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MODELING THE INFLUENCE OF SURFACE ROUGHNESS ON BOUNDARY LAYER TRANSITION

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Abstract: *This paper provides a summary of both history and current state-of-art in modeling of the surface roughness influence on boundary layer transition from laminar to turbulent regime. Discussed techniques are restricted to RANS models as these are nowadays still in major use in complex engineering applications. Present modeling techniques for surface roughness are critically reviewed. Finally, challenges connected with modeling of surface roughness influence are highlighted and potential ways for future work in this area are discussed.*

Keywords: CFD, turbulence, transition, boundary layer, roughness

1. Introduction

Before the end of 19th century, Osborne Reynolds showed the existence of laminar and turbulent flow in his well-known experiment (Reynolds, 1883). The decisive criterion for this transition was the ratio of inertial and viscous forces, which later got the name Reynolds number. Scientific effort then continued in two directions. First, to describe and quantify fluid behavior in turbulent motion, and second, to understand and predict the mechanisms of transition from laminar to turbulent flow under various stabilizing and destabilizing influences. One of which is surface roughness.

2. Transition modeling

Basic RANS models are unable to distinguish between areas with laminar or turbulent flow regime and instead assume turbulence in whole computational domain. Additional modeling is required in order to capture transition phenomena. By applying linear stability theory, Orr-Sommerfeld equation (Orr, 1907; Sommerfeld, 1909) and its approximate solution (Orszag, 1971) the e^N transition model was constructed. Another possibility is to use damping function as proposed by Wilcox (1994). Craft et al. (1997) proposed a modified k-ϵ model with damping functions and an additional transport equation for second invariant of anisotropic tensor. Another possibility is modifying the constitutional equation for eddy viscosity as proposed by Fujisawa (1990). Langtry and Sjolander (2002) proposed a variant of k-ω SST with modified relation for eddy viscosity and dumping functions. Another interesting group of transition models uses concept of laminar kinetic energy (LKE) as first proposed by Mayle and Schultz (1997). Walters and Leylek (2004) proposed a k_T-k_L-ω transition model, which was later extended for supersonic flows (Qin et al., 2017) and Liu et al. (2020) also attempted to model the influence of roughness.

Last but not least, there is a group of transition models based on intermitency. Such models always solely based on empirical correlations coming from experiment or DNS. Such models introduce either algebraic relations (Straka and Příhoda, 2010) or add one or more transport equations. A single additional equation was introduced by Suzen and Huang (2000) or in k-ω-γ model (Wang and Fu, 2009). Langtry et al. (2006) added two new transport equations to k-ω SST, creating a popular transition model γ-Re_θ (sometimes also called k-ω SSTLM). The transition phenomena is influenced by considerable number of factors as stated by Morkovin (1969). The most common in engineering application are pressure gradient (Spalart and Watmuff,

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1993), wall curvature (Patel and Sotiropoulos, 1997) and also surface roughness (Nikuradse, 1950; Saric et al., 1998; Reshotko, 2008).

3. Modeling the influence of surface roughness

Surface roughness greatly influences heat, mass and momentum transfer, which is confirmed in a complex summery done by Kadivar et al. (2021). The influenced aspects of fluid motion are plentiful and therefore various models differ not only in the way of modeling, but also in the chosen influences, which are supposed to get captured. Wilcox (1998) proposes amending the boundary condition (BC) for ω in order to model increased viscous surface drag. Usability and generality of such BC was questioned already by Patel and Yoon (1995), who showed that mesh convergent results with this BC can only be achieved using about 1000 times smaller first cell layer at a rough surface than in case of hydraulically smooth surface. One way around this was proposed by Knopp et al. (2009). Hellsten and Laine (1997) showed the necessity to amend the base SST model to prevent excessive limitation of eddy viscosity in the viscous sublayer and then also amended the BC by introducing a lower bound to SR factor (Hellsten, 1998).

Apart from intensifying heat and momentum transfer, surface roughness also influences the boundary layer transition Dryden (1953). Modeling such influence can be done by again amending the transition criterion, which comes from experimental data (Mayle, 1991; Straka and Příhoda, 2020). This first approach has restricted applicability for cases with non-uniform or localized surface roughness regions. The reason for this is dependency on the history of roughness, which according to Dassler et al. (2010) can be modeled by additional transport equation for so-called roughness amplification factor Ar. This approach was coupled with γ-Re_θ model and original production terms later morphed into BC (Dassler et al., 2012). Langel et al. (2014) followed up on this work, changing various parameters in the equations, adding a damping function to the interface with original model and used modified log-law Langel et al. (2017b). The last version with amended damping function and value of Ar diffusion coefficient is in Langel et al. (2017a). A similar approach to Dassler et al. (2012) was also implemented by Liu et al. (2020) to enhance the k_T-k_L-ω supersonic model and also by Yang and Xiao (2019) for k-ω-γ transition model.

The influence of surface roughness on boundary layer transition is still an unresolved issue both in experimental and computational fluid dynamics (Jiménez, 2004). Models which include the influence of surface roughness are often problematic in their applicability and (non-)generality. The non-united approach of various authors is to create their own model, calibrate it and apply it to a very narrow set of test cases (Liu et al., 2020; Dassler et al., 2010, 2012; Langel et al., 2014, 2017a,b; Yang and Xiao, 2019). Part of the problem is lack of experimental data, since most the most used experimental rough flat plate data set is from Feindt (1956), where, among other drawbacks, there is no information on free-stream turbulent intensity along the flat plate. Authors of surface-inclusive transition models, who use this test case, therefore differ in value of (not only) this parameter in their simulations, which makes their results very difficult to compare, to say the least.

To demonstrate the unreliability of current modeling methods, the γ-Re_θ was enhanced by a transport equation for roughness amplification factor Ar the same way as it is described by Langel et al. (2017a). Although the trend of the results shown in Fig. 1 is correct, the values vary for higher k_s from what is reported by Langel et al. (2017a).

4. Conclusion

The review presented in this paper shows that the influence of surface roughness on boundary layer transition and modeling of such influence is still an unresolved issue. The lack of modern, quality, public experimental data and variety of modeling approaches were found to be the main obstacles in future research.

Another fear is that applicability, reliability and also generality of modeling the influence of surface roughness on transition is highly dependable on CFD implementation i.e. the solver which is used to conduct simulations. Each CFD code introduces different amounts of numerical viscosity and error to the solution and it is highly probable, due to the nature of turbulent receptivity, that this plays a non-negligible role.

The aim of ongoing work is to compare all the newest models on a common test bed, i.e. same CFD code, using larger number of quality calibration/verification cases. Furthermore, preliminary results show that

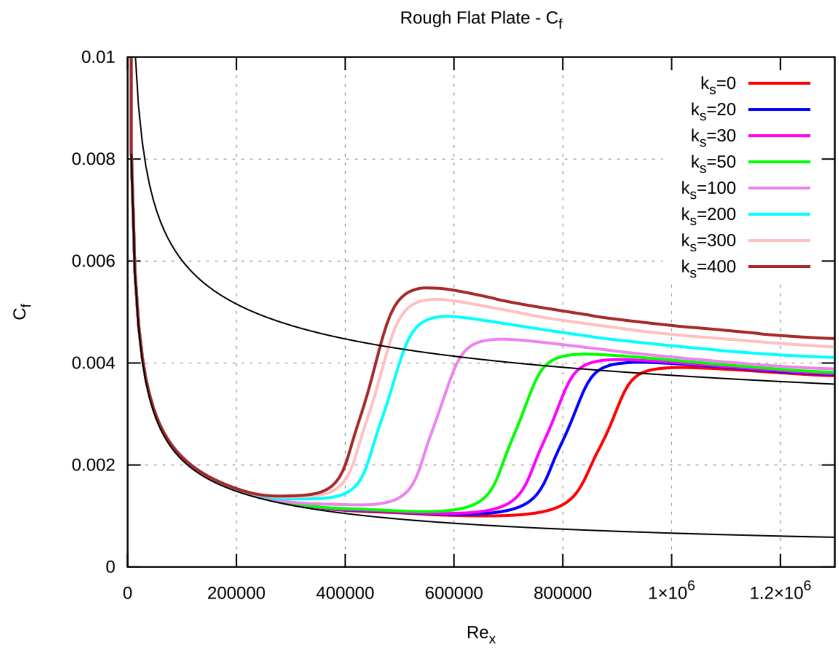

Fig. 1: Rough flat plate test case acording to experiment done by Feindt (1956). Simulations use γ-Re_θ transition model with added equation for roughness amplification factor as described by Langel et al. (2017a), implemented into OpenFOAM. With increasing sand grain roughness k_s, the transition location moves upstream, as well as the C_f value grows higher in turbulent region

adding additional transport equation for roughness amplification factor, which is so far the most popular approach, increases the computational cost. Future work should be aimed on simplifying this approach by removing the necessity to approximate the solution to an additional partial differential equation and on generally increasing reliability of transition prediction on rough surfaces.

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