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Simulation in production of open rotor propellers: from optimal surface geometry to automated control of mechanical treatment

A Grinyok[1], I Boychuk[2], D Perelygin[1], I Dantsevich[2]

[1] Shukhov State Technologica University, Belgorod, Kostyukova St., 46, Belgorod, Russia 308012
[2] Admiral Ushakov State Navy University, Lenin Av., 93, Novorossiysk, Russia 353918

E-mail: grinyokann@gmail.com

Abstract. A complex method of the simulation and production design of open rotor propellers was studied. An end-to-end diagram was proposed for the evaluating, designing and experimental testing the optimal geometry of the propeller surface, for the machine control path generation as well as for simulating the cutting zone force condition and its relationship with the treatment accuracy which was defined by the propeller elastic deformation. The simulation data provided the realization of the combined automated path control of the cutting tool.

1.Introduction
The open rotor propellers are technologically and quality sensitive complex objects. The development of propellers is followed by a number of issues: aerodynamics and dynamics, design and production technology, control and monitoring. The end-to-end computer-aided design is the most efficient technology to provide the accuracy and quality, which includes a set of tasks on the simulation of the object operation and development, on the identification of the feedback within a technological chain and the development of efficient control charts of mechanical treatment [1].

2. Research method
A comprehensive approach to the automated control system development using the cutting equipment involves the solution of a number of numerical engineering problems. So, it is required to study the integration of calculation modules into the available CAD-CAM process chains. E.g. the Teamcenter application is a good example of the integrated automation, which provides the shared data access, the NX CAM feedback connection as well as the manufacturing resource library, templates of the control applications and postprocessors. To control the quality of mechanical treatment, the feedback with equipment is required (Figure 1). The elements of the end-to-end design of the open rotor propellers are presented below from the surface geometry design to the circuit of the tool path control.

Propeller 3-D simulation.

The technologically intensive and quality sensitive complex objects such as propellers of aircraft engines imply a number of challenges related to reckoning the optimal surface geometry.

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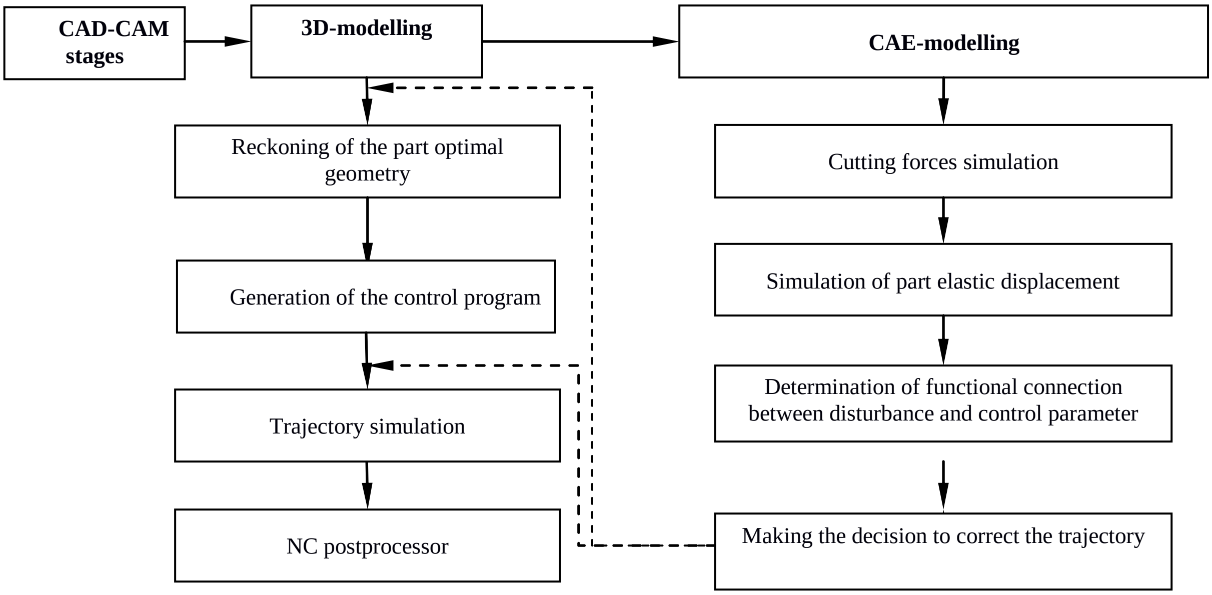

Figure 1. A diagram of development and correction of the cutting tool path with regard to the treatment errors caused by part elastic displacement

To solve the problems of propeller aerodynamics and dynamics, the propeller durability and the geometry of propeller blades to be evaluated. The fact that the propeller dynamics is always about the sound which overwhelms other sounds of the aircraft to be considered. So, to identify the aerodynamically effective shape of propeller blades, the optimization aerodynamic problem as well as the acoustic problem is to be solved [2]. For 3D parametric simulation of a compound propeller blade, a sketch obtained according to [3] was used with the rating table for blade sections. A design scheme of propeller sections is presented in Figure 2. According to the blade sketch, 10 section fragments at certain spaced positions were approximated with spines (Figure 3).

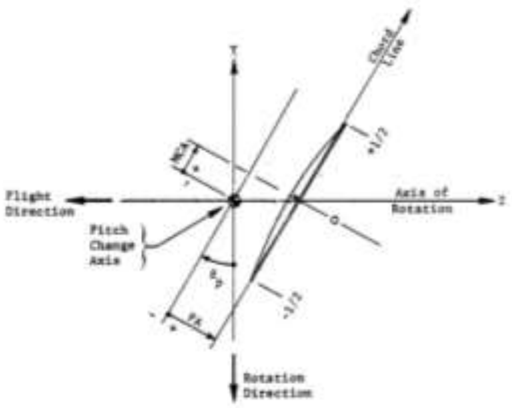

Figure 2. A design scheme of a blade section

Figure 3. The blade simulation through certain sections

10 parallel planes were defined in a model. A corresponding fragment of the blade section was taken into each plane taking into account the space orientation of every section, Then, a solid body with a double curved surface was designed. A propeller model is presented in Figure 4. To study the acoustic characteristics of the propeller, a test model was developed.

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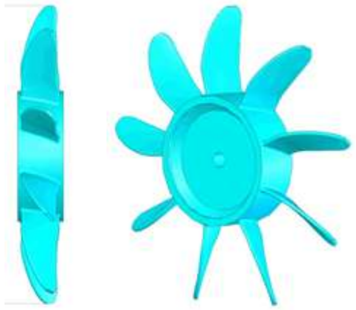


Figure 4. 3D model of propeller

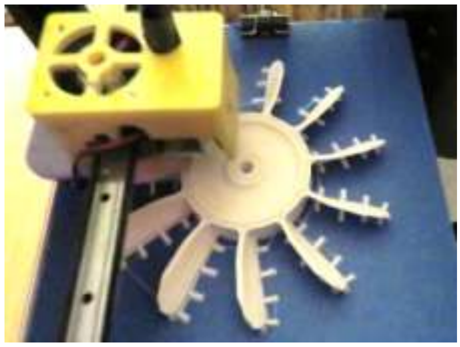


Figure 5. Test propeller printing

Experiments. A test propeller for study the geometry accuracy was printed with H-bot using the PLA plastic (Figure 5). It was balanced through grinding and then coated to provide the smoothness of surfaces.

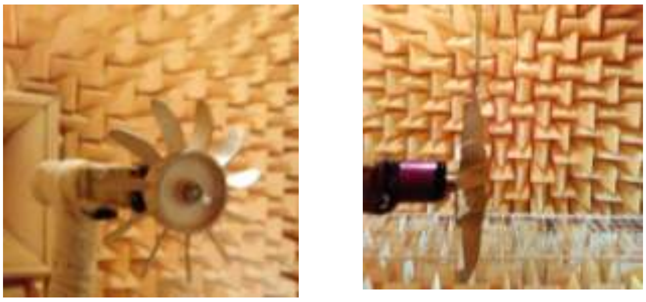


Figure 6. Test for propeller performance of designed geometry in anechoic chamber

The study of the propeller acoustic characteristics was carried out in an anechoic chamber (Figure 6). Altering the rotation rate, the sound generated by the propeller was measured by a microphone. As a result, the sound pressure levels and the noise directivity patterns for different rotation rates were defined. The functionally optimal surface of the designed propeller was identified.

The control program development. Figure 7 presents the order of the control program development using the CAM module (by the example of NX CAM) on the base of the designed 3D model of the propeller [4,5].

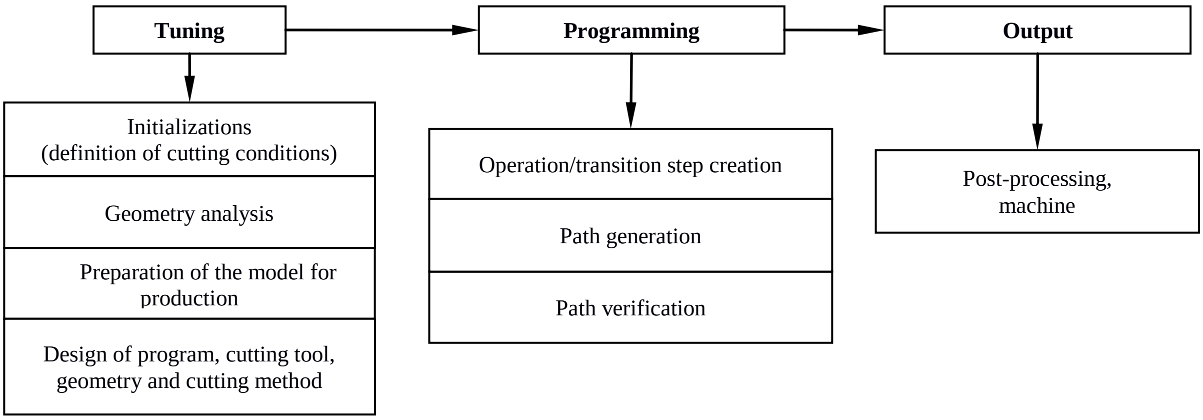


Figure 7. Stages of control program development

Simulation of the cutting zone force condition. As compared to the analytic and experimental research techniques, numerical simulation of the chip formation during mechanical treatment has a number of following advantages: a full 3D picture of elastic-plastic, force and heat transfer processes; the data on parameters which are not available for direct or indirect altering [6,7,8]. The milling simulation aimed at identifying the force condition of the propeller cutting zone made it possible to define the relationship of the cutting force components and the mechanical treatment modes. The power load is the source data to solve the problem of the propeller elastic deformation under treatment.

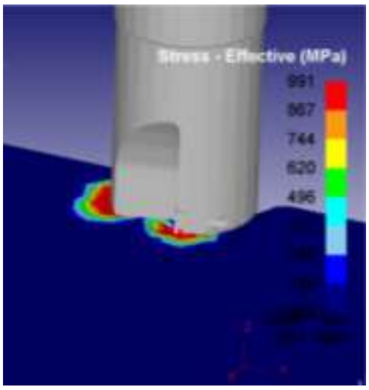


Figure 8. Stress in propeller cutting zone, MPa

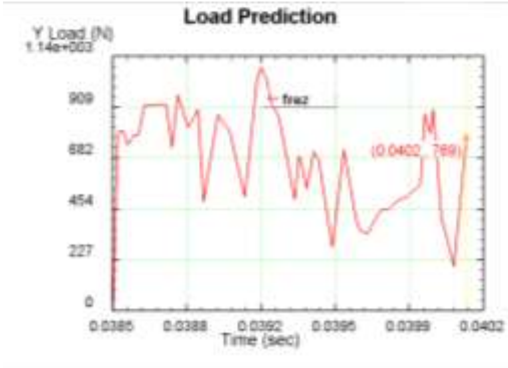
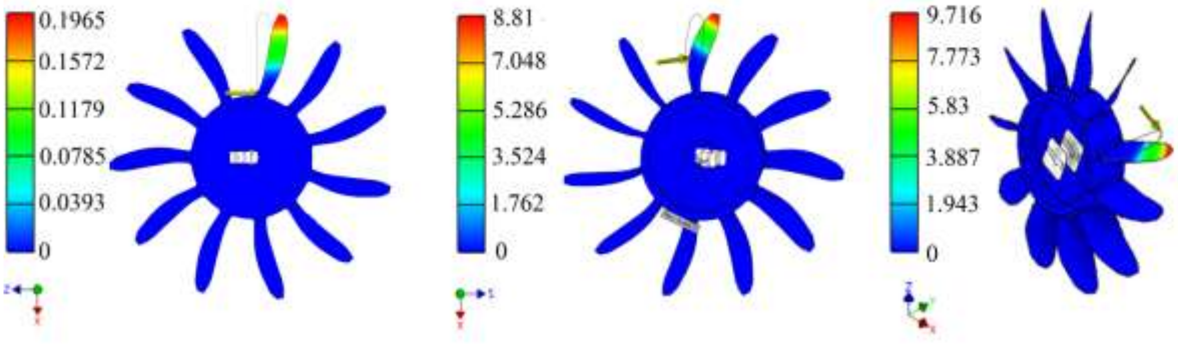


Figure 9. Simulation of radial cutting force during milling

According to the simulation results, a statistic component of the cutting force was obtained [9]. This cutting force is a part of source data for the problem of the propeller elastic deformation as well as a disturbance in the path control of a machine operating unit.

The disturbance and technological mode relationship. To solve the problem of the mechanical treatment error caused by the propeller elastic deformation due to the cutting force, a static problem was solved. Figure 10 presents the values of the blade displacement depending on an application point of the cutting force (points of force applications are indicated with arrows).



a) b) c)

Figure 10. Total displacement (μm) of treated surface depending on an application point of cutting force at the blade surface

The identification of the functional relationship of the treatment error and the workpiece geometry using the simulation data made it possible to link the disturbance with a tool position [10,11].

The tool path control. The development of the mechanical treatment control system requires the information about functional links between input and output parameters as well as disturbance impacts (in the disturbance control) [12,13]. E.g. it is possible to apply the deviation control: the feedback control in coordinates of a tool (an operating unit), or the open-loop disturbance-compensated control. The combined control systems include the advantages of both types, however, to obtain functional links between disturbance and the system output is often quite a challenging task. A general combined control of a cutting tool path is presented in Figure 11. A control device provides control using the data on the tool positional deviation and takes into account the functional link of the detected deviation – cutting force with a tool position (deviation control).

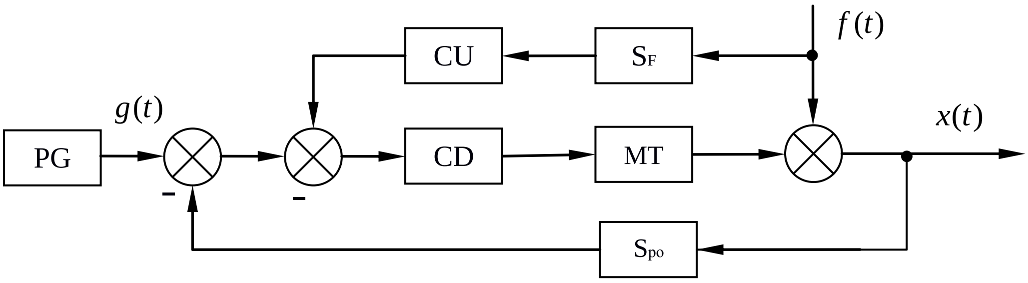


Figure 11. A diagram of combined control of a machine operating unit path: PG — operating unit path generator; CD – control device; MT – surface mechanical treatment; CU–computing unit; S_F – a cutting force sensor; S_{po} – tool position sensor

A simulation of the propeller stress-strain state allows us to define links between the disturbance in a control system (cutting force) and the elastic pressing of a propeller blade and relate it to an output parameter, the operating unit position. Based on those data, the open-loop control of a machine drive is available. Moreover, the application of the obtained results to non-rigid spatial workpieces of irregular shapes provides a solution for a number of design and technological problems

3. Summary

1. An end-to-end simulation of technological objects – open rotor propellers - was proposed based on a number of solved problems which describe the links between: a surface geometry and propeller operating mode; a cutting zone force and technological modes; a technological error and treatment conditions.
2. Using the 3D model, the mechanical treatment can be simulated, a cutting tool path can be generated as well as a control program for metal-cutting equipment can be developed.
3. The solution of a problem on the propeller stress and strain deformation under mechanical treatment provided the prediction of the technological error value. Moreover, the application of the results to the setting and fixing of non-rigid non-symmetric parts of irregular spatial shapes allows us to obtain the fixation error which is crucial for these parts during the mechanical treatment.
4. Using the data on functional links between the disturbance and elastic pressing, a combine automated system can be developed to control the operating unit path.

4. Acknowledgement

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