VIRTUAL MODELING, OPTIMIZATION, AND TESTING IN DESIGN OF HIGH ALTITUDE AIR PROPELLER

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ABSTRACT

The Virtual Testbed (VTb) is created for mathematical modeling and Virtual Testing (VT) of high altitude air propellers (AAP). There are 19 Virtual Test Rigs (VTR1-VTR19) in VTb. The model-driven development of AAP contains stages of modeling, virtual testing and optimization of the structure of AAP. The operator, using VTb, compares properties of AAP with the requirements of Technical Specification (TS), and “Goals and Limitations Matrix” (GLM). VTb is designed for integrated virtual development of AAP, including all key components.

KEYWORDS: UAV; Aircraft Propeller Design; Mathematical Modelling, Optimization & Virtual Testbed

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INTRODUCTION

The methods for design of wings (analogues of blades of propellers) are proposed, for example, in the article [1]. Some articles are devoted to design and analysis of propellers [2-5], optimization of propellers [6], investigation of a Pitch-Change Mechanism [7], and impact of a bird [8], noise control [9], and influence of a vortex stream [10]. However, a joint virtual instrument for modeling and testing of high altitude air propellers, which takes into account much factors, is absent. Quick development of modeling, of numerical analysis, and supercomputers generates new effective instruments for virtual design of aircraft propellers, which take into account all main elements of this development. Such instrument for design of high altitude air propellers is described here. The created Virtual Testbed takes into account all modern demands to propellers, and joint influence of most significant factors on states of AAP (the temperature and the pressure of air, a boundary layer, turbulence of air streams, wind, vibration of an engine, centrifugal forces of blades of propellers, impacts of hail and birds, influence of ice, etc.). VTb takes into account mutual influence of different factors (deformations of a propeller in streams of air, and reverse influence of deformations of a propeller blade on streams of air, flutter of blades, etc.). VTb uses modern state of the software solutions, and the possibilities of supercomputers.

The operator, using proposed VTb, verifies correspondence of AAP properties to the requirements of the TS and the GLM. The VTb is created for integrated virtual design of AAP including all key components: blades, a bush, a butt, a cuff, a Pitch-Change Mechanism (PCM), an Anti-Icing System (AIS).

The VTb is constructed for:

- virtual development of AAP, for all flight modes in wide range of Reynolds numbers, tailored to the requirements of the TS and the GLM;

- virtual design of high altitude air propellers;
- noise level analysis, testing of PCM and AIS capability;
- analysis of centrifugal forces of AAP, atmospheric turbulence, wind and random vibration in wide ranges to increase efficiency and reliability of AAP;
- an estimation of possible impact damages of AAP after action of different external factors (lightning strikes; impacts of birds, hail and debris);
- an estimation of frequency characteristics of AAP for minimization of resonances and flutters;
- providing necessary thrust and efficiency of AAP for different flight modes;
- an estimation of period of life of AAP components with taking into account cyclic loads.

Created VTb allows using significant possibilities of modern mathematical modeling in domains of continuum mechanics, numerical methods, and supercomputer calculations for depth analysis of AAP models. VTb gives to the engineer-designer of AAP wide possibilities for verification of accordance of properties of a propeller to all modern demands.

BLOCK-SCHEME OF THE DESIGN PROCESS. FUNCTIONAL CONFIGURATION OF VTb

The process of design of AAP is shown on figure 1. Initial 3D models of AAP elements, 2D models of the blade profiles, and the properties of materials are transferred from external databases.

The operator optimizes 2D blade profiles using “Method of optimization of mathematical models of 2D AAP blade profiles”, and the Virtual Test Rig 3 (VTR3). The models of blade profiles are the part of input data for creation and optimization of AAP blades, which are testing on all Virtual Test Rigs.

The scheme shows operating principles of VTb, the input and output data, the connections of VTRs, which providing use of test results and allowing transferring finite element models (FEM) between VTRs. The description of the scheme of VTb is in the part 3 of this article. Connections of different VTRs allow exchange of results of virtual tests – loads, FEMs and CAD models, and allow solving of multi-physics problems. For example, results of tests in VTR17 (impacts of birds) are used how the input data for VTR1 (static load) and VTR12 (centrifugal forces). Such connections of VTR17, VTR1, and VTR12, allow estimating strength of AAP after impacts of birds. The results of VTR8 (AIS analysis) and VTR14 (the atmospheric temperature) are used how the input data for VTR19 (period of life of AAP). The output data of VTR12 are used in VTR13 (the atmospheric pressure), VTR14 and VTR19.

Figure 1: The Process of Design of AAP.

STAGES OF VIRTUAL MODELING OF AAP

The operator uses the results of 2D optimization for creating the 3D model of AAP, and produces optimization and virtual tests of the 3D model. The operator checks properties of the model against requirements of the TS and the GLM on all stages of design of AAP. The main parts of the input data for creation of the 3D model of AAP are the optimized 2D models of blade profiles and the 3D models (the continuous blade, the bush, the butt, and the cuff) from external databases.

The operator prepares the input data in accordance with defined parameters of AAP and the flight conditions using “Method of AAP blade optimization” and creates the 3D model of AAP. The input data include the requirements of the TS, the optimized models of blade profiles, and the 3D model of the cuff. The operator optimizes the 3D model of blade of AAP using VTb. Deformations of AAP, produced by aerodynamic and centrifugal forces, are taken into account in the 3D optimization process. It outputs the optimal aerodynamic and strength parameters of AAP with the limitations for reaction torque and mass of AAP. The optimization criteria for all flight modes include the criteria of maximization of the thrust of the propeller. Main flight modes define weight coefficients in the expression of the thrust. The operator creates the CAD model of the AAP before the 3D models of a bush and butt are used in the VT, and also harmonizes sizes of the butt and optimizes the united 3D model of the AAP.

STAGES OF VT OF AAP

It is necessary to take into account deformations of blades, if length of the blade much exceeds width and thickness of the blade (for example, blades of a helicopter). Torsional-flexural deformations are large in such cases. For such propellers the correction of aerodynamic loads on blades is useful. This correction allows decreasing possible systematic errors of numerical analysis generated by influence of significant deformations of blades on parameters of air streams. The correction of aerodynamic loads on blades is not useful, if torsional-flexural deformations of blades are little. Then increased consumption of computation power for numerical analysis gives negligible variations of results. The operator estimates characteristics of AAP and makes the conclusion about usefulness of the correction of aerodynamic loads if air stream is stationary. The output data of VTR4 (aerodynamic forces) are used as the input data in the preprocessor of VTR9

(classical flutter). The new FEM of AAP is the result of VT in VTR9. This FEM takes into account the deformation of AAP for the case, when flutter is absent. The operator transfers this FEM in VTR4 and creates there the 3D CAD model of AAP for getting new data about the pressure and the temperature on the surface of blades on this step of iterations of the correction.

Such iterations are repeated when variations of aerodynamic loads are significant. Iterations are finished when the pressure, the temperature, and the shape of the blade are stabilized. The stabilization means that maximal variations of deformational displacements, maximal variations of the pressure and the temperature are lower than correspondently 0.001 of the radius of the propeller, 0.001 of maximal values of modules of the pressure and the temperature on the surface of the blade. These criteria define allowed errors of VT. The engineer-designer can to strengthen or to weaken the criteria, if to take into account the character of AAP and the region of use of AAP.

The operator begins VT of the 3D model of AAP and uses the results of VT in VTR4, without or with the correction of aerodynamic loads, in VTR5, VTR6, VTR8, VTR9, VTR10, VTR13, VTR14, VTR15, and VTR19. It forms the conclusion about continuation of main directions of design, optimization, and VT, or makes the conclusion about transfer of the 3D model to the engineer-designer for modification. Then, the operator optimizes and verifies the modified model in VTb.

The “Methodic of VT of AAP in VTR” (“MVT AAP in VTR”) defines the format of the input data of different VTRs and defines them transfer to processors of VTRs. In addition, “MVT AAP in VTR” defines the order of creation of FEM, the order of different VTs, the structure and the format of the output data in postprocessors of VTRs, the order of interpretation of results of VTRs, the order of verification of a correspondence of AAP properties and of the requirements of the TS and the GLM.

The results of VT in VTR7 are natural frequencies and modes in free and fixed states of AAP. The operator verifies the absence of the frequencies of free vibrations in the ranges of frequencies defined by the TS and the GLM. Then, tests of the AAP 3D model are continued or, if some frequencies belong to such ranges, the modification of the 3D model of AAP is realized together with the engineer-designer, the modified model is tested. Then, the operator takes from the postprocessor of VTR7 frequency characteristics of AAP, and from the postprocessor of VTR4 the fields of pressures and temperatures on the surface of AAP, and transfers this data in preprocessors of VTR9 (classical flutter), VTR10 (another flutter). The analysis of the output data of VTR9 and VTR10 generates conclusions about possibility of classical or another flutter of AAP. The output data of VTR9 and VTR10 are the input data for other VTRs. The results of VT in VTR9 and VTR10 are, in first, the frequency characteristics of AAP for little and large pitch angles of blades of AAP and, in second, stress-strain state of AAP for cases of minimal and maximal temperatures of air. After VT, the conclusions about the absence of classical or another flutter and about strength of AAP are made. The information about the aerodynamics resistance of AAP, which is necessary for analysis of efficiency of AAP, also follows from VTR9 and VTR10.

The configuration of analysis in VTR15 gives the estimation of influence of turbulence, and of influence of directions of air streams. This configuration depends of the pressure and the temperature of air, of rotation frequency of AAP, of initial turbulence of stream. The output data of VTR15 are used for engineer analysis, and are used and how the input data of other stands of virtual tests. The postprocessor of VTR15 allows getting pressures and temperatures on surfaces of blades, power and aerodynamic resistance of AAP, stress-strain state of AAP for different velocities and forces

of wind, for different turbulence. The operator analyses the results of VT in VTR15, takes into account the TS and the GLM, and makes conclusions about power, maximal efficiency, and strength of AAP and uses this data for design and VT of AAP.

After testing of bird-strike resistance, the FEM of AAP follows from VTR17 to VTR1, VTR12 for verification of strength of AAP after the impacts of birds. The operator analyses the results of VT in VTR17, VTR1, and in VTR12 for different defined in the TS and the GLM values of the parameters: elevation and azimuth angles, flight altitudes, velocities of an aircraft, rotation frequency of AAP, velocities of impacts, impact locations. It analyses damages of the PCM, separations of elements of AAP, sizes of damage regions of blades and makes conclusions in accordance to the TS and the GLM. The output data of VTR12 are used how the input data for VTR13 (an estimation of influence variations of the pressure of air on AAP), VTR14 (an estimation of influence variations of the temperature of air on AAP), VTR19 (period of life of AAP). The operator takes into account possible computational cases, the configurations of fixing of AAP, and conditions of rotation of AAP. The stress-strain state of the blade is the result of VT in VTR12 for different values of the temperature and different values of centrifugal forces. The results of VT in VTR12 (stress-strain state of blades, of elements of fixation for different values of the temperature and different loads) are compared with the limits of elasticity and strength of materials of AAP. The operator transfers the output data of VTR4, VTR12 in preprocessors of VTR13, VTR14 for estimations of influence on AAP variations of the pressure and the temperature of air.

The output data of VTR4 are the part of the input data of VTR5 (testing of PCM), VTR6 (noise level analysis), VTR8 (AIS analysis). The operator compares the results of VT in VTR5 and the data of the TS and the GLM in defined cases of the time of transition of blades from one state to another state. Next input data are defined in the preprocessor of VTR6: the mechanical properties of materials, the 3D model of AAP, the elements of fuselage and wing, the data of vibrations of the engine, the connections of elements, turbulence. The operator controls VT in VTR6 in accordance with “MVT AAP in VTR6”, realizes defined computational cases, and analyzes, using the TS and the GLM, the acoustic pressure in the cruise flight and in takeoff conditions. The conclusions about accordance of noise parameters of AAP to the requirements of the TS and the GLM are generated. The results of aerodynamic VT of AAP, which are produced in VTR4 with help of the ANSYS CFD, are used how the input data for VTR8. The possibilities of the CFD give fields of values of heat transfer coefficients on the surface of AAP. The operator prepares these fields in preprocessor of ANSYS before the computation of heat states of AAP and defines values of other heat parameters of AAP. The results of VT in VTR8 must to be in accordance with the criterion – the temperature for all points of the surface of AAP is positive. Then, the operator gives the estimation of the AIS of AAP. The plan of continuation of VT or the plan of modification of the 3D model of AAP is generated on base of analysis of results of VT in VTR5, VTR6, and VTR8.

The operator compares the output data of VTR11 (influence of vibrations in wide ranges) and the requirements of the TS and the GLM. Stresses in the layers of the materials must be lower than the limit of elasticity or strength defined in the GLM. Then, the operator continues VT of the 3D model of AAP or begins modification of the model with participation of the engineer-designer and conducts virtual testing of the modified 3D model.

The operator uses the results of VT in VTR16 for the visual estimation of dangerous damages of AAP after the lightning strike. The sizes of regions of AAP, which have the temperature more than the temperature of melting of the material, must coincide with the sizes of regions of damages in the physical experiment. The quantitative estimation of damages from the lightning strike is produced after VT in VTR1, and VTR12, and after the comparison with the

requirements of the TS and the GLM. VTR1 gives the possibility of the estimation of static strength of AAP after different external impacts, which are analyzed in other virtual stands. The operator analyzes the results of VT in VTR1 - the stress-strain state of elements of AAP, comparing the results of VT with the requirements of the TS and the GLM. The realization of VT in VTR2 for defined in the TS and the GLM cases is connected with defined impact on the elements of AAP. The analysis of results of VT in VTR2 gives the conclusion about the dynamic state of AAP. The levels of stresses in the layers of materials must be lower than the limits of elasticity or strength defined in the TS and the GLM.

The output data of VTR18 consist from stress-strain state of AAP, regions of possible damages of elements of AAP for defined in the TS and the GLM values of next parameters: rotation frequency of AAP, velocities and flight altitudes of the aircraft, elevation and azimuth angles, points of impacts of hail and debris. The operator analyzes the output data of VTR18 in defined cases and produces the estimation of the state of AAP after impacts of hail and debris. The analysis of damages of the PCM, separations of elements of AAP, sizes of damage regions of the blade generates the conclusion about accordance to the TS and the GLM.

The operator directs the output data of VTR4, VTR8, VTR12, and VTR14 in the preprocessor of VTR19 in accordance with "MVT AAP in VTR19", defines in the preprocessor of VTR19 loads and boundary conditions: the distribution of pressure – from VTR4, the temperature field – from VTR8 and VTR14, the stress fields – from VTR12. The operator, using VTR19, gets the conclusion about strength and the period of life of AAP. VTR19 is the instrument of decrease of number of natural tests of AAP, and the instrument of acceleration of making of AAP. VTR19 together with VTR4, VTR8, VTR12, and VTR14 gives the possibility of optimization of AAP on the period of life. The operator compares the output data of VTR19 and the requirements of the TS and the GLM, and makes conclusions about damages of AAP from 50-hour work of AAP, conclusions about summary damages from 110-hour work of AAP.

MODIFICATION OF AAP MODEL OR SUCCESSFUL COMPLETION OF THE DESIGN

The operator makes the conclusion about the transfer of the 3D model of AAP to the engineer-designer for the modification with participation of the operator, if the results of VT are not corresponding to the requirements of the TS and the GLM. The modification takes into account results of produced VTs in different VTRs. The operator makes the conclusion about the successful completion of the design, if the results of VT correspond to the requirements of the TS and the GLM. If the conclusion about the transfer of the 3D model of AAP to the engineer-designer for the modification was made, the engineer-designer modifies some elements of the 3D model in the CAD program, taking into account the data about not accordance of results of VT in different VTRs and the requirements of the TS and the GLM. Then, new model follows to the operator, which produces VTs in different VTRs, compares results of VTs and the requirements of the TS and the GLM.

THE EXAMPLES OF APPLICATION OF VTb

The examples of the application of the created VTb are presented in the articles [11, 12]. The article [11] is devoted to the VT of the pitch-change mechanism of the altitude propeller in VTR5 of VTb. This article shows the realization of the modern approach to modeling step responses of the PCM of the propeller in order to determine the PCM response, and demonstrates efficiency of created VTb. The following optimization problem of the propeller blade is considered in the article [12]: to find the optimal configuration of the composite material and its microgeometrical parameters along the height of the blade to minimize deformations and increase the thrust of the propeller. The optimization parameters are

limited by the weight of the propeller and the strength characteristics. The model of aeroelasticity allows solving the problem of fluid-structure interaction; the loads are transferred from the aerodynamic module in the stress-strain module and vice versa. A vortex approach and a modeling of turbulence are used. The obtained results [12] proved the possibility to apply the created VTb for solving these problems, and confirmed the correctness of using aerodynamic loads in the VTb for the considered problem and the accuracy of describing inertial characteristics of blades and the PCM.

CONCLUSIONS

The integrated VTb (VTR1, VTR2, VTR19; the methodic of modeling and optimization of AAP; the methodic of VTs in VTRs) is effective in modeling of the high altitude air propeller, and in optimization, and in virtual testing of such propellers. The created VTb uses significant possibilities of modern mathematical modeling in continuum mechanics, of numerical methods, and of supercomputers for wide and deep investigations of AAP models. It differentiates the VTb and other complexes of programs, and it allows significantly decrease a volume of physical experiments and a period of AAP design with increase of quality of design of AAP.

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