SIMULATION-BASED MULTI-CRITERIA ESTIMATION OF PLANS STABILITY

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ABSTRACT

A general scheme of multi-criteria estimation of plans stability via simulation of complex technical systems was proposed. Main variants of input data presentation (deterministic, stochastic, and interval) were considered.

INTRODUCTION

Analysis of the main trends for modern complex technical systems (CTS) indicates their peculiarities such as multiple aspects and uncertainty of their behavior, hierarchy, structure similarity and surplus for main elements and subsystems of CTS, variety for control functions implementations relevant to each CTS level, and territory distribution of its components. One of the main features of modern CTS is the variability of their parameters and structures as caused by objective and subjective reasons at different phases of the CTS life cycle.

An optimal plan of CTS functioning can be obtained as a result of a multi-stage iterative search process. The stability of the obtained plan is verified via the simulation models of CTS. The input data for the simulation models can have different form. We consider stability of CTS functioning plans for three variants of input data: the deterministic data, the stochastic data, and the interval data (Casti, 1979, Sterman et al., 2000). The specificity of CTS control problems necessitates different measures of program stability (Fox et al., 2006). So, multi-criteria approach should be used. Particular measures can be used to form one general stability measure by means of convolution. Pareto's stable plan can be also found in an interactive mode.

DETERMINISTIC DATA

The following notation was used:

$\mathbf{x}^{(s)}(T_f) = \left\| x_1^{(s)}, x_2^{(s)}, \ldots, x_k^{(s)} \right\|^{\mathrm{T}} \Big|_{t=T_f}$ is a state vector obtained as a result of CTS program control at the time point $t = T_f$;

$\mathbf{x}^{(p)}(T_f) = \left\| x_1^{(p)}, x_2^{(p)}, \ldots, x_k^{(p)} \right\|^{\mathrm{T}} \Big|_{t=T_f}$ is a perturbed vector obtained as a result of simulation replicating the conditions of plan realization;

$\boldsymbol{x}_a^*(T_f) = \left\| x_{a1}^*, \ldots, x_{ak}^* \right\|^{\mathrm{T}} \Big|_{t=T_f}$,

$\boldsymbol{x}_b^*(T_f) = \left\| x_{b1}^*, \ldots, x_{bk}^* \right\|^{\mathrm{T}} \Big|_{t=T_f}$ are vectors defining respectively the lower and upper bounds for vectors $\boldsymbol{x}^{(s)}(T_f)$, $\boldsymbol{x}^{(p)}(T_f)$;

$\mathbf{J}_{\tilde{n}}^{(s)} = \left\| J_{\tilde{n}1}^{(s)}, \ldots, J_{\tilde{n}I_M}^{(s)} \right\|^{\mathrm{T}} \Big|_{t=T_f}$ is a vector of CTS effectiveness measures (measures of goal potential (GP)) for the case of zero perturbation actions ($\tilde{n} = 1, \ldots, N$);

$\mathbf{J}_{\tilde{n}}^{(p)} = \left\| J_{\tilde{n}1}^{(p)}, \ldots, J_{\tilde{n}I_M}^{(p)} \right\|^{\mathrm{T}} \Big|_{t=T_f}$ is a vector obtained as a result of simulation replicating the conditions of plan realization ($\tilde{n} = 1, \ldots, N$);

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$$J_a^* = \left\| J_{a1}^*, \ldots, J_{aI_M}^* \right\|^{\mathrm{T}} \Big|_{t=T_f},$$

$$J_b^* = \left\| J_{b1}^*, \ldots, J_{bI_M}^* \right\|^{\mathrm{T}} \Big|_{t=T_f}$$ are vectors defining respectively the lower and upper bounds of $\boldsymbol{J}^{(s)}(T_f)$, $\boldsymbol{J}^{(p)}(T_f)$.

The following algorithm can be used to evaluate the stability of CTS functioning plans.

Step 1. Let $\tilde{n}$ be the number of a current plan $\tilde{n} = 1, \ldots, N$ then the following conditions are verified:

$$x_{ak}^* \le \mathbf{x}_{\tilde{n}}^{(p)}(T_f) \le x_{bk}^*, \quad (1)$$

$$\left| \mathbf{x}_{\tilde{n}}^{(s)}(T_f) - \mathbf{x}_{\tilde{n}}^{(p)}(T_f) \right| \le \varepsilon_1^{(s)}, \quad (2)$$

$\forall k \in \{1, \ldots, n_{ob}\}$, where $\varepsilon_1^{(s)}$ is a given constant, n_{ob} is the dimension of state vectors.

A result of the step 1 the set $\tilde{N}_g^{(1)} = \tilde{N} / \tilde{N}^{(1)}$ is constructed, where $\tilde{N} = \{1, \ldots, \tilde{N}\}$, $\bar{N}^{(1)}$ is a set of subscripts enumerating the invalid plans.

Step 2. For every $\mathbf{x}_{\tilde{n}}^{(p)}(t)$, $\tilde{n} \in \tilde{N}_g^{(1)}$ the following conditions are verified:

$$J_{ai}^* \le J_{\tilde{N}i} \le J_{bi}^*, \quad (3)$$

$$\left| J_{\tilde{n}i}^{(s)} - J_{\tilde{n}i}^{(s)} \right\|_{t=T_f} < \varepsilon_2^{(s)}, \quad (4)$$

where $\varepsilon_2^{(s)}$ is a given value, $i = 1, \ldots, I_M$.

If for some plan $\tilde{n} \in \tilde{N}_g^{(1)}$ at least one of conditions is not satisfied then the plan is stated to be unstable. So $\tilde{N}_g^{(2)} = \tilde{N}_g^{(1)} / \bar{N}^{(2)}$, where $\tilde{N}^{(2)}$ is a set of subscripts for unstable plans.

Step 3. Now one or more plans are to be chosen from the set $\tilde{N}_g^{(2)}$ of the stable plans. The choice can be performed in an interactive mode. Another approach to the choice problem is to construct a general stability criterion as a convolution of particular measures or by means of metrics in the criteria space. In the latter case we should obtain a solution of the optimization problem:

$$\rho(\mathbf{J}_{ob\tilde{n}}^{(s)}, \mathbf{J}_{ob\tilde{n}}^{(p)}) \to \min, \quad (5)$$

where $\tilde{n} \in \tilde{N}_g^{(2)}$.

STOCHASTIC DATA

For the stochastic input data (the second variant) the uncertainty factors of the environment influencing upon the CTS are replicated in detail. To provide statistical significance of stability estimations the multiple simulation experiments should be fulfilled (Casti, 1979). If we use the second variant of the input data then the estimate can be often expressed as a probability of some event. The most appropriate event for this purpose is the completion of a given mission in accordance with the plan. For certain cases, the necessary level of stability can be defined in the form of equality:

$$P\{\hat{z}_н \ge z_\alpha\} = \alpha, \quad (6)$$

where z_α, α are given values, $\hat{z}_{\tilde{n}} = \rho\left(\hat{\mathbf{x}}_{\tilde{n}}^{(p)}(T_f), \hat{\mathbf{x}}_{\tilde{n}}^{(s)}(T_f)\right)$ is the estimation of the difference between the planed state trajectory and the perturbed one.

The stability of control programs can be indirectly estimated by means of the following objective function:

$$M(\mathbf{J}_{ob\tilde{n}}^{(s)} - \mathbf{J}_{loss\,\tilde{n}}^{(p)}), \quad (7)$$

where M is the expectation sign, $\mathbf{J}_{ob\tilde{n}}^{(s)}$ is a general measure of CTS effectiveness (a convolution $J_{1\tilde{n}}^{(s)}, \ldots, J_{I_M\tilde{n}}^{(s)}$); $\mathbf{J}_{loss\,\tilde{n}}^{(p)}$ is a measure of losses caused by perturbation actions and resources consumption for compensative inputs. The probability of the situation such that the correction of the plan is not necessary until the given time point; the mean value of a time point such that the correction of the plan becomes necessary; mean value of plan's corrections during a given time period.

INTERVAL DATA AND ATTAINABILITY SETS

For the interval input data (the third variant) stability estimation can be performed on the basis of the *attainability sets* $D(t, T_0, X_0)$, where X_0 is a set of possible initial states of the system. The formal description of this task is based on the mathematical structure that determines the following model of the general dynamic system (DS):

$$\boldsymbol{x}(t) = \boldsymbol{\varphi}(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{v}(\boldsymbol{x}(t),t), \boldsymbol{\xi}(t), \boldsymbol{\beta}, t), \quad (8)$$

$$\boldsymbol{y}(t) = \boldsymbol{\psi}(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{v}(\boldsymbol{x}(t),t), \boldsymbol{\xi}(t), \boldsymbol{\beta}, t). \quad (9)$$

$$\boldsymbol{u}(t) \in Q(\boldsymbol{x}(t),t), \quad (10)$$

$$\boldsymbol{v}(\boldsymbol{x}(t),t) \in V(\boldsymbol{x}(t),t), \quad (11)$$

$$\boldsymbol{\xi}(t) \in \Xi(\boldsymbol{x}(t),t), \quad (12)$$

$$\boldsymbol{x}(t) \in \tilde{X}(t), \quad (13)$$

$$\boldsymbol{\beta} \in \mathbf{B}, \quad (14)$$

where $\boldsymbol{x}(t)$, $\boldsymbol{y}(t)$ are general vectors of DS states and outputs accordingly (DS describes processes of CTS functioning); $\boldsymbol{u}(t)$, $\boldsymbol{v}(\boldsymbol{x}(t),t)$ – general vectors of CTS management (CTS functioning plans) and management at the execution stage (plans under disturbances); $\boldsymbol{\xi}(t)$ is a vector of disturbances, that may be either goal-oriented or not; $\boldsymbol{\beta}$ is a vector of CTS structure parameters (characteristics) which determine its configuration at the moment $t \in (T_0, T_f]$; T_0, T_f are initial and final moments of time period for planning of CTS execution accordingly; $Q(\boldsymbol{x}(t),t)$, $V(\boldsymbol{x}(t),t)$, $\Xi(\boldsymbol{x}(t),t)$ are given areas of admissible program management, on-line managing actions and disturbances accordingly; $\tilde{X}(t)$ is an area of admissible current magnitudes of the vector of CTS state; $\mathbf{B}$ is an admissible area of structure parameters; $\boldsymbol{\varphi}$, $\boldsymbol{\psi}$ are given transition and output functions that generally may be described analytically (with logic-algebraical, logiclinguistical, and classical mathematical structures) and algorithmically. Combined variant is also possible.

Besides the mentioned restrictions while positing the formal task of CTS execution planning we must set the number of restrictions on vector $\boldsymbol{x}(t)$ at the initial (T_0) and final (T_f) time moments. The latter define an interval of CTS implementation planning:

$$\boldsymbol{x}(T_0) \in X_0(\boldsymbol{\beta}), \qquad \boldsymbol{x}(T_f) \in X_f(\boldsymbol{\beta}), \tag{15}$$

where $X_0(\boldsymbol{\beta}),X_f(\boldsymbol{\beta})$ – given areas.

In order to assess the efficiency and stability of CTS functioning plans the following vector of indices is introduced

$$\boldsymbol{J}(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{\xi}(t),t) = \|J_1,J_2,J_3,J_4,J_5,J_6,J_7,J_8\|^{\mathrm{T}}, \tag{16}$$

where $J_1,J_2,J_3,J_4,J_5,J_6,J_7,J_8$ are particular indices that evaluate the result of CTS functioning within plan $\boldsymbol{u}(t)$.

So, considering the above-stated positions, we conclude that the task of CTS planning within the proposed dynamic interpretation (Zaychik et al., 2005, 2006) comes to the search of program management $\boldsymbol{u}(t)$ $t \in (T_0, T_f]$, under which all time-spatial, technical and technological restrictions are fulfilled, and all components of general index of CTS functioning quality are extremities.

In its turn the task of stability assessment of elaborated CTS functioning plans comes to the calculation and analysis of possible magnitudes, which present the components of general index of CTS functioning quality for fixed disturbance scenarios $\boldsymbol{\xi}(t) \in \Xi(\boldsymbol{x}(t),t)$ within each obtained plan $\boldsymbol{u}_i(t) \in Q(\boldsymbol{x}(t),t)$ ($i = 1,\dots,m$; where m is a number of plans).

In dynamics, stability estimation can be performed on the basis of the attainability sets D (t, T_0, X_0) (Zaychik et al., 2005, 2006), where X_0 is a set of possible initial states of the system. To perform such analysis internal D^- (t, T_0, X_0) and external D^+ (t, T_0, X_0) approximations of D (t, T_0, X_0) should be constructed. Let us suppose that the space of admissible disturbances $\Xi(\boldsymbol{x}(t),t)$ is defined as follows:

$$\boldsymbol{\xi}_j^{(1)}(t) \le \boldsymbol{\xi}_j(t) \le \boldsymbol{\xi}_j^{(2)}(t), \; j = 1,\dots,m, \tag{17}$$

where $\boldsymbol{\xi}_j^{(1)}$, $\boldsymbol{\xi}_j^{(2)}$ are vector functions for minimal and maximal disturbance magnitudes consecutively. These disturbances may appear at the stage of each fixed plan execution ($\boldsymbol{u}_i(t)$, $t \in (T_0, T_f]$, $i = 1,\dots,n$) within some particular scenario of external pressure upon the CTS ($\boldsymbol{\xi}_j(t)$, $t \in (T_0, T_f]$, $j = 1,\dots,m$). Let the initial CTS status be $\boldsymbol{x}(T_0)$, hence we need to examine some fixed plan of its functioning $\boldsymbol{u}_i(t)$. So, the defined vectors and disturbance space for the fixed scenario $\boldsymbol{\xi}_j(t)$ are corresponded to the area of possible variable magnitudes of the model, i.e. the set of different execution scenarios.

Let us call this area the *attainability set of CTS under disturbances* and define it as follows:

$$D_x^{(\xi)}(T_f, T_0, X_0, \Xi, \boldsymbol{u}_i) \tag{18}$$

The set $D_x^{(\xi)}(T_f, T_0, X_0, \Xi, \boldsymbol{u}_i)$ is corresponded to the magnitude space of indices, which assess CTS efficiency and stability. The latter we define as follows:

$$D_J^{(\xi)}(T_f, T_0, X_0, \Xi, \boldsymbol{u}_i) \tag{19}$$

To make the further material more comprehensive we will examine only two components of index vector. These components correspond to the indicators of effectiveness (J_1) and resource-containing (J_2) of CTS functioning.

If for some fixed plan $\boldsymbol{u}_i(t)$, ($i = 1,\dots,n$) under disturbances $\boldsymbol{\xi}_j(t)$ the requirement (20) is fulfilled

$$D_J^{(\xi)}(T_f, T_0, X_0, \Xi, \boldsymbol{u}_i) \subset P_J, \tag{20}$$

the $\boldsymbol{u}_i(t)$ management program (the plan of CTS functioning) is considered to be stable under disturbances $\boldsymbol{\xi}_j(t)$. In other words, feasible J_1, J_2 deviations of quality indices of CTS functioning are considered to be acceptable.

So, to evaluate the stability of CTS functioning plan $\boldsymbol{u}_i(t)$ under disturbances $\boldsymbol{\xi}_j(t)$, which are defined as intervals, it is necessary to construct appropriate attainability areas (ATA). Our experience shows that it is very difficult to construct precise ATA. In practical applications an approximation of ATA can be used. For example, there exist approaches to ATA approximation, which are based on the task of optimal managing, on the construction of various classes of ellipsoids, etc. We will consider the first approach to the ATA approximation.

In this case the construction of the ATA is based on the result of some optimal program CTS management task of the following type:

$$J_g = \boldsymbol{c}^{\mathrm{T}}\boldsymbol{J} \to \min_{\boldsymbol{\xi}_i \in \Xi}, \tag{21}$$

where $\boldsymbol{c} = \|c_1, c_2\|^{\mathrm{T}}$ is a given vector that fulfils the normal conditions

$$|\boldsymbol{c}| = \sqrt{c_1^2 + c_2^2} = 1, \tag{22}$$

and $\boldsymbol{J} = \|J_1, J_2\|$ is a vector of particular indices of CTS functioning quality.

The goal of plan stability assessment is to find the point $\boldsymbol{J}^* = \| J_1^*, J_2^* \|^{\mathrm{T}}$, which lies on the border of the ATA and some line of the following type:

$$c_1 J_1^*, + c_2 J_2^* = 0, \tag{23}$$

that is tangent for the given set and includes the point J^*. After determining the multitude of points J_γ^* and appropriate tangents for some variants of vector $\boldsymbol{c}$ components $\gamma = 1,\dots,\Gamma$ (Γ – number of variants of indices $\boldsymbol{c}$), we obtain the external approximation, which is defined as follows:

$$\overline{\overline{D}}_J^{(\xi)}(T_f, T_0, X_0, \Xi, \boldsymbol{u}_i) \tag{24}$$

This ATA approximation is a geometrical figure that lies between the lines determined as $\boldsymbol{c}_\gamma^{\mathrm{T}}\boldsymbol{J}'^*$,

$\gamma = 1,\dots,\Gamma$.

It is reasonable to carry out the final selection of most stable CTS management programs according to the following condition:

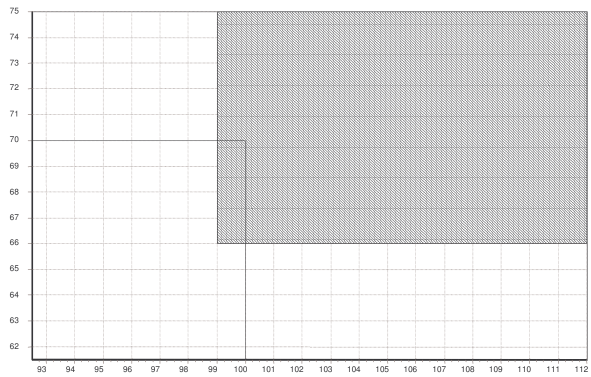
$$S_i^*(\boldsymbol{u}_i(t)) = \max_{1 \le i \le n} \min_{1 \le j \le m} S_i(\boldsymbol{u}_i(t)), \qquad (25)$$

where $S_i(\boldsymbol{u}_i(t))$ is the area of spaces $\overline{\overline{D}}_J^{(\xi)}(T_f, T_0, X_0, \Xi, \boldsymbol{u}_i)$ and P_J intersection; n is the total amount of analyzed plans; *m is* the total amount of disturbance scenarios at the stage of CTS plan realization. It is possible to show that the search of most stable CTS functioning plan due to statement (25) is the realization of the one of the basic principles of the multi-criteria selection under uncertainty, i.e. the principle of the guaranteed result

Let us consider a simplified example of quantitative estimation of plan stability. A comparative analysis of CTS control technologies was carried out for interval data describing perturbation actions of two types. Several plans of CTS functioning were examined. The attainability sets were constructed. Each plan was characterized with the data summarized in Table 1 and Fig.1. Abscissa axis represents the values of J1 (the first quality index), and ordinate axis represents the values of J2 (the first quality index). The hatched rectangle approximates the attainability set for a CTS functioning plan. The light-colored rectangle with the sides Ja1 and Ja2 represents the unwanted values of indexes. Different technologies of CTS functioning lead to differing attainability sets and unwanted intersections with Ja1 Ja2 rectangle. The considered control technology results in a decreased amount of operation data varying between 2 and 5 units of informational flow. This plan was the most preferable as involving lower amounts of flow processing (owing to more sophisticated algorithms of preliminary restructuring of operations). The stability index defined via the area of rectangles' interception is equal to 4. This value characterizes the "negative" stability as the smaller interception corresponds to more stable plans.

Table 1: Plan Characteristics: Loss of Effectiveness Under Perturbations

Possible scenarios of perturbation actions	Quality index J1	Quality index J2
Without perturbations	112	75
Reduction of the total amount of a resource (30% of nominal amount of operations)	99	71
Lowering of resource productivity (5% of nominal productivity)	112	71
Perturbation of two parameters (processing of 30% operations at productivity of 5%)	99	66



Figures 1: Graphical Presentation of a Stability Index

CONCLUSIONS

CTS functioning is challenged by high uncertainty. This leads to perturbations and deviations during the CTS execution. Stability is an appropriate category for the increasing quality of the CTS modeling and decision making under the terms of uncertainty. Although the issue of stability analysis in production and logistics has attracted increased attention and interest in recent years, stability analysis in the CTS settings has relatively poor methodological basis. We amplified basics of CTS stability analysis. Stability may be regarded as an additional indicator for the CTS analysis, modeling, planning, real-time management and forecasting. We presented conceptual model of CTS stability analysis at the stage of CTS configuration and extended stability analysis to the CTS execution provided its dynamical interpretation (Zaychik et al., 2005, 2006). We considered stability of CTS functioning plans for three variants of input data: the deterministic data, the stochastic data, and the interval data.

The stability analysis is especially useful in the situations, which are characterized by high level of uncertainty, which does not allow producing deterministic or stochastic models. The stability analysis allows proofing plan execution feasibility, selection of the plan with the sufficient stability degree, and scenario elaboration for decision making about the CTS reconfiguration in the execution phase based on indicating of permissible CTS execution parameters alteration.

Based on the stability analysis results, the decision maker can estimate the stability degree of the configured CTS. The decision maker can simulate various CTS configurations and execution scenarios trying to balance the goal criteria and the probability of goal achieving. The stability analysis can be considered as an efficient tool to improve the quality of CTS planning and execution models.

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