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EFFECT OF PARAGLIDING WING DOME SHAPE ON ITS AERODYNAMIC CHARACTERISTICS

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Double-membrane gliding parachutes (DGP) obtain their wide variety of application, including the solution of cargo transportation problems. This parachute is a flexible canopy, which shape is maintained by ram air. In terms of the aerodynamic performance calculation and analysis when operating, DGP is the most complex aero elastic system. The computation of DPG aerodynamic performance is only possible, utilizing the methods of nonlinear aerodynamics and the nonlinear theory of elasticity methods.
This paper investigates the aerodynamic characteristics of stable geometric shapes for various gliding parachutes, taking into account their dome shape both chord-wise and span-wise. Notably, the volumetric parachute profile is modeled by its median surface. The research, conducted by the authors, showed that such an aero elastic model of DGP allows you to obtain results that reflect correctly the qualitative effects of detached and free streamline flow. To solve the problem about the airflow over a gliding parachute, considering its canopy curvature, the method of discrete vortices with closed frames is employed, which allows you to calculate the paragliding wing aerodynamic performance within a wide range of angles of attack. There is also a possibility of flow separation simulation. The ideal incompressible liquid flow over the median surface of a stable shape for a double-membrane gliding parachute is regarded. The parachute fabric porosity is not analyzed, since the upper and lower DGP panels are made of either the low permeable or non-porous fabric. In the separated flow past, the aerodynamic coefficients are identified by time averaging to its large values after computing. The DGP aerodynamic performance computation results are given at a different value of its dome shape, as in the free streamline flow as in the flow separation. The computed coefficients, that allow us to consider the influence of canopy dome shape on its aerodynamic characteristics, are obtained. The proposed technique can be used for operational estimates of aerodynamic forces while designing and planning a pipe experiment.

Key words: aerodynamics, parachute, double-membrane gliding parachute, discrete vortex method, dome-shaped paragliding parachute, aerodynamics coefficients.

INTRODUCTION

Double-membrane gliding parachutes (DGP) obtain their wide practical application, including the cargo transportation issues solution. This parachute is a flex-wing, which shape is maintained by ram air. From the point of view of the aerodynamic characteristics calculation and analysis during operation, DGP is the most complex aero elastic system. The calculation of aerodynamic performance for a similar system is merely possible, using the methods of nonlinear aerodynamics and the nonlinear theory of elasticity.

A large number of experimental and theoretical researches, associated with the determination of the DGP dynamic and aerodynamic characteristics[1], for example, [1–9] are known. At the same time, obtaining reliable analytical results of the aerodynamic characteristics calculation is significantly complicated by the fact that DGP is actually a flex-wing, which shape is supported by the dynamic air pressure, so it represents an aero elastic system of immense complexity.

In order to identify characteristics of the given system, it is necessary to employ the methods of nonlinear aerodynamics and the nonlinear theory of elasticity, which specifies a significant computational problem. In this sphere the major researches on the basis of vortex methods were carried out by the Central Aerohydrodynamic Institute (TsAGI), the Scientific Research Institute of Parachute Construction, the Moscow State University, Zhukovsky Air Force Engineering Academy (see, for example, [10–13]).

[1] The Study of a Parachute Wing in a Wind Tunnel T-101 TsAGI. (1976). Scientific and Technical Department TsAGI № 3415. Moscow: TsAGI, 76 p.

In this article, the aerodynamic characteristics of various paragliding parachute stable shapes, taking into account their curvature, are explored. In this respect, the volumetric parachute profile is modeled by means of its median surface [14, 15]. The calculations, carried out by authors, showed that this DGP model allows you to obtain results reflecting correctly the qualitative effects of separation flow and free streamline flow. The DGP aerodynamic performance computational results with a different degree of a canopy curvature, as in the free streamline flow as in the separation flow, are given. The design coefficients, that enable you to consider the influence of a canopy dome shape on its aerodynamic characteristics, are obtained. The proposed technique can be used for operational assessments of aerodynamic forces during the design phase and while planning a pipe experiment. The obtained results can be useful while designing the DGP, setting up and conducting the pipe experiments.

METHODS AND METHODOLOGY OF STUDY

In this paper, in order to solve the problem of moving air current over a parachute, the method of discrete vortices with closed frames [12] is used, which permits us to calculate the aerodynamic performance of parachutes with a rather high practical accuracy. A principal assumption, demonstrated in [15], is used, according to which the DGP is modeled by a thin carrying surface. The given assumption allows you to conduct the research efficiently, both when solving the free streamline flow problems and considering the flow separation. A typical vortex diagram of the cutting out shape DGP for the closed-frame discrete vortex method is shown in Figure 1.

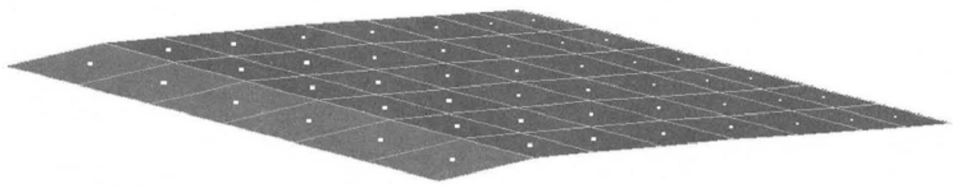

Fig. 1. Vortex diagram for the gliding parachute median surface

Replacing the DGP profile with its median surface makes it possible to obtain results, correctly reflecting the qualitative effects of separation flow and free streamline flow and can be applied when studying the major consistent patterns of airflow over parachute finite span wings. We will explore the flow by ideal incompressible liquid over the median surface of the double-membrane paragliding parachute of a stable shape. The parachute fabric permeability is not analyzed, since the DGP upper and lower panels are made of either low permeable or non-porous fabric, so that at the first stage of studies their permeability can be neglected (if necessary, it is taken into account by well-known modifications of the task boundary conditions [13]). In the separation flow, the aerodynamic coefficients are identified by time averaging to its large values after computing.

RESEARCH RESULTS AND THEIR DISCUSSION

The cutting out shape of the double-membrane gliding parachute changes significantly in the air flow (fig. 2), its wing takes a stable dome shape of span $l_и$ with the camber height f, which makes 10–20% of the initial span l. Obviously, the stated deformation influences the integral wing aerodynamic performance. This paper proposes a technique that allows you to assess the influence of the canopy dome shape on its aerodynamic characteristics and give formulae for a curved wing recalculation.

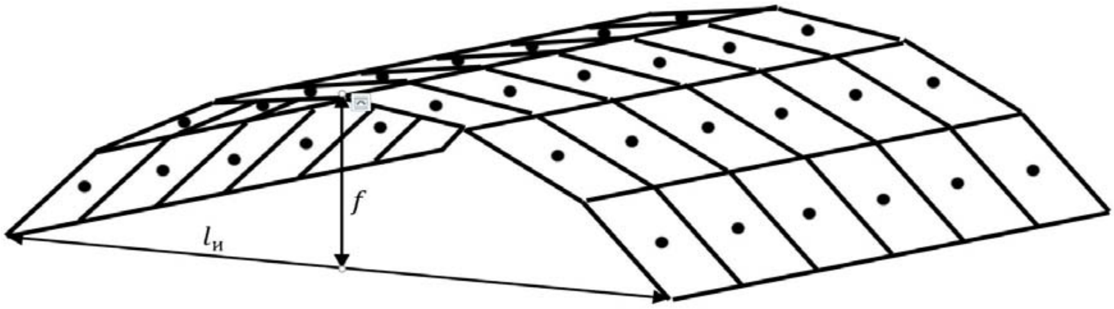

Fig. 2. The dome shape of the wing of the gliding parachute

As it has been shown in [15], the aerodynamic performance of the parachute cutting out shape is calculated with acceptable accuracy, applying the method of discrete vortices with closed frames as in the free streamline flow (small angles of attack) as in the separation flow.

Here we are going to illustrate how it will be possible to obtain the wing aerodynamic performance with the known camber height by a computational scheme for a cutting out shape.

First, let us explore the case where the parachute wing has a small extension λ. Generally speaking, for the most of practicable DGPs, the elongation does not exceed 2. (So, for a gliding parachute system of PO-9 series λ = 1.24, for PO-9-2 and PO-9-7 λ = 1.7). The sail-wings, which elongation value can reach 3÷4, are the exception. The following symbols are used for analytical studies in the given article. The dimensionless aerodynamic performance, assigned to the area in the design of the curved wing $S_и$, will be designated as $\tilde{c}_y$, and c_y as the symbol for the aerodynamic characteristics, assigned to the area in the design of the original wing S (cutting out shape). Then we have

$$\tilde{c}_y = \frac{Y}{qS_И}, c_y = \frac{Y}{qS} \tag{1}$$

where q is the air pressure, Y is the DGP normal force. When describing the parameters the subscript "и" indicates that one or another characteristic refers to a curved wing, for example, $c_{yи} = \frac{Y_и}{qS}$c is the coefficient of normal force for a curved wing, attributed to the non-curved wing area.

It is known that for small extension wings, the slope of lift curve is expressed as [16]

$$c_{ya}^{\alpha} = \frac{\pi\lambda}{2} = k\lambda \tag{2}$$

In the area where the aerodynamic performance is linear, it is possible to write (hereinafter, to reduce the entry, the subscript "a" in the designations for the lift coefficient is omitted):

$$c_{yи} = \frac{S_и}{S}\tilde{c}_{yи} = \frac{S_и}{S}\tilde{c}_y^{\alpha}\alpha. \tag{3}$$

Substituting c_y^{α} into (3) according to (2) and taking into account that $\lambda_и = \frac{l_и^2}{S_и}$, we get:

$$c_{yи} = \frac{S_и}{S}k\frac{l_и^2}{S_и}\alpha = k\frac{l_и^2}{S}\alpha. \tag{4}$$

For non-deformed wing

$$c_y = c_y^{\alpha}\alpha = k\frac{l^2}{S}\alpha. \tag{5}$$

Hence follows the following ratio

$$\frac{c_{y\text{и}}}{c_y} = \left(\frac{l_\text{и}}{l}\right)^2. \tag{6}$$

This formula is true for the wings of small elongation at small angles of attack.

In a similar way, for wings of very large elongation which curve slope of lift can be considered weakly dependent on λ value, we obtain:

$$\frac{c_{y\text{и}}}{c_y} = \frac{l_\text{и}}{l}. \tag{7}$$

Let us analyze the curvature effect on parachute wing drag. We will first make an analysis for small extension wings in the linear region. Taking into account the dependence for the drag coefficient (polar equation):

$$c_x = c_{x_0} + Ac_y^2, \tag{8}$$

where c_{x_0} is the wing profile drag, Ac_y^2 is the drag dependent on lift. So, we have the following for a curved wing:

$$c_{x\text{и}} = \left(\tilde{c}_{x_0\text{и}} + \tilde{A}_\text{и}\tilde{c}_{y\text{и}}^2\right)\frac{S_\text{и}}{S} = c_{x_0\text{и}} + \tilde{A}_\text{и}\tilde{c}_{y\text{и}}^2\left(\frac{S_\text{и}}{S}\right)^2\frac{S}{S_\text{и}} = c_{x_0\text{и}} + \tilde{A}_\text{и}\frac{S}{S_\text{и}}c_{y\text{и}}^2. \tag{9}$$

Since at small angles of attack you can take $c_y = c_y^{\alpha}\alpha$, so, $A = \frac{1}{c_y^{\alpha}}$. Then, considering (2), we get:

$$c_{x\text{и}} = c_{x_0\text{и}} + \frac{1}{k\tilde{\lambda}}\frac{S}{S_\text{и}}c_{y\text{и}}^2 = c_{x_0\text{и}} + \frac{S}{kl_\text{и}^2}c_{y\text{и}}^2, \tag{10}$$

$$c_x = c_{x_0} + \frac{S}{kl^2}c_y^2\ . \tag{11}$$

Since the value of drag at zero lift depends only on the profile shape, so, $c_{x_0\text{и}} = c_{x_0}$. Then

$$\frac{c_{x\text{и}}}{c_x} = \frac{c_{x_0} + \frac{S}{kl_\text{и}^2}c_{y\text{и}}^2}{c_{x_0} + \frac{S}{kl^2}c_y^2} = \frac{c_{x_0} + \frac{S}{kl_\text{и}^2}c_{y\text{и}}^2 - \frac{S}{kl^2}c_y^2 + \frac{S}{kl^2}c_y^2}{c_{x_0} + \frac{S}{kl^2}c_y^2} = 1 + \frac{\left(\frac{l}{l_\text{и}}\right)^2\left(\frac{c_{y\text{и}}}{c_y}\right)^2 - 1}{\frac{c_{x_0}}{\frac{S}{kl^2}c_y^2} + 1}.$$

To convert the denominator, we use (11), and consider (6) in the numerator, after that we finally have:

$$\frac{c_{x\text{и}}}{c_x} = 1 + \frac{\left(\frac{l_\text{и}}{l}\right)^2 - 1}{\frac{c_x}{c_x - c_{x0}}} = \left(\frac{l_\text{и}}{l}\right)^2 + \frac{c_{x0}}{c_x}\left(1 - \left(\frac{l_\text{и}}{l}\right)^2\right). \tag{12}$$

Formula (12) shows how the drag coefficient of the curved wing changes compared to the non-curved wing. The second addend appears when the wing has the drag equal to c_{x0} (for ideal liquid, it is observed when the wing curves along the chord). It is clear that the wing camber along the chord slightly attenuates the effect of curvature. If $c_{x0} = 0$ (there is no chord curvature), then the dome-shaped wing drag coefficient changes in the same way as the coefficient of lift.

Conducting the similar argumentation for the wing of big elongation, we get:

$$\frac{c_{xи}}{c_x} = \frac{l_и}{l} + \frac{c_{x0}}{c_x}\left(1 - \frac{l_и}{l}\right). \qquad (13)$$

The given formulae, obtained for small angles of attack, were later checked by numerical calculations under various flow conditions. A straight wing was taken as the initial carrying surface, coinciding in the shape and size with the lower surface of the parachute PO-9 (λ = 1.24). The aerodynamic characteristics c_{xa}, c_{ya} of this wing were calculated under its deformation over the cylindrical surface (fig. 2).

Figure 3 shows the dependences of c_{ya} coefficient of this wing from the angle of attack α in the free streamline flow for various deformations. Figure 3 shows clearly the slope of the lift curve of the deformed wing decreases when its span varies from 100 to 70% from the initial value and with the increase of camber height $\bar{f} = \frac{f}{l}$ from 0 to 20% of span l respectively. The wing drag coefficient without curvature along the chord depends on the canopy dome shape as well as the coefficient of lift.

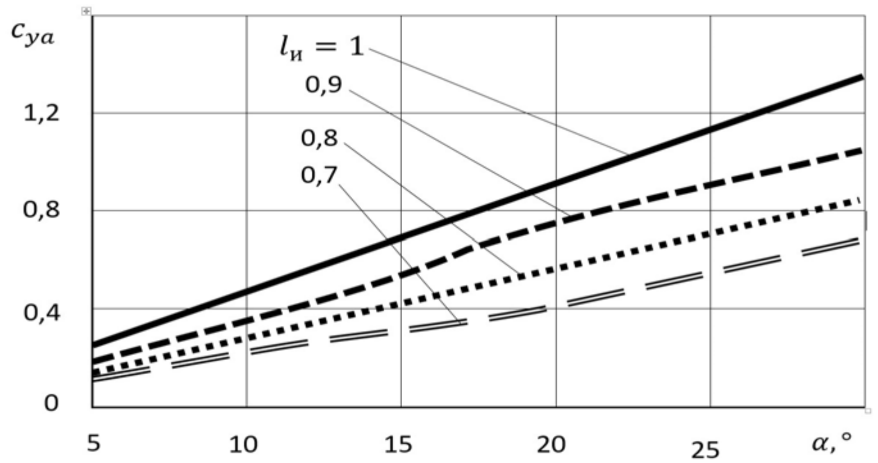

Fig. 3. Dependence of wing coefficient c_{ya} on the angle of attack α in the free streamline flow for different values of span $l_и$

Figure 4 shows the same dependencies, as Figure 2 does, after dividing them by $\left(\frac{l_и}{l}\right)^2$ – the recalculation coefficient from formula (6). Now it is obvious that all the dependencies practically coincide, which indicates the possibility of recalculating the aerodynamic characteristics of the dome-shape canopy of small elongation according to formula (6) in the free streamline flow within the range of $\alpha \leq 10^{\circ}$ angles of attack.

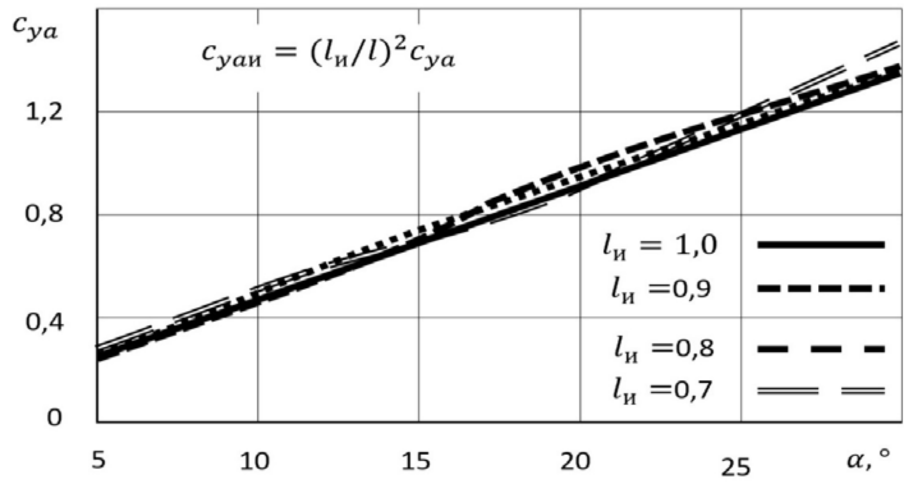

Fig. 4. Dependence of wing coefficient c_{ya} on an angle of attack α in the free streamline flow for different values of span $l_и$ after recalculation, using formula (6)

In case the wing surface is additionally curved along the chord (Figure 5, where PO-9 parachute median surface, which is the surface of two curvatures, is shown), in the free streamline flow, it is possible to recalculate the aerodynamic characteristics in conformity with formulae (6), (13), as it is illustrated in Figures 6 and 7.

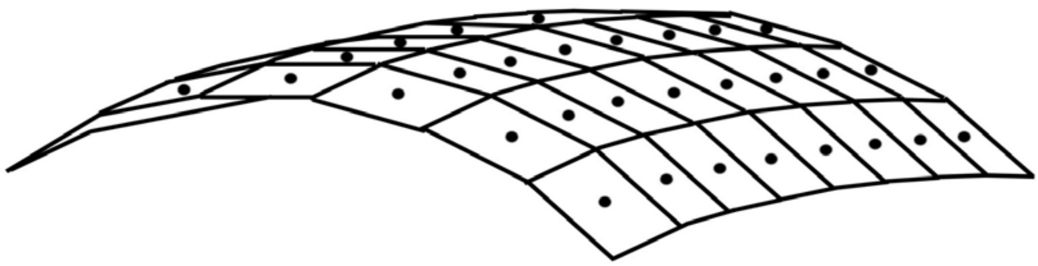

Fig. 5. Vortex diagram of the curved median surface of the gliding parachute with double curvature

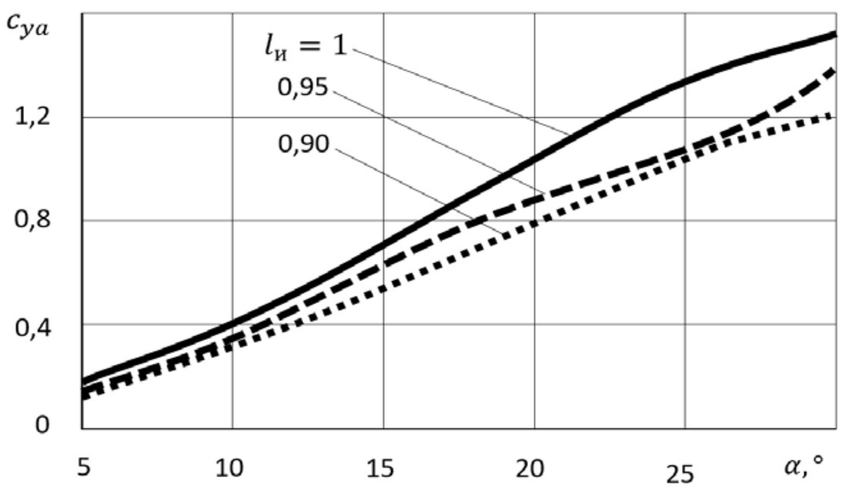

Fig. 6. Lift coefficient of PO-9 parachute median surface considering its dome shape (wing with double curvature)

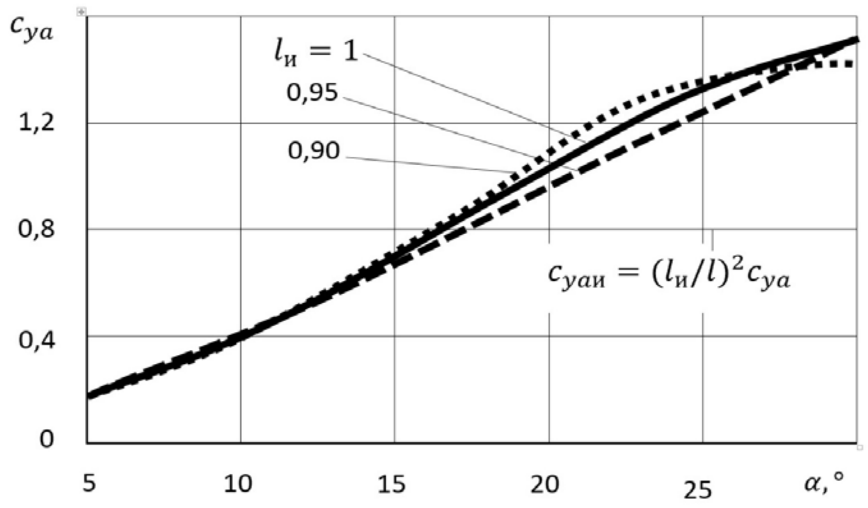

Fig. 7. To the possibility of recalculation of the lift coefficient for a dome-shaped wing with double curvature

In some cases, it is necessary to take into account the possibility of the flow separation from the surface of the parachute wings. Figure 8 shows the dependencies of c_{ya} coefficients in case of the separation flow of deformed wings when the span decreases from 100% to 85% from the original value due to their deformation. During the calculations, it was found out that the recalculation of coefficients, using formula (6), does not lead to positive results in the separation flow.

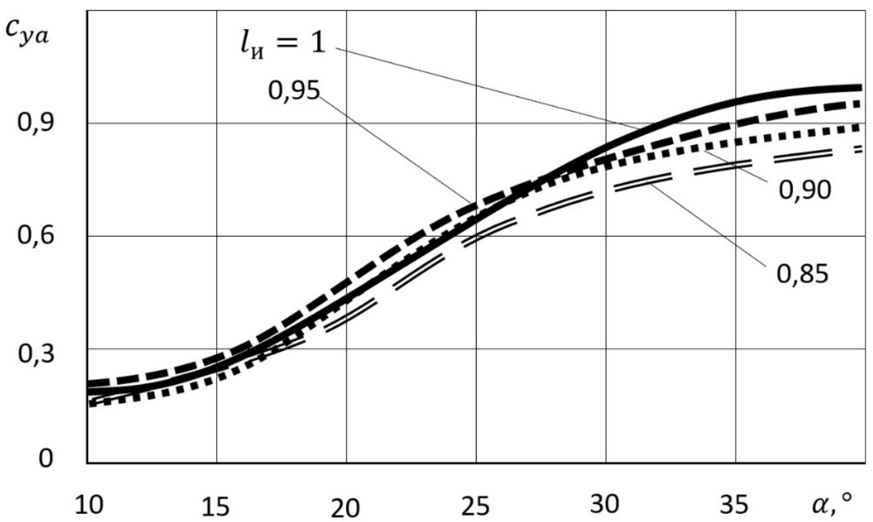

Fig. 8. Lift coefficient for the dome-shaped wing in the separation flow

Figure 9 represents the dependencies of aerodynamic performance of the deformed wings after dividing by $\frac{l_и}{l}$ coefficient. You can see that the curves are almost congruent.

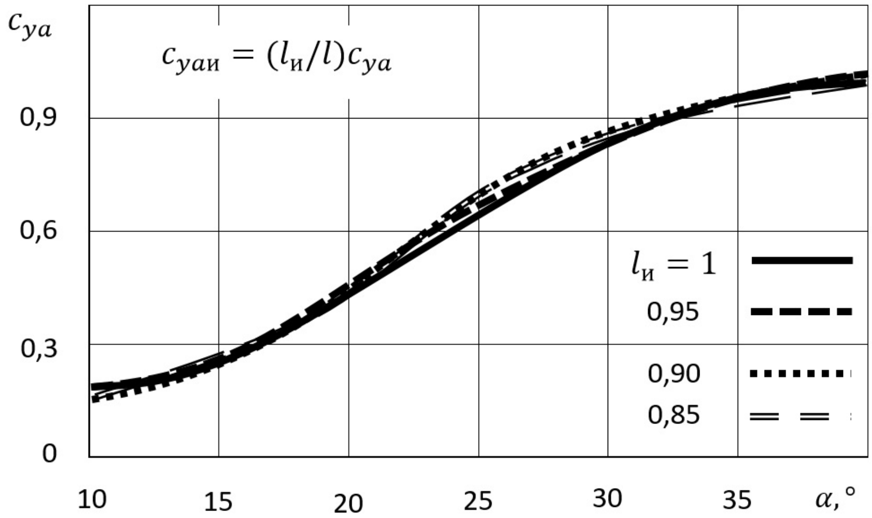

Fig. 9. To the possibility of recalculation of the lift coefficient of dome-shaped wings in the separation flow

It turns out that in the separation flow, the conversion calculation of the aerodynamic coefficients can be conducted, using formula (7) obtained for wings of large elongation. It can be explained by an insignificant influence of edges effects compared to the interaction effect of the vortex sheets in the separation flow over the parachute wing. Figure 10 and Figure 11 illustrate the formula application for the conversion calculation of the drag force coefficient (13), derived for a large elongation wing to recalculating the similar coefficient for a small elongation wing in the separation flow. It is clear that the use of this formula is quite justified.

Thus, the numerical simulation justifies the use of formulae (7) and (13) to recalculate the aerodynamic characteristics obtained for the parachute cutting shape on the dome-shaped wing in the flow separation.

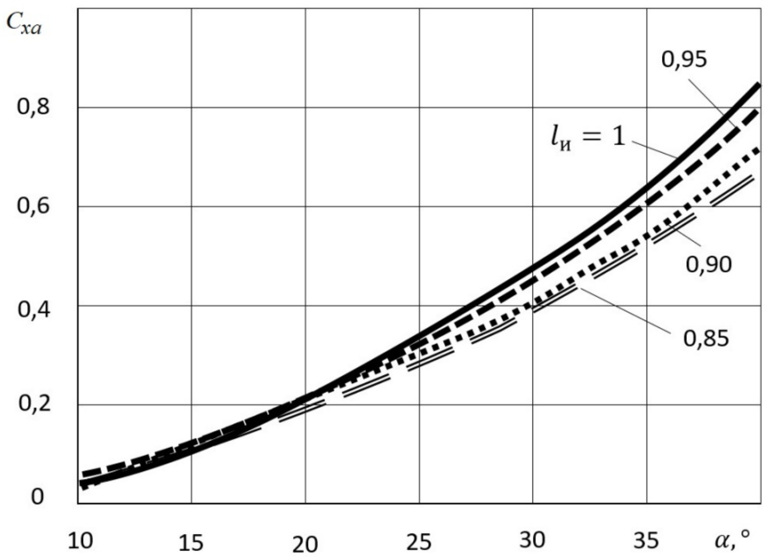

Fig. 10. Drag coefficient of a dome-shaped wing in the separation flow

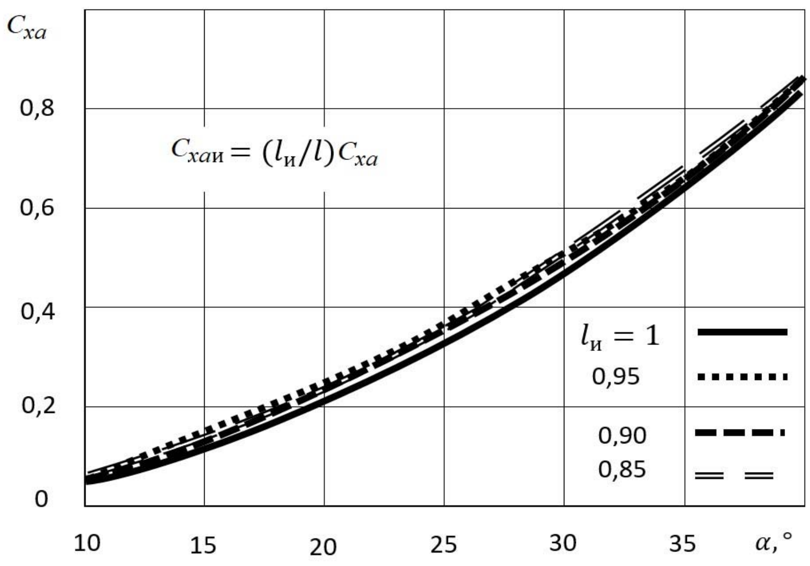

Fig. 11. To the possibility of recalculating the drag force coefficient of the dome-shaped wings in the separation flow

CONCLUSION

This paper provides the investigation results of influence of the median surface curvature (dome shape) of a double-membrane gliding parachute on its basic aerodynamic performance (normal force coefficient $\boldsymbol{c_{ya}}$ and drag coefficient $\boldsymbol{c_{xa}}$) at various values of the parachute dome, its elongation and angles of attack. The results were obtained, using the DGP mathematical model that was developed by the authors, as in the free streamline flow as in the flow separations from the parachute surface.

It is shown that in the free streamline flow at the high angles of attack and the parachute significant curvature ($l_и$ $up\ to$ 0,7), the normal force coefficient decrease comes to up to 50%. When taking into account the flow separation, the flow pattern changes significantly and c_{ya} coefficient decrease does not exceed 10%.

As a result of the calculated data and the analytical studies processing, allowing us to estimate the aerodynamic performance value, taking into account parachute curvature, were obtained. Such an approach enables you to utilize the simplified conversion formulae while designing the DGP and avoid solving the non-linear problems of the elasticity theory, taking into account quite accurately (the error does not exceed 3–5%) the curvature of wing span-wise.

Thus, the authors proposed the solution algorithm for aerodynamic problems when conducting the investigation of parachute optimal shapes and sizes: at the first stage, aerodynamic performance for the flat median surface of the parachute, as in the free streamline flow as in the separation flow, are calculated. Then the parachute dome shape is taken into account by means of utilizing the proposed conversion calculation coefficients. It is obvious that the DGP design the final problems should be solved in a general setting, using complete mathematical models.

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ВЛИЯНИЕ АРОЧНОСТИ ПАРАШЮТНОГО КРЫЛА НА ЕГО АЭРОДИНАМИЧЕСКИЕ ХАРАКТЕРИСТИКИ

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Двухоболочковые планирующие парашюты (ДПП) находят широкое практическое применение, в том числе для решения задач грузоперевозки. Данный парашют является мягким крылом, форма которого поддерживается набегающим потоком воздуха. С точки зрения расчета и анализа аэродинамических характеристик в процессе эксплуатации ДПП является сложнейшей аэроупругой системой. Вычисление аэродинамических характеристик такой системы возможно только с привлечением методов нелинейной аэродинамики и нелинейной теории упругости. В данной работе исследуются аэродинамические характеристики установившихся геометрических форм различных планирующих парашютов с учетом их арочности как по хорде, так и по размаху. При этом объемный профиль парашюта моделируется его срединной поверхностью. Проведенные авторами исследования показали, что такая аэроупругая модель ДПП позволяет получать результаты, правильно отражающие качественные эффекты отрывного и безотрывного обтекания. Для решения задачи об обтекании планирующего парашюта потоком воздуха с учетом его арочности используется метод дискретных вихрей с замкнутыми рамками, который позволяет вычислять аэродинамические характеристики парашютов в широком диапазоне углов атаки, а также имеется возможность моделирования отрыва потока. Рассматривается обтекание срединной поверхности установившейся формы двухоболочкового планирующего парашюта потоком идеальной несжимаемой жидкости. Проницаемость ткани парашюта не учитывается, так как верхнее и нижнее полотнища ДПП выполняются либо из слабо проницаемой, либо из непроницаемой ткани. При отрывном обтекании аэродинамические коэффициенты определяются путем усреднения по времени после расчета до его больших значений. Приводятся результаты расчетов аэродинамических характеристик ДПП при различном значении его арочности как при безотрывном обтекании, так и при наличии отрывов. Получены расчетные коэффициенты, позволяющие учесть влияние арочности парашюта на его аэродинамические характеристики. Предлагаемая методика может использоваться для оперативных оценок аэродинамических сил на этапе проектирования и при планировании трубного эксперимента.

Ключевые слова: аэродинамика, парашют, двухоболочковый планирующий парашют, метод дискретных вихрей, арочность парашюта, аэродинамические коэффициенты.

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