Mixed Kalman-Fuzzy Sliding Mode State Observer in Disturbance Rejection Control of a Vibrating Smart Structure

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In the controllers that are synthesized on a nominal model of a nonlinear plant, the parametric matched uncertainties and nonlinear/unmodelled dynamics of the high order nature can significantly affect the performance of the closed-loop system. On this note, owing to the robust characteristic of the sliding mode observer against modelling perturbations, measurement noise, and unknown disturbances and due to the non-fragile behaviour of the Kalman filter against process noise, a mixed Kalman sliding mode state-observer is proposed and later enhanced by the addition of an intelligent fuzzy agent. In light of the proposed technique, the chattering phenomena and the conservative boundary layer of the high gain sliding mode observer are addressed. Then, a robust active disturbance rejection controller is developed by using the static feedback of the estimated states using a direct Lyapunov quadratic stability theorem. The reduced order plant for control design purposes is subjected to some simulated square-integrable disturbances and is assumed to have mismatched uncertainties in the system matrices. Finally, the robust performance of the closed-loop scheme with respect to the mentioned perturbation signals and modelling imperfections is tested by implementing the control system on a mechanical vibrating smart cantilever beam.

1. INTRODUCTION

The uncertainty of the perturbation of the plant model from its real states may lead to unexpected behaviour of the closed-loop system. Thus, it is vital to take into account the effects of such perturbations in the structure elements during the modelling process.\(^1\)\(^-\)\(^3\) Such a view leads to robustness of the predicted response of the system as well as increasing the applicability and reliability of the designed controller. On the other hand, the model-based regulators were developed based on the simplified mathematical replicas of the real plant. These two modelling requirements constrain the control methodologies derived based on the norm-bounded representations of unmodelled dynamics, parametric uncertainties, and exogenous disturbance. Thus, a robust controller may be considered as the main candidate that justifies these inquiries.\(^4\)\(^,\)\(^5\)

Kalman filtering is extensively employed in state estimation. Nevertheless, it is recognized as unable to handle large modelling uncertainties.\(^6\)\(^,\)\(^7\) The sliding mode observer (SMO) was proposed to address this issue both for the dynamical systems with linear and nonlinear behaviour under large disturbance signals. Based on the classical sliding mode (SM) technology, a discontinuous switching function was utilized to hold the trajectory of the observation residuals on a manifold. Hence, the observation residuals became independent of the modelling perturbations in estimation error space. A central concern of the SM technique was the sensitivity of the control system to the uncertainties in the reaching phase, during which the error trajectory travelled toward the sliding surface.\(^8\) In recent years, some investigations were performed in order to examine the effects of these parametric uncertainties in the robust performance of SMO.\(^9\) A standard design configuration for SMO was based on the equivalent control (EC) theory. Accordingly, for nonlinear dynamical systems subjected to bounded uncertainties, the output observation error together with its high order derivative were employed to construct a sliding manifold.\(^10\)

A SM controller (SMC) and observer have one common drawback, namely, the chattering phenomenon that excites the high-order dynamics of the system, which were mostly neglected in the design procedure. The second issue in the actuating element was the high control activity, non-smooth actuation, and actuation saturation in the SMC.\(^11\) An accepted workaround for this problem was modifying the switching function of SM technique to a neighbouring boundary function such as saturation function which lead to a finite steady-state error.\(^12\) The neighbouring layer depth was dependent on the switching gain. Notably, if the system was exposed to a large disturbance amplitude and modelling perturbations, the SM system required a thick boundary layer to account for the chattering problem. Such a behaviour prevented the error dynamics to slide toward the SM manifold, and, therefore, a broad boundary layer was mostly undesirable in control systems. In contrast, an intelligent element such as a fuzzy set based on linguistic variables may transfer the knowledge of the SM expert to the observer element instead of a passive boundary neighbours function.\(^13\) In this paper, a Mamdani fuzzy mapping was used to create a smooth switching function that can: i) handle the parametric uncertain terms in state, input, and output matrices in state space representation of the plant; ii) treat the nonlinear norm-bounded globally Lipschitz unmodelled dynamics; and iii) mimic the behaviour of boundary layer neighboring function without the mentioned drawbacks. For this purpose, a nonlinear multi-input-multi-output (MIMO) system