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CIRCUIT DESIGN OF TRANSFORMATION AND TRANSFER PROCESSES IN HETEROGENEOUS MEDIUM

В. Тонконогий, О. Становський, М. Голофєєва, Ю. Голофєєв, Є. Науменко. Схемотехнічне проектування процесів перетворення і переносу в гетерогенних середовищах. Стаття присвячена дослідженню можливості використання принципів схемотехнічного проектування при моделюванні внутрішніх процесів, що протікають в гетерогенному середовищі. Сучасні складні об'єкти в машинобудуванні (елементи, процеси, вузли, суміші, сплави тощо) можуть бути представлені у вигляді важливих схем, під якими розуміється сукупність елементів і зв'язків між ними. Такі схеми дозволяють створювати однозначну модель об'єкта. Крім того, принципові схеми дозволяють оптимізувати їх (отже і об'єкти) у процесі побудови: змінювати кількість елементів; змінювати характеристики елементів. Основна перевага такого підходу випливає з того, що в даний час існують спеціальні програми, в тому числі комп'ютерні, що дозволяють будувати такі моделі на підставі мети функціонування об'єкта, що проектується, і можливостей його створення. Схемотехнічне проектування в механіці – це створення принципової схеми майбутнього об'єкта (методи, пристрої, речовини), який, будучи виконаним (виготовленим), дозволить об'єкту досягти поставленої мети. Розглянутий процес перетворення та перенесення інтенсивного параметра в гетерогенних середовищах на прикладі поширення в них пружних коливань та теплових процесів, що є цікавим з погляду моделювання процесів, що відбуваються в даних середовищах при їх дефектоскопії акустичним інфрачервоним термометричним методом, який заснований на взаємодії дефектів структури з акустичними хвилями. При цьому на їхніх межах генерується теплова енергія, що є індикатором не тільки наявності тріщин, а й їхнього напрямку та розвитку. При моделюванні пошкоджень типу тріщин та руйнувань у виробках з неметалевих гетерогенних матеріалів введені спеціальні додаткові елементи, що імітують порушення суцільності конструкції – релейні елементи.

Ключові слова: схемотехнічне проектування, гетерогенне середовище, внутрішні процеси

V. Tonkonogyi, O. Stanovskyi, M. Holofieieva, Yu. Holofieiev, Ye. Naumenko. Circuit design of transformation and transfer processes in heterogeneous medium. The article is devoted to the study of the possibility of using the principles of circuit design when modeling internal processes occurring in a heterogeneous medium. Modern complex objects in mechanical engineering (elements, processes, components, mixtures, alloys, etc.) can be represented in the form of circuit diagrams, which are understood as a set of elements and relationships between them. Such schemes make it possible to create an unambiguous model of this object. In addition, circuit diagrams allow you to optimize them (and hence objects) in the process of construction: change the number of elements; change the characteristics of the elements. The main advantage of this approach stems from the fact that at present there are special programs, including computer programs, that make it possible to build such models based on the purpose of the functioning of the designed object and the possibilities of its creation. Circuit design in mechanics is the creation of a concept diagram of a future object (method, device, substance), which, when completed (manufactured), will allow the object to achieve its goals. The process of transformation and transfer of an intensive parameter in heterogeneous media is considered, using the example of the propagation of elastic oscillations and thermal processes in them, which is interesting from the point of view of modeling the processes that take place in these media during their flaw detection by the acoustic infrared thermometric method, which is based on the interaction of structural defects with acoustic waves. At the same time, thermal energy is generated at their boundaries, which is an indicator not only of the presence of cracks, but also of their direction and development. When modeling damage such as cracks and fractures in products made of non-metallic heterogeneous materials, special additional elements are introduced that simulate structural integrity violations – relay elements.

Keywords: circuit design, heterogeneous medium, internal processes

Introduction

Many technological processes in mechanical engineering can be described in the form of a certain model that connects intensive (temperature, pressure, electric current, etc.) extensive (information) parameters of the elements of this process [1, 2, 3].

Such models have some features that allow them to be used in the circuit design of the indicated processes. These features include the multicomponent nature of the model, as it links various aspects of the activity of the object as a whole, for example, geometric, energy, procedural characteristics and many other components. It is clear that being built once, the circuit diagram does not structurally change during the entire process. For example, a component received at the input of the n -th element with the help of the m -th structural connection will always be transferred to $n+1$ components, and so on. This structural dependence is constant for a given scheme and can only be changed by introducing new elements or new connections, that is, in fact, by changing the structure. If, after leaving the ele-

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ment, the component split and passed to several elements, then such a structural approach should be unchanged in this scheme and, accordingly, reflect the subprocesses occurring in the object.

It should be noted that technological processes are built based on two types of sub-processes:

- sub-processes of processing (transformation of a component);
- component transfer subprocesses.

This gives rise to fundamentally different topological solutions in such circuits and allows the control process to influence quantitatively and qualitatively the processes occurring in the object under study. When designing new processes, such schemes allow you to select and calculate individual elements of transformations, as well as the relationships between them.

Analysis of publications on the research topic

Let us consider as an example the technological process of transferring an intense component (temperature, pressure, etc.) from a point source to a receiver. In the process of such processing and transfer, the transformation and transfer of process components takes place. Each of the transformation and transfer subprocesses, depending on its physical nature, can be described by different equations, and the set of such equations will represent a general mathematical model of the object under consideration.

As in a computer program, in such a system of equations, which is a model of the process, there should not be parameters that are taken from “no one knows where” and components that are “transferred to no one knows where”.

Let's consider the technology of creating schematic diagrams for transfer and transformation processes in heterogeneous environments. Such a medium consists of at least two components (phases). That is, the main feature of a heterogeneous structure is the phase boundary, through or through which the interaction of these components takes place. It is clear that the properties of such a medium differ from the properties of its components. At the same time, by selecting the composition (type of filler and binder, their ratio, orientation of the filler, etc.), the required operational and technological properties of a heterogeneous medium are achieved [4].

In mechanical engineering, heterogeneous structures are used as structural materials that perform heat-insulating, anti-friction, vibration-damping functions. They allow reducing the weight of the structure increasing the service life and other properties of products while maintaining, for example, strength characteristics. In addition, it becomes possible to create fundamentally new parts, assemblies and structures [5, 6]. The multilevel nature of the organization of heterogeneous media creates great opportunities for directed regulation of their physical and mechanical properties [7].

It should be noted that in most cases, heterogeneous media are characterized by specific physical and mechanical properties. First of all, this concerns non-metallic heterogeneous materials. They are distinguished, for example, by high vibration, sound and heat insulation properties, non-magnetic properties, anti-corrosion properties. Consequently, the processes of transformation and transfer of intensive parameters are characterized by certain features. This is primarily due to the complexity of the structure of heterogeneous media, and, accordingly, for each specific case such processes are described by individual models that are different from others.

In fact, a heterogeneous medium is a kind of construction with an internal architecture – a hierarchy of structural levels and sublevels [4]. Considering it in this form, one can evaluate the contribution of each structural element to the process of transformation and transfer of a certain intensive parameter.

Purpose and Objectives of the Research

The main objective of this article is to demonstrate the possibility of using the principles of circuit design when modeling internal processes occurring in a heterogeneous medium. In particular, the technology of creating schematics for transfer and conversion processes in heterogeneous environments is considered. Using the example of modeling damage such as cracks and fractures in products made of non-metallic heterogeneous materials, show the possibility of introducing special additional elements simulating a violation of the integrity of the structure – relay elements.

Research Methodology

Let us consider the process of transformation and transfer of an intense parameter in heterogeneous medium using the example of the propagation of elastic vibrations in them. It is known that heterogeneous medium is characterized by increased dissipative properties, which are determined by the value of irretrievable losses of vibration energy. Such processes must be considered in the inextricable relationship of design, technological and operational factors [8].

To characterize vibration energy damping in heterogeneous medium, the concepts of “internal” (scattering in a viscous matrix and rigid filler) and “constructive” (scattering at phase boundaries) scattering are used, which are influenced by structural features, mechanical stresses, phase transformations, temperature, sizes and shape of objects [9]. In addition, it is necessary to note the dependence

of the characteristics of the dissipation of vibration energy on the characteristics of the mechanical waves themselves (amplitude and frequency). Due to the adhesive bonds of the components at the phase boundary, which are characterized by different rigidity, a much higher level of vibration damping is provided in comparison with the total dispersion on these components. Therefore, in the circuit design of processes in heterogeneous media, it is necessary to build on the real-life mechanisms of energy dissipation that are characteristic of a particular heterogeneous object.

Let us consider the transformation of a mechanical wave when passing through a heterogeneous structure. During the excitation of oscillations in this structure, a number of modes arise, and, consequently, the wave itself is a combination of harmonic components, each of which has its own amplitude and frequency, combined with the rest of the components in various ratios [8]. The transformation model of a mechanical wave passing through a heterogeneous medium, taking into account its physical and mechanical characteristics, has the form:

$$u_2(t) = u_1(t) \cdot \sum_{i=1}^n e^{-\lambda_i f_i S} \sin[2\pi f_i(t - S/c)], \quad (1)$$

where S is the distance traveled by the wave; f is the oscillation frequency; λ is the oscillation damping decrement; i is an integer from 1 to ∞ , called the harmonic order (number of vibration modes); t is time; c is the speed of wave propagation; $u_1(t)$ – initial waveform; $u_2(t)$ is a wave with a modified shape.

As another example of the transformation and transfer of intense parameters in heterogeneous medium, let us consider thermal processes in them. Despite a large number of studies, the issue of modeling temperature processes in complex heterogeneous structures consisting of elements with different heat transfer characteristics, using mathematical models that would display temperature distributions with sufficient accuracy and make it possible to control them, remains open [10].

In the general case, the object under study is heated either due to internal sources, or due to surface heating from external sources, or as a result of a combination of these processes [11]. Internal sources of thermal energy, for example, can be defects in the structure of a heterogeneous medium during the passage of mechanical waves through it [12]. In the analytical theory of heat transfer, the temperature field is characterized by a continuous and differential function of time and coordinates of physical space points [13]. Both surface and internal heat fluxes are distributed in space in accordance with the Gaussian law, if the structure of the medium is without features, for example, cracks or cavities.

If the design of a heterogeneous object contains the regulation of energy flows in it, and such flow control is supposed to be carried out by changing the characteristics of the transfer, then the circuit of the heterogeneous object (also, the electrical circuit) should consist of elements simulating the intensity of the transfer, and elements simulating its direction. The mathematical analogy with electrical processes is complete here (capacitor – capacitance, resistor – transmission resistance, conductor – lossless transmission direction, etc.).

When building a circuit model of any transfer process, the following sequence of operations works:

- an electrical model of a non-electrical process is created in the form, for example, of an electrical circuit;
- the model is optimized in its electrical essence, but taking into account the commonality between the transfer process of any component and the electrical circuit;
- a return to the non-electric circuit, which we will consider optimal, is carried out.

This approach can significantly reduce the time for designing processes occurring in heterogeneous media. Separately, it should be noted the processes of synthesis and analysis, which are subjected to both the structure of the circuit diagram and the parameters of its elements. Approaches to structure formation are determined by the stratification of internal processes occurring in heterogeneous media. As for parametric synthesis, such tasks consist in establishing the values of the parameters of elements for the selected structure, namely:

- identification of the model, that is, the approximation of the parameters of the circuit to the characteristics of the process under study, obtained empirically;
- refinement of design parameters, approximation of known solutions to new conditions and search for parameters that provide the optimal solution to the problem.

The transfers of intense parameters considered earlier in heterogeneous objects (propagation of vibrations and thermal processes) are interesting from the point of view of modeling the processes occurring in these media during their flaw detection by the acoustic infrared thermometric method, which is based on the interaction of structural defects with acoustic waves. At the same time, thermal energy is generated at their boundaries, which is an indicator not only of the presence of cracks, but also of their direction and development.

When modeling damage such as cracks and fractures in products made of non-metallic heterogeneous materials, special additional elements can be introduced that simulate a discontinuity in the structure – relay elements. The main requirements for such elements are:

- a virtual relay element can be in two states: “off” – there are no defects in the structure of a non-metallic heterogeneous object and the element does not make changes to the result of modeling the transfer processes; “on” – damage is present, changes are made to the simulation result taking into account the nature of the structural defect;

- switching of the virtual relay element is carried out automatically after the next iteration of the simulation during the calculation of the transfer parameters.

The switching signal comes from a subsystem that simulates the mechanism of transfer of an intense parameter in a nonmetallic heterogeneous medium. The relay element is essentially a kind of non-linear model element. Its difference from the rest lies in the fact that the change in the characteristics of the parameter transfer in the specified environment is carried out after each time iteration by a relatively small amount, and the change in the relay element is made once, and the parameter jump is maximum (Fig. 1).

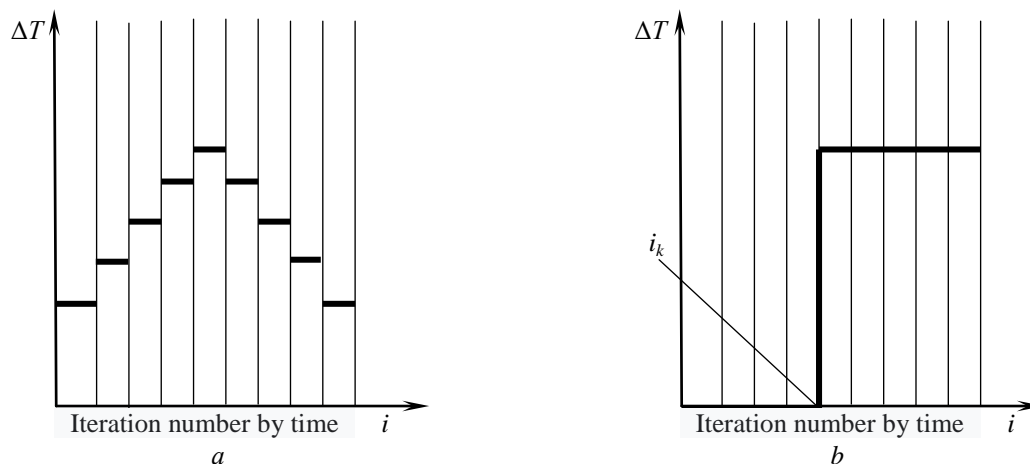


Fig. 1. Timing diagram of the temperature contrast of conventional non-linear (a) and virtual relay (b) elements when modeling the processes occurring during flaw detection of products from non-metallic heterogeneous materials by acoustic infrared thermometric method: i_k – the moment of “turning on” the relay element

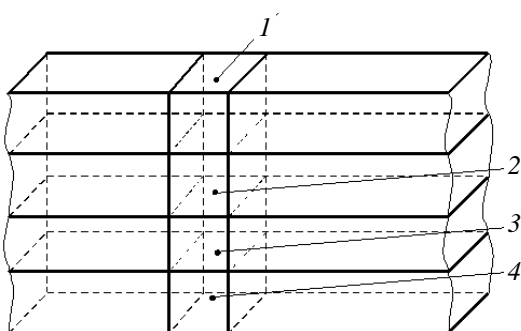


Fig. 2. Scheme for modeling the stage-by-stage development of a crack in a non-metallic heterogeneous structure: 1 – First relay element; 2 – Second relay element; 3 – Third relay element; 4 – Fourth relay element

If the model must take into account the development of a crack, then several relay elements are “inserted” in the cross section of a product made of non-metallic heterogeneous material, as shown in Fig. 2. In this case, it becomes possible to simulate the development of a “dangerous place” structure defect.

Results

To continue the modeling process, information is needed on the parameters of the transfer process at a given time iteration. That is, not only on the presence of temperature anomalies on the surface of a product made of non-metallic heterogeneous material, but also on the change in temperature contrasts over time, and, consequently, on the presence of structural defects, their geometric parameters and coordinates, including the depth of occurrence.

To prepare such information, the concept of “site of a structural defect” is introduced, which will unambiguously determine the location on corresponds to M_j of sites of structural defects. Thus, the total number of places of possible structural defects D taken into account by the system is equal to:

$$D = \sum_{i=1}^N \sum_{j=1}^{M_j} D_{ij}, \tag{2}$$

where D_{ij} is a structure defect of the i -th type in the j -th place.

Taking into account the above-described technique for modeling the development of a crack, each location of a structural defect is considered in the model as several (more than 1) relay elements. Let for each D_{ij} from D places of structural defects the number of relay elements is equal to K_{ij} . Then the total number of relay elements in the transfer process model will be:

$$R = \sum_{i=1}^N \sum_{j=1}^{M_j} \sum_{k=1}^{k_{ij}} r_{ij}k, \tag{3}$$

where $r_{ij}k$ is a relay element simulating the k -th degree of a structure defect of the i -th type in the j -th place.

Obviously, the maximum possible number of modeled structural defects is $z_{\infty}=R$.

The input data for modeling is the defect matrix at the beginning of each iteration of A_n^T ; the output data is the defectiveness matrix at the end of each iteration A_n^{T+1} . As for the function of the internal state, we accept as it the probability matrix of the occurrence of a structural defect of one type or another in one place or another of an object made of non-metallic heterogeneous material A_{δ} at a time iteration $T-(T+1)$. Then the exit function will look like:

$$A_n^{T+1} = A_n^T + A_{\delta}. \tag{4}$$

Let us consider the physical and mathematical meaning of the matrices in formula (4). Complete information about the location and number of relay elements of the model is a two-dimensional numerical array with the number of rows N , the number of columns M_j and the value of each element of the array, which is equal to $K_{ij}(i = 1, \dots, N; j = 1, \dots, M_j)$. Choosing from the number of array elements in each row the maximum $M_{\max}\{M_{\max} \subset M\}$ and complementing each row on the right with such a number of zero elements that their total number is equal to M_{\max} , we obtain a rectangular matrix with dimensions $N \times M_{\max}$, which can look like this, for example:

$$\mathbf{A}_R = \begin{pmatrix} K_{11} & K_{12} & K_{13} & 0 & 0 & 0 & 0 \\ K_{21} & K_{22} & K_{23} & K_{24} & K_{25} & 0 & 0 \\ K_{31} & K_{32} & K_{33} & K_{34} & K_{35} & K_{36} & K_{37} \\ K_{41} & 0 & 0 & 0 & 0 & 0 & 0 \\ K_{51} & K_{52} & K_{53} & K_{54} & 0 & 0 & 0 \end{pmatrix}. \tag{5}$$

Thus, the final machine code of the relay element will have the specification: “structure defect type – structure defect location – structure defect degree” and include the following bits (Fig. 3).

If the elements of the matrix \mathbf{A}_R are not the number of relay elements (that is, the potential for the appearance of a structural defect), but the structural defects themselves, then we get a matrix similar in size:

$$\mathbf{A}'_{\Pi} = f(t). \tag{6}$$

Such a matrix for an object that does not provide for the possibility of a defect will be zero, that is:

$$\mathbf{A}^0_{\Pi} = \begin{pmatrix} 0 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & \dots & 0 \end{pmatrix}. \tag{7}$$

For the case when all “planned” structural defects have taken place, matrix (6) will coincide with the matrix of relay elements:

$$\mathbf{A}^{\infty}_{\Pi} = \mathbf{A}_R. \tag{8}$$

Given the fact that time t is a discrete value with nodes $0; T_0; T_1; \dots; T_{\theta}$, then modeling of transport processes in non-metallic heterogeneous materials will consist of successive transformations of matrices:

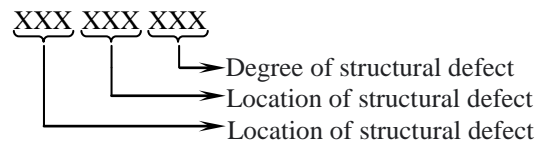


Fig. 3. The relay cod element generation

$$\mathbf{A}_{\Pi}^{T_0} = f(\mathbf{A}_{\Pi}^0; T_0); \quad \mathbf{A}_{\Pi}^{T_1} = f(\mathbf{A}_{\Pi}^{T_0}; T_1); \quad \dots; \quad \mathbf{A}_{\Pi}^{\theta} = f(\mathbf{A}_{\Pi}^{T_{\theta-1}}; T_{\theta}), \quad (9)$$

where T_{θ} is the time boundary of the simulation.

Transformation:

$$\mathbf{A}_{\Pi}^{T_i} = f_i(\mathbf{A}_{\Pi}^{T_{i-1}}; T_i), \quad (10)$$

is carried out on the basis of adding elements of the modernized δ -matrix similar in size to the elements of the input matrix $\mathbf{A}_{\Pi}^{T_i}$, that is:

$$\mathbf{A}_{\Pi}^{T_i} = \mathbf{A}_{\Pi}^{T_{i-1}} + \mathbf{A}_{\delta}^{T_i}. \quad (11)$$

The upgraded δ -matrix $\mathbf{A}_{\delta}^{T_i}$, in turn, is obtained by sequentially multiplying each element of the non-modernized P -matrix $\mathbf{A}_{\delta}^{T_{\delta i}}$ by the corresponding elements of the so-called “matrix-sieve” (S -matrix) \mathbf{A}_s , which can take on the values “0” or “1”, for example (Fig. 4).

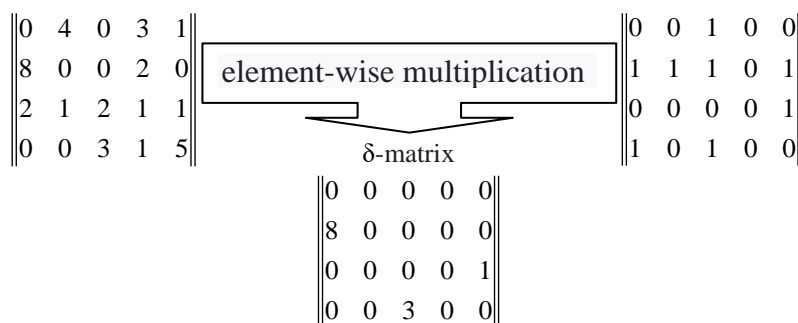


Fig. 4. The example of formation the δ -matrix

The sources of the non-modernized P -matrix and S -matrix after each time iteration of the simulation are the corresponding subsystems of the general system for assessing the states of a non-metallic heterogeneous object.

Conclusions

In this article, the possibility of using the principles of circuit design when modeling internal processes occurring in a heterogeneous medium is shown. In particular, the technology of creating schematics for transfer and conversion processes in heterogeneous environments is considered. Using the example of modeling damage such as cracks and fractures in products made of non-metallic heterogeneous materials, show the possibility of introducing special additional elements simulating a violation of the integrity of the structure – relay elements.

The described approach makes it possible to create an unambiguous model of the object under study. Its main advantage stems from the fact that at present there are special programs, including computer programs that make it possible to build such models based on the purpose of the functioning of the designed object and the possibilities of its creation. The developed models make it possible to relate such parameters as the distribution of temperature fields over the surface of a heterogeneous object during its control by an acoustic thermal imaging method with extensive parameters of the elements of this process, such as information about the presence of structural defects and their geometric characteristics, including the depth of occurrence.

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