Effect of Free-Stream Turbulence Intensity on Transonic Airfoil with Shock Wave

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Abstract. Airplanes regularly operate switching between various flight modes such as take-off, climb, cruise, descend and landing. During these flight conditions the free-stream approaching the wings undergo fundamental changes. In transonic flow conditions, typically in the military or aerospace applications, existence of nonlinear and unsteady effects of the airflow stream significantly alters the performance of an airfoil. This paper presents the influence of free-stream turbulence intensity on transonic flow over an airfoil in the presence of a weak shock wave. In particular, NACA 0012 airfoil performance at $Ma_\infty=0.7$ is considered in terms of drag, lift, turbulence kinetic energy, and turbulence eddy dissipation parameters under the influence of varying angle of attacks and free-stream turbulence. The finite volume method in a commercial CFD package ANSYS-CFX is used to perform the numerical analysis of the flow. Mesh refinement using a mesh-adaption technique based on velocity gradient is presented for more accurate prediction of shocks and boundary layers. A Shear Stress Transport (SST) turbulence model is validated against experimental data available in the literature. Numerical simulations were performed, with free stream turbulence intensity ranging from low (1%), medium (5%) to high (10%) levels. Results revealed that drag and lift coefficients are approximately the same at every aforementioned value of turbulence intensity. However, turbulence kinetic energy and eddy dissipation contours vary as turbulence intensity changes, but their changes are disproportionally small, compared with values adopted for free-stream turbulence.

1. Introduction

Nowadays one of the most complex problems under discussion in various engineering applications, such as aerospace, wind turbines and buildings is that of turbulence. By definition, it is a flow regime characterized by unpredictable unsteadiness and multidimensional changes in fluid flow properties around their time-averaged state. Along with its complex nature, it has significant effects on performance characteristics of internal and external flows, for example, the flows around an airfoil of a given airplane wing and a turbo machinery blade.

In the range of transonic speeds, the presence of free stream turbulence adversely affects the aerodynamic performance of an airfoil. Namely, it can affect boundary-layer transition, the development of turbulent boundary layers, separations and shock wave interactions [1]. These problems, in turn, cause alterations in pressure and skin drag force distributions over the surface of the airfoil. Hence, it is important to determine the effects of free-stream turbulence on the performance of a given airfoil in order to better control the lift and drag forces on the wing or blades and therefore increase, if possible, overall efficiency of the associated machinery operating with the airfoil in

transonic flow. This investigation focuses on determining any potential relationship between turbulence intensity and lift-drag coefficients for a range of different angles of attack in transonic flow. Moreover, especial attention is paid to the effect of free stream turbulence intensity on the turbulence kinetic energy and dissipation around the airfoil.

Transonic flow is a flow regime in which the fluid transits between subsonic-sonic-supersonic conditions, where the entire regions on the surface are considered as mixed flow in which the local Mach number is either less or more than 1 with imbedded intermediate sonic pockets (see Figure 1) The transition from subsonic to supersonic condition is generally accompanied by the appearance of shock waves of infinitesimal thickness separating well differentiated regions of the flow. This type of airflow is commonly found in applications such as airplane wings and turbo machinery blades, where turbulence intensities range from a low level of 0.4% to high of 10% [2].
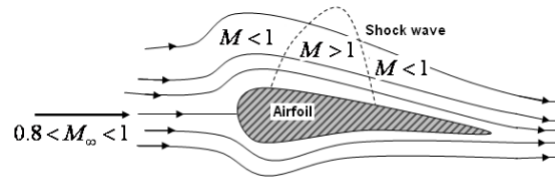

Figure 1. Transonic flow illustration.

Key parameters in this investigation are angle of attack (AOA) and levels of turbulence intensity (low, medium and high). The main purpose was to investigate if there could be significant effects of these parameters onto time-averaged dynamic phenomena such as lift and drag coefficients. In addition, turbulence eddy dissipation and kinetic energy were expected to vary in a non-linear manner.

2. Previous work

[2] studied the effect of turbulence intensity in the range of 2.4% to 5.4% on aerodynamic performance of airfoil NACA 0012 and found that the increase in air free stream turbulence intensity causes delay of the stall angle and the maximum lift coefficient. However, their results show that increase in intensity also causes increase in drag coefficient. Our study extends the study [2] by taking wider range of turbulence intensities, i.e., very low(1%), medium(5%) and very high(10%) and aims to observe whether this phenomenon occurs for such intensities.

Yap et al. [1] have shown that the NACA 0012 airfoil has a stall angle of 16 degrees and further increase of the angle leads to dramatic fall in lift due to rise in static pressure on the upper surface and significant increase in drag. Turbulence modeling for unsteady transonic flows over the rear half of an 18% thick circular airfoil at zero incidence, Ma_∞=0.76 and rebased on chord of $11*10^6$ was assessed by Marvin et al. [3]. They observed that a thick shear layer forms downstream of the shock wave, which led to dramatic increase in turbulence kinetic energy and shear stress, both of which reached a maximum when the dissipation and diffusion of turbulence kinetic energy exceeded its production and then, decreased substantially.

Another investigation about the effect of turbulence intensity with low Reynolds numbers on NACA-0012 airfoil performance characteristics was undertaken by Li et al. [4], who studied the forces acting on the airfoil at Re=5300 for free stream turbulent intensities between 0.6% and 6%, varying the AOA from 0 to 30 degrees. Their study showed that even at low Reynolds numbers the effect of turbulence intensity is significant, showing an apparent increase of lift coefficient and decrease of drag coefficient at stall angle of 12 degrees. Their observation at stall angle for 0.6% and 6 % of free stream turbulence intensity showed that at low free stream turbulence intensities stall can be phased out; however at sufficiently large values of turbulence intensity stall conditions can be clearly identified at regular stall angle.

Huang et al. [5] studied the aerodynamic performance (lift and drag) of a cantilever NACA 0012 wing model at Re between 0.5×10^5- 1.5×10^5 with free stream turbulence intensity varying between

0.2% and 0.65%. They came to the conclusion that stall angle is delayed as turbulence intensity increases up to 0.45%. However, the effect of increasing free stream turbulence intensity on maximum lift coefficient became significant only at turbulence intensity above 0.45%.

Ahmed et al. [6] investigated the aerodynamic characteristics of wind turbine blades at Re between $3.8 \times 10^4 - 2 \times 10^5$ at AOA from -2 to 20 degrees. These authors found that both increase of AOA and free stream turbulence intensity lead to increase of turbulent kinetic energy production. The distribution of turbulence kinetic energy indicated the location of transition to turbulent region and how it shifted upstream as turbulence intensity was increased.

The present study aims to consider the effects of free stream turbulence intensity on the performance of the NACA 0012 airfoil; specifically, variation in drag, lift, turbulence kinetic energy, and energy dissipation characteristics will be studied.

3. Numerical model setup

The setup of the mathematical model is performed using the commercial-academic CFD software ANSYS-CFX. The main premises adopted here are: steady state, Newtonian fluid, incompressible and turbulent air flow. Therefore, the following Reynolds-averaged governing equations and boundary conditions were prescribed: (a) mass conservation; (b) Navier-Stokes (momentum) equations; (c) energy conservation; (d) constitutive relations between p, T and H; and (e) shear stress turbulence model. These equations are shown as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho u_i\right) = 0 \tag{3.1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\tau_{ij} + \tau_{ij}^R\right) + S_i \quad ; \ i = 1,2,3 \tag{3.2}$$

with:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) \tag{3.3}$$

$$\tau_{ij}^R = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) - \frac{2}{3}\rho k \delta_{ij} \tag{3.4}$$

Where Boussinesq's assumption for the Reynolds-stress is adopted and δ_{ij} is the Kronecker delta function; μ is the dynamic viscosity, μ_t the turbulent eddy viscosity and k the specific turbulent kinetic energy.

The energy transport equation for the fluid in terms of the enthalpy is as follows:

$$\frac{\partial \rho H}{\partial t} + \frac{\partial \rho u_i H}{\partial x_i} = \frac{\partial}{\partial x_i}\left(u_j\left(\tau_{ij} + \tau_{ij}^R\right) + q_i\right) + \frac{\partial p}{\partial t} - \tau_{ij}^R\frac{\partial u_i}{\partial x_j} + \rho \varepsilon + S_i u_i + Q_H \tag{3.5}$$

where,

$$H = h + \frac{u^2}{2} \tag{3.6}$$

For air flow, the Ideal Gas state equation is prescribed to compute its density as a function of pressure and temperature:

$$\rho = \frac{p}{R_{air}T} \tag{3.7}$$

where,

$$R_{air} = \frac{R_{universal}}{Air\_Molecular\_Mass} \tag{3.8}$$

The Shear Stress Transport (SST) turbulence model consists of the well-known k-omega model near the wall and k-epsilon transport model in the free stream [7]:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \rho P - \beta^* \rho \omega k + \frac{\partial}{\partial x_j}\left((\mu + \sigma_k \mu_t)\frac{\partial k}{\partial x_j}\right) \tag{3.9}$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\gamma}{\nu_t} P - \beta^* \rho \omega^2 + \frac{\partial}{\partial x_j}\left((\mu + \sigma_k \mu_t)\frac{\partial \omega}{\partial x_j}\right) + 2(1-F_1)\frac{\rho \sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{3.10}$$

The constants $_\phi$ of the new model are found using Eq. (3.13) below:

$$\phi = F_1 \phi_1 + (1-F_1)\phi_2 \tag{3.11}$$

Eddy viscosity is calculated with

$$\nu_t = \frac{a_1 k}{\max(a_1 \omega; \Omega F_2)} \tag{3.12}$$

where Ω is the absolute value of the vorticity and also:

$$F_1 = \tanh(\arg_1^4)$$
$$F_2 = \tanh(\arg_2^2) \tag{3.13}$$

$$\arg_1 = \min\left[\max(\frac{\sqrt{k}}{0.09\omega y}; \frac{500\nu}{y^2 \omega}), \frac{3.424\rho k}{CD_{k\omega} y^2}\right]$$

$$\arg_2 = \max(2\frac{\sqrt{k}}{0.09\omega y}; \frac{500\nu}{y^2 \omega}) \tag{3.14}$$

$$CD_{k\omega} = \max(1.712\rho \frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}, 10^{-20})$$

The respective boundary conditions are no-penetration/no-slip on the airfoil surface and remaining conditions are presented in table 1.

Table 1. Boundary conditions.

Parameter:	Value:
Re	9e6
Ma_∞	0.7
$T_{air\ ideal\ gas}$	288 [K]
$P_{reference}$	56867 [Pa]
AOA	1.49^0-16.49^0
Turbulence intensity	1%, 5%, 10%
Inlet	U= [U_x, U_y, 0]

Outlet	$P_{relative}=0$ [Pa]

The set of governing equations are discretized and solved using the finite volume (FV) method on a spatially structured computational mesh refined locally at the solid/fluid interfaces and in specified fluid regions where high gradients are expected.

The solution convergence criterion is reached when the residuals of normalized parameters are equal or smaller than 1.0×10^{-4}. The mesh for the current project was provided by ANSYS Inc, which is depicted in Figure 2 and consists of 10,1520 nodes and 50,400 elements.
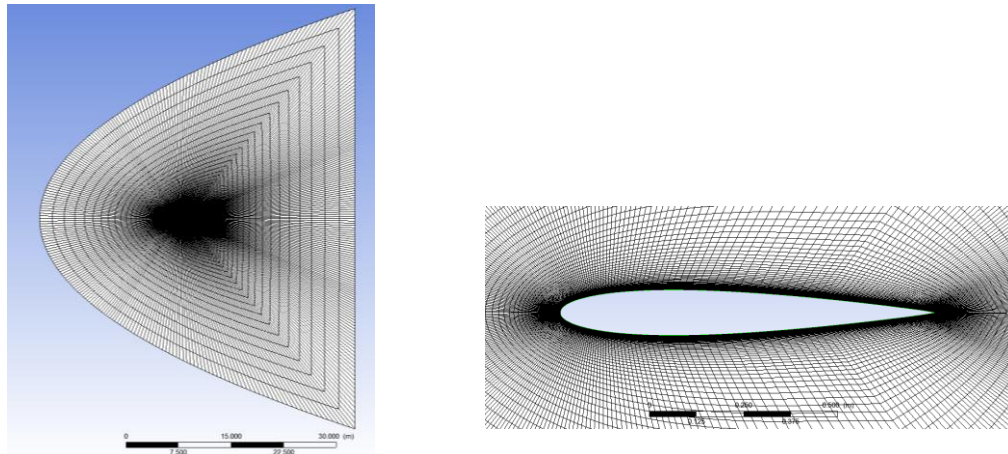

Figure 2. Computational mesh and its enlarged view.

The mesh was adopted from Ansys, therefore the only available option for mesh convergence study was to use the Mesh Adaption tool provided by the ANSYS software. This algorithm of mesh adaption, allows modifying certain regions within the mesh and consequently checking the corresponding solution for that adaption. Having adjusted the necessary criteria, simulations were run and results are summarized in Table 2.

Table 2. Mesh adaption setup parameters.

Test ID	Residual Target	Adaption criteria variable	Node factor	Maximum number of steps	Maximum iterations per step
1	1e-4	Density	2	5	50
2	1e-4	Velocity	2	25	250
3	1e-4	Density	2.5	25	300
4	1e-4	Density	1.5	25	300

21,000 iterations were performed until final mesh refinement was achieved. A final mesh of 108,642 nodes and 62,073 elements was obtained after subsequent steps of adaption, such that it satisfied the assigned residual target and number of iteration per step of adaption, as indicated in Table 2. Results of drag and lift were compared between initial and final meshes, finding a difference 0.2% for C_D and 0.3% for C_L coefficients. The difference was less than 1% and therefore, the adequacy of the original mesh structure was verified. Subsequently, all results are presented using the initial mesh.

A PC with an Intel® Xeon® E5620 CPU @ 2.40GHz with 4.00GB RAM running with two cores on a 64-bit Windows Operating System was used to perform the simulations. Each simulation with the chosen mesh took approximately 0.167 hours to fully converge.

SST turbulence model is validated using experimental results [8]. Results of Cp are presented in Figure 3, depicting a very good match between experiments and numerical results.
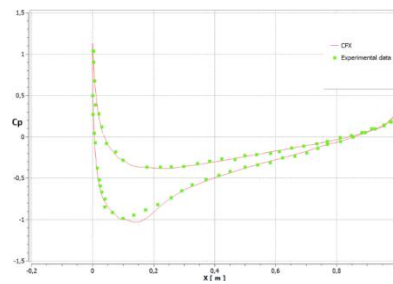
Figure 3. Comparison of pressure coefficient values between experimental data and ANSYS-CFX with SST turbulence model.

4. Numerical results

Values of C_D and C_L for different free-stream turbulence intensities were obtained. In order to observe the relation between the computed results, two separate figures were plotted. It was initially expected that there will be a reasonable deviation between the coefficients for different turbulence intensities, but the comparison revealed almost identical findings. According to figure 4, the drag coefficient C_D equally increases with the AOA growth. The same trend is observed for C_L parameters in figure 5, up to the point with AOA = 6.49 degrees, where stall occurs. The phenomenon of stall is recognized as it causes the boundary layer separation with subsequent dramatic fall of lift force and C_L. However, the later growth of AOA favors the lift coefficient recovery in all cases. In general, contrary to the expectations, the data closely fit into one common curve, no matter the intensity of free-stream turbulence being prescribed.

Results are partially understood by the fact that free-stream turbulence intensity, which is an independent variable for the simulations, does not affect the velocity mean value across the full domain. Obviously, the range of free stream turbulence levels does not have significant influence on the boundary layer and thus the lift and drag coefficients. However, the prescribed level of free-stream turbulence should have a direct impact on the magnitude of induced velocity fluctuations (i.e., turbulence kinetic energy) around the airfoil.

To see the real picture of the physical processes, it was decided to compare the turbulence kinetic energy and turbulence eddy dissipation fields among different cases. The 1% free-stream turbulence intensity case was taken as a benchmark, while others were compared with it. Simulations were performed for three different AOA: 1.49, 5.49 and 16.49 degrees. Turbulent kinetic energy plots at 1% and 5% turbulence intensity values are demonstrated on figure 6 and Figure 7. Numerical results revealed that there were significant differences in all situations, so the change in turbulence intensity had a finite effect on these turbulence fields. Nevertheless, changes are an order of magnitude smaller than absolute values of turbulence quantities and hence does not significantly affect the output parameter. For instance, the cases with low and medium turbulence intensities at 5.49 degrees AOA have order of magnitude 3, but their difference have and order of 2, as could be observed from Figure 8. This leads to the conclusion that despite the fact that some local turbulence quantities may be affected by changes of free-stream turbulence intensity, values of C_D and C_L are unaltered. Nevertheless, it is believed that the conditions just after the stall angle, require more research efforts due to expected much larger turbulence generation and therefore, it is proposed here for future work.

Finally, looking at the practical applications of the findings, the paper can assert that there is almost no effect of turbulence level variance within the range of 1 to 10% on the C_D and C_L parameters for NACA0012 airfoil.
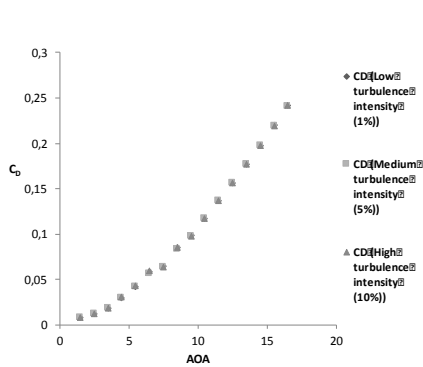
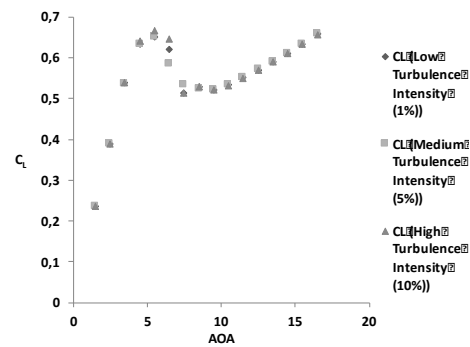**Figure 4.** Drag coefficient values versus AOA.

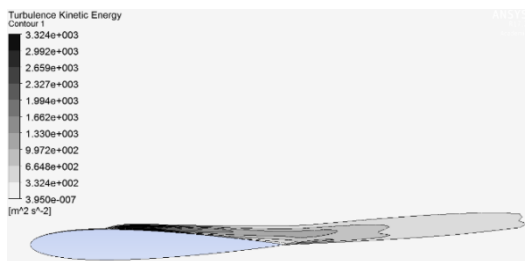**Figure 5.** Lift coefficient values versus AOA.

Figure 6. Turbulence KE for low turbulence intensity level (1%) at AOA 5.49 degrees
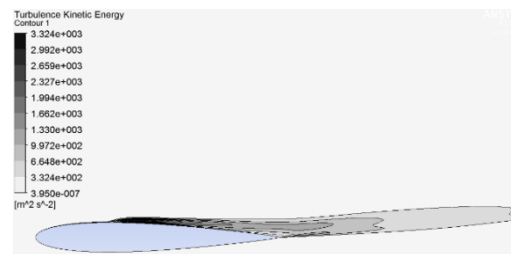

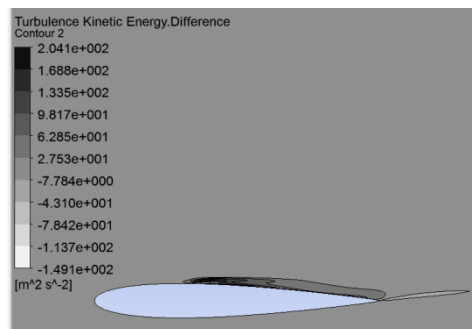**Figure 7.** Turbulence KE for medium turbulence intensity level (5%) at AOA 5.49 degrees.

Figure 8. Difference between Turbulence KE for medium (5%) and low turbulence intensity level (1%) at AOA 5.49 degrees.

5. Conclusion

The current paper was devoted to the investigation of the effects of free-stream turbulence intensity on NACA-0012 airfoil in transonic conditions in the presence of a shock wave.

Changes in the turbulence kinetic energy and dissipation fields were observed, in a non-linear proportion with respect to free-stream turbulence intensity being prescribed (1-10%). However, maximum changes with respect to 1%-benchmark condition were always one order of magnitude smaller than turbulence field values.

Furthermore, almost negligible effects were observed on C_D and C_L coefficients under the same different levels of free-stream turbulence.

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