

Stability Analysis and Control Design of Fuzzy Systems using Scilab Package

L. EKONOMOU

Public Power Corporation S.A.
22 Chalcocondyli Str., 104 32 Athens
GREECE

Abstract: The paper studies the stability analysis and the systematic control design of fuzzy systems which have been successfully applied to many practical industrial applications in the recent years. Despite the success it has become evident that many basic issues remain to be further addressed. These issues are based to the fact that there are not analytical tools, there is not a fuzzy systems theory like linear systems theory for fuzzy control systems. In this study two different fuzzy systems are studied. These are: a discrete-time system and a continuous-time system. Stability analysis and control design are performed to these systems using an approach based on Lyapunov stability techniques and linear matrix inequalities, which can be solved very efficiently by means of some powerful mathematical numerical tools such as the Scilab package.

Keywords: Stability analysis, Control design, Fuzzy systems, Linear matrix inequalities, Scilab package

1. Introduction

It is well known that there is a rapidly growing interest in fuzzy control in recent years [1, 2]. Fuzzy control has been successfully applied to many practical industrial applications. Despite the success it has become evident that many basic issues remain to be further addressed. These issues are based to the fact that there are not analytical tools, there is not a fuzzy systems theory like linear systems theory for fuzzy control systems.

Stability analysis and systematic control design are certainly among the most important issues for fuzzy control systems. That is the reason why recently, there have been significant research efforts in this direction.

In this study two different fuzzy systems are studied. These are: a discrete-time system and a continuous-time system. Stability analysis and control design are performed to both systems using an approaches based on Lyapunov techniques and linear matrix inequalities, which can be solved very efficiently by means of mathematical numerical tools such as the Scilab package.

2. Linear Matrix Inequalities (LMI)

A wide variety of problems arising in system and control theory can be reduced to a few standard convex or quasi-convex optimisation problems involving linear matrix inequalities (LMIs) [3]. Since these optimisation problems can be solved numerically very efficiently using recently developed interior-point methods, our reduction constitutes a solution to the original problem certainly in a practical sense. In

comparison, the more conventional approach is to seek an analytic or frequency-domain solution to the matrix inequalities.

A linear matrix inequality has the form:

$$F(x) = F_0 + \sum_{i=1}^m x_i F_i > 0$$

where $x \in R^m$ is the variable and the symmetric matrices $F_i = F_i^T \in R^{n \times n}$, $i = 0, \dots, m$ are given. The inequality symbol >0 means that $F(x)$ is positive-definite for all non-zero $u \in R^n$.

When matrices F_i are diagonal, the LMI $F(x) > 0$ is just a set of linear inequalities. Nonlinear (convex) inequalities are converted to LMI form using Schur complements. The basic idea is as follows: The LMI:

$$\begin{bmatrix} Q(x) & S(x) \\ S(x)^T & R(x) \end{bmatrix} > 0$$

where $Q(x) = Q(x)^T$, $R(x) = R(x)^T$, and $S(x)$ depend affinely on x , is equivalent to:

$$R(x) > 0, \quad Q(x) - S(x) R(x)^{-1} S(x)^T > 0$$

Very often in the LMIs the variables are matrices, for e.g. the Lyapunov inequality;

$$A^T P + P A < 0$$

where $A \in R^{n \times n}$ is given and $P = P^T$ is the variable. In this case, the LMI will not be written out explicitly in the form $F(x) > 0$, but instead must be made clear which matrices are the variables.

3. Stability Analysis and Control Design of Fuzzy Systems

3.1 Using simultaneous Lyapunov stability

The main feature of a fuzzy model is to express the local dynamics of its fuzzy implication

(rule) by a linear system model [4]. The overall fuzzy model of the system is achieved by fuzzy “blending” of the linear system models.

Specifically, the fuzzy system is described by fuzzy IF-THEN rules that locally represent linear input-output relations of the system. The fuzzy system is of the following form:

Rule i: IF $x_1(k)$ is M_{i1} ... and $x_n(k)$ is M_{in}

THEN $x(k+1) = A_i x(k) + B_i u(k)$

where $x^T(k) = [x_1(k), x_2(k), \dots, x_n(k)]$, $u^T(k) = [u_1(k), u_2(k), \dots, u_m(k)]$ and, $i = 1, 2, \dots, r$ where r is the number of IF-THEN rules. M_{ij} are fuzzy sets and $x(k+1) = A_i x(k) + B_i u(k)$ is the output from the i -th IF-THEN rule. Given a pair of $(x(k), u(k))$, the final output of the fuzzy system is inferred as follows:

$$x(k+1) = \frac{\sum_{i=1}^r w_i(k) \{A_i x(k) + B_i u(k)\}}{\sum_{i=1}^r w_i(k)} \quad (1)$$

where

$$w_i(k) = \prod_{j=1}^n M_{ij}(x_j(k))$$

and $M_{ij}(x_j(k))$ is the degree of membership of $(x_j(k))$ in M_{ij} .

The open loop system of (1) is:

$$x(k+1) = \frac{\sum_{i=1}^r w_i(k) A_i x(k)}{\sum_{i=1}^r w_i(k)} \quad (2)$$

where it is assumed that,

$$\sum_{i=1}^r w_i(k) > 0 \text{ and } w_i(k) \geq 0, i = 1, 2, \dots, r$$

for all k . Each linear component $A_i x(k)$ is called a subsystem.

In case of a fuzzy continuous-time model described by fuzzy IF-THEN rules which represent local linear input-output relation of a nonlinear system, the i -th rule of the fuzzy model is of the following form:

Plant Rule i

IF $z_1(t)$ is M_{i1} and ... and $z_p(t)$ is M_{ip}

THEN $\dot{x}(t) = A_i x(t) + B_i u(t)$, $i = 1, 2, \dots, r$ (3)

M_{ij} is the fuzzy set and r is the number of IF-THEN rules.

$x(t) \in R^n$ is the state vector, $u(t) \in R^m$ is the input vector, $A_i \in R^{n \times n}$ and $B_i \in R^{n \times m}$.

$z_1(t) \sim z_p(t)$ are the premise variables.

Given a pair of $(x(t), u(t))$, the final output of the fuzzy system is inferred as:

$$\dot{x}(t) = \sum_{i=1}^r h_i(z(t)) \{A_i x(t) + B_i u(t)\}$$

where $z(t) = [z_1(t) \ z_2(t) \ \dots \ z_p(t)]$,

$$h_i(z(t)) = w_i(z(t)) / \sum_{i=1}^r w_i(z(t)),$$

$$w_i(z(t)) = \prod_{j=1}^p M_{ij}(z_j(t)) \quad (4)$$

for all t . $M_{ij}(z_j(t))$ is the grade of membership of $z_j(t)$ in M_{ij} .

The parallel distributed compensation (PDC) offers a design procedure of a fuzzy controller from the fuzzy model. To realize the PDC, a controlled object should be represented by a fuzzy model. Each control rule is individually designed from the corresponding rule of a fuzzy model in the PDC. The designed fuzzy controller shares the same fuzzy sets with the fuzzy model in the premise parts. The PDC provides the fuzzy control rule structure (5) for the fuzzy model (3).

IF $z_1(t)$ is M_{i1} and ... and $z_p(t)$ is M_{ip}

THEN $u(t) = F_i x(t)$ $i = 1, 2, \dots, r$ (5)

The fuzzy control rules have linear state feedback laws in the consequent parts. The overall fuzzy controller is represented by:

$$u(t) = - \sum_{i=1}^r h_i(z(t)) F_i x(t) \quad (6)$$

The fuzzy controller design is to determine the local feedback gains F_i in the consequent parts. By substituting (6) into (4), we obtain:

$$\begin{aligned} \dot{x}(t) &= \sum_{i=1}^r \sum_{j=1}^r h_i(z(t)) h_j(z(t)) \{A_i - B_i F_j\} x(t) \\ &= \sum_{i=1}^r h_i(z(t)) h_i(z(t)) G_{ii} x(t) + \\ &\quad + 2 \sum_{i < j}^r h_i(z(t)) h_j(z(t)) \left\{ \frac{G_{ij} + G_{ji}}{2} \right\} x(t) \end{aligned}$$

where $G_{ij} = A_i - B_i F_j$.

4. Scilab Software Package

Scilab is a user-friendly software package which has been developed for system control and signal processing applications [5]. Scilab is similar to Matlab in that it is made up of three distinct parts, namely an interpreter, libraries of functions and libraries of Fortran and C routines. Scilab is capable of handling numerical matrices and even more complex functions, such as the manipulation of rational or polynomial transfer functions. This is done in Scilab by manipulating lists and typed lists which allow a natural symbolic representation of complicated mathematical expressions, such as transfer functions, linear systems or graphs. Polynomials, polynomials' matrices and transfer

matrices are also defined and the syntax used for managing constant vectors and matrices. Scilab provides a variety of powerful primitives for the analysis of nonlinear systems and nonlinear optimization.

Scilab has an open programming environment where the creation of functions and libraries of functions are completely under the control of the user. Functions are recognized as data. For example, functions can be defined inside Scilab and be passed on as input or output arguments of other functions. Finally, Scilab is easily interfaced with Fortran or C subprograms. This allows the use of standardized packages and libraries in the interpreted environment of Scilab.

5. Discrete-time fuzzy system

3.1 Description of the system

The system that was studied is a well-known system, called the Box and Jenkins' Gas Furnace. Air and methane are combined to form a mixture of gases containing CO₂. The air feed is kept constant, but the methane feed rate is varied in any desired manner. The system has a single input $u(t)$, and a single output $y(t)$. The input is the gas flow rate of the mixing chest which can be controlled by a valve. The output is the CO₂ concentration in the output gases, and gives a measure of quality of combustion in the boiler itself.

The Box and Jenkins' Gas Furnace is described by a fuzzy model of two rules which has the following form:

Rule 1: IF $y(t-1)$ is A_1 THEN $y_1(t) = 16.95 + 0.60 y(t-1) + 0.27 y(t-2) - 0.19 y(t-3) + 0.24 u(t-1) - 0.56 u(t-2) - 0.65 u(t-3)$ (7)

Rule 2: IF $y(t-1)$ is A_2 THEN $y_2(t) = 25.78 + 0.32 y(t-1) + 0.13 y(t-2) - 0.063 y(t-3) - 0.24 u(t-1) - 0.044 u(t-2) - 1.36 u(t-3)$ (8)

where A_1 and A_2 are linear membership functions.

5.2 Stability analysis and control design

Fuzzy rules (7) and (8) of the Box and Jenkins' Gas Furnace contain constant terms 16.95 and 25.78 respectively. This forces us to face the system in two steps. In the first step we omit the constants and study the homogeneous part, while in step two, the constant control terms are added to achieve the desired steady-state value.

The proposed method for checking the stability and designing a fuzzy controller consists of two main parts:

Step 1: Consider the homogeneous part of the system, omitting the constant terms from the fuzzy rules and follow the next steps:

Step i: Derive a total fuzzy system by connecting the fuzzy model of the objective system with a fuzzy controller by using connection theorems.

Step ii: Determine the parameters of the fuzzy controller so as to guarantee the stability of the linear subsystems in the total fuzzy system.

Step iii: Lastly, check the stability of the total fuzzy system by the procedure to find a common P matrix.

Step 2: Consider the original system, in which the fuzzy rules contain the constant terms. Use the same fuzzy controller obtained in Step 1, with the addition of constant terms satisfying the steady-state requirements. The above design method is applied to the Gas Furnace system. We try to stabilize the i -th subsystem by using a linear proportional controller C_i with a proportional gain k_i . This proposed controller takes the following form:

C_1 : IF $y(t-1)$ is A_1 THEN $u_1(t) = k_1 y(t)$

C_2 : IF $y(t-1)$ is A_2 THEN $u_1(t) = k_2 y(t)$

where A_1 and A_2 are as in figure 2.

Step 1: The constant terms are omitted from the fuzzy rules (7) and (8).

Step i: The connection of (Rule) _{i} with C_i is derived as follows:

S_1 : IF $y(t-1)$ is (A_1 and A_1) THEN $y_1(t) = (0.6 + 0.24 k_1) y(t-1) + (0.27 - 0.56 k_1) y(t-2) - (0.19 + 0.65 k_1) y(t-3)$

S_2 : IF $y(t-1)$ is (A_2 and A_2) THEN $y_2(t) = (0.32 - 0.14 k_2) y(t-1) + (0.13 - 0.044 k_2) y(t-2) - (0.063 + 1.36 k_2) y(t-3)$

S_3 : IF $y(t-1)$ is (A_1 and A_2) THEN $y_3(t) = (0.46 - (0.24 k_2 + 0.14 k_1)/2) y(t-1) + (0.2 - (0.56 k_2 + 0.044 k_1)/2) y(t-2) + (-0.1265 - (0.65 k_2 + 1.36 k_1)/2) y(t-3)$

Step ii: The two unknown parameters (k_1 and k_2) of the fuzzy controller were determined so as to satisfy the following design specifications:

(L₁) the eigenvalues of the system are:

$p_{1,2} = 0.5 \pm 0.5 i$, $p_3 = -0.7$,

(L₂) the CO₂ concentration is around 55, in other words the response of the system is stabilized in value 55.

k_1 and k_2 are determined so that the eigenvalues are equal or approximately equal with the desired for the linear subsystems 1 and 2 respectively. These parameters are $k_1 = 0.2610$ and $k_2 = 0.2740$. However, these parameters must be checked for subsystems 3 to determine whether are appropriate or not for it. This must be done because these parameters were determined considering only the

linear subsystems 1 and 2 and not the linear subsystem 3.

The eigenvalues of subsystem 3 are inside the unit circle and are: $p_{1,2} = 0.5359 \pm 0.5529 i$, $p_3 = -0.6629$, which are approximately equal with these of specification (L_1).

Step iii: Lastly the stability of the total fuzzy system is checked using the procedure to find a common P matrix. For the linear subsystems of S_1 , S_2 , and S_3 we obtain:

$$A_1 = \begin{bmatrix} 0.6 + 0.24k_1 & 0.27 - 0.56k_1 & -0.19 - 0.65k_1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} 0.32 - 0.14k_2 & 0.13 - 0.044k_2 & -0.063 - 1.36k_2 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} 0.46 - (0.24k_2 + 0.14k_1)/2 & 0.2 - (0.56k_2 + 0.044k_1)/2 & \dots \\ 1 & 0 & \dots \\ 0 & 1 & \dots \end{bmatrix}$$

$$A_3 = \begin{bmatrix} \dots & \dots & -0.1265 - (0.65k_2 + 1.36k_1)/2 \\ \dots & \dots & 0 \\ \dots & \dots & 0 \end{bmatrix}$$

where $k_1 = 0.2610$ and $k_2 = 0.2740$.

The fuzzy control system is going to be stable if a common positive definite matrix P exists, such that:

$$A_1^T P A_1 - P < 0 \quad A_2^T P A_2 - P < 0 \quad A_3^T P A_3 - P < 0$$

Using Scilab package for the solution of the above linear matrix inequality problem (LMI), the matrix

$$P = \begin{bmatrix} 11.417 & -2.081 & -1.529 \\ -2.081 & 5.987 & -0.284 \\ -1.529 & -0.284 & 3.851 \end{bmatrix}$$

is obtained, concluded that the system is stable.

Figure 1 shows the response of the fuzzy system with $k_1 = 0.2610$ and $k_2 = 0.2740$, and initial conditions $y(1) = y(2) = y(3) = 1$.

Step 2: The original system (7), (8) and the fuzzy controller:

C₁ : IF $y(t-1)$ is A_1 THEN $u_1(t) = k_1 y(t) + n_1$

C₂ : IF $y(t-1)$ is A_2 THEN $u_1(t) = k_2 y(t) + n_2$

are now considered.

The desired closed loop system response is $y(t) = 0.3 y(t-1) + 0.2 y(t-2) - 0.35 y(t-3) + 46.75$ and is plotted in figure 2. It must be mentioned that the above response satisfies the design specifications since it has poles at: $p_{1,2} = 0.5 \pm 0.5 i$, $p_3 = -0.7$ and settles down at the value of 55. Then by choosing parameters for n_1 and n_2 , the response of the original fuzzy control system is plotted. The suitable parameters for which the two responses become identical are $n_1 = -19$ and $n_2 = -19$, figure

3. Comparing figures 2 and 3, it is easily seen that the two responses are almost identical.

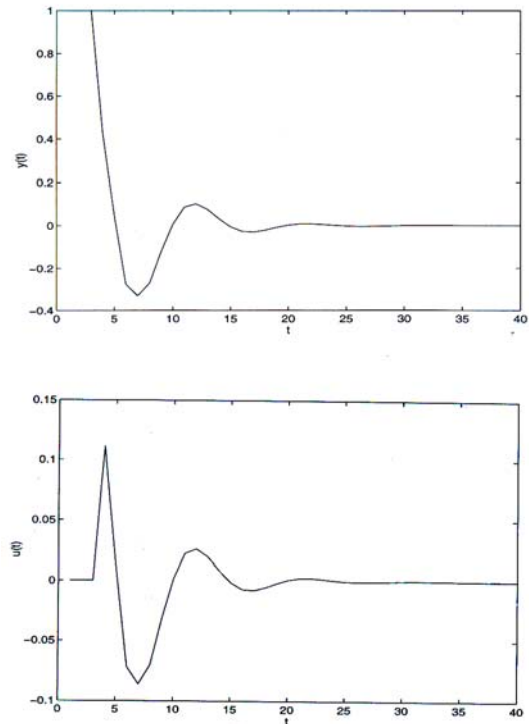


Figure 1: The output and input responses of the fuzzy system.

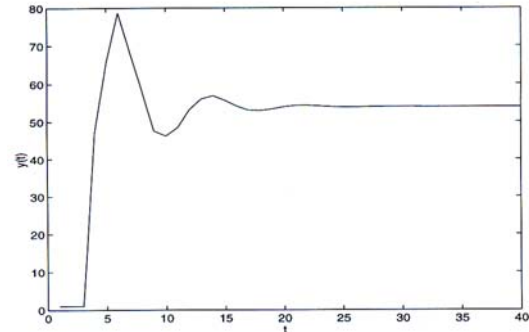
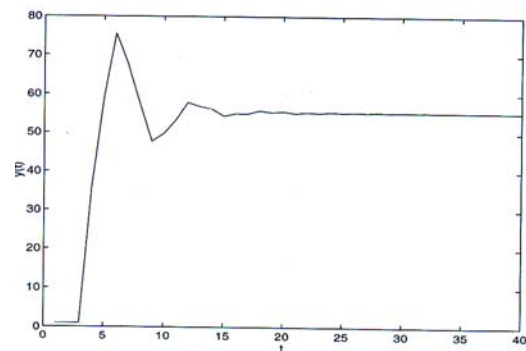


Figure 2: Desired closed loop system response.

It must be mentioned that figure 2 and 3 are plotted for initial conditions: $y(1) = 1$, $y(2) = 1$ and $y(3) = 1$.



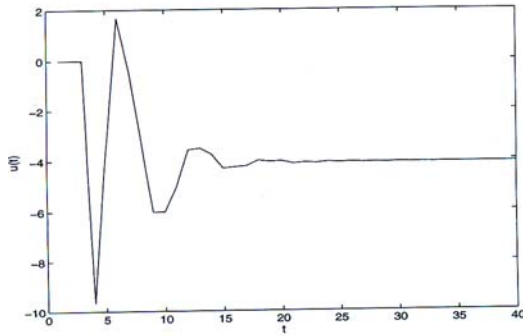


Figure 3: The output and input responses of the original fuzzy control system.

6. Continuous-time fuzzy system

3.1 Description of the system

The system that is studied in this chapter is a simple nonlinear mass-spring-damper mechanical system [6].

The nonlinear system can be represented exactly by the following fuzzy model:

IF $x(t)$ is F_1^1 and $\dot{x}(t)$ is F_2^1 , THEN $\ddot{x} = -0.02x + u$

IF $x(t)$ is F_1^1 and $\dot{x}(t)$ is F_2^2 , THEN

$$\ddot{x} = -0.225\dot{x} - 0.02x + u$$

IF $x(t)$ is F_1^2 and $\dot{x}(t)$ is F_2^1 , THEN $\ddot{x} = -1.5275x + u$

IF $x(t)$ is F_1^2 and $\dot{x}(t)$ is F_2^2 , THEN

$$\ddot{x} = -0.225\dot{x} - 1.5275x + u$$

where: $F_1^1(x(t)) = 1 - \frac{x^2(t)}{2.25}$, $F_1^2(x(t)) = 1 - F_1^1(x(t)) = \frac{x^2(t)}{2.25}$,

$F_2^1(\dot{x}(t)) = 1 - \frac{\dot{x}^2(t)}{2.25}$, $F_2^2(\dot{x}(t)) = 1 - F_2^1(\dot{x}(t)) = \frac{\dot{x}^2(t)}{2.25}$, and

$$x \in [-1.5 \ 1.5], \dot{x} \in [-1.5 \ 1.5].$$

The fuzzy model can be rewritten by introducing matrix representation as follows:

Rule 1: IF $x(t)$ is F_1^1 and $\dot{x}(t)$ is F_2^1 , THEN

$$\dot{x}(t) = A_1 x(t) + B_1 u(t),$$

Rule 2: IF $x(t)$ is F_1^1 and $\dot{x}(t)$ is F_2^2 , THEN

$$\dot{x}(t) = A_2 x(t) + B_2 u(t),$$

Rule 3: IF $x(t)$ is F_1^2 and $\dot{x}(t)$ is F_2^1 , THEN

$$\dot{x}(t) = A_3 x(t) + B_3 u(t),$$

Rule 4: IF $x(t)$ is F_1^2 and $\dot{x}(t)$ is F_2^2 , THEN

$$\dot{x}(t) = A_4 x(t) + B_4 u(t),$$

where: $x(t) = [\dot{x}(t) \ x(t)]^T$, $A_1 = \begin{bmatrix} 0 & -0.02 \\ 1 & 0 \end{bmatrix}$,

$$A_2 = \begin{bmatrix} -0.225 & -0.02 \\ 1 & 0 \end{bmatrix}, A_3 = \begin{bmatrix} 0 & -1.5275 \\ 1 & 0 \end{bmatrix},$$

$$A_4 = \begin{bmatrix} -0.225 & -0.02 \\ 1 & 0 \end{bmatrix}, B_1 = B_2 = B_3 = B_4 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}.$$

6.2 Stability analysis and control design

By applying relaxed conditions, decay rate, and constraints to the system described in the previous section, stability analysis is performed. The stability of the system is checked, using Lyapunov ideas. The existence of a common positive definite matrix P for all four subsystems (rules) is sufficient to guarantee stability.

Derived conditions satisfying decay rate, were applied to the system. Conditions for constraints on control input ($\|u(t)\|_2 \leq \mu$) were also applied. Having expressed all of them as LMIs as shown below, a solution was tried to be found.

maximize α **subject to** $X > 0, Y \geq 0$

$$-X A_i^T - A_i X + M_i^T B_i^T + B_i M_i - (s-1) Y - 2 \alpha X > 0,$$

$$2 Y - X A_i^T - A_i X - X A_j^T - A_j X + M_j^T B_i^T + B_i$$

$$M_j + M_i^T B_j^T + B_j M_i - 4 \alpha X > 0, i < j$$

$$\begin{bmatrix} 1 & x(0) \\ x(0) & X \end{bmatrix} \geq 0, \quad \begin{bmatrix} X & M_i^T \\ M_i & \mu^2 I \end{bmatrix} \geq 0.$$

where α is the decay rate, $\mu = 2.5$, $i = 1, 2, 3, 4$, $j = 1, 2, 3, 4$, $s = 4$, $x(0)$ is known initial conditions, $X = P^{-1}$, $M_i = F_i X$ and $Y = X Q X$.

The Scilab package was used for the solution of the above LMI problem. A common positive definite matrix X , a common positive semidefinite matrix Y , matrices M_i for $i = 1, 2, 3, 4$ and α were calculated. These results are shown below:

$$X = \begin{bmatrix} 5.64 & -1.5 \\ -1.5 & 6.4 \end{bmatrix}, Y = \begin{bmatrix} 1 & -2.914D-08 \\ -2.914D-08 & 1 \end{bmatrix},$$

$$M_1 = [1.53 \ 5.51], M_2 = [0.26 \ 5.85], \alpha = 29445778.$$

$$M_3 = [3.79 \ -4.14], M_4 = [2.52 \ -3.8]$$

From the above solutions, the feedback gains F_i and a common P matrix can be obtained as $P = X^{-1}$, $F_i = M_i X^{-1}$.

$$\text{So } P = \begin{bmatrix} 0.1891 & 0.0443 \\ 0.0443 & 0.1666 \end{bmatrix},$$

$$F_1 = [0.534 \ 0.986], F_2 = [0.309 \ 0.986],$$

$$F_3 = [0.534 \ -0.521], F_4 = [0.309 \ -0.521].$$

The above system is stable, since a common P matrix was obtained. However, this statement holds only for the initial conditions that applied to the system and for input constraint $\mu=2.5$. For input constraint $\mu < 2.5$, the common matrix P does not exist, and the system becomes unstable. Figure 4 shows the state trajectories for $t = 2$ sec and for eight different initial conditions.

A different design procedure is now presented. By selecting the closed-loop eigenvalues of the system to be $[-2, -2]$, the four consequent feedback gains of the fuzzy controller are obtained:

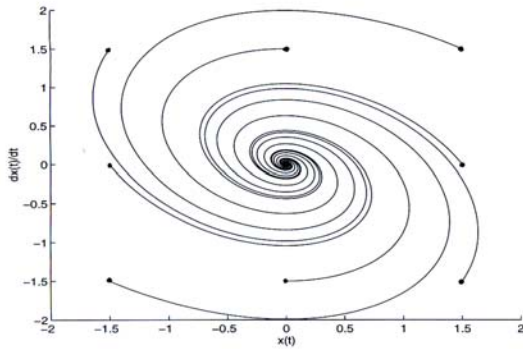


Figure 4: State trajectories of the system for t=2sec and several initial conditions.

$$F_1 = [4 \quad 3.98], F_2 = [3.775 \quad 3.98],$$

$$F_3 = [4 \quad 2.4725], F_4 = [3.775 \quad 2.4725].$$

Again derived conditions, as well as, input constraints converted in LMIs, are applied.

$$\text{maximize } \alpha \text{ subject to } X > 0, Y \geq 0$$

$$-X A_i^T - A_i X + (F_i X)^T B_i^T + B_i (F_i X) - (s-1) Y - 2 \alpha X > 0,$$

$$2 Y - X A_i^T - A_i X - X A_j^T - A_j X + (F_j X)^T B_j^T + B_j (F_j X) + (F_i X)^T B_j^T + B_j (F_i X) - 4 \alpha X > 0, i < j$$

$$\begin{bmatrix} 1 & x(0) \\ x(0) & X \end{bmatrix} \geq 0, \begin{bmatrix} X & (F_i X)^T \\ F_i X & \mu^2 I \end{bmatrix} \geq 0.$$

where α is the decay rate, $\mu = 12$, $i = 1, 2, 3, 4$, $j = 1, 2, 3, 4$, $s = 4$, $x(0)$ is known initial conditions, $X = P^{-1}$ and $Y = X Q X$.

Using Scilab package for the solution of the above LMI problem the following results were obtained:

$$X = \begin{bmatrix} 7.844 & -3.654 \\ -3.654 & 8.482 \end{bmatrix}, Y = \begin{bmatrix} 11.172 & 3.822 \\ 3.822 & 2.44 \end{bmatrix},$$

$$\alpha = 5.337D+08, \text{ and since } P = X^{-1},$$

$$P = \begin{bmatrix} 0.1595 & 0.0687 \\ 0.0687 & 0.1475 \end{bmatrix}.$$

The system is stable since a common matrix P exists. This holds for input constraint $\mu < 12$ only. Figure 5 shows the state trajectories for t = 2 sec and for eight different initial conditions.

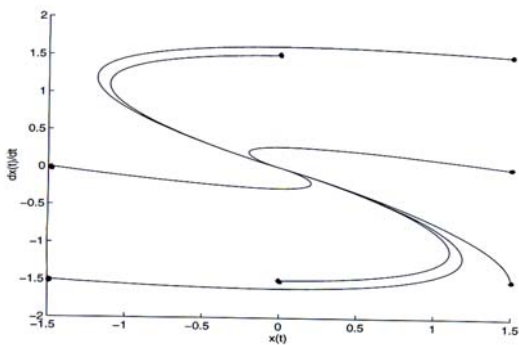


Figure 5: State trajectories of the system for t=2sec and several initial conditions.

7. Conclusions

There is a rapidly growing interest in fuzzy control in recent years. However, basic issues such as stability analysis and systematic control design remain to be further addressed. In this paper a method was presented based on Lyapunov ideas and linear matrix inequalities. The method is simple and straightforward. Linear feedback control techniques are utilised. Stability is guaranteed by the existence of a common positive definite matrix P. Moreover, the stability analysis and control design problems are reduced to LMI problems which can be solved very efficiently in practice by convex techniques. Furthermore, since the design is not based on membership function information, it covers a wide range of systems, which may possess different membership functions. However, this method restricts the use of complicated controllers since the order of the system increases causing difficulties in further analysis of it.

References:

- [1] Z. Li, H. Fang, "Fuzzy controller design for networked control system with time-variant delays", Journal of Systems Engineering & Electronics, vol 17, no. 1, 2006, pp.172-176
- [2] Z. Huang, S. Chen, Y. Xia, "Incorporate intelligence into an ecological system: An adaptive fuzzy control approach", Applied Mathematics & Computation, vol.177, no. 1, 2006, pp. 243-250
- [3] S. Boyd, L. El Ghaoui, E. Feron, V. Balakrishnan, "Linear Matrix Inequalities in Systems and Control Theory", SIAM, Philadelphia, PA, 1994.
- [4] K. Tanaka, M. Sugeno, "Stability analysis and design of fuzzy control systems", vol. 45, no.2, pp.135-156, 1992.
- [5] Scilab's package manual, email location: Scilab@inria.fr, web site: www.scilab.com.
- [6] .K. Tanaka, H.O. Wang, T. Ikeda, "Robust stabilization of a class of uncertain nonlinear systems via fuzzy control", IEEE Trans on Fuzzy Systems, vol.4, no.1, 1996.

Lambros Ekonomou received a BEng(Hons) in Electrical Engineering & Electronics in 1997 and a MSc. in Advanced Control in 1998 from University of Manchester Institute of Science & Technology in U.K. In 2006 he received a Ph.D. from the National Technical University of Athens in Greece. Currently he is working in Hellenic Public Power Corporation S.A. as an electrical engineer

His research interests concern high voltage transmission lines, lightning performance, lightning protection stability analysis, control design and artificial neural networks.