Numerical study of receptivity mechanism of bypass transition on flat-plate boundary layer subject to synthesized freestream turbulence

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Abstract

Comprehension of the bypass transition mechanism in laminar to turbulent boundary layer subjected to synthesized freestream turbulence takes great parts in an enhancement of inflow modeling for turbulence simulation in turbomachines. The artificial freestream turbulence (FST) is synthesized to investigate the receptivity mechanism among bypass transition region. This work is focusing on study parameters – intensity and length scale of synthesized freestream turbulence. Design of experiment (DOE) together with LES simulation using commercial CFD programme is introduced to study the receptivity process resulting from different synthesized freestream turbulence. Increasing in a turbulent intensity tends to strengthen Klebanoff modes and trigger turbulent spots earlier resulting in moving the transition onset upstream. Increasing turbulence length scale tends to increase turbulent spot production rate resulting in abridging transition length.

Keywords*:* Bypass transition, Synthesized Freestream Turbulence, Tubulent intensity, Turbulent Length Scale, Design of experiment (DOE).

1. Introduction

Since transition plays an important role in a modern gas turbine and aerodynamic flow applications. The study of transition mechanism is to be comprehended. Transition is the process among Laminar to Turbulent region which take place with a mysterious scheme. It can be divided in to a natural transition and bypass transition. Tollmein & Schlichting wave is the first observed region lies next to laminar region. As it convects by downstream, development of the wave form a 3D structure and eventually breakdown into a turbulent spot, so called natural transition. The absence of these scenarios according with a high free stream turbulent intensity (approximately more than 0.5%), Voke&Yang[1] shows that the bypass transition took place by using large eddy simulation with Smarkorinsky and lily.

Observation via its skin friction coefficient through the experiment, Narasimha proposes the terms of intermittency whereas the onset transtion and complete transition are the roots of component.

Jacob&Durbin [2] aim their studied to insight the process of bypass transition. Using of direct numerical simulation to solve the Navier-Strokes equation, their work is the first simulation that accomplish with the experiments case T3A and T3B provided by Roach & Brierly [3].

Later, Zaki&Durbin [4] introduce the trigger of transition which a low frequency activates an onset transition. They also show a key to the complete transition is the part of high frequency as well.

L. Brandt&et al. [5] reveal an interaction between receptivity mode and low – high frequency freestream. Wavy motion scenarios are observed along with a patch of irregular motion convects further downstream. Turbulent spot, as it moves downstream, become longer and wider. Streaks observed downstream of turbulent spot before they merge into turbulent.

Z. Xu&et al. [6] claim their studied shown the characteristic of transition is sensitive to the combination of low and high frequency mode.

Turbulent intensity and the turbulent length scale are characterized by the controlled parameters that thuthfully has an effective on the transition mechanism.

2. Numerical method

A method to model the laminar to turbulent case obtained from the calculation of laminar to turbulent boundary layer.

A computational domain is derived from which Jacob&Durbin studied and Z. Xu was proposed the compromise domain.

2.1 Boundary conditions

Firstly, this study aims to present the method to investigate the bypass transiton with an easy way to grap. The use of CFD commercial program is one of the simplifications of this work. So as a limit of computational resource, large eddy simulation (LES) is a reasonable way to deal with delicate flow applications. Turbulent kinetic energy model seems to provide a compatible solution. The SGS model, kinetic energy tranfer (KET), developed from Smakorinsky and lily to recover the recessive of energy dissipation. A synthesized freestream turbulence is obtained from the selection of turbulent intensity and length scale.

2.2. Computational domain

The computational section is a rectangular box with a size L_x x L_y x L_z of 137.53 x 13.4 x 4 (δ_{out}), the grid is 780 x 80 x 64 respectively.

The grid is uniformly spaced in x and z directions and grouped near a wall in y direction.

Fig. 1 computational domain

The domain is assumed to divide into 2 parts: the first part is considered a slip wall and the latter is main domain with no slip condition.

Inflow is obtained from artificial freestream turbuent which controlled by Tu and L as well as its hopefully isotropic condition with U = 1 m/s.

A periodic condition imposes on spanwise direction. The upper wall uses a symmetry condition to avoid some undeniable reverse flows. Additionally, outflow condition is chosen to deal with the exit.

2.3 Computational detail

Finite volumn with a mothod of large eddy simulation can somehow reproduce scenario of bypass transition with a reliable grid resolution. This work aims an advantage of previous studied from Z. Xu by using an ample domain compare to our numerical resourcement to develop an agreeable results. The time step is limited by a Courant number not more than 0.5 which is an acceptable value.

Table. 1 Resolution of previously works

	V&Y	J&D	Z. Xu	P&J
Lx	300mm	620	137.35	137.53
Ly	30mm	40	13.4	13.4
Lz	20mm	30	3.35	4
Nx	127	2048	820	780
Ny	56	180	120	80
Nz	48	192	50	64
Δx+	80	11.7	27	28.94
Δz+	14	6	11	10.26
Scheme	LES	DNS	LES	LES

To achieve a compromise solution Jacob & Durbin proposed, our simulation is derived from which Z. Xu claimed sufficient resolutions. We denote the blasius boundary layer thickness at the outlet, (δ_{out}), as a normalization with Rex equals to 448900. Therefore, the viscousity is obtained from where onset transition took place. The leading edge comes into play within this simulation. By the way, the level of turbulent intensity at leading edge has an agreement with the experiment of Voke & Yang.

3. Result

In this section, four cases corresponse to Case I, II, III, and IV. Where design of experiment use to investigate which the most proper outcome as its characteristic is. To model the freestream turbulence which tend to have a similar effect as its natural mechanism. The artificial freestream turbulence is generated by a selection of these effective parameters which are turbulent intensity and length scale given in table 2. The response reveals a good result compare to an experiment data. Length scale is firstly based on our computational domain.

Table. 2 Parameters of Interest in the simulation

Case	Tu (%)	L(δ_{out})
I	3	1
II	3	2
III	4	1
IV	4	2

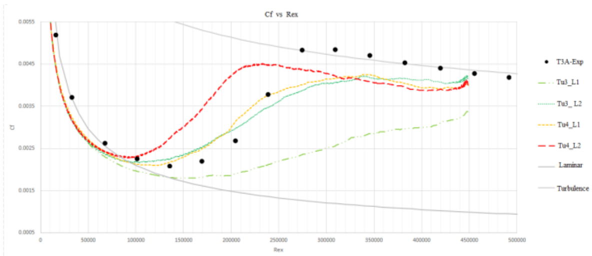

Fig. 2 An averaged skin friction coefficient

3.1 Turbulent intensity

Free stream turbulent is sythesized by (1) to be nearly isotropic, whereas

$$Tu = \sqrt{\frac{{u_{rms}}^2+{v_{rms}}^2+{w_{rms}}^2}{3}} \qquad (1)$$

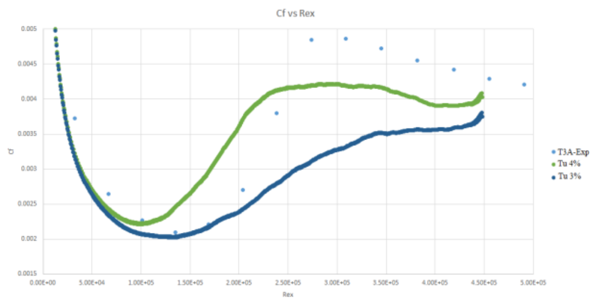

Fig. 3 Averaged length scale

Comparison with each of the turbulent intensity regardless of the length scale, Fig.3, the skin friction compares to T3A case. Onset transition is closely against the experiment. Eventhough the peak at complete transition seems to be a little lower than it should.

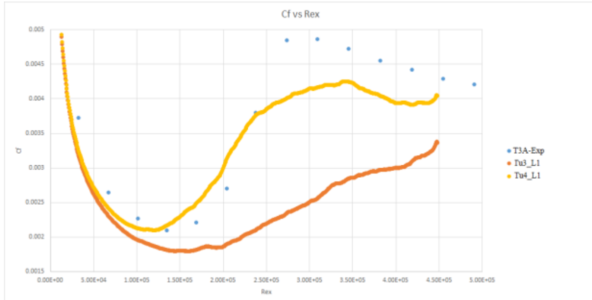

Fig. 4 Skin friction coefficient of case I, III

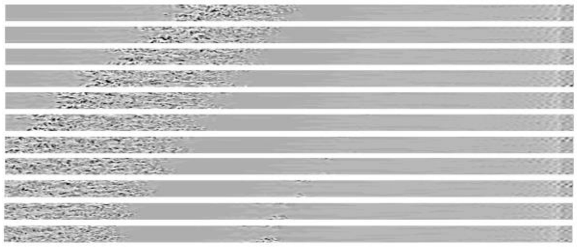
Fig. 5 Vy componet of case I

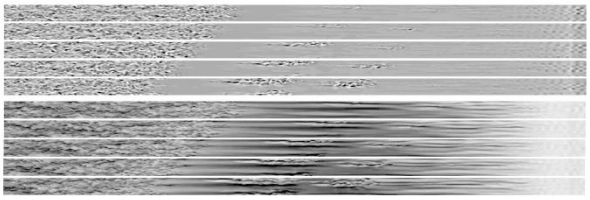
Fig. 6 Vy and Vx component of case III

When a small intensity, case I, comes together with a small length scale, transition is gradually developed. It is likely to curb and slow down a transition. It has an overwhelm effect on low turbulent intensity. Skin friction coefficient lies along with a laminar region. Consequently it raises up (Re_x ~ 1.43e5) with a slowly rate and undergoes with an experiment case. However, the visualization can confirm that the spot is swept away by the freestream turbulence and move out. It is clearly that transition location does not take place within a domain as shown in Fig.5.

Once turbulent intensity is increased, Fig.4, it can energize the transition process as well as its onset transition become earlier. Skin friction coefficient elevates (Re_x ~ 1.11e5) with a higher rate than the lower turbulent intensity. Increasing rate is quite similar to the experiment rate.

Fig.6, turbulent spot can be mentioned by Vy component and klebanoff mode [7] seems to dominent along side with a spot. Vx contour component reveals a streak before and after a turbulent spot. As it nexts to the spot, there is a variation of speed so the streak is apparently to notice.

3.2 Length scale

Value of length scale was firstly derived from our computational domain size because of a spanwise periordic limitation.

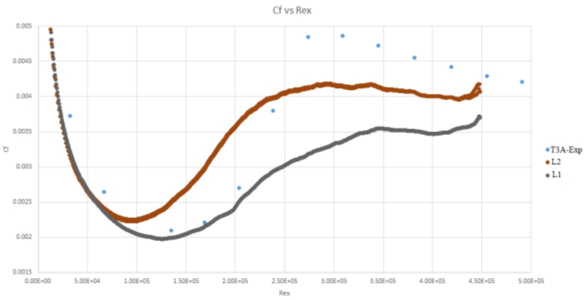

Fig. 7 Averaged turbulent intensity

From Fig.7, the skin friction coefficient shows a harmonic trend when averaged a turbulent intensity of each length scale. The lower length scale has a tendency to beneath an experiment case. The small length scale tends to prolong the transition region. In addition onset of transition seems to move downstream with a decreasing in length scale.

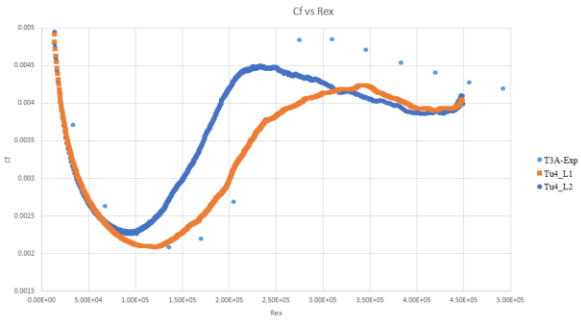

Fig. 8 Skin friction coefficient of case III, IV

Higher turbulent intensity seems to hinder the characteristic of length scale. Although the small length scale can relocate and elongate transition region, turbulent intensity has more potential to empower the transition mechanism such as an energy penetrtion through a boundary layer.

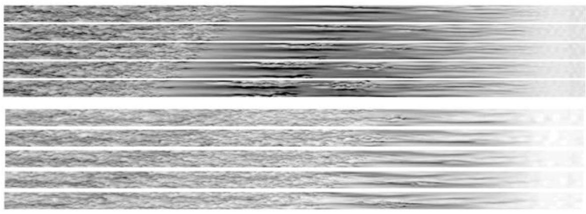

Fig. 9 Vx component of L1 and L2 at Tu 4%

Fig. 9 expose an obviously klebanoff modes can be observed through streaks among the transition region. Streaks elongate at the up stream and, once they are perturbed, they formed wavy streaks before becoming a spot. The higher length scale is, the shorter transition length becomes.

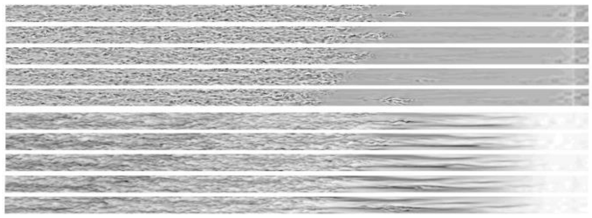

Fig. 10 Vy and Vx component of case IV

Vy and Vx velocity component have shown a good agreement with the onset location of transition. The higher turbulent intensity with the large length scale, Fig. 10, has an early trigger of onset transition. Turbulent spot appears earlier upsteam and rapidly merge into a turbulent region. It can be confirmed by a location of complete transition, Fig. 8.

About Rex ~ 9e4, onset transition occurred and quickly completed around Rex ~ 2.25e5. The higher in turbulence intensity leads to the higher in wavy motion of the streak and shortening a transition length. Turbulent spot rapidly growth and merge with a turbulent region. The skin friction coefficient tendency, case II and case IV, shows a reasonable outcome.

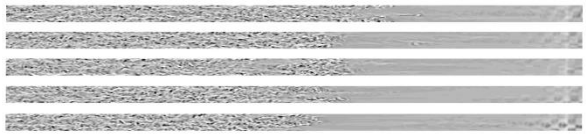

Fig. 11 Vy component of case II

Case II, the skin friction coefficient along with these Vy components give a significant consequence. The combination of turbulent intensity and length scale, with properly, create and control desireable characteristic of freestream turbulence resulting in naturally affects transition.

4. Conclusion

- A proper combination of turbulent intensity and length scale can describe the characteristic of transition.
- Higher turbulent intensity can overcome the effectiveness of length scale.
- Small length scale can penetrated into a boundary layer. However, it cannot last long to sustain downstream. It seems that free stream turbulence decays faster with a small

length scale therefore it is less effective on interaction with the streak downstream.

5. Acknowledgement

Author does love to give a sincerely acknowledge to all supporters especially the advisor who guide and dedicate to this work. Thanks to all colleagues who contribute to all needs.

6. References

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