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Oscillation damping of nonlinear control systems based on the phase trajectory length concept: An experimental case study on a cable-driven parallel robot

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ABSTRACT

In this paper, via shortening the phase trajectory length concept, a systematic approach for oscillation damping of nonlinear systems is introduced and the proposed procedure is applied in order to control an under-actuated cable-driven parallel robot both in simulation and experiment. In this regard, at first, the phase trajectory length concept in the state space of a multi-input multi-output nonlinear system is defined and then its lower and upper bounds are computed. Then, the concept of oscillation number index is defined and sufficient conditions for designing an anti-oscillation control system are presented. Moreover, the effect of including the time as a weight in the computation of the phase trajectory length in order to enforce the system response speed beside the oscillation damping is investigated. Finally, based on the governing equations of the robot under study, utilizing the genetic algorithm, the computed torque controller gains are explored in order to minimize the oscillation number index to alleviate the oscillation of the system. In this regard, the performance of the aforementioned index for alleviating the oscillation of the robot is compared with the integral absolute error index, experimentally. Moreover, the Fourier analysis of the obtained results is presented.

1. Introduction

These days, based on the economic and existing limitations on the real implementation and with a specific end goal to increase the performance, modern systems have been intended to work near their control and operational limits. Predicated on this fact, damping the oscillation of the swayed systems has engrossed in the dominating concentration among the controller designing criteria [1,2]. Such a concept has been widely used in robotics [3], electronic vehicles [4], power systems [5] and civil engineering [6].

The designed oscillation damping controllers in the literatures can be divided into the two main groups. In the first one, in order to damp the oscillation, the control strategy was founded on minimizing the traditional well-known index such as integral absolute error (IAE) and integral time-weighted squared error (ITSE), while in the second group, more complex control strategies were proposed in order to alleviate the oscillation of system. Predicated on this categorization, several

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List of acronyms

PTL	phase trajectory length
ITSE	integral time weighted square error
HJB	Hamilton Jacobi Bellman
MOC	minimum oscillation controller
ONI	oscillation number index
GA	genetic algorithm
ISE	integral square error
IAE	integral absolute Error
CTM	computed torque method
CDPR	cable-driven parallel robot
RT	rise time

List of nomenclature

γ	time weight
s	switching factor
$L(\boldsymbol{x}(t))$	PTL function
$r(\boldsymbol{x}(t))$	radius function
$r_{ON}(\boldsymbol{x}(t))$	oscillation number
$\boldsymbol{x}(t)$	state variable vector
ρ	state variables weight
$M_p(\%)$	over shoot
$\mathbf{f}_c(\boldsymbol{x}(t))$	closed loop field vector
$\mathbf{J}$	Jacobian of the robot

researches were accomplished to alleviate the oscillation of the power systems. In such systems, low frequency oscillations which may lead to the serious aftermath, involve many generators in the interconnected system [7].

In addition to power systems, anti-jerk controllers are widely used in order to damp the oscillation of driveline electrical vehicles which is crucial to improving driveability and passenger comfort [8]. In [9], an optimal controller was designed in which compensating the drivers engine torque leads to subside driveline oscillations. Moreover, in this field, robust pole placement strategy, H_∞ optimization approach and Model Predictive Control (MPC) strategy were employed in [10–12] as the anti-jerk and vibration damping controller, respectively.

In the context of the robotic application, one of the significant robot's performances is oscillation damping. In order to meet the aforementioned performance, beside the other criterion such as Rise Time (RT), overshot ($M_p\%$) and etc., some intelligent control techniques such as fuzzy logic control, neural network control and their hybrid combinations have been successfully applied to robotic manipulators, recently [13,14]. In terms of control aspect, tuning the PID controller based on the IAE and ISE was employed as a common method in order to design the anti-oscillation controller for the robotic purposes [15,16]. CDPRs utilize several cables instead of rigid links to control their end-effector pose. CDPRs possess many privileges compared to conventional serial-linked robot manipulators. With low-inertia cables, the aggregate mass of the moving parts of the robot is small and accordingly its acceleration can be high. Moreover, using longer cables, the larger workspace is achievable. Besides, due to the their relatively simple structure, it is easy to assemble and disassemble CDPRs [17]. Due to the plausibility of sagging the cables and considering the fact that the cables can exert pulling axial forces only, in order to have controllable workspace, CDPR systems need a larger number of cables than the number of degrees of freedom (DoFs) of the end-effector which are called over-constrained or fully-constrained CDPRs [18]. Contrariwise, when the number of cables is less than that of DoFs of the end-effector, they are called under-constrained –which are simpler, therefore they are less expensive and have a larger workspace compared to fully-constrained CDPRs. Predicated on the aforementioned features, under-constrained CDPRs can be seen in many application fields such as measurement, rescue, service and construction yards [19,20]. In the under-constrained CDPRs, in order to prevent the payload from oscillating, the trajectory of the end-effector should be carefully planned to suppress any payload oscillations. In the recent studies like [21] input-shaping scheme method was proposed to suppress unwanted sway or oscillations. Moreover, an anti-sway trajectory generation method based on input-shaping was studied in [22,23]. In [24], the dynamic stiffness matrix method was utilized to analyze the vibration of CDPRs. Furthermore, a fuzzy assistant controller based on merging feedback control with the shaping commands was employed in [25].

Despite the fact that all aforesaid studies are useful in smooth trajectory planning, they are too special and it is difficult for their methods to be extended to more general cases. Moreover, effect of controller performance is neglected and the latter issue brings about to consider CDPR as the proper case study to investigate the minimum oscillation controller (MOC) performance. Generally, although various methods have been proposed for oscillation damping, there is no comprehensive way to suppress oscillations concurrently in an arbitrary number of variables. This gap will be more critical when the system dimension increases. The main contribution of this paper can be regarded as follows: