VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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RESEARCH OF AERODYNAMIC CHARACTERISTICS OF WING AIRFOILS

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Introduction

The problem formulation. Airplane flight characteristics are mostly influenced by airfoil aerodynamic characteristics. For sailplanes, especially sport sailplanes – heavier than air manned aircraft without engine – special aerodynamic requirements are applied. Without an engine, a sailplane in calm air can only glide according to an inclined trajectory, i.e. descend. Therefore, for a sailplane airfoil aerodynamic characteristics are crucial. Usually, all aerodynamic innovations are tested on sailplanes and only then applied to planes. Therefore, research on aerodynamic characteristics of sailplanes has received a lot of focus.

Airplane and sailplane aerodynamic characteristics are defined by a polar of aerodynamic coefficients, which shows the relation between airfoil drag coefficient and lift coefficient. For a sailplane to spiral a high lift coefficient value is required, whereas for gliding the lift coefficient value must be low. A more accurate prediction of maximum lift allows assessing minimum flight speed of a sailplane more accurately. This provides the basis for assessment of designed and available airfoil aerodynamic characteristics and airfoil suitability for a sailplane, airplane or wind turbine blade.

Since a sailplane does not use an engine, in order to improve glide characteristics at cruise speeds, profile drag must be reduced. Airfoil drag usually comprises at least a half of all drag, when a sailplane is flying at a fast speed (150–200 km/h) and arround a quarter of it, when flight speed is slow (75–100 km/h). At low and medium speeds, a complex boundary layer structure emerges on airfopil surface and a lamiar separation bubble forms. A turbulator may be used for in this case. Therefore, for improving airfoil aerodynamic characteristics it is important to avoid the formation of this bubble and by doing this to reduce profile drag. Therefore, engineers in aerodynamics employ a turbulator, which can induce laminar to turbulent transition. However, laminar to turbulent transition alone does not guarantee that it will reduce drag efficiently at all flight modes. Therefore, not only flight conditions must be considered but also the location of turbulator fastening and turbulator shape.

Unfortunatelly, there is practically no scientific research carried out on the fastening location of a turbulator and there is no literature which would aid to assess what is the best shape of a turbulator. There are also no computational methods capable of modeling this task. Modeling is also complicated by the absence of experimental research results, which would indicate the location and length of laminar separation bubble since the location and size of a laminar separation bubble have a tendency to vary in relation to angle of attack and Reynolds number.

This dissertation aims to assess the impact of fundamental aerodynamic characteristics on airfoil. This study seeks to analyse and asses the impact of turbulator on profile drag by using computational methods, experimental research and comparative analysis. Also, the dissertation aims to improve the accuracy of prediction of maximum lift.

The relevance of the thesis. From the start of exploitation of composite material sailplanes the best sailplane airfoils were designed in Federal Republic of Germany. Currently this initiative has been undertaken by Delft University of Technology in the Netherlands. Warsaw Technical University in Poland is also a strong runner up. In order to remain the frontrunners in global sailplane manufacturing, the designers of airfoils in Federal Republic of Germany since 1976 ceased to publish coordinates and characteristics of new airfoils. Other airfoil designers publish very few results and only of non-commercial projects.

Since there is a lack of experimental results, it is important to assess impact of airfoil drag and maximum lift on airplane or sailpane flight characteristics. After reduction of profile drag and increase in maximum lift, it is possible to increase maximum aerodynamic quality of an airplane or sailplane, weight of payload, to shorten take-off and landing distance, reduce fuel expenditure, pollution, noise and stall speed.

The object of research. The research object is aerodynamic characteristics of airfoil. Drag coefficient, maximum lift coefficient, laminar to turbulent transition, flow separation, impact of laminar separation bubble and turbulator on airfoil drag are analysed.

The goal of the thesis. To analyse the reduction of aerodynamic drag by artificially creating laminar to turbulent transition by employing computational and experimental methods. Also, to analyse the accuracy of maximum lift prediction at average Reynolds numbers.

The tasks of the thesis. In order to achieve the research aim the following tasks must be accomplished:

1. Employ computational and experimental methods in order to analyse and determine the impact of tutbulator shape and location of fastening and laminar to turbulent transition on airfoil aerodynamic characteristics.

2. Upon completion of computational modeling and experimental research, to compare the results with results of other studies published in scientific literature.

3. To analyse the potential to increase the effectiveness of turbulator.

4. To analyse and improve the accuracy of prediction of maximum lift at average Reynolds numbers.

The methodology of research. Airfoil aerodynamic characteristics are analysed theoretically, by using various computational methods, and during free flight experiments by using wind tunnels. Therefore, the methods of computational modeling and experimental research were applied in the thesis. Comparative analysis is also carried out.

For computational modeling, codes of invisced flow with boudary layer without interaction (aerial non-interactional methods), invisced flow and viscous flow interaction (aerial interactional methods) and general Navier-Stokes equation solving method were chosen.

Wake survey method was chosen for analysis of profile drag of airfoil. For experimental research, experiments during sailplane free flight, using improved methodology and specially designed equipment, were carried out.

The relevance of scientific novelity. When preparing the dissertation the following new results in the scientific area of mechanics engineering were obtained:

1. The relation between turbulator fastening location on lower wing surface and laminar to turbulent transition were modeled computationally and analysed experimentally. The impact of turbulator on airfoil drag was assessed.

2. New shape turbulator tips, producing lower profile drag in comparison with currently used zig-zag type turbulators, were designed and experimentally analysed.

3. Accuracy of prediction of maximum lift was increased at average Reynolds numbers.

Ther practical significance of achieved results. Research results allow reducing saiplane or airplane profile drag by using a mechanical turbulator. This is especially important for sport sailplanes and light airplanes.

Research results allow predicting maximum lift according to the pressure difference rule more accurately. A more accurate prediction of maximum lift allows to assess minimum flight speed at design stage more accurately. Conditions are created for assessment of aerodynamic characteristics of currently designed and available profiles, and profile suitability for sailplane, plane or wind turbine blade.

Research results may by applied in enterprises which manufacture and exploit sailplanes and light airplanes to increase their competitveness in the market.

The defended statements

1. The analysed computational methods do not detect the accurate place for fastening a turbulator. Experimental analysis shows that in the scope of sailplane speeds, the transition occurs at 2 % chord distance behind turbulator.
2. After analysis of designed new shape turbulator tips, it has been determined that they are up to 9 % more effective than currently used zig-zag type turbulators.
3. It has been found that the bias of Valarezo & Chin method for prediction of maximum lift may reach up yo 24 % for symmetric airfoils and even up to 62 % for cambered airfoils. After improvement of the accuracy of this method maximum lift for symmetric airfoils may be predicted with a 9 % accuracy and up to 23 % acuracy for cambered airfoils.

The structure of thesis. The dissertation consists of introduction, four chapters, general conclusions, lists of references and author‘s publications.

The scope of the dissertation is 136 pages. 72 numbered formulas are used, 67 figures and 5 tables are presented. In the dissertation 181 references were used.

1. Analysis of airfoil aerodynamic characteristics

The first chapter analyses impact of airfoil aerodynamic characteristics on airplane and sailplane flight characteristics. The impact of and factors allowing to improve aerodynamic characteristics have been determined. Laminar to turbulent transition and laminar separation bubble, which influence them were analysed in greater detail. Methods for reducing and avoiding the laminar separation bubble have been determined, analysed, and terminology and classification of them have been proposed.

Also, experimental research during sailplane free fligh and methodology for experimental research have been analysed. The choice of methods for achieving the dissertation aim and task have been justified.

Airplane and sailplane aerodynamic characteristics are defined by the polar of aerodynamic coefficients, which shows the interdependence between profile drag coefficient and lift coefficient. The lift is produced mainly by the wing (impact of other elements is not significant), and drag is influenced by all elements: wing, fuselage and tail.

It is important for engineers in aerodynamics to be able to predict maximum airfoil lift beforehand. This way conditions are created for assessment of aerodynamic characteristics of all designed and current airfoils and airfoil suitability for airplane, sailplane and wind turbine blade.

In both experimental and computational aerodynamics it is hard to determine maximum lift and critical angle of attack, at which maximum lift is achieved. In order to determine maximum lift it is important to impose criteria for maximum lift prediction. Pressure difference rule could be one of these criteria. This rule is an improved empirical method, which is not accurate at average Reynolds numbers.

It is not hard to generate lift. The aim however, is to generate lift with lower drag. In all the scope of lift coefficient the highest drag is caused by airfoil drag. Airfoil drag induces a quarter of all sailplane drag, when lift coefficient values are high, and more than half of all drag, when lift coefficient values are low. Therefore a lot of attention is paid to airfoil drag.

The scope of sailplane airfoils Reynolds numbers is in average from $0{,}5\times10^{6}$ to $3{,}0\times10^{6}$. When Reynolds numbers are lower than $2{,}0\times10^{6}$, on the surface of the airfoil a complex boundary layer structure is created. The boundary layer may be laminar or turbulent. At certain conditions the laminar boundary layer usually quickly becomes unstable and becomes turbulent. Depending on Reynolds numbers and static pressure distribution along the flow, the transition may occur in a boundary layer or in a shear layer. After transition in a shear layer a laminar separation bubble forms.

Depending on Reynolds numbers and static pressure distribution along the flow, the transition may occur in a boundary layer or in a shear layer. After transition in a shear layer a laminar separation bubble forms.

Designers of airfoils try to reduce profile drag while retaining the laminar flow longer, and to avoid separation of flow which would increase profile drag afterwards. When changing angle of attack, pressure on the upper surface distributions so that by choosing an appropriate upper contour shape, it is possible to control laminar boundary layer separation tendencies. This allows avoiding or reducing separation of flow, without generating additional drag. On airfoil lower surface the dependence of pressure distribution on the angle of attack is different. Designers, therefore, use a turbulator, to induce a forced transition. Without using a turbulator the laminar flow would separate causing additional drag. Although a turbulator may prevent the emergence of a laminar separation bubble, it is important to observe that the additional friction drag must be smaller than the additional drag caused by the laminar separation bubble.

Turbulators may be classified into mechanical, pneumatic and acoustic. Mechanical turbulators are the simplest and most economical. Usually they are attached to airfoil surface as a simple straight tip. The process during which mechanical turbulator induces boundary layer transition is not clearly understood, but it is evident, that turbulators produce vortexes which cause the transition. The lack of such knowledge results in optimization difficulties. However, the deduction of optimum shape and location of fastening remains the main problem.

Location of turbulator may be determined via computational or experimental methods. During sailplane free flight the impact of turbulator may be assessed by measuring drag by wake survey or using oil flow technique. Other methods for obtaining experimental results are used rarely or are only useful for solving particular tasks. Therefore, there is no best experimental method.

During wake survey static pressure and reduced pitot pressure may be measured in the wake of airfoil and these results may be compared with free flow pitot pressure. This pressure difference or more accurately flow movement amount deficit is directly related to profile drag. For free flight measurements, integrating wake rakes are best suited as they are relatively simpler and may measure pressure in whole wake at the same time.

2. Computational analysis of fixed transition impact on profile drag

This chapter analyses computational modeling methods of airfoil aerodynamic characteristics. Taking into consideration that there is no sole computational method for modeling airfoil aerodynamic characteristics, computational analysis using all methods realized in different programmes was performed. Methods of modeling used in chosen programmes were described. The computational and comparative analyses of results obtained from different computational methods have been carried out.

Having determined the best computational modeling method, using it computational analysis of airfoil aerodynamic characteristics was performed. Impact of laminar separation bubble, fixed transition and its location on airfoil aerodynamic drag were analysed.

By carrying out analyses using computational methods realized in the XFOIL 6.96, RFOIL 1.1, R. Eppler (2006) and FLUENT 6.3 codes, it was determined if the computational modeling methodology in these codes assesses laminar to turbulent transition and formation of laminar separation bubble.

Computational analysis shows that currently widely applied Navier-Stokes equation solving methods realized in the FLUENT 6.3 code are not adequate for modeling airfoil aerodynamic characteristics at average Reynolds numbers. This is influenced by the complexity of formation of laminar to turbulent transition process and lack of accurate transition modeling methods.

Taking into consideration the analysed computational modeling methods, for computational analysis the method of interaction between invisced flow and viscous flow (aerial interaction methods) was realized using the XFOIL 6.96 and RFOIL 1.1 codes and invisced flow with boundary layer without interaction method (aerial non-interactive methods) was realized using R. Eppler programme.

After carrying out LAP 7-131/17 airfoil computational analysis it was found that the greatest impact of laminar separation bubble on profile drag occurs when lift coefficient is 0,4. Therefore, it is useful to analyse airfoil pressure distribution without and with fixed transition at this lift coefficient.

Figure 1 shows how pressure distributions in viscous and invisced flow along LAP 7-131/17 airfoil chord length without fixed transition. Vertical axis indicates pressure coefficient C_P, and horizontal axis – distance in the direction of airfoil chord. Here solid red curve indicates pressure coefficient distribution on the upper airfoil surface, the blue – on the lower. Dashed black line indicates pressure distribution in invisced flow. It is evident that pressure distribution in invisced and viscous flow are not identical.

On the upper arfoil surface at 67 % chord length form the leading edge, local deviation of pressure distribution in invisced flow from distribution in viscous flow is evident. The same local deviation is seen on the lower surface at 92 % of chord length form the leading edge. These deviations indicate that in viscous flow laminar to turbulent transition occurs. On the lower surface the so called exploded bubble forms, since the flow separated and could not merge till the trailing edge.

An 8 % chord line length laminar separation bubble which emerged on airfoil lower surface increased profile drag. Since laminar boundary layer separation location on the lower surface is almost independent of angle of attack, it is possible to reduce profile drag by artificially fixing transition in this location.

Figure 2 exemplifies LAP 7-131/17 airfoil pressure distribution on airfoil surface, when transition on lower surface is fixed at 92 % chord length from leading edge. It is clear that pressure coefficient distribution on lower surface in viscous flow is almost identical with pressure distribution in invisced flow. This suggests that there is no laminar separation bubble. Drag coefficient from 0,00497 distributiond to 0,00420, i.e. decreased by 16,8 %.

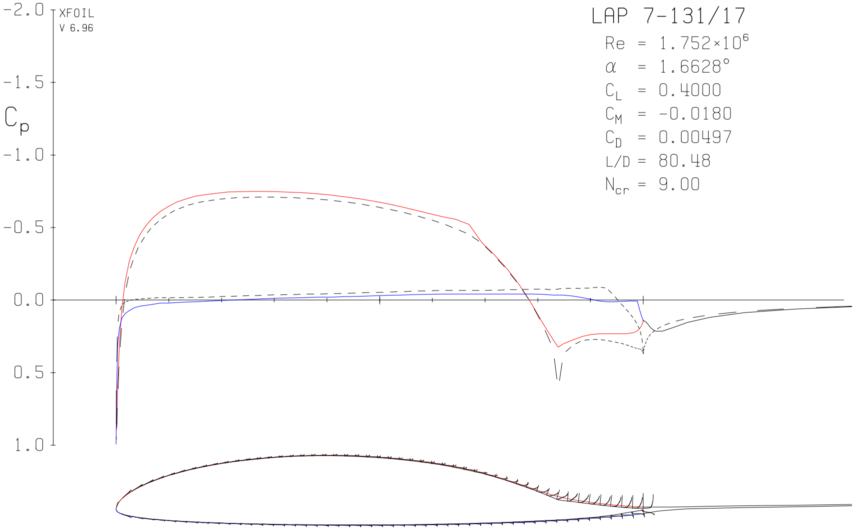

Fig. 1. Pressure distribution of the LAP 7-131/17 airfoil without fixed transition

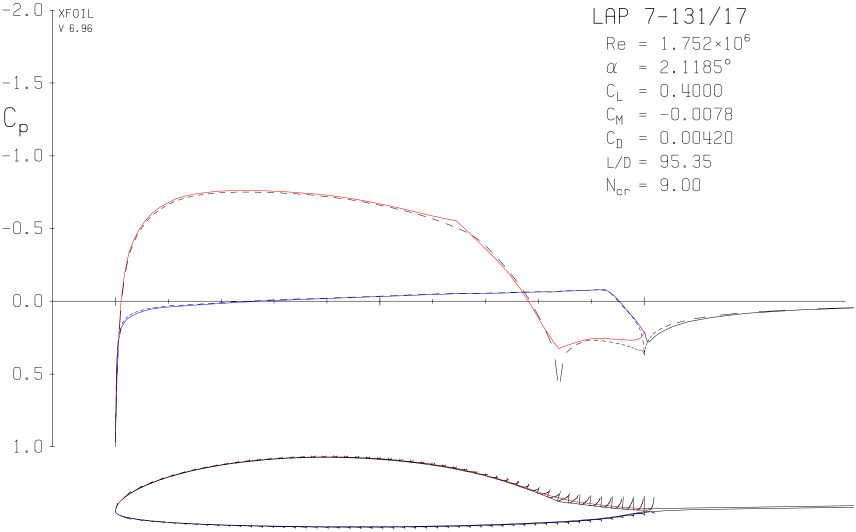

Fig. 2. Pressure distribution of the LAP 7-131/17 airfoil with fixed transition

It is evident from Figure 1 and Figure 2, that computational analysis suggests that forced transition or turbulator are necessary to reduce profile drag.

3. Analysis of impact of turbulators on profile drag

This chapter analyses impact of turbulator shape, fastening and laminar to turbulent transition locations on airfoil aerodynamic characteristics. Experimental research methodology and equipment are described. Results of computational modeling and experimental research are provided and their comparative analysis is presented. Computational modeling results are compared with experimental research results published in scientific literature.

After analysis of experimental research results obtained during sailplane flight test, the wake survey method was chosen for its simplicity and ease of calculating airfoil drag. However, in order to calculate airfoil drag according to this methodology pressure deficit in the wake must be measured far from airfoil trailing edge, so that static pressure would be the same as in free flow in front of airfoil. Unfortunately, it is very hard to measure static pressure rather far from trailing edge of airfoil during experimental flight tests. This is usually carried out in flying laboratories since it is hard to install the required equipment in an ordinary sailplane due to safety requirements. Therefore, integrated wake rakes were attached to the sailplane wing edge. In this way drag may be calculated according to improved methodology: by measuring pitot pressure deficit not in the wake but in the boundary layer.

Experimental research was carried out using sailplanes LAK-20T and LAK-17B produced by JSC "Sport aviation & Co" in Lithuania. Airfoil polars obtained from experimental results and computational analysis carried out by the XFOIL code are presented in Figure 3.

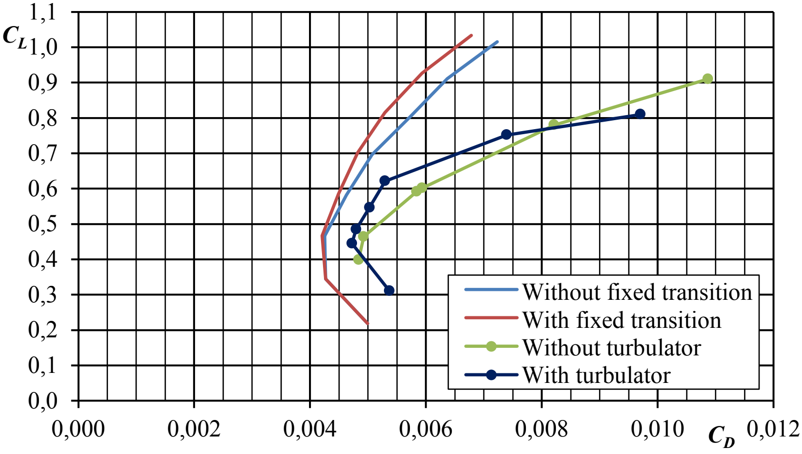

Fig. 3. The polars of the LAP 02-150 airfoil of the LAK-20T sailplane

It is evident that minimum drag coefficient between profile with turbulator and one with fixed transition differs by 11,5 %. Higher minimum drag coefficient is obtained experimentally and is equal to 0,00472, while computational results indicated that the drag is 0,00421. Experimentally obtained minimum drag coefficient for profile without turbulator is 0,00484 and is by 13 % higher, than computationally modeled minimum drag coefficient for profile without fixed transition which is equal to 0,00425.

These research performed with LAK-20T sailplane LAP 02-150 airfoil confirmed that at average sailplane speeds turbulator reduces profile drag. However, the fastening location and shape of the turbulator remain unclear. Sailplane LAK-17B with LAP 7-131/17 airfoil was chosen for experimental research and the obtained experimental results are provided in Figure 4. The blue curve indicates computationally modeled airfoil drag dependence on forced transition location in relation to chord. The red curve indicates the dependence of drag on turbulator fastening location calculated from experimental data results. Vertical axis indicates drag coefficient, and horizontal – distance in airfoil chord length. It is seen ithat the results obtained through computational and experimental analysis differ. Computational modeling indicated that lowest drag occurs when forced transition is fixed at 92 % of chord length. Experimental research suggests that turbulator must be fixed at 90 % of chord.

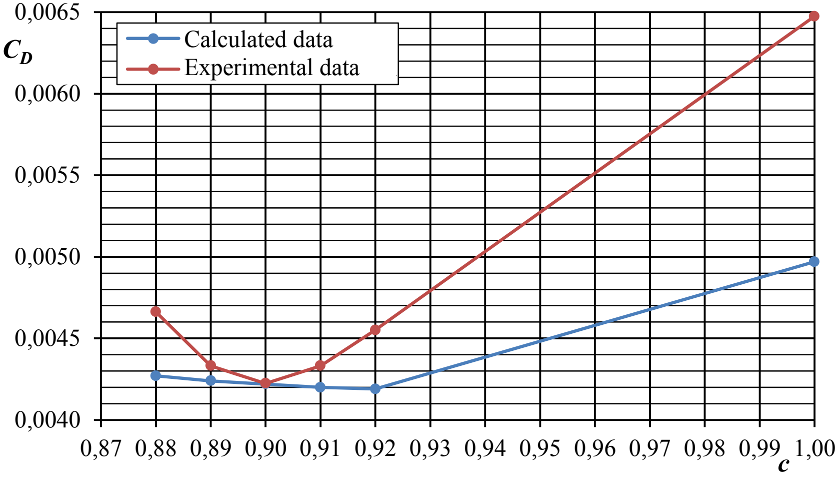

Fig. 4. Dependence of calculated fixed transition and experimentally researched turbulator location on the LAP 7-131/17 airfoil chord of the LAK-17B sailplane

It can be deduced from Figure 4 that XFOIL code cannot accurately determine the location of turbulator fastening. After comparison of results of computational and experimental analysis it can be claimed that zig-zag turbulator must be fastened at 2 % before transition, which is modeled computationally, since transition occurs from the trailing edge of turbulator.

After experimental research of sailplane free flight with zig-zag type turbulator the question is how much profile drag is dependent on turbulator shape. 8 designed turbulators are presented in Figure 5.

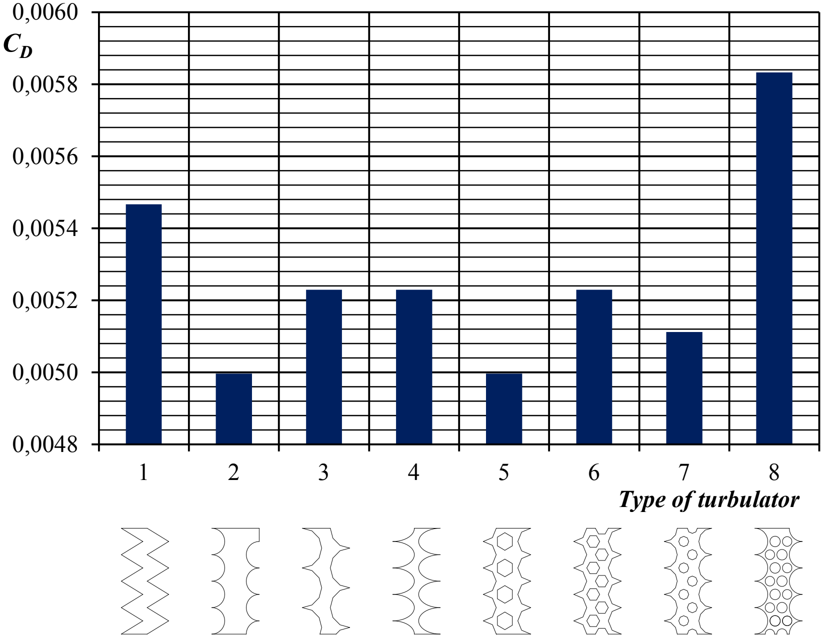

Fig. 5. Profile drag dependence of turbulator type

The designed turbulators were analysed only experimentally because computational modeling programme XFOIL can only model fixed transition. First turbulator is a zig-zag type turbulator and only included for comparison. All turbulators were fastened at 90 % chord length, according to experimental results which showed that in this location zig-zag type turbulator is most effective. This turbulator is regarded as a standard for comparative purposes for analysis of all turbulator effectiveness. It is evident from Figure 5 that it is possible to design more effective (about 9 %) turbulators than the currently used zig-zag type.

4. Prediction of maximum lift

This chapter discusses maximum lift prediction according to pressure difference rule. The performed computational analysis is compared with experimental results published in scientific literature. Improved methodology allowing to predict maximum lift of symmetrical and cambered airfoils more accurately is presented.

W. Valarezo and V. Chin developed a half empirical method for prediction of maximum lift coefficient of airfoil. They maintain that maximum lift is achieved, when pressure coefficient difference between minimum airfoil pressure coefficient and pressure near airfoil trailing edge coefficient is greatest. In order to verify the pressure difference rule, airfoils which were analysed in open type wind tunnel of University of Stuttgart, and whose experimental data was published, were chosen.

Unfortunately, the results obtained in this study indicate that the dependences do not coincide with Valarezo and Chin method. It is evident that with increasing relative thickness of symmetrical airfoils pressure coefficient increases. It could be maintained that the relatively thicker the airfoil, the higher minimum pressure coefficient difference at maximum lift. The following pressure coefficient difference dependences on Reynolds numbers and airfoil relative thickness t are obtained:

$$\Delta C_P = \left(b_{22}t^2 + b_{12}t + b_{02}\right)re^2 + \left(b_{21}t^2 + b_{11}t + b_{01}\right)re + \left(b_{20}t^2 + b_{10}t + b_{00}\right) \quad (1)$$

This $re = \mathrm{Re}/10^6$. Values for b_i coefficients are shown in table 1.

Table 1. Generalized airfoil polynomial values for b_i coefficients

	b_2	b_1	b_0
2	1303,7000	-286,5190	13,6864
1	-4109,2667	874,0487	-37,9103
0	4624,6667	-1099,0867	66,1044

The proposed approximation bias of experimental results at different Reynolds numbers is from 3 % to 9 %, and Valarezo and Chin method method bias is from 6 % to 17 %. Taking into consideration these results, it could be maintained that the suggested approximation can predict maximum lift more accurately.

Also this method suggested for prediction of maximum lift by Valarezo and Chin method is absolutely not suitable for cambered airfoils.

Pressure difference dependences on Reynolds numbers of cambered airfoils may be approximated by straight:

$$\Delta C_P = 0{,}0738re + 3{,}0258 \tag{2}$$

By inserting into equation (3.6) a Reynolds number maximum lift force may be predicted for cambered profiles.

After choosing maximum values of pressure difference coefficients, the difference between experimentally obtained maximum lift coefficient and one calculated according to the proposed equation is from 10 % to 16 %, after choosing minimum values – from 14 % to 23 %.

While using pressure difference values proposed by Valarezo and Chin method the bias scope is even from 16 % to 62 %. Taking into consideration these results, it could be maintained that the suggested approximation can predict maximum lift more accurately.

General conclusions

1. The analysed computational methods are not suitable for prediction of accurate turbulator fastening place. Experimental research shows that in the scope of sailplane speeds, the transition occurs at 2 % chord length behind turbulator.
2. New shape turbulator tips, using which profile drag is lower in comparison with currently used zig-sag type turbulators, were designed and experimentally tested.
3. It has been experimentally determined that LAP 7-131/17 airfoil turbulator can reduce profile drag up to 42 %. This is by 25,2 % more than determined by performed computational analysis. This difference might be influenced by the experimental equipment and by computational modeling methodology in the XFOIL code, which cannot accurately model exploded bubble and upper turbulent and lower laminar flow merge.
4. While comparing airfoil aerodynamic characteristics calculated via computational analysis with those obtained during experimental research and with experimental research results published in scientific literature, it has been determined that computational methods are reliable and accurate. In this case the possible greatest bias amounts to 10 %. Such a bias is not crucial since the difference of results obtained via computational methods and experimental research is in the same line, as the difference between experimental results obtained in two different aerodynamic tubes. If to compare results obtained using the same methodology, the bias is only of several percent.

5. The performed analyses revealed that the dependence in Valarezo and Chin method for prediction of airfoil maximum lift is not accurate at average Reynolds numbers. The bias scope of this method is up to 24 % for symmetric airfoils and 62 % for cambered airfoils.

6. A more accurate dependence for prediction of maximum lift of airfoils, better suited for prediction of maximum lift of symmetrical and cambered airfoils at average Reynolds numbers is presented. The bias scope is even 9 % to symmetric airfoils and 23 % to cambered airfoils. This provides conditions for assessment of aerodynamic characteristics of all airfoils under development and currently available ones, and assessment of airfoil suitability for sailplanes, airplanes and wind turbine blades.

7. With the aim to even more accuratley predict maximum lift of cambered airfoils, their relative thicknes, cambering and radius of leading edge must be evaluated. However, this way the methods becomes more complicated.

List of published works on the topic of the dissertation

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About the author

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SPARNO PROFILIŲ AERODINAMINIŲ CHARAKTERISTIKŲ TYRIMAS

Problemos formulavimas. Lėktuvo skrydžio charakteristikas daugiausia lemia sparno profilių aerodinaminės savybės. Sklandytuvams, o ypač sportiniams – sunkesniems už orą ir be jėgainės pilotuojamiems orlaiviams – keliami ypatingi aerodinaminiai reikalavimai. Neturėdamas jėgainės, sklandytuvas ramiame ore gali tik sklęsti nuožulnia trajektorija, tai yra žemėti. Todėl sklandytuvui sparno profilių aerodinaminės charakteristikos yra lemiamos. Dažniausiai visos aerodinaminės naujovės įdiegiamos sklandytuvuose, o tik vėliau pritaikomos lėktuvuose, todėl sklandytuvo sparno profilių aerodinaminių charakteristikų tyrimams visada buvo skiriama daug dėmesio.

Aerodinamines lėktuvo ir sklandytuvo charakteristikas apibūdina aerodinaminių koeficientų poliarė, rodanti profilio pasipriešinimo koeficiento ir keliamosios jėgos koeficiento tarpusavio priklausomybę. Sklandytuvui sukantis spirale reikia didelės keliamosios jėgos koeficiento reikšmės, o sklendžiant keliamosios jėgos koeficiento reikšmė privalo būti maža. Todėl tikslesnis maksimalios keliamosios jėgos prognozavimas leidžia tiksliau įvertinti sklandytuvo ar lėktuvo minimalų skrydžio greitį. Tokiu būdu sudaromos sąlygos tiksliau įvertinti projektuojamų ir esamų profilių aerodinamines charakteristikas, profilio tinkamumą sklandytuvui, lėktuvui ar vėjo jėgainės mentei.

Atsižvelgiant į tai, kad sklandytuvas nenaudoja jėgainės sukuriamos traukos, norint pagerinti sklendimo charakteristikas esant kreiseriniams greičiams, būtina sumažinti profilinį pasipriešinimą. Profilinis sparno pasipriešinimas paprastai sudaro apie pusę viso pasipriešinimo, kai sklandytuvas skrenda dideliu greičiu (150–200 km/h), ir apie ketvirtį, kai skrydžio greitis mažas (75–100 km/h). Esant mažiems ir vidutiniams skrydžio greičiams, profilio paviršiuje susidaro sudėtinga pasienio sluoksnio struktūra ir susiformuoja laminarusis atsiskyrimo burbulas. Todėl siekiant pagerinti aerodinamines sklandytuvo charakteristikas, būtina išvengti šio burbulo susidarymo. Tam galima panaudoti dirbtinį trikdį. Tačiau pats dirbtinis trikdis negarantuoja, kad, esant visiems skrydžio režimams, efektyviai sumažins pasipriešinimą. Todėl reikia įvertinti ne tik skrydžio sąlygas, bet ir dirbtinio trikdžio tvirtinimo vietą ir formą.

Deja, bet visiškai nėra mokslo tiriamųjų darbų apie dirbtinių trikdžių tvirtinimo vietą ir beveik nėra literatūros, kuria remiantis būtų galima įvertinti, kokia dirbtinio trikdžio forma geriausia. Taip pat nėra vieno efektyvaus skaitinio metodo, kuriuo vadovaujantis galima sumodeliuoti šį uždavinį. Modeliavimą apsunkina ir eksperimentinių rezultatų trūkumas, kurie parodytų laminariojo atsiskyrimo burbulo vietą ir ilgį, nes atsiskyrimo burbulo dydis ir vieta turi tendenciją kisti priklausomai nuo atakos kampo ir Reinoldso skaičiaus.

Atsižvelgiant į šią problematiką, disertacijoje siekiama įvertinti pagrindinių aerodinaminių charakteristikų įtaką sklandytuvo sparno profiliui. Taikant skaitinius metodus, eksperimentinius tyrimus ir lyginamąją analizę, siekiama ištirti ir įvertinti dirbtinio trikdžio įtaką profiliniam pasipriešinimui, patikslinti maksimalios keliamosios jėgos prognozavimą.

Darbo aktualumas. Nuo pat kompozitinių medžiagų sklandytuvų eros pradžios geriausi sklandytuvų profiliai buvo kuriami Vokietijos Federacinėje Respublikoje. Šiuo metu iniciatyvą perėmė Delft technologijos universitetas Olandijoje ir Varšuvos technologijos universitetas Lenkijoje. Norėdami išlaikyti sklandymo pramonės pirmavimą pasaulyje, Vokietijos Federacinės Respublikos profilių kūrėjai nuo 1976 m. nustojo publikuoti naujų profilių koordinates ir charakteristikas. Kiti profilių kūrėjai publikuoja labai mažai ir tik nekomercinių projektų tyrimų rezultatus.

Atsižvelgiant į mokslo darbų ir tyrimų rezultatų trūkumą būtina įvertinti profilinio pasipriešinimo ir maksimalios keliamosios jėgos įtaka lėktuvo ar sklandytuvo skrydžio charakteristikoms. Sumažinus pasipriešinimą ir padidinus maksimalią keliamąją jėgą, galima padidinti lėktuvo ar sklandytuvo maksimalią aerodinaminę kokybę, naudingo krovinio svorį, sutrumpinti kilimo ir tūpimo kelią, sumažinti degalų sąnaudas, aplinkos taršą, triukšmą ir smukos greitį.

Tyrimų objektas. Tyrimų objektas – sparno profilio aerodinaminės charakteristikos. Tiriamas pasipriešinimo koeficientas, maksimalus keliamosios jėgos koeficientas, laminarusis turbulentinis virsmas, srauto atsiskyrimas, laminariojo atsiskyrimo burbulo ir dirbtinių trikdžių įtaka sparno profiliniam pasipriešinimui.

Darbo tikslas. Skaitiniais ir eksperimentiniais metodais ištirti sparno profilių aerodinaminio pasipriešinimo mažinimo galimybes, sukeliant laminarųjį turbulentinį virsmą dirbtiniais trikdžiais. Ištirti maksimalios keliamosios jėgos prognozavimo tikslumą esant vidutiniams Reinoldso skaičiams.

Darbo uždaviniai. Darbo tikslui pasiekti būtina išspręsti šiuos uždavinius:

1. Naudojant skaitinius ir eksperimentinius metodus ištirti ir nustatyti dirbtinių trikdžių formos, tvirtinimo vietos ir laminariojo turbulentinio virsmo vietos įtaką sparno profilio aerodinaminėms charakteristikoms.
2. Atliktus skaitinius modeliavimus ir eksperimentinius tyrimus, palyginti su mokslinėje literatūroje publikuotais eksperimentiniais rezultatais.
3. Ištirti dirbtinių trikdžių efektyvumo didinimo galimybę.
4. Ištirti ir patikslinti maksimalios keliamosios jėgos prognozavimo metodo tikslumą esant vidutiniams Reinoldso skaičiams.

Tyrimų metodika. Profilių aerodinaminės charakteristikos tiriamos tiek teoriškai, taikant įvairius skaičiavimo metodus, tiek bandymais aerodinaminiuose vamzdžiuose ir laisvo skrydžio metu. Todėl darbe taikomi skaitinio modeliavimo ir eksperimentiniai tyrimų metodai, atliekama lyginamoji analizė.

Skaitiniams modeliavimams pasirinktos neklampiojo srauto su pasienio sluoksniu be sąveikos (zoniniai nesąveikaujantys metodai), neklampiojo srauto ir klampiojo srauto sąveikos (zoniniai sąveikaujantys metodai) ir bendrųjų Navjė ir Stokso lygčių sprendimų metodų programos.

Profiliniam pasipriešinimui tirti pasirinktas sparno profilio pėdsako tyrimo metodas. Eksperimentiniams tyrimams taikomi bandymai laisvo sklandytuvo skrydžio metu, kuriems patobulinta metodika ir pagaminta speciali įranga.

Darbo mokslinis naujumas. Rengiant disertaciją buvo gauti šie mechanikos inžinerijos mokslui nauji rezultatai:

1. Skaitiškai sumodeliuotas ir eksperimentiškai ištirtas ryšys tarp dirbtinio trikdžio tvirtinimo vietos ant sparno apatinio paviršiaus ir laminariojo turbulentinio virsmo. Įvertinta dirbtinių trikdžių įtaka sparno profilio pasipriešinimui.

2. Sukurtos ir eksperimentiškai ištirtos virsmą sukeliančios naujos formos dirbtinių trikdžių juostos su kuriomis profilio pasipriešinimas yra mažesnis, palyginti su šiuo metu plačiai naudojamais zigzago tipo dirbtiniais trikdžiais.

3. Patikslinta maksimalios keliamosios jėgos prognozavimo metodika esant vidutiniams Reinoldso skaičiams.

Darbo rezultatų praktinė reikšmė. Tyrimų rezultatai leidžia sumažinti sklandytuvo ar lėktuvo profilinį pasipriešinimą naudojant mechaninį dirbtinį trikdį. Tai ypač svarbu sportiniams sklandytuvams ir lengviems lėktuvams.

Tyrimų rezultatai leidžia tiksliau prognozuoti maksimalią keliamąją jėgą pagal slėgio skirtumo taisyklę. Tikslesnis maksimalios keliamosios jėgos prognozavimas leidžia tiksliau įvertinti lėktuvo ar sklandytuvo minimalų skrydžio greitį projektavimo etapu. Taip sudaromos sąlygos įvertinti projektuojamų ir esamų profilių aerodinamines charakteristikas, profilio tinkamumą sklandytuvui, lėktuvui ar vėjo jėgainės mentei.

Darbo rezultatus galima taikyti sklandytuvus ir lengvus lėktuvus gaminančiose ir eksploatuojančiose įmonėse, taip padidinant jų konkurencingumą.

Ginamieji teiginiai

1. Ištirti skaičiavimo metodai neįvertina tikslios dirbtinio trikdžio tvirtinimo vietos. Eksperimentiškai ištirta, kad sklandytuvo greičių diapazone virsmas įvyksta vidutiniškai 2 % stygos atstumu už dirbtinio trikdžio.

2. Ištyrus suprojektuotas naujos formos dirbtinių trikdžių juostas, nustatyta, kad jos efektyvesnės iki 9 % už šiuo metu plačiai naudojamus zigzago tipo dirbtinius trikdžius.

3. Ištirta, kad Valarezo ir Chin metodo maksimalios keliamosios jėgos prognozavimo metodo paklaidos simetriniams profiliams gali sudaryti iki 24 %, o gaubtiems profiliams – iki 62 %. Patikslinus šį metodą, maksimali keliamoji jėga simetriniams profiliams gali būti prognozuojama iki 9 %, o gaubtiems profiliams iki 23 % tikslumu.

Disertacijos struktūra. Disertaciją sudaro įvadas, keturi skyriai, bendrosios išvados, literatūros ir autoriaus publikacijų sąrašai. Disertacijos apimtis – 136 puslapiai. Joje yra 72 numeruotos formulės, pateikti 67 paveikslai ir 5 lentelės. Rašant disertaciją naudotasi 181 literatūros šaltiniu.

Pirmajame skyriuje išanalizuota sparno profilių aerodinaminių charakteristikų įtaka lėktuvo ir sklandytuvo skrydžio charakteristikoms. Nustatyta aerodinaminių charakteristikų reikšmė ir veiksniai, kurie leidžia jas pagerinti. Išanalizuoti eksperimentiniai tyrimai laisvame sklandytuvo skrydyje ir eksperimentinių tyrimų metodika.

Antrajame skyriuje išnagrinėti skaitiniai sparno profilio aerodinaminių charakteristikų modeliavimo metodai. Atlikti skaitiniai tyrimai ir palyginamoji analizė tarp įvairiais skaitinio modeliavimo metodais gautų rezultatų. Skaitiniais metodais ištirta laminariojo atsiskyrimo burbulo, fiksuoto virsmo ir jo vietos įtaka sparno profiliniam pasipriešinimui.

Trečiajame skyriuje tiriama dirbtinių trikdžių formos, tvirtinimo vietos ir virsmo vietos įtaka sparno profilio aerodinaminėms charakteristikoms. Aprašoma eksperimentinių tyrimų metodika ir įranga. Pateikiami skaitinio modeliavimo ir eksperimentinių tyrimų rezultatai ir jų palyginamoji analizė. Taip pat skaitinių modeliavimų rezultatai lyginami su mokslinėje literatūroje publikuotais eksperimentiniais tyrimais.

Ketvirtajame skyriuje pateiktas maksimalios keliamosios jėgos prognozavimas pagal slėgio skirtumo taisyklę. Atlikti skaitiniai tyrimai palyginti su mokslinėje literatūroje publikuotais eksperimentiniais rezultatais. Patobulinta metodika, kuri leidžia daug tiksliau prognozuoti maksimalią keliamąją jėgą esant vidutiniams Reinoldso skaičiams.

Bendrosios išvados

1. Ištirti skaitinio modeliavimo metodai neįvertina tikslios dirbtinio trikdžio tvirtinimo vietos. Eksperimentiniais tyrimais nustatyta, kad sklandytuvo greičių diapazone virsmas įvyksta vidutiniškai 2 % stygos atstumu už dirbtinio trikdžio.
2. Sukurtos ir eksperimentiškai ištirtos virsmą sukeliančios naujos formos dirbtinių trikdžių juostos, su kuriomis profilio pasipriešinimas yra mažesnis iki 9 %, lyginant su šiuo metu plačiai naudojamais zigzago tipo dirbtiniais trikdžiais.
3. Eksperimentiniais tyrimais ištirta, kad LAP 7-131/17 profilio dirbtinis trikdis gali iki 42 % sumažinti profilio pasipriešinimą. Tai 25,2 % daugiau, nei parodė atlikti skaitiniai tyrimai. Šį skirtumą galėjo paveikti bandymų įranga ir skaitinio modeliavimo metodika realizuota skaitinėje programoje XFOIL, kuri negali tiksliai modeliuoti sprogusio burbulo ir viršutinio turbulentinio ir apatinio laminariojo srauto susijungimo.
4. Lyginant skaitiniais metodais apskaičiuotas profilio aerodinamines charakteristikas su eksperimentiškai gautomis bei mokslinėje literatūroje publikuotais eksperimentinių tyrimų rezultatais nustatyta, kad skaitiniai metodai realizuoti skaitinėse programose yra patikimi ir tikslūs. Šiuo atveju galimos didžiausios paklaidos siekia 10 %. Tai nėra lemiamos paklaidos, nes skirtumas tarp skaitinių metodų rezultatų ir eksperimentinių tyrimų yra tokios pačios eilės, kaip skirtumas tarp eksperimentinių tyrimų, atliktų dviejuose skirtinguose

aerodinaminiuose vamzdžiuose. Kai lyginami rezultatai, gauti vienoda metodika, paklaida yra tik kelių procentų eilės.

5. Atlikti tyrimai parodė, kad Valarezo ir Chin maksimalios keliamosios jėgos prognozavimo metodo tikslumas esant vidutiniams Reinoldso skaičiams yra nedidelis. Šio metodo paklaidos simetriniams profiliams gali sudaryti iki 24 %, o gaubtiems profiliams – iki 62 %.

6. Pasiūlyta tikslesnė priklausomybė, tinkamesnė simetrinių ir gaubtų profilių maksimaliai keliamajai jėgai prognozuoti esant vidutiniams Reinoldso skaičiams. Didžiausios galimos paklaidos patikslintu maksimalios keliamosios jėgos prognozavimo metodu simetriniams profiliams gali sudaryti iki 9 %, o gaubtiems profiliams – iki 23 %. Tokiu būdu sudaromos sąlygos tiksliau įvertinti projektuojamų ir esamų profilių aerodinamines charakteristikas bei profilio tinkamumą sklandytuvui, lėktuvui ar vėjo jėgainės mentei.

7. Norint dar tiksliau prognozuoti maksimalią keliamąją jėgą gaubtiems profiliams, reikėtų įvertinti jų santykinį storį, gaubtumą ir noselės spindulį. Tačiau tuomet šis metodas tampa sudėtingesnis.

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