Robust Stability Analysis for Systems with Real Parametric Uncertainty: Implementation of Graphical Tests in Matlab

Radek Matušů, and Roman Prokop

***Abstract*—**This paper is focused mainly on demonstration of simple Matlab programs suitable for plotting the value sets of systems with real parametric uncertainty represented by families of polynomials. The behaviour of obtained value sets and especially their position in relation to the origin of the complex plane is convenient criterion of robust stability/instability. The paper presents number of illustrative examples for various simple as well as complicated structures of uncertainty mainly for continuous-time families including the Matlab codes and robust stability analyses. On top of that, the work covers also cases of a quasi-polynomial or discrete-time interval polynomial.

***Keywords*—**Real parametric uncertainty, value set concept, zero exclusion condition, Matlab.

I. Introduction

UNCERTAIN systems and robustness issues have represented attractive research topics with high application potential in control for the last decades. Unsurprisingly, a number of related publications have appeared, e.g. [1] – [6]. Among others, description of systems by means of real parametric uncertainty is very popular and effective approach to uncertainty modelling [7] – [9].

Definitely, the most critical feature of all control applications is the stability. Then, under conditions of uncertainty one speaks about robust stability. A universal graphical approach to robust stability analysis of systems with parametric uncertainty uses combination of the value set concept and the zero exclusion condition [7]. It is generally applicable and relatively easy to use method which is especially advantageous for systems with complicated uncertainty structures, because there is a lack of analytical tools for testing the robust stability of such kind of uncertain systems. From the practical viewpoint, analysis of robust stability for systems with real parametric uncertainty can be very comfortably performed with the assistance of the Polynomial Toolbox for Matlab [10]. However, the capabilities of the toolbox are much more extensive, not restricted only to this problem.

This work is a follow-up to the overview paper [11], where the robust stability tests were done with the help of the Polynomial Toolbox using commands khplot, vsetplot, ptopplot, etc. Nevertheless, this work provides the simple program codes for plotting the value sets of systems with parametric uncertainty which are applicable in Matlab itself. The "mini-programs", covering basic structures of uncertainty, are always specific with respect to the example and plotted figure. The paper is the extended version of the conference contribution [12].

The work is organized as follows. In section II, the fundamentals of parametric uncertainty modelling and robust stability analysis are introduced. The section III then briefly describes the value set concept and the zero exclusion condition. Next, the illustrative examples of Matlab programs and their results can be found in the extensive section IV, which consists of eight subsections. Finally, section V offers some conclusion remarks.

II. Uncertainty Modelling and Robust Stability Analysis

The uncertainty can be taken into consideration in the mathematical models in two basic ways – as unstructured or parametric uncertainty [11] – [16]. The unstructured description of uncertainty is given by restriction of the area of possible appearance of frequency characteristics and it is useful e.g. in the case of unmodelled dynamics. On the other hand, parametric approach represents known structure but imprecise knowledge of real physical parameters of the system. Their possible values are usually bounded by intervals.

In the next considerations, the problem of stability of a system is going to be assumed as the problem of stability of its characteristic polynomial. Thus, suppose the (continuous-time) uncertain polynomial:

$$p(s,q)=\sum_{i=0}^{n}\rho_i(q)s^i \tag{1}$$

where q is the vector of uncertainty and ρ_i are coefficient functions.

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The work was supported 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 family of polynomials is then [7]:

$$P = \{ p(\cdot, q) : q \in Q \} \tag{2}$$

where Q is the uncertainty bounding set (a multidimensional box in this paper).

The family of polynomials (2) is robustly stable if and only if $p(s,q)$ is stable for all $q \in Q$. Since the direct calculation of roots can be impractical due to potentially enormously long computation times, the more efficient techniques had to be studied [17]. The selection of method for robust stability analysis depends mainly on the structure of the uncertainty, i.e. on the way how the uncertain parameters enter into the coefficients of the polynomial (1). According to this, basic structures of uncertainty with increasing generality are distinguished as follows: independent (interval) uncertainty structure, affine linear uncertainty structure, multilinear uncertainty structure, nonlinear uncertainty structure (polynomial, general). On top of that, the single parameter uncertainty can be considered as a special case. Generally, the higher level of relation among coefficients means the more complicated robust stability analysis. An interested reader can find further information e.g. in [7] – [9], [11], [14].

III. Value Set Concept and Zero Exclusion Condition

Among robust stability analysis tools, one seems to be very unique from the viewpoint of its universality and applicability even for the very complex uncertainty structures. The method combines the value set concept and the zero exclusion condition [7].

Assume a family of polynomials (2). The value set at frequency $\omega \in \mathbf{R}$ is given by [7]:

$$p(j\omega, Q) = \{ p(j\omega, q) : q \in Q \} \tag{3}$$

In other words, $p(j\omega,Q)$ is the image of Q under $p(j\omega,\cdot)$. Practical construction of the value sets then means to substitute s for $j\omega$, fix ω and let the vector of uncertain parameters q range over the set Q.

The zero exclusion condition for Hurwitz stability of family of continuous-time polynomials (2) says [7]: Suppose invariant degree of polynomials in the family, pathwise connected uncertainty bounding set Q, continuous coefficient functions $\rho_i(q)$ for $i = 0, 1, 2, \ldots, n$ 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 $\omega \ge 0$, that is P is robustly stable if and only if:

$$0 \notin p(j\omega, Q) \quad \forall \omega \ge 0 \tag{4}$$

More details can be found especially in [7] or eventually in [11].

IV. Plotting the Value Sets in Matlab – Illustrative Examples

The examples within this section are intended to demonstrate possible ways of simple plotting the value sets for several uncertainty structures in Matlab. The provided codes are not in the form of general functions, but they are always specific with respect to the plotted figure. Moreover, commands for axes labels and auxiliary axes are omitted.

A. Single Parameter Uncertainty

The first example is focused on single parameter uncertainty. Quite naturally, object with such kind of uncertainty can contain just one uncertain parameter. The specific family of polynomials is considered as:

$$p(s,q) = 5s^3 + (2+2q)s^2 + (3+q)s + 1.5 + q; \quad q \in \langle 0; 1 \rangle \tag{5}$$

The fig. 1, where the (straight line) value sets of this family for frequencies from 0 to 1.2 with step 0.02 are plotted, can be obtained e.g. by using the following code:

```
%single parameter uncertainty
clear all
hold on
for w=0:0.02:1.2 %frequency range
  count=1; %auxiliary counter
  for q=0:0.1:1 %uncertain parameter
    p(count)=5*(j*w)^3+(2+2*q)*(j*w)^2+(3+q)*(j*w)+…
    1.5+q; %the polynomial
    count=count+1; %counter increment
  end
  x=real(p); %real part
  y=imag(p); %imaginary part
  plot(x,y)
end
hold off
```

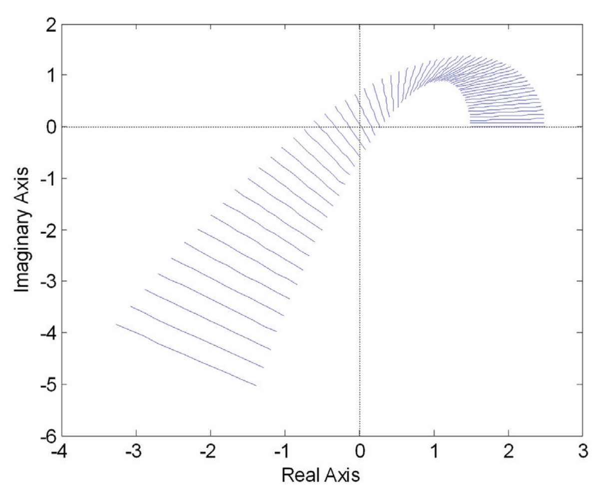

Fig. 1 straight line value sets for the family (5)

However, the presented procedure does not represent the only way of obtaining the value sets from the programmer viewpoint. An example of another approach can be seen here:

```
%single parameter uncertainty - alternative
clear all
q=(0:0.1:1)'; %uncertain parameter
count=1; %auxiliary counter
for w=0:0.02:1.2 %frequency range
  p(:,count)=5*(j*w)^3+(2+2*q)*(j*w)^2+(3+q)*(j*w)+…
  1.5+q; %the polynomial
  count=count+1; %counter increment
end
plot(p)
```

Obviously, the resulting plot of value sets would be the same as in fig. 1, but, among others, this second version would automatically change colors of the individual lines. Incidentally, the same color changing effect for all figures in the paper would have just using command “hold all” instead of “hold on” in the presented codes.

One way or another, it can be seen that the complex plane origin in fig. 1 is included in the value sets and thus the family of polynomials (5) is not robustly stable.

Now, assume a family of polynomials with slightly changed last coefficient:

$$p(s,q) = 5s^3 + (2+2q)s^2 + (3+q)s + 0.5 + q; \quad q \in \langle 0;1 \rangle \tag{6}$$

This time, the zero point is excluded from the corresponding value sets plotted in fig. 2 and the family (6) contains a stable member (the value sets round the origin counter-clockwise). It means that the family of polynomials (6) is robustly stable.

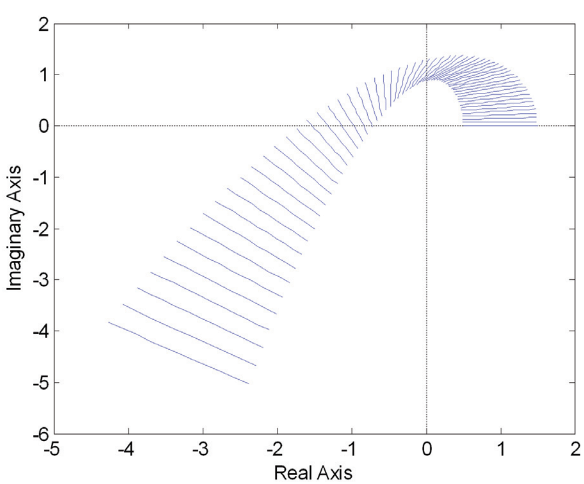

Fig. 2 straight line value sets for the family (6)

However, consider another modification of the polynomial family:

$$p(s,q) = 5s^3 + (2+2q)s^2 + (3+q)s + 2.5 + q; \quad q \in \langle 0;1 \rangle \tag{7}$$

The value sets for this case (7) are visualized in fig. 3. As can be seen, the origin of the complex plane is not included in the value sets, but since the family (7) does not have any stable member, it is robustly unstable. More specifically, all members of this family are unstable.

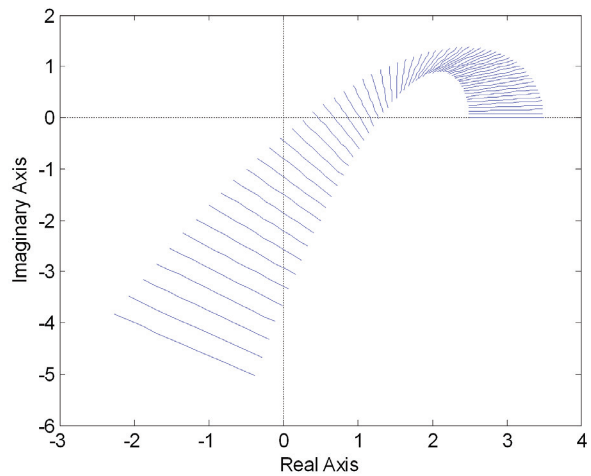

Fig. 3 straight line value sets for the family (7)

B. Single Parameter Uncertainty (in Quasi-Polynomial)

In this case, the investigated family still has a single uncertain parameter, but now it is a quasi-polynomial:

$$\begin{aligned} p(s,T_d) &= (5s+1)(s^2+0.13s)+\cdots \\ &\cdots 2e^{-T_d}(0.15s^2+0.05s+0.004); \\ T_d &\in \langle 2;10 \rangle \end{aligned} \tag{8}$$

This type of object typically occurs as a closed-loop characteristic quasi-polynomial under assumption of a controlled plant with uncertain time-delay term and a fixed controller [11], [18]. The fig. 4 shows the value sets consisting of more complex single parameter curves. It can be plotted using:

```
%single parameter uncertainty (quasi-polynomial)
clear all
hold on
for w=0:0.002:0.3 %frequency range
  count=1; %auxiliary counter
  for TD=2:0.1:10 %uncertain time-delay term
    p(count)=(5*(j*w)+1)*((j*w)^2+0.13*(j*w))+…
    2*exp(-TD*(j*w))*(0.15*(j*w)^2+0.05*(j*w)+0.004);…
    %the quasi-polynomial
    count=count+1; %counter increment
  end
  x=real(p); %real part
```

```
  y=imag(p); %imaginary part
  plot(x,y)
end
hold off
```

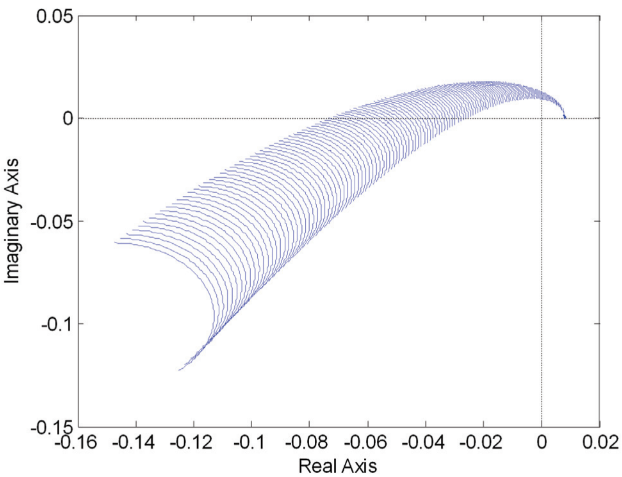

Fig. 4 value sets for the family (8)

Now, the zero point is excluded from the value sets. Moreover, the family (8) definitely has a stable member and thus this family is robustly stable.

C. *Interval Uncertainty*

The next example is going to deal with interval polynomial, which is given typically by shorthand notation with lower and upper bounds of polynomial coefficients:

$$p(s,q) = [1;\,2]s^3 + [2;\,3]s^2 + [3;\,4]s + [0.5;\,1] \tag{9}$$

The key feature of the interval polynomial family is that it has independent structure, i.e. each uncertain parameter can enter into only one coefficient. The famous tool for investigation of robust stability of interval polynomials is Kharitonov theorem [19] which uses four Kharitonov polynomials, specially constructed by means of upper and lower bounds of the interval coefficients. In fact, this principle is applied also in the presented simple Matlab program (which produces fig. 5):

```
%interval uncertainty
clear all
hold on
for w=0:0.02:1.5 %frequency range
  q3_min=1; q3_max=2; %definition of interval coefficients
  q2_min=2; q2_max=3;
  q1_min=3; q1_max=4;
  q0_min=0.5; q0_max=1;
  K_1=q0_min+q1_min*(j*w)+q2_max*(j*w)^2+…
  q3_max*(j*w)^3; %Kharitonov polynomials
  K_2=q0_max+q1_max*(j*w)+q2_min*(j*w)^2+…
  q3_min*(j*w)^3;
  K_3=q0_max+q1_min*(j*w)+q2_min*(j*w)^2+…
  q3_max*(j*w)^3;
  K_4=q0_min+q1_max*(j*w)+q2_max*(j*w)^2+…
  q3_min*(j*w)^3;
  x=real([K_1,K_3,K_2,K_4,K_1]);
  y=imag([K_1,K_3,K_2,K_4,K_1]);
  plot(x,y)
end
hold off
```

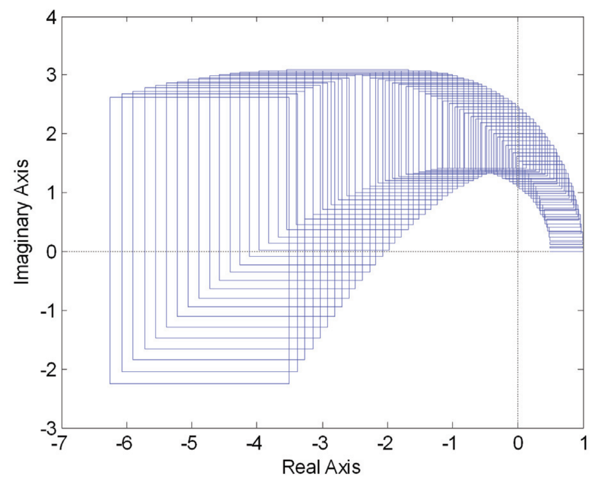

Fig. 5 rectangular value sets for the family (9)

The vertices of the rectangular value sets from fig. 5 correspond to four Kharitonov polynomials. The interval polynomial family (9) is robustly stable because it has a stable member and the origin of the complex plane is excluded from the value sets.

D. *Affine Linear Uncertainty Structure*

Now, the consideration is going to be focused on family of polynomials with affine linear uncertainty structure taken from [11], inspired by [7]:

$$\begin{aligned} &p(s,q) = (2q_1 - q_2 + 2q_3 + 1)s^3 + (3q_1 - q_2 - q_3 + 2)s^2 + \cdots \\ &\cdots (3q_1 + q_2 + 7q_3 + 5)s + (2q_1 - 2q_2 + 5q_3 + 4); \\ &|q_i| \le 0.2 \;\; \text{for} \;\; i = 1, 2, 3 \end{aligned} \tag{10}$$

Affine linear uncertainty structure can be found quite frequently because e.g. interval plant in feedback loop with fixed controller leads to the closed-loop characteristic polynomial with this uncertainty structure. More generally, the affine linear uncertainty structure itself is preserved during transmission from the open loop to the closed loop [20]. The shape of value set for this uncertainty structure is polygonal (convex) as can be seen in fig. 6 which is obtained with the assistance of:

```
%affine linear uncertainty structure
clear all
hold on
```

```
for w=0.05:0.05:3 %frequency range
  count=1; %auxiliary counter
  for q1=-0.2:0.4:0.2 %uncertain parameters for…
  %2^3=8 generators
    for q2=-0.2:0.4:0.2
      for q3=-0.2:0.4:0.2
        p(count)=(2*q1-q2+2*q3+1)*(j*w)^3+(3*q1-q2-q3+…
        2)*(j*w)^2+(3*q1+q2+7*q3+5)*(j*w)+(2*q1-2*q2+…
        5*q3+4); % the polynomial
        count=count+1; %counter increment
      end
    end
  end
  x=real(p); %real part
  y=imag(p); %imaginary part
  k=convhull(x,y); %convex hull
  plot(x(k),y(k))
end
hold off
```

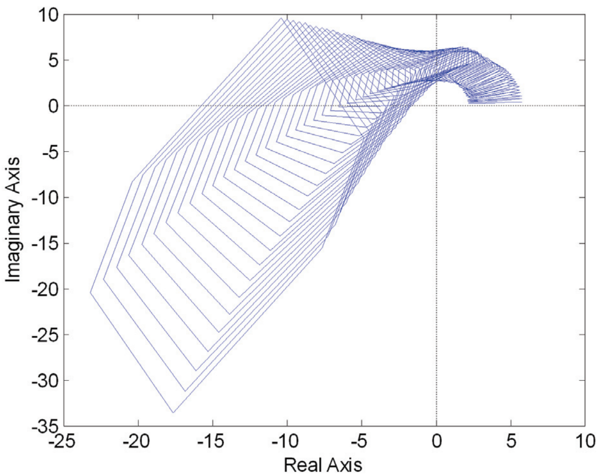

Fig. 6 polygonal value sets for the family (10)

Analogically to the previous cases, the family (10) contains a stable member and the value sets do not cross the zero so the family is robustly stable again.

E. Multilinear Uncertainty Structure

The fifth example analyzes the polynomial family with multilinear uncertainty structure, adopted from [7]:

$$\begin{aligned} &p(s,q) = s^4 + \left(5 + 0.2q_1q_2 + 0.1q_1 - 0.1q_2\right)s^3 + \cdots \\ &\cdots\left(6 + 3q_1q_2 - 4q_2\right)s^2 + \left(6 + 6q_1 - 8q_2\right)s + \left(0.5 - 3q_1q_2\right); \\ &\left|q_i\right| \le 0.25 \text{ for } i = 1, 2 \end{aligned} \tag{11}$$

The value sets for the polynomial (11) can be visualized (see fig. 7) using the code:

```
%multilinear uncertainty structure
clear all
hold on
for w=0:0.1:1.2 %frequency range
  count=1; %auxiliary counter
  for q1=-0.25:0.01:0.25 %sampling of uncertain parameters
    for q2=-0.25:0.01:0.25
      p(count)=(j*w)^4+(5+0.2*q1*q2+0.1*q1-0.1*q2)*…
      (j*w)^3+(6+3*q1*q2-4*q2)*(j*w) ^2+(6+6*q1-8*q2)*…
      (j*w)+(0.5-3*q1*q2); % the polynomial
      count=count+1; %counter increment
    end
  end
  x=real(p); %real part
  y=imag(p); %imaginary part
  plot(x,y,'.')
end
hold off
```

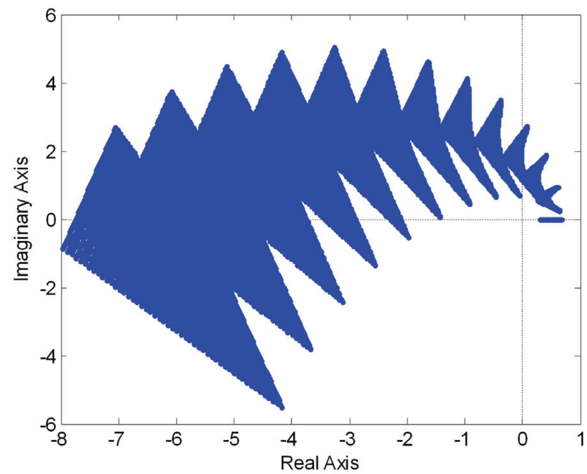

Fig. 7 value sets for the family (11)

Application of the same principles as in the previous cases leads to the result that the investigated family (11) is robustly stable.

One can notice that the value sets are not convex anymore and that “brute-force method”, i.e. sampling of uncertain parameters and computing the image of the corresponding polynomial in the complex plane, has been used. The reason consists in the fact that there is a lack of analytical tools for the multilinear or even more complicated (polynomial, general) uncertainty structures.

F. Polynomial Uncertainty Structure

Next, the family with polynomial uncertainty structure (from [11]) is supposed:

$$\begin{aligned} &p(s,q) = s^3 + \left(q_1q_2 + 2\right)s^2 + \cdots \\ &\cdots\left(q_1^3 - q_2^3 - q_1q_2 + q_2 + 10\right)s + \left(q_1^3 + q_2^3 + q_1q_2 + q_2 + 5\right); \\ &q_1, q_2 \in \left\langle -1;1 \right\rangle \end{aligned} \tag{12}$$

The program for plotting the value sets of (12) is essentially the same as in the previous example, i.e.:

```
%polynomial uncertainty structure
clear all
hold on
for w=0:0.3:5.1 %frequency range
  count=1; %auxiliary counter
  for q1=-1:0.02:1 %sampling of uncertain parameters
    for q2=-1:0.02:1
      p(count)=(j*w)^3+(q1*q2+2)*(j*w)^2+(q1^3-q2^3-…
      q1*q2+q2+10)*(j*w)+(q1^3+q2^3+q1*q2+q2+5);…
      % the polynomial
      count=count+1; %counter increment
    end
  end
  x=real(p); %real part
  y=imag(p); %imaginary part
  plot(x,y,'.')
end
hold off
```

The resulting value sets are shown in fig. 8. They clearly demonstrate robust stability of family (12).

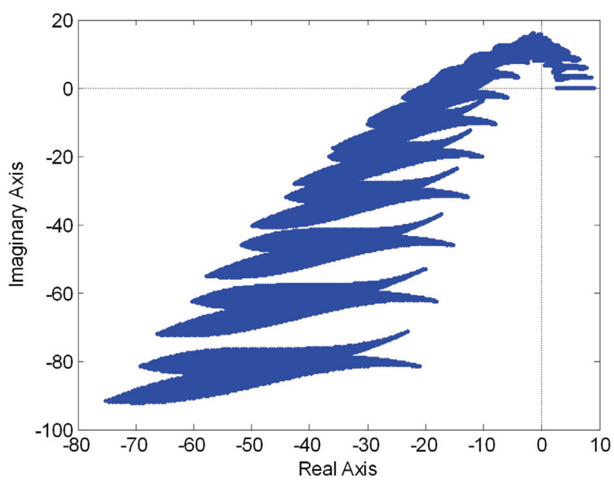

Fig. 8 value sets for the family (12)

G. General Uncertainty Structure

In the seventh case, the assumed uncertainty structure is even more complicated and can not be classified as any of the previous types. So, the family with general uncertainty structure (again from [11]) is given as:

$$
\begin{aligned}
&p(s,q) = s^3 + \left[\cos(q_1 q_2)\right] s^2 + \cdots \\
&\cdots \left[5\sqrt{|q_1|} - 3\sin q_2 - \cos(q_1 q_2) + 4\right] s + \cdots \\
&\cdots \left[-4\sqrt{|q_1|} + \sin q_2 + \cos(q_1 q_2) + 0.1\right]; \\
&q_1, q_2 \in \langle -1;1 \rangle
\end{aligned}
\tag{13}
$$

The corresponding value sets (fig. 9) can be obtained by using the “brute-force” code:

```
%general uncertainty structure
clear all
hold on
for w=0:0.2:4 %frequency range
  count=1; %auxiliary counter
  for q1=-1:0.01:1 %sampling of uncertain parameters
    for q2=-1:0.01:1
      p(count)=(j*w)^3+(cos(q1*q2))*(j*w)^2+…
      (5*sqrt(abs(q1))-3*sin(q2)-cos(q1*q2)+4)*(j*w)+…
      ((-4*sqrt(abs(q1))+sin(q2)+cos(q1*q2)+5));…
      % the polynomial
      count=count+1; %counter increment
    end
  end
  x=real(p); %real part
  y=imag(p); %imaginary part
  plot(x,y,'.')
end
hold off
```

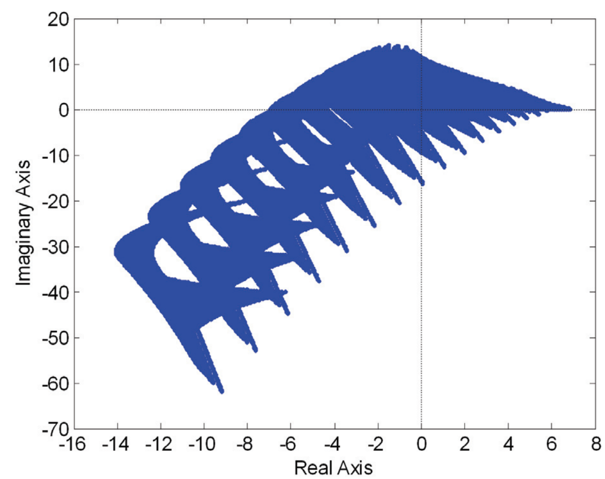

Fig. 9 value sets for the family (13)

As the origin of the complex plane is included in the plotted value sets, the family of polynomials (13) is robustly unstable.

H. Discrete-Time Interval Polynomial

The last example is intended to demonstrate the generality of possible application of the value set concept and the zero exclusion condition by means of discrete-time interval polynomial. Unfortunately, the Kharitonov-like extremal results are not generally available for discrete-time systems so they can not be utilized. Besides the existence of several analytical methods, the universal graphical approach can be advantageously employed here.

The continuous-time versions of the value set concept and the zero exclusion condition has been already presented. Nevertheless, the idea can be extended and generalized to so-called robust *D*-stability framework [7] which allows investigating robust stability for an arbitrary stability region *D*. The exact definition of the value set concept and the zero exclusion condition for robust *D*-stability can be found primarily in [7] or subsequently in [21]. Roughly speaking, in discrete-time case one has to go through the unit circle (stability boundary for discrete-time systems) as the generalized frequency (instead of frequency from zero to "infinity" as in the continuous-time case). Then, the key idea of the zero exclusion condition remains basically the same, i.e. the family is robustly *D*-stable if and only if it has at least one *D*-stable member and zero point is excluded from the value sets.

Consider the fifth order discrete-time interval polynomial taken from [21]:

$$p(z,q)=[1,2]+[3,4]z+[5,6]z^2+\cdots \\ \cdots[7,8]z^3+[9,10]z^4+[11,12]z^5 \tag{14}$$

The one of possible methods for plotting the value sets of the polynomial (14) has been implemented in the simple routine:

```
%discrete-time interval polynomial
clear all
hold on
for c=0:0.01:1 %generalized frequency range
  count=1; %auxiliary counter
  for q0=1:0.5:2 %sampling of uncertain coefficients
    for q1=3:0.5:4
      for q2=5:0.5:6
        for q3=7:0.5:8
          for q4=9:0.5:10
            for q5=11:0.5:12
              z=exp(j*c*2*pi); %unit circle
              p(count)=q0+q1*z+q2*z^2+q3*z^3+ q4*z^4+…
              q5*z^5; % the polynomial
              count=count+1; %counter increment
            end
          end
        end
      end
    end
  end
  x=real(p); %real part
  y=imag(p); %imaginary part
  plot(x,y,'.')
end
hold off
```

The resulting value sets are depicted in fig. 10. It is effortless to verify in Matlab that the family has a stable member (choose any fixed polynomial from the family and check the stability). Consequently, due to the exclusion of the complex plane origin from the value sets, the discrete-time interval polynomial (14) is concluded to be (Schur) robustly stable.

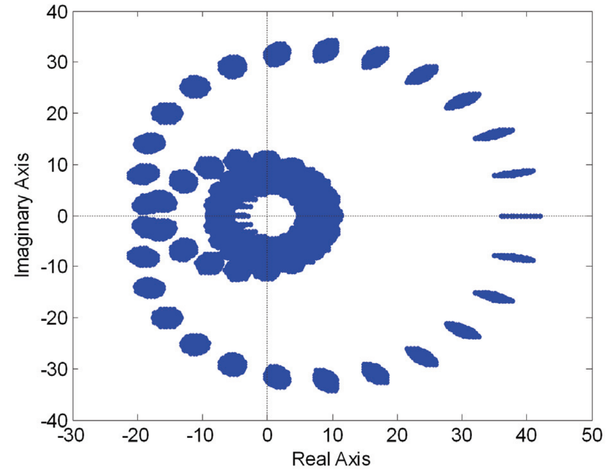

Fig. 10 value sets for the family (14)

V. Conclusion

The paper has been focused on presentation of simple Matlab codes for plotting the value sets of polynomials with real uncertain coefficients under several uncertainty structures. On the basis of the obtained figures, the robust stability can be analyzed easily using the zero exclusion condition. Altogether, eight illustrative examples given in the paper have covered seven cases of continuous-time uncertain polynomials, namely with single parameter uncertainty ("ordinary" uncertain polynomial and uncertain quasi-polynomial), independent (interval) uncertainty structure, affine linear uncertainty structure, multilinear uncertainty structure, polynomial uncertainty structure and general uncertainty structure, and moreover also one discrete-time interval polynomial.

Acknowledgment

The authors would like to thank Bilal Şenol (İnönü Üniversitesi) for his interest in the paper [11] which inspired them to write this work.

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