



Design optimization of aircraft structures using virtual proving ground

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Abstract

The main challenges of aerospace industry are increased flight range, fuel, and operating costs. There is an urgent need for more efficient design methods and rational use of composite materials in order to reduce the weight of the aircraft and increase strength and reliability. The use of optimization methods, modern software, and supercomputer technologies plays a key role in shortening the product development cycle. It allows many design options to be analyzed and compared in the early design stages. This paper presents an approach to using optimization methods in conjunction with virtual tests. The Virtual Proving Ground (VPG) includes Virtual Testbeds (VTB) such as “Aerodynamics,” “Statics,” and “Dynamics.” VPG provides end-to-end transfer of results and boundary conditions between blocks and systems of automated post-processing of the results. Thus, the results of the aerodynamic tests are transferred as input data for the static strength tests. The results of static and dynamic tests allow to perform multicriterion optimization considering different loading conditions. Automated post-processing allows to track the miscellaneous parameters at every testing stage. The aim of this work is to develop an approach to optimization of a composite structures using VPG. The presented approach was developed and tested on the example of the unmanned aerial vehicle.

Keywords Optimization · Composite structure · Virtual testing · Test bench

1 Introduction

Ensuring the competitiveness of aviation technology requires constant improvement of design and calculation methods to determine the optimal aircraft design, flight performance, strength, and reliability.

Among the main problems to be solved during the aircraft design process are the tasks of ensuring the strength and stiffness of the structure, as well as reducing its weight. Successful solution of these problems allows increasing the flight range and safety, the economic efficiency of aircraft operation.

In recent years, the use of composite materials in aviation has increased significantly, which makes it possible to improve the strength characteristics of structural elements with reducing their weight. At the same time, composite materials have a complex response to static and dynamic loading. This results in many difficulties in the design of aircraft structures that should meet technical, technological, and economic requirements.

It is estimated in [1] that 90% of the cost of product development is accounted for in the first 10% of the design cycle. Methods of virtual testing allow companies to reduce development time and costs, as well as to use a wider range of innovative materials.

The use of optimization methods, modern software, and supercomputer technologies plays a key role in shortening the product development cycle and allows engineers to explore many design options in the early design stages

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and compare and reject unsuccessful ones for further detailed study.

In recent years, more and more attention has been paid to the development of virtual testing methods [2–5]. This fact underlines the relevance of the topic presented in the article. In this paper, the application of optimization methods using Virtual Proving Ground (VPG) [5] is presented on the example of the airplane structural layout. A modular digital twin of the aircraft was created and tested.

2 Virtual Testbeds

Generally, VPG is to be understood as integrating system. It has flexible modular scheme and primarily consists of Virtual Testbeds (VTB) and could include different other systems of analysis. Every Virtual Testbed consists of modeling strategies, solver settings, modules of automatic post-processing, and load cases that match typical airplane tests and operating conditions. Inclusion of any module can relatively easy be done due to standardized (but flexible) input and output formats of data. For example, aeroelasticity module using Nastran software can be added to the design process. Figure 1 shows the general data flow between modules of VPG.

The development and subsequent testing of Virtual Testbeds was carried out using the example of UAV.

2.1 VTB Aerodynamics

VTB Aerodynamics is used for numerical study of the flow around the aircraft at the various angles of attack (AOA).

The size of the computational domain should be large enough to neglect possible side effects. For the aircraft of this size, a computational domain with dimensions of $30 \times 10 \times 5 \text{ m}^3$ was considered. Simulation was carried out for the half of the model due to symmetry options.

Studies have been conducted for various flight configurations and angles of attack: basic configuration with no deflection of ailerons and rudders, deflection of ailerons $\pm 14^\circ$, and deflection of rudders $\pm 7^\circ$. All calculations refer to subsonic region.

Scripted post-processing of the results generates a report with pictures of pressure and velocity distribution on key surfaces in computational domain (Figs. 2, 3, and 4), list of aerodynamic force and moment coefficients ($C_x, C_y, C_z, M_x, M_y, M_z$), lift-to-drag ratio graphs, and other valuable information. This allows the engineer to make a brief look and make the first assessment of the calculation results.

The list of aerodynamic coefficients can be used in additional modules for the performance checks.

2.2 VTB Static Strength

In the “Static Strength” module, a numerical simulation of aircraft is performed to assess the stress-strain state of the

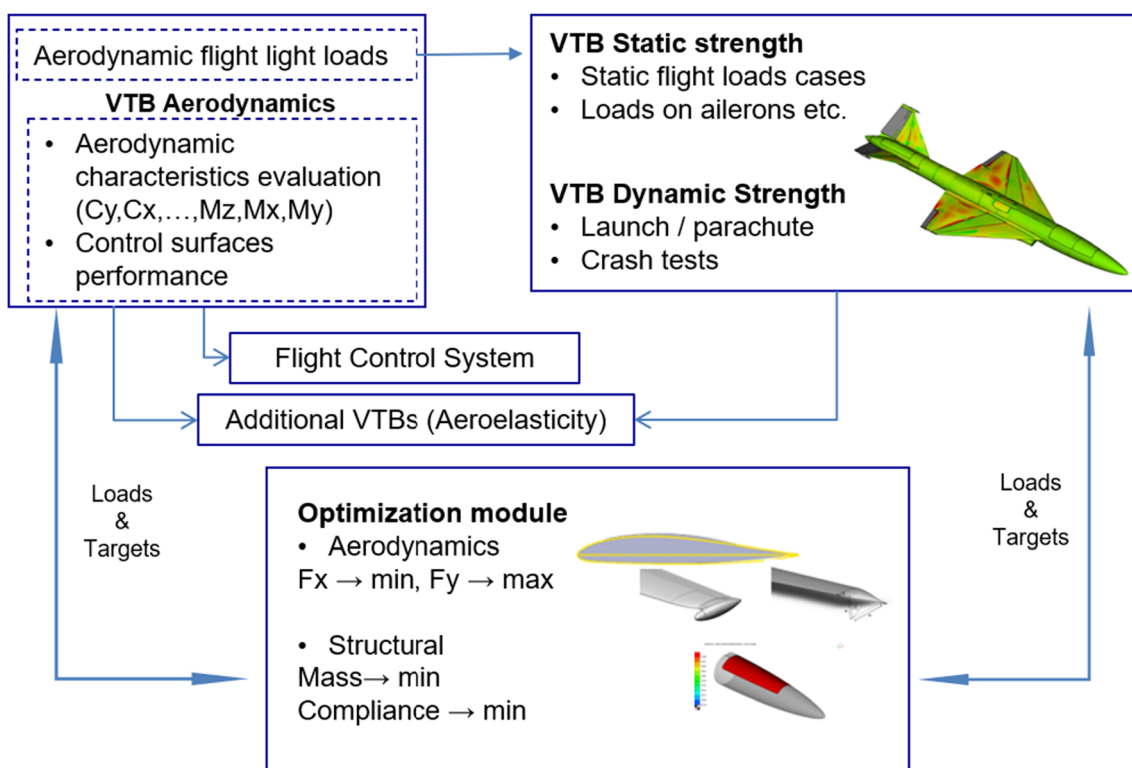


Fig. 1 VPG data flow

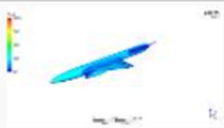





<input type="checkbox"/> Name ▾	Overview
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<input type="checkbox"/> Velocity	80.000[m s ⁻¹]
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<input type="checkbox"/> pressure3.jpg	
<input type="checkbox"/> Pressure2.jpg	
<input type="checkbox"/> Mz_center_of_mass	-288.000[N m]
<input type="checkbox"/> mz_center_of_mass	-0.065
<input type="checkbox"/> Mz	-3176.550[N m]
<input type="checkbox"/> mz	-0.717

Fig. 2 Pictures and key values

structure under the influence of various loads and their combinations.

The construction of the FE model is an important stage in the creation of VTB. The quality of the model directly affects the quality of the results. Thus, it is important to use validated modeling techniques. The principles of working with CAD

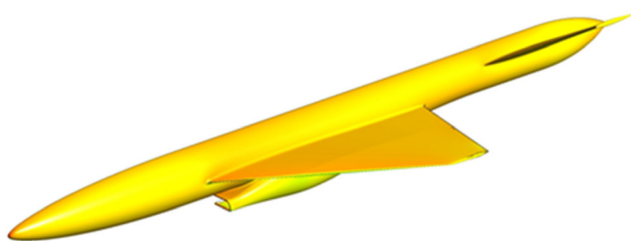


Fig. 3 Pressure distribution on UAV surface, AOA = - 10°

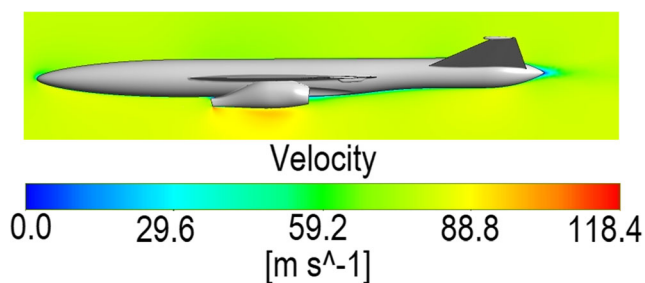


Fig. 4 Velocity distribution on symmetry plane, AOA = - 10°

models, methods and features of modeling aircraft parts using two-dimensional and three-dimensional FEs, bolted and riveted joints, and quality criteria for FE mesh are presented in [6]. The problem of correct modeling of bolted and riveted joints is discussed in [7–11]. Possible options for fastening plates modeled by both shell elements and three-dimensional solid elements are analyzed. The modeling method that was proposed by Rutman [7, 9] is one of the most commonly used in the aerospace industry. This method is recommended for use in all VTB.

VTB Static Strength uses MSC Nastran finite element analysis software with the Inertia Relief setting. It allows to perform static calculations of loose or partially constrained structures. Inertia Relief uses an algorithm of applying additional accelerations to elements to balance external forces and create a state of static equilibrium.

The structure of the tested UAV is made of composite materials. There are also steel elements—bolts, axles, and cage nuts. The material properties are presented in Table 1.

The UAV has adhesive and bolted connections. In the airplane structure, all composite elements are connected along the contact area with glue. Hatches are connected to the structure with screws.

The finite element model uses bonded contacts with the IGLUE setting for adhesive joints. Bolted joints are modeled using a combination of RBE2-BEAM-RBE2 elements.

CONM2 elements are used to take into account the weight and inertial characteristics of the UAV hardware, control units, fuel in tanks, and engines.

VTB uses Python scripts to interpolate pressures on aerodynamic surfaces. To reduce the number of simulations, the flight modes of the aircraft at extreme positions of the control surfaces and extreme values of the angle-of-attack can be used to assess the general strength.

Aircraft was tested at flight speed of 80 m/s and 250 m/s for angle-of-attack range from - 8 to 16°. The deflection of rudders and ailerons was set by ± 14°.

For virtual testing, it is important to create a matrix of parameters that characterize the state of the object under study. In case of strength, such parameters are stresses in composite material along and across the fibers, equivalent stresses in isotropic materials, strains, and deformations of the details of

Table 1 Material properties

Material	Young's modulus		Poisson's ratio, μ	Shear modulus G , MPa	Density ρ , kg/m ³
	E_1 , GPa	E_2 , GPa			
Fiberglass T-10	45	30	0.3	3000	1800
Carbon fiber GG 200P 3K	245	245	0.35	2942	1500
Prepreg KMSK-1.80.T10.37	22	17	0.29	3000	1800
Steel 30HGSA	210	210	0.3	80769	7850

the aircraft. Axial and transverse forces in the elements of the axles and screws are also crucial.

These parameters are monitored and compared with their target values for each load case. This is done due to automatic post-processing as a result of the execution of a special script for post-processing of the simulation results. Figure 5 shows the example of the matrix that is based on the aircraft's static testing results. It displays the values of the monitored parameters (columns) and their compliance with the specified permissible values for selected set of experiments (rows). Figure 5 indicates that maximum shear force in beam element exceeds the limit more or less for some cases.

2.3 VTB Dynamic Strength

VTB “Dynamic Strength” is designed for non-linear dynamic simulations, including high-speed processes and impacts. It is used to test structural design version (initial or based on optimization results). This VTB uses explicit FEA solvers: LS-Dyna and Abaqus.

The UAV finite element model for dynamic tests is an adapted version of the model for static tests. Bonded contacts without ability of destruction are used for modeling glued surfaces.

Conducting of the virtual tests also requires the use of highly adequate mathematical models of materials. Thus, the appropriate model is required to describe the nonlinear behavior of structures under high-speed dynamic impacts. The development of mathematical models for isotropic materials was carried out in [12].

Suggested material model for high velocity impact simulations – elasto-thermo-visco-plastic constitutive relationship [13].

Since the main details of the aircraft are made from composite material, the areas of its destruction were outputted in the results. The Hashin criterion was used as failure criteria, so that destruction was considered as the fulfillment of one of its conditions [14]. According to this criterion, there are four conditions: the destruction of the matrix or fibers as an effect of the compressive or tensile stresses. Following material properties were set to specify damage initiation for each condition of Hashin criterion: longitudinal tensile strength, longitudinal compressive strength, transverse tensile strength, transverse compressive strength, longitudinal shear strength, and transverse shear strength of the lamina. Physical destruction of the material is not specified. This fact imposes restrictions on virtual testing.

Dynamic tests of the aircraft were performed for the case of its falling to the ground at an angle of 30° with a speed of 50

Simulations	Airspeed 80_Altitude 0							
	Max Stresses VonMises MaxofTopBottom Cells MaxofIn_PSolid < 220.000 MPa	Max Stresses VonMises MaxofTopBottom Cells MaxofIn_PShell < 500.000 MPa	Max AuxForces AxialForce in_PBeam < 100.000 N	Max AuxForces ShearForce in_PBeam < 100.000 N	Max Composite Stress Normal 1 in_PComp < 500.000 MPa	Min Composite Stress Normal 1 in_PComp > -300.000 MPa	Max Composite Stress Normal 2 in_PComp < 500.000 MPa	Min Composite Stress Normal 2 in_PComp > -300.000 MPa
static_Alt0_V80_rudder_up14_v_4	46.90	23.00	25.27	135.3	140.4	-154.7	105.8	-114.1
static_Alt0_V80_rudder_down14_v_4	45.30	9.260	24.67	188.8	138.5	-149.6	104.8	-113.2
static_Alt0_V80_eleron_up14_v_4	40.30	10.02	25.27	101.3	140.5	-154.9	99.70	-105.0
static_Alt0_V80_eleron_down14_v_4	65.30	16.68	24.75	136.7	141.1	-150.3	109.8	-119.0

Fig. 5 Example of key value matrix (over-limit values are colored red and yellow)

m/s. Ground was defined as an absolutely rigid body. This case allows to simulate the UAV launch failure.

The results of calculations include information about zones of material failure, as well as the reasons why the failure occurred. The reasons of failure could be identified due to automatic post-processing and key values report generation. The areas of fibers' failure under the action of compressive and tensile stresses are shown in Figs. 6 and 7. Such pictures with color markings are generated automatically.

VTB “Dynamic Strength” can be used for other dynamic loading (starting from the catapult, landing, parachute deployment) or full-scale modeling of critical zones during reinforcements design optimization or material selection.

2.4 Optimization module

The layout of composite structures used in the aviation industry [15, 16] is usually a multilayer material with different fiber orientation angles. Layer thickness is limited by manufacturing constraints, and fiber orientation angles are often limited to discrete sets such as 0° , $\pm 45^\circ$, and 90° .

The simplest optimization method is to vary the angles of the prepreg placement.

In this paper, we propose to use parametric optimization methods with other facilities of Virtual Proving Ground. As a result of a parametric study, by purposefully changing the structural parameters of the composite material, it is possible for certain typified loads and constraints to obtain a set of optimal parameters of a composite part: the number of layers, their thickness, fiber angles, and the sequence of layers.

Composite structures' optimization cycle can be divided into three stages [17]:

- Free-Size: determination of the thickness and shape of the layers of the composite material

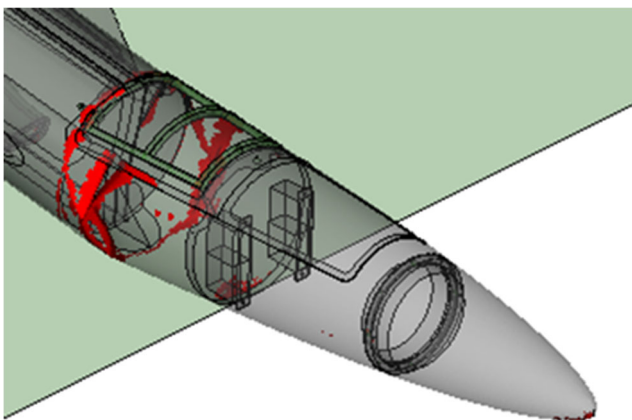


Fig. 6 Compressive failure zones

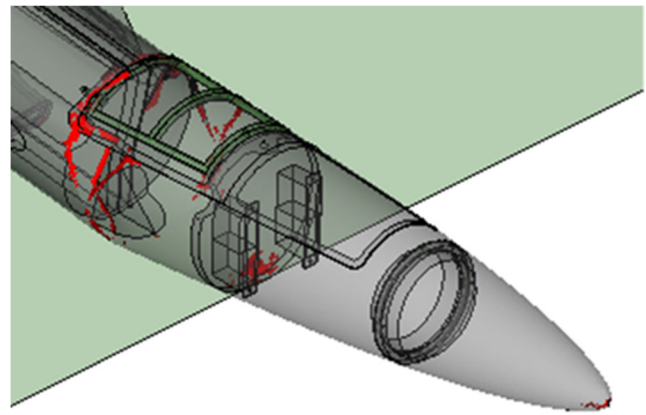


Fig. 7 Tensional failure zones

- Sizing: determination of the number of layers for a given angle, layer thickness, taking into account technological and production restrictions
- Shuffle: determination of the optimal stacking direction for the composite layers, shuffling of the layers to meet the constraints

It is also necessary to indicate the design constraints and the objective function. The objective function is a mathematical expression of some criteria of the quality of one object (for example, weight reduction) in comparison with another. The most often controlled parameters are mass, volume, static compliance, static displacements, stresses, center of mass, normal mode frequencies, etc.

The resulting layers after optimization may turn out to be difficult for manufacturing or even impossible. Sizing step also includes the study of manufacturing possibility. Layer thickness changing on this step occurs discretely from layer to layer. Unnecessary layers will be assigned to have a zero thickness, and they will be removed from further optimization.

At the Shuffle stage, sequence of plies is changing to maximize performance characteristics. At shuffling stage, design constraints such as direction of the surface layer, fiber angle coincidence of neighbor layers, and ply layup for the middle layers are set. The process of shuffling of layers is to be performed until it is impossible to change the value of the objective function between two successive iterations.

The optimization of the composite wing is carried out separately from the entire UAV. Also, ailerons are excluded from the optimization process. Optimization of these elements does not provide sufficient weight reduction because of the small area of the elements in relation to the entire UAV. Thus, optimization was carried out for the wing skin and spar inside the UAV wing (Fig. 8, the surfaces to be optimized are marked in green). Parts that were not optimized are marked in red in Fig. 8.

The model includes an aileron kinematic scheme modeled with beam elements and joints, which also takes into account

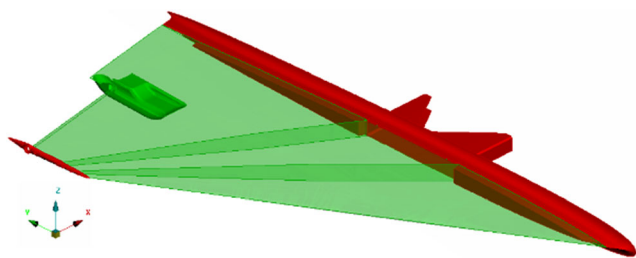


Fig. 8 Wing optimization area

the loads on the bearing assemblies and the mounting points of the servo drives. Forces from kinematic analysis can be used as design constrains in the cycle of optimization.

Wing model is constrained on the spar and along the contour of the fairing. Pressure fields have been obtained for a variety of flight cases using VTB Aerodynamics. Python scripts for VTB “Static Strength” were used for automatic pressure field interpolation.

One of the purposes of optimization is to get better construction with less or roughly equal plies than in basic model. To comply this restriction maximum thickness of skin and spar was limited. This limitation regulates the maximum and minimum number of layers. The initial material thickness distribution before optimization is shown in Fig. 9.

Optimization of the wing surface was carried out in conjunction with the spar. To make the wing more stiff, additional plies were added to the spar, while the number of plies of skin did not change.

The optimization of the wing was held for two different objective functions. In the first case, it is the minimization of the wing compliance, and in the second, it is the minimization of the mass (Fig. 10). Upper branches marked with red are for

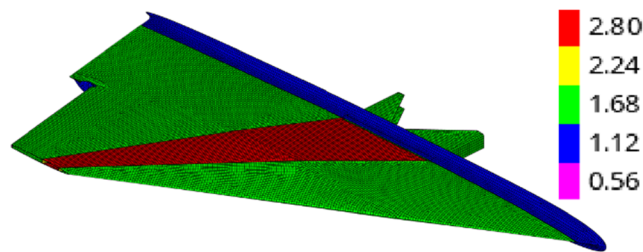


Fig. 9 Material thickness distribution, mm

objective function of mass minimization; lower branches marked with blue are for the objective function of compliance minimization.

Some branches are dead-ended because of the inconsistency to targets and limitation matrix. Successful optimization results are marked with green points.

The result of the first optimization stage is the design concept that does not take into account manufacturing and technological limitations. In this concept, all layer have different thickness and shape, but the structure layout meet all technological constraint, such as minimum and maximum thickness of laminate, mass, and displacements. Figure 11 shows the distribution of material as a result of optimization for one of the models.

The concept design after the first stage of optimization (Fig. 12) is not replicable because of the irregular shape. That is why the first step in the second stage of optimization is to modify layers according to technological requirement. During this modification, engineer removes small pieces of layers or combines them with larger part of layers to make each layer more complete or continuous. The result is a structure shown in Fig. 13.

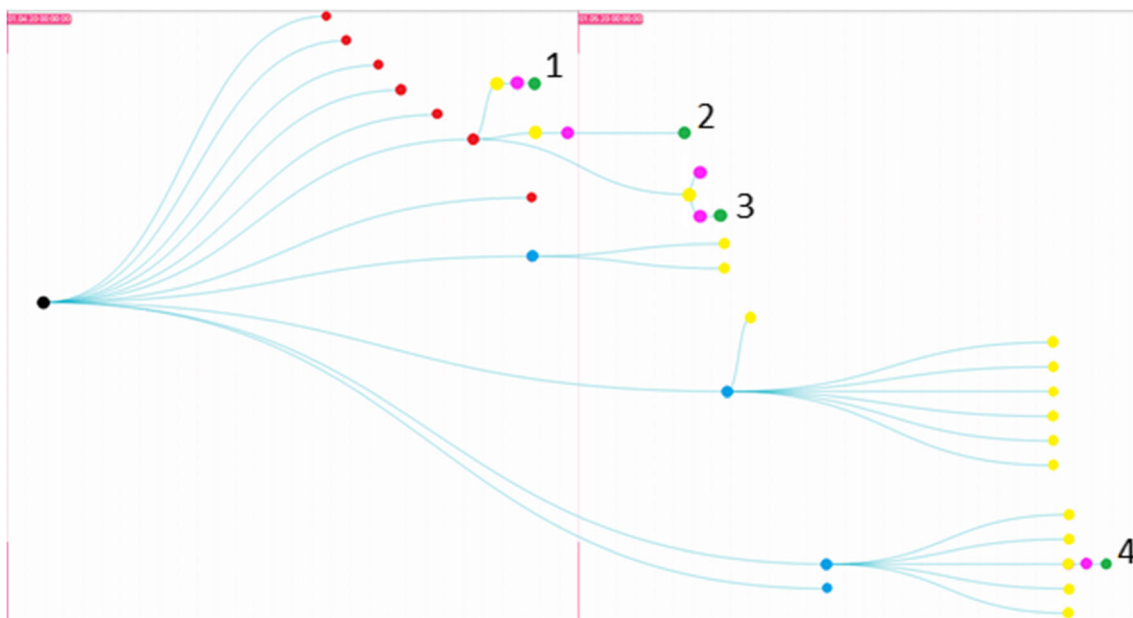


Fig. 10 Optimization process timeline visualization

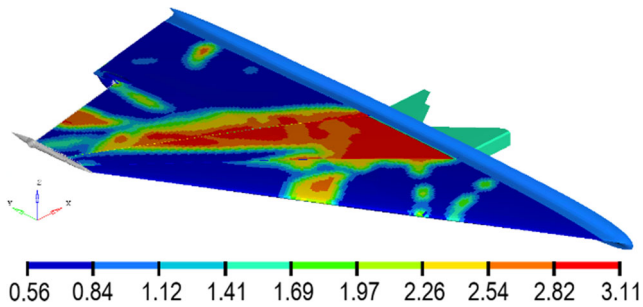


Fig. 11 Material distribution after the first step, mm

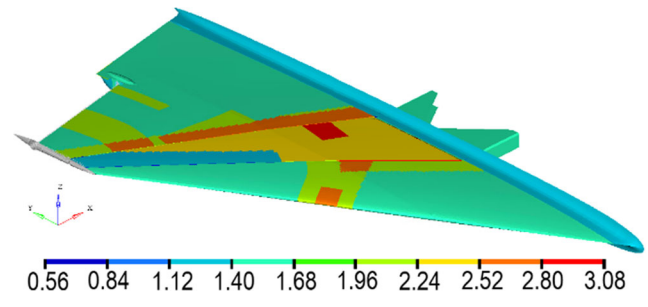


Fig. 13 Material distribution after the second step, mm

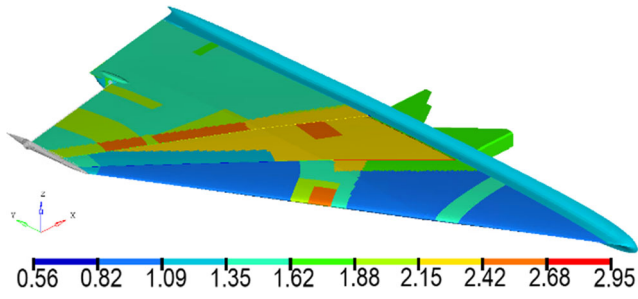
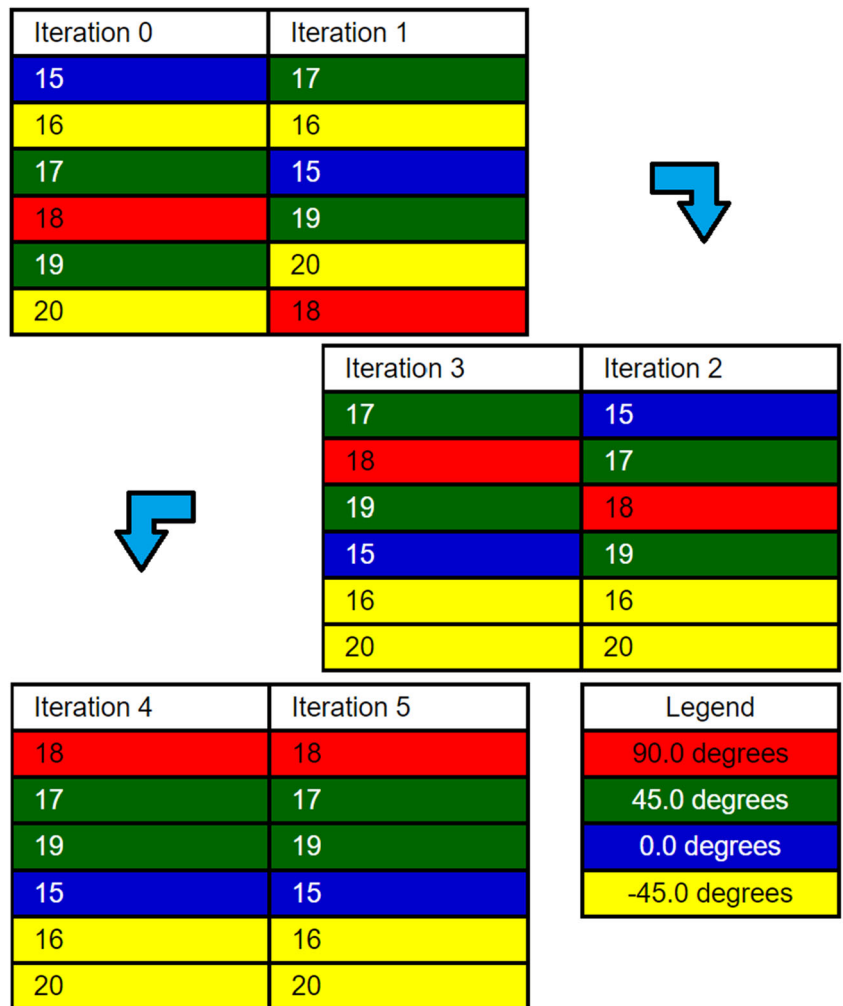


Fig. 12 Material distribution after the design processing, mm

At the third stage of optimization, layers with different fiber orientations are shuffled. At this stage, all design constraints continue to operate from the previous stages. It could also be added extra constraints, such as limitation of the number of plies of the same type (orientation), preferred orientation for core and cover plies. The shuffling of plies is shown in Fig. 14. An example of deformations before and after the 3rd step is shown in Figs. 15 and 16.

Fig. 14 Process of shuffling plies



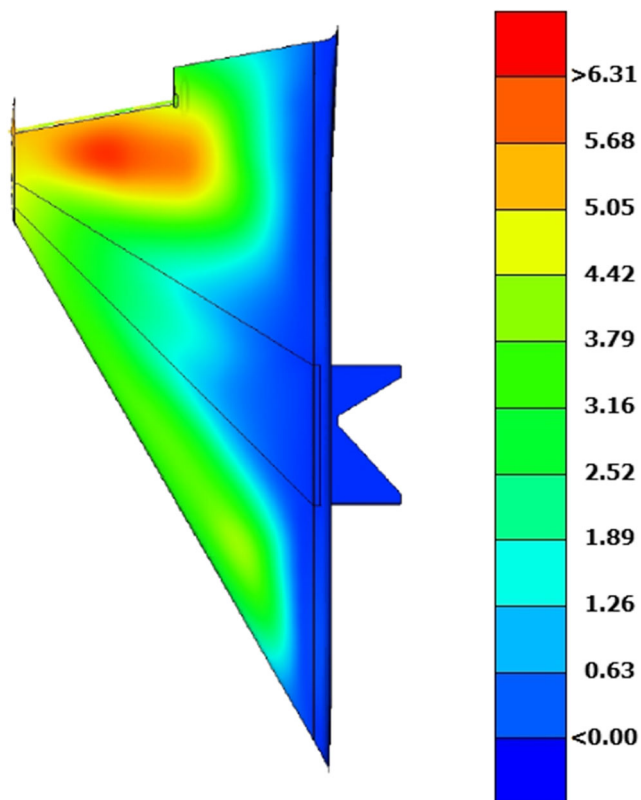


Fig. 15 Deformation after the second optimization step, mm

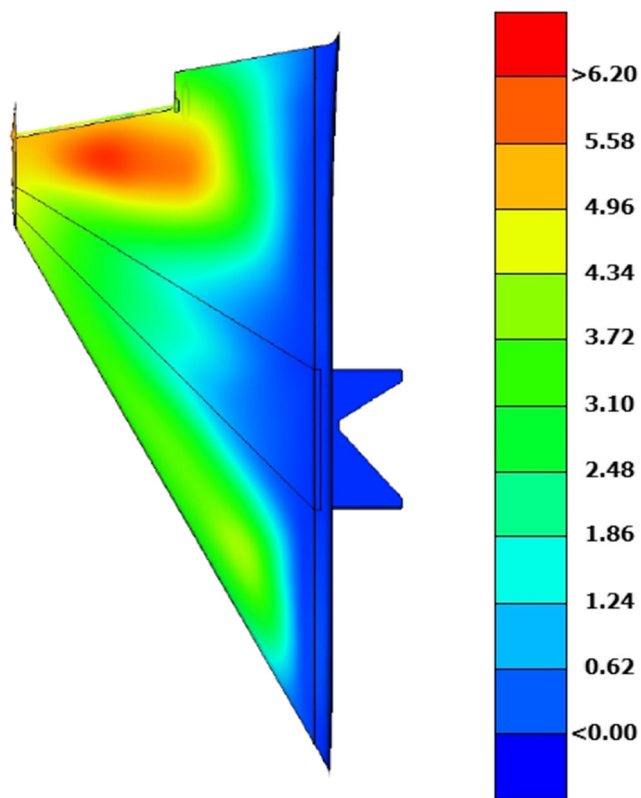


Fig. 16 Deformation after shuffling layers, mm

2.5 Optimization results

As a result of optimization, a construction that satisfies all the design and technological constraints is reached. In the course of optimization, different objective functions were set. Figures 17, 18, and 19 show the material distribution in the case of the wing compliance minimization; Fig. 20 presents the construction in the case of mass minimization. The progress of optimization can be traced in Fig. 10.

As a result of the wing optimization, a set of structures was obtained that satisfy the given conditions of mass and stiffness. Weight of the wing was reduced by 11–14% without any loss of aerodynamic and strength characteristics.

3 Conclusion

This paper provides a method of a comprehensive process for design optimization based on Virtual Proving Ground. The VPG was used to unite virtual tests: to determine the aerodynamic characteristics of structures, obtain boundary conditions for strength and optimization problems, check structures for static and dynamic strength, and automatically post-process the results of the research.

Proposed methodology was shown using the example of a multicriteria multidisciplinary optimization of the UAV structure.

A number of modifications for VPG have been identified for further improvements:

- Buckling of structural elements
- Use a wider range of load cases for optimization
- Taking into account more technological features of the materials

It is also necessary to add the material destruction to obtain a more adequate structure response to the dynamic impact.

Nevertheless, the disadvantage of the proposed method is the lack of automation in the VTB “Optimization,” since the participation of an engineer is required to draw the composite layers.

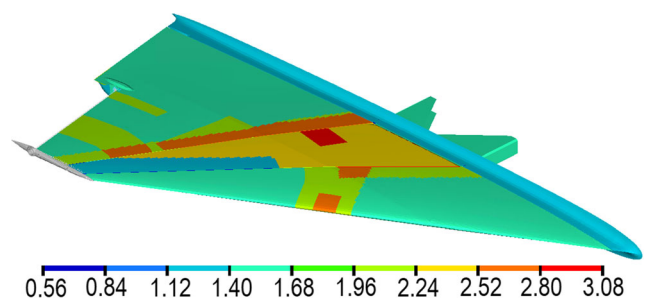


Fig. 17 Material distribution. Rev 1

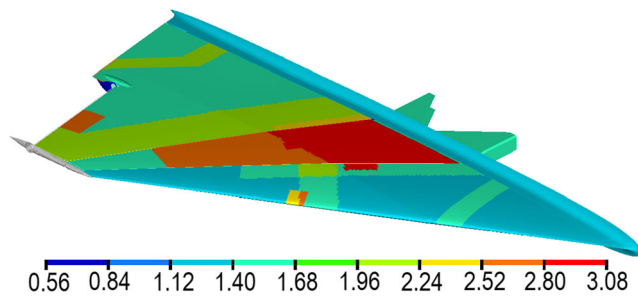


Fig. 18 Material distribution. Rev 2

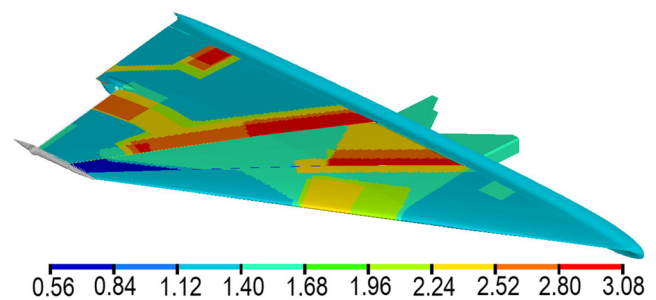


Fig. 20 Material distribution. Rev 4

Also, it is necessary to carry out full-scale tests to validate the methodology, which will be done in further work.

Author contribution Gorskii Yu.A. and Gavrilov P.A. conceived of the presented idea and developed the theoretical formalism. Nikitin G.I. and Pautova T.A. performed the calculations. Tamm A.Yu. aided in interpreting the results. Gorskii Yu.A., Nikitin G.I., and Pautova T.A. wrote the manuscript in consultation with Tamm A.Yu. and Gavrilov P.A. All authors discussed the results and contributed to the final manuscript.

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Data availability The data that support the findings of this study are available from the corresponding author, Gorskii Yu. A., upon reasonable request.

Declarations

Ethical approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

Competing interests The authors declare no competing interests.

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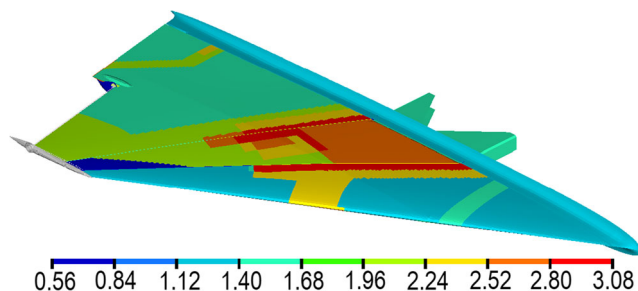


Fig. 19 Material distribution. Rev 3

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