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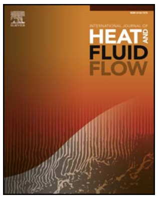

A novel laminar kinetic energy model for the prediction of pretransitional velocity fluctuations and boundary layer transition

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ABSTRACT

Boundary layer transition onset estimation and modelling are essential for the design of many engineering products across many industries. In this work, a novel model for predicting pretransitional boundary layer fluctuations is proposed. The laminar kinetic energy (LKE) concept is used to represent such fluctuations. The new LKE model is implemented in OpenFOAM within the Reynolds-Averaged Navier-Stokes (RANS) framework. Only two approaches for modelling the LKE can be found in the literature. Mayle and Schulz (1997) has the limitation of requiring an initial LKE profile. Walters and Cokljat's (2008) approach has been found to significantly overpredict the growth of the LKE. In addition, their model is tightly coupled with the specific dissipation rate and turbulent kinetic energy equations. The new model proposed here can act as a stand-alone equation for the LKE, making it portable and potentially facilitating the development of new transition models tailored to various industrial applications. Comparison with experiments shows that the new LKE model correctly predicts the growth of pretransitional velocity fluctuations and skin friction for a flat plate at zero-pressure gradient. To illustrate its practical application for transitional flows, the LKE model is coupled with an existing $k - \omega$ model using a new approach that requires minimal modifications. The resulting model ($k - \omega$ LKE) demonstrates excellent predictive capabilities when applied to a number of validation test cases.

1. Introduction

The principal focus of the subject of boundary layer transition modelling is to develop and use models that can predict the extent of the laminar, transitional and turbulent regions that may appear in a given application and system configuration. The ability to accurately predict the breakdown to turbulence is essential to engineers in many engineering applications. Specific examples include: aircraft drag estimation and fuel consumption, turbine blades, pressure losses in automotive emission reduction systems, etc.

When the freestream turbulence intensity is low, disturbances within the boundary layer predominantly grow in the form of Tollmien-Schlichting waves (although other modes may also arise (Kachanov, 1994; Saric et al., 2002)) until they eventually amplify to the point when they breakdown into turbulence. This process is known as natural transition. In natural transition, the growth of disturbances can be described by the primary modes of the Orr-Sommerfeld equation. The e^N method (Smith and Gamberoni, 1956; Smith, 1956; van Ingen, 1956), which is popular within the aerospace industry, examines the amplification rate of the most unstable Tollmien-Schilchting wave along a surface and transition onset is assumed once a given N-factor is reached. Whilst the e^N has been widely successful, it is difficult to extend to complex geometries or implement into general Computational Fluid Dynamics (CFD) codes. On the other hand, bypass transition occurs as the freestream turbulence intensity is increased and Tollmien-Schilchting waves no longer develop and are altogether bypassed (intermediate paths exist, see e.g. Saric et al., 2002). Under these conditions, the e^N method is no longer suitable and, traditionally, correlation based methods have been employed (Abu-Ghannam and Shaw, 1980; Mayle, 1991). More recently, boundary layer transition has also been investigated using high-fidelity simulation techniques such as Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) (Chen et al., 2010; Borodulin et al., 2002; André et al., 2017; Makino et al., 2015; Mistry et al., 2015). Despite growing computing power, their computational cost is too restrictive for day-to-day industrial applications (Choi and Moin, 2012; Wilcox, 2006). Consequently, the Reynolds-Averaged Navier Stokes (RANS) approach for modelling transitional flows continues to be an area of interest because RANS-based modelling offers a reasonable compromise between computational expense and accuracy. For this reason and due to the potential

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Nomenclature

CFD	Computational fluid dynamics
DNS	Direct numerical simulation
LES	Large eddy simulation
LKE	Laminar kinetic Energy
RANS	Reynolds-Averaged Navier Stokes
ZPG	Zero pressure gradient

Greek symbols

α_L	Laminar diffusion eddy viscosity [m^2/s]
ϵ	Dissipation rate [$\mathrm{m}^2/\mathrm{s}^3$]
η	Laminar production coefficient
γ	Transition initiation function
Λ	Integral length scale [m]
ν	Laminar kinetic viscosity [m^2/s]
ν_L	Laminar kinetic “eddy” viscosity [m^2/s]
ν_R	Eddy viscosity ratio: ν_t/ν
ν_t	Turbulent kinetic eddy viscosity [m^2/s]
$\nu_{t,s}$	Small-scale eddy viscosity [m^2/s]
Ω	Magnitude of shear rate tensor: $\sqrt{2\Omega_{ij}\Omega_{ij}}$ [s^{-1}]
ω	Specific dissipation rate [s^{-1}]
ω_d	Frequency driving LKE growth [s^{-1}]
ρ	Fluid density [$\mathrm{kg/m}^3$]
τ_η	Komogorov’s time scale [s]
τ_w	Wall shear stress: $\mu\left(\frac{\partial U}{\partial y}\right)_{y=0}$ [$\mathrm{N/m}^2$]
υ	Kolmogorov’s velocity scale [m/s]
ξ	Convective frequency: $\xi = S$ [s^{-1}]

Roman symbols

C'_P	Modified pressure coefficient
C_P	Pressure coefficient
f_v	Viscous damping function
f_{SS}	Shear-sheltering damping function
k	Turbulent kinetic energy [$\mathrm{m}^2/\mathrm{s}^2$]
k_L	Laminar kinetic energy [$\mathrm{m}^2/\mathrm{s}^2$]
P	Mean pressure [Pa]
p'	Fluctuating pressure [Pa]
P_{k_L}	Production of k_L [$\mathrm{m}^2/\mathrm{s}^3$]
Re	Reynolds number: $\frac{U_\infty L}{\nu}$
Re_Λ	Integral Reynolds number: $\frac{U_\infty \Lambda}{\nu}$
S	Magnitude of strain rate tensor: $\sqrt{2S_{ij}S_{ij}}$ [s^{-1}]
S_{ij}	Strain rate tensor: $\frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$ [s^{-1}]
t	Time [s]
t_Λ	Integral time scale [s]
Tu	Turbulence intensity: u'_{rms}/U_∞
U	Mean velocity [m/s]
u'	Streamwise fluctuating velocity [m/s]
u_i	Velocity vector [m/s]
v'	Wall-normal fluctuating velocity [m/s]
x	Streamwise coordinate [m]
y	Wall-normal distance [m]
y^+	Dimensionless wall-normal distance

Subscripts

∞	Refers to freestream condition
eff	Refers to effective
inlet	Refers to inlet condition or value
L	Refers to laminar
max	Refers to maximum condition
min	Refers to minimum condition
rms	Root-mean squared of quantity
SS	Refers to shear-sheltering effects
T	Refers to turbulent
wall	Refers to wall or near-wall conditions

engineering applications of this work a RANS-based approach has been adopted here.

Progress on the development of transition sensitive RANS models has been steady. An examination of the literature on recent RANS models developed to predict boundary layer transition shows that there are two main approaches: (i) to couple turbulent models with empirical correlations and (ii) to extend turbulence models by including additional transport equations to model transitional behaviour. The first approach involves the incorporation of suitable experimental transition correlations (Abu-Ghannam and Shaw, 1980; Mayle, 1991) which are used to control transition initiation. The difficulty of using this approach is that experimental correlations often require non-local variables such as the momentum thickness or displacement thickness which makes them challenging to implement into CFD packages. Additionally, models based on empirical correlations may not be universal since their range of applicability is limited to how closely the intended application operating conditions match those of the experiments from which the correlations were derived in the first place. The second approach involves the development of more general transition sensitive models by incorporating additional transport equations. For instance, Suzen and Huang (2000) used an equation for intermittency to control transition onset. The approach of using auxiliary equations to complement turbulence models has also been successfully demonstrated by Steelant and Dick (2001) and Menter et al. (2004, 2015). Since experimental correlations are embedded into these models, their predictive capabilities are limited. An alternative method is to develop phenomenological models or physics-based models (Edwards et al., 2001; Walters and Leylek, 2004, 2005; Walters and Cokljat, 2008).

The development of phenomenological transitional models is certainly desirable since they attempt to incorporate the physics of boundary layer transition directly. Nonetheless, this is a very challenging endeavour particularly due the fact that many of the mechanisms influencing boundary layer transition are not yet fully understood e.g. receptivity mechanisms to external disturbances or 3-dimensional effects due to pressure gradients of complex geometries. However, Walters and Cokljat (2008) developed a three equation phenomenological transition model ($k - k_L - \omega$) based on the concept of the laminar kinetic energy, first proposed by Mayle and Schulz (1997). The $k - k_L - \omega$ model has the advantage of using local variables to predict the onset of transition. Also, thanks to its ease of implementation the $k - k_L - \omega$ is available in commercial and open source CFD packages. Furthermore, Medina and Early (2014) demonstrated the flexibility of the laminar kinetic framework by proposing a simple modification to enable the prediction of boundary layer transition due to aft-facing steps. Recently, Qin et al. (2017) showed that the laminar kinetic framework used by the $k - k_L - \omega$ can also be extended to accommodate hypersonic flow. Despite the many advantages of the $k - k_L - \omega$ model, there is evidence in the literature (Chitta and Walters, 2012; Zhang et al., 2017) that this model, whilst capable of predicting the linear portion of the lift curve (lift coefficient versus angle of attack), it tends to fail in capturing stall on aerofoils and overpredicts lift generation. In an attempt to identify the reason for this behaviour the authors of this work realised that the $k - k_L - \omega$ model can drastically over predict the laminar kinetic energy and consequently the relative influence of streamwise fluctuations within the boundary layer (as it will be shown later). This realisation provided the motivation for this work.