Analysis of spacecraft actuator mechanisms design process using tensor method

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Abstract. There is high topicality of more and more complicated systems analysis currently. One of the means to do such analysis is to use Gabriel Kron tensor method. The process of spacecraft driving gear design is analysed by using tensor method. The problematic stages of the process are determined.

1. Introduction

The processes of modern engineering are constantly becoming more complex, and their complexity grows exponentially [1]. The complexity of existing processes has now reached this level due to external and internal business conditions, and it is almost impossible now to find a process that is restricted to one department or employee of a machine-building enterprise.

All processes require a constant active interaction of many departments and subsystems, which does not always go perfectly or in a way that was originally intended. The analysis of processes and their deviations can be applied in business modelling, reengineering, functional-cost analysis, automation of technological processes [2-5].

The authors propose to apply Gabriel Kron tensor analysis method [6, 7] to determine the most problematic stages in the process of designing mechanical systems, in which the inter-action between the stages leads to the greatest number of failures.

2. Statement of the problem

As an example, let us consider the process of designing mechanisms for the spacecraft drives [8], the stages of which are shown in figure 1.

The process consists of the following steps:
1 - requirements for mechanical blocks of the spacecraft;
2 - development of technical specifications for design;
3 - evaluation of previously developed devices;
4 - selection of the basic design;
5 - requirements for the construction of mechanical blocks of the spacecraft;
6 - restrictions on material and time resources;
7 - technological limitations;
8 - decomposition of the object in the system of transformations relations;
9 - deterministic estimation of transformation relations and data requirements;
10 - heuristics;
11 - formation of catalogues of objects;
12 - cost estimate;

13 - preliminary design;
14 - evaluation of tests of elements and prototypes;
15 - calculated models;
16 - data;
17 - selection of the strategy of design calculations;
18 - experimental substantiation of the parameters change boundaries;
19 - designing;
20 - models and methods for estimating parameters and working out the mechanics of the drive;
21 – manufacturing process;
22 - preparation for operation (testing);
23 - test plan;
24 - data requirements;
25 - tests.

3. Solution method
In the framework of the method application [9, 10], it is necessary to transform the process and further split into parts (obtained by spacing the process structures into an infinite distance), used to describe the process, according to the number of closed circuits in the transformed circuit (figure 2) taking into account the principle of hitting each element in only one part.

In total, 27 parts are available for analysis, indicated by Roman numerals in the figure. A circle with an arrow and a number indicates the transitions between the stages of the original scheme and the

Figure 1. Scheme of process of designing spacecraft drives mechanisms.
direction of information movement. The stages of the original scheme are indicated by Arabic numerals.

Figure 2. The transformed scheme of the process of designing spacecraft drives mechanisms.

The state of each part of the process is then described. Let us analyse the analysis of the first part - figure 3. In the figure, the circle with the arrow and the number indicates the transitions between the stages of the original scheme, the Latin Letter A denotes the failure rate vector in the part of the process under consideration, B and G are the failure rate vectors in the adjacent parts. The rest of the process is analyzed in a similar way.
The state of each part of the process is then described. Let us review the analysis of the first part - figure 3. In the figure, the circle with the arrow and the number indicates the transitions between the stages of the original scheme, the Latin Letter A denotes the failure rate vector in the part of the process under consideration, B and G are the failure rate vectors in the adjacent parts. The rest of the process is analyzed in a similar way.

As the matrix equation of state of the primitive scheme, the following relation is chosen:

$$Y = N \cdot y,$$

where $y$ is a vector with the components representing the failure rates occurring in the corresponding stages of the process, $Y$ is a vector with the components representing the failure probabilities at some stage, $N$ is Square matrix, the elements of the main diagonal of which are the duration of the process steps.

For the first part of the process, these elements will take the following form:

$$y_0 = [ y_{01}; y_{02}; y_{03}; y_{04} ],$$

We will construct the transition matrix $C$ for a given part of the process, consisting of zeros and ones with respect to the sign:

$$C = \begin{bmatrix} A & B & G \\ 1 & -1 & 0 & 0 \\ 2 & -1 & 1 & 0 \\ 8 & 1 & 0 & -1 \\ 9 & -1 & 0 & 1 \end{bmatrix}.$$
Using the formulas proposed by G. Kron [1], we will proceed to describe the state of the analysed part of the process:

\[
Y'_t = C_t^T \cdot Y_t = \begin{bmatrix} -1 & -1 & 1 & -1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 1 \end{bmatrix} \cdot \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \end{bmatrix} = \begin{bmatrix} -Y_1 - Y_2 + Y_8 - Y_9 \\ Y_2 \\ -Y_8 + Y_9 \end{bmatrix}
\]

(5)

\[
N'_t = C_t^T \cdot N_t \cdot C_t = \begin{bmatrix} -1 & -1 & 1 & -1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 1 \end{bmatrix} \cdot \begin{bmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \end{bmatrix}
\]

(6)

Further, based on the results of calculations for all parts of the process, we will compile matrices for the total process \(Y'\), \(N'\) and the transition matrix from parts to the whole process. We make similar transformations for the matrices obtained, on the basis of which we compose a system of equations:

\[
y_1(N_1+N_2+N_3+N_4)-y_2N_2-y_3(N_4+N_6+N_8+N_9) = Y_1 + Y_2 + Y_3 + Y_4
\]

\[
-y_1N_2+y_2N_1+N_2+y_4(N_3+N_5)-y_6N_7-y_8N_9 = Y_5 + Y_6 + Y_7 + Y_8 + Y_9
\]

\[
y_2N_3+y_3N_1+y_4N_2+y_5N_3+y_6N_4+y_7N_5+y_8N_6+y_9N_7 = -Y_1 - Y_2 - Y_3 - Y_4 - Y_5
\]

\[
y_3N_2+y_4N_3+y_5N_4+y_6N_5+y_7N_6+y_8N_7+y_9N_8 = Y_2 + Y_3 + Y_4 + Y_5 + Y_6 + Y_7 + Y_8
\]

\[
y_4N_1+y_5N_2+y_6N_3+y_7N_4+y_8N_5+y_9N_6 = -Y_2 - Y_3 - Y_4 - Y_5 - Y_6 - Y_7 - Y_8
\]

(7)
The solution of the obtained system of dependent equations will be the values of failure intensities for each of the 27 parts of the process. The maximum value in the absolute one (without regard to the direction of information flow) the intensity value will indicate the part of the process most prone to failures.

| Stage | The sequence number of the transition between the stages, figure 2 | Failure probability, Y | Duration of the process stage, weeks, N |
|-------|---------------------------------------------------------------|------------------------|----------------------------------------|
| 1     | 1                                                             | 20%                    | 3,5                                    |
| 2     | 2                                                             | 5%                     | 10,0                                   |
| 3     | 3 4 5                                                         | 40%                    | 15,0                                   |
| 4     | 6 51                                                          | 40%                    | 2,0                                    |
| 5     | 7                                                             | 33%                    | 20,5                                   |
| 6     | 8 9                                                           | 20%                    | 3,0                                    |
| 7     | 10 11                                                         | 20%                    | 3,5                                    |
| 8     | 12                                                            | 70%                    | 2,5                                    |
| 9     | 13 14                                                         | 70%                    | 3,0                                    |
| 10    | 15 16 17                                                      | 50%                    | 0,0                                    |
| 11    | 18 19                                                         | 50%                    | 3,5                                    |
| 12    | 20                                                            | 50%                    | 3,5                                    |
| 13    | 21 22 23                                                      | 43%                    | 6,7                                    |
| 14    | 24 25                                                         | 43%                    | 6,7                                    |
| 15    | 26 27 28 29 30 31 32                                         | 43%                    | 6,7                                    |
| 16    | 33                                                            | 43%                    | 6,7                                    |
| 17    | 34 35                                                         | 43%                    | 6,7                                    |
| 18    | 36 37                                                         | 43%                    | 6,7                                    |
| 19    | 38 39 40                                                      | 43%                    | 6,7                                    |
| 20    | 41 42 43                                                      | 43%                    | 6,7                                    |
| 21    | 44                                                            | 43%                    | 6,7                                    |
| 22    | 45                                                            | 43%                    | 6,7                                    |
| 23    | 46                                                            | 43%                    | 6,7                                    |
| 24    | 47                                                            | 43%                    | 6,7                                    |
| 25    | 48 49 50                                                      | 26%                    | 3,5                                    |

In the considered case, the failure rates taking into account the empirical data (table 1) take values from 0.00108 (interaction between stages 3, 16, 25, part V) to 0.16486 (interaction between stages 10 and 15, part XII). Based on the results obtained, it is advisable to consider in more detail the interaction between stages 10 and 15 of the process in order to improve the effectiveness of interaction at these stages.

4. Conclusion

Thus, within the framework of the study, the following results were obtained, which are of great importance for the analysis of the processes of designing complex mechanical systems (for example, the mechanisms of space vehicle drives):
The tensor method of G. Crohn's analysis has been successfully used to analyze the process of designing the mechanisms of space vehicle drives.

A system of equations describing the process of designing the mechanisms of space vehicle drives is constructed.

On the basis of empirical data (expert assessments), we determined the part of the process which is mostly vulnerable to failures (interaction of stages 10 and 15).

The conclusion is made about the need to optimize the identified problem interaction.

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