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NUMERICAL AND EXPERIMENTAL MODELLING OF TRANSITION IN A SEPARATED BOUNDARY LAYER ON THE NACA63A421 AIRFOIL

NUMERICKÉ A EXPERIMENTÁLNÍ MODELOVÁNÍ PŘECHODU DO TURBULENCE V ODTRŽENÉ MEZNÍ VRSTVĚ NA PROFILU NACA63A421

Abstract

The paper is concerned with numerical modelling of transition in a separated boundary layer. The model of laminar/turbulent transition is based on the combination of empirical terms determining position of the transition and averaged Navier – Stokes equations closed by the k – ω SST turbulence model. The model of transition is applied in computation of 2D flow past NACA63A421 airfoil. Computation is performed using the commercial code ANSYS Fluent 6.3.26, in which the transition method is implemented as a User-Defined-Function. Computed distributions of *Cp* along the airfoil are verified by comparison with experimental data, which were obtained by measurements in a closed circuit wind tunnel at the constant Reynolds number and several angles of attack. Comparisons prove applicability of the implemented transitional model.

Abstrakt

Práce se zabývá numerickým modelem dvourozměrného proudění na profilu NACA63A421 zaměřeným zejména na přechod v odtržené smykové vrstvě. Výpočet je založen na kombinaci empirických vztahů pro určení polohy přechodu a řešení středovaných Navier-Stokesových rovnic uzavřených dvourovnicovým k – ω SST modelem turbulence. Je použit komerční software FLUENT 6.3.26 doplněný funkcemi definovanými uživatelem. Výsledky numerické simulace jsou experimentálně ověřeny. Měření tlakových rozložení na profilu byla provedena v cirkulačním tunelu při jednotném Reynoldsově čísle Re = 250 000 a mnoha úhlech náběhu. Výsledky experimentu prokazují funkčnost implementovaných funkcí.

1 INTRODUCTION

The numerical modelling of the transition is still topical problem for applications in internal and external aerodynamics. There exist two qualitatively different ways of boundary layer transition. These are the transition in attached flow (natural transition and bypass transition) and the transition in separated flow (so-called laminar separation bubble). Apart from practical methods using solution of series of boundary layer integral equations (e.g. software Xfoil), most computations are based on solving system of the averaged Navier – Stokes equations closed by the model of turbulence with a bypass-transition model. All methods of transition modelling based on algebraic or transport equations for an intermittency factor use empirical relations to determine beginning and length

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of the transition region. In the current study the position of transition is determined using the Reynolds number related to momentum boundary layer thickness and the Reynolds number related to the length of laminar part of the separation bubble respectively. In order to prove applicability of the method described in this paper to solutions of flow past airfoils, corresponding measurements were performed to validate results of computations.

2 TRANSITION IN ATTACHED FLOW

In the case of the bypass transition in attached flow the beginning of the transition is altogether determined by an empirical relation for Reynolds number related to momentum boundary layer thickness $Re_{\theta t} = u_e \theta_t / \nu$. Out of many existing empirical correlations the relation proposed by Příhoda et al. [1] was used in the current computation. It is of the form

$$\mathrm{Re}_{\theta t} = 402 Tu^{-0,6}\left[1 + 0.25\exp\left(-Tu\right)\frac{1-\exp\left(-40\lambda_t\right)}{1+0.4\exp\left(-40\lambda_t\right)}\right], \tag{1}$$

where Tu [%] is the turbulence level and λ_t is the dimensionless pressure gradient. Index t indicates the beginning of the transition region. The phase of the transition is determined by the intermittency function proposed by Narasimha [2] in the form

$$\gamma = 1 - \exp\left[-\hat{n}\sigma\left(\mathrm{Re}_s - \mathrm{Re}_{st}\right)^2\right] \tag{2}$$

Thus, the intermittency function depends on the coordinate s only. The length of the transition region is determined by parameters $\hat{n}$ and σ describing generation rate and propagation rate of turbulent spots. These parameters are determined by relation

$$\hat{n}\sigma = \frac{N}{\mathrm{Re}_{\theta t}^3}, \tag{3}$$

where parameter N expresses the influence of turbulence level and pressure gradient and according to Solomon, Walker and Gostelow [3] it is determined by empirical relation

$$N = 0.86\times10^{-3}\exp\left(2.134\lambda_t \ln Tu - 59.23\lambda_t - 0.564\ln Tu\right), \text{ for } \lambda_t < 0$$

$$N = 0.86\times10^{-3} Tu^{-0.564}\exp\left(-10\sqrt{\lambda_t}\right). \text{ for } \lambda_t > 0 \tag{4}$$

Since the position of the transition strongly depends on the free stream turbulence level, Straka and Příhoda [4] proposed a smooth function between intermittency in the boundary layer γ_i given by equation (2) and intermittency in the free stream γ_e in the form

$$\gamma = \frac{\gamma_e + \gamma_i}{2} + \frac{\gamma_e - \gamma_i}{2}\tanh\left[C_\gamma\left(\frac{y}{\delta} - 1\right)\right], \tag{5}$$

where constant $C_\gamma = 12 \div 18$. Thus, effective viscosity is determined as

$$\mu_{eff} = \mu + \gamma\mu_T . \tag{6}$$

Hence the intermittency function $\gamma \in \langle 0;\ 1\rangle$ influences production and diffusion terms in transport equations of the turbulence model within the transition region. In the laminar flow, the intermittency function is equal to 0 and in the turbulent flow it is equal to 1.

3 TRANSITION IN SEPARATED FLOW

When air flows past airfoil at lower Reynolds numbers, laminar boundary layer usually separates just behind the point of maximal velocity, where the flow starts to decelerate. However, due to disturbances in the separated laminar boundary layer transition takes place and the turbulent boundary layer reattaches (laminar separation bubble). A simple model of transition in the separated boundary layer was proposed by Roberts [5]. His solution is based on empirical relation between the Reynolds number Re_{l_1} related to the length of the laminar part of the separation bubble and the free stream turbulence level. This relation was perfected by Jakubec [6], who performed significant number of experiments and arrived at the form

$$\mathrm{Re}_{l_1} = 2\times10^4 \log\left[\operatorname{cotgh}\left(3.5\frac{Tu_e}{100}\right)\right], \tag{7}$$

where Tue is local free stream turbulence level, defined by equation

$$Tu_e = \frac{1}{u_e}\sqrt{\frac{2k_e}{3}}\,. \tag{8}$$

the Reynolds number Re_{l_1} is defined as

$$\mathrm{Re}_{l_1} = \frac{u_e l_1}{\nu}\,. \tag{9}$$

The position of the transition in the separated flow is determined by the coordinate $s_t = s_s + l_1$, where s_s is position of the separation on the airfoil. In the computations of transition in the separated flow the transition is supposed to be sudden.

4 MODIFIED CALCULATION PROCESS

Calculations were provided using the commercial code ANSYS Fluent 6.3.26. System of governing equations was closed by the k-ω SST turbulence model (Menter [7]), which was modified with UDF so that the production terms in transport equations are affected and the turbulence model is able to predict transition. Note, in laminar boundary layer the turbulent viscosity is zero. The production terms can by written as

$$P_{k,\omega} = \mu_T f\left(\vec{x},\vec{u},k,\omega\right), \tag{10}$$

and with respect to eq. (6) it is sufficient to estimate the intermittency correctly. The modified calculation process is shown in Fig. 1. At the start of calculation grid topology is dealt with. Then governing equations together with transport equations for turbulent scales are solved. At the end of iteration or time step, flow field analysis is performed, transition models evaluated and turbulent viscosity recalculated. This procedure is applicable for incompressible and compressible flow too.

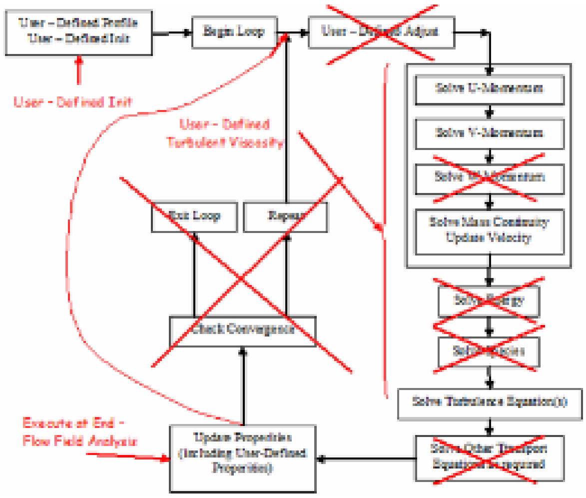

Fig. 1 Modified calculation process in Fluent (incompressible model)

5 EXPERIMENT

Experimental data for validation of numerical model were obtained by measurements performed in the closed circuit wind tunnel at the Institute of Thermomechanics, AS CR. A prismatic model of NACA 63A421 with chord c = 0.25 m was mounted in the vertical position in the centre of the 865×485 (W×H) test section (Fig.2) and spanned from the bottom to the upper wall of the tunnel. The model of the airfoil was equipped with 31 static pressure tapings on both pressure and suction surface including one common taping on the leading edge. Positions of individual static pressure tapings are shown in Fig. 3. Tapings were arranged in the special way in order to prevent them from influencing each other.

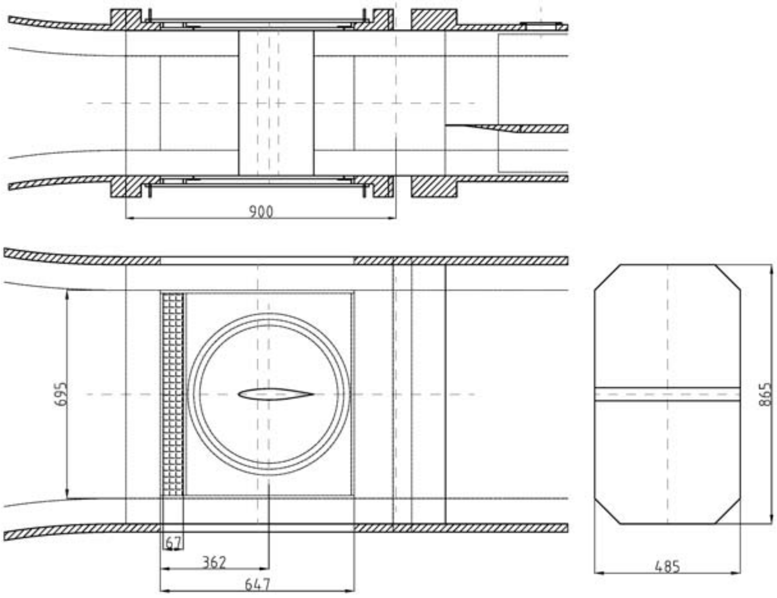

Fig. 2 Scheme of the test section with airfoil mounted inside

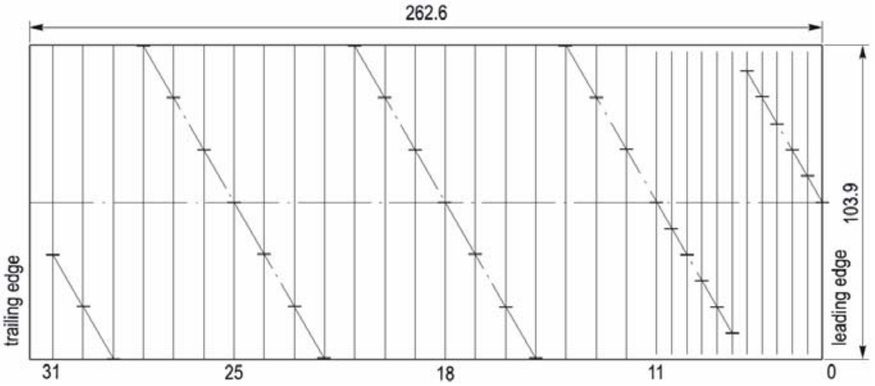

Fig. 3 Scheme of the distribution of static pressure tapings on the unfolded upper surface

6 RESULTS

All calculations and measurements were performed at the constant Reynolds number $Re = 250\,000$, and the angle of attack ranging from $\alpha = -5°$ to $\alpha = +10°$. Turbulence intensity in the empty wind tunnel test section is approximately 0.25%. The computational grids are structured and orthogonal. Figs. 4÷7 show comparisons of distributions of pressure coefficient obtained by computation and experimentally. We can see from these figures that qualitative agreement of *Cp* distributions in all cases of angle of attack is reasonably good. Applied transition model was able to predict separation bubbles and transitions respectively on both airfoil surfaces at correct locations. Good agreement can be seen also in the course of the lift curve in Fig. 8, where results of calculations are also compared with data calculated by Xfoil. Little departures of *Cp* values can be probably attributed to the fact that the flow past the airfoil in the wind tunnel is not ideally 2D due to 3D effects taking place at sidewalls of the wind tunnel.

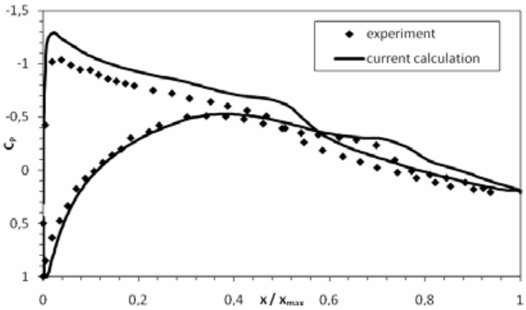

Fig. 4 Distribution of pressure coefficient, α = -5°

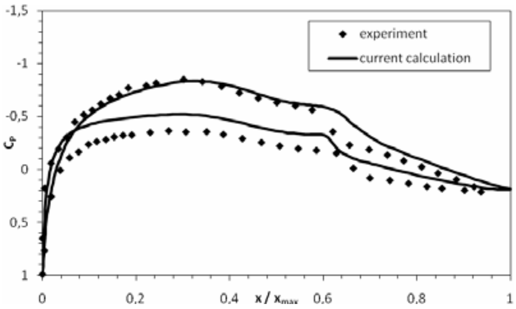

Fig. 5 Distribution of pressure coefficient, α = 0°

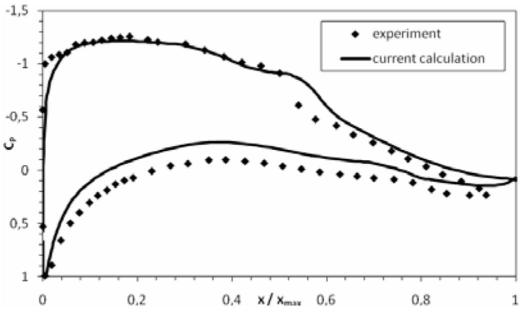

Fig. 6 Distribution of pressure coefficient, α = 5°

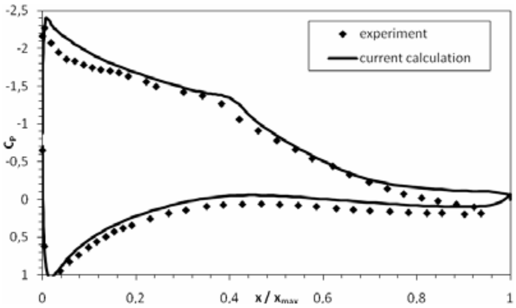

Fig. 7 Distribution of pressure coefficient, α = 10°

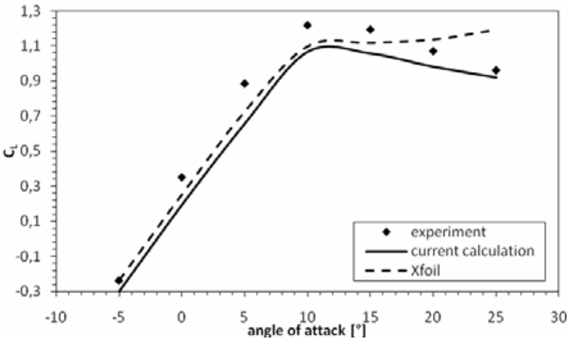

Fig. 8 Comparison of lift coefficient

7 CONCLUSIONS

The current work is concerned with computation of flow past the airfoil NACA63A421 with transition to turbulence in separated flow. Calculations were performed using commercial code ANSYS Fluent with User-Defined-Function based on empirical equations, which describe the transition to turbulence both in separated and in attached flow. Results were compared to experimental data and a good agreement was observed. The next step will be to apply this method to investigation of synthetic jet separation control.

NOMENCLATURE

C_P - pressure coefficient, $C_P = (p - p_\infty)/(0.5\rho u_\infty^2)$ [-],

l_l - length of laminar part of separation bubble [m],

n - spot generation rate [m·s^{-1}],

Re_θ - momentum Reynolds number [-],

x, y - cartesian coordinate [m],

s - coordinate along airfoil surface [m],

Tu - turbulence level [%],

u,v - velocity [m·s^{-1}],

δ - boundary layer thickness [m],

θ - momentum boundary layer thickness [m],

γ - intermittency function [-],

λ - dimensionless pressure gradient, $\lambda = (\theta^2/\nu)(du_e/ds)$ [-],

μ - molecular viscosity [Pa·s],

μ_T - turbulent viscosity [Pa·s],

ν - kinematic viscosity [m^2·s^{-1}],

ρ - density [kg·m^{-3}],

σ - Emmons spot propagation parameter [-],

Index

e - free stream,

s - separation,

t - transition,

∞ - inlet.

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REFERENCES

[1] PŘÍHODA J., HLAVA T., KOZEL K.: Modelling of bypass transition including the pseudo-laminar part of the boundary layer, *Zeit. Angew. Math. Mech.* 79, S3, S699-S7000, 1999

[2] NARASIMHA R.: The laminar-turbulent transition zone in the boundary layer, *Progress in Aerospace Science*, 22, 29-80, 1958

[3] SOLOMON W.J., WALKER G.J., GOSTELOW J.P.: The laminar-turbulent transition zone in the boundary layer, *Journal of Turbomachinery*, 118, 744-751, 1996

[4] STRAKA P., PŘÍHODA J.: Modification of an algebraic bypass-transition model for internal flows, *Proc. Conf. Topical Problems of Fluid Mechanics*, Institute of Thermomechanics AS CR, Praha, 139-142, 2010, ISBN 978-80-87012-25-3

[5] ROBERTS W.B.: Calculation of laminar separation bubbles and their effect on airfoil performance, *AIAA Journal*, 18, 1, 25-13, 1980

[6] JAKUBEC V.: *The effect of the Reynolds number on flow around bodies* (in Czech), Diploma Thesis, Fac. Mech. Eng. CTU in Prague, 41 p., 2003

[7] MENTER F.R.: Two-equation eddy-viscosity turbulence models for engineering applications, *AIAA Journal*, 32, 1598-1605, 1994