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Robust fault-tolerant controller design for aerodynamic load simulator

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ABSTRACT

Load simulator is one of the main mechanisms for stability and performance evaluation of the rotational/translational actuators in the laboratory. The movement of (under testing) actuator generates a large disturbance on the load simulator known as "extraneous torque". Elimination of this large surplus disturbance is the main concern of the dynamic load simulator design. The faults are unavoidable events in system operation. Sensor or actuator faults frequently occur in flight systems. The design method based on Quantitative Feedback Theory (QFT) can be used as a passive Fault-Tolerant Control (FTC) of the plants with sensor or actuator faults. In this paper, a QFT-FTC is proposed for the electric load simulator (ELS) in presence of sensor and actuator faults. For this purpose, a particular type of faults is used, which the sensor and actuator faults are considered as semi-deterministic jumps that occurring at random intervals with random amplitudes. In the first step, the faults are converted to parameter uncertainties and disturbance is transferred to the input and output of the plant. Then, a QFT controller is designed for this uncertain plant. Proposed QFT-FTC attenuates the large disturbance even if the control effort is limited. Under these circumstances, an adequate bandwidth is achieved. Furthermore, semi-deterministic jumping faults on sensor and actuator are applied during the simulations and high robust tracking performance is obtained in presence of the saturated control. Compared to H-infinity Controller, the proposed controller has a simpler structure and its tracking performance is better than H-infinity method.

1. Introduction

In flight systems, aerodynamic loads influence on the control surface continuously. These dynamic loads depend on flight conditions and actually they are complex functions of surface angle, altitude, Mach number and so on [1]. The actuators that control these surfaces ought to tolerate the dynamic load and simultaneously continue their operation without interrupting. Load simulator generates the dynamic load in the laboratory and is a key device in the hardware-in-the-loop simulation (HILS) [2]. Traditionally, electro-hydraulic load simulators (EHLS) have been commonly used for evaluating the stability and performance of the actuators. However, recently Electric Load Simulators (ELS) have been improved and are used in practical applications and academic researches. Nowadays, ELSs are used in the various technical fields such as robotics, aerospace, wind energy and elevator systems [3].

In loading process, (under testing) actuator rotates in a different scenario and the load simulator should generate the desired loading torque and simultaneously follows the actuator rotation. However, rotation of the actuator shaft generates a redundant or extraneous torque on the load simulator. Attenuation of this large surplus disturbance is the main concern in the ELS control design problem.

Feedforward compensation was used in many researches to overcome surplus torque in ELS [4,5]. In [6], the invariance theory was used for ELS design by using a feedforward compensator for external disturbance attenuation. A speed controller for ELS was proposed in [3], to improves the dynamic performance and stability of ELS. This controller was composed of a proportional control, a speed reference feedforward and a load torque compensation terms. For implementation of the feedforward compensator, the actuator's angle/speed signal and its derivatives are used. However, there are some limitation for "selecting the feedforward parameters", "the higher-order differentiating of actuator's angle/speed" and "improving the control effort", which degrade the performance of ELS in practice [7]. In [8], the mathematical model of the ELS is built using the physical modeling of Permanent Magnet Synchronous Motor (PMSM) for controller design, in addition, the effect of the rudder performance on the model was discussed. Many efforts have been made to avoid higher-order differentiat-

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ing. However, to reach this goal, the accurate models of ELS and actuator are necessary [3].

Because of nonlinear and uncertain nature of electro-hydraulic torque/force simulator models, robust control methods have been used commonly for EHLS. The mu-synthesis control theory was applied to design a robust controller to deal with various system uncertainties for controlling torque in EHLS in [9]. This method receives 10 Hz bandwidth with dual-ten performance index (i.e. error in amplitude less than $\pm 10\%$ and the lag of phase less than $10°$). Quantitative Feedback Theory (QFT) is used in [10,11] for designing a controller for linear movement elector-hydraulic force simulator. Although the self-tuning QFT controller [12] improved the classic design tracking performance, it resulted in poor performance and narrow bandwidth. Variable structure sliding mode controller was proposed in [13,14] and eliminated extraneous disturbance with high tracking performance.

Adaptive design methods are another strategies commonly used in EHLS and ELS. Authors in [15] proposed an adaptive predicting schema to predict the surplus disturbance. A model-based Adaptive Robust Torque Control (ARTC) algorithm was proposed in [16], which converts the external disturbance attenuation problem to a performance-oriented problem, under uncertainties and nonlinearities. An Adaptive Fuzzy Torque Control (AFTC) algorithm was proposed in [17]. Although theoretically these methods improve the ELS performance, the achieved bandwidth is low and the control effort limitation is not considered during the design stages. In addition, these strategies are not fault tolerance.

Many intelligent control strategies have been presented, to improve the tracking performance of ELS in presence of complex nonlinearities and uncertainties (e.g., friction, backlash, etc.). For example, an adaptive wavelet neural network with double sliding modes controller was proposed in [2]. In [18], a Variable-Structure Wavelet-Neural-Network (VSWNN) identification strategy was used. An adaptive fuzzy self-recurrent wavelet neural network controller with variable structure (VSFSWC) was introduced in [19]. In [20,21], the fuzzy logic was applied to cerebellar model articulation controller (NFCMAC), furthermore, the PID controller based on Wavelet Neural Network (WNN) was proposed in [22]. The fuzzy multi-resolution WNN (FMWNN) controller with dynamic compensation was used in [23] and the adaptive fuzzy fractional order sliding mode control (FFOSMC) was proposed in [24,25]. These methods were presented to resolve the parameter uncertainties and model nonlinearities problem. Other methods based on fuzzy control and neural network were proposed for ELS in [26,27]. Theoretically, these strategies received good performance and stability; in addition, they are dependent on the training/adaption process. These methods require the appropriate conditions for good learning/adaption; therefore, the achieved bandwidth in presence of control effort constraints is limited. Furthermore, most of these intelligent schemes have no practical application or have undesirable performance [15].

Fault-Tolerant Control (FTC), commonly known as reliable control, takes into account unexpected system failures at the early design stage. FTC is a design method that maintains an acceptable level of control even after the occurrence of the faults [28]. A more formal definition of the FTC is given as "a control system where a fault is accommodated with or without performance degradation, but a single fault does not develop into a fault on subsystem or system level" [29].

As previously mentioned, many control methodologies have been designed for ELS. The passive loading process and active rotation of actuator enlarge the extra torque and shrink the practical bandwidth of ELS [30]. The tracking error is significantly large and computational complexity is high when the actuator changes its direction fast or when its frequency is large [18].

The faults/failures in the system are categorized in three class as follows [31]:

1. Additive measurement faults: discrepancies between the measured and true value of the plant output or input variables, e.g., sensor bias,
2. Additive process faults: acting disturbances (unmeasured inputs) on the plant, which are normally zero and cause a shift in the plant output independent of measured inputs, e.g., plant leaks and loads,
3. Multiplicative process faults: abrupt or gradual changes of plant parameters.

In this paper, the sensor and actuator faults are considered as semi-deterministic jumps occurring at random intervals with random amplitudes. The ELS has special loading conditions (such as large surplus torque, limited bandwidth, nonlinearity and uncertainties in modeling, etc.). Therefore, the load simulator is an appropriate case study for designing a variety of controllers. Furthermore, while the load simulator is used on-ground to test the actuators, previously mentioned conditions motivate us to use the ELS for QFT-FTC design. The results of the proposed QFT-FTC design shows that this methodology can be used to design fault tolerant servo-systems for actuators.

Passive FTC is a class of the FTC that does not take into account fault detection and diagnosis (FDD) during the plant operation. Once a fault occurs, the control system tolerates the faults robustly without instability and reducing the performance from designing specifications. Passive FTCs are based on robust controller design techniques and aim at synthesizing one (robust) controller that makes the closed-loop system insensitive to certain faults. This approach requires no online detection of the faults, and is therefore, computationally more attractive [32,33]. However, the passive FTCs can only consider the limited type of fault. These FTC methodologies, conservatively consider the faults at the early stages of the design (usually as uncertain parameters or unknown inputs).

QFT design method is suitable for plants with parametric and unstructured uncertainties. The concept was introduced by Horowitz in the early 1960s and was later refined by him and others into a controller design technique [34]. QFT emphasizes the fact that feedback is only necessary because of uncertainty and that the amount of feedback should be directly related to the extent of plant uncertainty and unknown external disturbances. Therefore, the method takes into account quantitative information on plant's variability, robust performance requirements, tracking performance specification, and disturbance attenuation requirement. The controller is designed to ensure that robustness and disturbance rejection requirements can be met [32].

In this paper, some special characteristics are considered in the FTC design of the ELS that are more important in practical applications:

- First, the control effort limitation: in the most situations, when a fault takes place the control effort increase significantly. In addition, large surplus disturbance requires significantly control actions,
- Second, the presence of large disturbance, simultaneously with time-varying jumping faults, which increases the complexity of controller design,
- Third, frequency-dependent disturbance affects not only the output directly, but also acts as a load on the ELS. Therefore, this is not standard case for QFT design.

In this paper, a fault tolerant controller based on QFT (called QFT-FTC) for ELS is proposed. Sensor and actuator faults are considered, and these faults are converted to parametric uncertainties.