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Textile Cover Effect on Aerodynamic Characteristics of a Paraglider Wing

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Abstract
Defined herein are the two PA-fabrics covering a paraglider wing, with the comparative object being permeable clothing material. The material parameters of textiles are applied in numerical simulations of aerodynamic characteristics using the program ANSYS. The state variable is the pressure within the airfoil profile. The space model of a paraglider wing and plane model of its cross-section in the symmetry plane are analysed. The model was approximated by the coordinates of crucial points and smoothed by the spline-curves. The visualisation of stream filaments shows that it is advisable to cover the wing with the impermeable fabric.

Key words: *textile cover, aerodynamic characteristics, paraglider wing.*

Nomenclature

b	*wing/airfoil span, m*
c	*wing/airfoil chord, m*
c_k	*external chord of wing/airfoil, m*
c_0	*internal chord of wing/airfoil. m*
c_w	*specific heat, J/(kg K)*
$c_x; c_z$	*air resistance coefficient along the corresponding axis, –*
F_x	*elementary mass force, kg*
$\vec{F}_m$	*vector of unit body forces, N/kg*
P	*aerodynamic lift, N*
P_x	*component of aerodynamic lift parallel to flight direction, N*
P_z	*component of aerodynamic lift orthogonal to flight direction, N*
p_n	*surface stress/pressure, Pa,*
$\dot{q}_m \rho dV$	*heat flux density transmitted through the volume dV in unit of time, N/(m s)*
$\dot{q}_n dA$	*heat flux density transmitted through the surface dA in unit of time, N/(m s)*
S	*airfoil area, m²*
T	*temperature, °C/K*
V	*volume of airfoil area bounded by external surface of profile A, m³*
v	*flying speed, km/h*
v_c	*circulation speed, m/s*
λ	*wing/airfoil extension, –*
ρ	*air density, kg/m³*

■ Introduction

The prototype of the hang-glider was known in the 1960s as the Rogallo wing, which was successively improved towards the paraglider idea. The basic parameters of the paraglider were permanently optimised, primarily the shape and material properties. There are general sources describing the choice of coating materials for paraglider wings [1,2]. Specialised companies publish a precise description of textile material parameters

[3, 4], but the literature available does not analyse the textile coverage effect on the aerodynamic characteristics of a paraglider wing. Some articles incorporate different textiles of variable characteristics [5]. The first step of analysis is to define the physical model, i.e. the physical phenomena within the airfoil profile. The physical model of different materials was discussed in [6, 7]. Future trends can introduce optimisation techniques connected with the ideas of mechanics and heat transport [8-10]. Basic information concerning the paraglider and flight are published in [11-13].

The paraglider is characterised by a flexible structure without stiffening rods, and usually consists of four basic elements: the wing, control ropes, supporting tapes and body harness. The wing contour is elliptical in the top view, and the cross-section is an airfoil profile securing advantageous pressure distribution during flight, shown in *Figure 1*. The covering material is designed at the analysis stage according to assumed requirements, and should be lightweight as well as resistant to the load applied, weather and UV-radiation. The internal reinforcements should be relatively rigid and fail-safe.

The wing cover is made of impregnated synthetic textiles, which reduces the permeability coefficient and influences aerodynamic perfection. The fabrics are manufactured using the reinforcing technology Rip-Stop [3, 4]. The thick threads are regularly interleaved according to the transverse scheme during weaving, *Figure 2*. The fabrics, being of high tenacity, have an insignificant weight, which is secured by polyamide PA 6.6. The typical linear mass of single fibres is equal to 3.3 tex. The thick threads are composed of 10 filaments of 3.3 dtex linear mass which generate the corresponding strength and resistance of the fabric.

The impregnate on the external surface reduces the fabric permeability, thereby ensuring adequate rigidity and UV-resistance. To ensure top quality, the impregnate layer should be very uniform, with an accuracy of 10^{-3}kg/m². The ingredients and proportions of the impregnate are not announced by producers but change according to the properties required, with the most important component being polymer PU [1, 3, 4].

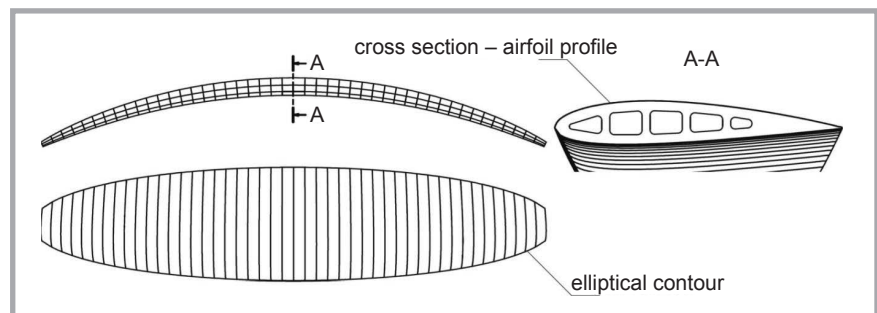The main goal is to analyse the textile cover effect on the aerodynamic char-

Figure 1. Airfoil of paraglider in front view, top view and cross-section.

acteristics of a paraglider wing. The dynamics of air motion are determined by conservation equations of mass, momentum and energy in a general vector form accompanied by the boundary conditions i.e. the environmental conditions. The problem is solved numerically using a model of a paraglider wing according to the program ANSYS.

The novelty elements are the following: (i) A similar analysis was not found in the literature available; (ii) the different physical phenomena are introduced, for example the lifting vortex, circulation vortex, and boundary vortex at the wing tip; and (iii) the pressure distribution obtained can explain the aerodynamic behaviour of a paraglider during flight.

Aerodynamic characteristics: physical and mathematical model

The paraglider wing should ensure aerodynamic lift near orthogonal to the flight direction, shown in **Figure 3**. Advantageous for flight is the component P_z, and component P_x is the resisting force. The more deviated force P_x is from the flight direction, the more perfect the wing. Aerodynamic perfection d is defined according to the formula.

$$d = \frac{P_z}{P_x} \qquad (1)$$

Aerodynamic perfection depends on the shape of the airfoil profile, the inclination of the profile in respect of the flight direction, and on the geometry of the wing contour.

The geometry of the wing contour is defined by (i) the airfoil area, (ii) the wing span, (iii) the chord, and (iv) the extension, as in **Figure 4**. The wing extension is determined by the equation.

$$\lambda = \frac{b^2}{S} \qquad (2)$$

The higher the extension λ, the better the paraglider performance. It is usually assumed that sport- and high-performance-oriented paragliders have the extension $\lambda \geq 6$. On the other hand, higher values of extension define the deformable and exacting paraglider as its working and flight need advanced skills. The aerodynamical lift is defined as follows.
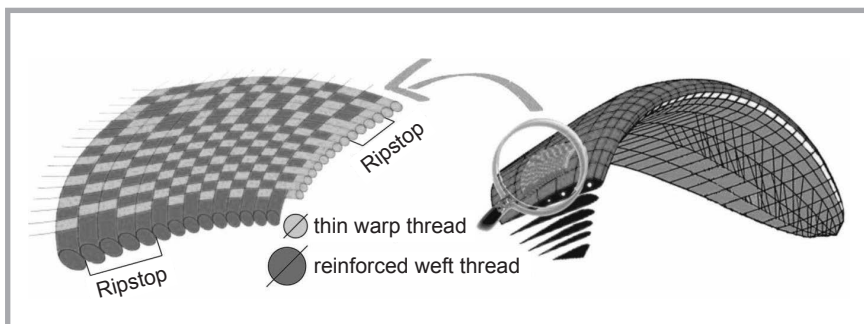
$$P = c_x S \rho \frac{v^2}{2} \qquad (3)$$

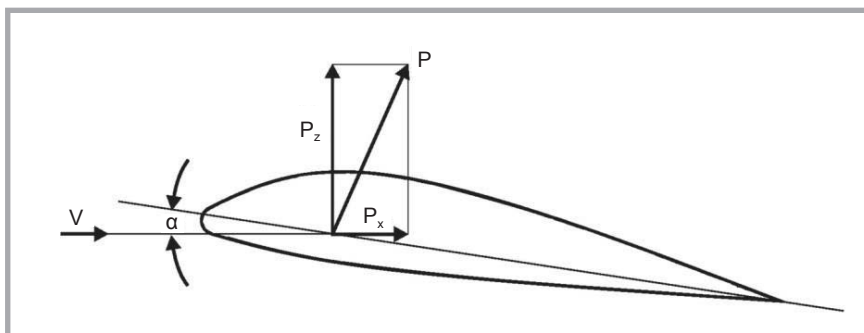**Figure 2.** *Simplified fabric structure applied to airfoil coverage (according to [3]).*

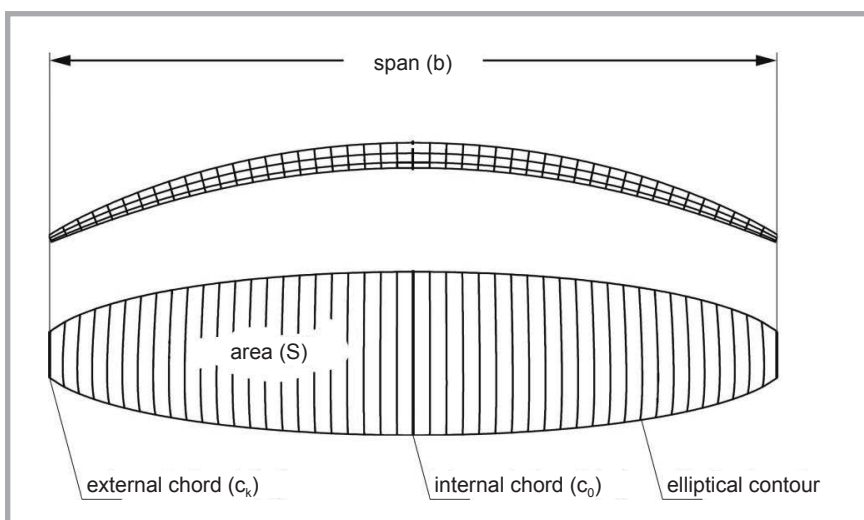**Figure 3.** *Aerodynamical force during the flight (according to [11]).*
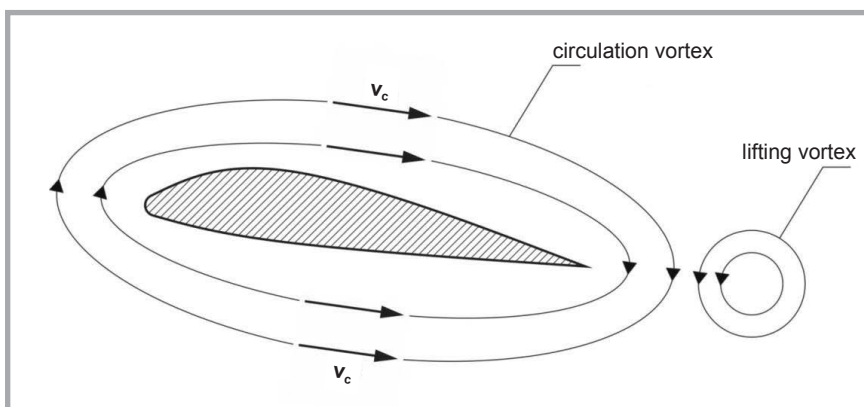

Figure 4. *Geometry of wing contour.*

Figure 5. *Generation of aerodynamical lift – lifting and circulation vortexes.*

PROBLEM FORMULATION

Definition of problem and finite volume geometry.

⬇

PRE-PROCESSING

Determination of physical model. Creation of geometry and computational net.

⬇

NUMERICAL SOLUTION

Iterative procedure of solution.

⬇

POST-PROCESSING

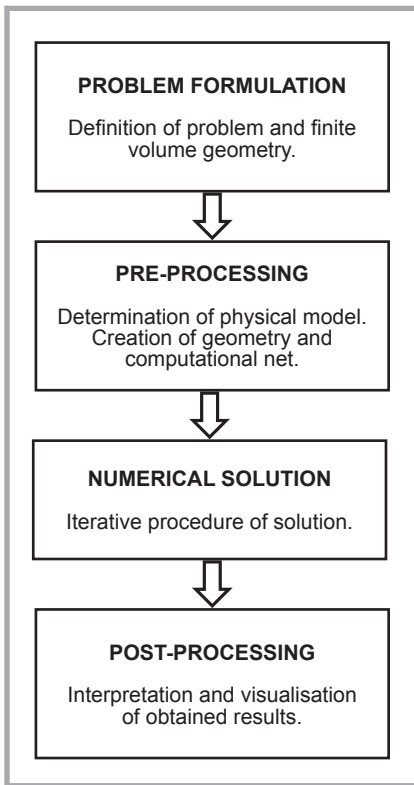Interpretation and visualisation of obtained results.

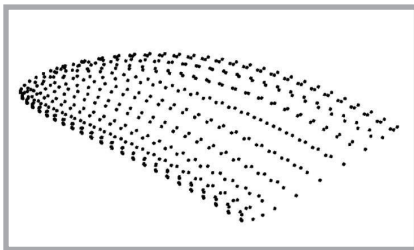*Figure 6. Block diagram of solution procedure.*

Figure 7. Crucial points of upper and lower surface of paraglider wing.

The aerodynamic lift of a paraglider airfoil is generated by advantageous pressure distribution, i.e. the subatmospheric pressure on the upper plane and the overpressure on the lower surface. The path of stream filaments along the upper plane is longer than along the lower surface, which causes the lifting vortex. Introducing the principle of conservation of momentum, the lifting vortex is accompanied by a circulation vortex, as in *Figure 5*. Consequently the speed on the upper surface is the sum of the flying speed and circulation velocity $(v + v_c)$, whereas on the lower surface it is their difference $(v - v_c)$.

The physical state of a dynamical system is determined by the state variables which should be representative for the system and depend on the particular problem. The aerodynamic lift results

Table 1. Characteristics of fabrics using to cover the wing surface of paraglider.

Charactristics		Unit	SKYTEX 32 – Universal	DOKDO-20DMF(WR)	Clothing material
Surface mass		g/m²	32	33	480
Air permeability (under pressure 2000Pa)		l/(m² min)	≤20	6	10800 under pressure 100Pa
Tensile strength	warp	daN/5cm	≥25	25	26
	weft	daN/5cm	≥33	25	32
Tearing strength	warp	daN	≥1.5	1.5	4
	weft	daN	≥1.5	1.5	5.2
Extension	1.36 kg	%	≤10	10	-
	2.27 kg	%	≤18	20	-
	4.54 kg	%	≤30	30	-

from the pressure difference above and below the wing. Thus the physical state is described by second-order differential correlations of the pressure p which is the state variable.

The dynamics of air motion is defined using conservation equations of mass, momentum and energy in a vector form, which can be simplified to a set of equivalent scalar equations [14].

$$\frac{d}{dt}\iiint_V \rho\, dV + \iint_A \rho v_n\, dA = 0$$

$$\frac{d}{dt}\iiint_V \rho\vec{v}\, dV = \iint_A \vec{p}_n\, dA + \iiint_V \vec{F}_m \rho\, dV$$

$$\frac{d}{dt}\iiint_V \rho(c_w T + \frac{v^2}{2})dV = \iint_A \vec{p}_n \cdot \vec{v}\, dA +$$
$$+ \iiint_V \rho\vec{F}_m \cdot \vec{v}\, dV + \iint_A \dot{q}_n\, dA +$$
$$+ \iiint_V \dot{q}_m \rho\, dV \qquad (4)$$

In respect of the large dimensions of the computational volume, the differential equations are accompanied by the boundary conditions, which are the environmental conditions.

Mathematical model and numerical solution

The problem is solved numerically by means of the finite volume method, which allows to introduce an inhomogeneous, non-orthogonal computational net. Conservation equations of mass, momentum and energy are determined for each volume element. The number of volume elements is significant, thus the solution is iterative until the exit criterion is satisfied. A block diagram of the solution is shown in *Figure 6*. Creation of the geometry and computational net as well as the numerical solution can be accelerated using processing programs, although problem formulation as well as pre- and post-processing are determined individually.

The crucial point is to define the computational net. The bigger the volume around the object analysed, the more precise the calculation results. The computational space is cubicoid, whose length before the frontal edge of the wing is equal to 10 maximal chords and in other directions 20 maximal chords. The boundary conditions are now the surrounding values of the prescribed parameters. It is impossible to introduce the model of the airfoil into the computational volume as an imported file in the CAD-system because of the immense storage size. The shape of the airfoil is created individually using the program ANSYS Design Modeller with the sequence: (i) design of the aerodynamical profile, (ii) duplication of profiles; (iii) reduction of aerodynamic profiles in the area of the trailing edge, and (iv) the shape design of the trailing edge in the top view. Initially we introduce the coordinates of 20 crucial points on the upper surface, and next the coordinates of the consecutive 20 points on the lower surface of the wing. These points are duplicated using the same program in respect of the wing contour and deflection, shown im *Figure 7*. The ribs are modeled using spline-curves i.e. the rib profile is determined by the smoothed contour on the basis of the coordinates introduced. Due to the symmetry of the object, only half of the contour can be created, which reduces both the calculation effort and time significantly.

The wing is covered by two synthetic fabrics: Skytex 32 – Universal, manufactured by the French company Porcher Sport; and DOKDO-20DMF(WR), produced by the Korean company Dominico Tex. Material parameters are obtained thanks to Dudek Paragliders Company. Both woven fabrics have the following characteristics: a plain weave reinforced by Rip-Stop technology; composition PA6.6 impregnated by PU (composition is not given by manufacturer); and the

number of threads – 65/cm for the weft/warp. The material data are correlated in **Table 1**. The PA-fabrics are ultra-light, resistant in respect of mass, and have minimal air permeability. The clothing material serves as a comparative, air permeable fabric of higher surface mass, not usually applied on a paraglider. Thus the material does not generate an adequate pressure difference to stimulate flight. The characteristic are the following: plain weave; composition – 70% PU, 30% cotton, not impregnated; and the number of threads – 25/cm for the weft/warp.

The computational net is irregular, consists of 509218 elements, and some volumes located near the airfoil profile are condensed, shown in **Figure 8**. The finite element net is evaluated as regular and adapted to the real shape of the wing, because the adequate indexes are in the range *very good*. The Skewness-index defines the deviation between the shapes of the element applied and the primary element of the regular shape. Thus the ideal is Skewness = 0 (a regular net), whereas the worst is Skewness = 1 (a degenerated net of almost coplanar nodes). The mean value obtained is Skewness = 0.259 (the range *very good* is from 0.250 to 0.500). The maximal value of Skewness = 0.755 is located in the range *good* (from 0.500 to 0.800). The other measure is the Orthogonal Quality index, determining the adaptation of the net applied to the real shape of the wing. The optimal value is Orthogonal Quality = 1 (optimal orthogonality to the surface), while Orthogonal Quality = 0 is unacceptable. The mean value obtained is Orthogonal Quality = 0.744 (the range *very good* is from 0.700 to 0.940). The minimal value of Orthogonal Quality = 0.245 is from the range *good* (from 0.200 to 0.690).
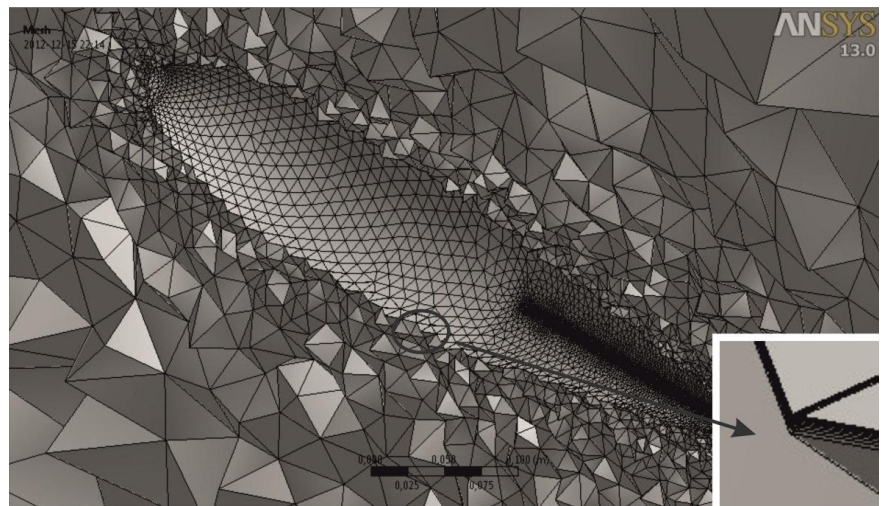

Figure 8. *Progressive reduction of elements near the object according to CFD software.*

The flow is a steady (the parameters are time independent) and turbulent one. The air density is determined as the solution of the ideal gas law. The absolute viscosity is assumed equal to $\mu = 1{,}7984 \cdot 10^{-5}$ kg/m·s². The surrounding temperature is $T_\infty = 288$ K, the surrounding pressure p = 101325 Pa, the flying speed v = 0.037 Ma (corresponding to the speed v = 45 km/h), the air flow directed to the trailing edge, and the angle of incidence is 6°.

Because both textiles have similar parameters, we have assumed an air impermeable material of characteristics compatible with DOKDO-20DMF(WR). The calculations are finished after 900 iterations for stable values, as in **Figure 9**. The air resistance coefficients obtained – c_x = 0.0403 & c_z = 0.5834 correspond to aerodynamic perfection d = 13.2. The mean pressure within the paraglider profile is p = 101418Pa. The pressure maps on the surface and in the symmetry plane are illustrated in **Figure 10**.

The energy is additionally dissipated by the vortex at the wing tip. The problem is simulated and analysed only for space problems. On the upper surface of the wing there is subatmospheric pressure, whereas on the lower surface – overpressure. The stream filaments are dissipated at some distance after the wing, which results from air viscosity, causing aerodynamic resistance (induced resistance), which is a function of the aerodynamic lift.

The distributions obtained are determined for the impermeable covering material i.e. using the boundary condition Wall [15]. The other boundary condition – Porous Jump is adequate to describe air permeability for porous/permeable material of infinitesimal thickness in respect of other dimensions. Irrespective of the settings of the FLUENT-program, the flow parameters (temperature, pressure, and air density) are very close to surrounding values. Thus these maps are not demonstrated.
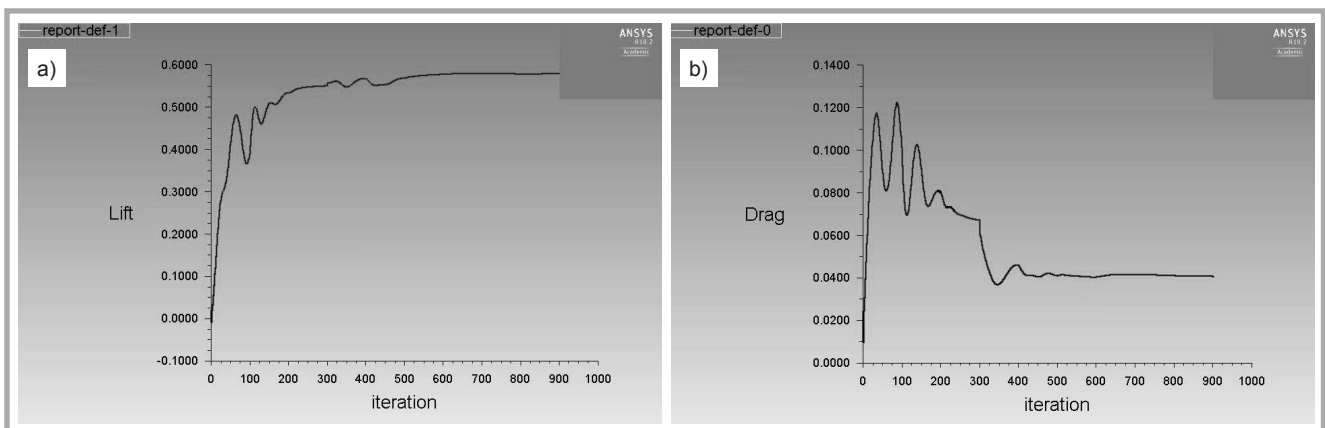

Figure 9. *Aerodynamical lift and resisting force (drag) vs. number of iteration.*
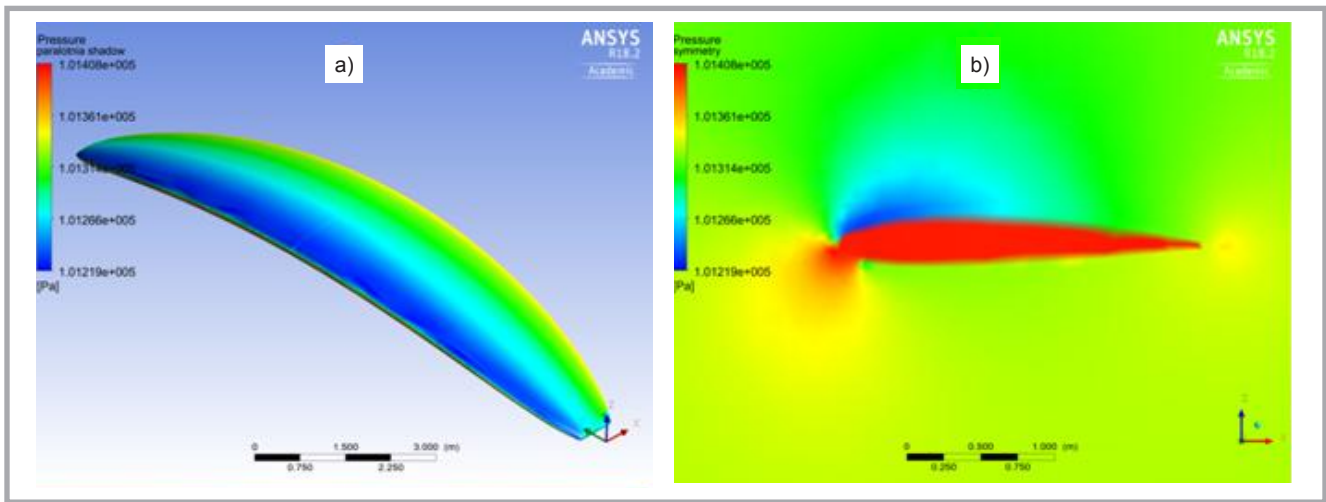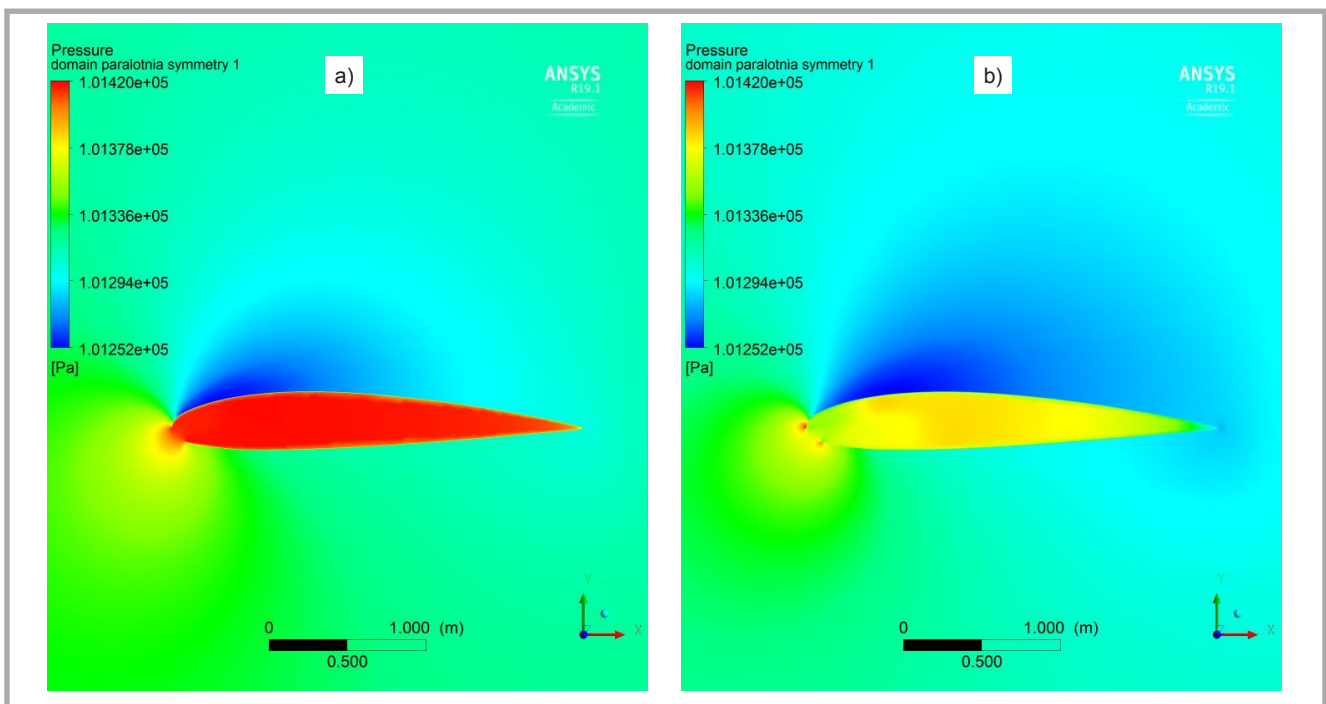
Figure 10. *Map of pressure in paraglider surface.*

Figure 11. *Map of pressure in paraglider cross-section: a) Skytex 32 – Universal material manufactured by Porcher Sport, b) clothing material.*
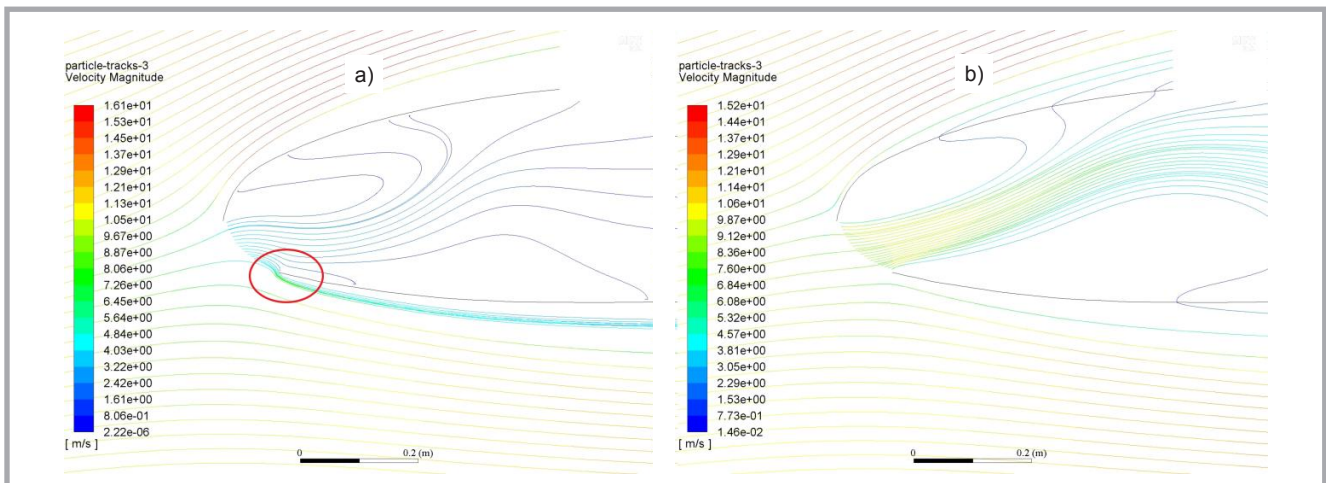

Figure 12. *Paths of stream filaments in paraglider cross-section: a) Skytex 32 – Universal material manufactured by Porcher Sport, b) clothing material.*

Aerodynamic properties of the paraglider vs. air permeability are determined using a plane/2D model of the surface thickness equal to $5 \cdot 10^{-4}$ m. Both boundary conditions – Wall and Porous Jump (i.e. permeable and impermeable material) are applied for the same flow parameters as within the space structure.

The alternative model introduces the cross-section in the symmetry plane of the paraglider accompanied by the wing span reduced to a length of 1 m. Assuming the wing chord c = 2.65 m, the airfoil area is S = 5.31 m². Two coating materials are introduced of appropriate air permeability: Δp = 2000 Pa, which describes Skytex 32 – Universal material, produced by Porcher Sport; and Δp = 100 Pa, defining the clothing material. We have introduced the material Skytex 32 – Universal because the characteristics of the second are nearly the same.

The calculations are stopped after 900 iterations for the stabilised values of parameters. In the case of Skytex-material, the air resistance coefficients are c_x = 0.0358 & c_z = 0.6158, and the aerodynamic perfection is d = 16.4. The mean pressure within the profile is p = 101417 Pa, and the mass flux density through the walls is $\dot{m}$ = 0,2948 kg/s. The dynamic characteristics for the cross-section are better than those formulated for the space problem. The energy is not dissipated by the boundary vortex at the wing tip, which improves the dynamic behavior of the airfoil.

In the case of clothing material, the corresponding coefficients after 900 iterations are c_x = 0.1420 & c_z = 0.5354, and the aerodynamic perfection is d = 3.8. The mean pressure within the profile is p = 101381Pa, and the mass flux density through the walls is $\dot{m}$ = 0,9981 kg/s. The air resistance coefficient c_x is considerably greater than for the impermeable material, and the aerodynamic perfection decreases rapidly.

Pressure maps for both cases are illustrated in *Figure 11*. The interior of a profile created by the almost impermeable fabric Skytex 32 is filled by air of a mean value of p = 101417 Pa. Therefore the profile preserves its shape in relation to decreasing pressure outside the wing. The pressure in the profile created by the clothing material is reduced to p = 101381 Pa. Additionally the pressure within the inlet area is greater outside than inside the

profile, which can cause the perturbation of aerodynamic characteristics.

Let us compare the path of stream filaments for the permeable and impermeable material, shown in *Figure 12*. The impermeable fabric Skytex 32 demonstrates a concentration of stream filaments under the bottom surface of the airfoil. In the case of clothing material, a large majority of stream filaments penetrate the inside of the profile.

Summarising, the aerodynamic characteristics of a profile coated by the almost impermeable fabric are excellent. A paraglider made of clothing material has poor aerodynamics, and the pressure inside is insufficient to create a complete airfoil profile.

■ Conclusions

The physical parameters of two typical textiles covering a paraglider wing were determined, with the comparative object being clothing material permeable to air. The material parameters were applied in numerical simulations of aerodynamic characteristics using the program AN-SYS. Analysed were the space model of a paraglider wing and plane model of its cross-section in the symmetry plane (i.e. the airfoil profile). The model was approximated by the coordinates of crucial points and smoothed by the spline-curves. Due to the symmetry and economising the computational effort, only half of the wing was modelled. The finite volume net was determined using cubicoid elements supplemented by tetrahedron elements. The computational net is composed of 509218 elements of fine quality, with the mean adequate indexes in the range of very good and extremal indexes for single elements in the range of good.

The cubicoid computational space should be considerably greater than the overall dimensions of the object and equal to 10 maximal chords before the frontal edge of the paraglider and 20 maximal chords in other directions. Calculations of the turbulent flow and typical parameters of flight are finished after 900 calculations for stabilised values of the parameters.

The space analysis proved physically and mathematically that there is an additional boundary vortex dissipating the energy at the wing tip. The problem is determined only for the 3D problem because of the space formulation of the phenomenon.

On the other hand, the calculations of the plane model introduce the precise distribution of the state variable (the pressure) in the wing profile. The visualisation of stream filaments shows that it is advisable to cover the external wing surface by an almost impermeable fabric. The aerodynamic characteristics and perfection are considerably greater than the values determined for the comparative clothing fabric. Summarising, the material parameters of the textiles applied influence the aerodynamic characteristics of the paraglider wing and can be adequately created to optimise the shape and properties of the airfoil.

❑

References

1. Anonymus, http://www.paragliding-tales-and-reviews.com/paraglider-fabric.html
2. Anonymus, https://www.up-paragliders.com/en/content/item/502-paraglider-line-materials,-and-why-they-matter-to-you
3. Anonymus, http://www.porcher-sport.com/fr
4. Anonymus, https://www.porcher-ind.com/en
5. Korycki R, Więzowska A. Modelling of the temperature field within knitted fur fabrics, *FIBRES & TEXTILES in Eastern Europe* 2011; 19, 1 (84): 55-59.
6. Korycki R. Modeling of transient heat transfer within bounded seams. *FIBRES & TEXTILES in Eastern Europe* 2011; 19, 5 (88): 112-116.
7. Korycki R, Szafrańska H. Modelling of temperature field within textile inlayers of clothing laminates. *FIBRES & TEXTILES in Eastern Europe* 2013; 21, 4(100): 118-122.
8. Korycki R. Sensitivity oriented shape optimization of textile composites during coupled heat and mass transport. *Int. J. Heat Mass Transfer* 2010; 53: 2385-2392.
9. Dems K, Korycki R. Sensitivity analysis and optimal design for steady conduction problem with radiative heat transfer. J. Thermal Stresses 2005; 28: 213-232.
10. Korycki R. Shape optimization and shape identification for transient diffusion problems in textile structures. *FIBRES & TEXTILES in Eastern Europe* 2007; 15 (1): 43-49.
11. Abłamowicz A, Nowakowski W. *Basis of aerodynamics and mechanics of flight* (in Polish), Wydawnictwo Komunikacji i Łączności, Warsaw 1980.
12. Krzyżanowski A. *Mechanics of flight* (in Polish), WAT, Warsaw, 2009.
13. Dudek P, Włodarczak Z. *Paragliding* (in Polish), Arete, 2013
14. Kazimierski Z. Bases of fluid mechanics and computer simulation of flows (in Polish), Publishing House of Lodz University of Technology, Lodz, Poland, 2005.
15. ANSYS FLUENT User's Guide, ANSYS, Inc., Canonsburg, U.S.A., 2010.

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