Design of Robust PI/PID Controller for Fuzzy Parametric Uncertain Systems

R. J. Bhiwani and B. M. Patre

Abstract

In this paper, a design method for a robust PI/PID controller for fuzzy parametric uncertain systems is proposed. An uncertain Linear Time Invariant (LTI) system with fuzzy coefficients is referred as fuzzy parametric uncertain system. The fuzzy coefficients are approximated by intervals (crisp sets) using the nearest interval approximation approach to obtain an interval system. Further, a robust controller is designed using a necessary condition and a sufficient condition for stability of the interval polynomial. These conditions are used to derive a set of inequalities in terms of controller parameters which are solved using linear programming (LP) optimization to obtain a robust controller. The numerical examples and simulation results successfully demonstrate the efficacy of the proposed method for design of robust PI/PID controller for fuzzy parametric uncertain systems.

Keywords: Robust controller, Fuzzy Parametric Uncertain System, PI/PID controller.

1. Introduction

In the real world, the controlled plant, represented with its mathematical model is bound to have a certain amount of uncertainty. The model is known approximately and hence it is necessary to incorporate the robustness in design. The problem of designing a robust controller for process plants having unknown but bounded parameter uncertainties, which are often called the interval process [1-2], has attracted considerable attention of researchers. For example, in modeling chemical process, there exist uncertainties due to poor process knowledge, nonlinearities, unknown external or internal noise, environment influence, time varying parameters, changing operating conditions etc. Other examples include aircraft model, robotic manipulators, nuclear reactors, electrical machines, and large power networks etc., which have parametric uncertainties for the entire range of operation. Two main types of uncertainties are significant [3-4], they are:

- **Unstructured uncertainty** - The model of plant is not available or feasible, hence an unmodeled dynamics is considered for design. Such problems are successfully treated within $H_\infty$ framework. The plant having such unstructured uncertainty is not considered in this paper.

- **Structured uncertainty** - Also called as parametric uncertainty, wherein uncertainty in the parameters of a plant is considered to be unknown but bounded. The fuzzy parametric uncertain system is converted into an interval plant using a nearest interval approximation of a fuzzy number.

The structured (parametric) uncertainty in a plant model can be expressed in terms of the gain, pole and zero locations or in terms of the transfer function coefficients. Each of these set of parameters are subject to variation. In most of the control systems, the controller remains fixed during operation while the plant parameters vary over a wide range about a certain nominal value. The term robust parametric stability refers to the ability of a control system to maintain stability despite such large variations [4]. Most of the time, precise intervals for the uncertainties in the plant parameter variations are difficult to be specified. Also measurement or estimates might be not obtainable in reality. In such a situation many mechanisms like intervals, linguistic information, experts’ knowledge, etc. can be used as the representations of uncertainties which can be helpful for the design of robust controller to the variations of the plant dynamic structure [5-8]. One of the popular ways to interpret the linguistic terms is fuzzy set representation. For each fuzzy set, a membership function is defined to assign a value from $[0, 1]$, to every element in the input universe of discourse [9-10]. The fuzzy representation of uncertainties indicates the interval of variations (by the support of the fuzzy set), and the possibility of each different value in the variation interval (by the membership function). An uncertain plant with fuzzy representation of uncertainty which is approximated by an interval number is termed as fuzzy parametric uncertain plant. The design of robust control for such fuzzy uncertain parametric system is an important research problem [3,
5-6, 11-14]. An algorithm is developed in [11], which calculates the degree of belief that the chosen control strategy can stabilize the linear system with fuzzy representation of uncertainties. But the algorithm suffers a serious drawback of computational complexity. This drawback was overcome in [14], where a sufficient condition is derived for a crisp set to be the best approximation of a fuzzy set. The best crisp approximation of a fuzzy set indicates an interval with high possibility elements which may actually represent the region of the regular occurrence of a parameter. In [5], an approach is proposed to design robust controllers for uncertain systems with the linguistic uncertainties represented by fuzzy set. The drawback of the method suggested in [5] is in the technique used for approximation of a fuzzy set by an interval set since it involves computational complexity. In this paper, a robust PI/PID controller for fuzzy parametric uncertain system is designed. The linguistic information is approximated as a fuzzy set which is represented by a unique crisp set using interval approximation operator called the nearest interval approximation as suggested in [15]. This approximation involves less computational complexity as compared to approximation used in [5] and gives the same corresponding interval set. Thus the system with fuzzy uncertainties becomes a system with interval uncertainties. For a linear system with interval structured (parametric) uncertainties, a robust controller is designed using a necessary condition and a sufficient condition for robust stability of interval plants as proposed in our earlier work [1]. This method is simple, involves less computational complexity and robust controller can be designed easily. The stability analysis of polynomials subjected to parametric uncertainty have received considerable attention after the celebrated theorem of Kharitonov [16], which assures robust stability under the condition that, four specially constructed “extreme polynomials” called Kharitonov polynomials are Hurwitz. Although, we have used the robust stability conditions in [1] for designing a robust controller, we have tested the stability of the closed loop interval polynomial using Kharitonov theorem also.

The present paper is organized as follows. In Section 2, system representation with fuzzy parametric uncertainty is described. In Section 3, the nearest interval approximation of a fuzzy set is explained with an example. In Section 4, we describe a necessary condition and a sufficient condition for robust stability of interval polynomial. Section 5, describes the design procedure for robust stability of interval plants. In Section 6, the design of a robust PI/PID controller is carried out for fuzzy parametric uncertain system using proposed technique. The simulation results show the efficacy of the proposed method. Finally, Section 7, concludes the paper.

2. System Representation with Fuzzy Parametric Uncertainty

The system in which coefficients depends on parameters described by fuzzy function are called extended system or fuzzy parametric uncertain system. A system has parametric uncertainty if there exist a model of it, but the value of its parameters is not exactly known [3, 5, 17]. A fuzzy parametric uncertain system with single input and single output can be represented by a set of differential equations of the kind

\[ f(y(t), \dot{y}(t), \ddot{y}(t), ..., y^{(n)}(t), u(t), \dot{u}(t), \ddot{u}(t), ..., u^{(m)}(t), \bar{q}) = 0 \]  

(1)

where, \( \bar{q} = (\bar{q}_1, \bar{q}_2, ..., \bar{q}_r) \), \( q_i \in \bar{P}(\mathbb{R}) \), \( i = 1, ..., r \) is a vector of fuzzy numbers and \( \bar{P}(\mathbb{R}) \) denotes the set of all possible fuzzy sets with real universe of discourse. In case of linear systems, the fuzzy parametric uncertain system in (1) can be represented in transfer function form as,

\[ \tilde{G}(s, \bar{q}) = \frac{b_m(\bar{q})s^m + b_{m-1}(\bar{q})s^{m-1} + ... + b_0(\bar{q})}{s^n + a_{n-1}(\bar{q})s^{n-1} + ... + a_0(\bar{q})} \]

(2)

If the degree of confidence in the coefficient is mentioned, the system in (2) can be represented as an interval system described by the transfer function as,

\[ [\tilde{G}(s, \bar{q})]_a = \frac{b_m(\bar{q}_a)s^m + b_{m-1}(\bar{q}_a)s^{m-1} + ... + b_0(\bar{q}_a)}{s^n + a_{n-1}(\bar{q}_a)s^{n-1} + ... + a_0(\bar{q}_a)} \]

(3)

where, \( \bar{q}_a = (q_{a1}, ..., q_{ara}) \), \( q_{ai} \in [\bar{q}_{ai}, \bar{q}_{ai}^+] \), \( i = 1, ..., r \) is a vector of intervals corresponding to the \( \alpha \)-cuts of the parameters \( \bar{q}_i \). To obtain an interval system (3) corresponding to fuzzy parametric uncertain system (2), a nearest interval approximation of fuzzy number is used. The membership value \( \alpha \) can be interpreted as the confidence degree in which the value of parameter equals its nominal value. Thus, a value \( \alpha = 1 \) indicates the precise knowledge \( q = \text{ker}(\bar{q}) \), whereas \( \alpha = 0 \) represents maximum uncertainty \( q = \text{supp}(\bar{q}) \).

3. The Nearest Interval Approximation

In this section, interval approximation operator called the nearest interval approximation for fuzzy set is explained. This interval approximation is best with respect to a certain measure of distance between fuzzy numbers. Suppose \( A \) is a fuzzy number and \([A^-() \sigma), A^+() \sigma])\) is its \( \alpha \)-cut. For given \( A \) we will try to find a closed interval \( C_\sigma(A) \) which is the nearest to \( A \) with respect to metric \( d \) given below. We can do it since each interval is also a fuzzy number with constant \( \alpha \)-cuts for...
all $\alpha \in (0,1]$. For two arbitrary fuzzy numbers $A$ and $B$ with $\alpha$ -cuts $[A^-(\alpha), A^+(\alpha)]$ and $[B^-(\alpha), B^+(\alpha)]$ respectively, the quantity

$$d(A,B) = \frac{1}{0} \int \frac{1}{(A^-(\alpha) - B^-(\alpha))^2} d\alpha + \frac{1}{0} \int \frac{1}{(A^+(\alpha) - B^+(\alpha))^2} d\alpha$$

(4)

is the distance between $A$ and $B$. Hence, let $C_d(A) = [C^-, C^+]$, i.e. $(C_d(A))_\alpha = [C^-, C^+], \forall (0,1)$

Now we have to minimize following equation with respect to $C^-$ and $C^+$.

$$d(A,C_d(A)) = \frac{1}{0} \int \frac{1}{(A^-(\alpha) - C^-(\alpha))^2} d\alpha + \frac{1}{0} \int \frac{1}{(A^+(\alpha) - C^+(\alpha))^2} d\alpha$$

(5)

In order to minimize $d(A,C_d(A))$ it suffices to minimize function $D(C^-, C^+) = d^2(A,C_d(A))$. Finding the solution, we get an interval

$$d(A,C_d(A)) = \frac{1}{0} \int \frac{1}{(A^-(\alpha) - C^-(\alpha))^2} d\alpha + \frac{1}{0} \int \frac{1}{(A^+(\alpha) - C^+(\alpha))^2} d\alpha$$

(6)

which indeed is the nearest interval approximation of a fuzzy number $A$ with respect to metric $d$ [15].

**Example 1:** Let $A$ be a fuzzy number with following membership function, (shown in Figure 1)

$$\mu_A(x) = \begin{cases} 1 - \left(\frac{x-5}{2}\right)^2, & \text{if } 3 \leq x \leq 7, \\ 0, & \text{if otherwise.} \end{cases}$$

(7)

![Figure 1. Membership function of the fuzzy number A.](image)

Then for $\alpha \in (0,1]$, we get following $\alpha$ -cuts:

$$C^- = \frac{1}{0} \int A^-(\alpha) d\alpha = \frac{1}{0} \int (5 - 2\sqrt{1-\alpha}) d\alpha = 3.667$$

$$C^+ = \frac{1}{0} \int A^+(\alpha) d\alpha = \frac{1}{0} \int (5 + 2\sqrt{1-\alpha}) d\alpha = 6.333$$

Hence

$$C_d(A) = [C^-, C^+] = [3.667, 6.333].$$

The following lemma from [15] describes one of the property, that nearest interval operator holds.

**Lemma 3.1:** In the family of trapezoidal fuzzy numbers the interval approximation operator $C_d$ and $C_0.5$ are equivalent i.e. $C_d(A) = C_{0.5}(A), \forall (A) \in F^T(\mathbb{R})$ where, $F^T(\mathbb{R})$ denotes the sub family of all trapezoidal fuzzy numbers.

### 4. Condition for Robust Stability of Interval Polynomial

Consider the set of real polynomials of degree $n$ of the form

$$\delta(s) = \delta_0 + \delta_1 s + \delta_2 s^2 + \delta_3 s^3 + \delta_4 s^4 + \cdots + \delta_n s^n$$

(8)

where the coefficients lie within given ranges, $\delta_i \in [x_i, y_i], \delta_i \in [x_i, y_i], \cdots, \delta_n \in [x_n, y_n]$. It is assumed that the degree remains invariant over the family, so that $0 \not\in [x_n, y_n]$. Such a set of polynomials is called a real interval family and is referred as an interval polynomial. The set of polynomials given by (8) is stable if and only if each and every element of the set is a Hurwitz polynomial. In [1] a necessary and sufficient condition for the robust stability of interval polynomial is proposed using algebraic stability criterion for fixed polynomials due to Nie [18], which are stated in following lemmas.

**Lemma 4.1:** The interval polynomial $\delta(s)$ defined in (8) is Hurwitz for all $\delta_i \in [x_i, y_i]$ where, $i = 0,1,2,\cdots, n$ if the following necessary conditions are satisfied

$$y_i \geq x_i \geq 0, \quad i = 0,1,2,\cdots, n$$

$$x_i x_{i+1} > y_{i-1} y_{i+1}, \quad i = 1,2,\cdots, n-2$$

(9)

**Lemma 4.2:** The interval polynomial $\delta(s)$ defined in (8) is Hurwitz for all $\delta_i \in [x_i, y_i]$ where, $i = 0,1,2,\cdots, n$ if the following sufficient conditions are satisfied

$$y_i \geq x_i > 0, \quad i = 0,1,2,\cdots, n$$

$$0.4655 x_i x_{i+1} > y_{i-1} y_{i+1}, \quad i = 1,2,\cdots, n-2$$

(10)

### 5. Design Procedure for Robust Stabilization of Interval Plant

Consider a strictly proper interval plant family consisting of all plants of the form:

$$\tilde{G}(s, \tilde{p}, \tilde{q}) = \frac{N(s, \tilde{p})}{D(s, \tilde{q})}$$
where the numerator and denominator polynomials are of the form:
\[ N(s, \bar{p}) = \bar{p}_0 + \bar{p}_1 s + \bar{p}_2 s^2 + \cdots + \bar{p}_{n-1} s^{n-1} + \bar{p}_n s^n \]
\[ D(s, \bar{q}) = \bar{q}_0 + \bar{q}_1 s + \bar{q}_2 s^2 + \cdots + \bar{q}_{m-1} s^{m-1} + \bar{q}_m s^m \]
where, vector \( \bar{p} \) and \( \bar{q} \) lie in the rectangles \( p \) and \( q \) respectively such that
\[ \bar{p} \in P : p_i^- \leq p_i \leq p_i^+ \text{ for } i = 0, 1, 2, \ldots, m. \]
\[ \bar{q} \in Q : q_i^- \leq q_i \leq q_i^+ \text{ for } i = 0, 1, 2, \ldots, n. \]

6. Design of Robust Controller

In this section, a design procedure for a robust PI and a PID controller for two different plants are illustrated.

A. Design of PI controller:

Example 1: Consider an uncertain plant with three fuzzy parameters \( \bar{p}_0, \bar{q}_0, \) and \( \bar{q}_1 \). The transfer function of the uncertain plant [19] is
\[ \tilde{G}(s, \bar{p}, \bar{q}) = \frac{\tilde{p}_0}{s^{n+1} + \tilde{q}_0 s^n + \tilde{q}_1 s^{n-1}} \]
Assume that the only information available for the values of uncertain parameters \( \tilde{p}_0, \tilde{q}_0, \) and \( \tilde{q}_1 \) is linguistic information. The linguistic information may be represented as fuzzy sets with triangular membership functions and is given as \( \tilde{p}_0 = tri(2, 2.5, 3), \tilde{q}_0 = tri(0.1, 0.5, 1) \) and \( \tilde{q}_1 = tri(2, 2.5, 3) \). We are interested in finding the nearest interval approximation of these triangular membership functions. Let us consider \( \tilde{p}_0 \) which can be expressed as
\[ 2x - 4, \text{ if } 2 \leq x \leq 2.5, \]
\[ \mu_{\tilde{p}_0}(x) = -2x + 6, \text{ if } 2.5 \leq x \leq 3, \]
\[ 0, \text{ if otherwise.} \]

Then, for \( \alpha \in (0, 1] \), we get following cuts using method in [15].
\[ [A^-(\alpha), A^+(\alpha)] = \left[ \frac{\alpha + 4}{2}, \frac{6 - \alpha}{2} \right] \]
\[ C^- = \int_0^1 A^-(\alpha) d\alpha = 2.25 \]
\[ C^+ = \int_0^1 A^+(\alpha) d\alpha = 2.75 \]

So, \( C_d(A) = [C^-, C^+] = [2.25, 2.75] \). Therefore nearest approximated interval is \([\tilde{p}_0^-, \tilde{p}_0^+] = [2.25, 2.75]\), similarly \([\tilde{q}_0^-, \tilde{q}_0^+] = [0.3, 0.75]\) and \([\tilde{q}_1^-, \tilde{q}_1^+] = [0.3, 0.45]\).

We now design a controller \( C(s) \) such that it is stable in the above approximated intervals. If the controller designed is stable for the given interval we say that it is robust. Let the controller be a PI type given as
\[ C(s) = k_1 + \frac{k_2}{s} = \frac{N_c(s)}{D_c(s)} \]

Now our system will be as shown in Figure 2.

Figure 2. Fuzzy uncertain system with a robust controller.

The closed loop polynomial will be given by the characteristic equation
\[ \Delta(s, p, q) = s^3 + [0.3, 0.45]s^2 + [2.25k_1, 0.3, 2.75k_1, 0.75]s + [2.25k_2, 2.75k_2] \]

By applying the conditions given in Lemma 4.1 and 4.2 to equation (13) we obtain a set of inequality constraints. Hence the optimization problem can be stated as: Find \( k_1 \) and \( k_3 \) such that objective function
\[ J = \sum_{j=1}^{n} k_j \]
minimized, subject to following constraints.
\[ 9.166k_2 - 2.25k_1 - 0.3 + \varepsilon < 0 \]
\[ 19.692k_2 - 2.25k_1 - 0.3 + \varepsilon < 0 \]
\[ -2.25k_2 + \varepsilon < 0 \]
\[ -2.25k_1 - 0.3 + \varepsilon < 0 \]
The objective function \( J \) is purposely chosen to restrict the magnitudes of the controller parameters \( k_1 \) and \( k_2 \) small. The linear programming problem consists of two decision variables and merely four constraints. The purpose of putting a small positive number \( \varepsilon \) into LP is to make feasible set closed. The value of \( \varepsilon \) will affect feasible parameter region. We have used “FMINCON” to minimize the function \( J \) in Matlab. It finds a constrained minimum of a function of several variables. It attempts to solve problems of minimization subject to linear as well as nonlinear constraints [20]. Table 1 shows the various values of \( k_1 \) and \( k_2 \) for different \( \varepsilon \). The values of the controller parameters \( k_1 \) and \( k_2 \) increase as \( \varepsilon \) is increased which shows the sensitivity of the controller parameters with respect to LP parameter \( \varepsilon \).

Remark 1: It is also possible to choose the objective function in terms of controller parameters \( k_1 \) and \( k_2 \) as,
\[ J = (k_1 - k_1^0)^2 + (k_2 - k_2^0)^2 \]
where \( k_1^0 \) and \( k_2^0 \) are nominal controller parameters obtained by comparing the closed loop characteristic polynomial (13) for its nominal value with the third order optimal characteristic equation that minimizes the Integral time absolute error (ITAE) performance for a step input [1]. In this case, the nonlinear programming (NLP) optimization problem needs to be solved. Thus one can choose objective function depending on the application and performance to be achieved.
It can be verified that each of the obtained PI controller is able to stabilize the closed loop system under parameter variations. The closed loop step response for all the sets of extreme plants with \( \varepsilon = 0.05 \) are shown in Figure 3, for PI parameters set as \( k_1 = 0.0834 \) and \( k_2 = 0.0222 \).

Table 1. Variation of \( k_1 \) and \( k_2 \) for different \( \varepsilon \).

<table>
<thead>
<tr>
<th>( \varepsilon )</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
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<tbody>
<tr>
<td>0.03</td>
<td>0.0033</td>
<td>0.0133</td>
</tr>
<tr>
<td>0.04</td>
<td>0.0400</td>
<td>0.0178</td>
</tr>
<tr>
<td>0.05</td>
<td>0.0834</td>
<td>0.0222</td>
</tr>
<tr>
<td>0.06</td>
<td>0.1267</td>
<td>0.0267</td>
</tr>
</tbody>
</table>

All the four Kharitonov polynomials given below are Hurwitz stable. It implies that the designed PI controller is stable.
\[ k_1(s) = 0.0500 + 0.4870s + 0.45s^2 + s^3 \]
\[ k_2(s) = 0.0611 + 0.9794s + 0.30s^2 + s^3 \]
\[ k_3(s) = 0.0611 + 0.4870s + 0.30s^2 + s^3 \]
\[ k_4(s) = 0.0500 + 0.9794s + 0.45s^2 + s^3 \]

The closed loop response clearly demonstrates that the designed PI controller achieves the requirement of stability.

The Bode plot for PI controller designed is shown in Figure 4.

Also the root space plot for this controller can be seen in Figure 5. It is clear that all the roots lie strictly in the left half of the s-plane.
B. Design of PID controller:

Example 2: Consider an uncertain plant with two uncertain parameters, $\bar{q}_1$ and $\bar{q}_2$. The transfer function of the uncertain plant [5] is

$$\tilde{G}(s, \tilde{\theta}, \tilde{\beta}) = \frac{1}{s^3 + 2s^2 + \tilde{\theta}s + \tilde{\beta}}$$

where,

$$\tilde{\theta} = -1 - \tilde{q}_1 - \tilde{q}_2 - \tilde{q}_2^2 \quad \text{and} \quad \tilde{\beta} = -\tilde{q}_2^2 - 3\tilde{q}_2 - \tilde{q}_1 - \tilde{q}_1\tilde{q}_2 - 2$$

Assume that the only information available for the values of the uncertain parameters $\tilde{q}_1$ and $\tilde{q}_2$ is the linguistic information ‘Around Zero’, as shown in Figure 6. The nearest interval approximation using [15] is found as $[q_1^-, q_1^+] = [-0.3, 0.3]$ and $[q_2^-, q_2^+] = [-0.2, 0.2]$. Using these values the uncertain plant parameters are calculated and are given by the intervals

$$\tilde{\theta} = [\theta^-, \theta^+] = [-1.54, -0.54]$$

and $$\tilde{\beta} = [\beta^-, \beta^+] = [-3, -1.2]$$

Now consider a PID controller $C(s)$ given as:

$$C(s) = k_1 + \frac{k_2}{s} + k_3s$$

The closed loop interval polynomial after substituting the interval values will be

$$\Delta(s, \theta, \beta) = s^4 + 2s^3 + [(k_1 - 1.54), (k_3 - 0.54)]s^2 + [(k_1 - 3), (k_1 - 1.2)]s + k_2$$

By applying the conditions given in Lemma 4.1 and 4.2, we obtain a set of inequality constraints. Hence the optimization problem is to find $k_1, k_2,$ and $k_3$ such that the objective function $J = \sum_{j=1}^{3} |k_j|$ is minimized subject to the following constraints.

Solving the above constraints, we get the controller parameters for $\varepsilon = 0.01$ as $k_1 = 4.295$, $k_2 = 1$ and $k_3 = 4.875$. The closed loop response for the step input is shown in Figure 7. The bode plot for PID controller designed is given in Figure 8. Also the root space plot for this controller can be seen in Figure 9. It is clear that all the roots lie strictly in the left half of the s-plane.
The four kharitonov polynomials given below are Hurwitz stable which proves that the PID controller designed is stable for the desired intervals.

\[
\begin{align*}
    k_1(s) &= 1 + 1.295s + 4.335s^2 + 2s^3 + s^4 \\
    k_2(s) &= 1 + 3.095s + 4.335s^2 + 2s^3 + s^4 \\
    k_3(s) &= 1 + 1.295s + 3.335s^2 + 2s^3 + s^4 \\
    k_4(s) &= 1 + 3.095s + 3.335s^2 + 2s^3 + s^4
\end{align*}
\]

7. Conclusion

In this paper, a method is proposed to design robust PI/PID controller for fuzzy parametric uncertain system. The fuzzy coefficients are approximated by interval number using a nearest interval approximation. The method uses a necessary condition and a sufficient condition for stability of interval polynomial. These conditions are used to derive a set of inequalities in terms of the controller parameters which can be solved to obtain a robust controller. The stability of the designed controllers is also checked by applying Kharitonov theorem. The method used is simple, involves fewer computations and is easily implemented. The results reflect convincingly the efficacy of the proposed method.

References

R. J. Bhiwani and B. M. Patre: Design of Robust Controller for Fuzzy Parametric uncertain Systems


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