Inter-Disciplinary Approach to Suborbital Reusable Spaceplane Composite Wing Design

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Abstract. The development of the wing of suborbital reusable spaceplane is a complex task due to conflicting requirements that are sufficient for its structure. They include high mass and cost efficiency, sustainability, low g-forces, effective heat protection under the consideration of technological restraints. To satisfy outlined requirements in the design of the composite wing the inter-disciplinary approach is presented relying on advanced methods of mathematical modelling. The approach starts with wing shape optimization enabling to get good aerodynamic performance. Subsequent optimal re-entry trajectory planning which use both angle-of-attack and angle-of-bank changes to control the re-entry provides a set level of g-forces and heat flux. Then based on the obtained trajectory the aerodynamic loads for the wing are gained. To acquire composite materials properties of the wing the analysis/test approach is applied that comprises multilevel modelling of mechanical and thermal material properties by commercial software. The results of modelling are validated by experiment. In addition, to enhancing mass efficiency of the wing structure the topology optimization of its wing box and structural optimization of the wing skin is conducted which uses both angles of orientations and thicknesses of composite monolayers as the variables with constraints on the strength and stiffness of wing skin. Furthermore, the approach includes thermal design due to high aerodynamic heating taking place during re-entry. Thermal loads are analysed by modelling the thermal state of the structure. The analysis showed that the wing skin needs thermal protection. As the thermal protection coating, the material based on glass microspheres was chosen. Its thickness through wing is obtained in the result of parameter optimization. As the result, the interdisciplinary approach to the design of the spaceplane composite wing is developed that allows feeding back mass, economic, aerodynamic, heat and strength impact into the spaceplane wing design synthesis.

1. Introduction
Human spaceflight and space exploration has traditionally been a well-funded domain of government [1]. Nevertheless, over the past decades, the interest to the business-driven space transportation systems has increased considerably [2]. Nowadays robust technological development by certain private companies, entrepreneurs, and research groups to make private spaceflight an everyday reality has surged. SpaceX Crew Dragon launch to the ISS successfully demonstrated private sector capability to design, test and operate a spacecraft for human spaceflight [3]. This event marked the start of a new era of commercial access to space.

The prominent branch of the space industry that has advantageous commercial application is space tourism [4-7]. Current market trends show a huge potential demand for space tourism especially for suborbital one [5]. In contrast to orbital space tourism, suborbital travel represents a brief spaceflight
that fails to complete one full orbit of the Earth. The suborbital spaceflight bases on using reusable launch vehicles that can achieve an altitude of about 100 km above sea level and then subsequently land safely and after some time take-off again. This type of travel lets passengers experience g-forces, the curvature of the Earth and weightlessness by taking them up to the Karman Line, which is at an altitude of about 100 km [6, 7]. Recently, a number of private companies all over the world are involved in the space tourism activity. The examples of suborbital reusable spaceplane projects could be RocketplaneXP (Rocketplane Kistler, USA, 2005), New Shepard (Blue Origin, USA, 2006), Space Plane (EADS Astrium, France, 2007), Lynx Mark (XCOR Aerospace, USA, 2008), SpaceShipTwo (Virgin Galactic, USA, 2010), Oduvanchik (Bauman MSTU, Russia, 2007), Reusable Suborbital Space Complex (Cosmocourse, Russia, 2014) and others [8].

In Bauman University [9-11] during some years the suborbital spaceplane Oduvanchik is being developed. The general scheme of spaceplane is presented in figure 1.

The spaceplane flight profile includes the following phases: vertical lift-off by means of a booster stage, the spaceplane separation from a booster at an altitude of approximately 46 km, and the next flight under inertia forces up to an altitude of 102 km. At the apogee, tourists enjoy the view of Earth and experience the microgravity environment for 4 minutes as the spaceplane slowly decelerated before its descent into the atmosphere. At the end of the mission, the spaceplane lands horizontally.

The spaceplane structure contains 9 m fuselage length and V-shaped empennage that consists of two slanted control surfaces that operate as both vertical and horizontal stabilizers and perform the functions of rudder and elevator.

The essential structural element of the suborbital spaceplane that significantly determines its design appearance and weight efficiency is the wing. According to design data, the spaceplane consists of the trapezoidal wing that is an aerodynamic surface with leading edge sweep and straight trailing edge. High wing configuration offers better visibility below the vehicle and its stability. The span of 7.5 m and the area of 20 m² characterize the wing. The root and the tip chords are 4.3 m and 1.6 m respectively.

The wing skin is designed to minimize its weight by using composite materials and represents a sandwich panel made of lightweight aramid honeycomb core and hybrid polymer matrix composite (PMC) layers. For technological and economic reasons, hybrid composite layers consist of glass fibre fabric with harness-satin weave and unidirectional carbon fibre tape, as well as an epoxy resin are used. The hybrid PMC layers is mainly carrying tension and compression loads while the honeycomb bears compression and shear loads (figure 2) [12].
2. Literature Review

The engineering design of the spaceplane wing is a complex scientific and technical issue. Because the wing of the suborbital reusable spaceplane is highly complex, interconnected, and operates in extreme conditions, its design represents a challenge of the highest order [13]. Spaceplane requires both very high cost and mass efficiency, sustainability, low g-forces, effective heat protection under the consideration of technological restraints. Low g-forces requirement is driven by medical reasons. High values of g-forces cause blood pooling in the extremities because the heart is unable to overcome the acceleration forces and complete the circulatory process [13]. Meeting the design challenges resulting from the combination of the preceding factors demands the interdisciplinary approach and is presented relying on advanced methods of mathematical modelling [14-16].

The literature review shows that nowadays there are traditional [13] and recently developed [17-19] approaches to spaceplane design. The presented suborbital spaceplane occupies an intermediate position between hypersonic spaceplanes such as the Space Shuttle [20] and the Buran [21] and traditional supersonic aircraft. However, the traditional design methodologies that are used for aircraft or Space Shuttle are not applicable for the suborbital spaceplane due to significant differences that are described hereinafter. The velocity of the suborbital spaceplane is close to a jet fighter’s velocity, but unfortunately, in open sources there is no information about detailed methodology characterized in that the spaceplane composite wing as a particular design object is considered.

As compared with aircraft the spaceplane gathers higher velocity. The significant thermal and force loads that occur during re-entry defines special requirements that were listed hereinbefore. Moreover, as the suborbital spaceplane is not provided with a powerplant, it glides into the atmosphere under gravity and aerodynamic forces. Hence, the lift should be sufficient for comfortable and safe landing [8]. To develop optimal wing configuration that provides sufficient aerodynamic quality whilst landing is a complex, iterative, and interconnected procedure. For instance, the change in wing configuration leads to changes in its aerodynamic characteristics that, in return, initiates changes in trajectory parameters. Wing configuration also defines the g-loads. The increase in the wing area leads to g-loads reduction, but it also initiates weight and cost rising. Moreover, the large-area wing is ineffective at high Mach. Note that spaceplane wing is made of PMC that allows to reduce the weight of the wing and to increase cost efficiency by obtaining the optimal layout of the multilayer wing skin and rational wing box of the irregular structure by means of topology optimization.

In contrast to Space Shuttle, the suborbital spaceplane has at least eight times lower re-entry velocity in the atmosphere and a significantly different flight profile. Furthermore, the structural frame of Space Shuttle mainly made of metal whilst load-carrying elements of suborbital vehicles can be manufactured from PMC that is connected with lower thermal fluxes occurring during re-entry [22]. Temperature of the Space Shuttle wing leading edges reached about 1650 °C during re-entry. It required the development of the combined thermal protection system that covered essentially the entire surface and consisted of several types of materials such as tiles, advanced flexible reusable surface insulation, reinforced carbon-carbon. In case of the suborbital spaceplane, such thermal protection measures are
redundant as the thermal fluxes are much lower. In order to provide suborbital spaceplane thermal protection, the different approaches should be considered in terms of weight and cost. Furthermore, the methodologies developed in the 1980s can be amplified by advanced methods of mathematical modelling that are available nowadays.

The aim of the current study is to present an inter-disciplinary methodology relying on advanced methods of mathematical modelling for the suborbital spaceplane composite wing design in order to satisfy outlined requirements. The synthesis design methodology for spaceplane is a systematic or orderly way to the design of complex aerospace vehicle systems, where the interaction among several disciplines must be considered. The methodology couples key design disciplines such as trajectory, aerodynamics, weight, thermal, material science, economy, and performance. As a consequence, valuable feedback for design feasibility, sensitivities, and constraints can be obtained in a short time.

3. Design philosophy of the spaceplane wing

The design methodology of the spaceplane wing is a complex iterative procedure. The comprehensive illustration can be viewed in wheel-like fashion as shown in figure 3. The mainstream design process is broken down into nine stages: aerodynamic shape optimization, choice of rational trajectory parameters, aerodynamic flow analysis, obtaining of material properties by test/analysis approach, topology optimization of the wing box and thermal design.

![Figure 3. The representation of design procedure for suborbital spaceplane wing design.](image)

The first step of the methodology is aerodynamic shape optimization that allows generating wing appearance based on the aerodynamic characteristics calculation [23, 24]. There are two design cases considered successively for shape optimization: subsonic and supersonic flight. Subsonic one is associated with the need to ensure the required lift level immediately before the landing and touchdown speed. In this case, the objective is to minimize wing square that drives mass reduction. The supersonic case involves maximization of aerodynamic quality of the wing at an altitude of approximately 30 km, which is characterized by maximum aerodynamic loads [25, 26]. For both stages as design variables the following geometry dimensions of the wing are considered: length, leading-edge sweep angle, taper
ratio and a maximum thickness of root and tip chord. Note that constraint on the minimum wing sweep angle equal to 40 degrees is applied.

For obtained wing appearance the flight profile is developed. Firstly, the aerodynamic coefficients that define the aerodynamic performance of the unpowered spaceplane are acquired by CFD analysis in commercial software. Next, by the solution of the equations of three-dimensional gliding dynamics, the time-dependencies of basic trajectory parameters are obtained. Use both angle-of-attack and angle-of-bank changes to control the re-entry provides a set level of g-forces and heat flux during spaceplane re-entry into atmosphere. As the result, the time-dependencies of altitude, velocity, flight path angle, g-load factor variation, bank angle, dynamic pressure and heating rate variations are found. The developed flight profile is then used in the computation of thermal, strength loads for structure and thermal protection system designs.

According to flight profile, the suborbital spaceplane operates in a wide range of velocities (its maximum speed is 3.6 M at an altitude of approximately 40 km) and is exposed to intensive aerodynamic heating during re-entry into the atmosphere [27]. Therefore, the spaceplane design requires data on the thermal properties of hybrid composites applied in structure (thermal conductivity coefficients in different directions, heat capacity and density) in dependence on temperature. In addition to thermal properties, the reliable information on physical and mechanical characteristics is required in order to develop the composite wing box and to define the overall wing strength level. To acquire composite materials properties of the wing the analysis/test approach is applied. It comprises the multilevel modelling of material properties via generation of a representative volume element (RVE) of the composite. Obtaining of material properties includes the generation of a RVE, the application of load to its faces, and the subsequent calculation the values of both physical and mechanical properties such elastic and shear modulus, Poisson’s ratio and thermal properties such thermal conductivity coefficients via finite element analysis.

To confirm the reliability of the numerical modelling results, its validation by comparison with the data obtained by experimental studies is conducted. As the result of the experimental research, thermal conductivity through-plane is obtained by laser flash method as well as thermal conductivity in-plane – by specialized heat equipment developed in Bauman University with a subsequent solution of the inverse heat conduction problem. The physical and mechanical properties are also validated by tensile strength tests.

To reduce the mass of the spaceplane wing, the topology optimization of the wing box is carried out in two stages. Firstly, the number and arrangement of the structural frame components are determined. In this case, an objective function is used to minimize the wing compliance with a constraint on the material volume fraction inside the wing and the total displacement. Secondly, the optimal layout of the composite structure elements is obtained [28]. To find the optimal layout of the obtained through previous optimization stage the topology optimization is conducted and formulated as follows: minimization of the weight with a constraint on the composite failure index of the wing skin, which value is chosen due to reusability of the vehicle, and the wing total displacement. To check optimization results and fulfillment of the applied constraints, the validation procedure is conducted in order to evaluate the composite failure index.

In addition, to enhancing mass efficiency of the wing structure, the optimization of its skin is conducted which uses both angles of orientations and thicknesses of composite monolayers as the variables with constraints on the strength and stiffness of wing skin. Described topology and structural optimizations allow not only design the lightweight structures but also realize the benefits of anisotropic composite microstructures.

Furthermore, the methodology includes thermal design due to high aerodynamic heating taking place during re-entry. Thermal loads are analysed by modelling the thermal state of the structure. The analysis showed some wing sections are exposed to the influence of the temperatures exceeding the allowable service temperature for polymer composites and need thermal protection (TP). Thus, the maximum service temperature for epoxy resin does not exceed 420 K. As the TP, coating based on glass microspheres is chosen. Its thickness through the wing is obtained in the result of parameter optimization in commercial software. Therefore, the leading edge as well as parts of the windward and
leeward sides of the wing needs to be thermally protected. As the temperature distribution is uneven within the wing surface and thereby it is reasonable to apply different thicknesses of the TP layer on the different sections. Hence, it’s necessary to find an optimum distribution of the TP within the RSV wing surface. However, parametric optimization of the TP thickness is necessary. Such optimization could be conducted by means of the introduction of the set of line-segment functions with apexes, which are coincident with the borders of the root and tip wing chords. Between these borders, the TP thickness varies linearly in both directions – along the chord length and along the wingspan.

To demonstrate the feasibility of the developed approach the solution of one of the methodology stages – aerodynamic coefficients determination for obtaining the mission profile is presented. In addition, pressure coefficients for subsonic and supersonic regimes are presented.

4. Solving of the formulated tasks

4.1. Aerodynamic coefficients determination

For trajectory design, the unpowered reusable spaceplane is assumed as a point mass. In order to obtain input aerodynamic coefficients versus Mach number, the modelling of aerodynamic flow field over the spaceplane surface for reference suborbital trajectory is conducted using the commercial software [29]. Baseline spaceplane configuration obtained in the result of shape optimization for subsonic and supersonic regimes is used [8, 30]. The complexity of the aerodynamic flow analysis is in the variety of flow conditions associated with wide ranges of the angle-of-attack and Mach. This required detailed tuning of each design case and careful control over the level of residuals, especially for supersonic gas flows.

The resulting dataset contains values for drag coefficient \( C_x \) and lift coefficient \( C_y \) over a range of angles-of-attack \( 10^\circ \leq \alpha \leq 40^\circ \) and Mach numbers \( 0.1 \leq M \leq 4 \). The datasets are depicted in figure 4.

It is shown that up to \( M \approx 0.5 \), the values of aerodynamic coefficients are practically constant since the compressibility of the medium (air) is practically not manifested. The transonic transition (“the sound barrier”) is clearly visible. It is accompanied by an abrupt change in the flow phenomena around the spaceplane and a sharp increase in the drag coefficient. The values of the aerodynamic coefficients decrease with a further increase in the velocity \( M > 1 \). Obtained coefficients are used for further analysis of trajectory parameters and choice of the optimal wing configuration.

![Figure 4. Aerodynamic coefficients: (a) \( C_x \) and (b) \( C_y \) vs. Mach number](image-url)

4.2. Determination of pressure and temperature fields for the spaceplane wing

Analysis of spaceplane aerodynamic flow is performed by means of Fluid Flow module of FEA-package ANSYS Workbench. Modelling is conducted for landing and the most critically loaded trajectory interval – spaceplane re-entry with a high angle of attack at an altitude of approximately 30 km. To describe turbulence processes in the flow, two-equation k-\( \varepsilon \) turbulence model with standard wall
functions is used. The resulting pressure coefficients distribution that demonstrates the difference in lift creation by over- and under-pressure between subsonic and supersonic flight is depicted in figure 5. Comparison of the velocity streamlines that demonstrates the flow phenomena for both velocity regimes is illustrated in figure 6.

**Figure 5.** Pressure coefficient contours for the spaceplane:
(a) at 30 km altitude at the angle-of-attack 40 ° and
(b) landing at angle-of-attack 10 ° (1 – upper surface; 2 – lower surface).

**Figure 6.** Velocity streamlines for the spaceplane:
(a) at 30 km altitude at the angle-of-attack 40 ° and (b) landing at angle-of-attack 10 °.

**Figure 7.** Temperature on the spaceplane surface at 30 km altitude at the angle-of-attack 40 ° [K].
Critical regions of the wing surface could be distinguished, e.g. the leading edge and neighbouring section in the windward side of the wing are subjected to the highest temperatures influence. Thus, the spaceplane surface temperature could reach 496.5 K (figure 7). As obtained in the result of CFD-analysis temperature exceeds the allowable service temperature of the matrix based on epoxy resin. As the TP the different materials are considered. In the result of weight analysis, the coating based on glass microspheres is chosen. Its thickness through the wing is obtained in the result of parameter optimization in commercial software [10].

5. Conclusion
In this study, we presented the interdisciplinary methodology of the spaceplane composite wing design. The methodology couples key design disciplines such as trajectory, aerodynamics, weight, thermal, economy, and performance. As a consequence, valuable feedback discussing design feasibility, sensitivities, boundaries, and constraints can be obtained in a short time from this top-level simulation process.

The feasibility of the developed methodology is illustrated with an example of a composite wing for spaceplane developed in Bauman University. By CFD analysis, the aerodynamic coefficients that define the aerodynamic performance of the unpowered glider are obtained. The results of aerodynamic flow analysis that are used for further analysis of trajectory parameters and choice of the optimal wing configuration, also in the strength and thermal spaceplane wing design are presented.

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