

High Altitude Transitional Flow Computation for a Propulsion System Nacelle of MAAT Airship

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ABSTRACT

The flow around the nacelles of high altitude airships is very important in order to assess the inlet conditions and losses associated to their propulsion systems. The aerodynamics prediction of low Re number flows is a problem usually associated to the lack of accuracy of most of the turbulence models in everyday use. Herein we present a laminar kinetic energy transitional model that is then applied on the analysis of the flow around an example of the MAAT airship nacelle. The model is also validated using several well known test cases from the literature. Results indicate the effects of accurate transition prediction in the redesign of the nacelle for improvement in efficiency.

CITATION: Vizinho, R., Pascoa, J., and Silvestre, M., "High Altitude Transitional Flow Computation for a Propulsion System Nacelle of MAAT Airship," *SAE Int. J. Aerosp.* 6(2):2013, doi:10.4271/2013-01-2268.

INTRODUCTION

The MAAT project is a revolutionary concept of transportation presented in works such as the ones of Ilieva et al. [1] and Trancossi et al. [2]. MAAT stands for Multi-body Advanced Airship for Transport. Due to its high altitude flight conditions, low turbulence intensities are predominant. Thus critical elements of the feeders and cruiser vehicles, such as propulsive systems, will be exposed to late transition and consequently considerable sized laminar flow regions. The design of these components will be strongly conditioned by the predicted flow conditions. This implies that possession of a tool able to calculate transitional flows is of fundamental importance. Prediction of flow separation, drag and even pressure distribution along component surfaces will deeply depend upon whether the flow is laminar or turbulent.

Industry reliable turbulence transitional models are a relatively recent development. Previously, designers relied on experimental data and on the first effective transition prediction model, the e^N method. Developed simultaneously by Smith et al. [3] and Ingen [4], this model predicts only natural transition conditions. Later on, with the works of Abu-Ghannam [5] and Mayle [6], the first empirical

correlations for transition onset were created. Using these, the first turbulence transitional models based on empirical correlations were formulated. Some of these works were performed by Cho [7] and Suzen [8]. The latter models were initially non-locally formulated. This results in a problematic issue for parallel processing of large mesh computational problems. The reason for this is related to the processing nodes need of access to information that may not be in their computational domain. However, with the recent accomplishment of Menter [9] and Langtry [10], locally formulated empirical correlation turbulence transition models are being developed.

Due to the transition process complexity, up until now only empirical models were successfully developed with practical industry application. Besides the linear stability theory based transition onset model, e^N , no model attempts to simulate the physics of transition. However, alternatives were formulated that attempt to predict transition onset as well as calculate its development process. Through the award winning paper by Mayle [11], a new type of turbulence transitional model was introduced. Although this first model is non-locally formulated, and therefore, not yet easily applicable to industry, it suggests a revolutionary concept for

transition calculation. It relies on an experimentally confirmed fact by Dryden [12] and Schubauer [13], and also analytically confirmed by Lin [14]. Under the influence of free-stream turbulence, a laminar boundary layer will develop velocity fluctuations maintaining its Blasius velocity profile. Although these fluctuations are far from those encountered in a fully turbulent region, they have been related to a laminar kinetic energy. Based on this, the works of Lardeau [15] and Walters [16] developed the first phenomenological transitional models. The former work was still non-locally formulated. The author of the latter work developed and published various versions of its transition model. Presented in [17] is the latest version of these models.

The current work objectives are the implementation and validation of our corrected version of the previous transitional closure under several geometries and boundary conditions. Throughout the present paper, an initial detailed description of the k-kl- ω as published by Walters in [17] is given. Comparisons are performed between the original, corrected and commercial versions of the transition model. Beginning with an experimental flat-plate T3A test case. Following that, a multiple boundary condition battery of tests are performed over the flat-plate. For the final case, two low-Reynolds turbulence models, the Spalart-Allmaras and k- ω -SST and our corrected transition model are used to run a three-dimensional nacelle geometry under two flow conditions.

MATHEMATICAL FORMULATION OF THE TRANSITION MODEL

The modified implementation of the turbulence transition model was performed based on the proposal of Walters and Cokljat [17].

From now on the modified transition model coded by us in OpenFOAM will be referred in the displayed results as OurCode-Corrected. The original formulation of the transition model, also coded by us in OpenFOAM, will be designated as OurCode-Original. As for the ANSYS Fluent 13.0 transition model, this will be presented in the results as Code-1. This is a phenomenological model, i.e. it simulates a physical process that occurs prior to transition. The model calculates laminar flow up to fully turbulent regime, including the flow transition phase. The presented formulation corresponds to the published version of Walters and Cokljat [17]. Its formulation is then constituted by a set of three transport equations. The equations' variables are the laminar fluctuations kinetic energy (k_L), the turbulent kinetic energy (k_T), and the specific turbulent kinetic energy dissipation rate (ω). The transport equations for incompressible flow are shown in (1), (2), (3).

$$\frac{Dk_T}{Dt} = Pk_T + R_{BP} + R_{NAT} - \omega k_T - D_T + \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\alpha_T}{\sigma_k} \right) \frac{\partial k_T}{\partial x_j} \right] \quad (1)$$

$$\frac{Dk_L}{Dt} = Pk_L + R_{BP} + R_{NAT} - D_L + \frac{\partial}{\partial x_j} \left[\nu \frac{\partial k_L}{\partial x_j} \right] \quad (2)$$

$$\begin{aligned} \frac{D\omega}{Dt} = & C_{\omega 1} \frac{\omega}{k_T} Pk_T + \left(\frac{C_{\omega R}}{f_W} - 1 \right) \frac{\omega}{k_T} (R_{BP} + R_{NAT}) \\ & - C_{\omega 2} \omega^2 + C_{\omega 3} f_\omega \alpha_T f_W^2 \frac{\sqrt{k_T}}{y^3} \\ & + \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\alpha_T}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_j} \right] \end{aligned} \quad (3)$$

The production terms in (1) and (2) depend on velocity strain rate and are given by,

$$Pk_T = \nu_{T,s} S^2,$$

$$Pk_L = \nu_{T,l} S^2.$$

Turbulence is divided in two scales. The large scale is limited by the wall and related to laminar fluctuation kinetic energy production through the “splat mechanism”, as suggested by Volino [18]. The small scale is related to regular turbulence. Far from surfaces the small scale turbulent kinetic energy and the free-stream turbulent kinetic energy are the same. According to the work of Walters and Leyleek [16] the definition of the dividing length scale is obtained from (6), where λ_T , (7), is the turbulent small length scale,

$$\lambda_{\text{eff}} = \min(C_\lambda y, \lambda_T) \quad (6)$$

$$\lambda_T = \frac{\sqrt{k_T}}{\omega} \quad (7)$$

The small scale turbulent kinematic viscosity is calculated in (8). This is performed using several damping functions simulating various mechanisms. These are the shear-sheltering effect (9), the turbulence intermittency (10) and the kinematic and viscous wall effect (11)(12). The last damping function is based on effective turbulent Reynolds number (13). Also, in order to satisfy realizability C_μ is calculated according to (14). In [17] and [16], C_μ is a simplified version of its original form according to the work of Shih et al. [19] and [20].

$$\nu_{T,s} = f_\nu f_{\text{INT}} C_\mu \sqrt{k_{T,s}} \lambda_{\text{eff}} \quad (8)$$

$$f_{SS} = e^{\left[-\left(\frac{C_{SS} \nu \Omega}{k_T} \right)^2 \right]} \quad (9)$$

$$f_{INT} = \min\left(\frac{k_L}{C_{\omega 1} k_{TOT}}, 1\right) \quad (10)$$

$$f_W = \left(\frac{\lambda_{eff}}{\lambda_T}\right) \quad (11)$$

$$f_V = 1.0 - e^{\left(-\frac{\sqrt{Re_T}}{A_v}\right)} \quad (12)$$

$$Re_T = \frac{f_W^2 k_T}{\nu \omega} \quad (13)$$

$$C_\mu = \frac{1}{A_0 + A_s \left(\frac{S}{\omega}\right)} \quad (14)$$

The k_{TOT} in equation (10) is the sum of k_T and k_L . The small scale turbulent kinetic energy, (15), is calculated as,

$$k_{T,s} = f_{ss} f_W k_T \quad (15)$$

The large scale turbulent kinematic viscosity, (16), is related to the transition onset, where the first term accounts for bypass transition and the second to natural transition. In order to account for the latter a Tollmien-Schlichting threshold function, (17), is applied. The limiting third term ensures the realizability constraint. The large scale turbulent kinetic energy is exhibited in (18).

$$\nu_{T,l} = \min\left\{f_{\tau,l} C_{11} \left(\frac{\Omega \lambda_{eff}^2}{\nu}\right) \sqrt{k_{T,l} \lambda_{eff}} + \beta_{TS} C_{12} Re_\Omega y^2 \Omega, \frac{0.5(k_L + k_{T,l})}{S}\right\} \quad (16)$$

$$\beta_{TS} = 1.0 - e^{\left(-\frac{\max(Re_\Omega - C_{TS,crit}, 0)^2}{A_{TS}}\right)} \quad (17)$$

$$k_{T,l} = k_T - k_{T,s} \quad (18)$$

The previous equations make use of,

$$Re_\Omega = \frac{y^2 \Omega}{\nu} \quad (19)$$

$$f_{\tau,l} = 1.0 - e^{\left(-C_{\tau,l} \frac{k_{T,l}}{\lambda_{eff}^2 \Omega^2}\right)} \quad (20)$$

The destruction terms in the laminar fluctuations and turbulent kinetic energy equations are calculated as,

$$D_L = \nu \frac{\partial \sqrt{k_L}}{\partial x_j} \frac{\partial \sqrt{k_L}}{\partial x_j} \quad (21)$$

$$D_T = \nu \frac{\partial \sqrt{k_T}}{\partial x_j} \frac{\partial \sqrt{k_T}}{\partial x_j} \quad (22)$$

The effective turbulent diffusivity is,

$$\alpha_T = f_V C_{\mu, std} \sqrt{k_{T,s}} \lambda_{eff} \quad (23)$$

In Eq.(3) the f_ω term is a damping function related to the boundary layer wake region, as explained in [17]. Although not mentioned in [17], in the RHS fourth term of the Eq.(3), which includes the f_ω function, is very similar to the well known Yap length scale correction from the work of Yap [21]. A term responsible for the stabilization of the length scale of turbulent flows in stagnation and separated flow regions. The f_ω function is then calculated as,

$$f_\omega = 1.0 - e^{\left[-0.41 \left(\frac{\lambda_{eff}}{\lambda_T}\right)^4\right]} \quad (24)$$

The transition process is mainly conducted through the transfer of energy from the laminar fluctuation's kinetic energy to the turbulent kinetic energy by (25) or (26), depending on whether it is bypass or natural transition respectively.

$$R_{BP} = C_R \beta_{BP} k_L \frac{\omega}{f_W} \quad (25)$$

$$R_{NAT} = C_{R,NAT} \beta_{NAT} k_L \Omega \quad (26)$$

Additionally, we need to make use of the following supporting functions,

$$\beta_{BP} = 1.0 - e^{\left(-\frac{\phi_{BP}}{A_{BP}}\right)} \quad (27)$$

$$\phi_{BP} = \max\left[\left(\frac{k_T}{\nu \Omega} - C_{BP,crit}\right), 0\right] \quad (28)$$

$$\beta_{NAT} = 1.0 - e^{\left(-\frac{\phi_{NAT}}{A_{NAT}}\right)} \quad (29)$$

$$\phi_{NAT} = \max\left[\left(Re_\Omega - \frac{C_{NAT,crit}}{f_{NAT,crit}}\right), 0\right] \quad (30)$$