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The flow separation development analysis in subsonic and transonic flow regime of the laminar airfoil

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Abstract

Wind tunnel tests of a laminar airfoil have been performed at the Institute of Aviation in Warsaw. The main goal of the investigation was to study the separation process development in subsonic and early transonic flow regime. The airfoil chord was 0.2m. During wind tunnel test the natural laminar-turbulent transition was applied. The Mach numbers were 0.3 and 0.7. Reynolds number were approximately equal to $1.22 \cdot 10^6$ and $2.85 \cdot 10^6$ respectively. The angle of incidence was increased up until the flow was fully separated. During the experimental research, chosen test methods such as pressure measurements and schlieren visualization were applied. Wind tunnel results were analyzed in terms of aerodynamic coefficients and flow separation type identification. The wind tunnel investigation revealed that separation phenomena at subsonic and transonic flow regime affected in a different manner on the airfoil aerodynamic performance. This was mainly because of the change of the flow pattern influencing on the separation process.

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Keywords: laminar airfoil, separation, experiment, subsonic, transonic

1. Introduction

The flow separation phenomenon is related to each aviation airfoil and is associated with the break-off of the thin layer (called boundary layer), right at the wing surface. The way in which the flow separation develops to the moment of the full separation occurrence, is strictly dependent on various factors: an airfoil thickness (thin, moderate, thick), an airfoil type (turbulent, laminar, supercritical), an airfoil surface quality (smooth or with roughness), the angle of attack, flow conditions (altitude and air turbulence), and Reynolds number. The exemplary

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flow separation development with the angle of incidence rise at subsonic speed was presented by Talay (1975). The flow separation development appears on the upper airfoil surface and propagates upstream, into the leading edge direction. When it occurs, the increment of lift coefficient with angle of attack began to decrease until the maximum lift coefficient value is reached. Afterwards, when angle of attack is still increased, the lift decrease appears. This phenomenon is strictly related to the pitching moment change and a drag increase. For subsonic speeds, there are indicated characteristic types of the wing-section stall, according to Gault (1957), Whitford (1987) and Raymer (1992): the trailing-edge, the leading-edge, and an thin-airfoil (or combined: trailing-edge and the leading-edge).

For the transonic flow range, above critical Mach number value over an airfoil surface appears shock wave terminating the supersonic region. The shock wave interaction with boundary layer (laminar, transitional or turbulent) modify the way of the flow separation (Haynes et al., 1957), causing the boundary layer thickening or shock-induced separation of the boundary layer. The structure of the flow separation at transonic speeds depends additionally on: the free stream Mach number value, the shape and strength of the shock and pressure fluctuations in the flow (resulting the frequency and amplitude of shock oscillations). The proposition of the shock wave separation process classification (bubble separation) was presented by Pearcey (1968). Pearcey proposed classification of the separation types based on a stationary shock interacting with a turbulent boundary layer. Two models were specified: A) only rearward growth of laminar bubble and B) applicable when the rear separation is incipient or present. The B) model was detailed and divided in three groups: 1) a rear separation provoked by bubble, 2) a rear separation provoked by shock and 3) with a rear separation already present. Mundell and Mabey (1986) proposed classification of the shock wave boundary layer interaction and excitations on airfoils in unsteady transonic flow with shock oscillations. The following classification of the flow separation with increasing incidence was proposed: a) type 1: for a low angle weak shock thickens boundary layer, b) type 2: a stronger shock locally separates boundary layer for higher values of angles, c) type 3: for high values of the angle of incidence a very strong shock separates the boundary layer to the trailing edge.

The presented paper contains experimental results of the flow separation over laminar airfoil for chosen subsonic and transonic Mach numbers and various angles of incidence. The schlieren method was used for a visualization and pressure measurements were used for the lift and drag coefficients estimation (averaged values). The flow separation development influenced on a pressure coefficient distribution and airfoil aerodynamic characteristic values. Results showed different conditions of the flow separation for tested subsonic and transonic flow values.

Nomenclature

BL	boundary layer
c	airfoil chord
CD	drag coefficient
CL	lift coefficient
C_p	pressure coefficient
C_p*	critical pressure coefficient
LE	leading edge
M	Mach number
Re	Reynolds number
SW	shock wave
TE	trailing edge
αi	angle of incidence

2. Approach

The wind tunnel research was carried out in the trisonic N-3 wind tunnel at the Institute of Aviation.

The N-3 wind tunnel, described by Wiśniowski (2016), is a closed circuit blow-down type with a partial flow recirculation. Dimensions of the test section are: the cross-section 0.6x0.6m, the length 1.5m. The tested 2D airfoil model was of the laminar type with maximum thickness 15% c and the chord length 0.2 m. The V2C airfoil shape was designed by Dassault Aviation (France) and described by Grossi (2014). At the beginning of the investigation, the wind tunnel run for fixed angle of incidence 0° and chosen Mach numbers in range 0.3-0.8 was conducted. Afterwards, the 2D airfoil model was tested at two Mach numbers: 0.3 and 0.7. Reynolds numbers were approximately equal $1.22 \cdot 10^6$ and $2.85 \cdot 10^6$ respectively. The angle of incidence was increased from 0° up to the full separation occurrence. For the airfoil model natural laminar-turbulent transition was applied. During the investigation, pressure measurements and colour schlieren visualization were applied. In order to measure pressure distribution (thus lift and pitching moment of the airfoil), pressure taps were located on the upper and lower surface of the airfoil. The aerodynamic rake was used for momentum loss in wake measurement, from which aerodynamic drag was determined. Results from PIV flow visualisation method (Particle Image Velocimetry) for Mach number 0.7 were described by Stryczniewicz et al. (2016) and are not presented in this paper.

The V2C laminar airfoil shape with pressure orifices distribution indication is presented on Fig. 1.

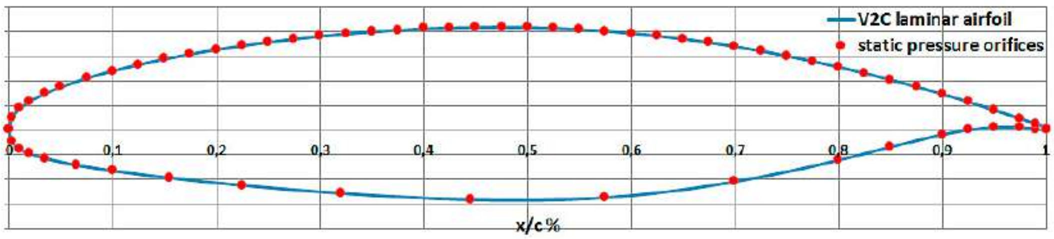

Fig 1. The static pressure orifices location at V2C airfoil.

3. Results

The performed research of the laminar airfoil refers to two flow regimes: a subsonic (M=0.3) and an (early) transonic (M=0.7). For tested airfoil at the angle of incidence αi=0°, the drag coefficient achieved minimum values(CD(M=0.3)=0.005; CD(M=0.7)=0.01). The higher CD referred to a greater Mach number (M=0.7), which reached approximately drag rise Mach number value. The Fig. 2. shows, that above M>0.7 the lift coefficient CL decrease. In Fig. 3, pressure distributions plots for set Mach numbers and αi=0° are shown. The Cp distribution shape over the upper airfoil surface (behind the point of maximum airfoil thickness and upstream TE) indicates on laminar separation bubble appearance (~C_p plateau). BL separates, changes from a laminar to a turbulent (due to a positive pressure gradient) and reattaches. The approximate BL transition location for the M=0.3, Re=$1.22 \cdot 10^6$ (x/c≈0.78), according to Horton (1968) was estimated by the locating of the end of the pressure plateau of a surface pressure distribution. It was quite consistent with a position determined by an empirical method based on wind tunnel research described by Zaks (1957) – see Fig. 3. According to this method, the BL transition for low Mach numbers and the low angle of incidence occurs downstream from the point of the maximum airfoil thickness and is the function of Reynolds number. The BL transition occurrence for M=0.7, Re=$2.85 \cdot 10^6$ is far upstream (at about x/c=0.67) close to x/c location, where the SW terminating subsonic region just became appearing. At the angle αi=0°, the SW was weak (SW shape was low and hardly visible on schlieren picture) and its presence did not caused a noticeable rise in drag.

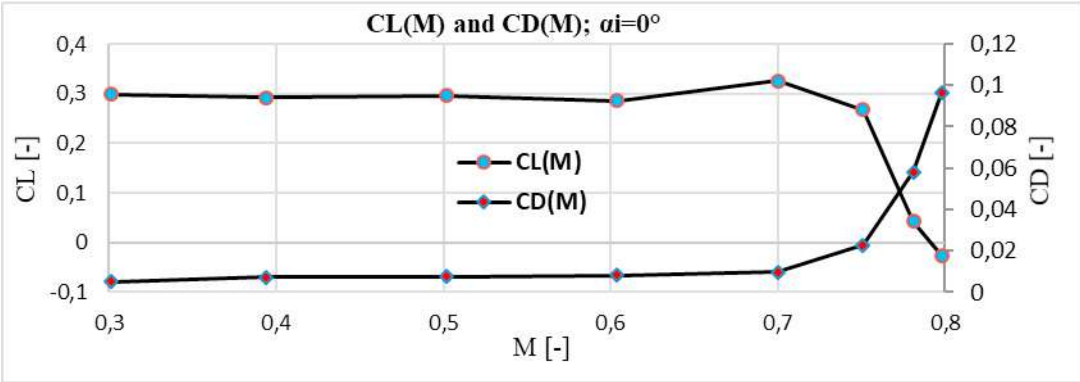

Fig 2. The CL(M) and CD(M) characteristics of the V2C airfoil; αi=0º.

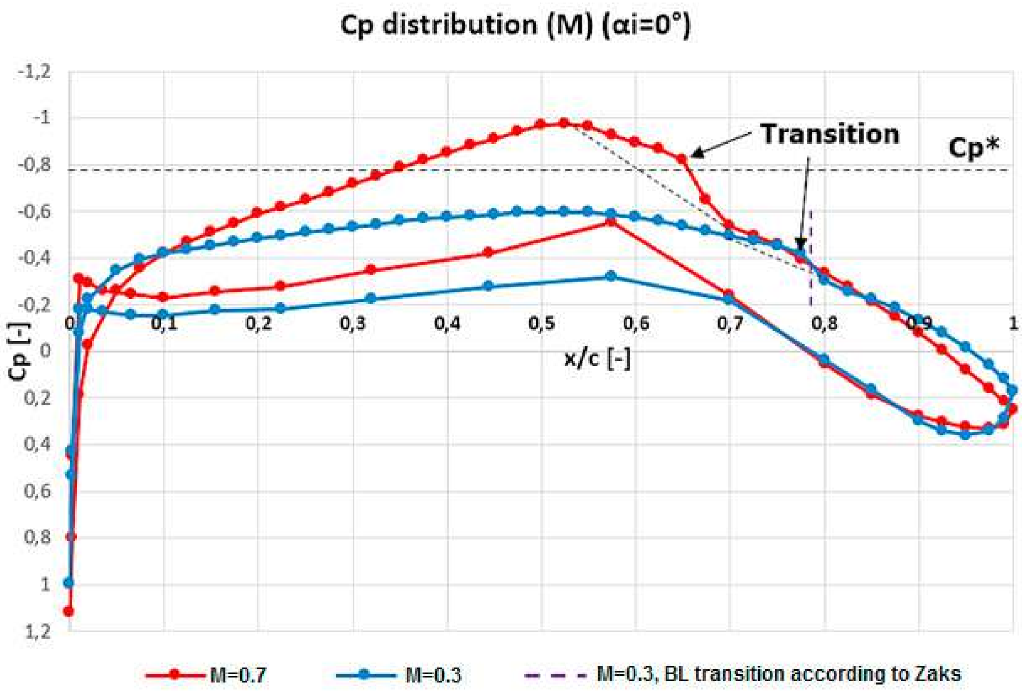

Fig 3. The pressure distribution of the V2C airfoil; M=0.3 and M=0.7; αi=0º.

3.1. M=0.3; Re=1.22·10^6

The flow separation at subsonic Mach number for the V2C laminar airfoil started developing from the trailing edge in the upstream direction. This was because the BL of the moving air over the airfoil, under the adverse pressure gradient influence, decelerated near TE to zero and detached from the surface. With an incidence rise, the flow separation started moving into the LE direction (αi>2°). Drag and lift value were increasing steadily. Above incidence αi>12° separated region of the flow expanded and covered the whole upper surface. The airfoil stall caused lift reduction and a large pressure drag rise (Fig. 4., from αi 12° to 13°). The CL(αi) characteristic character (a steady growth ahead and a rapid decrease behind the maximum CL value) according to Gault (1957), indicate on the combined stall type (trailing-edge and leading-edge stall characterized by i.e. semi rounded lift-curve peak and followed by rapid decrease in lift).

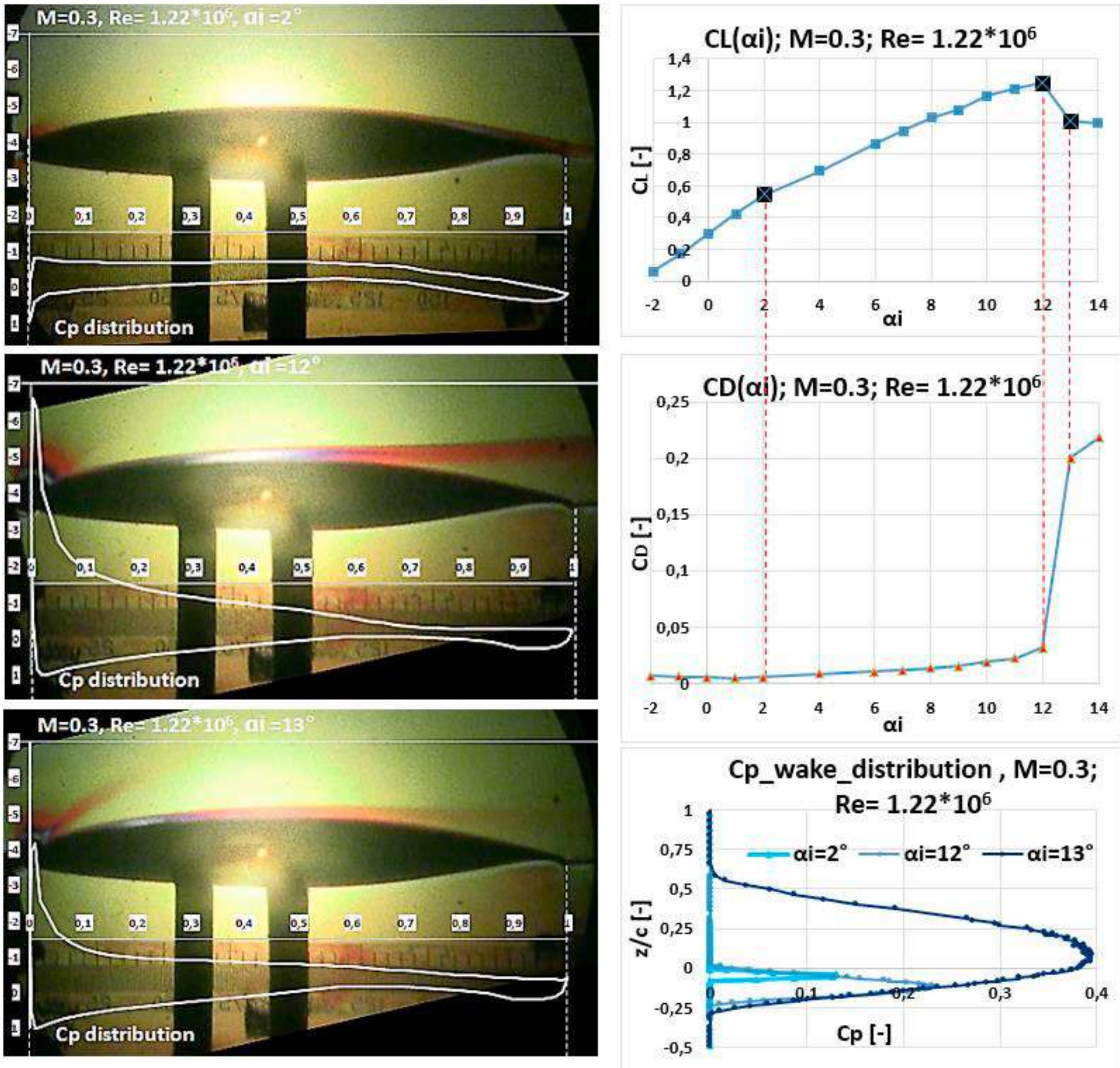

Fig 4. The separation process development at the V2C airfoil; M=0.3; $Re=1.22{\cdot}10^6$.

3.2. $M=0.7$; $Re=2.85{\cdot}10^6$

The flow separation at transonic Mach number for the V2C laminar airfoil occurred in the front of the SW, in the laminar BL. It was associated with the laminar bubble occurrence. For low angles of attack, tubulised flow behind SW was reattaching to model surface. The BL nature of the stream in the front of the SW was laminar. Identification of the BL type was investigated experimentally and described by Placek and Stryczniewicz (2016). At the angle of incidence αi= 2°, behind the normal SW, the smaller supplementary SW was observed (Fig. 5). Its appearance was evidential of the laminar BL interaction with the main SW, according to Shapiro (1954). During the angle of incidence rise, the supersonic region upstream main SW began to expand and SW was becoming stronger (Fig. 5). Simultaneously, supplementary SW was vanishing. The BL behind the SW thickened and the drag was increasing. Above the incidence angle αi≈4° observable unsteadiness of the SW has been noticed. Moving separation region from the TE into the SW location reached the separation bubble. Then, the turbulent boundary layer detached from the airfoil surface underneath the SW. The SW stall phenomenon occurred and a further incidence increase made the SW moving upstream (Instantaneous vector velocity fields over tested airfoil for chosen incidence angles were presented in [10]). Described process of the flow separation development over laminar airfoil in transonic flow regime, based on achieved results from wind tunnel measurements, indicates on the "B" separation model according to Pearcey [6]. The increase of incidence at constant free stream Mach number caused increase the local Mach upstream of the SW and SW strengthen. Further increase of incidence caused decreasing pressure at TE. The interactions between separation bubble, SW and rear separation caused stronger disturbance at the wake. Finally, after flow separation at the foot of SW, the drag rise was greater and SW started moving upstream.

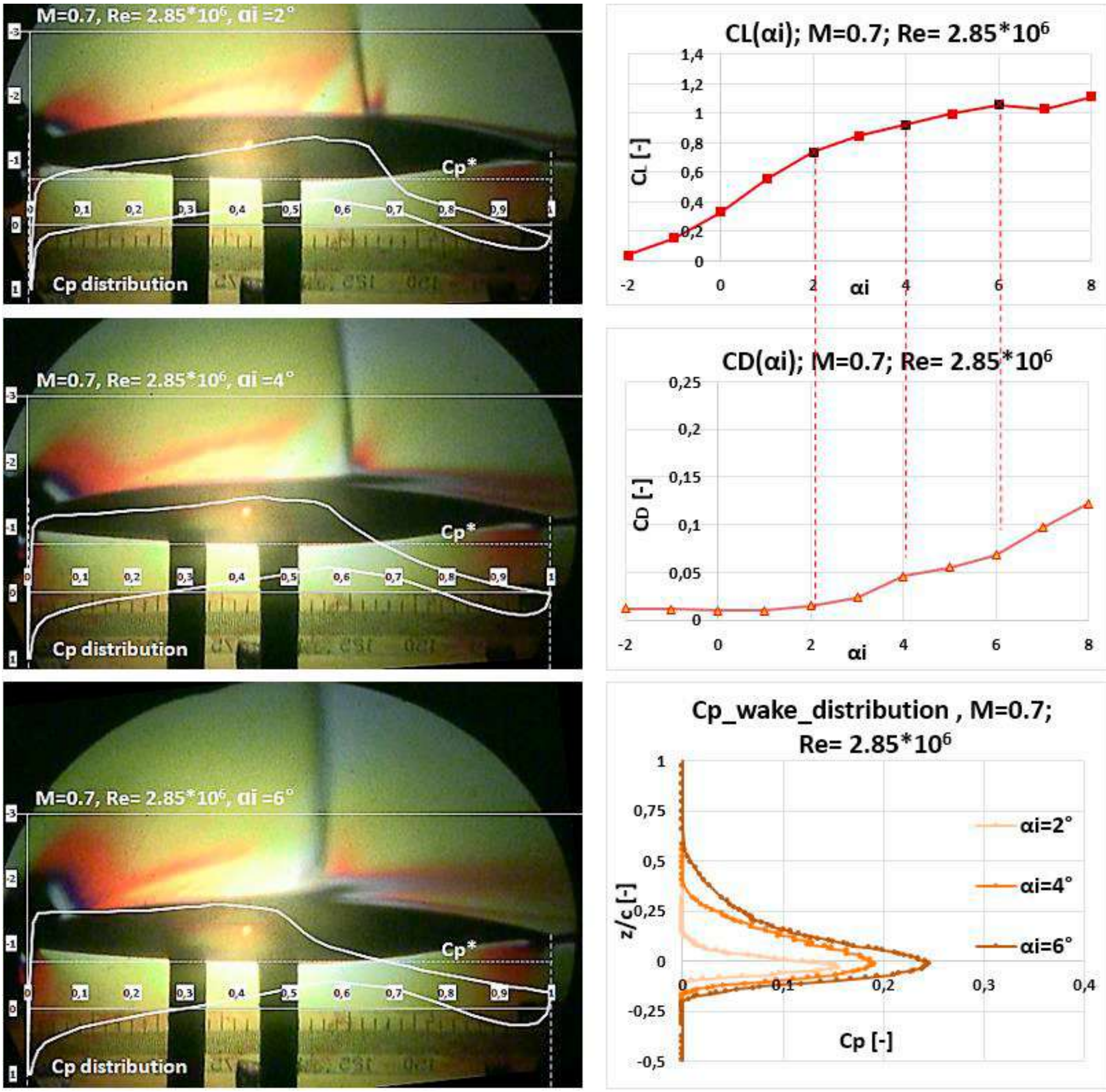

Fig 5. The separation process development at the V2C airfoil; M=0.7; Re=2.85$\cdot10^6$.

4. Conclusions

The wind tunnel tests of the laminar airfoil have been conducted for selected Mach numbers. During investigation incidence angle was increased. Measurements techniques: pressure measurements and schlieren visualization were applied. From pressure distribution data, aerodynamic coefficients were obtained. Reduced measurement data, plots and schlieren pictures were presented in terms of flow separation development. Achieved results allowed to classify the separation process of the laminar airfoil respectively at subsonic and transonic flow regimes.

5. Discussion

Although the separation process of the tested 2D airfoil model was defined, the more accurate and reliable analysis would be possible with use additional data, from other measurement methods. Shear layer measurements and BL velocity profiles along the airfoil model surface could indicate the exact BL transition location and/or laminar bubble position/length. Moreover, high-frequency measurements of unsteadiness, such as pressure fluctuations on the airfoil surface or the SW movement would enriched the separation process analysis.

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