Досліджено застосування евристичних методів при проектуванні трансмісій. За допомогою методів активізації творчої діяльності знайдені конструктивні особливості, що не використовуються у редукторах. Метод дослідження структури проблеми, побудований на використанні матричних та графових моделей, дозволив створити оригінальну конструкцію редуктору. Доведено, що запропонована конструкція має мінімальні габарити у порівнянні з існуючими

Ключові слова: евристичні методи, проектування трансмісій, редуктор, графова модель, матрична модель

Исследовано применение эвристических методов при проектировании трансмиссий. С помощью методов активизации творческой деятельности найдены конструктивные особенности, которые не используются в редукторах. Метод исследования структуры проблемы, построенный на использовании матричных и графовых моделей, позволил создать оригинальную конструкцию редуктора. Доказано, что предложенная конструкция имеет минимальные габариты по сравнению с существующими

Ключевые слова: эвристические методы, проектирование трансмиссий, редуктор, графовая модель, матричная модель

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ANALYSIS OF MATRIX AND GRAPH MODELS OF TRANSMISSIONS FOR OPTIMIZATION THEIR DESIGN

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1. Introduction

In the development of gearboxes, computer-aided design software packages are commonly used. These are, for example, Mechanical Desktop, Pro Engineer, Inventor and others. In this case, as a rule, the search in libraries of standard elements, preparation of documentation and calculations are automated. Heuristic methods are not used and are not part of the mentioned software packages. There is a widespread opinion that for such a simple object as a gearbox, the use of such methods is not advisable. One of the consequences of this approach is the maximum possible complication of design schemes, with the aim of using all the possibilities inherent in software packages. At the same time, insufficient attention is paid to the search for a rational design of gearboxes.

The object of this study is two-stage right-angle gearboxes, which are widely used and manufactured in various layouts. Typical gearboxes, produced serially, have a high-speed bevel gear stage and slow-moving cylindrical stage. This is due to the fact that the bevel gear train is more compact. This is important, since the ratio of the high-speed stage is always greater than the slow-moving stage. In special gearboxes used in lifting mechanisms, a cylindrical stage is high-speed, and a bevel gear stage is slow-moving. This is due to the peculiarities of the layout of the lifting mechanisms. In gearboxes, as a rule, the bearing arrangement of the bevel pinion is cantilevered, and the bevel wheel is between the bearings. In aviation and automotive engineering, the pinion and wheel are usually located between the bearing units. There are examples of applications of a power split gearbox. This design is common in ships engineering. Right-angle gearboxes used in the industry have different schemes and many design features that can be varied. The possibilities of searching for a fundamentally new scheme with better technical characteristics are not fully realized.

Usually, the designer is given a number of recommendations for improving the design quality: gear wheels should not be located as a cantilever, to increase the rigidity, improve lubrication conditions, etc. Recommendations on how to achieve, this are general in nature:

– to take the best samples of transmissions that are produced by the industry as an example;

– to take into account the experience of industries, producing more complex products, such as instrument-making;

– to try to reduce the weight and dimensions of the design, etc.

With a high degree of automation of calculations, drawings and interactions of the designers group, the most important issue – the choice of the principle transmission scheme is in no way formalized in the form of certain algorithms, or as part of decision support systems. An important problem is the development of methods for finding rational designs, in which there is a certain algorithm of action. The only basis for such methods can be heuristics.

2. Literature review and problem statement

The search for fundamentally new designs is possible with the help of heuristic methods. To analyze the specific schemes, the most suitable methods are those based on the schemes representation in the form of a matrix or graph. Matrices are also used to present information about design elements in a form suitable for computer processing.

In the method of morphological maps, the problems, solved by the designer, are divided into three classes: problems for solving which you can use a relatively small number of already known elements; problems for the solution of which it is required to use still unknown new elements; problems of large numbers [1]. The original idea of the method is to use matrices to work out all possible combinations of elements. The disadvantage of the method is the cumbersomeness of the resulting matrix, which contains hundreds of solutions, the choice of the optimum is difficult. Therefore, it is desirable that the number of rows and columns does not exceed ten. A particular, but very effective way of constructing the matrix is to use the parameters or units of the projected machine as columns, and the heuristic techniques as rows.

The interaction matrix method is aimed at identifying the interrelations between the structural elements and their systematization. The application of the interaction matrix method requires the following steps:

– to define the concepts of «element» and «interconnection»;

– to create a matrix, in which each element can be matched with any other;

– on the basis of objective data, to determine whether there is a relationship between each pair of elements [2].

A matrix diagram (quality table) is a tool that allows you to determine the presence and importance of interrelations between the elements, functions or characteristics of an object. It is a table that includes the elements between which you need to establish a relationship. The first row and column contains the elements to be examined, the other cells contain symbols or numbers indicating the presence and strength of relationship. It is suggested that the columns should be the main causes of the problem, and the lines – possible means of eliminating these causes [2].

The interaction network method partially repeats the steps inherent in the interaction matrix method. But the analysis is based not on the construction of a matrix, but on the construction of a graph in which – the vertices are elements, and the edges – the interrelation between the elements. Then you need to change the position of the vertices so as to minimize the number of intersections of edges and identify the network structure more clearly [3].

The method of analysing interconnected decision areas (AIDA) is aimed at identifying and evaluating all compatible combinations of individual solutions to the problem. The application of the method of analysis of interconnected decision areas requires the following stages:

– to identify several possible options in each decision area;

– to specify which options are incompatible and which can be combined with each other;

– in the presence of a single quantitative criterion (for example, cost), to find the goal sets that best meet this criterion [4].

The components determination method is aimed at finding the correct physical components of a particular structure, which could easily be varied independently of each other in accordance with the following design changes. The application of this method requires the following stages:

– to classify requirements:

– to determine whether each pair of requirements is independent or not;

– to fix each solution in the interaction matrix;

– to decompose the matrix into groups with a close interrelationship and a weak connection between groups;

– to develop specific components for each set of requirements [5].

The variant of the mechanism description in the form of a graph is proposed in [6] and is based on the design method using signal flow graphs (SFG). In this method, the nodes are variables, and the edges are functional dependencies. The SFG method is based on four principles:

– the direction of flows between nodes is marked by arrows;

– the input signal is multiplied by the weighting coefficient of the given edge to obtain the output signal;

– the signal value in the node is the sum of all incoming signals;

– the signal value in the node is transmitted by all the edges emanating from the node.

The fundamental design method (FDM) can solve the problem of design and evaluation of structures found with logical certainty. The method includes the following steps:

– to identify variables that are independent of the designer's will;

– to identify the relationship between the variables;

– to assign numerical values to each of the factors;

– to choose the values at which the largest sum of numerical values is achieved for all purposes, taking into account their weight (the optimal version of the project) [7].

Matrices and graphs are complementary ways of expressing the same system of interrelations. These two methods can be used simultaneously. The analysis of the methods showed that most of them, as the first stage, assume the separation of the system into elements. The elements are nodes (engine, variator, gearbox, transmission, operating mechanisms) or machine elements. The second stage is the establishment of interrelations between the elements using the constructed matrix or graph. The «matrix diagram», «interaction matrix» and «interaction network» methods include the majority of the steps of all the methods considered. They can be recommended for use, as a priority. Separately, it is necessary to highlight the FDM method that can be used to analyze the solutions obtained.

3. The aim and objectives of the study

The aim of the work is to develop heuristic methods to find new designs of transmissions.

To achieve this aim, the following objectives should be accomplished:

– to divide the known heuristic methods into three groups, the methods that are appropriate to use at the phase of development of the design requirements, then the phase of preliminary design and finally the phase of development of the detailed design;

– to develop methods for each of the design phases, including all heuristic techniques of the known methods belonging to a particular group, which should be used in the design of transmissions;

– to apply the developed methods for a specific object of a two-stage right-angle gearbox in order to develop a new design with better technical characteristics, namely, smaller weight and dimensions.

4. Materials and methods for studying the matrix and graph models of transmissions

4. 1. Investigation methods of the process of searching for a new transmissions design

Methods of research are heuristic methods, which are divided into three groups: creativity enhancement; based on the use of matrix and graph models; evaluation of the design quality. These methods are consistently used at design phases: design requirements, preliminary design and detailed design. The design features of the two-stage right-angle gearboxes are analyzed using design methods: power split, rigidity enhancement of machine elements, rational layout and the like.

4. 2. Search for design features of right-angle gearboxes and application of the creativity enhancement methods at the design requirements phase

At the initial design stage, it is necessary to generate possible solutions. To do this, a heuristic technique of «collective discussion» is used. We proposed to discuss the identification of two classes of features, most characteristic of this type of transmission [8]. Then the heuristic technique of «collective discussion» includes the following operations:

– formulation of goals and limitations;

– formation of the composition of participants by number and specialization, definition of the facilitator and distribution of roles among other participants;

– ideas generation on the selection of two classes of features.

The heuristic technique, which generates possible solutions should be followed by heuristic techniques that cut off solution options [9]. Such techniques are «time differences between the suggestion and criticism of ideas» and «expert evaluations». Using the technique of «time differences between the suggestion and criticism of ideas» makes it possible to reduce the number of solutions from tens to several. The technique of «expert evaluations» provides the possibility to focus on one option and finally formulate two classes of features that characterize this type of machine. The heuristic techniques, which cut off solution options should be followed by heuristic techniques that extend the boundaries of search, these are the «free associations» and «analogy» techniques [8]. The proposed goal of using these techniques is to make a substantive content of two classes of features. The technique of «analogy» of the features of the designed transmission with existing transmissions for performing similar functions is efficient. At the same time, among the features considered, there may be previously non-existent and even fantastic properties or units. It is advisable to create a list of the first class of features by taking the «analogy» technique, as and the second class – by taking the «free association» technique. The final selection of the set of varying features is performed with the repeated use of the «expert evaluations» technique.

To search for new design solutions, the key «matrix» technique is required. The matrix whose columns can, for example, be the features of a transmission, and rows – the units of a transmission is constructed. To analyse the possible combinations of features and units, the heuristic technique of «collective discussion» is used. The recommended number of matrix elements should not exceed thirty. With a larger dimension of the matrix, in order to reduce the number of options that are considered in the future, the technique of «time differences between the suggestion and criticism of ideas» can be applied. All selected combinations are divided into four types:

– existing technical solutions for this type of transmission;

– those that cannot be implemented, taking into account technological limitations;

– existing technical solutions, but not implemented for this type of transmission;

– technical solutions, that can be solved in principle, but the implementation of which requires solving the problems that are more complex than the design problems directly, are solved by this group.

For further consideration, combinations of the third group are selected, combinations of the fourth group are addressed again, if the processing of options based on a combination of the third group did not produce results.

Thus, a number of known heuristic techniques that belong to different heuristic methods are used to search for new design solutions. There is a sense, instead of a number of heuristic methods: brainstorming, free associations, analogy, expert evaluation, morphological analysis, to use heuristic techniques that constitute these methods, in the generalised method. Taking into account the specifics of the tasks to be solved in the design of transmissions, the creativity enhancement method is proposed, which includes the following heuristic techniques and procedures:

– the procedure for formulating goals and limitations;

– the procedure for selecting two classes of transmission element features;

– the heuristic free association technique – the generation of ideas to make a substantive content of the first class of features;

– the heuristic analogy technique – the generation of ideas to make a substantive content of the second class of features;

– the heuristic matrix technique;

– the procedure for analyzing all possible combinations of features and units, as well as dividing combinations into four classes;

– the procedure for additional analysis and design study of the third class of combinations.

Procedure – formulation of goals and limitations. The schemes of the designed gearbox, should allow the reduction of dimensions compared to the known gearbox schemes. Limitations: gear trains on fixed axes; input and output axes of the shaft do not coincide; two stages; one stages is bevel, another stage is cylindrical. Procedure – selecting two classes of transmission element features. Given the imposed limitations, the designed gearbox can be characterized by the following classes of features: type of transmission; type of bearing arrangement; type of bearings; relative position of the shafts; type of the stage according to its location in the gearbox; type of the stage on the basis of power split. On the basis of the analysis, we selected the classes of features that have the greatest effect on the scheme and dimensions of the gearbox: type of train; type of bearing arrangement; type of the stage according to its location in the gearbox; type of the stage according to power split.

The morphological analysis method, also known as the morphological box, provides for constructing a multidimensional matrix based on the described features. In accordance with the proposed method, we need to select only two classes of features of the object in order to obtain a two-dimensional matrix, with the number of elements that can be subjected to a detailed analysis. Finally, two classes – the gear train type and design features are selected. The class of design features includes the following features: type of bearing arrangement; type of the stage according to its location in the gearbox; type of the stage according to power split.

Heuristic free association technique – the generation of ideas to make a substantive content of the first class of features. In this case, given the imposed limitations, there are only two types of gear train – cylindrical and bevel.

Heuristic analogy technique – the generation of ideas to make a substantive content of the second class of features. Design features known from the literature: non-cantilever gear; cantilever gear; high-speed stage; slow-moving stage; single or power split.

Heuristic matrix technique. We construct a morphological map (Table 1).

Procedure – analysis of all possible combinations a of features and a units, as well as dividing combinations into three classes: known, which cannot be realized and existing technical solutions, but not implemented for this type of transmission. Design features of cylindrical and bevel gears used in gearboxes, are identical in all points except one. The combination of bevel gear – power split refers to the third class, namely «existing technical solutions, but not implemented for this type of transmission».

Table 1

A morphological map for two classes of features

Train type / Design Features	Cylindrical gear train	Bevel gear train
Between the bearings	+	+
Cantilever	+	+
High-speed	+	+
Slow-moving	+	+
Without power split	+	+
Power split	+	Idea!

Procedure – «additional analysis and design study of the third class of combinations». Based on the heuristic analogy technique, we can assume that the bevel gear with the power split should exist. A comparative analysis of all combinations showed that if the power split at the bevel stage could be realized, then it would be possible to reduce the dimensions of the gearbox.

4. 3. Search for a design of right-angle gearbox with a power split bevel stage at the phase of preliminary design

The next task of the study is to create a design of right-angle gearbox with a power split bevel stage. For this, we use research methods based on the application of matrix and graph models. Heuristic technique «to define the inputs and outputs of the system» in this case is not used as input and output elements are usually set in advance. In this example, the input element is a high-speed shaft and the output element is a slow-moving shaft. Heuristic technique «to identify interrelated and independent groups of elements» was not effective because of a small number of elements. In this example, depending on the selection criteria for elements, the number of the elements does not exceed two or three dozen.

Given this, we use the method of studying the structure of the problem, consisting of only three heuristic techniques that are used in such a sequence [10]:

– to select elements;
– to identify interrelations between the elements;
– to apply matrix and graph models.

Heuristic technique – to select elements. As the system elements, we have selected the original elements of the gearbox, with the exception of housing and lid, which are present in all types of gearboxes. The elements are: input shaft 1, output shaft 7, bevel pinion 2.1 and 2.2, bevel wheel 3.1 and 3.2, cylindrical pinion 4.1 and 4.2, intermediate shafts 5.1 and 5.2, cylindrical wheel 6.1 and 6.2.

Heuristic technique – to identify interrelations between the elements. Usually, interrelated elements in the gearbox are coupled gear wheels, and also the shafts and the gears set on them. We have identified the following types of interaction between the elements: interaction required for the gearbox functioning, possible interactions, impossible interaction.

Heuristic technique – to use a matrix model. The interrelation between the elements can be identified using a matrix or graph. For clarity of the developed method, we use both heuristic techniques. We construct a matrix commonly called an interaction matrix (Table 2). Rows and columns correspond to the chosen elements. The possible types of interaction are given the following notation: required – 1, possible – 2, impossible – 0.

Table 2

The interaction matrix of the gearbox elements

	1	2.1	2.2	3.1	3.2	4.1	4.2	5.1	5.2	6.1	6.2	7
1	–	1	1	0	0	0	0	0	0	0	0	0
2.1	–	–	2	1	0	1	0	0	0	0	0	0
2.2	–	–	–	0	1	0	1	0	0	0	0	0
3.1	–	–	–	–	2	2	2	2	2	0	0	0
3.2	–	–	–	–	–	2	2	2	2	0	0	0
4.1	–	–	–	–	–	–	2	1	0	1	0	0
4.2	–	–	–	–	–	–	–	0	1	0	1	0
5.1	–	–	–	–	–	–	–	–	0	0	0	0
5.2	–	–	–	–	–	–	–	–	–	0	0	0
6.1	–	–	–	–	–	–	–	–	–	–	0	1
6.2	–	–	–	–	–	–	–	–	–	–	–	1
7	–	–	–	–	–	–	–	–	–	–	–	–

Heuristic technique – to use a graph model. Fig. 1 shows a graph called an interaction network. The necessary interrelation between the elements is shown by lines, possible interrelation – by dashed lines.

In the phase of preliminary design, it is revealed that the impediment to power split is that when meshed with one bevel pinion, two bevel wheels must rotate in different directions. One more element – bevel wheel 2.2 was added. The scheme with one bevel pinion in mesh with two bevel wheels cannot be realized because the wheel in mesh with one pinion must rotate in one direction, and with another – in the opposite direction. To resolve this conflict, it is necessary that each pinion meshed with one wheel. Thus, the main problem of creating a design is to solve the issue of the lack of interconnections between elements 2.1 and 3.2, as well as elements 2.2 and 3.1. This is possible if an angle between the axes of the bevel gears is not equal to 90° (Fig. 2).

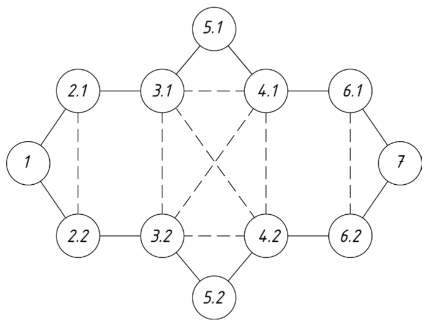


Fig. 1. The graph model «Interaction network»

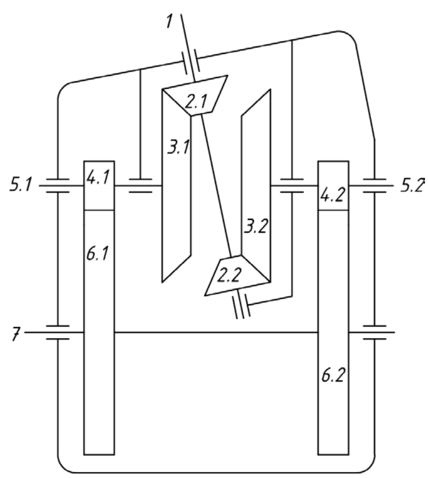


Fig. 2. A scheme of a right-angle gearbox with a power split bevel stage

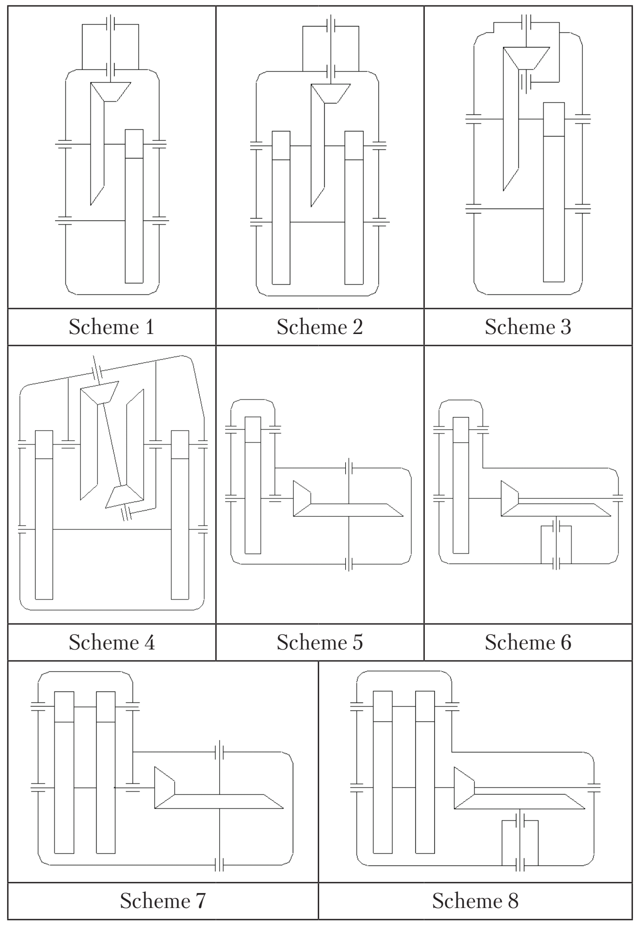
Two gear wreaths of pinion 2.1 and 2.2 are one piece, like two gear wreaths of a herringbone gear wheel. Bevel wheels 3.1 and 3.2 rotate in one direction. Thus, the power split in a bevel stage is realized. Bevel wheels 3.1 and 3.2 are different elements, so the power split must also be in the slow-moving cylindrical stage (Fig. 2).

5. The result of the research and the developed method of comparing the gearbox design at the phase of detailed design

In order to determine how much the variant found corresponds to the set conditions, we will develop a new method based on the FDM. Let us compare the found design of the gearbox with the known ones. For the analysis, all possible schemes of bevel-cylindrical (schemes 1–4) and cylinder-bevel gearboxes (schemes 5–8) without power split (schemes 2, 3, 5, 6) and with power split (schemes 7, 8), cantilever (schemes 1, 2, 5, 7) and non-cantilever (schemes 3, 6, 8) (Table 3) are selected [2].

Table 3

Gearbox schemes



It is possible to evaluate the conformity of the found variants with the given conditions using a heuristic technique «to prepare a list of tasks, control questions that the design solutions must meet». When using this heuristic technique, there are no numerical evaluations. For each item from the checklist, the answer should be «yes» or «no». A numerical evaluation of the design quality is given. For this, the heuristic technique «to distribute tasks according to the degree of advantage, assign a weighting factor to each task» or the heuristic technique «to assign a numerical value (rank, weight and cost) to each combinations of elements» are used. It is better to use the latter heuristic technique because it is more formalized.

To evaluate design solutions, a number of heuristic techniques that belong to heuristic methods are used: rank-ordered search, Kvirk's index, ranking and weighing, checklists, function cost analysis, FDM. The technique «to define the function and quality of each element» is a component of all the methods mentioned, except for the method of checklists. The heuristic method «to assign a numerical value to each combination of elements» is included in function cost analysis, FDM and other methods and differs only in the form of evaluation.

It is advisable to combine all the heuristic techniques that are components of this group of methods, in one method for evaluating the variants of a design solution, including heuristic techniques in the following sequence:

– to define the function and quality of each element;

– to identify the elements that the designer can vary and unchanging elements;

– to assign a numerical value (rank, weight and cost) to each combination of elements;

– to evaluate the degree to which the design solution is consistent with the task.

Heuristic technique – «to define the function and quality of each element». A bevel gear allows placing the input and output shafts at a certain angle, the presence of bevel and cylindrical gear allows angular velocity reduction corresponding to the two-stage gearbox. The power split bevel or cylindrical stage allows reducing the dimensions of the bevel and cylindrical gears. The layout of the bevel gear requires that one of the shafts was cantilever. The gearbox layout depends on which of the pinion or wheel shafts is cantilever.

Heuristic technique – «to identify variable elements that the designer can vary and invariable elements». Invariable elements are: housing, input and output shafts. The variable elements included in the scheme are the following: bevel stage (*a*), cylindrical stage (*b*), I stage (*c*), II stage (*d*), power split (*e*), bearing arrangement design (*f*).

Heuristic technique – «to assign a numerical value to each combination of elements». Assume the following evaluation of the combinations of these elements:

– bevel stage high-speed – 4, slow-moving – 2 (it is known that bevel-cylindrical gearboxes are more compact than cylindrical-bevel ones);

– cylindrical stage high-speed – 2, slow-moving – 4 (the slow-moving stage is more loaded, it limits the dimensions of the gearbox);

– bevel stage without power split – 2, with power split – 5 (the highest score is assigned taking into account the low load capacity of the bevel gear as compared to the cylindrical gear);

– cylindrical stage without power split – 2, with power split – 4;

– power split stage slow-moving – 4, high-speed – 2 (the slow-moving stage is more loaded, it limits the dimensions of the gearbox);

– bearing arrangement design of gears: the wheel is cantilever – 1, the pinion is cantilever – 2, all gears aren't cantilever – 3;

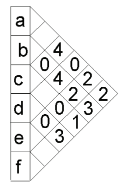
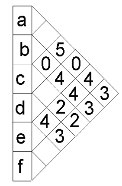
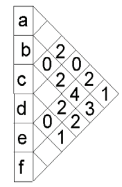
– bearing arrangement design of the stages: the slow-moving stage is cantilever – 1, non-cantilever – 3, the high-speed stage is cantilever – 1, non-cantilever – 2.

6. Discussion of research results and comparison of the found design with the known gearboxes design

Heuristic technique – «to evaluate the degree to which the design solution is consistent with the task». There are various options for implementing the assessment of the design solution. In this example, we use the FDM method, in which the evaluation is carried out using matrices. In triangular matrices, there are numerical values corresponding to combinations of the elements. For unconnected elements, «0» is set. If it is impossible to combine the elements, table cells are not filled. The design quality is determined by the sum of all ratings (Table 4).

Table 4

Evaluation of variants of the gearbox schemes

<table>
<tr><th>Scheme 2</th><th>Scheme 4</th><th>Scheme 8</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td colspan="3">The sum of estimates</td></tr>
<tr><td>$S=21$</td><td>$S=34$</td><td>$S=19$</td></tr>
</table>

Calculations are given – the sum of the estimates for the most common gearbox design (scheme 2) is $\Sigma=21$, the weakest design (scheme 8) $\Sigma=19$ and the proposed, based on the analysis results, design with power split in the high-speed and slow-moving stage (scheme 4) $\Sigma=34$ (Table 4).

It should be noted that the design of the gearbox that we found has minimal dimensions in comparison with all other variants of the design. And the gain in compactness is considerable. Also, the advantage of the found design is a smaller weight.

The disadvantage of the gearbox is structural complexity, as well as design, manufacturing and installation complexity. Because of this, the cost of the proposed design is somewhat greater than that of typical gearboxes. Therefore, such a gearbox should be used primarily for military equipment, as well as for vehicles, including helicopters, cars, boats.

The developed heuristic methods are based on matrix and graph models. This allows them to be used for the analysis of complex technical objects. Also, matrix and graph models allow certain formalization of such an unpredictable process, as heuristic search. Instead of many heuristic methods and their variants, three methods corresponding to a certain design phase are proposed. Evidence of the effectiveness of heuristic methods is the development of a new gearbox design with better technical characteristics.

This study is a continuation of previous comparisons, analysis of the structure and classification of existing heuristic methods. Further work should be carried out in the direction of further formalization of heuristic search, development of a series of cognitive maps for each design phase. This should create the basis for developing an automated decision support system for the transmissions design. Also, the disadvantages associated with the lack of certainty, regarding the application of the proposed methods in the work of one designer or a group of designers whose members interact in a certain way need to be eliminated.

7. Conclusions

1. Heuristic methods are divided into three groups according to three phases of design. It is offered to apply the generalized heuristic method that includes all heuristic techniques of the known methods belonging to a particular group, which should be used in the design of transmissions for each phase.

2. The method of creativity enhancement is expedient to use at the phase of development of the design requirements. It contains heuristic techniques: free association, analogy, matrix.

3. The method of studying the structure of the problem is advisable to use at the phase of preliminary design. It contains heuristic techniques: to select elements, to identify interrelations between the elements, to apply matrix and graph models.

4. The method of evaluating the variants for a design solution is expedient to use at the phase of detailed design. It contains heuristic techniques:

– to define the function and quality of each element;

– to identify the elements that the designer can vary and invariable elements;

– to assign a numerical value to each combination of elements;

– to evaluate the degree to which the project solution is consistent with the task.

5. The original design of a two-stage right-angle gearbox has been developed, which has minimal dimensions and weight compared to known gearbox designs. It is found that the power split in a bevel stage is possible at an angle between the axes of the bevel gear not equal to 90°.

References

1. Ritchey, T. Outline for a Morphology of Modelling Methods: Contribution to a General Theory of Modelling [Text] / T. Ritchey // Acta Morphologica Generalis. – 2012. – Vol. 1, Issue 1. – Available at: http://www.amg.swemorph.com/pdf/amg-1-1-2012.pdf
2. Howard, T. J. Describing the creative design process by the integration of engineering design and cognitive psychology literature [Text] / T. J. Howard, S. J. Culley, E. Dekoninck // Design Studies. – 2008. – Vol. 29, Issue 2. – P. 160–180. doi: 10.1016/j.destud.2008.01.001
3. Yan, S. A planning model and solution algorithm for multi-trip split-delivery vehicle routing and scheduling problems with time windows [Text] / S. Yan, J. C. Chu, F.-Y. Hsiao, H.-J. Huang // Computers & Industrial Engineering. – 2015. – Vol. 87. – P. 383–393. doi: 10.1016/j.cie.2015.05.034
4. Hickling, A. AIDA and the Levels of Choice in Structure Plans [Text] / A. Hickling // Town Planning Review. – 1978. – Vol. 49, Issue 4. – P. 459. doi: 10.3828/tpr.49.4.v4314t7172h3vu23
5. Goel, V. The structure of Design Problem Spaces [Text] / V. Goel, P. Pirolli // Cognitive Science. – 1992. – Vol. 16, Issue 3. – P. 395–429. doi: 10.1207/s15516709cog1603_3
6. Pennestri, E. On Crossley's contribution to the development of graph based algorithms for the analysis of mechanisms and gear trains [Text] / E. Pennestri, N. P. Belfiore // Mechanism and Machine Theory. – 2015. – Vol. 89. – P. 92–106. doi: 10.1016/j.mechmachtheory.2014.09.001
7. Halder, S. Design Process and Its Application on the Improvement (Re-Design) of the Coke Bottle [Text] / S. Halder, V. Pratap Singh, D. Ganguly // International Journal of Advanced Packaging Technology. – 2016. – Vol. 4, Issue 1. – P. 185–199. doi: 10.23953/cloud.ijapt.23
8. Liu, A. Alternation of analysis and synthesis for concept generation [Text] / A. Liu, S. C.-Y. Lu // CIRP Annals – Manufacturing Technology. – 2014. – Vol. 63, Issue 1. – P. 177–180. doi: 10.1016/j.cirp.2014.03.094
9. Ivanov, V. V. Ehvristicheskie metody pri proektirovanii mashin [Text] / V. V. Ivanov, A. M. Harsun // Problemy tekhniky: naukovo-vyrobnychyi zhurnal Odeskoho natsionalnoho morskoho un-tu. – 2010. – Issue 1. – P. 78–86.
10. Ivanov, V. V. Obobshchennye ehvristicheskie metody proektirovaniya transmissiy [Text] / V. V. Ivanov // Visnyk Khmelnytskoho natsionalnoho universytetu. – 2014. – Issue 5. – P. 24–28.