Analysis of transformed fifth order polynomial curve for the contraction of wind tunnel by using OpenFOAM

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Analysis of transformed fifth order polynomial curve for the contraction of wind tunnel by using OpenFOAM

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Abstract. Contraction is the vital part in wind tunnel hence the designing of contraction is having greater interest among the researchers. Bell and Mehta proposed a fifth order polynomial for the design of the contraction and was widely accepted among the wind tunnel designers. Daniel Brassard proposed a transformed fifth order to provide better results for the fifth order polynomial design by making the radius at the inlet of contraction higher than the radius at the outlet. In this paper the analysis of the transformed fifth order polynomial is investigated by using the open source CFD tool OpenFOAM. Analysis was basically taken considering the uniformity of air flow, wall shear stress distribution and turbulence intensity at contraction outlet and the mid vertical plane at the test section. From the analysis it is found that the transformed model is better compared to the untransformed one in terms of uniformity and turbulence intensity.

1. Introduction

The fluid flows about a body and the forces caused by the fluid-body interaction can be simulated with the help of a wind tunnel. Wind tunnel can be used to measure local and total velocity along with the pressure and temperature around the body. The main purpose of a wind tunnel is to create the controlled wind speed of similar environment that facing the model for unlimited time to obtain the aerodynamic steady-state experimental results [1]. Main components of a wind tunnel are the test section, contraction, diffuser, settling chamber and driving unit (Fan). Based upon the practical application of wind tunnel, a lot of effort has been done in its designing [2-4]. The designing of the wind tunnel components was one of the interested area for the researchers. The present work deals with the analysis of transformed fifth order polynomial contraction design for the contraction.

The contraction is the crucial component of wind tunnels to produce a uniform flow with marginal turbulence. Lots of research work has been done in the designing of contraction of wind tunnel [4-14]. The optimization of contraction design was based on flow uniformity at the test section mid plane, avoidance of separation in the contraction, minimizing the boundary layer thickness at entrance to the working section and minimization of turbulence intensity [9]. Curve obtained by higher order polynomial equation has got more significance in due time.

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2. Principles and Transformation of contraction design.

Bell and Mehta suggested a polynomial of fifth order for the contraction design [7]. The design was made by considering most of the criteria followed for the designing of contraction. This fifth order contraction design was very well accepted design and was using widely for the designing of wind tunnel contraction. The polynomial design recommended by Bell and Mehta is as follows

$$\mathrm{h} = [-10\varsigma^3 + 15\varsigma^4 - 6\varsigma^5](H_i - H_0) + H_i \tag{1}$$

Where, $\varsigma = \frac{\mathrm{x}}{\mathrm{L}}$; H_i and H_o is the height of contraction inlet and outlet from the centre axis and L is the length of contraction. From the analysis of this fifth order polynomial curve, it was found that it has better result for having maximum uniformity of flow along the test section and minimal turbulence intensity at the contraction outlet compared to other contraction designs. The fifth order design satisfies all the criteria required for the curve design except that its inlet curve radius is not much greater than the outlet radius. In this design both inlet and outlet radii are almost same which is contrary to the criteria of contraction design that the inlet and outlet radii must be proportional to the area. Daniel Brassad had done a study on the transformation of fifth order polynomial curve to provide better results by making the radius at the inlet of contraction higher than the radius at the outlet [14]. In this present study the analysis of curves obtained by the transformation of fifth order polynomial by providing various values for the factor ‘α’ was evaluated with help of open source CFD tool OpenFOAM. The transformation equation used for the analysis is shown below in equation (2).

$$y = (\,\eta\left(H_i^{\frac{1}{\alpha}} - H_e^{\frac{1}{\alpha}}\right) + H_e^{\frac{1}{\alpha}}\,)^{\alpha} \tag{2}$$

Where

$$\eta = 10\zeta^3 - 15\zeta^4 + 6\zeta^5$$

Where ζ is the dimensionless axial distance measured from the inlet, with ζ=1 at the outlet. In order to present the resulting contraction profiles consistently and intuitively, Daniel Brassad proposed the transformation equation (2). In this paper the values taken for α are 0.3, 0.5, 0.7, 1.5, 2, quadratic function of ζ and sine function of ζ. The curves produced by using these transformed equation using different values of α are plotted in the Figure 1.

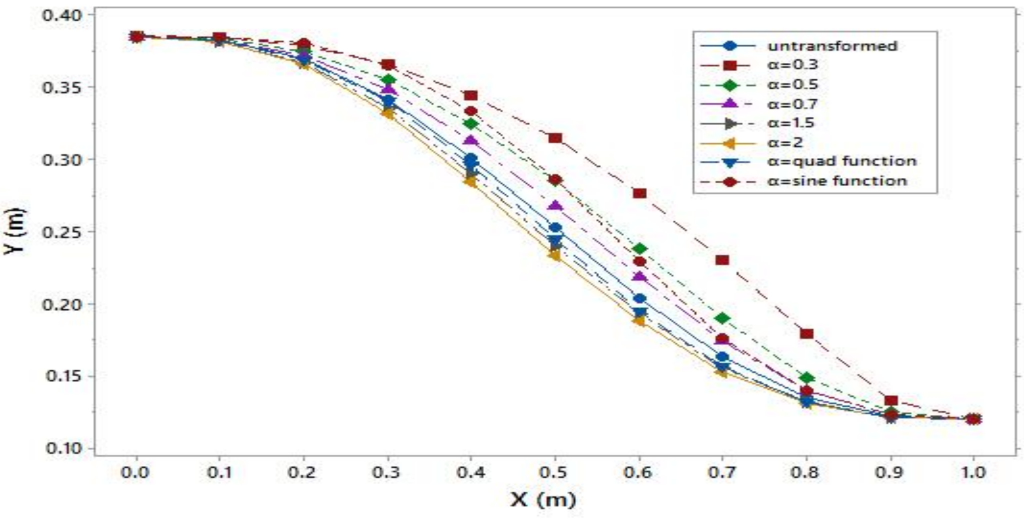

Figure 1. Contraction curves obtained by varying the value of α

3. Mathematic modelling and computation

The computations consisted in solving the steady-state, incompressible, Reynolds-Averaged Navier–Stokes equations using a segregated approach for the pressure-velocity coupling. The solutions were obtained using the OpenFOAM-provided solver simpleFoam, which implements the SIMPLE algorithm (Semi-Implicit Method for Pressure Linked Equations) to produce separate equations for velocity and pressure [16]. Turbulence properties were computed by employing K-ε model. The steady state equations of mass and momentum can be written as follows in a stationary frame

$$\frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} = 0 \tag{3}$$

$$u\frac{\delta u}{\delta x} + v\frac{\delta u}{\delta y} = -\frac{\delta P}{\delta x} + \mu \nabla^2 u + \frac{\delta}{\delta x}\left(-\rho\overline{u'^2}\right) + \frac{\delta}{\delta y}\left(-\rho\overline{u'v'}\right) \tag{4}$$

$$u\frac{\delta v}{\delta x} + v\frac{\delta v}{\delta y} = -\frac{\delta P}{\delta x} + \mu \nabla^2 v + \frac{\delta}{\delta x}\left(-\rho\overline{v'^2}\right) + \frac{\delta}{\delta y}\left(-\rho\overline{u'v'}\right) \tag{5}$$

To do this, first, the structural grids are generated for the all the profiles and very fine grids are used for regions near the walls. The models were meshed using SnappyHexMesh utility into hex-dominant meshes (Figure 3) of total 248750 elements with 123651 nodes. However a grid convergence study was not conducted in due time. The minimum y+ value for the models presented in this paper was below 10. Velocity at the inlet and pressure at the outlet are used as boundary conditions. Outlet pressure is given such that the total pressure at the inlet of each nozzle is equal to atmospheric pressure. The residual of 10^{-5} was taken as the convergence criterion in this numerical solution.

4. Validation of SimpleFOAM solver

The performance of the solver SimpleFOAM was evaluated based on the experimental data collected from the wind tunnel facility at thermal lab of College of engineering, Adoor. The contraction of the wind tunnel has a length of 1m and square cross section with dimension at inlet and outlet are 0.75m and 0.2m respectively. At first the experimental data from the wind tunnel was collected and then simulated the same on OpenFOAM. The geometry was created and meshed using open source geometry tool SALOME. The mesh details of the created geometry is shown in the Figure 3.

The fluid (air at 30ºC) kinematic viscosity is υ= 1.6036 x 10^{-5} m^2/s. At the domain inlet, the flow velocity is about 2.1 m/s and at the domain exit a constant pressure condition P= 0 Pa was set. Figure 2 shows a comparison between the computed velocity profile at x = 0.45 m from the outlet of contraction outlet and the velocity obtained by Pitot tube experimentally at same position (at a motor rpm of 180). The comparison shows a good agreement between the computed and the experimental value, which gives confidence in the numerical model.

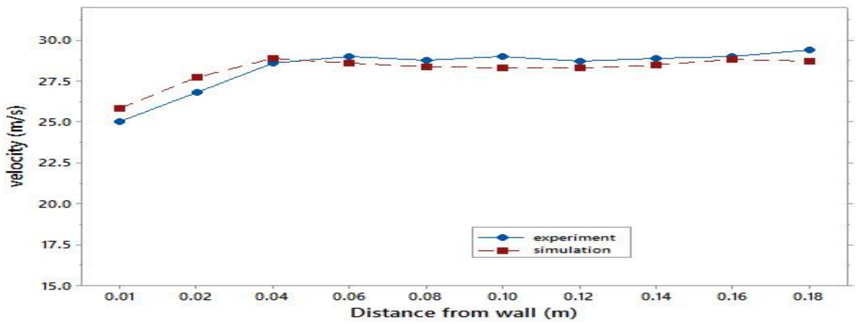

Figure 2. Velocity profile along the vertical plane at x=05m from the outlet of contraction

The analysis of this paper was also done by taking the dimension of the contraction (outlet dimension = 0.77m X 0.77m, inlet dimension = 0.2mX 0.2m and a length of 1m) and test section of the wind tunnel (dimension of 0.2m X 0.2m X 0.56m) which was used for the experimentation. A geometry was made for the contraction and test section. It was then meshed using the SnappyHexMesh utility available at Open FOAM [17]. The mesh grid created for the geometry is shown on the Figure 3. The boundary condition was also given the same which is used for the validation (inlet velocity of 2.1 m/s and atmospheric pressure at the outlet)

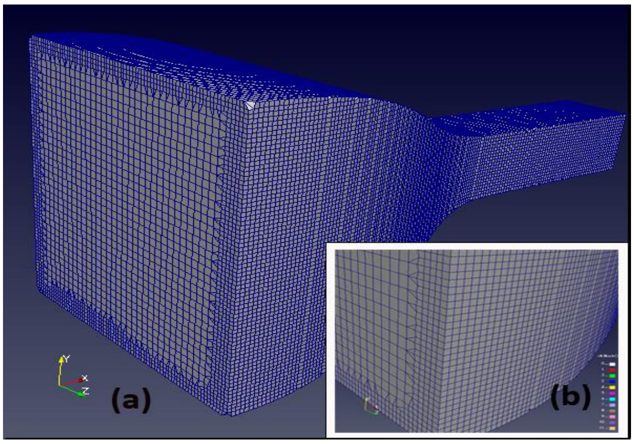

Figure 3. (a) Hex-dominant mesh created by using SnappyHexMesh. (b) enlarged view of the mesh details at the corner of the geometry

5. Result and Discussion

Boundary layer separation occurs when the portion of the boundary layer closer to the wall or leading edge reverse in flow direction. The separation occurs at the point where the shear stress become zero. From the analysis it was found that none of the model are experiencing separation [12]. In Figure 4 shows the typical wall shear plotted for all models and validates the lack of separating flow.

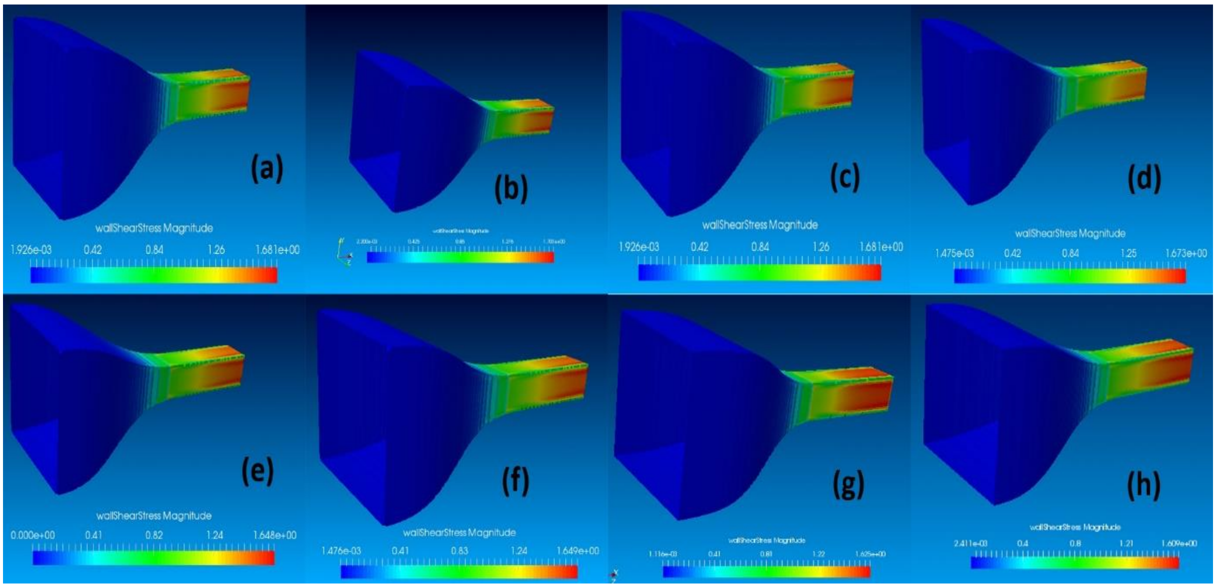

Figure 4. Wall shear stress distribution of various contraction profiles when (a) α=0.3 (b) α=0.5 (c) α=0.7 (d) α=1.5 (e) α=2 (f) α=quadratic function of ζ (g) α=sine function of ζ (h) untransformed

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The uniformity of flow was analysed and the velocity profile was plotted at the mid-plane of test section as shown in the Figure 5. The flow uniformity was disturbed near the walls due to the increase in turbulence created by the formation of boundary layer. From the Figure it is seen that the uniformity is better when the "α" value is lesser. It is observed that the contraction with "α" value 0.3 possess better uniformity compared to all other contraction profile. On comparing the sine function and quadratic function transformation, sine function is having better uniformity compared to the quadratic function transformation. And it is clear that the transformed profile provides better uniformity compared to untranformed.

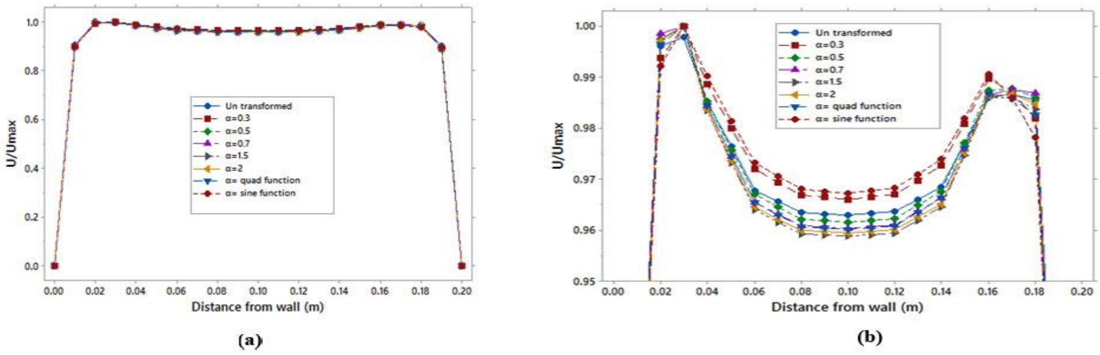

Figure 5. Velocity profile at the mid vertical plane of test section (b) detailed view of velocity profile mid vertical plane of test section

In case of turbulence also it has been noted that the performance of transformed contraction profile is better compared to untransformed profile. The comparative analysis of turbulence intensity of various transformed profiles with the untransformed profile is shown in Figure 8. From the simulation results it is evident that the profile can be bettered compared to untransformed if it is transformed by giving higher values to"α". Better performance in turbulence is obtained when alpha value is selected as α=2 followed by α=1.5. The quadratic function of ζ and sine function of ζ are also taken into consideration and was analysed. As seen from the simulation result it is seen that the quadratic function of ζ outperformed the sine function in the case of turbulence intensity at mid-section. When the value is lesser the performance trend is also decreasing. Turbulence intensity at was found to be very high in the case of alpha =0.3, followed by sine function of ζ and α =0.7.

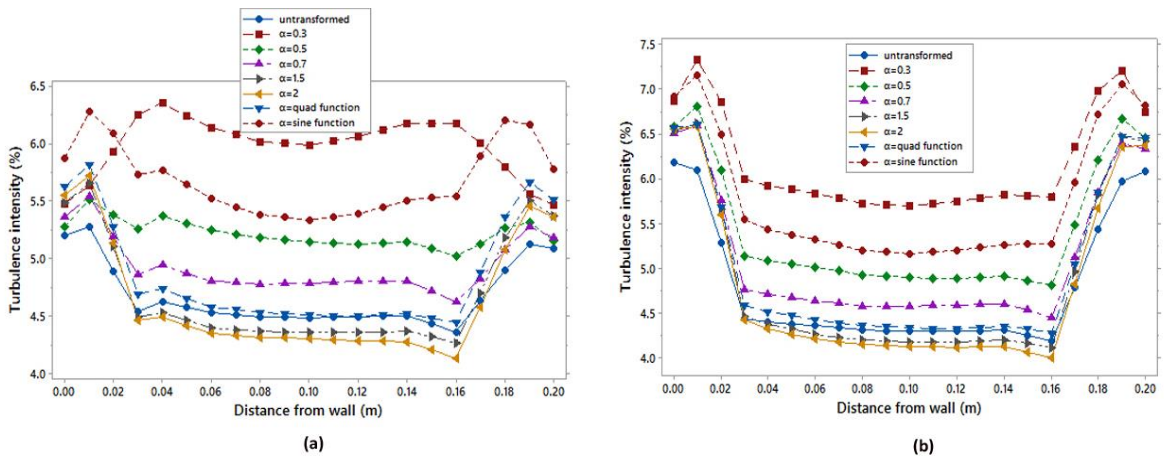

Figure 6. Turbulence intensity profile at the outlet of contraction (b) Turbulence intensity profile at the mid vertical plane of test section

6. Conclusion

The fifth order polynomial contraction profiles proposed by Bell and Mehta was analysed and found that the inlet and outlet radii was almost similar. The outlet and inlet radii of the contraction curves must be such that the radius of inlet must be greater than the radius at the outlet. For this reason Daniel Brassad proposed a transformed fifth order polynomial by using the equation (2). The performance of this transformed polynomial was analysed and compared with the help of the open source CFD tool OpenFOAM. The validation of the simulation was done by comparing the velocity profile obtained from the experimentation and the one obtained from the simulation.

From the results it is found that, better result is obtained for transformed contraction profiles than the untransformed profile. In the case of turbulence intensity, as the value of 'α' increase the level of turbulence intensity decreases. The maximum uniformity also increased with transformed profile compared to untransformed. From the results it can be concluded that by transforming the fifth order polynomial better results can be achieved. This proves the relevance of contraction design by using transformed polynomial.

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