TRIPPING AND LAMINAR–TURBULENT TRANSITION: IMPLEMENTATION IN RANS-EVM

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Abstract

Fundamental fluid-mechanics studies and many engineering developments are based on tripped cases. Therefore, it is essential for CFD simulations to replicate the same forced transition in spite of the availability of advanced transition modelling. In the last decade, both direct and large-eddy simulations (DNS and LES) include tripping methods in an effort to avoid the need for modeling the complex mechanisms associated with the natural transition process, which we would like to bring over to Reynolds-averaged Navier–Stokes (RANS) turbulence models. This paper investigates the necessity and applications of numerical tripping, despite of the developments in numerical modeling of natural transition. The second goal of this paper is to assess a technique to implement tripping in eddy-viscosity models (EVM) for RANS. A recent approach of turbulence generation, denoted as turbulence-injection method ($kI$), is evaluated and investigated through different test cases ranging from a turbulent boundary layer on a flat plate to the three-dimensional (3D) flow over a wing section. The desired tripping is achieved at the target location and the simulation results compare favourably with the reference results (DNS, LES and measured data). With the application of the model, the challenging transition region can be minimised in a simulation, and consequently more reliable results are obtained.

1 Introduction

Modeling the laminar–turbulent transition is still a challenging subject, especially for engineering computational fluid dynamics (CFD). The exact placement of the laminar–turbulent transition has a significant effect on relevant characteristics of the boundary layer and aerodynamics, such as drag, heat transfer and flow separation on e.g. wings and turbine blades. For instance, the inaccuracy in prediction of the transition onset can result in larger separation regions near the wing trailing edge. Such limitations of CFD simulations increase the discrepancy between experimental and numerical data in the design processes.

Tripping, which fixes the transition position, has been implemented in wind-tunnel experiments to promote early transition to turbulence in the boundary layer for the past 70 years, because it makes the transition independent of the local condition of the freestream. In the first part of the paper in section 2, the applications of the tripping technique are discussed, in order to describe why one needs a tripping model rather than a model to simulate different transition mechanisms. To bring tripping to practical applications, there is a demand to assess the implementation of tripping mechanisms with Reynolds-averaged Navier–Stokes (RANS) approach which can also serve as a design tool. The laminar–turbulent transition models are discussed in section 3, focusing on RANS-EVM.

With the goal of replicating the same transition point as in the experiments (and corresponding resolved simulations), and removing the uncertainty in the numerical model of forced transition, this study investigates a numerical approach that mimics the effect of a turbulence trip. Tripping in experiments is not always implemented at the natural transition point, rather the target point of forced transition may shift for different reasons such as control. Therefore, a flexible numerical approach is required to control the flow condition, as it has already been investigated in LES and DNS. The present work considers a method to implement tripping with RANS as well as its assessment compared to wind-tunnel experiments, beside the similar tripping approaches in LES and DNS. The methodology and the results are described in sections 3 and 4, respectively. The ultimate goal of the project is to develop a numerical–simulation approach which can represent the complex experimental setup and measurements in a typical wind tunnel, reduce the uncertainty in design of a setup, and thus increase the fidelity of a campaign. This motivates to include three-dimensional (3D) setups as a part of this research, such as complete wind-tunnel setups, in the framework of a virtual wind tunnel [31].
2 Tripping applications and models

Due to the variety of transition types and the complexity of modeling the different mechanisms in numerical simulations, one alternative is to start with a correct boundary layer at a certain Reynolds number ($Re_\theta$), using fully turbulent boundary-layer data as inflow, e.g., from a direct numerical simulation, DNS. In this way, there is no need to go through any transition model, i.e., the flow is turbulent throughout the computational domain. However, such data are not always available. Another possibility is to skip the whole transition process by tripping the boundary layer. In this way, transition is forced at a prescribed and meaningful location, rather than the natural transition process.

Additionally, the action of forcing transition from a laminar to a turbulent boundary layer (BL) is common in wind-tunnel testing to eliminate the later transition caused by testing at reduced Reynolds numbers ($Re_\theta$) [13]. For example, at low $Re_\theta$ and for an airfoil at stall-angle, it is essential to ensure that the transition occurs before the laminar flow separation. BL trips are traditionally also used in scale-model testing to aid in scaling the flow characteristics, where duplicating full-scale $Re$ is not feasible in the wind tunnel which leads to the fact that the developed BLs on wind-tunnel models do not correspond to the BLs which develop on full-scale vehicles. For this purpose, tripping devices are placed on models to hasten the BL transition from laminar to turbulent flow. In this way, the characteristics which are sensitive to the condition of the BL are more accurately simulated in tripped cases [19], since the transition is modeled independent of the local condition of the free-stream which may differ from case to case. Furthermore, the key idea of passive techniques is to trip the BL to re-energize the flow so that the flow remains attached [29]. The skin friction, and consequently the drag, change due to the shift of the transition position from one test to another, which defines the turbulent portion of the model. The different transition onset in adverse-pressure-gradient (APG) flow can also result in larger separation regions farther downstream, with the corresponding impact on aerodynamic performance [30]. In addition, it is sometimes possible to duplicate the relative thickness of the full-scale turbulent BL at certain locations on the wind-tunnel model by fixing transition at the proper location [3].

Most studies focusing on the physics of turbulent BLs employ tripping to promote early and robust transition to turbulence [5, 14, 24]. For instance, different tripping devices were studied, in the context of a flatplate BL [3, 20]. Roughness elements were also used to force transition in order to eliminate the transitional effects [9, 21]. The wide and continuous application of tripping in wind tunnels [25] motivated the use also in numerical methods to model similar effects in order to replicate the experimental data. Therefore, tripping methods evolved beside the numerical transition models that attempted to model the natural transition process. Referring to the variety of transition types and the complexity of modeling the complex physical interactions and mechanisms leading to transition, tripping models have the advantage of simplicity, which results in a much lower uncertainty. For instance, various tripping strategies were assessed over a flat plate by DNS [27] and were later implemented in large-eddy simulation (LES) for a 2D airfoil [11].

3 Laminar–turbulent transition and tripping in EVM

Among eddy-viscosity RANS models (EVM), the one-equation turbulence model of Spalart–Allmaras (SA) contains a trip term [28]. These authors used the word “trip” to mean that the transition point is imposed by an actual trip, or natural but obtained from a separate method” [28]. The trip version of the SA model, named as SA-Ia, is rarely used, because the model is most often employed for fully-turbulent (FT) applications [33]. Its trip term was found to be inadequate to force transition at a specified location, specifically for hypersonic flows [22]. The $k − \omega$ SST model, as the most common two-equations EVM model, was developed in 1994 [16]. The formulations of both turbulence transport equations ($k$ and $\omega$) are based on the features of FT-BL and so the initial laminar region, and consequently the transition part, are not modeled accurately. Such a formulation induces an early turbulent–viscosity buildup (as if for e.g., there is a surface roughness) and therefore causes FT flow over the region which is laminar in the physical model and leads to over-estimating the drag [11, 50]. RANS-based BL transition algorithms have been broadly considered in literature since few decades ago [7, 34]. Most commonly transition models consist of two main parts: 1. Define the laminar, transition and FT regions, i.e. the intermittency ($\gamma$) distribution. This can be done via two, one, or even zero transport equations [2, 15, 10]; 2. Apply the modifications into the turbulence model, i.e. in the $k$ and $\omega$ equations, which is referred to as ‘coupling with $k − \omega$ SST’ model. The currently available transition models in RANS are typically based on empirical correlations, but are not specifically aimed at representing the physical mechanisms in the transition process. As discussed by Langtry [10], “They do not attempt to model the physics of the transition process (unlike e.g. turbulence models), but form a framework for the implementation of transition correlations into general purpose CFD methods”. They are basically designed to cover the standard ‘bypass transition’, as well as flows in low free-stream turbulence environments (since the transition location is correlated with the free-stream turbulence intensity, based on laboratory data) [2]. In addition to becoming unstable (in terms of convergence) [11], it was observed that setting a lower value for the free-stream turbulence in the CFD simulations would result in a
later transition prediction than observed in the physical model. Apart from the pros and cons of such approaches in simulating the transition process, recent studies show that “there is potential for uncertainty or error in simulating the forced transition case with RANS models”. In order to initiate transition at the same location as the experimental data, zigzag tapes were used as the model, but the uncertainties inevitably appeared even in the calculations of the integrated parameters, e.g. the total power of the whole turbine rotor. Certainly, it is more challenging when a point-to-point comparison is intended, e.g. in chordwise $C_p$ distribution. Similarly, turbulence tripping was implemented in RANS using a specific type of obstacle in the geometry, which caused flow disturbances that facilitated the transition from laminar to turbulent flow. Although a sudden jump in the local pressure was achieved, a spurious small vortex emerged downstream of the obstacle. According to section 2, tripping would be a required feature in RANS models, while on the numerical side, we found that there is no suitable model to implement tripping. In the following sections we discuss a method of tripping for $k$-ω SST.

4 Methodology

We start with describing a turbulence-generation mechanism, which was recently adopted by Fahland for the RANS simulation of the flow around an airfoil. We denote this as ‘injection method’ ($kI$), and it is based on directly modifying the turbulent kinetic energy, $k$, at the target trip point. This technique serves as an efficient tripping and the results are in agreement with the other methods described in Ref. 6.

Note that the injection of extra $k$ effectively promotes transition at the position or shortly downstream of it. The modelled transport equation for $k$ may be written as

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_j k)}{\partial x_j} = P_k - D_k + \frac{\partial}{\partial x_j} \left[ \left( \mu + \sigma_k \mu_t \right) \frac{\partial k}{\partial x_j} \right] + S_k,$$

(1)

where $P_k$ and $D_k$ denote the production and dissipation terms respectively. The coefficients $\mu$ and $\mu_t$ denote the dynamic viscosity and turbulent dynamic viscosity, respectively, and the corresponding term (the third term on the right-hand side) refers to the diffusion of $k$. The last term on the right-hand side, $S_k$, is included to account for the sources of turbulent kinetic energy. The $kI$ approach is based on adding a local $S_k$ at the target trip point so that the flow becomes FT immediately, in the same way as in the experimental tripping. Furthermore, the standard $k - \omega$ SST model leads to an early transition so that the BL becomes FT even before the physical transition position. In order to ensure the turbulence model does not lead to a premature deviation from the laminar solution, the value of $k$ can be set to zero in the domain just upstream the tripping. This constraint is set to avoid an over-estimation of $k$ in the laminar region, which is anyway calculated from the FT equations in the $k - \omega$ SST model.

![Figure 1: Illustration of the injection–tripping procedure in various flows relevant for the present work. See text for more details.](image)

Note that the value of $S_k$, the injection magnitude, should be large enough to raise the local skin-friction coefficient $C_f$ at the tripping point. An advantage of the $kI$ method is the simplicity of the implementation, because the source terms can typically be externally modified without changing the core of the solver. Fig. 1 illustrates how the injection area is specified for a flat plate and a wing model, similar to tripping in the experiments. The laminar region, i.e. the $k = 0$ area, is defined to implement the turbulence constraint, which was defined at the beginning of this section. The approximated depth of the injected area is suggested to be approximately equal to the momentum thickness $\theta$ at the tripping location, since the tripping should be located inside the BL region. The $k_1$ part in Fig. 1 bottom shows the injection section, as well as the injection bar assigned on the wing in Fig. 1 top.

The assessment includes three test cases. We consider the Minimum-Turbulence-Level (MTL) wind tunnel at KTH Royal Institute of Technology. The NACA4412 profile is the reference airfoil selected for this study. As the base turbulence model, a two-equation EVM model is considered: $k$-$\omega$ SST. Open-
FOAM is used as the CFD solver.

5 Results

The results are shown in terms of $C_f$, which is the normalized wall shear stress at the wall. The shape factor $H_{12}$ is also plotted as an indication of the boundary-layer development, since it is the ratio of the displacement to momentum thicknesses. For the mid-height section of the wing, the chordwise $C_p$ distribution is plotted, where the static pressure $p$ is non-dimensionalized with the dynamic pressure $P_d$. Three test cases are discussed in the following. Two main features are intended to ensure proper tripping: i) a sufficiently sharp $C_f$ increase, which is ii) immediate at the intended tripping location.

I. Flat plate with zero pressure gradient (ZPG):

In Fig. 2, two scenarios are tested to assess the method efficiency: early and delayed tripping. First the flow is tripped immediately after the domain inlet as an ‘early-trip’. Conversely, in the case denoted as ‘delayed trip’, the simulation keeps the flow laminar for some distance before it is tripped, see Ref. [32]. It is shown that boundary-layer development can be controlled with this tripping method, which results in an adaptive laminar-turbulent transition.

To evaluate the $k_1$ tripping in RANS, in this part we focus on the low-$Re_\theta$ trends, which were studied in Ref. [27] via the use of different tripping parameters in DNS, see Fig. 3. The resulting turbulent flow with $k_1$ tripping quickly adapts to the canonical form of the turbulent BL, with shorter development length than the non-optimal tripping as studied by DNS.

II. 2D airfoil:

Tripping with RANS has been implemented for an isolated airfoil (a NACA4412 wing section in free-flight conditions) and compared with a well-resolved LES of the same case [33], tripped with the method in Ref. [27]. Skin-friction plots are in very good agreement, as observed in Figure 4a. The $k_1$ tripping (RANS-$k_1$) is applied to an airfoil in a wind tunnel and the results are in agreement with another tripping method, described in Ref. [32]. The standard $k-\omega$ SST is denoted as RANS.

III. 3D wing in a wind tunnel:

A 3D RANS simulation of wing at 11-degree angle of attack is performed considering the same tripping location as that in the wind-tunnel experiment. The qualitative velocity contours at several selected sections are illustrated as well as the chordwise $C_p$ distribution (Figure 5a). At such a high angle of attack, 3D RANS results in a lower suction compared to experiments, while a perfect agreement is achieved through the proposed tripping technique (Fig. 5b). Similar good agreement is also observed for $C_f$ (not shown here).

6 Conclusions and outlook

An adaptive method for forced laminar–turbulent transition is assessed in this paper. Different applications of this tripping are discussed in an effort to replicate the tripped experimental tests, which is the specific purpose of this research. The implementation of laminar–turbulent tripping is assessed in a RANS–EVM turbulence model with the purpose of developing more reliable aerodynamic simulations, in which the uncertain (and ultimately unnecessary) modeling of the transition process is avoided. Two main features are intended via the numerical tripping in the $k-\omega$ SST model, which are according to the function of the ex-
Figure 4: Skin-Friction Factor $C_f$ for 2D cases at two angles of attacks (AOA): (a) isolated airfoil at AOA=5°, (b) airfoil in a wind tunnel at AOA=11°.

Experimental trip devices: first, the transition onset at the exact target trip location; and second a short development length. The results from the turbulence-injection ($kI$) method show a fair agreement with DNS and LES tripping approaches and experimental data. The tripping technique in 3D RANS simulation improves the results significantly so that a very good agreement between the experimental data and the 3D RANS is achieved. Therefore, the proposed tripping method is indicated as a potential approach to replicate experimentally-measured data from a real wind tunnel. This opens the way for faithful predictions of wind-tunnel experiments using RANS.

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