Parametric and unstructured approach to uncertainty modelling and robust stability analysis

Radek Matušů, Roman Prokop, and Libor Pekař

***Abstract*—**The paper deals with comparison of two principal approaches to uncertainty modelling and related robust stability analyses for a system with uncertain time-delay. A paper bleaching process, used as a testing plant, is described first as a system with parametric uncertainty and then in the form of unstructured multiplicative uncertainty model. The robust stability or instability of closed control loop with appropriate uncertain model of the controlled system and selected controller is verified and obtained results are compared. Moreover, the issue of conservatism in uncertainty description and in subsequent robust stability analysis is also discussed.

***Keywords*—**Uncertainty modelling, time-delay systems, parametric uncertainty, unstructured uncertainty, robust stability analysis.

I. Introduction

The whole classical control theory as well as many contemporary methods use some form of mathematical model of a controlled system for a controller design. The crucial problem, however, is that assumed ideal mathematical model, due to many reasons, practically never exactly matches the real behaviour of the plant. One of possible approaches how to overcome this discrepancy grounds in utilization of an uncertain model and subsequent robust controller design.

Robust control, time-delay systems, and related issues belong among very deeply studied and attractive disciplines [1]–[5]. There are two principal ways of uncertainty modelling in the literature – parametric or unstructured approach [6]–[10]. Both of them have their advantages and drawbacks. Consequently, each of approaches is more suitable for different situations.

This paper presents the comparison of uncertainty modelling and subsequent closed-loop robust stability analyses for a fist order system with uncertain time-delay term. The tests are performed by means of the simulation examples with a paper bleaching process [11]. The initial robust stability investigations and control results for two PI controllers are subsequently enriched by outline of a conservatism issue. The paper is the extended version of the contribution [12].

The work is organized as follows. In Section II, the various approaches to uncertainty modelling and description are described. The Section III then presents analysis of robust stability under parametric uncertainty. The following Section IV has the same purpose, but for systems with unstructured uncertainty. Further, the comparative example with control of the paper bleaching process can be found in the extensive Section V. The next Section VI deals with the problem of conservatism in uncertainty description and in robust stability analysis. And finally, Section VII offers some conclusion remarks.

II. Uncertainty Modelling

The introductory part has already foreshadowed that difference between real process and its mathematical model is the fundamental and omnipresent control problem. For example, the parameters of controlled plant need not to be known exactly or they can be even time-variant (however, only "slowly" from the robust control point of view). Then, nonlinearity in controlled system can be neglected and consequently discrepancy could originate in linear approximation in given operational point. Or a simplified model can be intentionally used instead of originally very complex system (e.g. caused by neglecting the fast dynamic effects due to system order reduction, assumption of a distributed-parameter system as a lumped-parameter one, or time-delay neglect) because of easier calculations [11].

In robust control, respecting these factors in mathematical description leads to the use of uncertain model. In other words, not only one nominal model, but the whole family of models given by some neighborhood of the nominal one is defined. The "size" of this neighborhood can be described in two main ways – as a parametric or unstructured uncertainty. The combination of both main methods is also possible. Then one speaks about mixed uncertainty.

The real parametric uncertainty is utilized if the structure of system is known but its actual physical parameters are not. On

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This research was supported by the Ministry of Education, Youth and Sports of the Czech Republic under the Research Plan No. MSM 7088352102 and by the European Regional Development Fund under the project CEBIA-Tech No. CZ.1.05/2.1.00/03.0089. This assistance is very gratefully acknowledged.

the contrary, unstructured uncertainty does not require even knowledge of structure (order) of model. Parametric uncertainty is defined through intervals which the imprecisely known parameters lie within. The unstructured uncertainty description is based on restriction of the area of possible appearance of frequency characteristics [11].

However, the terminology used in this paper is not the one and only possible. The scientific literature presents also different nomenclatures, e.g. structured (=parametric) vs. nonparametric (=unstructured) or possibly parametric vs. dynamic, which are subsequently divided into unstructured and structured (with different meaning than in the previous case). Thus one has to be careful about the terminology of each author. This paper adopts probably the most frequent version, i.e. parametric vs. unstructured uncertainty [13].

It is known that robustness means preservation of a selected property of control loop not only for one nominal system but also for the whole family of systems given by the uncertain model and appropriate boundary. Generally, the most important control problem consists in ensuring the stability and so, quite naturally, one of the typical robust control problems is robust stability analysis. It investigates if the closed-loop stability is assured for all possible systems from the family. If this is fulfilled, then the system is called as robustly stable. Furthermore, the aim of robust synthesis is to find a controller which guarantee robustness (robust stability, robust performance, etc.) of the closed control loop. This paper is focused on analysis of robust stability.

III. Robust Stability Analysis under Parametric Uncertainty

The systems with parametric uncertainty [7] are frequently described by means of a vector of real uncertain parameters q:

$$q = [q_1, q_2, \dots, q_m]; \quad q \in \mathbb{R}^m \tag{1}$$

implemented into the transfer function:

$$G(s,q) = \frac{b(s,q)}{a(s,q)} \tag{2}$$

Many tests of robust stability under parametric uncertainty are based on direct analysis of uncertain characteristic closed-loop polynomial which can be assumed as:

$$p(s,q) = \sum_{i=0}^{n} \rho_i(q) s^i \tag{3}$$

where ρ_i are coefficient functions.

The vector of uncertain parameters (1) is usually defined by some uncertainty bounding set Q. The mostly common scenario takes advantage of the application of L_∞ norm which leads to Q in the shape of box set by components. Combination of the uncertain system structure with its uncertainty bounding set constitutes a family of systems.

Generally, the family of polynomials:

$$P = \{ p(\cdot,q) : q \in Q \} \tag{4}$$

is robustly stable, if and only if $p(\cdot,q)$ is stable for all $q \in Q$, i.e. all roots of continuous-time $p(s,q)$ must be located in the left half of the complex plane for all $q \in Q$. However, straightforward computation of all roots suffers from momentous disadvantage. It brings the extremely long computational time for a higher number of uncertain parameters, which makes it very unpractical [14]. Consequently, the more convenient techniques had to be investigated.

The way of entering the coefficient functions ρ_i into the polynomial (3) is very important for decision on the potential tool for robust stability analysis. Thus, one can distinguish among several basic structures of uncertainty with increasing generality:

- Independent (interval) uncertainty structure
- Affine linear uncertainty structure
- Multilinear uncertainty structure
- Nonlinear uncertainty structure (polynomial, general)

On top of that, single parameter uncertainty can be considered as a special case.

The higher degree of dependence among coefficients makes the analysis more complicated. For that reason, many uncertainty structures have their own specific tools for investigation of robust stability. A very important method consists in combination of the value set concept with the zero exclusion condition [7], [15]. This very universal technique can be relatively needlessly complicated one for the simplest structures, but on the other hand it represents the convenient approach for the more complex structures.

The value set [7], [15] for the family of polynomials (4) at frequency $\omega \in \mathbb{R}$ is defined as:

$$p(j\omega,Q) = \{ p(j\omega,q) : q \in Q \} \tag{5}$$

that is, $p(j\omega,Q)$ is the image of Q under $p(j\omega,\cdot)$. For the continuous-time case, one must substitute s for $j\omega$ in a family:

$$P = \{ p(s,q) : q \in Q \} \tag{6}$$

fix ω and let the vector of uncertain parameters q range over the set Q.

The zero exclusion condition [7], [15] for Hurwitz stability of family of continuous-time polynomials (6) says: Suppose invariant degree of polynomials in the family, pathwise connected uncertainty bounding set Q, continuous coefficient functions $\rho_i(q)$ for $i = 0, 1, 2, \dots, n$ and at least one stable member $p(s,q^0)$. Then the family P is robustly stable if and only if the complex plane origin is excluded from the value set

$p(j\omega,Q)$ at all frequencies $\omega \geq 0$, that is P is robustly stable if and only if:

$$0 \notin p(j\omega,Q) \quad \forall \omega \geq 0 \tag{7}$$

The applicability of this graphical method is very universal and so it can be used also for testing the robust stability of quasipolynomials which appear during analysis of closed control loop containing time-delay plant. This will be shown in the Section V.

An interested reader can find a lot of additional information about robustness of systems with parametric uncertainty and related topics e.g. in [6]–[10], [15]–[17].

IV. Robust Stability Analysis under Unstructured Uncertainty

As it has been already outlined, the unstructured uncertainty is useful especially when the structure of model is not known, so it is related for example to the unmodelled dynamics, truncation of high frequency modes or nonlinearities. Its description grounds in restriction of frequency characteristics.

There are several types of unstructured uncertainty models in literature [10], [13], [16], [17], i.e.:

- Multiplicative model:

$$G(s) = \left[1 + W_M(s)\Delta_M(s)\right]G_0(s) \tag{8}$$

- Additive model:

$$G(s) = G_0(s) + W_A(s)\Delta_A(s) \tag{9}$$

- Inverse multiplicative model:

$$G(s) = \left[1 - W_{IM}(s)\Delta_{IM}(s)\right]^{-1} G_0(s) \tag{10}$$

- Inverse additive model:

$$G(s) = G_0(s)\left[1 - W_{IA}(s)\Delta_{IA}(s)G_0(s)\right]^{-1} \tag{11}$$

where $G(s)$ represents a perturbed model, $G_0(s)$ stands for a nominal model, $W_M(s)$ is a (stable) weight function representing uncertainty dynamics, i.e. the distribution of the maximum amplitude of the uncertainty over the frequency, and $\Delta_M(s)$ means the uncertainty (uncertain information about actual magnitude and phase of perturbation), which can be an arbitrary stable function fulfilling the inequality:

$$\left\|\Delta_M(s)\right\|_\infty \leq 1 \quad \Rightarrow \quad \left|\Delta_M(j\omega)\right| \leq 1 \quad \forall \omega \tag{12}$$

Furthermore, in multiplicative model, it can be formally distinguished between the uncertainty in the input or output of the system for multi-input multi-output (MIMO) systems. However, it is not important for single-input single-output (SISO) case. The inverse versions of the models allow describing also the unstable dynamics. Graphical interpretations of these uncertainties can be found in figs. 1 – 4.

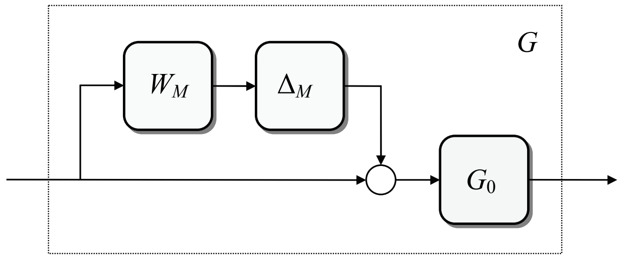

Fig. 1 multiplicative model of uncertainty (8)

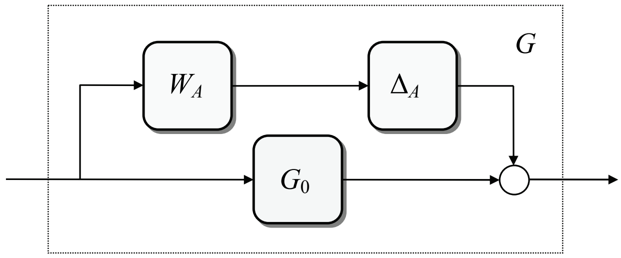

Fig. 2 additive model of uncertainty (9)

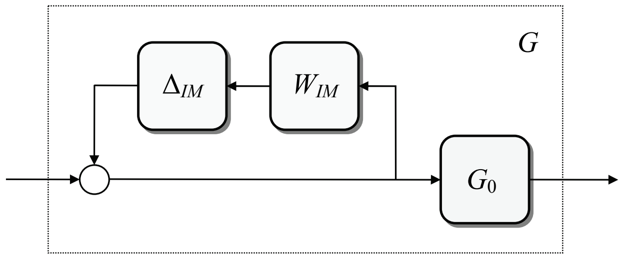

Fig. 3 inverse multiplicative model of uncertainty (10)

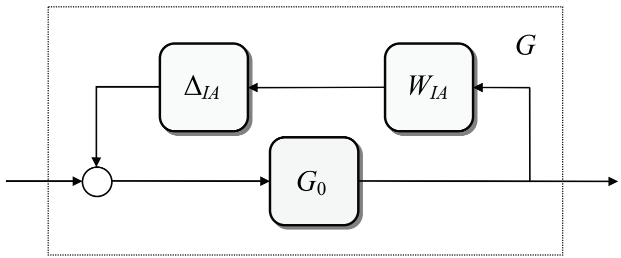

Fig. 4 inverse additive model of uncertainty (11)

For multiplicative uncertainty, it holds true:

$$\left|\frac{G(j\omega)}{G_0(j\omega)} - 1\right| \leq \left|W_M(j\omega)\right| \quad \forall \omega \tag{13}$$

Moreover, many theoretical tools for analysis and synthesis require that $G(s)$ and $G_0(s)$ have to have the same amount of poles for all $\Delta_M(s)$.

Under assumption of multiplicative uncertainty, the closed-loop system is robustly stable if and only if:

$$\|W_M(s)T_0(s)\|_\infty < 1 \tag{14}$$

where $T_0(s)$ is a complementary sensitivity function:

$$T_0(s) = \frac{L_0(s)}{1 + L_0(s)} \tag{15}$$

and where the term $L_0(s)$ represents open-loop frequency transfer function:

$$L_0(s) = C(s)G_0(s) \tag{16}$$

The inequality (14) can be adjusted into:

$$\begin{aligned} &\left|\frac{W_M(j\omega)L_0(j\omega)}{1+L_0(j\omega)}\right| < 1 \quad \forall\omega \quad \Rightarrow \\ &\Rightarrow \quad |W_M(j\omega)L_0(j\omega)| < |L_0(j\omega) - (-1)| \quad \forall\omega \end{aligned} \tag{17}$$

which practically says that the envelope of Nyquist diagrams with radius $|W_M(j\omega)L_0(j\omega)|$ and centre $L_0(j\omega)$ must not include the critical point $[-1, 0j]$. The graphical interpretation of this condition is shown in fig. 5.

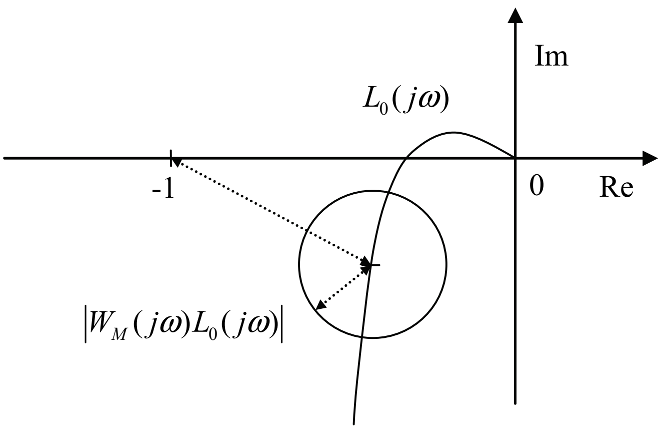

Fig. 5 graphical interpretation of the robust stability condition for multiplicative uncertainty

Alternatively, the robust stability condition (14) can take also the form:

$$|T_0(j\omega)| < \frac{1}{|W_M(j\omega)|} \quad \forall\omega \tag{18}$$

The other than multiplicative uncertainties have different versions of such conditions [10], [13], [16], [17].

V. Comparative Example – robust Stability Analysis for a Paper Bleaching Process

A bleaching process in a paper-making machine is adopted from paper [11] where it is modelled as a first order plant with uncertain time-delay. More specifically, it describes the dependency of lignin amount on chlorine flow-rate. The known part of time-delay results from sensor placement while the unknown one originates in neglect of fast dynamics of the chemical process. Thus, the nominal model of the controlled process is defined as:

$$G_0(s) = \frac{1}{2s+1}e^{-0.1s} \tag{19}$$

and the class of uncertain models can be described by:

$$G(s) = \left\{\frac{1}{2s+1}e^{-(0.1+\Theta)s} : 0 \le \Theta \le 0.9\right\} \tag{20}$$

The task is to verify if this system is robustly stabilized by the following PI controllers:

$$C_1(s) = \frac{3s+2.5}{s} \tag{21}$$

$$C_2(s) = \frac{1.5s+0.5}{s} \tag{22}$$

by means of parametric and unstructured uncertainty modelling approach, respectively.

A. Parametric Uncertainty Approach

First, the controlled plant is assumed as a transfer function with single uncertain parameter (time-delay term):

$$G(s,\tilde{\Theta}) = \frac{1}{2s+1}e^{-\tilde{\Theta}s} = \frac{1}{2s+1}e^{-[0.1,1]s} \tag{23}$$

The closed-loop characteristic quasipolynomial of the circuit with plant (23) and the controller (21) can be simply expressed as:

$$\begin{aligned} &p_{CL1}(s,\tilde{\Theta}) = (2s+1)s + e^{-\tilde{\Theta}s}(3s+2.5); \\ &\tilde{\Theta} \in \langle 0.1, 1\rangle \end{aligned} \tag{24}$$

In accordance with theory from Section III, the value set for one fixed frequency ω can be obtained, roughly speaking, by substitution of s for $j\omega$ in the family (24) and letting the time-delay term $\tilde{\Theta}$ range over the prescribed set. The fig. 6 shows such value sets plotted in complex plane for several non-negative frequencies starting from 0 to 2.4 with step 0.05.

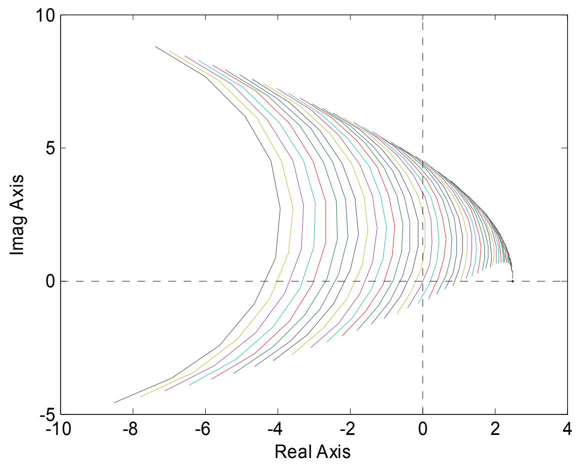

Fig. 6 the value sets of uncertain quasipolynomial (24) – robustly unstable case

As can be seen, the origin of the complex plane is included in the value sets which means that quasipolynomial (24) and consequently also the whole control system with controller (21) and time-delay plant (23) is not robustly stable.

The second controller (22) and the same controlled system (23) lead to the uncertain closed-loop characteristic quasipolynomial:

$$p_{CL2}(s,\tilde{\Theta}) = (2s+1)s + e^{-\tilde{\Theta}s}(1.5s+0.5);\quad \tilde{\Theta} \in \langle 0.1, 1 \rangle \tag{25}$$

The corresponding value sets for the identical range of frequencies is depicted in fig. 7.

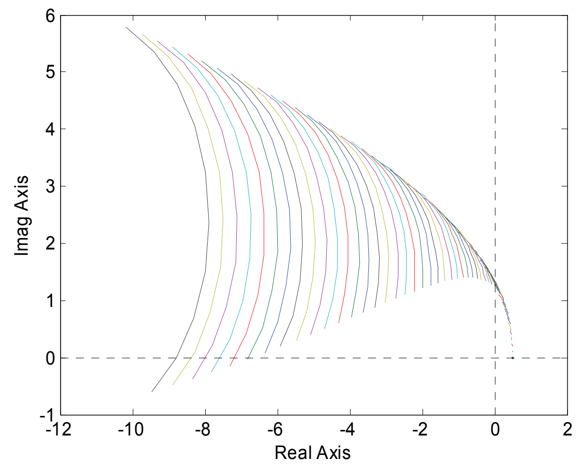

Fig. 7 the value sets of uncertain quasipolynomial (25) – robustly stable case

Due to the fact that the family has a stable member and the origin of the complex plane is excluded from the value sets, one can conclude that the quasipolynomial (25) and thus also the control system is robustly stable for this controller parameters.

B. Unstructured Uncertainty Approach

In the second case, the system (20) is considered to be described as an unstructured multiplicative uncertainty model (8). The normalized perturbation of the plant (20) can be obtained using (13):

$$\left|e^{-\Theta j\omega} - 1\right| \leq \left|W_M(j\omega)\right| \quad \forall\,\omega \tag{26}$$

The object of interest is just the amplitude of perturbation. The phase is not restricted. So, the suitable weight function, considered as the envelope of the uncertainty, is chosen in [11] as:

$$W_M(s) = \frac{2.1s}{s+1} \tag{27}$$

The fig. 8 shows the comparison of Bode plots of the weight (27) and normalized perturbations for three values of time-delay ($\Theta = 0.9$, $\Theta = 0.1$, and $\Theta = 0.01$). It can be seen how $|W_M(j\omega)|$ approximates even the worst case of $\Theta = 0.9$ from the upper side.

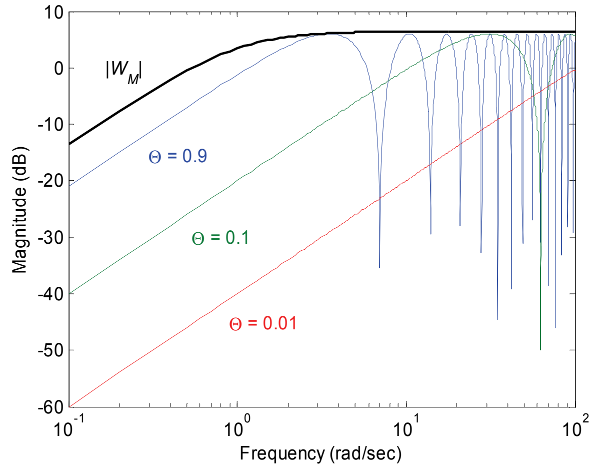

Fig. 8 Bode plots – envelope of the uncertainty

Thus, remember that the aim is to analyze the robust stability of closed-loop with the family of systems:

$$\begin{aligned} &G(s) = \left[1 + W_M(s)\Delta_M(s)\right]G_0(s) \\ &\left\|\Delta(s)\right\|_\infty \leq 1 \\ &G_0(s) = \frac{1}{2s+1}e^{-0.1s} \\ &W_M(s) = \frac{2.1s}{s+1} \end{aligned} \tag{28}$$

and with the controllers (21) and (22).

For the first controller (21), the envelope of Nyquist diagrams given by circles with radius $|W_M(j\omega)L_0(j\omega)|$ around the Nyquist diagram of $L_0(j\omega)$ (red curve) is plotted in fig. 9

(with frequency step 0.1). It shows that the critical point [-1, 0*j*] is included in the envelope. Consequently, the closed loop with controller (21) and family of systems (28) is robustly unstable.

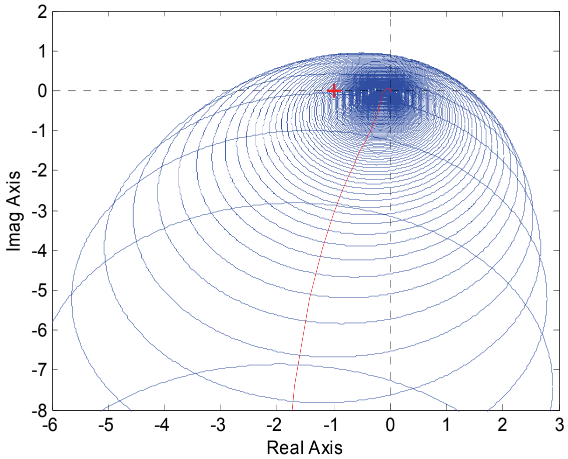

Fig. 9 graphical interpretation of stability condition (14) for controller (21) – robustly unstable case

Analogically, but now under assumption of the second controller (22), the envelope of Nyquist diagrams is shown in fig. 10 (again with frequency step 0.1). For this case, the point [-1, 0*j*] is excluded from the envelope which means robust stabilization of the closed-loop with controller (22) and family of systems (28).

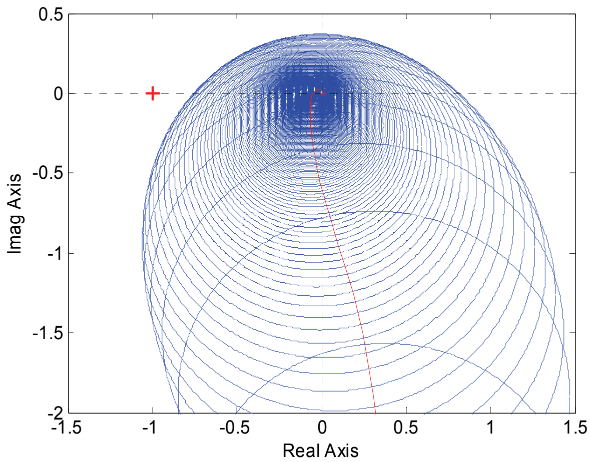

Fig. 10 graphical interpretation of stability condition (14) for controller (22) – robustly stable case

C. Control Simulations

For the purpose of simulations, the time-delay term in controlled plant (20) has been sampled into 91 fixed values from 0.1 to 1 with step 0.01. Thus, it has resulted in 91 "representative" systems for simulations.

First, the robustly unstable case with the controller (21) has been verified. The fig. 11 presents the output signals of this "representative" set of systems while the fig. 12 depicts the corresponding control (actuating) signals. Next, the analogical graphs can be seen in figs. 13 and 14 but here for the robustly stable scenario with the controller (22).

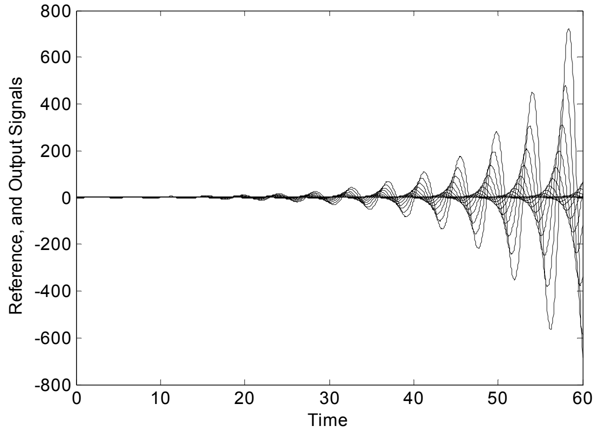

Fig. 11 output signals of 91 "representative" systems for the controller (21) – robustly unstable case

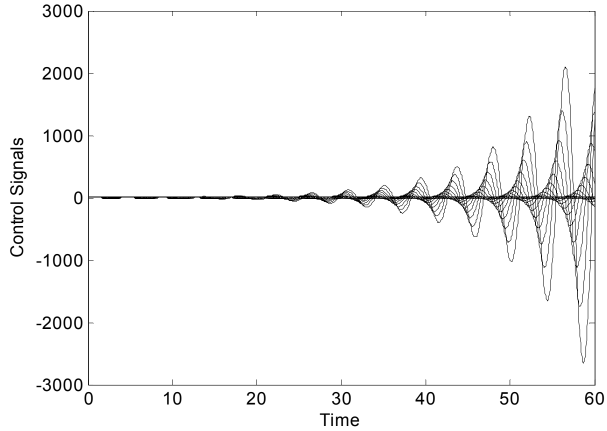

Fig. 12 control signals going from the controller (21) to 91 "representative" systems – robustly unstable case

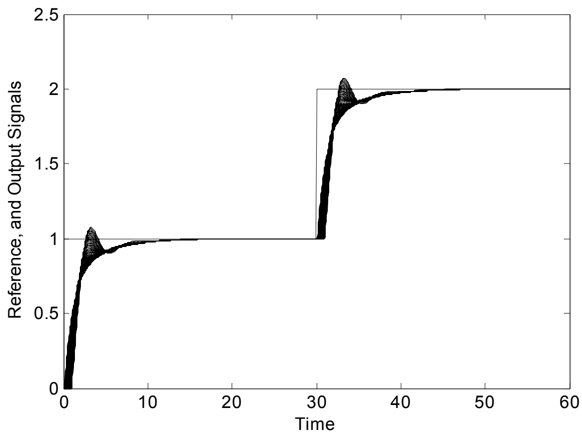

Fig. 13 output signals of 91 "representative" systems for the controller (22) – robustly stable case

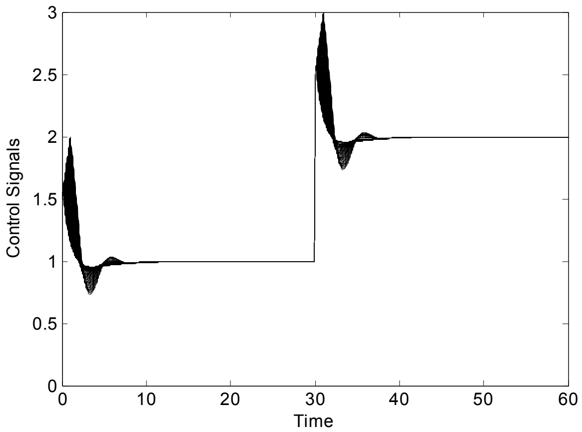

Fig. 14 control signals going from the controller (22) to 91 “representative” systems – robustly stable case

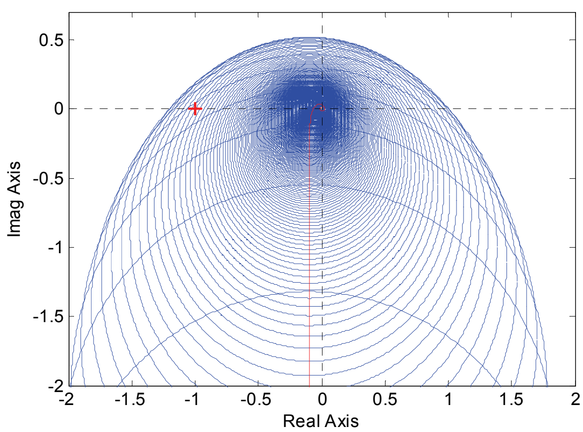

Fig. 15 graphical interpretation of stability condition (14) for controller (29) – robustly ?unstable? case

VI. Conservatism in Robust Stability Analysis

As expected, the obtained results of robust stability analysis from parts A and B of the previous Section mutually concur and, moreover, they are confirmed by simulations from part C. However, it needs not to be true under all circumstances. One has to be careful about the conservatism during investigation of robust stability under unstructured uncertainty as it is going to be explained bellow.

The unstructured uncertainty has a substantial advantage in the fact that not only changes in parameters can be taken into consideration by such description. Actually, this approach is very useful under various unmodelled dynamics. On the contrary, this merit can turn into a drawback in our case of only parametrically uncertain plant assumed as a system with unstructured uncertainty because of conservatism in description and consequent robust stability analysis. In other words, e.g. multiplicative model (28) “overbounds” the “real” plant (20) – see envelope of the uncertainty in fig. 8. It means that even if the robust stability test is not positive for the model (28), the actual control behaviour can be still robustly stable as will be demonstrated in the following example.

Assume a controller:

$$C_3(s) = \frac{2s+1}{s} \tag{29}$$

and the multiplicative uncertain model (28). Even though the envelope of Nyquist diagrams visualized in fig. 15 includes the critical point which indicates the robust instability for model (28), the true closed control loop with the controller (29) and plant (20) is robustly stable. This is confirmed e.g. by fig. 16 where the output responses for 91 “representative” systems are plotted. Besides, the related control signals can be seen in fig. 17.

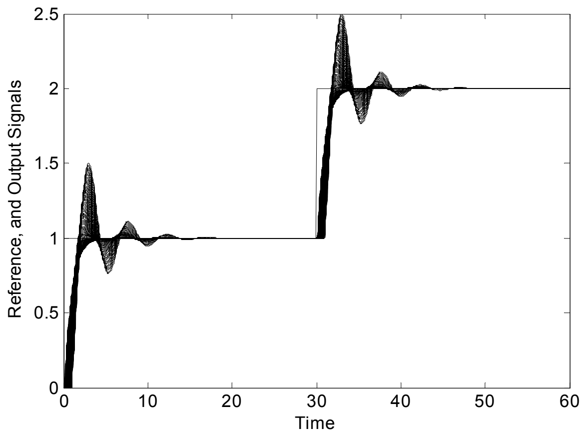

Fig. 16 output signals of 91 “representative” systems for the controller (29) – robustly ?unstable? case

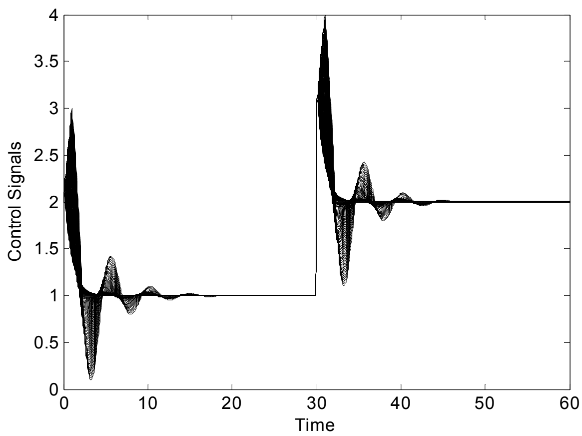

Fig. 17 control signals going from the controller (29) to 91 “representative” systems – robustly ?unstable? case

VII. Conclusion

The paper has dealt with comparison of parametric and unstructured approaches to uncertainty modelling and robust stability analysis. The parametric way of description seems to be more natural and comprehensive and robust stability analysis is also relatively straightforward under parametric uncertainty scenario. On the other hand, application of unstructured uncertainty model is very convenient especially for systems with various unmodelled dynamics and nonlinearities and, furthermore, this approach allows taking advantage of wider range of more sophisticated controller design methods.

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