RELIABILITY ESTIMATION OF THE DISCRETE-TIME CONTROL SYSTEMS WITH RANDOM PARAMETERS

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SUMMARY

This paper deals with a method for reliability estimation of the discrete-control systems with random parameters. The problem of probability stability and a method for probability stability estimation of the arbitrary order systems are also considered.

Keywords: *Discrete-time systems, reliability estimation, probability stability, random parameters*

1. INTRODUCTION

In many different industries, such as chemical industry, plastic industry and especially in rubber industry, there are systems with random parameters. It is well-known in case of the systems with determined parameters that the systems can be either stable or unstable. But, in case of the random parameters the systems can be stable, unstable, or stable with some probability.

The stability problem of the systems with geometrical imperfection is very well known. In this paper we are considering the stability problem of the linear discrete-time system with a parametric imperfection. The main result in this paper is the estimated reliability of systems with random parameters.

There are several modes of stochastic stability: stability of probability, stability of the K-th moment, almost certain stability, Lyapunov average stability, exponential stability in the K-th moment, monotonic entropy stability, asymptotic entropy stability, etc. For all definitions of stochastic stability it is necessary for probability stability to be p=1. Caughey and Gray [2] determined almost certain stability of linear dynamic systems with stochastic coefficients. Khasminski [5], Kozin [6, 7] and Pinsky [10] gave various definitions and properties of stochastic stability of ordinary differential equations. Necessary and sufficient conditions guaranteeing the average square stability were obtained by Sawaragi [9]. In researching stochastic stability of systems with random parameters, we have also considered the systems with random time-varying parameters by Gaussian distribution [4]. Stochastic stability of systems with random imperfection is considered in [11, 12]. Probability stability estimation of the linear systems with random parameters is considered in [1] for continuous systems, and in [3, 14] for discrete-time systems. In [13], the geometrical imperfection is interpreted as having spatially fluctuating structural properties with respect to perfect geometry. In [8], the failure probability of the systems has been considered.

As for the stability probability of the systems with imperfect parameters, this probability is computed by integration of the probability density of the random parameters over the stability domain S in the parametric space:

$$p_r = \int_{V_s} \dots \int f\left(a_1, a_2, ..., a_n\right) da_1 da_2 ... da_n . \tag{1}$$

2. PROBABILITY STABILITY OF THE DISCRETE-TIME CONTROL SYSTEMS

The mathematical model of discrete-time control system be given by:

$$\sum_{i=0}^{n} a_i x\left(k+n-i\right) = u\left(k\right), \quad a_0 = 1 \tag{2}$$

It is known that the stability of this control system is determined by stability of the homogenous difference equation, i.e.

$$\sum_{i=0}^{n} a_i x\left(k+n-i\right) = 0, \quad a_0 = 1 \tag{3}$$

The stability (3) is determined by distributions of the zeroes of their characteristic equation:

$$z^n + a_1 z^{n-1} + ... + a_{n-1} z + a_n = 0 \tag{4}$$

Sufficient and necessary conditions for stability (3) are that all roots of equation (4) are within the unit circle. Using the bilinear transformation, $z = \frac{s+1}{s-1}$, and rearranging the previous equation a new equation is obtained:

$$\varphi_n s^n + \varphi_{n-1} s^{n-1} + ... + \varphi_1 s + \varphi_0 = 0 \tag{5}$$

where φ_i are functions of parameters a_1, a_2 ..., a_n.

For instance, in the case of the second order system we have

$$z^2 + a_1 z + a_2 = 0 \tag{6}$$

and using $z = \frac{s+1}{s-1}$ we obtain:

$$s^2(1 + a_1 + a_2) + 2s(1 - a_2) + 1 - a_1 + a_2 = 0 \qquad (7)$$

then

$$\varphi_0 = 1 - a_1 + a_2,\ \varphi_1 = 2(1 - a_2),\ \varphi_2 = 1 + a_1 + a_2 \qquad (8)$$

System (3) is stable if all the zeros of (5) are in the left half of s plane. To determine stability region in the parametric space $(a_1, a_2, ..., a_n)$ we use well known Hurwitz criterion: if all zeros of the equation (5) are in the left half of s plane, it is necessary and sufficient that the determinant D_n,

$$D_n = \begin{vmatrix} \varphi_{n-1} & \varphi_{n-3} & \varphi_{n-5} & \cdots & 0 \\ \varphi_n & \varphi_{n-2} & \varphi_{n-4} & \cdots & 0 \\ 0 & \varphi_{n-1} & \varphi_{n-3} & \cdots & 0 \\ 0 & \varphi_n & \varphi_{n-2} & \cdots & 0 \\ . & . & . & \cdots & . \\ 0 & 0 & 0 & \cdots & \varphi_0 \end{vmatrix} \qquad (9)$$

and all diagonal minors of D_i $i = 1, 2, ..., n$ are positive, i.e.:

$$D_1 = \varphi_{n-1} > 0,\ D_2 = \begin{vmatrix} \varphi_{n-1} & \varphi_{n-3} \\ \varphi_n & \varphi_{n-2} \end{vmatrix} > 0,$$

$$D_3 = \begin{vmatrix} \varphi_{n-1} & \varphi_{n-3} & \varphi_{n-5} \\ \varphi_n & \varphi_{n-2} & \varphi_{n-4} \\ 0 & \varphi_{n-1} & \varphi_{n-3} \end{vmatrix} > 0, ..., D_n > 0. \qquad (10)$$

Stability region of the system (3) is determined by inequalities (10) in parametric space.

For the first order system characteristic equation is: $z + a_1 = 0$

Applying bilinear transformation we obtain: $(1 + a_1)s + (1 - a_1) = 0$

The necessary and sufficient conditions are:

$D_1 = \varphi_0 > 0$ and $\varphi_1 > 0$

where: $\varphi_0 = 1 - a_1$, $\varphi_1 = 1 + a_1$ and

$D_1 = \varphi_0 = 1 - a_1 > 0 \Rightarrow a_1 < 1$

$\varphi_1 = 1 + a_1 > 0 \Rightarrow -1 < a_1$

Stability region V_1 for the first order system is:

$$-1 < a_1 < 1 \qquad (11)$$

For the second order system characteristic equation is: $z^2 + a_1 z + a_2 = 0$

Applying bilinear transformation we obtain:

$(1 + a_1 + a_2)s^2 + 2(1 - a_2)s + 1 - a_1 + a_2 = 0$

The necessary and sufficient conditions are:

$D_1 = \varphi_0 > 0$, $D_2 = \begin{vmatrix} \varphi_0 & 0 \\ \varphi_2 & \varphi_1 \end{vmatrix} > 0$ and $\varphi_2 > 0$

where:

$\varphi_0 = 1 - a_1 + a_2$, $\varphi_1 = 2(1 - a_2)$, $\varphi_2 = 1 + a_1 + a_2$ and

$D_1 = \varphi_0 = 1 - a_1 + a_2 > 0$

$\varphi_2 = 1 + a_1 + a_2 > 0$

$D_2 = \varphi_1 \varphi_0 = 2(1 - a_2)(1 - a_1 + a_2) \Rightarrow a_2 < 1$

Stability region V_2 in the parametric plane (a_1, a_2) for the second order system is:

$$\begin{aligned} &1 - a_1 + a_2 \geq 0 \\ &1 + a_1 + a_2 \geq 0 \\ &a_2 \leq 1 \end{aligned} \qquad (12)$$

as shown in Figure 1:

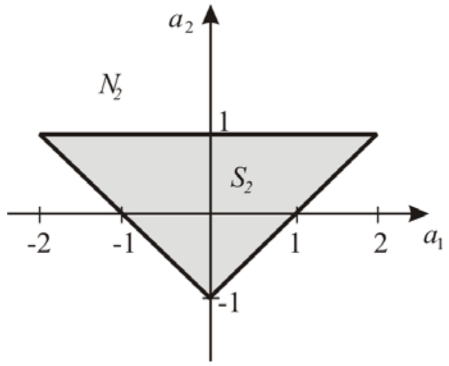

Fig. 1 Stability region for the second order system

For the third order system characteristic equation is: $z^3 + a_1 z^2 + a_2 z + a_3 = 0$

Applying bilinear transformation we obtain:

$(1 + a_1 + a_2 + a_3)s^3 + (3 + a_1 - a_2 - 3a_3)s^2 +$

$+ (3 - a_1 - a_2 + 3a_3)s + 1 - a_1 + a_2 - a_3 = 0$

The necessary and sufficient conditions are:

$D_1 = \varphi_2 > 0$, $D_2 = \begin{vmatrix} \varphi_2 & \varphi_0 \\ \varphi_3 & \varphi_1 \end{vmatrix} > 0$, $D_3 = \begin{vmatrix} \varphi_2 & \varphi_0 & 0 \\ \varphi_3 & \varphi_1 & 0 \\ 0 & \varphi_2 & \varphi_0 \end{vmatrix} > 0$

and $\varphi_3 > 0$

where:

$\varphi_0 = 1 - a_1 + a_2 - a_3$, $\varphi_1 = (3 - a_1 - a_2 + 3a_3)$,

$\varphi_2 = (3 + a_1 - a_2 - 3a_3)$, $\varphi_3 = 1 + a_1 + a_2 + a_3$

and

$D_1 = \varphi_2 = 3 + a_1 - a_2 - 3a_3 > 0$

$\varphi_3 = 1 + a_1 + a_2 + a_3 > 0$

$D_2 = \varphi_1\varphi_2 - \varphi_0\varphi_3 = -8(-1 + a_2 - a_1 a_3 + a_3^2) \Rightarrow a_1 a_3 + 1 > a_2 + a_3^2$

$D_3 = \varphi_0\varphi_1\varphi_2 - \varphi_0^2\varphi_3 = -8(-1 + a_1 - a_2 + a_3)(1 - a_2 + a_1 a_3 - a_3^2)$

$\Rightarrow a_1 - a_2 + a_3 < 1$

Stability region V_3 in the parametric plane (a_1, a_2, a_3) for the third order system is:

$$a_1 + a_2 + a_3 > -1$$
$$a_1 - a_2 + a_3 < 1 \quad (13)$$
$$a_1 a_3 + 1 > a_2 + a_3^2$$

The stability region V_3 in the parametric space (a_1, a_2, a_3) is given in Figure 2:

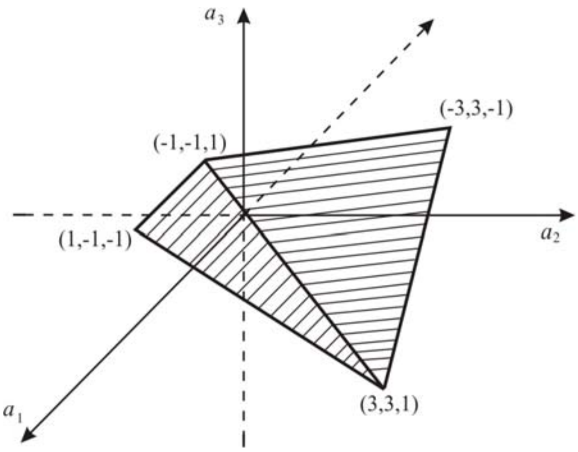

Fig. 2 Stability regions for the third order system

For the systems order higher than three we use same procedure, applying *n*-order Hurwitz determinant.

Let multidimensional density probability of the parameters $a_1, a_2, ..., a_n$ be:

$$f(\mathbf{a}) = f(a_1, a_2, ..., a_n) \quad (14)$$

Thus probability stability of the system (3) is:

$$P = \int_{V_n} \cdots \int f(a_1, \ldots, a_n) da_1 \cdots da_n \quad (15)$$

In the case of the n-th order systems, determination of the stability region V_n is very complicated. We can estimate the stability region of the system (3) using the two following theorems.

Theorem 1: If

$$|a_1| + |a_2| + ... + |a_n| < 1 \quad (16)$$

then all zeros (z_i) of the polynomial $z^n + a_1 z^{n-1} + ... + a_{n-1} z + a_n = 0$ are in the unit circle, i.e.

$$|z_i| < 1, \quad i = 1, 2, ..., n \quad (17)$$

Proof:

Suppose that the zeros of characteristic polynomial

$$z^n + a_1 z^{n-1} + ... + a_{n-1} z + a_n = 0 \quad (ii)$$

is not in the unit circle i.e.:

$$|z_k| \geq 1, \ k = 1, 2, ..., n \quad (iii)$$

Using (ii) we obtain: $z_k^n = -\left(a_1 z_k^{n-1} + a_2 z_k^{n-2} + ... + a_n\right)$ i.e. $|z_k|^n \leq |a_1||z_k|^{n-1} + |a_2||z_k|^{n-2} + ... + |a_n|$

Dividing by $|z_k|^n$ $\left(|z_k| \neq 0\right)$, we obtain:

$$1 \leq \frac{|a_n|}{|z_k|^n} + \frac{|a_{n-1}|}{|z_k|^{n-1}} + ... + \frac{|a_1|}{|z_k|}$$

Because of proposition: $|z_k| \geq 1, \ k = 1, 2, ..., n$ it follows: $|a_1| + |a_2| + ... + |a_n| > 1$ which is opposite to (17). Thus $|z_k| \geq 1$ is not true, therefore: $|z_k| < 1$

Conditions (17) are necessary but not sufficient for stability of the system (3).

Theorem 2: If all zeros of the polynomial $z^n + a_1 z^{n-1} + ... + a_{n-1} z + a_n = 0$, are in the unit circle, $|z_i| < 1$ then:

$$|a_i| \leq \binom{n}{i} = \frac{n!}{i!(n-i)!}, \qquad i = 1, 2, \ldots, n \quad (18)$$

Proof:

If the polynomial

$$z^n + a_1 z^{n-1} + ... + a_{n-1} z + a_n = 0 \quad (i)$$

is stable, it has all zeros in the unit circle i.e.:

$$|z_k| < 1, \ k = 1, 2, ..., n \quad (ii)$$

Using Viet's rules:

$$a_1 = -\sum_{k=1}^{n} z_k$$
$$a_2 = \sum_j \sum_k z_j z_k$$
....
$$a_n = (-1)^n \prod_{i=1}^{n} z_i$$

we obtain:

$$|a_1| \leq \sum_{k=1}^{n} |z_k| < \sum_{k=1}^{n} |1| = \binom{n}{1}$$
$$|a_2| \leq \sum_j \sum_k |z_j z_k| < \sum_j \sum_k |1| = \binom{n}{2}$$
....
$$|a_n| \leq \left|\prod_{i=1}^{n} z_i\right| < 1 = \binom{n}{n}$$

Because of $|z_k| < 1$ we obtain:

$$\left|a_n\right| \le \binom{n}{i},\ i = 1,2,...n\ .$$

Condition (18) is sufficient, but not necessary, for the stability of the system (3).

Denote by:

V_{on} - region $\left|a_1\right| + \left|a_2\right| + ... + \left|a_n\right| < 1$

V_n - stability region

V_{pn} - region $\left|a_i\right| \le \binom{n}{i}$

in n-th order parametric space.

Theorems 1 and *2* implies:

$$V_{on} \in V_n \in V_{pn} \tag{19}$$

The probability stability for the *n*–th order system can be estimated by:

$$p_o = \int_{V_{on}} ... \int f(a_1,...,a_n) da_1 ... da_n$$

$$p_p = \int_{V_{pn}} ... \int f(a_1,...,a_n) da_1 ... da_n \tag{20}$$

$$p_o < p < p_p$$

In the case of the Gaussian probability density function:

$$f_i(a_i) = \frac{1}{\sqrt{2\pi}\sigma_i} e^{\frac{(a-\overline{a}_i)^2}{2\sigma_i^2}}$$

$$f(a_1, a_2, ..., a_n) = \prod_{i=1}^{n} f_i(a_i) = \frac{1}{\left(\sqrt{2\pi}\right)^n \prod_{i=1}^{n} \sigma_i} e^{\sum_{i=1}^{n} \frac{(a-\overline{a}_i)^2}{2\sigma_i^2}} \tag{21}$$

using (18) and (20) the probability stability can be estimated by:

$$p < p_p = \left(\frac{1}{2}\right)^n \prod_{i=1}^{n} \left\{ Erf\left[\frac{\binom{n}{i} - \overline{a}_i}{\sqrt{2}\sigma_i}\right] - Erf\left[\frac{-\binom{n}{i} - \overline{a}_i}{\sqrt{2}\sigma_i}\right] \right\} \tag{22}$$

where $Erf\left[x\right] = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$ is the error function.

In the case of the uniform distribution:

$$f_i = \begin{cases} \dfrac{1}{\left(a_i^+ - a_i^-\right)}; & a_i^- \le a_i \le a_i^+ \\ 0; & a_i^+ < a_i < a_i^- \end{cases} \tag{23}$$

Using (18), (20) and (23) we obtain:

$$p < p_p = \frac{\prod_{i=1}^{n} \left\{ \left[\left| a_i^+ + \binom{n}{i} \right| - \left| a_i^+ - \binom{n}{i} \right| \right] - \left[\left| a_i^- + \binom{n}{i} \right| - \left| a_i^- - \binom{n}{i} \right| \right] \right\}}{2^n \prod_{i=1}^{n} \left(a_i^+ - a_i^-\right)} \tag{24}$$

Using (16), (20) and (23) we obtain:

$$p > p_o = 1 - \frac{1}{n} \frac{\sum_{i=0}^{2^n - 1} f_{ij}^n h\left(f_{ij}\right)}{\prod_{i=1}^{n} \left(a_i^+ - a_i^-\right)} \quad \text{where}$$

$$f_{ij} = \sum_{j=0}^{n-1} \left\{ \frac{1 + (-1)^{\left\lfloor \frac{i}{2^j - 1} \right\rfloor}}{2} a^+ + \frac{1 - (-1)^{\left\lfloor \frac{i}{2^j - 1} \right\rfloor}}{2} a^- \right\} - 1 \tag{25}$$

3. EXAMPLES

First order system is given by a mathematical model:

$$x\left((k+1)T\right) + a_1 x\left(kT\right) = u\left(kT\right) \tag{26}$$

For *T*=1 characteristics polynomial is:

$$z + a_1 = 0 \tag{27}$$

where stability domain is $\left|a_1\right| < 1$. Let a_1 be random parameter with Gaussian probability function ($\sigma = 1,\ \overline{a} = 0.8$):

$$f\left(a_1\right) = \frac{1}{\sqrt{2\pi}} e^{-\frac{\left(a_1 - 0.8\right)^2}{2}} \tag{28}$$

Probability stability (19) is:

$$p = \frac{1}{\sqrt{2\pi}} \int_{-1}^{1} e^{-\frac{\left(a_1 - 0.8\right)^2}{2}} da_1 = 0.543 \tag{29}$$

As show in Figure 3.

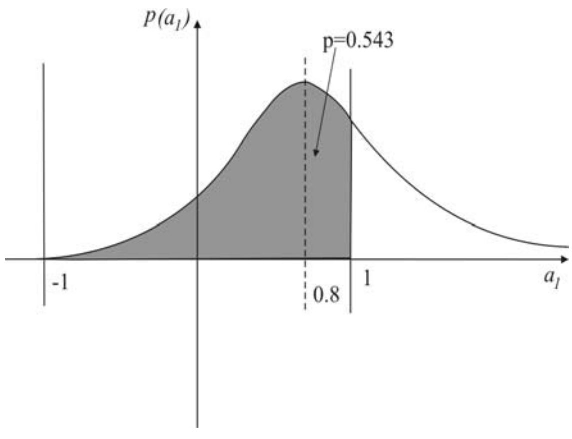

Fig. 3 Probability stability for the first order system

In case of the uniform distribution:

$$f(a_1)=\begin{cases}\dfrac{1}{\left(a_1^+-a_1^-\right)}; & a_1^- \le a_1 \le a_1^+\\ 0; & a_1^+ < a_1 < a_1^-\end{cases} \tag{30}$$

for a_1^- and $a_1^+ > 0$, probability stability is:

$$p=\begin{cases}1, & a_1^- < a_1^+ < 1\\ \dfrac{1-a_1^-}{a_1^+-a_1^-}, & a_1^- < 1 < a_1^+\\ 0, & 1 < a_1^- < a_1^+\end{cases} \tag{31}$$

For stochastic stability in the case of the uniform distribution we have:

$$E(a_1)^{2k}=\frac{a_1^{+\,2k+1}-a_1^{-\,2k+1}}{(2k+1)\left(a_1^+-a_1^-\right)} \tag{32}$$

it is obvious that the system (29) is stochastically stable when $0 < a_1^- < a_1^+ < 1$, and unstable when $a_1^+ > 1$, in accordance with (31).

The second order system is given by:

$$x((k+2)T)+a_1x((k+1)T)+a_2x(kT)=u(kT) \tag{33}$$

For T=1 characteristic polynomial is:

$$z^2+a_1z+a_2=0 \tag{34}$$

Let a_1 and a_2 be random parameters with Gaussian probability density function ($\sigma_1=1,\ \overline{a}_1=0.8,\ \sigma_2=1,\ \overline{a}_2=0.8$):

$$f(a_1,a_2)=\frac{1}{2\pi}e^{-\left[\frac{(a_1-0.8)^2}{2}+\frac{(a_2-0.8)^2}{2}\right]} \tag{35}$$

Probability stability is:

$$p=\frac{1}{2\pi}\int_{-1}^{1}\int_{a_2-1}^{a_2+1}e^{-\left[\frac{(a_1-0.8)^2}{2}+\frac{(a_2-0.8)^2}{2}\right]}da_1da_2=0.309 \tag{36}$$

See Figure 4.

Now we shall discuss discrete-time control system where are a_1, a_2, a_3, random parameters with Gaussian probability density function where: $\overline{a}_1=0.5,\ \overline{a}_2=0.3,\ \overline{a}_3=0.4$ and $\sigma_1=0.3, \sigma_2=0.2, \sigma_3=0.4$.

Mathematical model of the given system is:

$$x((k+3)T)+a_1x((k+2)T)+a_2x((k+1)T)+a_3x(kT)=u(kT) \tag{37}$$

For $T=1$, characteristic polynomial is:

$$z^3+a_1z^2+a_2z+a_3=0 \tag{38}$$

Using (12) and (14) we obtain the exact value for probability stability: $p=0.912$.
Using (21), for $n=3$ estimated probability stability P_p is:

$$P_p \approx \frac{1}{8}\prod_{i=1}^{3}\left[Erf\left[\frac{\binom{3}{i}-\overline{a}_i}{\sqrt{2}\sigma_i}\right]-Erf\left[\frac{-\binom{3}{i}-\overline{a}_i}{\sqrt{2}\sigma_i}\right]\right] \tag{39}$$

i.e. $P_p \approx 0.933$. Thus $p < p_p$, which is the expected result.

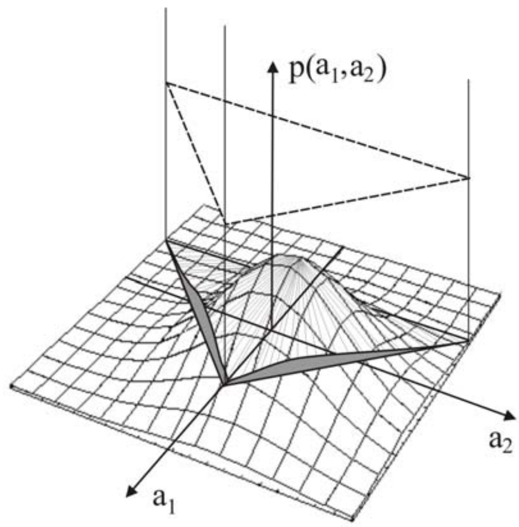

Fig. 4 Probability stability for the second order system

4. CONCLUSION

A method for probability stability and reliability estimation of discrete-time control system with random parameters is presented. It shows that the exact determination of probability stability is very difficult for the high order systems. The formulae for estimation probability stability and reliability for high order discrete-time system are also given.

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