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PROJECT CONCEPTION OF CAE-SYSTEM FOR WEAR ANALYSIS OF FRICTION BEARING UNDER CONDITIONS OF SHAFT AND LINER AXIS MISALIGNMENT

Modelling of wear processes is an important stage in the design of mechanisms. Such virtual studies allow predicting the service life of components and the machine as a whole. Modern algorithms of CAE-systems allow performing such analysis with high accuracy and taking into account not only material and operating conditions of the mechanism, but also errors that occurred during the manufacturing and assembly of a particular part. These parts require high requirements to the accuracy of manufacturing and assembly, but within the tolerances of the fields errors of mutual positioning are still allowed, which in turn can significantly affect the service life of the mechanism. Therefore, the task of modeling the wear process of the shaft and sleeve in conditions of mutual misalignment of the axes is relevant. Such sliding pairs exist in almost all machines, including car engines, power generation turbines, etc.

In this article it is offered to use the module-integrated approach for modeling of wear processes in tribotechnics, providing use of CAE-systems for definition of functioning conditions of friction units as a system core, and construction of separate modules which in this or that degree are integrated into existing CAE systems. to define values of wear of elements of friction pairs that allows to consider mutual influence of wear and change of functioning conditions in the course of operation.

The practical implementation of the module-integrated approach is shown by the example of solving the problem of radial plain bearings wear during the misalignment of the shaft and bush axes in the ANSYS environment. The module of representation of multidimensional matrixes of static or dynamic data, providing essential increase in speed of data processing and quality level of the further analysis of the visualized information from any subject area, is developed.

Key words: modeling, friction, CAE-systems, wear of machine parts, mutual misalignment of axes, bearing, software.

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РОЗРОБКА САЕ-СИСТЕМИ АНАЛІЗУ ЗНОШУВАННЯ ПІДШИПНИКІВ В УМОВАХ ПЕРЕКОСУ ОСЕЙ ВАЛА І ВТУЛКИ

Моделювання процесів зношування є важливим етапом при проектуванні механізмів. Такі віртуальні дослідження дозволяють спрогнозувати ресурс роботи вузлів та машини в цілому. Сучасні алгоритми САЕ-систем дозволяють виконувати такий аналіз з високою точністю та враховувати не лише матеріал та умови роботи механізму, а й похибки, які виникли під час виготовлення та складання конкретної деталі. Дані деталі вимагають високих вимог до точності виготовлення та складання, проте в межах полів допусків все ж таки допускаються похибки взаємного розташування, що в свою чергу може суттєво вплинути на ресурс роботи механізму. Тому задача моделювання процесу зносу вала і втулки в умовах взаємного перекосу осей є актуальною. Подібні пари ковзання існують майже у всіх машинах, зокрема двигунах автомобілів, електрогенеруючих турбінах, тощо.

У роботі запропоновано для моделювання процесів зношування в триботехніці використовувати модульно-інтегрований підхід, який передбачає використання САЕ-систем для визначення умов функціонування вузлів тертя в якості ядра системи, та побудови окремих модулів, які в тій чи іншій мірі інтегровані в існуючі САЕ-системи, для визначення величин зносу елементів пар тертя, що дозволяє враховувати взаємний вплив зносу та зміни умов функціонування в процесі експлуатації.

Практична реалізація модульно-інтегрованого підходу показана на прикладі розв'язання задачі про зношування радіальних підшипників ковзання при перекосі осей вала і втулки в середовищі САЕ-системи ANSYS. Розроблено модуль представлення багатовимірних матриць статичних або динамічних даних, який забезпечує суттєве підвищення швидкості обробки даних та рівня якості подальшого аналізу візуалізованої інформації з будь-якої предметної області.

Ключові слова: моделювання, тертя, САЕ-системи, знос деталей машин, взаємний перекос осей, підшипник, програмне забезпечення.

Introduction

Reliability of design is laid at the stage of designing of machines and mechanisms. Management of machine reliability indicators at the design stage is inseparably connected with the development and improvement of calculation methods of their determination. Strength calculations are widely used in design practice due to the availability of a wide range of both analytical calculation methods and software that implements both numerous methods, such as finite element method [2] and limit element method.

At the same time, it should be taken into account that the most frequent cause of failure of machines is not their destruction due to insufficient strength, but the wear of friction units. As a result of wear of friction units there are functional failures, kinematic accuracy of mechanisms is violated, additional loads, vibrations, etc. appear unforeseen by calculation. Analysis of the methods used in the design practice for calculating the wear resistance and predicting the service life of friction units by the wear criterion showed a significant lag from the strength calculations.

Difficulties in the development of calculation methods for predicting the service life and wear of friction units are due to the presence of diverse in nature processes occurring on friction surfaces, and the influence on these processes of a large number of interrelated factors. Thus in the course of functioning of a tribo-node the factors change both in time, and on a contact surface of details of knots of a friction. Insufficient study of complex physical and chemical processes on the contact surfaces during friction, probabilistic nature of friction and wear processes, random nature of external influence parameters, material properties and initial geometry of the connected parts complicates the development of methods for calculating wear and predicting the resource. Proceeding from the aforesaid, the development of methods for calculating the resource and wear of friction units is the most important task, the solution of which is aimed at increasing the reliability and wear resistance of machines and equipment.

Presentation of main material

When developing the methods for predicting the service life of friction units it is necessary to take into account the peculiarities of wear as a specific type of destruction, take into account that the fact of this process is not critical for the joint operation. When modeling mechanical wear it is necessary, first of all, to determine the stress state arising in the body at the given external conditions of interaction, properties of materials of contacting pair and macro- and microgeometry of surfaces.

In many cases, when building a model to analyze the serviceability of a friction unit, the most important characteristics of the process are macro changes in the shape of the elements of the tribunal. The task of stage-by-stage modeling (Fig. 1) of wear is to predict the transition from one macrostate to another under given external conditions.

The theoretical basis for the construction of phenomenological models of tribocouplings wear is made by the wear-contact problems, in which the contact pressures and the relative sliding velocity of friction pairs elements are considered as the main external characteristics.

To separate the solution of contact interaction problems and the forms of change of tribocoupling elements due to wear, an iterative approach is used, which implies consideration of a number of discrete states, through which the connection passes in the process of functioning.

The analysis of wear processes shows that the changes occurring in friction pairs are stochastic in essence, and the wear process, in the general case, is a random process. On the basis of theoretical processing of a huge experimental material it has been proved that processes of accumulation of tribo-damages belong to a class of cumulative damages and are most accurately described by Markovian random processes with discrete times and states [1, 2, 7]. The generalized scheme of construction of a three-boelement model of a friction pair is presented in Fig. 2. Thus, the algorithm for solving the wear-contact problems is based on the following steps:

1. Design of the geometrical model of the friction pair.

2. Representation of a worn surface in the form of some number of triboelements with preservation of their geometrical position in the form of an array of data.

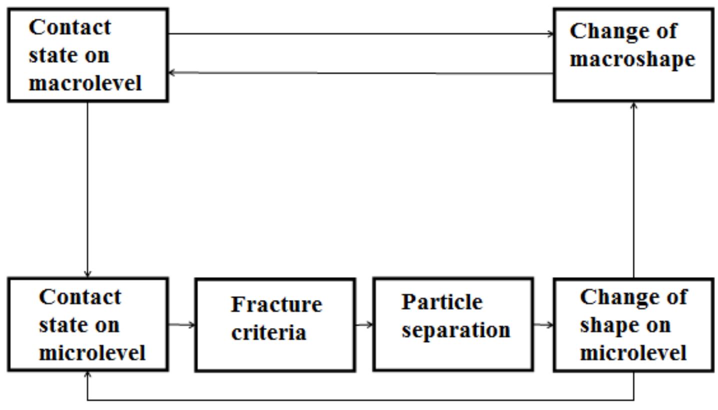


Figure 1. The main stages of wear modeling

3. Design of finite-element model of elastic elements of friction pair. The condition of geometrical coincidence of a part of knots of the end elements, located on a wear surface, with the location of triboelements is imposed.

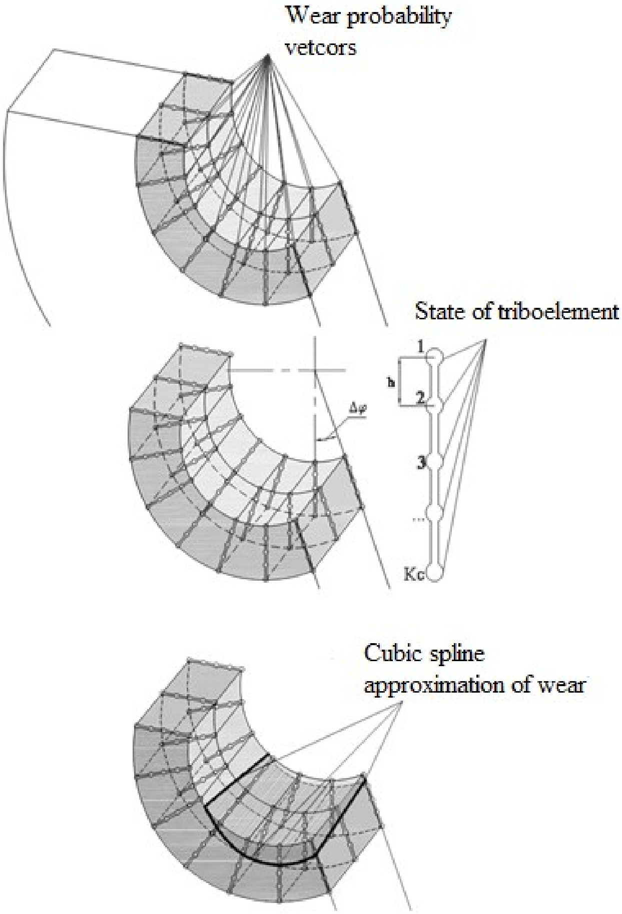


Figure 2. Generalized scheme of triboelement model

4. Determination of contact pressures in the nodes located in the locations of the triboelements
5. Determination of the parameters of the triboelement wear model using the obtained solution results.
6. Determination of mathematical expectation of wear value for each triboelement with keeping the received vectors of unconditional probabilities of staying of triboelements in this or that state.
7. Determination of new coordinates of the end element nodes located on the wear surface in the locations of the triboelements, taking into account the wear value.
8. Design of cubic spline of geometric model of wear surface.
9. Cyclic execution of items 3 - 9 of this algorithm until reaching the wear limit or a given time of wear of elements of the friction pair.

Simulation of wear processes is an important stage in the design of mechanisms. Such virtual studies allow predicting the service life of components and the machine as a whole. Modern algorithms of CAE-systems allow performing such analysis with high accuracy and taking into account not only the material and operating conditions of the mechanism, but also the errors that occurred during the manufacturing and assembly of a particular part. For example, when considering predictive modeling of the cutting process for coated tools, it is necessary to know the basic parameters of the uncoated tool transition zone and the relative increase or decrease in the adhesion properties of this zone when the coating is applied there [4].

During the operation of machines, rotating and moving parts, in particular shafts, bushings, are subject to the greatest wear, so the analysis of predicting their service life is an important task. These parts require high requirements to the accuracy of manufacturing and assembly, but within the tolerances of the fields errors in mutual arrangement are still allowed, which in turn can significantly affect the service life of the mechanism [5]. Therefore, the task of modeling the wear process of the shaft and sleeve in conditions of mutual misalignment of the axes is relevant. Such sliding pairs exist in almost all machines, including car engines, power generation turbines, etc.

The analysis of the serviceability of plain bearings must take into account the design features of the machine design. One feature that can have a significant impact on the service life of a plain bearing is the relative alignment of the shaft and bearing sleeve axes. Deviations from parallelism can occur due to bending of the shaft, causing the axes of the shaft and the sleeve of the plain bearing to be positioned at a certain angle.

The contact of a rigid shaft of radius R_1 (Fig. 3) and an elastic cylindrical antifriction layer of thickness ε coupled with a rigid sleeve is envisaged. The shaft is inclined at an angle θ to the sleeve. The z-axis is directed along the bearing axis. The origin of the z-axis is located at the end of the bearing, and the angle φ is counted from a plane passing through the bearing axis parallel to the main vector of forces acting on the shaft.

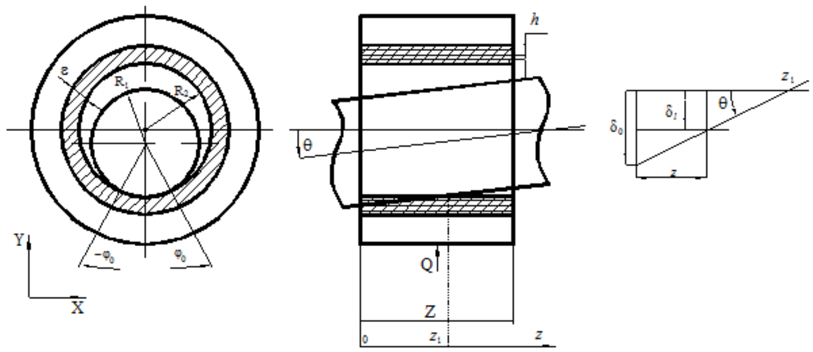


Figure 3. Schematic diagram

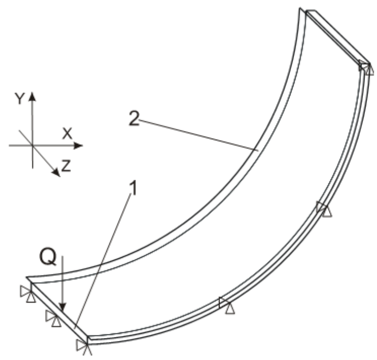


Figure 4. Schematic diagram:
1 - antifriction element;
2 - rigid shaft

To solve the wear-contact problems in the spatial formulation, it is necessary to take into account that in this case a cubic spline of the wear surface is constructed. The spline approximation is built on the points of antifriction layer [1], in the locations of triboelements, in two directions - along the z axis and in the radial direction. Thus, after each iteration of determining the wear value, a cubic spline of the wear surface is built, the geometry of which takes into account the wear at the previous step.

Based on the above calculation model, a parametrized calculation model was built, which is shown in Figure 3. When building the model, taking into account the conditions of the problem, the contact interaction of elements of the tribocoupling is modeled by a rigid-submissive contact. The shaft 2 (Fig. 4), as rigid, is taken as the target surface. The antifriction element 1 is taken as the contact surface. On the contact surface of the antifriction layer the geometric position of triboelements is determined. Twenty-node SolidWorks spatial elements were used to create a finite-element mesh model of the antifriction layer. To create the contact pair "bushing-antifriction element" contact elements "surface-surface" were used.

Wear was considered as a random Markov-type process with discrete time and states. At time t = 1, the probability locations of TO in one or another state were defined as the product of the vector of initial states $\left[\boldsymbol{\pi}_i\right]$ on the transition probability matrix $\left[\boldsymbol{W}_{ij}\right]$:

$$\left[\boldsymbol{\pi}_j\left(t=1\right)\right]=\left[\boldsymbol{\pi}_j\left(t=0\right)\right]\left[\boldsymbol{W}_{ij}\right],\quad i,j=1,2,\ldots,\ K_C, \tag{1}$$

where $\left[\boldsymbol{\pi}_j\left(t=0\right)\right]$ is initial states vector; $\left[\boldsymbol{\pi}_j\left(t=1\right)\right]$ – vector of unconditional probabilities of TO in j-th states $\left(j=1,\ldots,K_C\right)$ at a point in time $t=1$; $\left[\boldsymbol{W}_{ij}\right]$ – transition probability matrix.

The probabilities of TO states at time t > 1 were determined as the product $\left[\boldsymbol{\pi}_j(t-1)\right]$ of the vector of unconditional probabilities at time t - 1 on the transition probability matrix, which defines the behavior of TO at time t:

$$\left[\boldsymbol{\pi}_j\left(t\right)\right]=\left[\boldsymbol{\pi}_j\left(t-1\right)\right]\left[\boldsymbol{W}_{ij}\right],\quad i,j=1,2,\ldots,\ K_C. \tag{2}$$

The components of the vector of initial states $\left[\boldsymbol{\pi}_j\left(t=0\right)\right]$ were determined from the assumption that at the initial moment of time TO was in the first state:

$$\left[\boldsymbol{\pi}_j\left(t=0\right)\right]=\left[1,0,0,\ldots,0\right]. \tag{3}$$

A transition probability matrix [7] with unit jumps up and the presence of an absorbing state was used to describe the TO behavior:

$$\left[\boldsymbol{W}_{ij}\right]=\begin{bmatrix} w_{11}(t) & w_{12}(t) & 0 & 0 & 0 & 0 \\ 0 & w_{22}(t) & w_{23}(t) & 0 & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \tag{4}$$

The absorbing state is understood as the state of complete wear of the antifriction layer.

The components $w_{ij}(t)$, were determined as follows:

$$w_{ij}\left(t\right)\cong_I\left(t\right)\Delta t,\quad \text{for } i\neq j, \tag{5}$$

where $_I\left(t\right)=V_I\left(t\right)/h$ - wear flow rate; Δt – time step of loading; h - value determined from the condition of ordinality of the wear flow; $V_I\left(t\right)$ – the wear rate at the time t.

The value of wear h is chosen from the condition that in one load cycle the probability of a wear value greater than h is negligible. The value of the layer wear was determined because of the mathematical expectation $\bar{m}_t$:

$$z_t=\left(\bar{m}_t-1\right)h, \tag{6}$$

where $\bar{m}_t=\sum_{i=1}^{K_C} i\boldsymbol{\pi}_i\left(t\right),\quad i=1,2,\ldots,K_C$; $\boldsymbol{\pi}_i\left(t\right)$ – unconditional probabilities of TO states; $h=\varepsilon/\left(K_C-1\right)$ – the amount of wear that determines the condition of the triboelements.

At the initial moment of time, it was assumed that all elements were in state 1. As the dependence of the wear rate on the contact pressures and sliding velocity, a stepwise dependence of the form was used:

$$V_I=K_wV^{\gamma}p\left(\varphi,\varphi_0\left(t\right)\right)^{\alpha}, \tag{7}$$

where V_I – wear rate; K_w – depreciation rate; V – sliding velocity of the shaft on the sliding layer; $p\left(\varphi,\varphi_0\left(t\right)\right)$ – contact pressures; α,γ – degree indicators [3].

Simulation of the wear process of parts in conditions of deviation from parallelism of shaft and bush axes allows to predict the possible places of defects in the operation of machines and mechanisms, as well as to calculate the durability of mechanisms. Such modeling contributes to reducing the number of repairs and increasing the life cycle of triboelements.

Visualization of repetitive cyclic loads in graphical format is characterized by reproducibility of large arrays of numerical data reduced to a unified form. If we consider the information presented in the form of multidimensional matrices with statistical data, the level of perception of such information is much lower than in the visual form.

The creation of multidimensional data matrices is an obligatory step of conducting process modeling for further analysis. Static matrices describe processes based on fundamental laws, while dynamic matrices include all iterative processes. When studying physical processes (especially iterative ones) there are cases when the corresponding data cannot be completely covered by a three-dimensional graph divided by a color spectrum, because it is impossible to demonstrate the dynamic process of parameters change from time by means of a static image. In such cases, it is advisable to use animation types of data representation, which allow to visually display the change of state of the processes depicted on the three-dimensional graph in time.

To solve the task, the module of calculation of friction unit wear was developed. The first step of the module is initialization and creation of a graphical model based on the received data. The created geometric model is broken down into finite elements, after that the contact pair is created and the constraints on freedom and value of friction knot loads are set. After the corresponding calculation, the constructed geometric model is destroyed and the process is repeated again for the number of iterations specified by the user.

Practical application of the developed system of modeling of wear processes confirmed the high efficiency of the visual display of the data characterizing the dynamics of wear processes for the general study of pressure and wear changes depending on time.

The multidimensional matrices, containing numerical data, are difficult in perception of the information, especially in the presence of its large number [6]. They do not allow to observe the general picture of researched processes, to give their generalized estimation, to carry out the concrete analysis.

In cases requiring the rapid formulation of generalized conclusions, the practical application of the developed system confirmed the high efficiency of applying the method of visualization of pressure and wear data in the study of shaft and bushing wear at mutual misalignment of the axes.

The basic interface of the developed software product is shown in Fig. 5. In order to increase the level of perception of the information depicted in the graph, the module implements the appropriate toolkit. The toolkit allows you to shift and rotate the graph around the abscissa and ordinate axes, to scale and build the graph step by step. Such step-by-step construction allows to distinguish moments of transition from normal conditions of node operation to critical wear conditions.

Within the framework of research of effectiveness of application of the system of modeling and visualization of wear processes its testing on the data characterizing different variants of dynamics of wear and pressure processes within the framework of the problem of radial plain bearings wear at misalignment of shaft and bush axes was carried out.

For example, in Fig. Fig. 6 shows graphs of pressure dependence on time under condition of rapid initial pressure value (Fig. 6, a), smoothed dependence of pressure on time when studying the wear process of shaft and bushing under condition of mutual misalignment of their axes (Fig. 6, b), and also cases of jump-like pressure growth in a critical situation in the form of peak dynamics of friction pair elements change (Fig. 6, c) and linear dependence of wear process of friction pair elements depending on time of mechanism operation (Fig. 6, d).

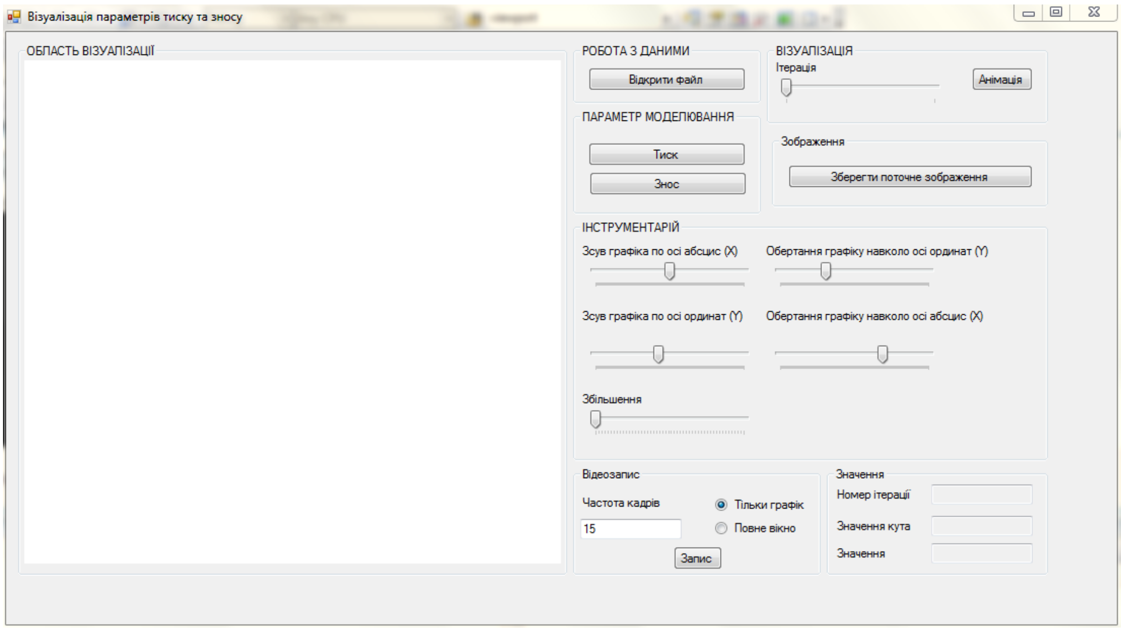
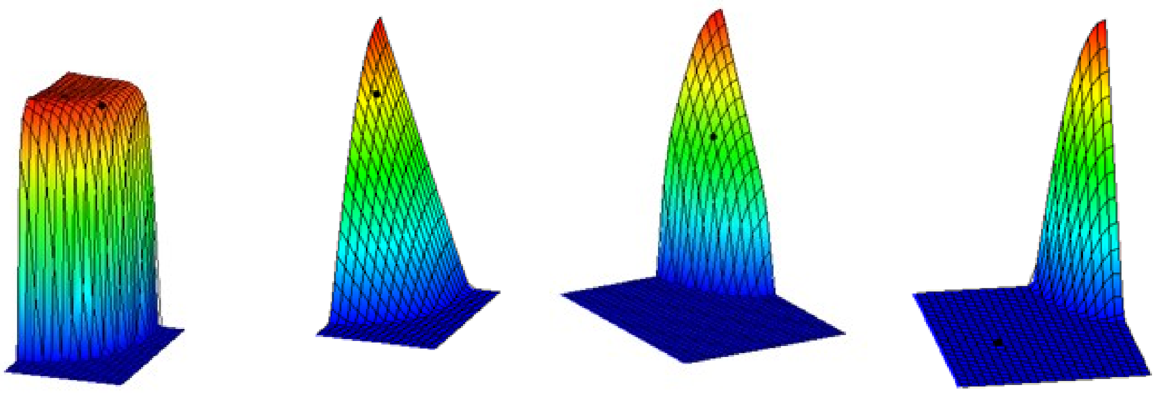


Figure 5. Basic interface of the module



a) b) c) d)

Figure 6. Examples of construction of shaft and liner wear models over time

For better perception of information and further analysis of critical areas of the node conditions, the module implements scaling of abscissa and ordinate axes, as well as rotation of the graph relative to its axis. In addition, the program implements the selection of a particular value from a multidimensional matrix of input data. To do this, the user needs to click the appropriate area of the graph and in the fields Iteration number, Angle value and Wear value the corresponding data will be displayed in numerical format.

If you need to present dynamic information in the absence of the module, it has the ability to record video files, providing several functions. The user can define the video quality himself, with the default setting of 15 frames per second. The program also allows you to save the current image that is in the visualization area.

Conclusions

The developed system allows to visualize different cases of temporal changes of pressure and wear parameters, wear processes of friction elements, which allows to take into account mutual influence of wear and changes of functioning conditions in the process of operation. In addition, the use of such a system by an expert in the relevant subject area, in which there is a need to process multidimensional matrices, leads to the rapid determination of critical situations in the operation of the mechanism.

By means of visual representation of multidimensional numerical matrices there is a possibility to analyze general dynamics of wear and friction process, to obtain specific data in a certain period of mechanism operation time, to use obtained multimedia files for demonstration of modeling process in future depending on needs (scientific, training, analytical, etc.). The scope of application of the developed module is defined by its use in any field of knowledge in which there are multidimensional data matrices, especially in those areas where data change with time or by another parameter.

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