ISA Transactions xxx (2018) 1–21

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Modal space three-state feedback control for electro-hydraulic servo plane redundant driving mechanism with eccentric load decoupling

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A R T I C L E I N F O

Article history:
Received 14 December 2017
Received in revised form
8 March 2018
Accepted 6 April 2018
Available online xxx

Keywords:
Electro-hydraulic servo system
Planar parallel mechanism
Dynamic coupling
Modal space three-state feedback

A B S T R A C T

The shaking table based on electro-hydraulic servo parallel mechanism has the advantage of strong carrying capacity. However, the strong coupling caused by the eccentric load not only affects the degree of freedom space control precision, but also brings trouble to the system control. A novel decoupling control strategy is proposed, which is based on modal space to solve the coupling problem for parallel mechanism with eccentric load. The phenomenon of strong dynamic coupling among degree of freedom space is described by experiments, and its influence on control design is discussed. Considering the particularity of plane motion, the dynamic model is built by Lagrangian method to avoid complex calculations. The dynamic equations of the coupling physical space are transformed into the dynamic equations of the decoupling modal space by using the weighted orthogonality of the modal main mode with respect to mass matrix and stiffness matrix. In the modal space, the adjustments of the modal channels are independent of each other. Moreover, the paper discusses identical closed-loop dynamic characteristics of modal channels, which will realize decoupling for degree of freedom space, thus a modal space three-state feedback control is proposed to expand the frequency bandwidth of each modal channel for ensuring their near-identical responses in a larger frequency range. Experimental results show that the concept of modal space three-state feedback control proposed in this paper can effectively reduce the strong coupling problem of degree of freedom space channels, which verify the effectiveness of the proposed model space state feedback control strategy for improving the control performance of the electro-hydraulic servo plane redundant driving mechanism.

1. Introduction

The parallel mechanism has the advantages of strong bearing capacity, small inertia, fast movement and so on. At present, the parallel mechanism is widely used in parallel machine tool [1], flexible cable drive parallel mechanism [2], seismic performance test [3], automobile and other walking machinery road environment simulation tests [4,5]. Electro-hydraulic servo shaking table is a typical application of electro-hydraulic servo parallel mechanism. In order to carry out its motion control, the parallel mechanism dynamic model needs to be built first. Liu et al. [6] used Kane method to establish the dynamic model, in which mechanism was divided into some sub-structures to be modeled separately. After establishing constraint relationships among these sub-structures, the kinetic equation was obtained. Varedi et al. [7] developed dynamic modeling using ADAMS, which focused on verifying the correctness of the modeling method. In Ref. [8], the common methods for simplifying the analysis of complex dynamic models were proposed, and the real-time control was optimized. Fu et al. [9] proposed an energy balance equation based on Lagrangian modeling method, the modeling approach of which is relatively simple and easy to observe the coupling of system. These modeling methods have their own outstanding advantages. And considering the particularity of plane motion, the dynamic model is built by

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https://doi.org/10.1016/j.isatra.2018.04.002

Lagrangian method to avoid complex calculations. However, in the modeling process, strong coupling caused by eccentric load was found. In Ref. [10], the vibration theory is proposed to study the coupling. And the principle of virtual work [11] can express the force relationship among degree of freedom (DOF) space of the planar redundant drive mechanism and the joint space. The vibration theory and principle of virtual work can be conveniently combined together by Lagrangian method for dynamic decoupling strategy. Motived by this idea, the modeling in this paper combines Lagrangian modeling method, with the vibration theory to study the coupling problem caused by eccentric load.

The decoupling strategy for the parallel mechanism usually includes two aspects: one is to design the structure of mechanism with a decoupling feature [12,13]; The other is designing an effective controller to achieve decoupling [14,15]. The dynamic cross couplings of the novel 2-DOF translational parallel micro-positioning stage between the two linear motions are below −45 dB. The decoupling effect is very significant. However, the parallel micro-platform design can only achieve partial decoupling, and the maximum load is only 300 N. The effect is not ideal under heavy load and high frequency response. The proposed modal space three-state feedback controller in this paper can be a good solution to the aforementioned problems. In the case of an eccentric load of 2 tons, the high frequency dynamic decoupling can still be realized in any position. In contrast, controller decoupling design is more varied. The electro-hydraulic servo shaking table is a complex multi-degree-of-freedom system with strong coupling and non-linearity [16,17]. There are two control frameworks [18] for the parallel mechanism such as the shaking table. The first way is joint space control [19,20], which utilizes the feedback of actual motion state of each actuator to form a control system with all the joint channels keeping closed-loop. The other way is designing controller based on DOF [21,22], which means each DOF channel is in a state of closed-loop. In these two typical frameworks, PID control strategy is used widely due to its simple structure and easy realization [23,24], based on which even some advanced nonlinear control methods, such as Internal model control (IMC) with optimal H2 minimization framework [25], LMS adaptive filtering algorithm [26], robust controller [27], artificial neural networks [28,29], are proposed for improving the performance of parallel mechanism. The above various control strategies have been evaluated and verified according to sinusoidal tracking curve and different performance parameters such as the settling time, overshoot/undershoot in the time domain curve. For example, robust nonlinear task space control [22] sinusoidal tracking error range is reduced by 50% than PID control. In Ref. [23], the system overshoots decayed to 19% in the case of adaptive weighted PSO and around 18% in the case of GA. Indeed, these advanced algorithms are effective in improving system response and tracking performance. However, due to they are designed in DOF space, the strong coupling between the DOF space is determined by the structure parameters of the mechanism itself and belongs to the inherent attributes of the mechanism. Therefore, the controller designed in the physical space can not eliminate the influence of the system coupling. In other words, the controller can not effectively regulate the each DOF space independently. It can only meet the stability of the lowest DOF frequency while sacrificing the rapidity of other DOFs and reducing the dynamic quality to ensure the stability of the overall system, which are only suitable for applications where the accuracy requirement is not high. It is excited that modal space control can rightly solve the problem of strong coupling between DOF space. The most difference is no dynamic coupling exists in the proposed modal space. By coordinating and controlling each independent channel in the modal space, the amplitude of the coupled output is reduced by more than 90%. The decoupling effect is very significant.

Lin et al. [30] and Fang et al. [31] used an inverse system method to realize system decoupling for the multi-degree-of-freedom nonlinear systems. However, these two methods are based on the precise mathematical model of the controlled plant, which is difficult to be obtained. For the linear multi-input and multi-output system, the diagonal matrix method is used as a kind of decoupling control, which means electro-hydraulic robots was decoupled based on a decoupled matrix obtained by the singular value decomposition algorithm [32,33]. In Ref. [34], dynamic pressure feedback was introduced in the modal space. According to the proposed independent control of decoupling channels, the rapidity [32] can be improved by 34% in yaw, 55% in roll, and 56% in yaw. The accuracy of force control of the parallel robotic manipulator [33] can be improved by more than 78%. In Refs. [32–34], the centroid of the load generally coincides with the platform centroid, and the system is studied only in the low frequency range (not larger than 10 Hz). There is no further analysis in the high frequency band. Under the independent modal control, the control performance may be found not to achieve the desired target, because these studies do not show how to achieve the DOF decoupling by coordinating controllers in the modal space. For aforementioned problems, this work has analyzed how each modal channel's closed-loop frequency characteristic to affect the coupling of the DOFs outputs on basis of the deduced modal space theories, and propose the condition of decoupling for DOF channels. As an effective method to expand frequency bandwidth, the three-state feedback control is widely used in the shaking table filed. In order to expand the frequency bandwidth of each model channel, the three-state feedback control was implemented on the position closed-loop by adding velocity and acceleration feedback [35,36]. Velocity feedback can increase the system's natural frequency, and acceleration feedback can increase the damping ratio. Finally, the conclusion is obtained. The amplitude of the coupled output is reduced by more than 90%. And the bandwidth of each DOF channel has also been effectively broadened to 80 Hz. Therefore, this paper will use three-state feedback to control the electro-hydraulic servo system, not in the physical space but in the proposed modal space.

The main contribution of this work is to propose a new control concept, modal space three-state feedback control, for electro-hydraulic servo planar redundant driven mechanism (PRDM). It can effectively reduce the strong coupling among DOFs of the parallel mechanism. The biggest difference is that this paper will analyze how each modal channel's closed-loop frequency characteristic to affect the coupling of the DOFs outputs on basis of the deduced modal space theories. The final conclusion is obtained that the decoupling among the DOF channels can be realized if the dynamic characteristics of modal channels are consistent. And the three-state feedback control can be used to improve the rapidness, stability and accuracy of each modal channel, which can cancel the final output coupling among the DOFs for the parallel mechanism in a lager frequency domain. It is significant to implement modal space three-state feedback control for PRDM.

This paper is organized as following. Section 2 presents the dynamic model of electro-hydraulic servo PRDM. The theoretical modal space analysis of the PRDM and the corresponding decoupling control strategy are elaborated in Section 3 and Section 4, respectively, meanwhile the corresponding theorems are given and proved in these two sections. In Section 5, we analyze and evaluate the designed modal space three-state feedback control by experiments. Finally, main conclusions are summarized in Section 6.

Please cite this article in press as: Zhao J, et al., Modal space three-state feedback control for electro-hydraulic servo plane redundant driving mechanism with eccentric load decoupling, ISA Transactions (2018), https://doi.org/10.1016/j.isatra.2018.04.002