Advanced morphological approach to finding novel solutions for automated finishing of GTE blades

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Abstract. This article deals with the search, structural analysis, synthesis and modelling of complex automatic systems during preliminary design phase on a basis of advanced morphological approach. The research aims were to develop and use an advanced morphological approach, a technique for modelling the new systems for automated finishing of gas turbine engine (GTE) blades. The approach is based on cluster analysis, set theory, set of rules and maximization a gain by the innovative automation systems potential. Based on this study, the proposed method shows a meaningful potential compared to the methods presently used.

1. Introduction

In engineering practice there is usually a need for direct finding a new optimum engineering solution (ES) within the constraints of the project at the beginning. The search for new ES is necessary for research and development from the main tasks of system analysis – decomposition, analysis and synthesis of ES – point of view. Analysis is carried out to determine the properties of the ES and its operation, and the task of synthesis consists in the development of an ES model, the determination of its structure (structural synthesis) and the corresponding parameters (parametric synthesis or parametric optimization), necessary for the efficient functioning of the ES and the achievement of the stated goal.

One of the key stages in the mechanical systems design process is the preliminary design phase. Preliminary design is considered to be the most difficult engineering design phase, with its success depending to a great extent on the expertise of the designer. Automation and “intellectualization” of some aspects of this phase would be of immense practical benefit [1]. During the conceptual phase, the designer must devise an initial design which (a) incorporates “working principles” or physical solutions for all required “essential” features of the problem and which (b) has been evaluated to be acceptable and feasible [2]. This is the phase of the design process “that makes the greatest demands on the designer, and where there is the most scope for striking improvements and where the most important decisions are taken” [3].

Therefore, preliminary (conceptual) design is the fundamental and indispensable forerunner of the more detailed design phases. It is well known that the right design concept is the key factor influencing the majority of product life-cycle cost and defines the level of product innovation. But an excellent detailed design based upon a poor and inappropriate design concept can never compensate the shortcomings of that concept. Conceptual design is the first and early phase of the design process, involving the generation of solutions, of engineering concepts and of design principles to satisfy the
functional requirements for a given design problem. As more than only one solution of a problem exists, improved designs can be identified within the defined design space if the set of potential ES can be enlarged compared to present possibilities [4]. As shown in figure 1 the largest information uncertainty exists during the concept phase and then it decreases towards the development phase. The accumulated project costs are minimal at the concept stage, but the impact of engineering solutions decided during this phase is maximal. Typically, the conceptual design phase absorbs only around 5% but determines around 70% of the total project cost. Therefore, the conceptual design is the basic phase of design process – Computer Aided Innovation (CAI), which can be considered as part of knowledge-based engineering.

The more variants of ES are analyzed, the higher are the quality of the study and the confidence to achieve the project requirements and objectives. For this reason, the choice and the consideration of alternative variants is the main task of the design process.

![Figure 1](image.png)

**Figure 1.** Changes in project cost, cost influence and uncertainty of information during project execution

The great uncertainty of information during conceptual design leads to a consideration of “crude” models and multi variant design solutions, i.e., parallel processing of a number of alternative variants. Such a detailed system and mathematical study needs to reproduce the interaction of external and internal factors during the design process. The automation of the process itself creates patterns in the solution space influenced by the defining process characteristics.

The design of a device (system, process) is a set of two main tasks: the definition of (a) the structure (structural synthesis) and (b) of parameter range for the synthesized structure (parametric synthesis or parametric optimization). The solution strategies for these two tasks are different: parametric synthesis tasks are usually reduced to the determination of solutions satisfying the metric criteria, making them formally resolved while the task of structural synthesis is absolutely different. The latter cannot be generally allocated to the class of formally solvable problems. The result of structural synthesis is the choice of the rational structure of the object. Structural synthesis requires to work with uncertain structural connections, non-metrical attributes of the structure elements and quality criteria. The objective function of a structural synthesis does not correspond to the main requirements of usual
optimization methods because (1) it is discontinuous or cannot always be determined; (2) it exists in operator notation; (3) it is not based on analytical expressions; (4) it is not differentiable, not unimodal, not separable, and not additive [5]. The solution of the structural synthesis task is the main and exclusive subject of the researcher’s creative activity.

The specifics of structural synthesis tasks consist in the discreteness of variables and presence of conditionally logical limitations. To this we will add the need to work with multiple conflicting criteria. The essence of project research consists in the purposeful alteration of characteristic values for variants improving the initial ones. The very notion of “the best” in project tasks is undefined and vague, since a number of criteria are not quantifiable and/or conflict with each other. The main difficulty in the search for a designed of an ES is the uncertainty of the results due to incomplete information on evaluation criteria [6, 7].

2. The advanced morphological approach to finishing automation of GTE blades

In particular, the clusters of ESs were investigated. The matrix was constructed that contained about 560 thousand potential variants. Some of the feasible engineering solutions that were generated using morphological approach are shown in figure 2.

![Figure 2](image-url)

**Figure 2.** Feasible engineering solutions of machine tool for machining of gas turbine engine blades

Two experts selected nine basic criteria and evaluated the attributes and alternatives for compliance with the criteria selected [8]. At the next stage the generation of variants, their estimation and initial selection are carried out and some array of rational variants for the subsequent analysis is formed. Then the clustering of the variants using the defined measure of similarity is carried out. For final analysis 130 generated rational variants, grouped in 17 clusters were chosen (figure 3). After
clustering the variants analysis of the final choice sets from morphological matrix was made for optimization and experimental investigations.

The calculations showed that the clusters №8 and №17 have the highest rating (the value of the objective function), so they were investigated in the first instance. In these clusters there are variants with the best estimates of the objective function.

Cluster №17 consists of single engineering solution and some of its general features are as follows: 1) workpiece is machining by moving cutting tool, 2) embedded combined measurement module is used for workpiece surface roughness inspecting, 3) toroidal cutting tool has a single degree of freedom, 4) portal is moving in horizontal plane and workpiece has no rotation, 5) there is a support accessory for unfixed workpiece end to increase its stiffness during machining and measuring, 6) measurement module and carriage with cutting tool are located on the separate platforms (figure 4).

Figure 3. Solutions space of ESs with 17 clusters (a) and the reference variants position (b)

Figure 4. ES variant in cluster 17
Detailed morphological analysis showed that most of the clusters that do not include reference variants have lower average ranking of objective function than those that include reference variants. Thus, it is advisable to extend the set of reference variants and include into this set the variants with higher level of objective function. In this way the set of analyzed engineering will be extended.

The set of engineering solutions for different machining techniques for GTE blades finishing was generated as result of morphological analysis along with the set of machine tool configurations that are realized appropriate techniques.

For example, one of these techniques includes geometric dimensioning of workpiece, comparing geometry of workpiece and intended geometry of finished part, determination of workpiece zones for machining, cutting tool trajectory planning, setting the cutting condition parameters (cutting mode) based on measurement of workpiece geometry and execution of finishing operation using toroidal cutting tool.

Workpiece is moved into cutting zone and then it is “scanned” by measurement module to define its geometric dimensions in 3 orthogonal axes (in transversal, lengthwise and vertical directions, i.e. along X, Y and Z axis respectively). In doing so, measurement module is moving linearly and uniformly along the axis of rotating workpiece and after that measured parameters of workpiece are transfer to CNC system.

CNC handles the received data to compare workpiece measured geometry with intended (theoretical) geometry of finished part and to determine the set of workpiece zones (fragments of workpiece surface) which have to be exposed to finishing. On this basis CNC generates commands for cutting tool movement. Finishing operations is implemented by means of joint movement of cutting tool in three orthogonal axes (X, Y and Z) and information from force/torque sensor which control parameters of finishing is transferred to CNC for generating control commands.

During all operations cutting tool is forced to rotate about X (longitudinal) axis of machine tool base, and workpiece is rotated about its rotation axis (there is also an opportunity to fix workpiece in specific position).

3. An example of engineering solution for finishing automation of GTE blades

Engineering system that realizes above mentioned technique of finishing operation for gas turbine engine blades is presented in figure 5. It consists of base (1) upon which there is a portal (2) with opportunity to move along Y axis with respect to base by two ball screw drive (3) and step motors 4 on linear rails (they are not shown in figure 5). A carriage (5) is located on the portal with opportunity to move along the X axis by ball screw drive 6 and step motor 7. A housing (8) with a work (cutting) tool (9), for example, grinding or polishing wheels, which is rotated by motor (10), is located on the carriage. The housing has possibility to move along Z axis and rotate about the same axis by other motor (not shown in figure). A force/torque sensor (not shown in figure), connected with the work tool is also located in the housing.

A sensor for workpiece (12) surface coordinates measurement is also located on the carriage. The measurement system for workpiece coordinates measurement – measurement module (11) – is installed with opportunity to move along Z axis with respect to the carriage. It could be used both optical and mechanical measurement module for workpiece measurement. Workpiece is fixed in workpiece feed manipulator (13) with opportunity of rotation about X and Y axes by the motors (not shown in figure). The force/torque sensor, measurement module and all motors are connected to CNC (not shown in figure), which handles information received from force/torque sensor and measurement module and generates control commands for work tool displacement.

Workpiece is moved to machine tool by robot (not shown in figure), then it is allocated fixation device (not shown in figure) of workpiece feed manipulator which rotates workpiece in 180 degrees, thus moves it into cutting zone. Measurement of the geometric parameters of workpiece is produced by optical or mechanical measurement system by moving of the measurement module along Z axis, the carriage along X axis and the portal along Y axis. It is possible to do contactless workpiece surface coordinate measurement too by moving only the carriage along X axis and portal along Y axis.
Figure 5. Portal-type machine tool for finishing machining of GTE blades

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An information on workpiece measured geometry is transferred to CNC system where comparison of experimentally measured geometry of workpiece with theoretical geometry of finished part is made and a set of “should to be processed” zones are determined. The trajectories and cutting conditions (cutting mode) for work tool are also specified. Then machining of workpiece by work tool is made by moving the housing, the portal and the carriage. The workpiece machining parameters from force/torque sensor are transferred to CNC system for working out of the control commands. If necessary a verification of the geometrical parameters of workpiece is carried out after machining by measurement module. In case of desired accuracy is reached the CNC system send finished part to next operations, otherwise the set of above mentioned procedures is repeated.

Analysis of the morphological matrix shows also that there exists some other engineering solution with high rating (level of objective function) in form of machine tool with two moving portals, with one of them has installed carriage with cutting tool, and another – manipulator with workpiece and measurement module, and both portals are located on the same base. 

There are the following advantages of finding solutions with a help of suggested approach:

- surface finishing operations - grinding and polishing - and also preliminary and final inspection and measurement of workpiece and finished part are made with single workpiece installation; this feature deliver decreasing of positioning error and increasing machining accuracy of finished part;
- high accuracy of geometry measurements of workpiece is reached due to affixment location of measurement module to the carriage and work cutting tool;
- increasing of the performance due to decreasing of number of auxiliary operations (measurements, re-installation of workpiece etc.);
- it is possible to make all finishing operations – grinding and polishing – with the single workpiece installation;
– it is provided a possibility of measuring (before and after machining) without making re-installation of workpiece;
– there is an opportunity to choose an appropriate variant of installation of workpiece (console or with both fixed ends – depending of stiffness and dimensions of blades);
– it is possible to use different techniques of measuring of workpiece geometry;
– there is a possibility to inspect both macro (dimensions) and micro (surface roughness) geometry at the single installation of workpiece;
– higher structure stiffness of both machine tool and whole system (“machine tool-accessory-cutting tool-workpiece”) allows to use more productive cutting mode or provide lower levels of vibrations for similar – from the performance point of view – cutting conditions;
– it is possible of parallel handling of two cutting tools (for example, simultaneous precise grinding and polishing);
– there is an opportunity to use sliding carriage only for displacement of workpiece (with manual and automatic installation) to accelerate feed of workpiece into cutting zone;
– there is a variant with measurement module embedded into portal columns;
– it is provided an opportunity to use additional holding device connected with carriage for increasing stiffness of workpiece;
– there is an opportunity for rotation of workpiece about Z axis;
– it is possible to process disk and the blades assembly.

4. Conclusions

Above-described approach allows to formalize the solution for structural synthesis of machine tools that referred pre-described requirements, to extend a set of investigating engineering solutions and streamline search of most rational among them. For engineering solutions selected during the phase of structural synthesis later should be developed mathematical models for parametric synthesis and optimization. The suggested approach gives opportunity to increase a quality of developing engineering systems and technologies.

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