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Comparison of various input shaping methods in rest-to-rest motion of the end-effecter of a rigid-flexible robotic system with large deformations capability

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ABSTRACT

Motion control of flexible robots is one of the concerns of the researchers in the field of robotics. When the deflection of the flexible arms increases, considerable complexity is imposed in the problem. In the current study, for the first time, various approaches based on the frequency shaping method will be analyzed in motion control of the *very* flexible robot, in the point to point paths. To this end, a precise system modeling, based on the Absolute Nodal Coordinates (ANC) method, will be employed to the motion study of the system, containing the rigid and the very flexible parts. The provided formulation is very accurate and does not consider any simplifying assumption. As a result, it can exhibit the system behavior once the system undergoes large deformation and the resulted system is highly nonlinear. Comparing the obtained results with the previous conducted researches, the system modeling will be verified. Since the resulted nonlinear differential equations are highly stiff, some sophisticated numerical dynamics model methods, such as alpha technique, are utilized to numerical simulation of the system. Despite of the various advantages of the ANC modeling method, the controller designing is complicated based on this method. Therefore, the Input Shaping (IS) method are utilized to this end, in the current study. The IS method is based on the identification of the excited frequency modes of the system during the motion, and reduction of these frequencies energy in the resulted shaped inputs. The various shaping methods, such as Zero Vibration (ZV), Zero Vibration Derivative (ZVD), Extra Insensitivity (EI), and negative shaping method, will be utilized in the motion control of the very flexible link. The performance of the aforementioned methods will be evaluated using some criteria such as, time duration for the system transferring, the control effort, the robustness, and the steady state vibrations. Finally, the advantages/disadvantages of the mentioned methods will be discussed.

1. Introduction

Necessity of appropriate operation speed and use of low cost actuators, in the robotics systems, justify utilizing the light weight robotics systems. The light weight robotic systems contain large value flexibility which cause serious complexity in the end-effector position control. Therefore, control of the robotic systems containing flexibility has been one of the concerns of the robotics.

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The intelligent Proportional Integral (PI) control of a flexible-link manipulator, using Euler–Bernoulli beam equations, was conducted in [1]. Designing an adaptive control for a single-link flexible manipulator in a rest-to-rest motion, was accomplished in [2]. Sliding mode control of a flexible robot, making sliding surface of the robot motion was carried out in [3]. In [4] a neural network was designed to control a flexible link. Control of a flexible robot using the fuzzy logic and the artificial neural network was conducted in [5]. The trajectory tracking of a single-link flexible arm was studied in [6]. The proposed controller had guaranteed stability in the presence of the small uncertainties in the parameters such as stiffness or motor friction. One of the problems of the previously developed controllers is that, since the flexible system modeling was accomplished based on the floating frame coordinates, the actuation speed of the system should not exceed the limited bound. This occurs, because of keeping the system deformations in the linear domain. Although extensive researches have been rendered in the field of flexible robotics systems, most of them were carried out based on the assumption of small deflection of the flexible links [7–10]. Additionally, in some researches in which the system links are assumed to be very flexible, the system is actuated so that the links deflection remains very small. However, in some control problems such as minimum time transferring [11], the system may experience large deflections and large velocity/acceleration. Therefore, any research in the control of the systems containing flexible elements with large deformations is welcome.

The ANC method is an appropriate approach in the modeling of the flexible robotic systems containing large deformations and/or velocities. In this method, the flexible coordinates and the rigid ones, are considered in one reference coordinate frame. The position of the nodes in the reference frame and their gradients are the generalized coordinates, in this method. The merit of this method includes obtaining a constant mass matrix. Additionally, all nonlinear terms are considered in the elastic potential energy, and in the elastic force term. Also, in this technique, no simplifying assumption, such as small deflection and/or low rotational velocity, is not considered. In [12], a simple method was introduced to modeling of the two dimensional beam based on the ANC, in which the rotational inertia and shearing effects were ignored. The two dimensional shear deformable beam was introduced in [13] for the first time. In this study, to prevent the locking problem, the considered beam is divided to the more number of elements. This in turn produces high computational burden which is its drawback. The locking issue causes inaccuracy in the computation of the beam deflection. This problem is solved, partially, in [14] by neglecting Poisson's effect and linearizing the transverse normal strain. However, the obtained equations are more nonlinear than the previously resulted equations. Moreover, other locking problems are still remained, as before. The proposed approach in [15] was capable of eliminating the locking problem in the modeling, and consequently, could model the shear deformable beam with low number of elements. In [16], an efficient evaluation method was introduced to derive the elastic force and the Jacobian. Internal damping modeling, based on the linear viscosity for ANC, was studied in [17]. It was shown that, this damping is ineffective in the rigid body motion of the system, and only damps the flexible motions of the system. In this study, the proposed approach in [15] was used for the flexible link modeling.

Although, the ANC method is able to model the rapid motion and large deformations of the flexible link, precisely, the controller design based on that method is a complicated task [11]. Most of the developed controller using ANC modeling method, are based on the try-and-error techniques, such as [18], in which a Proportional Derivative (PD) controller was designed to track the desired path around the rigid state of the beam. Also, in [19] a feedforward input, based on the virtual work principle, in the joint space was designed for the equations obtained based on the ANC method. Additionally, a Proportional Integral Derivative (PID) controller was designed, to track the desired path.

The IS technique is one of the vibration control methods in the flexible links. This method was introduced in [20], for the first time. The IS method is one of the subdivisions of the Finite Impulse Response (FIR) filters. In [21] using the IS method, a smooth path was designed to transfer the flexible robot with small deflections, in a rest-to-rest motion. Additionally, the IS method was compared with the other FIR filters. In [22], it was shown that the control method will be more robust considering an allowable bound for vibrations. In [23], it was shown that if the impulse sequences contain negative amplitudes, they will be more suitable from time duration point of view. Determination of non-parametric estimates of a response function between the motor torque and motor velocity in the frequency domain was accomplished in [24]. A wide analysis was conducted on the robust negative shapers in [25], and results of the applying the various inputs on the 2nd order linear system, were compared each other. In [26] the dynamics of a double-pendulum system with a distributed-mass payload is modelled, and a command smoothing scheme is presented to suppress the complex payload oscillations. In [27] a double-pendulum systems subject to external disturbances has been controlled by using input-shaping technique and feedback control.

In the current research, for the first time, several shaping methods including ZV, ZVD and EI, with negative and positive amplitudes will be studied on a system compounded of rigid and very-flexible-link, and the obtained results will be analyzed. It will be shown that, which method results better performance. In order to design the feedforward control path, a Bang-Bang (BB) input will be applied to the system. Then, identifying the natural frequencies of the system, the input shaper impulses will be designed, for each ZV, ZVD, and EI shaping methods, with the positive and negative amplitudes. The amplitudes of the impulse sequences and their time locations will be obtained based on the natural frequencies and the damping ratio. Then, the derived impulse sequences will be convolved with the initial BB input, and the new version of the input will be formed, in which the energy of the natural frequencies are reduced.

The rest of the paper is organized as follows. In Section 2, the modeling of the hub-beam system utilizing the ANC method is developed. In Section 3, the IS control method is explained in 3 parts. In the first part, the required constraints equations, to design the impulses in various methods, are presented. In the second part, the IS method based on the ZV, ZVD, and EI categories will be studied. In the third part, the IS methods utilizing the positive and the negative amplitude impulses will be