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Robust SISO H_∞ controller design for nonlinear systems

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Abstract

Presented in this paper is a nonlinear SISO controller design methodology for a class of Hammerstein models. The design process is composed of standard system identification techniques integrated with an H_∞ linear controller synthesis formulation. The system identification portion of this work first identifies the static, single-valued nonlinearity capturing the nonlinear behavior of the system. This nonlinearity is then inverted and serves as a precompensator to the system input. The frequency response function is then identified with the precompensator in place to capture the linear dynamics of the system. Errors associated with the nonlinear inversion are addressed in an unstructured uncertainty formulation. A robust H_∞ controller is synthesized using the identified uncertain Hammerstein model and a systematic performance weighting selection process for a class of L_∞ constraints. Closed-loop performance and stability are assessed via sector bounds quantifying the maximum allowable precompensator error. Frequency domain conditions guaranteeing an L_2 output provided the system input belongs to L_2 are also presented. To illustrate the procedure, the design methodology is applied to synthesize a robust feedback controller to regulate the mass air flow of a 4.6 L V8 spark ignition engine equipped with an electronic throttle.

Keywords: Control system analysis; Control system design; Engine control; H-infinity control; Nonlinear models; Robust control; Weighting functions

1. Introduction

Today there exist many techniques that separately address system identification and controller design. However, these individual knowledge bases have not been harvested to produce a systematic controller design solution. Furthermore, after the controller has been determined, it is not always clear how to quantify the robustness of the design.

El-Farra developed an approach to design SISO controllers for nonlinear systems with uncertainty and input constraints (El-Farra & Christofides, 2001). This method focused on a general Lyapunov-based design that did not provide a direct method of enforcing output constraints. Hedrick presented a multiple sliding surface method developed for a class of uncertain nonlinear systems (Hedrick, 1998). In this method, input and output constraints are not considered. Genetic Algorithms (Al-Duwaish & Bettayeb, 1997) and sinusoidal-input describing functions (Zhuang & Atherton, 1996) have also been used to design controllers for nonlinear systems. However, none of these methods have incorporated system identification techniques, input and output constraints, and an evaluation of modeling error into the total controller design process.

The controller design methodology advanced in this manuscript addresses the robust SISO controller design problem for nonlinear systems, specifically uncertain

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linear plants preceded by static nonlinearities (Hammerstein models). Existing system identification techniques have been integrated with a controller design process in this methodology. The contributions of this work are four fold: (1) a methodology for robust SISO controller synthesis for class of nonlinear systems described by uncertain Hammerstein models, (2) a systematic method for selecting H_∞ weighting functions for a class of L_∞ constraints, (3) a measure of system robustness specifically addressing the maximum allowable modeling and nonlinear inversion errors, and (4) frequency domain conditions guaranteeing an L_2 output provided the system input belongs to L_2.

The systematic robust SISO controller design process for nonlinear systems presented in this manuscript combines a common technique for system identification and a controller synthesis process into a complete systematic procedure. The process is broken into three distinct parts: system identification, controller synthesis, and system analysis.

Modeling efforts are focused on an experimental method of system identification that captures nonlinear plant characteristics. The system identification process involves the identification of the plant nonlinearity followed by the identification of the uncertain linear plant dynamics. The errors between the nonlinear model and the actual system data are incorporated as unstructured uncertainty. Since uncertainty is present, a robust controller design methodology that guarantees system performance is required.

A result of choosing the H_∞ design methodology is that the closed-loop system performance is contingent upon the choice of the performance weighting functions. The selection of these weighting functions is often difficult, although, general guidelines for their development do exist. Many papers document techniques and guidelines for weighting function selection. General frequency domain guidelines are given in Meghani and Latchman (1992) and Grimble and Biss (1988). Chun and Hori (1996) provide typical weighting functions and tuning methods. A method for determining weighting functions which represent position and rate limit constraints of an actuator as well as a procedure for controlling the closed-loop system overshoot are provided in Hu, Unbehauen, and Bohn (1996), Hu, Bohn, and Wu (1999), Hu, Bohn, and Wu (2000). An experimental solution for weighting function selection, implementing orthogonal arrays, is presented by Yang, Ju, and Liu (1994). Genetic algorithms have also been employed to search for suitable weighting function solutions (Donha, Desanj, & Katebi, 1997). Further studies regarding methods of weighting function selection may be found in Postlethwaite, Tsai, and Gu (1990) and Beaven, Wright, and Seaward (1996). The technique chosen for the procedure described in this manuscript was developed by Franchek where the weighting functions are chosen in a manner which enforces time domain tolerances (Franchek, 1996). This method of weighting function selection will be extended in this work to address the controller design objectives of maximizing the allowable reference step size to the system and maximizing the system tracking response.

Following the controller synthesis process, the maximum allowable modeling and nonlinear inversion errors are determined from a stability analysis. Finally, provided certain frequency domain conditions are satisfied and the system input belongs to L_2, an L_2 output may be guaranteed.

To illustrate this procedure, the design methodology is applied to synthesize a robust feedback controller to regulate the mass air flow (MAF) of an engine. In this application, a Hammerstein model of a 4.6 L V8 spark ignition engine from an electronic throttle input to engine MAF output is identified. An H_∞ tracking controller is then designed to control engine MAF with zero steady-state error while addressing the nonlinear throttle characteristics and time delay. Experimental data validates successful closed-loop performance which includes noise and disturbance rejection while maintaining good transient and steady-state performance.

2. Problem statement and method of solution

Consider the standard Hammerstein model given in Fig. 1 where $\tilde{u}(t) \in L_\infty$ is the system input, $n(\cdot)$ is a static single-valued nonlinearity operating on $\tilde{u}(t)$, $p(t) \in L_2$ is an impulse response function, and $y(t) \in L_\infty$ is the measured system output (Ljung, 1999). It is assumed that both $n(\cdot)$ and $p(t)$ exist but are unknown a priori.

The closed-loop tracking performance specifications for this class of systems includes a control effort constraint and an allowable tracking error constraint. The time domain control effort constraint about a nominal effort is given as

$$|u(t)| \leqslant \kappa \quad \forall t > 0 \tag{1}$$

and the tracking deviation constraint is

$$|e(t)| \leqslant \delta \quad \forall t > 0, \tag{2}$$

where $e(t)$ is the tracking error of the closed-loop system. All time domain specifications are known a priori and it is assumed the system is initially at rest. The goal specifically addressed in this work is to design a nonlinear feedback controller that meets the closed-loop performance specifications of Eqs. (1) and (2).

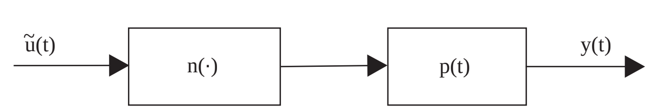

Fig. 1. General Hammerstein model.