for the lumped parameter system was developed [18]. Vincent et al. designed a two-stage control algorithm for concentric parameter systems [19]. The first stage of this algorithm was open loop high speed positioning while the second stage was closed loop damping.

The problem of vibration control in lumped parameter systems also has a popular research area for different engineering areas, such as automotive [20–22] and construction [23,24]. In civil engineering, active and passive vibration control with tuned mass damper, active tuned mass damper, viscoelastic damper are proposed for seismic mitigation and earthquake excitation. The control of nonlinear systems was studied with different control strategies such as neural network, fuzzy and Lyapunov based on H_∞ [25–28].

In this study, the integration of the closed loop control strategies of a flexible mechanical system into the Newmark solution is presented. Dynamic analyses of different systems have been widely analyzed by the Newmark method as discussed above. The major contribution of the study is to integrate the PID control actions into the Newmark solution and to evaluate an average feedback signal to achieve an active control effectively. A 4-degree-of-freedom (DOF) mass-spring system is considered. The analytical solution using Laplace transform method is also given to verify the numerical results. The effect of damping is studied. A procedure to define the PID parameters is presented.

2. Mathematical model of system

The system given in Fig. 1 is considered as an example to explain the procedure developed in this study.

The parameters in the figure m_1, m_2, m_3, m_4 and c_1, c_2, c_3, c_4 and k_1, k_2, k_3, k_4 are the masses, the dampers and the spring constants, respectively. The parameters $x_1(t)$, $x_2(t)$, $x_3(t)$ and $x_4(t)$ are the displacement of each mass. $z(t)$ is the base excitation as the input of the open loop system. t is the time. The displacement $x_4(t)$ of the end mass is evaluated as the open loop system response.

The mathematical model of the open loop system is established by using the Lagrange equations. The equation of motion for the multi-degrees of freedom vibrating system is given as

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{u} \tag{1}$$