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Impact vibration reduction for flexible manipulators via controllable local degrees of freedom

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Abstract When performing operation tasks, the interaction between a flexible manipulator and a grasped object usually results in an impact. In this paper, a new way is suggested to alleviate impact vibration of a flexible manipulator via its structural characteristic when capturing a moving object. Controllable local degrees of freedom are introduced to the topological structure of the flexible manipulator, and used as an effective tool to combat impact vibration through dynamic coupling. A corresponding method is put forward to reduce impact vibration responses of the flexible manipulator via the controllable local degrees of freedom. By planning motion of the controllable local degrees of freedom, appropriate control force can be constructed to increase the modal damping and stiffness and eliminate the exciting force simultaneously, thereby reducing impact vibration responses of the flexible manipulator. Simulations are conducted and results are shown to prove the presented method.

1. Introduction

Impact is a complex physical phenomenon, which occurs when two or more bodies collide with each other. Since most of robotic manipulators make some physical contacts as part of their jobs, such as capture and assembly, impact phenomenon inevitably arises.

As far as a flexible manipulator is concerned, due to the presence of system flexibility, vibration is an unavoidable problem.[1,2] When the flexible manipulator collides with other bodies, impact can excite severe vibration responses and deteriorate end-effector accuracy. In addition, since the manipulator is often required to keep moving after the collision, new vibration responses will arise and be accumulated on the existing impact vibration responses, thereby further degrading its working performance. Furthermore, after capturing an object successfully, the dynamic structure of the flexible manipulator will suddenly change due to incorporation of the grasped object, thus altering its dynamic behavior of the post-impact phase accordingly. Therefore, study on vibration alleviation for a flexible manipulator undergoing an impact collision is theoretically challenging.

In the past decades, impact modeling for rigid and flexible manipulators has been researched.[3–6] However, in contrast to a number of papers on impact control for rigid manipulators,[7–12] insufficient work has been conducted on impact

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vibration reduction for flexible manipulators.[13–16] Due to abrupt changes in system velocities and dynamic structures, it is difficult for conventional control methods to deal with. Therefore, new ways are worth trying.

Recently, special attention has been paid to reducing impact influences of manipulators via their structural characteristics. Compared with conventional configurations, new structural characteristics may provide extra capabilities to improve working performance.[17–21] Typically, some researchers have explored reducing impact vibration of manipulators via redundant degrees of freedom. Walker studied how to use kinematic redundancy to alter dynamic effects of a collision between a robot and its environment, and proposed several vulnerability measures to evaluate effects of different configurations of kinematically redundant arms on impact forces.[22] Kim et al. made use of configurations of larger damping and less stiffness to minimize penetration and impact force via redundancy.[23] Yoshida et al. suggested a method to reduce impact force by properly selecting the manipulator configuration prior to the impact.[24] However, these methods only studied rigid manipulators. For flexible manipulators, Xu and Yue utilized kinematic redundancy of flexible manipulators to alleviate impact vibration resulting from capturing objects, and proposed a vibration alleviating measure.[25] However, all of these methods are passive ways, because they merely apply stronger configurations of manipulator arms to resist an impact, but are not active in reducing impact vibration of the post-impact phase.

Inspired by redundant degrees of freedom, we proposed a concept of controllable local degrees of freedom (CLDoF) and introduced it to the topological structure of a flexible manipulator.[26,27] This manipulator consists of one flexible main chain and one or more rigid branch links. Although the branch links have no direct kinematic relation to the main chain, independent motions introduced by CLDoF can strongly affect dynamic performance of the main chain. Using this advantage, adverse influences on working performance are expected to decrease via CLDoF.

In this paper, CLDoF are examined to alleviate impact vibration of a flexible manipulator. Special application of the independent motions, introduced by CLDoF, in impact vibration reduction of the flexible manipulator is studied. A method is suggested to alleviate impact vibration responses of the flexible manipulator via CLDoF.

2. Dynamics model of the flexible manipulator with CLDoF

As shown in Fig. 1, the manipulator consists of one flexible main chain and one or more rigid branch links. The branch

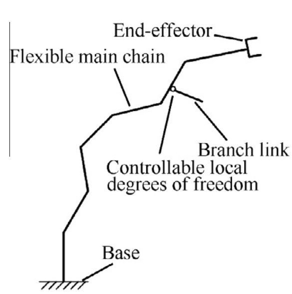

Fig. 1 Schematic of a flexible manipulator with controllable local degrees of freedom.

links, connected to the main chain through joints, can move actively. Although the branch link motion has no direct relation to the nominal end-effector motion, it can greatly affect dynamic performance of the main chain. Therefore, the branch link motion is expected to attenuate impact vibration via dynamic coupling.

The desired position/posture of the end-effector $\boldsymbol{x}$ is the function of the joint angles $\boldsymbol{q}_{\mathrm{M}}$, that is,

$$\boldsymbol{x} = \zeta(\boldsymbol{q}_{\mathrm{M}}) \tag{1}$$

where $\boldsymbol{x} \in \mathbf{R}^{m}$ is the nominal position/posture of the end-effector with respect to the base frame; m is the number of degrees of freedom of the end-effector in the work space; $\boldsymbol{q}_{\mathrm{M}} \in \mathrm{R}^{n_{\mathrm{M}}}$ is the vector describing the joint angles of the main chain; n_{M} is the number of joints in the main chain.

For the flexible manipulator without redundant degrees of freedom in its main chain, $n_{\mathrm{M}} = m$, and

$$\dot{\boldsymbol{q}}_{\mathrm{M}} = \boldsymbol{J}_{\mathrm{M}}^{-}\dot{\boldsymbol{x}} \tag{2}$$

where $\boldsymbol{J}_{\mathrm{M}} \in \mathbf{R}^{m\times n_{\mathrm{M}}}$ is the nominal Jacobian matrix of the main chain and $\boldsymbol{J}_{\mathrm{M}}^{-}$ is the inverse matrix of $\boldsymbol{J}_{\mathrm{M}}$.

Differentiating Eq. (2) with respect to time, we have

$$\ddot{\boldsymbol{q}}_{\mathrm{M}} = \dot{\boldsymbol{J}}_{\mathrm{M}}^{-}\dot{\boldsymbol{x}} + \boldsymbol{J}_{\mathrm{M}}^{-}\ddot{\boldsymbol{x}} \tag{3}$$

Because the branch link motion has no direct relation to the nominal end-effector motion, we have

$$\dot{\boldsymbol{q}}_{\mathrm{B}} = \boldsymbol{\varepsilon}_{\mathrm{B}} \tag{4}$$

where $\boldsymbol{q}_{\mathrm{B}} \in \mathbf{R}^{n_{\mathrm{B}}}$ is the vector describing the joint angles of the branch links; $\boldsymbol{\varepsilon}_{\mathrm{B}} \in \mathbf{R}^{n_{\mathrm{B}}}$ is the arbitrary vector; n_{B} is the number of joints in the branch links.

Based on Kane's method and the assumed-modes method, dynamics equations of the flexible manipulator with CLDoF are derived as follows[24]

$$\boldsymbol{D}\ddot{\boldsymbol{q}} + \boldsymbol{e} = \boldsymbol{\tau} \tag{5}$$

$$\boldsymbol{M}\ddot{\boldsymbol{\varphi}} + \boldsymbol{C}\dot{\boldsymbol{\varphi}} + \boldsymbol{K}\boldsymbol{\varphi} = \boldsymbol{f} - \boldsymbol{G}\ddot{\boldsymbol{q}} \tag{6}$$

where $\boldsymbol{D} \in \mathbf{R}^{n_R\times n_R}$ is the inertia mass matrix; $\boldsymbol{e} \in \mathbf{R}^{n_R}$ is the force vector including centrifugal, coriolis, gravitational force, the term of rigid and flexible coupling, and the link flexibility term; $\boldsymbol{\tau} \in \mathbf{R}^{n_{\mathrm{R}}}$ is the set of actuator torques applied to the joints; $n_{\mathrm{R}} = n_{\mathrm{M}} + n_{\mathrm{B}}$; $\boldsymbol{M} \in \mathbf{R}^{n_{\mathrm{F}}\times n_{\mathrm{F}}}$ is the mass matrix; $\boldsymbol{C} \in \mathbf{R}^{n_{\mathrm{F}}\times n_{\mathrm{F}}}$ is the damping matrix; $\boldsymbol{K} \in \mathbf{R}^{n_{\mathrm{F}}\times n_{\mathrm{F}}}$ is the stiffness matrix; n_{F} is the number of flexural degrees of freedom in the main chain; $\boldsymbol{f} - \boldsymbol{G}\ddot{\boldsymbol{q}}$ is the generalized force vector; $\boldsymbol{f} \in \mathbf{R}^{n_{\mathrm{F}}}; \boldsymbol{G} \in \mathbf{R}^{n_{\mathrm{F}}\times n_{\mathrm{R}}}; \ddot{\boldsymbol{q}} \in \mathbf{R}^{n_{\mathrm{R}}}$ is the vector describing the joint accelerations; $\dot{\boldsymbol{\varphi}} \in \mathbf{R}^{n_{\mathrm{F}}}$ and $\ddot{\boldsymbol{\varphi}} \in \mathbf{R}^{n_{\mathrm{F}}}$ are the flexural velocity and acceleration vector, respectively.

Substituting Eq. (3) into Eq. (6), we obtain

$$\boldsymbol{M}\ddot{\boldsymbol{\varphi}} + \boldsymbol{C}\dot{\boldsymbol{\varphi}} + \boldsymbol{K}\boldsymbol{\varphi} = \boldsymbol{u} \tag{7}$$

$$\boldsymbol{u} = \boldsymbol{f} - \boldsymbol{G}\ddot{\boldsymbol{q}} = \boldsymbol{f} - \boldsymbol{G}_{\mathrm{M}}(\dot{\boldsymbol{J}}_{\mathrm{M}}^{-}\dot{\boldsymbol{x}} + \boldsymbol{J}_{\mathrm{M}}^{-}\ddot{\boldsymbol{x}}) - \boldsymbol{G}_{\mathrm{B}}\ddot{\boldsymbol{q}}_{\mathrm{B}} \tag{8}$$

where $\boldsymbol{G}_{\mathrm{M}} \in \mathbf{R}^{n_{\mathrm{F}}\times n_{\mathrm{M}}}$ represents the first n_{M} columns of $\boldsymbol{G}$, $\boldsymbol{G}_{\mathrm{B}} \in \mathbf{R}^{n_{\mathrm{F}}\times n_{\mathrm{B}}}$ represents the last n_{B} columns of $\boldsymbol{G}$.

Eq. (7) describes the flexural vibration of the flexible manipulator with CLDoF.

3. Dynamics of capturing an object

In general, a capturing operation includes two specific phases: the impact phase and the post-impact phase. The flexible