Virtual proving ground for aircraft structures

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Abstract. This paper presents an approach to development of complexes and programs of virtual experimental investigation in order to reduce full-scale testing in the design process of new products via state-of-the-art computer simulation techniques. Generally Virtual Proving Ground (VPG) is to be understood as integrating system for modeling strategies, solver settings, modules of automatic post-processing and load cases that match typical airplane tests and operating conditions. In the VPG environment has been developed a set Virtual Test Beds corresponding to tasks from various technical areas:
- VTB «Static structural strength» for virtual static strength tests to determine the stress-strain state of the structure and identify potentially critical places;
- VTB «Fatigue» for estimating fatigue life under the influence of a multi-cycle load;
- VTB «Durability» for simulating crack growth in the most critical places based on VTB «Fatigue» and «Static structural strength» data;
- VTB «Birdstrike» for simulating tests of bird collisions with aircraft panels;
- VTB «Hailstrike» for simulating tests of hailstones collisions with aircraft panels;
- VTB «Aerodynamics» for determining the aerodynamic characteristics of an aircraft.

Preliminary estimation of structure is possible due to automatic post-processing module: visualization of virtual testing, documentation of results (graphs, pictures, key values) and union of all experimental data into a presentation. The application of presented approach is described on example of stringer panel of a real airplane.

1. Introduction
Over the past few years, more attention has been paid to the development of virtual test methods [1-4]. This fact emphasizes the relevance of the topic presented in the article.
A presented approach is a set of complex (using several interacting types of models) approaches for virtual testing, which allows computer simulation of testing of aircraft products, providing a low error in terms of target characteristics.
The research process includes both the tests themselves and the preparation of the model (preprocessing), as well as the processing of the results (postprocessing). Automation of pre- and postprocessing of mathematical models in addition to automatic interconnection of multidisciplinary tasks, allows to increase the speed and accuracy of engineering calculations and presentation of results.
Preprocessing includes preparation of finite element (or finite volume) models, boundary conditions, material models selection etc.
Effective use of virtual testing is possible only with proper planning of design cases. Boundary conditions (fixing and loading) should as fully as possible reflect the actual working conditions of the structure or the actual conditions of the experiments (including the rig influence in the experimental bench). Virtual tests based on experimental stands should include equipment models as well.
Another no less important step is the development of a matrix of targets and limitations. In relation to the design of aircraft structures it expressed in translating the technical task into digital form: formalizing requirements, determining the group of monitored parameters and results. A mandatory element is the correction of requirements, taking into account the characteristics and limitations of technological processes of production.

A presented approach to virtual testing of aircraft structures is well suited to study the following design scenarios, compiled on the basis of the possible design loads acting on the fuselage of the aircraft [5]:
- Inertial forces from the masses of bodies placed inside the fuselage and its own mass;
- Internal and external pressure on the airtight compartments of the fuselage, the loads from the aerodynamic effects of the incoming flow;
- Local impacts caused by collisions with birds and hail.

2. Virtual proving ground

As said before, Virtual Proving Ground is an integrating system for modeling strategies, solver settings, modules of automatic post-processing etc. It requires well-organized structure for data storage, transfer and management. VPG is based on Digital twin development and computer engineering management system CML-Bench™.

![Figure 1. Scheme of data transfer in VPG.](image)

Models and calculations should be carried out in a measurement system in which the derived units are obtained by multiplying or dividing the base units without using numerical factors. SI units form a coherent system; for example, the unit of force is a newton; kilogram, meter and second are the basic units of the system.

For user convenience FE-models may have modular or include structure:
- Linker: defines the reading order of submodels;
- Submodel of the material base;
- Submodels of FE mesh;
- Submodel of solver settings: BCs, solver cards, output cards;
- Additional submodels.

Usually, due to the size of aircraft structures, the construction of design models is carried out simultaneously by several employees. For the correct assembly of models into one, it is necessary to avoid the same numbers and indices for nodes, elements, sets, etc.

Compliance with the numbering rules allows you to change the FE-model of parts independently from each other without harm for subsequent assembly into a global model.

Often of interest is not only the general behavior of the structure, but also the specified stress-strain state of an individual part (for example determining the risk of cracks in loaded joints and fillets).

For Abaqus and Nastran solvers, scripts have been developed for reading items (nodes and elements sets) of interest for postprocessing. In this case numbering rules are good pointers.
The accuracy and adequacy of the calculation results directly depends on the finite element representation of the structure. Special attention should be paid for modelling strategies including shell-modeling, FE representation of bolted and riveted joints, different metrics for finite element quality etc. The problem of correct modeling of bolt and rivet joints was considered in articles [6-10].

The main tasks performed in postprocessing module are:
- Visualization of virtual tests of the object;
- documentation of the results (creation of graphs, figures, tables);
- combining the data obtained about the object of study into a presentation.
- Processing and recording of so-called keyresults allows engineer to make an express assessment of the design: strength, weight optimization, etc. For analysis of structural strength, keyresults may include:
  - Movements in a given set of points;
  - Maximum stresses in parts;
  - Safety margin in details;
  - Special flags of the boolean type (the fact of non-destruction or destruction).

A function is provided for comparing a key parameter with predetermined values (yield strength, safety factor, etc.). For the convenience and simplicity of the search in a detailed analysis, each result is recorded with an indication of an element or node.

Automated processing of the results is carried out in a post-processor program using session files — a sequence of commands that can be parameterized and executed without manual intervention. The functionality of postprocessors is accessed through the API (Application Programming Interface) using scripting languages such as Python.

3. Virtual test beds

Virtual Test Bed is a set of configuration files for the solver and post-processor, communications between modules are configured for one or a group of specific testings. In general, any software may be used as solvers and this approach allows you to use most suitable software solutions. In this work, the VPG is configured to work with the packages Nastran, Abaqus, nCode and CFX.

3.1. VTB «Static structural strength»

Carrying out virtual tests for static strength allows you to get the stress-strain state of the structure and identify potentially critical places.

For virtual tests were selected the stringer-frame section of the aircraft fuselage (Figure 2) loaded by pressure and the wing mechanization elements: aileron and spoiler loaded by testing rig. These parts are made of high-strength aircraft aluminum. VTB includes base of materials with basic mechanical properties and the material stress-strain curve.

![Figure 2. Airplane stringer-frame section.](image-url)
Results of virtual testing are automatically post-processed and user can make a rapid analysis of structure. Basic available results are the section deflection forms (Figure 3) and stress fields (Figure 4); additionally, 3D-PDFs with displacement and stress fields are created for pre-selected parts, a video of the loading process, types of the part in several projections are recorded.

![Figure 3. Deformed shape of stringer-frame section.](image)

![Figure 4. Stress state of stringer-frame section.](image)

A static strength virtual testing of an aircraft wing mechanization elements allows you to evaluate the stress-strain state of the structure and obtain the value of the shear force in the earrings of the elements. The stand for full-scale tests is a lever design, therefore, in the VTB, the special FE-models of loading pads were developed (Figure 5).
As a result, stress-strain states of the aileron and interceptor are obtained. Deflection forms of the front and rear panel edges are defined. Potentially critical structural locations have been identified. The automatic postprocessing is configured, the main key results are displayed:

- Strength on the booster;
- Moving at the points of the leading edge;
- Moving at the points of the trailing edge;
- Strains in specific places (compared with voltages received from strain gauges).

All these values are automatically compared with the "targets" - the values obtained as a result of field tests.

### 3.2. VTB «Fatigue»

Fatigue virtual testing is performed by applying multi-cyclic loading in order to identify critical areas for crack growth. Testing is carried out on the basis of the stress-strain state obtained during the static structural analysis of VTB «Static structural strength».

VTB includes material fatigue characteristics: S-N type fatigue curves (Stresses - loading cycles).

The picture of damage accumulation in the central frame of the stringer-frame panel is shown in Figures 6 - 7.

In the areas highlighted in Figure 7, damages begin to appear after 3600 cycles.

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**Figure 5.** An aileron loading scheme.

**Figure 6.** The most damaged frame.
3.3. VTB «Durability»

Durability calculations are based on the results of VTB «Static structural strength» and VTB «Fatigue». The most critical places of the structure are determined and graphs of crack growth in these places are obtained.

VTB uses the same loading cycles as were used for fatigue loading and includes material fracture toughness characteristics (generally obtained by field tests):
- fracture toughness;
- crack growth rate curves (Crack growth rate - stress intensity factor).

Based on the geometry of the section in which the crack will propagate, and the stress-strain state in this section, obtained as a result of static analysis, a mathematical model is selected to obtain the dependence of the stress intensity factor on the length of the crack.

Then, a cyclic loading is to be applied to the calculation model. The main measurable criterion is the growth of the crack length depending on the number of loading cycles applied.

The most critical crack growth graph is shown on a figure 9. In the presence of an initial crack, structural failure will occur between 350-400 loading cycles.
3.4. VTB «Birdstrike»

Bird resistance testing is an essential part of aircraft development. Such testing refers to high-speed dynamic effects involving the “soft” body. This indicates that the stresses arising in the contact area significantly exceed the strength of the impactor (bird), but are lower in relation to the strength of the test structure (parts of the wings, tail, etc.). Due to the high deformability of the impactor, the shock propagates rapidly in a certain area at the moment of impact. In this regard, it is necessary to use special material models taking into account the influence of the strain rate.

It was shown in [11] that during high-speed processes, the bird's body behaves like a liquid. Therefore, it is proposed to use a hydrodynamic model of the material to describe the rather complex structure of the bodies of real birds under high-speed impacts.

A mathematical model of a bird impactor was developed and validated at SPbPU [12], which corresponds to 1.8 kg of bird impactors actually used in field tests. This mathematical model is an integral part of the VTB. As a solver, ABAQUS software version 6.14 of the developer Simulia was chosen, which for many industries is certified for solving problems of high-speed dynamic interaction, which includes the task of assessing bird resistance.

This VTB uses the Coupled Euler-Lagrange (CEL) approach. In this case, the target with which the contact interaction occurs is modeled by the standard Lagrange method. The impactor is modeled using the Euler method. In this case, the finite element mesh can move after the main part of the material and change its dimensions in the process of solving the problem.

Verification of the bird impactor model and analysis of modeling techniques were carried out in [12] using the parameters: maximum values of interaction forces and contact stresses, value of stationary flow pressure and Hugoniot pressure.

As part of the development of the VTB, a program was developed for solving the system of transcendental equations (48) - (61) from [11] in the Mathcad package. As input data, material properties, porosity (an indicator of the volume fraction of air in the material) and the initial impactor speed are set. The calculations for the following materials are implemented: water, gelatin, vulcanized rubber, "bird". The result of the solution (the equation of state coefficients) from equation (1), are used to construct a model of the impactor material in a finite element formulation.

\[ P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 \]  

where \( P \) – pressure; \( \rho_0, \rho \) – material density at atmospheric pressure and in the shock wave formation phase; \( C_i \) (\( i = 0-3 \)) – experimental polynomial coefficients.

Model is calibrated to simulate collisions with velocities up to 500 km/h. Figures 10-11 demonstrate the aftermath of bird strike in different areas of stringer-frame section – critical damaging with breaking of skin surface.
3.5. VTB «Hailstrike»

In concert with Birdstrike, Hailstrike resistance testing is an essential part of aircraft development. A mathematical model of a hail developed and validated at SPbPU is based on a series of experiments [12] on the collision of ice spheres with a titanium plate at high speeds (73.5-126 m/s). This mathematical model is an integral part of the VTB.

Currently, commercial FE packages do not have a suitable ice material template for modeling high-speed collisions, despite interest from the aerospace industry. It is also worth noting that ice is not one type of material with well-known properties; in the literature there is a description of about 13 different crystalline structures and two amorphous ones.

In this paper for ice is used a homogeneous elastoplastic material with linear hardening and yield strength, which depends on the strain rate.

The hail model is a sphere with a diameter of 50 mm. In contrast to birdstrike analysis the Lagrangian formulation is used, since hail behaves like a solid at high speeds. The hail material takes into account its destruction at stresses of 5.2 MPa. During the simulation, the hail completely collapses during a collision with a stringer-frame panel. The hail material also takes into account the plastic behavior of ice, which depends on the rates of plastic deformation [13, 14].

Model is calibrated to simulate collisions with velocities up to 500 km/h. Figures 12-13 demonstrate the aftermath of hail strike in different areas of stringer-frame section – plastic strains occurred.
3.6. VTB «Aerodynamics»

High efficiency and aerodynamic qualities of the aircraft are laid at the design stage of the appearance. The main geometric parameters, such as the length, width and height of the aircraft, as well as the wing span, profile selection, determination of the area of the control planes, on which its aerodynamic characteristics directly depend: lift coefficient, drag coefficient and others, must be determined at the development of any project. VTB «Aerodynamics» provides wide opportunities of virtual testing: simplifies the process of obtaining aerodynamic characteristics, allows an increase a number of tests without raising costs, consider all possible design options.

VTB was tested and models were calibrated on a set of airfoils: A-12, P-III, NASA-0018 [15] and ultralight aircraft A-8 at different angles of attack. Values of the lift and drag coefficients obtained
during the TsAGI experiment practically coincide with the values obtained in the numerical solution (Figure 14).

![Figure 14. Lift coefficient, SLA A-8.](image1)

Special scripts have been developed for data transfer between multidisciplinary tasks of VTB «Static structural strength» and VTB «Aerodynamics». For example, one of them read pressure distribution (Figure 15) on aerodynamic faces and interpolate them to finite element mesh.

![Figure 15. Pressure distribution, SLA A-8.](image2)

VTB «Aerodynamics» can be used for optimization purposes: searching for an optimal wing profile shape with multiple geometry changes. Automatic systems of pre- and postprocessing provide multiple speed-up in engineering work. Optimal shape searching history is shown on figure 16. The best modes with high lift and low drag coefficient are marked with numbers 1 and 2.
4. Conclusion
The developed modeling methods of aircraft structures (FE-mesh criteria, model structure, numbering, features of connection models), material models, data transfer paths allow virtual testing of structures made of metal and composite materials.

The main advantage of this work is the use of a highly adequate and multidisciplinary approach for virtual testing and optimization of an aircraft elements, which gives a significant reduction in costs during its development.

Developed Virtual Proving Ground covers wide variety of technical areas and easily can be expanded with additional Virtual Test Beds due to flexibility of data management system.

References
[1] Ostergaard M G, Ibbotson A R, Roux O L and Prior A M 2011 Virtual testing of aircraft structures CEAS Aeronautical Journal (Vol.1) pp 81-103
[2] Chirme A., Parle D, Awati N, Udali R and Kulshreshtha S 2012 Integrated Tool for Strain Extraction in Virtual Testing SIMULIA Community Conference
[3] Wang Ch 2016 A multidisciplinary design and analysis environment and its application to aircraft flight dynamics analysis Journal of Industrial Information Integration (Vol.1) pp14-19
[4] Nu X 2005 Digital Simulation of Full Scale Static Test of Aircraft Chinese Journal of Aeronautics (Vol. 18 №2) pp 138-141
[5] Chepurnykh I V 2013. Prochnost konstruktsiy letatelnykh apparatov [The strength of aircraft structures. Training manual] FSFEI HPL “KnASTU”
[6] Rutman A and Bosher C 2007 Fastener Modeling for Joining Parts Modeled by Shell and Solid Americas Virtual Product Development Conference
[7] Martins R, Ermani S P and Lorentz A 2017 Influence of Types of Discrete Modelling of Fasteners in FEM Models NAFEMS World Congress
[8] Rutman A, Viisoreanu A and Parady J 2000 Fasteners Modeling for MSC.Nastran Finite Element Analysis SAE Transactions (Vol. 109 Section 1: JOURNAL OF AEROSPACE) pp 1220-1237
[9] MSC Software. Case Study: Gulfstream 2015 (Retrieved from https://www.mscsoftware.com/sites/default/files/cs_gulfstream_ltr_w.pdf)
[10] Martins R, Ermani S P and Santos M 2018 Fastening Analysis Using Low Fidelity Finite Element Models 31st Congress of the International Council of the Aeronautical Sciences
[11] Wilbeck J S 1974 Impact Behavior of Low Strength Projectiles Final Report. Air Force Materials Lab
[12] Carney K S, Benson D J, DuBois P and Lee R 2006 A phenomenological high strain rate model with failure for ice International Journal of Solids and Structures (Vol 43) pp 7820-7839
[13] Kim H and Kuene J N 2007 Compressive Strength of Ice and Impact Strain Rates Journal of Material Science (Vol.42) pp 2802-2806
[14] Sain T and Narasimhan R 2011 Constitutive modeling of ice in the high strain rate regime
International Journal of Solids and Structures (vol. 48)

[15] Spravochnik aviatsionnykh profiley [Aviation airfoils handbook] (Retrieved from
https://kipla.kai.ru/liter/Spravochnic_avia_profiley.pdf)