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Fuzzy robust nonlinear control approach for electro-hydraulic flight motion simulator

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Abstract A fuzzy robust nonlinear controller for hydraulic rotary actuators in flight motion simulators is proposed. Compared with other three-order models of hydraulic rotary actuators, the proposed controller based on first-order nonlinear model is more easily applied in practice, whose control law is relatively simple. It not only does not need high-order derivative of desired command, but also does not require the feedback signals of velocity, acceleration and jerk of hydraulic rotary actuators. Another advantage is that it does not rely on any information of friction, inertia force and external disturbing force/torque, which are always difficult to resolve in flight motion simulators. Due to the special composite vane seals of rectangular cross-section and goalpost shape used in hydraulic rotary actuators, the leakage model is more complicated than that of traditional linear hydraulic cylinders. Adaptive multi-input single-output (MISO) fuzzy compensators are introduced to estimate nonlinear uncertain functions about leakage and bulk modulus. Meanwhile, the decomposition of the uncertainties is used to reduce the total number of fuzzy rules. Different from other adaptive fuzzy compensators, a discontinuous projection mapping is employed to guarantee the estimation process to be bounded. Furthermore, with a sufficient number of fuzzy rules, the controller theoretically can guarantee asymptotic tracking performance in the presence of the above uncertainties, which is very important for high-accuracy tracking control of flight motion simulators. Comparative experimental results demonstrate the effectiveness of the proposed algorithm, which can guarantee transient performance and better final accurate tracking in the presence of uncertain nonlinearities and parametric uncertainties.

1. Introduction

Hydraulic flight motion simulator (HFMS) has been widely used in hardware-in-the-loop simulation of various aircraft to verify performance indices of sensors, inertial navigation systems and flight control systems. It possesses many advantages including greater power-to-weight ratio, faster response time, larger force/torques output, higher stiffness and less electromagnetic interference compared with the corresponding

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electrical simulator.[1–3] As the typical hydraulic position/angle servo system, hydraulic rotary actuators in HFMS are highly nonlinear, including the nonlinear pressure-flow characteristics of servo valve, nonlinear friction, nonlinear dynamics of pressure, etc.[4,5] Aside from the above nonlinear nature of hydraulic dynamics, HFMS also has a large extent of uncertainties. The uncertainties can be classified into two categories: parametric uncertainties and uncertain nonlinearities.[6] Parametric uncertainties include the large change of payload and the variations in the hydraulic parameters (e.g. bulk modulus and leakage coefficient) due to the change of temperature and component wear. The other category is called uncertain nonlinearities which cannot be modeled exactly, such as nonlinear friction, unstructured leakage and external disturbances. How to deal with these uncertainties, improve the transient performance and guarantee steady-state accuracy, is a key issue in HFMS.

Lots of hydraulic controllers were designed by linear methods.[7–9] However, with increasing high tracking performance requirements in modern industrials, it is hard for linear controllers to achieve higher performance if a working point or the system properties change drastically in hydraulic systems. Vossoughi and Donath[10] developed feedback linearization techniques in electro-hydraulic control systems. Alleyne and Hedrick[11] applied the nonlinear adaptive control to solve parametric uncertainties of hydraulic cylinder. Yue et al.[12] developed robust adaptive control with state observers in hydraulic simulator. The direct adaptive robust control technique proposed by Yao et al.[13] was applied to precision motion control of single-rod actuators. To achieve better online parameter estimation properties to assist in secondary purposes such as fault detection and health monitoring, an indirect adaptive robust control design has recently been proposed.[14–16]

But most aforementioned adaptive controllers based on feedback linearization techniques largely focus on the structured uncertainties, or are restricted to unknown linear parameters. If there exists the unstructured nonlinear uncertainties, tracking precision will be affected due to incomplete compensation unless using switching functions or high feedback error gain. Therefore, unstructured uncertainties in hydraulic systems are the main obstacles to develop high-accuracy tracking control in HFMS. Fuzzy logic systems, radial basis function neural networks or feed-forward neural networks have been proved to be particularly powerful tools for solving uncertain nonlinear problems due to their universal approximation capability.[17–21]

Lots of fuzzy controller are PID-like controllers based on a nonlinear function of the errors, change of errors or acceleration errors, which rely on the trial and error method or a priori expert knowledge of the characteristic of the hydraulic actuators and lack enough adaptability.[22,23] The neuro-fuzzy controller tuned by the gradient-descent method was employed to get the actuator inverse-model, which did not contain stability analysis.[24] A sliding mode control scheme based on fuzzy cerebellar model articulation controller was proposed for the control of electro-hydraulic position system, whose adaptive law was derived based on Lyapunov method. However, the acceleration signal and third order derivative of desired signal must be known in its sliding mode control.[25] The adaptive fuzzy controller was introduced to approach the equivalent control of sliding mode control based on a linearized model of electro-hydraulic system and was verified by simulation. However, it must require the signals of acceleration and the derivative of acceleration as input variables to the fuzzy controller, which are always noisy and are not recommended in practice.[26,27] Most of the above adaptive fuzzy controller adopted the error equations of velocity, acceleration and jerk, which were required in the design procedure of the back-stepping control or sliding mode variable structure control. In this paper, a simple robust nonlinear controller based on adaptive multi-input single-output (MISO) fuzzy compensators are synthesized to deal with uncertain nonlinearities and parametric uncertainties in hydraulic rotary actuator of HFMS, which does not need acceleration, jerk and high-order derivative of desired signal.

A method to reduce the number of total fuzzy rules through the decomposition of uncertainty function is also proposed. Uncertainty functions are decomposed into two parts, uncertainty related with leakage and uncertainty related with fluid elastic. Due to the special composite vane seals of rectangular cross-section and goalpost shape used in hydraulic rotary actuators of HFMS, the leakage model is more complicated than that of traditional linear hydraulic cylinders. So different from traditional leakage model proportional to the load-pressure P_L, the leakage model in this paper is considered as the nonlinear function related to P_L and the output angle x_1 of motor. The flow of fluid elastic compression is also taken as the nonlinear function related to load-pressure's derivative $\dot{P}_L$ and x_1. So two MISO fuzzy logic compensators (FLCs) are adopted to estimate the above nonlinear functions respectively. Different from other adaptive fuzzy compensators,[24–30] in order to guarantee that the estimation process is bounded and the system is stable, a discontinuous projection mapping is employed in adaptive fuzzy compensators. So the proposed controller accounts for not only the structured uncertainties (i.e. parametric uncertainties), but also the unstructured uncertainties (i.e. unstructured items of leakage and fluid elastic compression). Furthermore, the controller can theoretically achieve a guaranteed transient performance and final tracking accuracy in the presence of the above uncertainties, which is very important for high-accuracy tracking control of HFMS. Finally, comparative experimental results are presented for the motion control of a hydraulic rotary actuator to verify the effectiveness of the proposed controller.

2. System description and problem formulation

The flight motion simulator in Fig. 1 is configured with an orthogonal outer axis frame (yaw), a middle axis frame (pitch) which is horizontal to the outer axis, and an inner axis frame (roll) supported by the middle axis frame and a base. The inner axis has limited angular freedom and is driven by a hydraulic rotary actuator that is fixed onto the middle frame to rotate about the roll axis. A hard-anodized aluminum tabletop on the roll axis serves as the payload mounting surface. The outer axis frame with limited angular motion rotates around a vertical yaw axis and is driven by a hydraulic rotary actuator located inside the base. The middle axis frame with limited angular motion moves around a horizontal pitch axis and is driven by another hydraulic rotary actuator, which is fixed onto the outer frame. The hydraulic rotary actuator in HFMS is also described by Fig. 1, which consists of servo-valve, controller, hydraulic motor, load and angle encoder.