Chinese Journal of Aeronautics, (2017), **xxx**(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Design and performance analysis of position-based impedance control for an electrohydrostatic actuation system

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Received 10 January 2017; revised 5 April 2017; accepted 19 May 2017

KEYWORDS

Actuation system;
Aerospace;
Electrohydrostatic actuator;
Force control;
Nonlinear dynamics;
Particle swarm optimization;
Position control

Abstract Electrohydrostatic actuator (EHA) is a type of power-by-wire actuator that is widely implemented in the aerospace industry for flight control, landing gears, thrust reversers, thrust vector control, and space robots. This paper presents the development and evaluation of position-based impedance control (PBIC) for an EHA. Impedance control provides the actuator with compliance and facilitates the interaction with the environment. Most impedance control applications utilize electrical or valve-controlled hydraulic actuators, whereas this work realizes impedance control via a compact and efficient EHA. The structures of the EHA and PBIC are firstly introduced. A mathematical model of the actuation system is established, and values of its coefficients are identified by particle swarm optimization. This model facilitates the development of a position controller and the selection of target impedance parameters. A nonlinear proportional-integral position controller is developed for the EHA to achieve the accurate positioning requirement of PBIC. The controller compensates for the adverse effect of stiction, and a position accuracy of 0.08 mm is attained. Various experimental results are presented to verify the applicability of PBIC to the EHA. The compliance of the actuator is demonstrated in an impact test.

1. Introduction

The aerospace industry is in search of innovative technologies to realize greener, safer, and cheaper commercial air transport with environmental, competitive, and economic benefits.[1] Many research activities have been conducted in the develop-

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER **Production and hosting by Elsevier**

http://dx.doi.org/10.1016/j.cja.2017.08.015
1000-9361

Please cite this article in press as: FU Y et al. Design and performance analysis of position-based impedance control for an electrohydrostatic actuation system, *Chin J Aeronaut* (2017), http://dx.doi.org/10.1016/j.cja.2017.08.015

ment of power-by-wire (PbW) actuators,[2,3] including electrohydrostatic actuators (EHAs) and electromechanical actuators, to replace conventional hydraulic ones in various applications of electrical actuation systems, such as flight control, landing gears, thrust reversers, thrust vector control, and space robots.[4,5] EHAs are considered the most promising PbW actuators in the medium term for all hydraulic and all electric evaluations. Thus, the use of EHAs is deemed attractive. For EHAs applied in aviation, continuous effort is still being made to improve the performance of a hydraulic system. Nonlinearities[6,7] and parameter uncertainties[8] should be considered during controller design. In addition, the parasitic (mechanical) stiffness should also be considered, which originates from the actuator itself and the environment that affects the airframe; the driven load (non-infinite anchorage and attachment stiffness) should be mitigated. The effect of stiffness-induced resonance on the driven load is serious (i.e., chattering of flight control surface or vibration of landing gear). Several studies have been conducted to realize the force control[9–12] or vibration control[13,14] of an actuator, and effective reactions to external force disturbances have been reported. EHAs can also be used in spaceflight applications. With the continuous development of human space activities, including the establishment of spacecraft and space stations, in-space assembly, space experiments, and space repair work, relying solely on astronauts is inadequate. Consequently, space robotic manipulators have attracted increasing attention, and EHAs may be proven useful in such applications. However, in consideration of environment stiffness uncertainties, relative motion should be considered for precise position control. Thus, force control or feedback should be introduced for these specific applications.

Impedance control allows manipulators to interact with environments in a controlled manner. It is a unified method that allows manipulators to work in both constraint and unconstraint environments. Impedance control has been extensively applied to robotic manipulators[15–17] and hydraulic actuation systems.[18–20] Unlike position control or force control, impedance control can adjust the apparent dynamics of an actuated system. The merits of impedance control become evident in situations wherein an' actuated system is required to interact with the environment and expected to be compliant to avoid damage due to undesirable collision. Impedance control achieves desirable dynamic interaction responses by modifying the relationship between the end-effector motion and the external force. Conventional methods adopt two control algorithms to handle unconstrained and constrained motion states. As a result, algorithms have to detect any occurrence of contact and switch schemes accordingly. Impedance control can be used in the two motion states without incorporating a switching algorithm.

The two types of impedance control are torque-based impedance control (TBIC) and position-based impedance control (PBIC). In TBIC, a torque/force controller is required in the inner loop. Based on the impedance model, the actual position signal adjusts the required torque/force to achieve the desired impedance. By contrast, the inner loop in PBIC is a position loop, and the required position is modified based on the measured interaction force. In robotic applications, TBIC demands an accurate dynamics model of the system, including friction and nonlinearity, and it is sensitive to uncertainties and time-variant parameters.[21] PBIC, however, only requires robotic inverse kinematics, which can be easily computed. Furthermore, PBIC is ideal for hydraulic systems due to the difficulty of force control.[22]

In previous studies, the concept of impedance control was implemented in the contact task control of a manipulator[23] and various robots in manufacturing,[24] rehabilitation,[25–27] cooperation,[28] and service tasks.[29,30] In these applications, all the systems were completely driven by electric motors. However, several hydraulically actuated systems in the industry can benefit from the application of impedance control. Hydraulic systems with high power/weight ratios are appropriate in situations requiring a high torque/force.[31] Heinrichs et al.[32] developed an impedance controller for an industrial hydraulic manipulator with valve-controlled actuators. Impedance control was also implemented in a hydraulic hexapod robot to render the robot adaptable to uneven and soft terrain.[33] As a machine for digging soil or lifting heavy objects, excavators frequently interact with unstructured environments. The implementation of impedance control in autonomous hydraulic excavators has also been reported in the literature.[34,35] For improved vehicle handling and passenger comfort, active suspension systems are used to accommodate the dynamics under different road surface conditions. Robust and adaptive impedance controllers have been introduced to isolate vibration by regulating the interaction between the hydraulic suspension system and the road surface.[36–38]

However, much of previous research on hydraulic impedance control, including the aforementioned studies, focused on valve-controlled actuators/hydraulic servo actuators (HSAs), which suffer from high throttling losses in servovalves. In particular, the application of position-controlled impedance to EHAs is limited and needs immediate attention because most hydraulically actuated machines are moving from valve-controlled actuations to pump-controlled ones. Any development in that direction can increase energy efficiency and benefit the industry. Consequently, studying impedance control applied to EHAs is important due to many applications, in which a system interacts with an unstructured environment and a controlled motion is needed. Kaminaga et al.[39–41] designed backdrivable EHAs and applied them to a humanoid robot, robot hand, and knee power assist device with impedance control. However, these inherently flexible EHAs are passive compliant actuators. Their incapability to achieve high positioning accuracy renders them inappropriate in applications that require precise impedance relationships between the position and the force. To date, impedance control of a general EHA without flexibility has not yet been developed. Further research on the application of PBIC to general EHAs is clearly needed.

In this study, we implement the concept of PBIC in a general EHA. An EHA model is firstly constructed. Knowledge of the model is essential for examining position controller stability and the implementing stable and compliant impedance control. A particle swarm optimization (PSO) algorithm[42] is employed because of the difficulty of identifying the four coefficients in the model. In this algorithm, massive particles are generated to search for the optimal result via iterative calculation. The foundation of PBIC is an accurate and reliable position controller. Friction, inertia, and inevitable leakage are detrimental to an accurate implementation of the position control of the EHA. The nonlinear proportional-integral (PI) position controller introduced by Sepehri et al.[43] for a valve-controlled hydraulic actuator is adopted to achieve

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