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Research article

Active disturbance rejection control based robust output feedback autopilot design for airbreathing hypersonic vehicles

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ABSTRACT

Since motion control plant ($y^{(n)} = f(\cdot) + d$) was repeatedly used to exemplify how active disturbance rejection control (ADRC) works when it was proposed, the integral chain system subject to matched disturbances is always regarded as a canonical form and even misconstrued as the only form that ADRC is applicable to. In this paper, a systematic approach is first presented to apply ADRC to a generic nonlinear uncertain system with mismatched disturbances and a robust output feedback autopilot for an airbreathing hypersonic vehicle (AHV) is devised based on that. The key idea is to employ the feedback linearization (FL) and equivalent input disturbance (EID) technique to decouple nonlinear uncertain system into several subsystems in canonical form, thus it would be much easy to directly design classical/improved linear/nonlinear ADRC controller for each subsystem. It is noticed that all disturbances are taken into account when implementing FL rather than just omitting that in previous research, which greatly enhances controllers' robustness against external disturbances. For autopilot design, ADRC strategy enables precise tracking for velocity and altitude reference command in the presence of severe parametric perturbations and atmospheric disturbances only using measurable output information. Bounded-input-bounded-output (BIBO) stable is analyzed for closed-loop system. To illustrate the feasibility and superiority of this novel design, a series of comparative simulations with some prominent and representative methods are carried out on a benchmark longitudinal AHV model.

1. Introduction

Owing to its bright prospect of reliable and cost-effective access to space and great potential for prompt global reaching capability, scramjet powered airbreathing hypersonic vehicle (AHV) has received tremendous attention since it appears. From 1980s' NASP program to latest X-51 program, vast quantities of theoretical research and flight tests are lastingly conducted on it and many significant achievements have been reached in the past four decades. But at the same time, quite a little sobering failure also reveals some key technologies supporting the realization of AHV are still need further advance, among which is the flight control system design.

In general, AHV could speed up to Mach 5 and above within a quite huge flight envelope, which results in dramatic and rapid variation of atmospheric parameters in a large range [1]. And for the absence of hypersonic wind-tunnel and high expense, there is currently no adequate wind-tunnel or flight test data to refine existing empirical aerodynamic model [2]. To optimize aerodynamic characteristics, airframe/propulsion/structural integrated design is widely adopted in AHV configuration. Nevertheless, this design leads to strong thermal-flow-elastic coupling and further intensifies nonlinearity of dynamics model [3]. All of these make the control system design for AHV highly challenging and being an attractive hot topic within both aerospace and control community. Despite abundant pioneering and valuable fruits of years of extensive research on this topic, few of them can be applied in practice for complicated controller structure, unaffordable computation burden for onboard computer, as well as certain unreasonable assumptions. For instance, a common assumption can be found in majority of previous research is full vehicle states are available for measurement [4,5]. In fact, accurate and real-time measurements of certain states of vehicle, such as angle of attack and flight path angle, are usually difficult and costly [6]. Therefore, besides supplying precise tracking performance to guidance command and satisfying stability for whole closed-loop system, a desired AHV autopilot for aerospace control

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engineers should also be simple in structure, fast in computation, robust against disturbances, and the most importantly realizable in practice.

Conventionally, to guarantee a stable flight for most traditional AHV controllers, encountered internal perturbations and external disturbances are contended with either by utilizing robust control technique to enhance robustness of controllers or by implementing an adaptive strategy to attenuate the adverse effect of perturbations for baseline controllers. As early as 1994, Gregory et al. had elaborated the applicability of robust control technique to a 10-state linear AHV model [7]. Recently, Lan et al. developed H_∞ control to realize decoupling tracking control for a hypersonic vehicle [8]. Based on hybrid particle swarm optimization algorithm, stochastic robustness analysis is utilized to search for the optimum controller parameters to maximum system robustness [9]. However, robust control methodology is developed for linear models. So, as stated in Ref. [10], it is unreasonable to expect an acceptable performance to be maintained over the entire flight envelope or a large set of trim conditions for a robust controller. To address this problem, a group of linear parameter varying (LPV) based AHV autopilots are proposed. By using Jacobian linearization or tensor-product modeling method, a series of controllers synthesized based on obtained linear time invariant system, such as H_∞ controller in Ref. [11] and robust model predictive controller in Ref. [12], are scheduled by a priori unknown but measurable exogenous parameter. Adaptive control is another frequently-used methodology to accommodate to parametric uncertainties. Enhanced by adaptive strategy, the autopilots synthesized based on sliding mode control [13], fault-tolerant control [14], back-stepping control [15], and $\mathcal{L}_1$ control [16], etc., were developed to suppress parametric perturbations for AHV attitude control. Although being able to improve robustness against parametric uncertainties, these controllers need further investigation on diminishing the influence of unmodeled dynamics and unknown disturbances. Since no sufficiently precise control-oriented model is accessible to engineers, intelligent control strategy is recently applied to approximate complicated flight dynamics [17] and/or unknown exogenous disturbances [18,19] with Takagi-Sugeno (T-S) fuzzy model and/or neural network (NN). To reduce considerable computational burden because of using NN, Bu et al. proposed employing only one NN to approximate the lumped uncertainty for each decomposed velocity and altitude subsystem and adopting minimal-learning-parameter scheme to estimate the norm rather than the elements of NN's weight vector [20]. For all aforementioned methodologies, the internal perturbations and external disturbances are both suppressed passively by controllers' robustness authority. However, if the encountered uncertainties are beyond inherent authority, the deterioration in tracking control performance would not be tolerated for high-performance AHV. In Ref. [21], Liang et al. attempted to address the climbing, cruising and descending flight control problem for a longitudinal AHV model with proportional-integral-derivative (PID) strategy. Similarly based on this principle of eliminating the error based on the error, more researchers turned to an emerging disturbance-centric controller-rejector tandem paradigm. Unlike traditional model-based control methodologies, this error-driven controller focuses more on reconstructing and actively rejecting "total disturbance" so as to make nominal system disturbance-free no matter the "total disturbance" is stemmed either from an internal source or from the external environment. Owing to this unique philosophy, these dual-unit controllers always exhibit unbelievable excellent control performance and strong robustness. A plenty of research efforts are available in literature based on extended state observer (ESO) (or active disturbance rejection control (ADRC)) [22–24] and nonlinear disturbance observer (NDO) [25–27], both of which are the two significant methods mainly studied in this field. However, for this promising methodology, several intractable puzzles are still left to be solved.

Various unknown uncertainties usually interrupt AHV dynamics via different channels from control inputs and are conventionally called mismatched disturbances. Whereas, how to cope with mismatched disturbances for observer based control is always thorny. For NDO based control (NDOBC), this issue boils down to designing a mismatched disturbance compensation gain to attenuate the adverse effect from output channel, such as [28]. But designing an appropriate compensation gain is too skilful to complete in effect. In addition, the disturbance compensation gain and the baseline controller gain that serves to achieve desired nominal performance are conventionally devised simultaneously in an integral manner. Thus, as pointed out by Peng et al. [29], two kinds of controller gains always influence each other, which further results in receiving robustness against disturbances inevitably at the expense of sacrificing nominal performance to some extent. More importantly, entire controlled system model as well as all system states are required for constructing a disturbance observer. However, since certain flight states, such as angle of attack and flight path angle, can not be accurately measured in real-time, this requirement can not be satisfied in an actual flight. Hence, despite such fruitful theoretical results corresponding to NDOBC, few of them can be directly applied in practice. To bridge this gap between theoretical investigation and engineering practice, several observers are proposed to estimate those unmeasurable flight states, such as immersion and invariance observer [6], high-gain observer [14], sliding mode observer [30]. However, all of these observers are constructed based on disturbance-free dynamics model and the stability condition will be broken if disturbances exist. Therefore, only mild uncertainties and/or disturbances can be accommodate to for these controllers.

Compared to NDOBC, ADRC only requires input-output information, thus aforementioned problem is completely avoided. For instance, Zhang et al. proposed a robust autopilot based on high-order ESO for a longitudinal AHV model just relying on measurable output information [23]. To satisfy the canonical form for constructing ESO, feedback linearization (FL) technology is applied in this study. Whereas, no any uncertainty is taken into consideration when implementing FL but a lumped disturbance is directly augmented to resultant linearized model. Although this handing can be found in many related literature, such as Refs. [4,27], it stands to reason that controller synthesized in such way can not fully attenuate the adverse effect of those omitted but unavoidable perturbations and/or disturbances. Actually, a significant reason for adopting such less rigorous handing is lacking a systematic method to answer the problem that how to apply ADRC to nonlinear uncertainty systems, which would be neither integral chain systems nor (block) strict feedback plants. The complicated flight dynamics system is a good case in point. Since motion control plant ($y^{(n)} = f(\cdot) + d$) was repeatedly used to exemplify how ADRC works when it was proposed [31], the integral chain system subject to matched disturbances is always regarded as a canonical form and even misconstrued as the only form that ADRC is applicable to. To the best of authors' knowledge, Li et al. first proposed a generalized ESO based control (GESOBC) to extended ADRC to non-integral chain linear systems subject to mismatched disturbance [32]. This pioneering work gave researchers a refreshingly new outlook for utilizing ADRC, especially for flight autopilot design [33–35]. However, this methodology still focuses on linear systems, which means complicated nonlinear flight dynamics has to be linearized and the stability for closed-loop system is only guaranteed around operating point. In addition, just like NDOBC, mismatched disturbance is compensated for in this design also by designing a mismatched disturbance compensation gain. Similarly, this is not an easy job to fulfil, especially for multi-input-multi-output (MIMO) system. To handle nonlinear flight dynamics, a six degree of freedom nonlinear missile dynamics model was described as block strict feedback form for the first time in Ref.