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SOLUTION OF THE STRUCTURAL OPTIMIZATION PROBLEM OF A MULTIAGENT APPROACH BASED CUTTER DESIGN

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This article proposes a decision support system project to find the optimal milling cutter design. At the preliminary design stage, morphological analysis is used. It allows us to find and systematize all possible milling cutter structures with the necessary functional purpose. To automate the design formation process, an algorithm based on a resolution method is applied, with the algorithm using the logic of first-order predicates. An enumeration of possible states and assembly of a milling cutter structure from ready-made elements are carried out. It is expedient to describe this algorithm in terms of logical operations. It consists in a deductive derivation of the sentence of the form: "There are dimensional parameters $x_1,...,x_n$ *and forces such that a constructive solution satisfying the given properties* $P\ (x_1...,x_n)$ *is deduced from a set of possible connections* $\forall x_1... \ \forall x_n\ (K_1(x_1,...,x_n) \wedge .. \wedge K_n(x_1,...,x_n) \Rightarrow B(x_1,...,x_n))$, *which denote dimensional, force and other real connections that arise between the parts of real structures." The condition for the transition from the specific parts to the logic of first-order predicates is the capability of a certain part (for example, plate P) to function in real conditions if and only if there is a set of fixing forces f1, f2, ..., fn that are applied at points* $x_1,x_2,...,x_n$. *The basic effectiveness parameters of milling cutter design are: reliability, productivity, and energy efficiency that are set as objective functions. They also take into account the static and dynamic design characteristics. The variable parameters are the geometric shape and dimensional parameters of a milling cutter. For each variant of the geometric form, a 3D model of the milling cutter is constructed and its static and dynamic characteristics are calculated. These parameters are then included in the objective functions. Optimization is carried out on the basis of the gradient descent method. The optimal design is chosen with the interaction of intelligent agents. In this case, the milling cutter design provides the best ratio of the objective functions. The architecture of the system is based on the integration of CAD/CAE systems with a multi-agent system (MAS). The search for a solution is carried out automatically as a result of the interaction of independent task-oriented software agents. To build MAS, we use the Java Jade library in the NetBean development environment. The considered approach allows us to reduce the time expenditures in designing or choosing the design of a metal cutting tool.*

Keywords*: structural optimization, multi-agent system, milling cutter, business process, object-oriented approach, performance, reliability, energy efficiency.*

Introduction

In a competitive environment, the desired economic efficiency of production can only be achieved through the introduction of comprehensive design automation, with the inclusion of the means of production, which comprise metal cutting tools [1].

Industry often faces the task of not only creating a design model, but also choosing its optimal variant from several possible alternatives, with certain constraints, properties and technical characteristics taken into account.

Analysis of Literary Sources

Traditional software systems can operate mostly on the basis of their strict sequences. There are several approaches to creating software complexes built on integrating CAD/CAE systems with MAS. The main advantage of MAS is flexibility. MASs can navigate in a difficult environment, deal with unclear tasks, adapt to changing conditions. In MAS, each entity is in conformity with a program agent that meets its interests [2, 3].

The multi-agent approach is based on the concept of a mobile software agent, which is implemented and functions as an independent specialized computer program or element of artificial intelligence. In contrast to the

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classical method, in which a certain well-defined algorithm is searched for, in multiagent technologies, the solution is automatically obtained as a result of the interaction of several independent task-oriented software agents [4].

The more complex the product, the more significant the errors due to the uncoordinated decisions made by different specialists. As noted in [5], MASs work well to prevent similar situations.

In optimal solution search problems, the number of iterations depends on the chosen optimization method and search space dimensionality. The most effective approaches that make it possible to reduce the computational time are genetic algorithms and the distributed calculations based on intelligent agents [6, 7].

In order to solve complex poorly formalized tasks, intelligent programs are used. This leads to a significant increase in the resource intensity and complexity of the programs. One of the most successful approaches is the development of distributed intelligence systems based on MAS [8].

One of the largest corporate taxi companies in the world, Addison Lee (London), uses a system that allows distributing and scheduling about 13,000 orders per day, with several thousands of its own vehicles (from which up to 800 are operating ones) equipped with GPS-navigation equipment.

Intelligent agents are also used in work management systems.

To provide comprehensive vehicle safety on the road, an information-diagnostic "Automated Roadside Assistance" (ARA) subsystem is used. This subsystem provides the online service for the drivers that use modern sensors and controllers, as well as overall control system based on the multi-agent approach.

Many MASs have computer-based implementations based on step-by-step simulation: BTexact Technologies (UK) uses the ZEUS agent platform; Comtec (Japan), Comtec Agent Platform; Comtec Agent Platform, JADE; Fujitsu Labs (USA), AAP; Nortel Networks (UK), FIPA-OS.

At the stage of preliminary design, it is advisable to apply a morphological method, which distinguishes analysis and synthesis [9]. It is one of the widely used combinatorial methods for evaluating the existing and finding new solutions [10; 11]. It allows finding and systematizing all possible structures of an object with the necessary functional purpose. A generalized class structure is presented in the form of morphological tables, often referred to as a morphological box. They can be both binary and multidimensional [9; 12].

Such a morphological table a simple object with well-crafted rules of infilling and finding solutions. The morphological method is well suited for formalization, which allows it to be used during automated design processes [13].

Morphological analysis and synthesis are actively used by Yu. M. Kuznetsov for designing machine clamping mechanisms [14]. An object is divided by either functional or technological features, and a combinatorial file is created, with all possible constructive and technological object implementations and constraints taken into account.

The morphological method was used by S. G. Nagorniak [15] for designing face-milling cutters with elastic damping elements and V. A. Nastasenko [16] for designing chip grooves of modular worm milling cutters.

The task of choosing an optimal determinate structure is to find a structure that best performs (in the sense of the chosen criterion) a given set of functions Z for given conditions of operation [17] $Z = \max\limits_{S \in S(F)} L(S) = \max\limits_{S \in S(F)} \sum\limits_i \left(\sum\limits_j l_{ij} - C_i \right)$, where $S(F')$ is the set of all the structures corresponding to the set F'; l_{ij} is the effectiveness of object i executing operation j; C_i is costs.

Further, the problem of structural optimization, which consists in determining the form of the functional F, is solved by one of the known methods.

Purpose and Tasks of the Research

The purpose of the research is to develop a decision-making support application for determining the optimal milling cutter design based on a combination of the calculation of its structural characteristics with a further optimization of its productivity, reliability, and energy efficiency.

Methods and Materials of the Research

This work investigates a specific technical product, an interlocking face-milling cutter.

To represent the business process to be designed, it is expedient to use SADT diagrams. For an adequate system description, a few ones are required. Diagrams, collected and linked together, become an SADT model. The top-level diagram describes the system in the general terms of a "black box" (SADT diagram of Level 0), and the lower-level diagrams are highly detailed aspects and operations of the system (detailed SADT diagrams of Level 1, 2, etc.).

During the analysis of the subject area problems, the basic business process (A_0) "Structural optimization of a milling cutter design" was selected, and on its basis, an SADT diagram of Level 0 was constructed (see the table below).

Description of the context structural and functional model for the structural optimization of a milling cutter design

Input data	Management	Executor	Output data
– list of properties; – list of criteria; – list of designs; – 3D model; – objective functions	– normative documents; – instructions; – mathematical model limitations; – cutter physical and technical limitations	– program-methodical complex (PMC); – researcher; – intelligent agents	– optimal design option

To construct detailed SADT diagrams of activity, let us decompose the business process and distinguish the following steps:

– A_1 – morphological analysis and synthesis, on which morphological tables are constructed, existing designs of milling cutters are classified, and new design structures are formed;

– A_2 – choice of the milling cutter design;

– A_3 – optimization of the milling cutter design according to working parameters.

– A_4 – check of static and dynamic characteristics.

A detailed SADT diagram of Level 1 is shown in Fig. 1.

Several criteria are usually used in production to evaluate the expediency of operating a certain tool design. The most commonly used are:

– productivity;
– reliability;
– energy efficiency;
– costs.

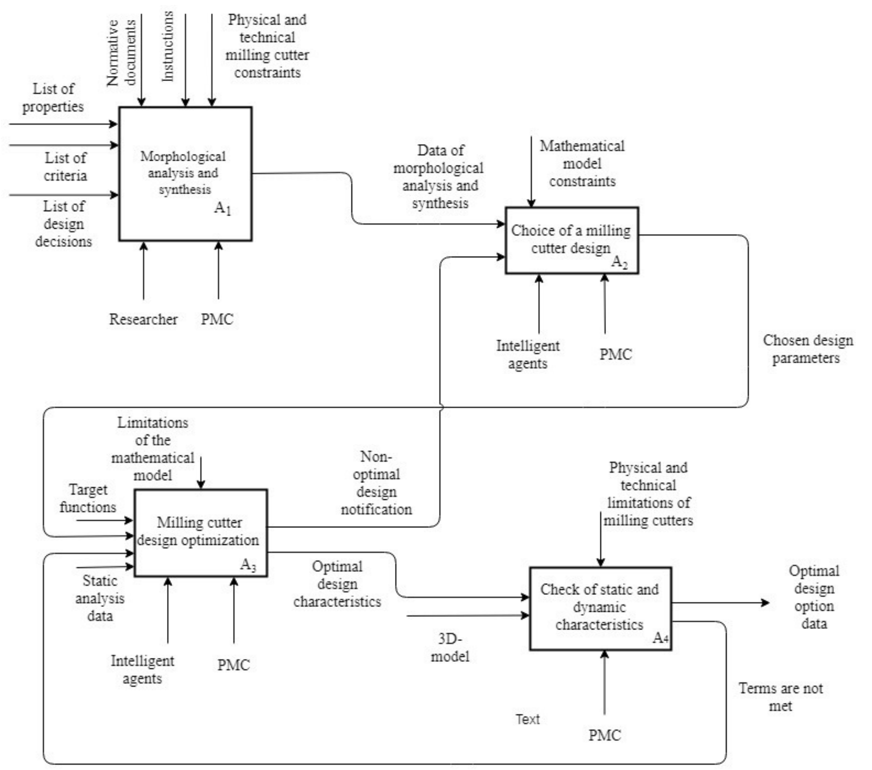


Fig. 1. Detailed structural-functional Level 1 model for the structural optimization of a milling cutter design

Finding the design of a cutting tool, which will provide the best value for the desired criterion, is a priority task.

Variable indicators can be the geometric shape and size of a milling cutter and cutting plates. For each variant of the milling cutter geometry, a 3D model is constructed and the calculation of the plate mount assembly static characteristics are calculated. The parametric optimization of the cutter design elements is performed using the work of a system of several intelligent agents. The agents are responsible for calculating the optimal values of the objective functions: productivity, reliability, energy efficiency, and costs. This allows us to choose the shape and size of cutting plates.

Usually, the optimization of productivity, reliability, and energy efficiency is carried out to the maximum, and that of costs, to the minimum. In all the cases, the cutting depth will be variable. There is a dependence of the main size of a cutting plate (length) on the depth of cutting. Subsequently, the estimated value of the plate length is given to the nearest large value from the standard row.

The productivity of a milling cutter is characterized by the material removal rate according to the formula

$$Q = t \cdot ae \cdot \frac{V_f}{1000},\ \text{cm}^3/\text{min} \tag{1}$$

where t is the cutting depth, mm; ae is the milling width, mm; V_f is the table feed, mm/min.

The reliability of a milling cutter is characterized by the period of stability

$$T = \left(K_v \frac{C_v \cdot D^{qv}}{V \cdot t^{xv} \cdot fz^{yv} \cdot ae^{uv} \cdot z^{pv}} \right)^{\frac{1}{mv}},\ \text{min} \tag{2}$$

where C_v is the dimensional factor of processing conditions; D is the milling cutter diameter, mm; K_v is the correction factor; V is the speed of cutting, m/min; fz is the feed per tooth, mm/tooth; z is the number of teeth, pieces; qv, xv, yv, uv, pv, mv are the dimensional factors of model parameters.

The estimation of the milling cutter operation energy effectiveness is expressed by the power that can be determined by the formula

$$P_C = \frac{t \cdot ae \cdot V_f \cdot kc}{60 \cdot 1000000 \cdot \eta},\ \text{kW} \tag{3}$$

where η is the efficiency coefficient, %; kc is the actual specific cutting force, N/mm^2.

The cost of processing a 1 m^2 surface area can be approximated as the sum of the following parts:

$$A = A_1 + A_2 + A_3,\ \text{US \$}$$

where A_1 is the machine operating costs; A_2 is the solid alloy costs; A_3 is the tool costs.

Results of the Work

Functions of the developed program for the structural optimization of a milling cutter design are shown in Fig. 2.

The main window of the program complex for the structural optimization of a milling cutter design is shown in Fig. 3. In order to build MAS, we use the Java Jade library in the NetBean development environment.

The "Construction of 3D models and CAE-calculation" button on the form of the software complex (Fig. 3) provides the ability to execute the macro by means of the external CAD-system and thus execute the formation of 3D cutter blade models. The results of CAE analysis are visualized using a CAD system.

The study was conducted for a conditional surface of a 1 m^2 gray cast iron component. The output values are the characteristics of the material being treated and cutting modes during the machining process.

The results of the calculation and optimization according to the above criteria are the chosen shape of the cutting plate and its size, as well as the numerical values of the criteria.

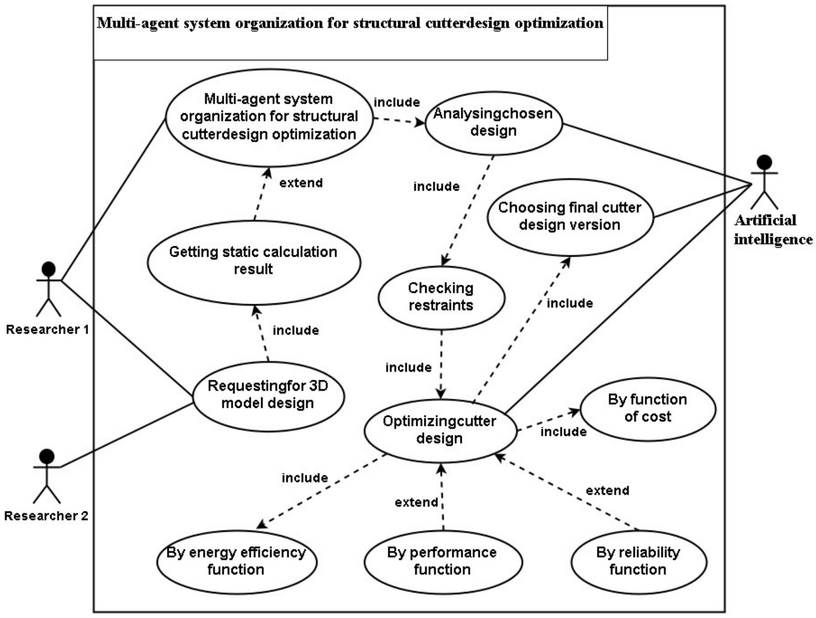


Fig. 2. Precedence diagram of the software complex

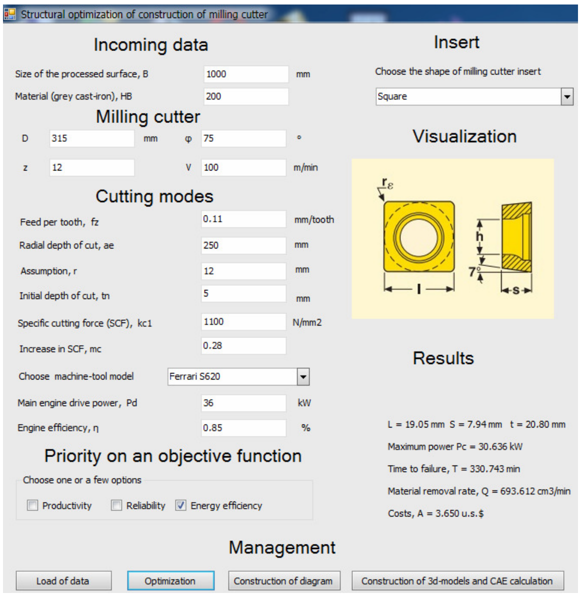
A circular plate with a diameter of 16 mm does not meet the conditions of equivalent stresses. The boundary of the cutting plate material creep is 1270 MPa, and the maximum stresses for a cutter blade with a plate of 16 mm in diameter reach 2.683 MPa. For the value of the size of the square plate with the 19 mm long cutting edge, stresses reach only 1.149 MPa, making it possible to use precisely such a standard plate size.

With the use of the morphological method, a cut distribution milling cutter was designed, which allows us to increase machining performance. The cut distribution is accomplished by using two angles in the plane (60° and 75°) and a different blade overhang. The implementation of the design is shown in Fig. 4 [18].

Conclusions

The offered approach allows us to solve more difficult tool design tasks and minimize mistakes in choosing the specific cutting mill, which will increase the quality of the milling process.

The offered algorithm was used as a basis for the design and program implementation of the information system prototype. This satisfies the need for specialized software when technical objects are designed.


Structural optimization of construction of milling cutter

Incoming data

Size of the processed surface, B 1000 mm

Material (grey cast-iron), HB 200

Milling cutter

D 315 mm φ 75 °

z 12 V 100 m/min

Cutting modes

Feed per tooth, fz 0.11 mm/tooth

Radial depth of cut, ae 250 mm

Assumption, r 12 mm

Initial depth of cut, tn 5 mm

Specific cutting force (SCF), kc1 1100 N/mm2

Increase in SCF, mc 0.28

Choose machine-tool model Ferrari S620

Main engine drive power, Pd 36 kW

Engine efficiency, η 0.85 %

Priority on an objective function

Choose one or a few options

☐ Productivity ☐ Reliability ☑ Energy efficiency

Insert

Choose the shape of milling cutter insert Square

Visualization

Results

L = 19.05 mm S = 7.94 mm t = 20.80 mm

Maximum power Pc = 30.636 kW

Time to failure, T = 330.743 min

Material removal rate, Q = 693.612 cm3/min

Costs, A = 3.650 u.s.$

Management

Fig. 3. Interface of the program for the structural optimization of a milling cutter design

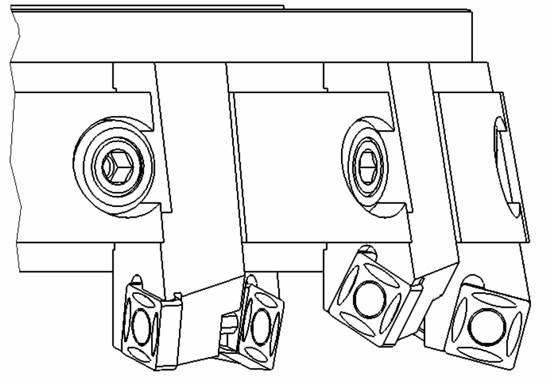


Fig. 4. Face milling cutter with cut distribution in width and thickness

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Розв’язання задачі структурної оптимізації конструкції фрези на основі мультиагентного підходу

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Наведений проект системи підтримки прийняття рішень для пошуку оптимальної конструкції фрези. На стадії попереднього проектування використовується морфологічний аналіз. Він дозволяє знайти і систематизувати усі можливі структури фрези з необхідним функціональним призначенням. Для автоматизації процесу формування конструкції застосовується алгоритм, що ґрунтується на методі резолюцій, який використовує логіку предикатів першого порядку. Робиться перебір можливих станів і складання конструкції фрези з готових елементів. Цей алгоритм доцільно описувати в термінах логічних операцій. Він полягає в дедуктивному виведенні пропозиції вигляду: «Існують розмірні параметри $x_1, ..., x_n$ *і сили, такі, що конструктивне рішення, яке задовольняє задані властивості* $П(x_1, ..., x_n)$ *виводитися з набору можливих зв'язків* $\forall x_1 ... \forall x_n (K_1(x_1, ..., x_n) \wedge ... \wedge K_n(x_1, ..., x_n) \Rightarrow B(x_1, ..., x_n))$*, які означають розмірні, силові та інші реальні зв'язки, що виникають між деталями реальних конструкцій». Переходом від конкретних деталей до логіки предикатів першого порядку є положення, що деяка деталь (наприклад пластина П) може функціонувати в реальних умовах тоді і тільки тоді, коли існує сукупність сил,* $f_1, f_2, …, f_n$*, що її фіксують, які прикладені в точках* $x_1, x_2, ..., x_n$*. Основними параметрами ефективності конструкції фрези прийняті: надійність, продуктивність, енергоефективність, задані як цільові функції. Вони враховують також статичні та дина-*

мічні характеристики конструкції. Змінними показниками є геометрична форма і розмірні параметри фрези. Для кожного варіанта геометричної форми проводиться побудова 3D-моделі фрези і розрахунок її статичних і динамічних характеристик. Далі ці параметри включаються в цільові функції. Оптимізація здійснюється на основі методу градієнтного спуску. Вибір оптимальної конструкції здійснюється за взаємодії інтелектуальних агентів. Водночас конструкція фрези забезпечує найкраще співвідношення цільових функцій. Архітектура системи побудована на інтеграції CAD/CAE-систем з мультиагентною системою (МАС). Пошук рішення здійснюється автоматично в результаті взаємодії самостійних цілеспрямованих програмних модулів – агентів. У цій роботі для побудови МАС використовується бібліотека Jade мови Java в середовищі розробки NetBean. Розглянутий підхід дозволяє зменшити витрати часу під час проектування або вибору конструкції металорізального інструменту.

***Ключові слова**: структурна оптимізація, мультиагентна система, фреза, бізнес-процес, об'єктно-орієнтований підхід, продуктивність, надійність, енергоефективність.*

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