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Vibration analysis of cable-driven parallel robots based on the dynamic stiffness matrix method

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ABSTRACT

This paper focuses on the vibration analysis of Cable-Driven Parallel Robots (CDPRs). An oscillating model of CDPRs able to capture the dynamic behavior of the cables is derived using Lagrangian approach in conjunction with the Dynamic Stiffness Matrix method. Then, an original approach to analyze the modal interaction between the local cable modes and the global CDPR modes is presented. To illustrate this approach, numerical investigations and experimental analyses are carried out on a large-dimension 6-DOF suspended CDPR driven by 8 cables.

1. Introduction

A parallel robot can be defined as a closed-loop kinematic chain mechanism whose end-effector is linked to the base by several independent kinematic chains [1].

Cable-driven parallel robots (CDPRs) are a special variant of traditional rigid-link parallel robots such as the Stewart platform [2] and the Delta robot [3]. Flexible cables are used instead of rigid links to connect the movable end-effector and the fixed base. The end-effector is manipulated by changing the lengths of the cables by means of winches.

CDPRs have several advantages. First, CDPRs can achieve large workspaces. The cables being flexible, large cable lengths can easily be released and retracted. Thus, cables allow much larger ranges of motion compared to conventional rigid-links. CDPRs can be designed to be very large with an acceptable cost, such as the Skycam[1], and the Five hundred meter Aperture Spherical Telescope (FAST) [4].

In addition, CDPRs have high energy efficiency and large payload-to-weight ratios since they use lightweight cables and usually have stationary heavy components and few moving parts.

Another advantage of CDPRs is their simple structure. They can be relatively easily disassembled, transported, re-assembled, and reconfigured which makes them suitable for search and rescue applications [5–7]. Last but not least, since

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[1] Skycam is a product of Skycam company: http://www.skycam.tv/.

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Nomenclature

$\mathbf{K}^{2D}_{\mathrm{dyn-h}}(\omega)$	dynamic stiffness matrix of a horizontal sagging cable in the cable plan (2-D)
λ^2	fundamental cable parameter representing the elastic stiffness relative to the sag-induced stiffness
ε	ratio between the horizontal cable weight and the cable tension
L_e	cable length parameter
Ω	dimensionless frequency parameter
Ω_c	dimensionless frequency–damping parameter
$\mathbf{K}^{3D}_{\mathrm{dyn-h}}(\omega)$	dynamic stiffness matrix of a horizontal sagging cable in 3-D
$\mathbf{K}^{2D}_{\mathrm{dyn}}(\omega)$	dynamic stiffness matrix of an inclined sagging cable in the cable plan
$\mathbf{K}^{3D}_{\mathrm{dyn}}(\omega)$	dynamic stiffness matrix of an inclined sagging cable in 3-D
${}^{ci}\mathbf{K}_i(\omega)$	dynamic stiffness matrix of the ith inclined sagging cable expressed in the cable frame $\mathfrak{R}_{ci}$
${}^{G}\mathbf{K}_i(\omega)$	dynamic stiffness matrix of the ith inclined sagging cable expressed in the global frame $\mathfrak{R}_G$
${}^{G}\mathbf{K}_E(\omega)$	dynamic stiffness matrix of CDPRs expressed in the global frame $\mathfrak{R}_G$
${}^{e}\mathbf{K}_E(\omega)$	dynamic stiffness matrix of CDPRs expressed in the end-effector frame $\mathfrak{R}_e$
T	kinetic energy of the system
V	potential energy of the system
q_i	generalized coordinate
$\mathbf{q}$	column vectors of the generalized coordinates
$\dot{q}_i$	time derivatives of the generalized coordinate
$\dot{\mathbf{q}}$	column vectors of the time derivatives of the generalized coordinates
f_i	nonconservative generalized force or moment applied to the end-effector
$\mathbf{w}$	column vector of the nonconservative forces and moments
$\mathbf{f}(t)$	column vector of the harmonic excitations applied to the end-effector
$\bar{\mathbf{f}}$	column complex-valued vector representing the amplitudes and the initial phases of the excitations
$\mathbf{q}(t)$	column vector of the harmonic responses of the end-effector
$\bar{\mathbf{q}}$	column complex-valued vector representing the amplitudes and the initial phases of the responses
$\mathbf{H}(\omega)$	frequency response function matrix
FRF	frequency response function

cables are flexible, interferences between cables and/or collisions between cables and other objects in the operating environment may cause less accident or damage [8,9], which is notably useful for haptic devices, such as the NEREBOT [10] and the STING-MAN [11].

Due to the compliance of cables, vibrations can become a crucial concern for CDPRs. Vibrations have a significant effect on the static and dynamic behaviors of CDPRs, such as on the positioning accuracy, settling time, trajectory tracking, as well as on force distribution and control [1,12,13]. Although there are a lot of previous works on the vibration analysis and control of rigid-link parallel robots, e.g. [14–22], only few studies are dedicated to the vibration analysis of CDPRs [23–30]. Vibrations can notably be induced by (brutal) end-effector velocity changes, wind disturbance, and/or friction of the cables around pulleys [24]. In applications requiring high performances, especially dynamic performances, e.g. [13,31], or in the presence of wind, e.g. [4,32], vibrations are an issue since they can affect the positioning accuracy of the end-effector, and yield fluctuations around a desired nominal end-effector trajectory.

Cables have been modeled as linear massless axial springs, and end-effector vibrations caused by axial and transverse cable flexibilities have been analyzed in simulations in [23,26]. Using the same cable model, vibration characteristics of a CDPR for processing applications are presented in [27] while, in [28], a new approach to compensate for the rotational oscillations of the end-effector using reaction wheels is proposed. [23,26–28] only consider cable elasticity, while neglecting the effect of cable mass on the cable dynamics. Although the effect of cable weight on the static cable profile has been considered in a number of works, e.g. [33–36], the effect of cable mass on the cable dynamics is totally ignored in the computation of the CDPR eigenfrequencies. An important issue of the dynamic analysis of CDPRs is to find out whether the cable natural modes and induced vibrations affect the dynamics of CDPRs. Finite Element Method (FEM) has been used in the modeling of cable dynamics [24,25,37,38]. Using FEM, the end-effector vibrations and the system eigenfrequencies have been studied in simulations in [24,25]. However, cable modeling based on FEM uses distributed point mass and ideal lines between them to simulate a continuous cable. Hence, it leads to a complex system with many partial differential equations. Moreover, as well-known, the accuracy of FEM depends on the number of elements so that there exists a strong trade-off between accuracy and computational complexity. The dynamic behavior of CDPRs with long sagging cables has been recently investigated in an analytical way using Hamilton's principle [30]. The assumed mode method is used to solve the obtained time-varying partial differential equations of motion. In the assumed mode method, the shape functions are a linear combination of the eigenfunctions of the related simpler problem of transverse cable vibrations with standard boundary conditions. The accuracy of the dynamic model thereby obtained highly depends on the adopted shape functions of the transverse cable vibrations and on their number. In [30], no experimental validation of the theoretical predictions of the CDPR dynamic responses has been presented. Moreover, it should also be noted that the time integration of such dynamic models has not received particular attention. There are two primary issues in time integrating these dynamic models. First, the discrete time-step integration method used for solving the dynamic equations should be carefully selected