Ocean Engineering 164 (2018) 1–12

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Extending the applicability of RANS turbulence closures to the simulation of transitional flow around hydrofoils at low Reynolds number

Liangyu Xu[a], Emilio Baglietto[b,*], Stefano Brizzolara[c]

[a] Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, 02139, USA
[b] Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, 02139, USA
[c] Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech, 460 Old Turner Street, Blacksburg, VA, 24061, USA

ARTICLE INFO

Keywords:
Flow around hydrofoils
Separation-induced transition
Natural transition
Turbulence model
Separation bubble

ABSTRACT

Growing interest in marine autonomous systems such as underwater gliders and autonomous underwater vehicles (AUVs) has led to the increase of research on hydrofoil performance at low Reynolds numbers, bringing forward the issue of simulating laminar to turbulent transition using computational fluid dynamics (CFD). Most conventional turbulence closures in practical Reynolds-averaged Navier-Stokes (RANS) simulations are incapable of predicting transition with excessive turbulence generation near the leading edge, deriving from their eddy viscosity assumption. Having the potential of inherently predicting transition by solving the near wall flow accurately, three Low-Re RANS closures with anisotropy consideration are selected and evaluated for their ability to capture both separation-induced transition and natural transition. The empirical $\gamma - \mathrm{Re}_\theta$ transition model is also assessed in this work. Comparison with published experiments shows the capability of the four turbulence closures to capture separation-induced transition accurately. Predicting natural transition remains more challenging: two Low-Re closures exhibit the potential to capture natural transition only at medium grid finesse levels, whereas the $\gamma - \mathrm{Re}_\theta$ model evidences challenges in reproducing the correct flow physics. The lag elliptic blending model provides the most accurate solution owing to its consistent grid convergence, high accuracy for predicting the hydrodynamic coefficients, and ability to reproduce the correct transition physics.

1. Introduction

Research on hydrofoil performance at low Reynolds numbers has seen renewed attention due to the growing interest in marine autonomous systems, including underwater gliders (Lemaire et al., 2016), autonomous underwater vehicles (AUVs), and micro-unmanned surface vessels (USVs) for monitoring the marine environment and supporting maritime security. Mainly working in the low Reynolds number range, their propelling hydrofoils can suffer from laminar to turbulent transition, which poses a great challenge for accurate CFD simulation. Other applications with transition issues include marine current turbines, offshore wind turbines, ship rudders, stabilizers, and propellers.

Transition, depending on its occurring mechanism, is commonly divided into three different modes (Mayle, 1991). Natural transition is caused by inherent instabilities in the laminar boundary layer which becomes unstable beyond a critical Reynolds number while the free-stream turbulence is very low ($< 1\%$). Bypass transition is caused by the convection and diffusion from high-level free-stream turbulence into the boundary layer and other external disturbances, such as wakes, vortices and surface defects. Separation-induced transition happens when a laminar boundary layer separates due to a strong adverse pressure gradient, and the separated flow undergoes transition as a result of inviscid instability mechanism. The separated layer may reattach and form a separation bubble on the surface. For hydrofoil flows, typically natural transition or separation-induced transition may occur depending on the foil shape, Reynolds number, and angle of attack, while bypass transition is mostly encountered in turbomachinery applications.

The process of boundary layer transition from laminar to turbulence is a basic scientific problem of fluid dynamics and one that has been extensively examined both theoretically and experimentally. Theoretical methods based on stability theory trace back to 1950s when the e^n method was proposed for predicting transition onset by Smith (1956) and Ingen and van, 1956. Stability of a laminar boundary layer has been analyzed through the linearized Orr-Sommerfeld equations, and disturbance growth is integrated from the boundary layer neutral point to the transition location. The main obstacle for the stability-theory-based methods is the requirement of streamline information, which demands the coupling to a CFD solution. On the other hand, new experimental data for transitional boundary layers have enabled the

---

* Corresponding author.
E-mail addresses: liangyux@mit.edu (L. Xu), emiliob@mit.edu (E. Baglietto), stebriz@vt.edu (S. Brizzolara).

https://doi.org/10.1016/j.oceaneng.2018.06.031
Received 25 October 2017; Received in revised form 7 April 2018; Accepted 9 June 2018

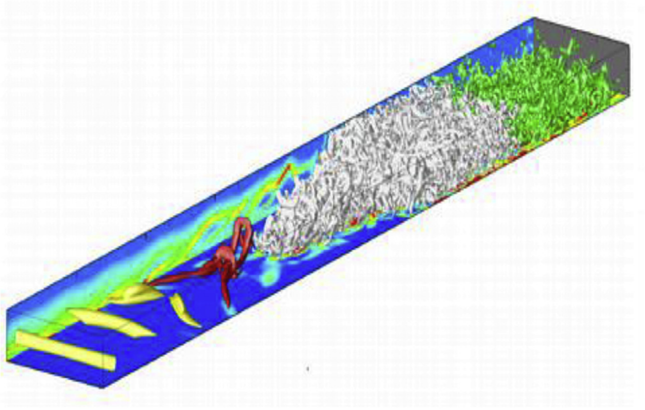

Fig. 1. Stages of natural transition in plane channel flow (Schlatter, 2005).

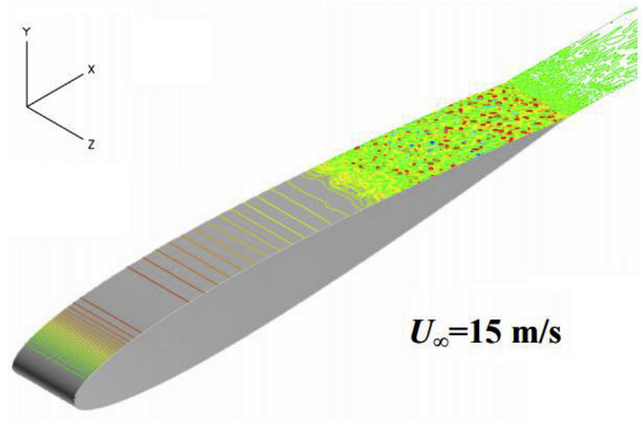

Fig. 2. Instantaneous vorticity $-\omega_z$ from LES of natural transition on NACA0012 (Kurotaki et al., 2007).

development of several correlation-based transition models: Abu-Ghannam and Shaw (1980), Mayle (1991), Kohama and Davis, 1993, etc. for predicting transition onset, and Dey (1990), Cho and Chung's (1992), Steelant and Dick (1994) for predicting transition length. Typically, the correlation models again require a combination to a CFD solution in order to capture the interaction between laminar and turbulent regimes (Pasquale et al., 2009).

In recent years, with the advancement of supercomputers, high fidelity DNS and LES computations have also become possible for uncovering transition physics and mechanisms. For example, LES of a plane channel flow by Schlatter (2005) clearly showed various stages of natural transition ranging from Tollmien-Schlichting streamwise instability waves, spanwise vorticity, 3D breakdown, turbulent spots, to fully turbulent flow (Fig. 1). DNS study by Jacobs and Durbina (2001) visualized the formation of streaks, spots, and transition to turbulence phenomenon in bypass transition. However, presently the computational cost for DNS and LES studies is still too high for routine use in industrial applications, which propels the need for practical RANS-based CFD simulations with proper transition models.

The applicability of conventional RANS closures to the transition process is certainly questionable, especially for natural transition, where the linear disturbance growth effect is not directly reproducible with RANS averaging (Rodi, 2007). Bypass and separation-induced transition are expected and have shown to be reproducible with some versions of low Reynolds number RANS closures since their triggering mechanisms, diffusion from freestream turbulence and laminar separation respectively, are amenable to RANS modeling. While the averaged nature of the RANS equations cannot describe the disturbance growth and the evolution of the natural transition process, hence the transition length, we suggest that Low-Re RANS closures have the ability to distinguish the laminar and turbulent regions if the correct level of eddy viscosity is generated. Therefore, accurate RANS models could have the potential of capturing the transition onset with a 'point transition' to turbulence. For a hydrofoil, natural transition progresses rapidly, with a relatively short transition length, as shown in Fig. 2, making the point transition assumption reasonable for engineering applications. Based on these observations we postulate that accurate Low-Re RANS closures may retain the ability to predict both natural and separation-induced transition on hydrofoils.

Rather than attempting to predict transition inherently, using a Low-Re RANS closure, a more popular approach has been to make use of empirical information to develop specialized transition models. This approach also presents a number of challenges. The e^n method is not compatible with general-purpose CFD codes since it requires prior knowledge of geometry and grid topology, on the other hand, most empirical correlations involve non-local operations precluding their implementation into general purpose CFD codes. To deal with this limitation, Langtry (2006) and Menter et al., 2006 proposed the $\gamma - \mathrm{Re}_\theta$ transition model with fully local formulations, which currently is one of the most widely adopted transition models in industrial CFD applications. The model leverages empirically optimized correlations to try to predict all three transition modes and has been applied to several applications. Having been calibrated against a specific set of experimental data, this model does not guarantee broad applicability and still requires extensive validation studies for assessing its application limits and suitability.

The aim of the present work is to assess the applicability of several RANS turbulence closures for predicting both natural and separation-induced transition on hydrofoil Eppler 387, for which experimental data are available in the literature. In addition to the empirical $\gamma - \mathrm{Re}_\theta$ transition model, three Low-Re closures are selected for their ability to include near wall anisotropy effects. The elliptic blending $k - \varepsilon$ model of Billard and Laurence's (2012) and the lag elliptic blending model of Lardeau and Billard (2016) leverage the elliptic blending approach to account for the near wall stress anisotropy, while Lien's Low-Re model (Lien et al., 1996) combined with the NLEVM of Baglietto and Ninokata (2006), (2007) adopts a cubic stress-strain correlation therefore including also the effects of curvature, and rotation. Results for the $k - \omega$ *SST* model of Menter (1994) are also presented as they provide a reference solution of a broadly adopted eddy-viscosity model.

2. RANS turbulence closures

Assuming incompressible Newtonian fluid, the Reynolds-averaged equations for mass and momentum conservation are commonly expressed as:

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \nu\frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j} \tag{2}$$

where ρ is the fluid density, ν the kinematic viscosity, and the Reynolds stress term $\overline{u_i' u_j'}$ requires closure.

According to the Boussinesq hypothesis, the Reynolds stress can be linked to the mean rate of strain S_{ij} through the eddy viscosity ν_t:

$$\overline{u_i' u_j'} = \frac{2}{3}k\delta_{ij} - 2\nu_t S_{ij}\ , \quad S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

where k is the turbulent kinetic energy, and δ_{ij} is Kronecker symbol.

Different eddy viscosity models provide different methods for deriving the turbulent viscosity ν_t, mostly by solving transport equations for scalar quantities, such as k and ε in the popular standard $k - \varepsilon$ turbulence model of Jones and Launder (1972), or k and ω in the