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Adaptive Stabilization of Uncertain Generalized Duffing-Holmes Control Systems via a Single Input

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Abstract :*This paper investigates the adaptive controller design problem for a class of uncertain nonlinear control systems characterized by a single control input. In particular, by employing appropriate differential and integral inequalities, together with time-domain analysis techniques, an adaptive single-input control strategy is systematically developed for uncertain generalized Duffing-Holmes control systems. The proposed adaptive control scheme is designed to compensate for the effects of system uncertainties and nonlinear input characteristics, thereby ensuring the global stability of the resulting closed-loop system. Furthermore, the developed methodology provides an effective approach to handling the control difficulties arising from uncertain nonlinear dynamics under the restriction of a single control input. Finally, several numerical simulation studies are conducted to demonstrate the applicability of the proposed controller and to further verify the feasibility, reliability, and effectiveness of the theoretical results established in this paper.*

Keywords: adaptive stabilization, nonlinear system, uncertain systems, single input

I. INTRODUCTION

In recent years, a considerable amount of research attention has been devoted to the investigation of various chaotic systems and their associated control problems; representative studies can be found in [1]-[15] and the references cited therein. The growing interest in chaotic systems arises not only from their considerable theoretical significance in nonlinear dynamics but also from their potential applications as useful analytical tools in practical system modeling, performance analysis, and control system design. In many engineering applications, chaotic behaviors may lead to undesirable dynamic characteristics, potentially resulting in system instability, irregular oscillations, and unpredictable state responses. Consequently, developing effective control strategies to suppress chaotic oscillations and regulate the dynamic behavior of nonlinear systems has become an important research topic. Over the past several decades, numerous control methodologies have been proposed and successfully applied to the robust control and stabilization of chaotic systems. These approaches include variable structure control methods, adaptive sliding mode control techniques, adaptive control strategies, backstepping-based control approaches, and several other nonlinear control methodologies.

As is generally recognized, the design and analysis of controllers for nonlinear dynamical systems are considerably more complicated than those associated with conventional linear systems. This difficulty becomes even more pronounced when the system under consideration involves multiple types of uncertainties, since uncertain parameters and external disturbances may significantly affect the system dynamics and consequently increase the complexity of controller construction and stability analysis. In addition, when a control system is restricted to using only a single control input, the controller design problem becomes particularly challenging because the available control authority must be appropriately utilized to compensate for different uncertain and nonlinear effects simultaneously. Compared

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with control systems equipped with multiple independent control inputs, single-input control systems provide fewer degrees of freedom for controller design, thereby making the development of an effective stabilization strategy substantially more demanding.

Motivated by the aforementioned considerations, our research focuses on addressing the challenging controller design problem for a class of uncertain nonlinear control systems involving multiple uncertainties and only a single control input. More specifically, this study investigates the stabilization problem of generalized Duffing-Holmes control systems in the presence of mixed uncertainties and uncertain input nonlinearities. By utilizing time-domain analysis techniques in conjunction with several algebraic inequalities, an adaptive control scheme is developed to ensure the global stability of the entire closed-loop system. The proposed control strategy is intended to effectively compensate for the adverse influences caused by uncertain system dynamics while maintaining the stabilization capability under the restriction of a single control input. Furthermore, to demonstrate the validity and practical applicability of the theoretical developments, an illustrative example accompanied by several numerical simulation results is presented. These simulation studies provide further evidence of the effectiveness of the proposed controller and verify the correctness of the main theoretical results established in this paper.

The remainder of this paper is organized as follows. Section II introduces the mathematical formulation of the uncertain generalized Duffing-Holmes control system and establishes the main theoretical results concerning the proposed adaptive stabilization approach. Section III presents an illustrative numerical example and provides several simulation results to demonstrate the effectiveness and applicability of the developed control methodology. Finally, Section IV summarizes the major findings of this investigation and presents the concluding remarks.

II. DESCRIPTION AND MAIN RESULTS OF UNCERTAIN NONLINEAR SYSTEMS

Terminology and notation

$\Re^n$	the n-dimensional Euclidean space;
$\|x\|$	the Euclidean norm of the vector $x \in \Re^n$;
$R^{m\times n}$	the set of all real m by n matrices;
$\|a\|$	the modulus of a complex number a;
I	the unit matrix;
A^T	the transport of the matrix A;
$\sigma(A)$	the spectrum of the matrix A;
$P > 0$	the matrix P is a symmetric positive definite matrix.

In this paper, we consider a class of uncertain generalized Duffing-Holmes control systems subject to uncertain input nonlinearities, which can be mathematically represented by

$$\dot{x}_1 = x_2, \tag{1a}$$

$$\dot{x}_2 = q_1x_1 + q_2x_2 + q_3x_1^3 + q_4x_1^5 + q_5\cos(w_1t) + \Delta f(x_1, x_2) + \Delta\varphi(u),\ \forall t \geq 0. \tag{1b}$$

In this formulation, $x = [x_1 \quad x_2]^T \in \square^{2\times1}$denotes the state vector, u∈R represents the control input, Δ f(x_1,x_2) characterizes the mixed uncertainties arising from parameter mismatches and external excitations, and Δ φ(u) describes the uncertain nonlinear characteristics associated with the control input. To guarantee the existence and continuity of the solutions of system (1), it is assumed that the unknown functions Δf(x_1,x_2) and Δφ(u) are continuous with respect to their corresponding arguments. It is worth noting that, in the absence of uncertainties, system (1) may exhibit chaotic dynamic behavior for certain selections of system parameters, which makes its stabilization and control design particularly challenging. To address the aforementioned control problem, the concept of adaptive stabilization is introduced and incorporated into the controller design framework. Inspired by the fundamental principles of adaptive control and robust control theory, a novel adaptive control methodology is developed to deal with the combined effects of uncertain system parameters, external disturbances, and nonlinear input characteristics. The primary objective of this study is to construct an effective robust adaptive controller that can guarantee the adaptive

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stabilization of a class of uncertain nonlinear systems subject to input nonlinearities. In particular, the proposed control strategy is designed to simultaneously compensate for uncertain input nonlinearities, suppress mixed system uncertainties, and eliminate undesirable chaotic oscillations. Through the appropriate adjustment of the adaptive control mechanism, the resulting closed-loop system can achieve the desired adaptive stabilization performance despite the presence of multiple uncertain factors. Therefore, the developed methodology provides a systematic solution to the stabilization problem of uncertain generalized Duffing-Holmes control systems with a single control input.

Throughout this paper, the following assumption is introduced to facilitate the subsequent controller development and theoretical stability analysis.

(A1) There exist continuous functions $g_i(x_1, x_2) \geq 0$, a positive constant r_1, and unknown nonnegtive constants β_i such that, for all admissible arguments,

$$|\Delta f(x_1, x_2)| \leq \sum_{i=1}^{s} \beta_i g_i(x_1, x_2),$$
$$u \cdot \Delta\varphi(u) \geq r_1 u^2.$$

Remark 1: In general, when the uncertain input nonlinearity satisfies

$$r_1 \cdot u^2 \leq u \cdot \Delta\varphi(u) \leq r_2 \cdot u^2, \quad \forall u \in \square,$$

the parameter r_2 can be interpreted as the gain bound, whereas r_1 represents the allowable gain reduction margin or gain attenuation tolerance. Accordingly, based on Assumption (A1), it follows that r_2=∞, as illustrated in Figure 1. This observation provides a useful characterization of the uncertain input nonlinearities and serves as an important foundation for the subsequent adaptive controller construction.

Before proceeding to the development of the main theoretical results, a precise definition of adaptive stabilization is provided below. This definition establishes the fundamental stability objective that will be adopted throughout the subsequent analysis.

Definition 1: The uncertain nonlinear system (1) is said to achieve adaptive stabilization if there exists an appropriate control input u such that the corresponding state trajectory satisfies

$$\lim_{t\to\infty} \|x(t)\| = 0$$

With the above definition and assumption established, we are now in a position to present the principal theoretical result concerning the adaptive stabilization of system (1). The following theorem provides a sufficient condition under which the considered uncertain nonlinear system can be adaptively stabilized by the proposed single-input control strategy.

Theorem 1. Suppose that the uncertain nonlinear system (1) satisfies Assumption (A1). Then, under the following control law

$$u(t) = -r(t) \cdot (p_3 x_1 + p_2 x_2), \tag{2}$$
$$r(t) := \frac{4\square^2(t)}{4r_1 \cdot h(t) \cdot |p_3 x_1 + p_2 x_2| + \left(\frac{a}{t^2+1}\right)}, \tag{3}$$
$$\square(t) := |q_1 x_1 + q_2 x_2 + q_3 x_1^3 + q_4 x_1^5 + q_5 \cos(w_1 t) + \alpha^2 x_1 + 2\alpha x_2| + |\sum_{i=1}^{s} b_i(t) g_i(x_1, x_2)|, \tag{4}$$
$$\dot{b}_i(t) = |p_3 x_1 + p_2 x_2| \cdot g_i(x_1, x_2), \quad \forall\, i \in \{1,2,3,\cdots,s\}, \tag{5}$$

system (1) can achieve adaptive stabilization, where $P := \begin{bmatrix} p_1 & p_3 \\ p_3 & p_2 \end{bmatrix} > 0$ is uniquely determined as the solution of the Lyapunov equation

$$\begin{bmatrix} 0 & 1 \\ -\alpha^2 & -2\alpha \end{bmatrix}^T P + P \begin{bmatrix} 0 & 1 \\ -\alpha^2 & -2\alpha \end{bmatrix} = -2I, \tag{6}$$

with $\alpha > 0$ and $a > 0$.

Proof. From (1), the state equation is given by

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ -\alpha^2 & -2\alpha \end{bmatrix} x$$
$$+ \begin{bmatrix} 0 \\ 1 \end{bmatrix} \cdot [\Delta\varphi + \Delta f + q_1 x_1 + q_2 x_2 + q_3 x_1^3 + q_4 x_1^5 + q_5 \cos(w_1 t) + \alpha^2 x_1 + 2\alpha x_2\,]$$
$$= Ax + B \cdot [\Delta\varphi + \Delta f + q_1 x_1 + q_2 x_2 + q_3 x_1^3 + q_4 x_1^5 + q_5 \cos(w_1 t) + \alpha^2 x_1 + 2\alpha x_2\,],\ \forall\, t \geq 0,$$

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where $A:=\begin{bmatrix}0 & 1\\ -\alpha^2 & -2\alpha\end{bmatrix}$ and $B:=\begin{bmatrix}0\\1\end{bmatrix}$. Obviously, one has $\sigma(A)=\{-\alpha\}$, which implies A is Hurwitz and the Lyapunov equation of (6) has the unique posive definite solution P. Let

$$V(x(t)) = x^T(t)Px(t) + \sum_{i=1}^{s}[b_i(t)-\beta_i]^2. \tag{7}$$

The time derivative of $V(x(t))$ along the trajectories of the system (1) with (2)-(6) is given by

$$\dot{V}(x(t)) = x^T[A^TP + PA]\ \ x + 2\sum_{i=1}^{s}\dot{b}_i(t)[b_i(t)-\beta_i]$$
$$+2x^TPB\cdot[\Delta\varphi + \Delta f + q_1x_1 + q_2x_2 + q_3x_1^3 + q_4x_1^5 + q_5\cos(w_1t) + \alpha^2x_1 + 2\alpha x_2\ ]$$
$$\le -2x^Tx + 2x^TPB\cdot\Delta\varphi + 2\sum_{i=1}^{s}\dot{b}_i(t)[b_i(t)-\beta_i]$$
$$+2|x^TPB|\left[|q_1x_1 + q_2x_2 + q_3x_1^3 + q_4x_1^5 + q_5\cos(w_1t) + \alpha^2x_1 + 2\alpha x_2| + \sum_{i=1}^{s}\beta_ig_i(x_1,x_2)\right]$$
$$= -2x^Tx + 2x^TPB\cdot\Delta\varphi + 2\sum_{i=1}^{s}|x^TPB|\cdot g_i(x_1,x_2)[b_i(t)-\beta_i]$$
$$+2|x^TPB|\left[|q_1x_1 + q_2x_2 + q_3x_1^3 + q_4x_1^5 + q_5\cos(w_1t) + \alpha^2x_1 + 2\alpha x_2| + \sum_{i=1}^{s}\beta_ig_i(x_1,x_2)\right]$$
$$\le -2x^Tx + 2x^TPB\cdot\Delta\varphi$$
$$+2|x^TPB|\left[|q_1x_1 + q_2x_2 + q_3x_1^3 + q_4x_1^5 + q_5\cos(w_1t) + \alpha^2x_1 + 2\alpha x_2| + \left|\sum_{i=1}^{s}b_i(t)\cdot g_i(x_1,x_2)\right|\right]$$
$$= -2x^Tx + 2x^TPB\cdot\Delta\varphi + 2\square(t)\cdot|x^TPB|$$

$$= -2x^Tx - \left(\frac{2}{r}\right)\cdot(u\cdot\Delta\varphi) + 2\square\cdot|x^TPB|$$
$$= -2\|x(t)\|^2 - \left(\frac{2}{r}\right)\cdot(r_1u^2) + 2\square\cdot|x^TPB|$$
$$= -2\alpha\|x(t)\|^2 - 2r_1\cdot r\cdot|x^TPB|^2 + 2\square\cdot|x^TPB|$$
$$= -2\|x(t)\|^2 - 2r_1\cdot r\cdot|p_3x_1 + p_2x_2|^2 + 2\square\cdot|p_3x_1 + p_2x_2|$$
$$= -2\|x(t)\|^2 - \frac{8r_1\cdot\square^2(t)\cdot|p_3x_1 + p_2x_2|^2}{4r_1\cdot h(t)\cdot|p_3x_1 + p_2x_2| + \left(\frac{a}{t^2+1}\right)} + 2\square\cdot|p_3x_1 + p_2x_2|$$
$$= -2\|x(t)\|^2 + \frac{2\square\cdot|p_3x_1 + p_2x_2|\cdot\left(\frac{a}{t^2+1}\right)}{4r_1\cdot h(t)\cdot|p_3x_1 + p_2x_2| + \left(\frac{a}{t^2+1}\right)}$$
$$= -2\|x(t)\|^2 + \left(\frac{1}{2r_1}\right)\cdot\frac{[4r_1\cdot h(t)\cdot|p_3x_1 + p_2x_2|]\cdot\left(\frac{a}{t^2+1}\right)}{4r_1\cdot h(t)\cdot|p_3x_1 + p_2x_2| + \left(\frac{a}{t^2+1}\right)}, \quad \forall\, t\ge 0.$$

By the inequality

$$x\left(\frac{yz}{y+z}\right) \le xz, \quad \forall\, x>0, y\ge 0, \text{ and } z>0.$$

It can be deduced that

$$\dot{V}(x(t)) \le -2\|x(t)\|^2 + \left(\frac{1}{2r_1}\right)\left(\frac{a}{t^2+1}\right), \quad \forall\, t\ge 0.$$

It results that

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$$\|x(t)\|^2 \le \frac{-\dot{V}(x(t))}{2} + \left(\frac{1}{4r_1}\right)\left(\frac{a}{t^2+1}\right)$$

$$\Rightarrow \int_0^\infty \|x(t)\|^2 dt \le \int_0^\infty \frac{-\dot{V}(x(t))}{2} dt + \left(\frac{1}{4r_1}\right)\int_0^\infty \left(\frac{a}{t^2+1}\right)^2 dt$$

$$= \frac{V(x(0))}{2} - \frac{V(x(\infty))}{2} + \left(\frac{a}{8r_1\pi}\right) \le \frac{V(x(0))}{2} + \left(\frac{a}{8r_1\pi}\right)$$

Consequently, we conclude that $\lim_{t\to\infty} \|x(t)\| = 0$, in view of $x(t) \in L_2$. This completes the proof. □

Remark 2. Based on the theoretical result established in Theorem 1, an implementable procedure for constructing the robust adaptive controller specified in (2) is presented below. The proposed algorithm provides a systematic sequence of design steps, allowing the required control parameters and adaptive control components to be determined in accordance with the conditions established in the preceding analysis.

Algorithm: Procedure for Constructing the Robust Adaptive Controller

Input: The uncertain generalized Duffing-Holmes control system described by (1).

Output: The corresponding adaptive control law specified in (2).

Step 1: Select the parameters $g_i(x_1, x_2) \ge 0$, r_1, and s appropriately so that the required condition in Assumption (A1) is satisfied.

Step 2: Choose the parameter $\alpha > 0$ and subsequently calculate the matrix $P := \begin{bmatrix} p_1 & p_3 \\ p_3 & p_2 \end{bmatrix} > 0$ by solving the Lyapunov equation given in (6).

Step 3: Determine the corresponding expressions of □(t) and $\dot{b}_i(t)$ according to the definitions provided in (5) and (4), respectively.

Step 4: Select a suitable parameter $a > 0$ and construct the corresponding expression of $r(t)$ based on (3).

Step 5: Finally, obtain the desired adaptive control input $u(t) = -r(t) \cdot (p_3 x_1 + p_2 x_2)$, in view of (2).

III. ILLUSTRATIVE EXAMPLE AND NUMERICAL SIMULATIONS

To further demonstrate the applicability and effectiveness of the proposed adaptive control methodology, an illustrative example involving an uncertain generalized Duffing-Holmes control system with uncertain input nonlinearities is considered in this section. Consider the following uncertain generalized Duffing-Holmes control systems with uncertain input nonlinearities described as

$$\dot{x}_1 = x_2, \tag{8a}$$

$$\dot{x}_2 = q_1 x_1 + q_2 x_2 + q_3 x_1^3 + q_4 x_1^5 + q_5 \cos(w_1 t) + \Delta f(x_1, x_2) + \Delta\varphi(u),\ \forall t \ge 0, \tag{8b}$$

where

$$q_1 = 1, \quad q_2 = -0.25, \quad q_3 = -1, \quad q_4 = 0, \quad q_5 = 0.3, \quad w_1 = 1,$$
$$\Delta f(x_1, x_2) = \Delta a \cdot x_1^2, \quad \Delta\varphi(u) = \Delta b \cdot u + \Delta c \cdot u^3,$$
$$|\Delta a| \le \eta \in \Re, \quad 1 \le \Delta b \le 3, \quad \Delta c \ge 0.$$

The main purpose of this example is to demonstrate how the proposed single-input adaptive controller can be constructed and applied to the considered uncertain nonlinear system. More specifically, our objective is to design an appropriate feedback control law such that the uncertain generalized Duffing-Holmes system described in (8) can successfully achieve the desired adaptive stabilization performance.

Step 1. The condition (A1) is clearly satisfied if we let

$$s = 1, \quad g_1(x_1, x_2) = x_1^2, r_1 = 1.$$

Step 2. From (6) with $\alpha = 1$, we have

$$P = \begin{bmatrix} 3 & 1 \\ 1 & 1 \end{bmatrix}, \quad p_2 = 1, \quad p_3 = 1.$$

Step 3. From (4) and (5), it can be readily obtained that

$$□(t) := |x_1 - 0.25x_2 - x_1^3 + 0.3\cos t + x_1 + 2x_2| + |b_1(t)x_1^2|,$$

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$$\dot{b}_1(t) = |x_1 + x_2| \cdot x_1^2(t).$$

Step 4. From (3) with $a = 1$, one has

$$r(t) := \frac{4\square^2(t)}{4\square(t)\cdot|x_1+x_2|+\left(\frac{1}{t^2+1}\right)}.$$

Step 5. The desired control, given by (2), can now be calculated as

$$u(t) = -r(t) \cdot (x_1 + x_2). \quad (9)$$

According to the theoretical statement established in Theorem 1, it can be concluded that the uncertain nonlinear system (8), when operating under the proposed control law (9), achieves adaptive stabilization. To further illustrate the dynamic behavior of the considered system and evaluate the effectiveness of the developed control strategy, several numerical simulations are performed under both uncontrolled and controlled operating conditions. The representative state trajectories corresponding to the uncontrolled and controlled systems are presented in Figures 2 and 3, respectively. A comparison of these simulation results provides a clear illustration of the influence of the proposed feedback controller on the dynamic responses of the uncertain nonlinear system. Furthermore, the corresponding control input signal and the variation of the adaptive gain are displayed in Figures 4 and 5, respectively. These simulation results provide additional insight into the operational characteristics of the proposed adaptive control mechanism and demonstrate how the controller responds to the uncertain system dynamics during the stabilization process. By examining the state trajectories together with the control signal and adaptive gain, the effectiveness of the proposed control strategy can be further verified from different perspectives. Based on the overall numerical simulation results, it is evident that the uncertain generalized Duffing-Holmes control system described in (8) can achieve adaptive stabilization under the designed control law (9). Consequently, these numerical findings are consistent with the theoretical conclusions established in Theorem 1 and further confirm the feasibility and effectiveness of the proposed adaptive controller.

IV. CONCLUSION

In this paper, the adaptive controller design problem for a class of uncertain nonlinear control systems subject to a single control input has been systematically investigated. In particular, an adaptive stabilization strategy has been developed for uncertain generalized Duffing-Holmes control systems by employing appropriate differential and integral inequalities, together with time-domain analytical techniques. The proposed controller provides an effective means of addressing the stabilization problem in the presence of uncertain system dynamics and nonlinear input characteristics while maintaining the restriction of a single control input. Through the theoretical analysis, the developed adaptive control methodology establishes the conditions under which the considered uncertain nonlinear system can achieve the desired global stability properties. Furthermore, the proposed approach is capable of simultaneously dealing with mixed uncertainties, uncertain input nonlinearities, and undesirable chaotic oscillations, thereby providing a unified control framework for the considered class of nonlinear systems. Finally, several numerical simulation studies have been conducted to illustrate the implementation of the proposed controller and to demonstrate its stabilization performance. The obtained simulation results further support the theoretical findings and confirm the feasibility and effectiveness of the main results established in this study.

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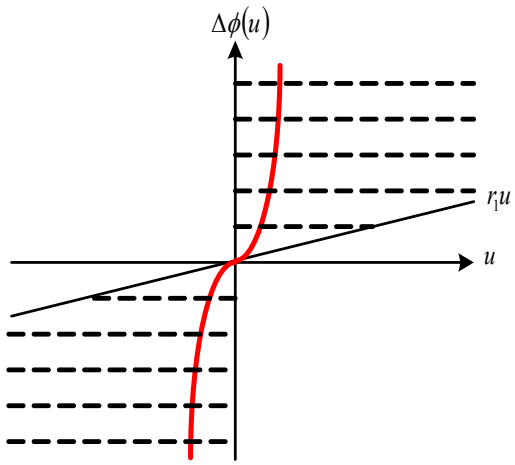


Figure 1: Uncertain input nonlinearity.

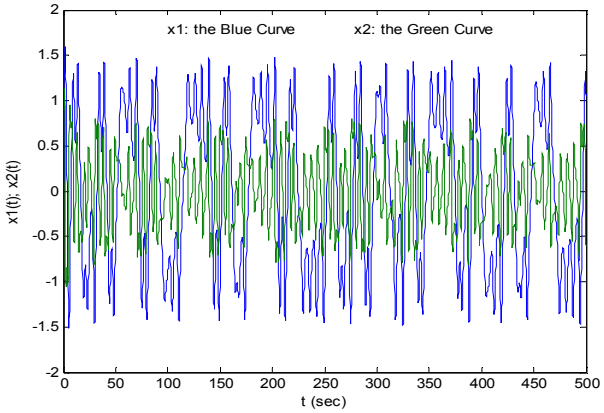


Figure 2: Typical state trajectories of the uncontrolled system of the Example.

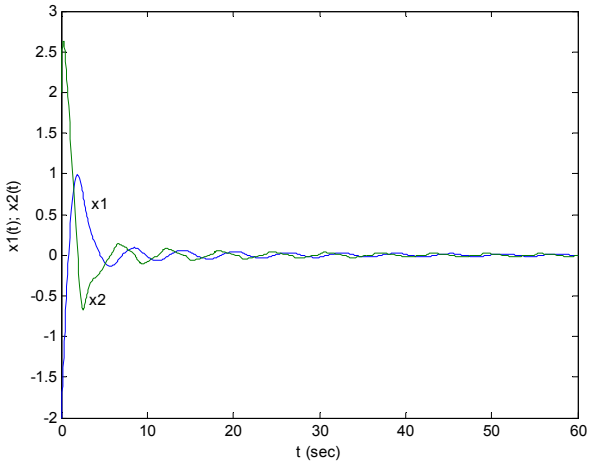


Figure 3: Typical state trajectories of the feedback-controlled system of the Example.

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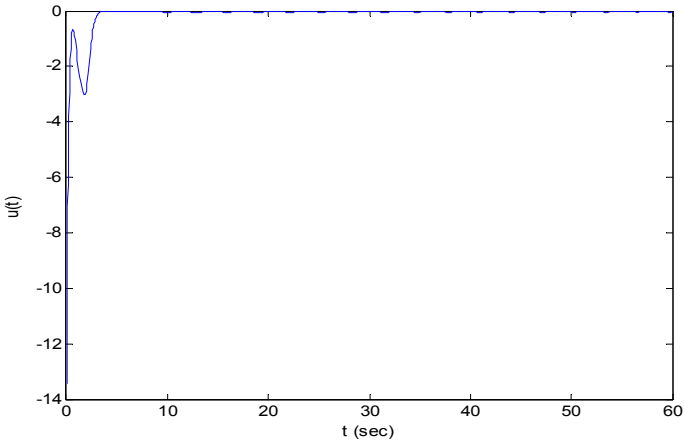


Figure 4: Control signal of the Example.

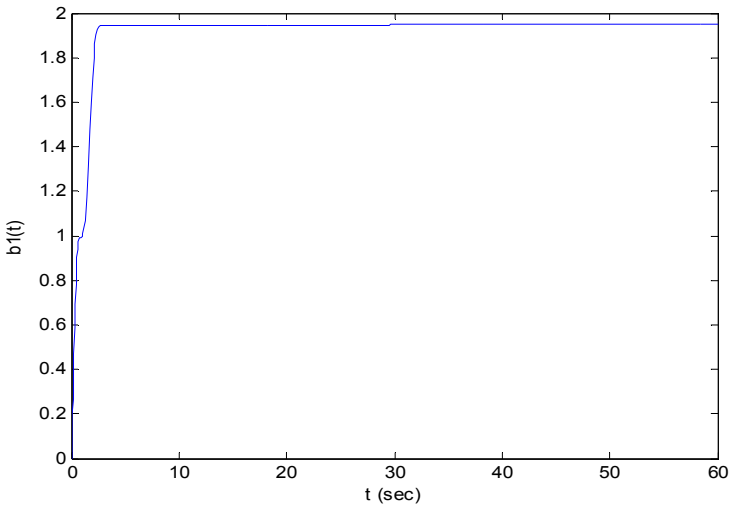


Figure 5: The signal of adaptive gain.

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