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The Importance of Turbulence in Assessment of Wind Tunnel Flow Quality

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1. Introduction

The objective of obtaining a spatially standardized steady stream of air across and along the test section of a wind tunnel has been considered by several researchers. When a wind tunnel is manufactured or montage or move to another position, the study about variation of pressure, Mach number, density and temperature distribution, the variation of pitch and yaw components of flow angularity, boundary layer treatment near the walls, noise and acoustics and the behaviors of vortexes in the entire parts of it must be identify. Flow Field Survey by rake or hot-wire in different stations, pressure and velocity contours, boundary layer total pressure survey are another activities that must applied for flow quality. White explains that the most important measure of performance in a wind tunnel is its turbulence; the level of unsteady velocity fluctuations about the flow's average velocity [1]. Designer of wind tunnels strive to grade up the flow quality of wind tunnels by using the best design rules and some manipulators to improve the role of wind tunnel in industrial designs. One area that has of high importance is the reduction of the turbulence intensity across the test section that more discussion about it will be considered in this study.

2. The definition of turbulence

Today, one of most complicated area under discussion in physics, mathematics, fluid mechanics, and also different industries i.e. aerospace engineering, wind turbines, buildings, combustion, biology, climate behaviors, oceanography is turbulence. Turbulence is highly versatile motion that it is impossible to predict it in any way. There are various definitions for turbulence that they are similar concepts. Turbulence has been defined by Bradshaw as:
"A three-dimensional time-dependent motion in which vortex stretching causes velocity fluctuations to spread to all wavelengths between a minimum determined by viscous forces and a maximum determined by the boundary conditions of the flow. It is the usual state of fluid motion except at low Reynolds numbers." [2].
Jean Leary presents the following state for turbulence[3]:
"Turbulence is due to the formation of point or line vortices on which some component of the velocity becomes infinite" and Hintz define according to the below sentences:
"Turbulent Fluid motion is an irregular condition of flow in which the various quantities show a random variation with time and space coordinates, so that statistically distinct

average values can be observed [3]". At the result, from abovementioned definitions for turbulence, one may conclude that Turbulence has its origins in the inherent instabilities of laminar flow. Turbulence dies out because of viscous damping unless some mechanism carries on pumping energy into the velocity fluctuations. The most important mechanism for generating and maintaining turbulence is shear in the mean flow. Another important mechanism consists of different forms of stirring. In geophysical flows and in combustion, turbulence can be generated by buoyancy forces associated with variations in the mass density of the fluid [4]. In other word, shear stress, secondary flows, vortex shedding, noise and unwanted fluctuations are the most sources for turbulence. Turbulent flow is chaotic and the flow velocity is very insightful to perturbations and fluctuates wildly in time and in space, and also contains swirling flow structures (eddies) with characteristic length, velocity and time scales which are spread over very wide ranges [4].

3. Undesirable effects of turbulence in experimental measurements

The unwanted effects of turbulence on the results of wind tunnel are studied by author in [3]. These studies show that if the turbulence intensity in the test section is large enough, they may trigger unfavorable transition and the measurements i.e. drag, lift and velocity profiles may be incorrect. In the other word, the flow shift from laminar to turbulent flow on the model surface significantly upstream of its actual location in an environment where the free stream turbulence level is more than real value. Further, it has long been documented that free stream turbulence can alter the effective Reynolds number in turbulent flow somewhere, the almost of significant parameters are the function of Reynolds number. Small variations of the free stream turbulence can change the behavior of boundary layer, skin friction and shape factor. However, the influence of free stream turbulence scale has not been determined completely. Wind tunnels with identical levels of turbulence can produce different test results due to differences in their turbulence spectra [5]. An acceptable value for turbulence level of wind tunnel is a provision and preliminary condition for dynamic similarity between the flow around the aircraft in flight and the flow around the model in the wind tunnel. Turbulence also can excite the local Mach number, pressure, density and other coupled parameters in the test section. The flow angularity distorted in high turbulence level. Briefly, the turbulence can produce menace errors in measurements. For example, Eiffel in 1911 and Fopple in 1912 reported the drag coefficient of similar sphere equal to 0.18 and 0.44 respectively, in different subsonic wind tunnel. Wieelsberger by using screens show that this dissimilarity in the drag coefficient of the sphere is due to different turbulence level of wind tunnels. As the result, the turbulence can lead to more errors in aerodynamic measurements in wind tunnels.

Some possible sources of errors or discrepancy in empirical data, related to the effects of free-stream turbulence on the flow about bluff bodies, have been examined by Bell [6].Figure 1 shows, first of all, a so-called "standard" drag curve which illustrates the major features of the drag sustained by a circular cylinder in a very-low-turbulence flow. The drag coefficient lies approximately in the range 1.0-1.2 until the critical region is reached at a Reynolds number of about 2×10^5. Here, natural instabilities cause the previously-laminar flow in the boundary layer to become turbulent through a linear disturbance amplification process known as the Tollmien-Schlichting (T-S) instability

mechanism. The higher kinetic energy associated with the turbulent boundary layer permits greater penetration into the adverse pressure gradient on the rear half of the cylinder so that, compared to the laminar case, separation is delayed, the wake width is substantially reduced and base pressure recovery is improved. The net result is drastic relatively low intensity turbulence in the free-stream can trigger the T-S instability waves, leading to an early onset of the critical regime. The Bruun and Davies (1975) data in Fig. 1, for a turbulence intensity of 3.8%, illustrate this well-known and expected phenomenon. Bell believe that The influence of turbulence, and the parameters of importance, vary with the phenomenon considered. Properties averaged over the entire turbulent spectrum appear not to be wholly satisfactory for correlating the various effects; most often it seems that the intensity over a particular bandwidth is of primary importance. Free-stream turbulence increases entrainment into the shear layers at the surface of a body, or in its wake, affecting the energy distribution and altering the locations of transition, separation and reattachment. There is an enhanced diffusion of organized vorticity, presumably affecting eddy-shedding phenomena and base pressures. Distortion of the vorticity field, with resultant changes in intensity, occur in the flow about an object. All of these factors influence the fluid-dynamic forces on a bluff body in a way which has not yet been fully or satisfactorily explained. This study shows that more information is required for an improved understanding of the forces on a body immersed in a turbulent flow [6].
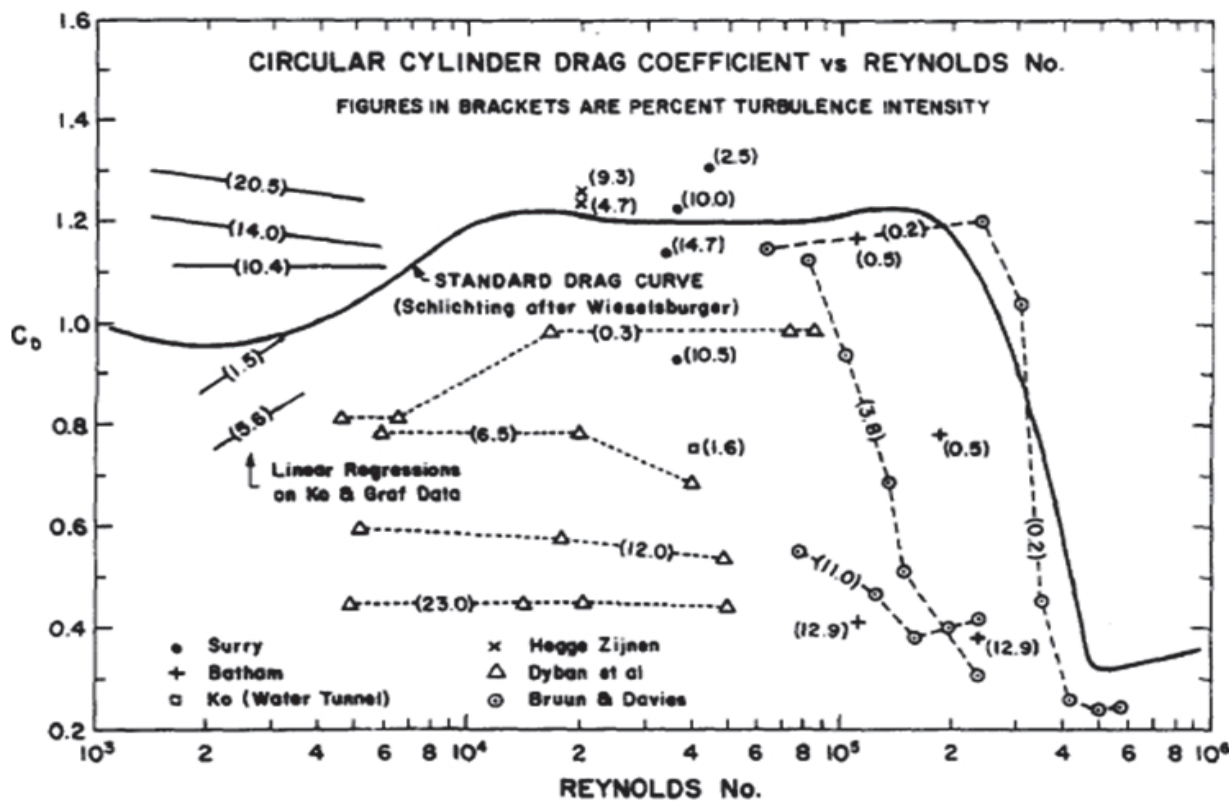

Fig. 1. Circular Cylinder drag coefficient vs Reynolds number as obtained by several investigations at various values of turbulence intensity [6]

4. Measurements of turbulence

A chief research tool for the majority of turbulent air/gas flow studies is Hot-Wire Anemometry (HWA) that is used to measure the flow parameters such as turbulent intensity, mean velocity and root mean squares. There are two categories for hot wire anemometry, i.e., single and X-probes. Single wire probes, where the wire is oriented normal to the mean flow direction, are used to measure the velocity component in the mean flow direction. Where, crossed wire probes or X-probes, consisting of two wires arranged in an X-configuration, are used to measure both stream-wise and cross-flow velocity components simultaneously. A normal wire is usually calibrated by recording its output voltage as a function of the velocity. The sensitivity is then given by the slope of the velocity–voltage relationship and curve-fitting is commonly used to reduce the error in differentiating the discrete data. Polynomials as well as curves based on the King's law have been used by various researchers [7-10].

In a 2-D crossed wire probe the sensitivity may be found by a method similar to that used in calibrating a normal wire. To determine the sensitivity to the cross-flow velocity, 'static' or 'dynamic' methods may be used [10]. In a static calibration scheme, two ways are possible: the V_e -analysis method [8] and the $(\tilde{V}, \theta)$ direct analysis [8, 9]. Manshadi et-al introduce a new genetic algorithm based method for direct calibration of 2-D hot-wire probe [10]. This new method is an alternative for the previous QR method that is commonly used for calibration of the X-probe hot wires. Proposed genetic algorithm method in [10] resulted in a much smaller error in velocity estimation while preserving the number of sentences in its calibration equation format. In addition, it preserves the magnitude of its error even when the number of sentences in the calibration equation is decreased while the error in the QR method increases substantially for the same situation [10]. Figure 2 show that the calculated velocities from the GA method are closer to the reference velocities while preserving the number of terms of the calibration equation.
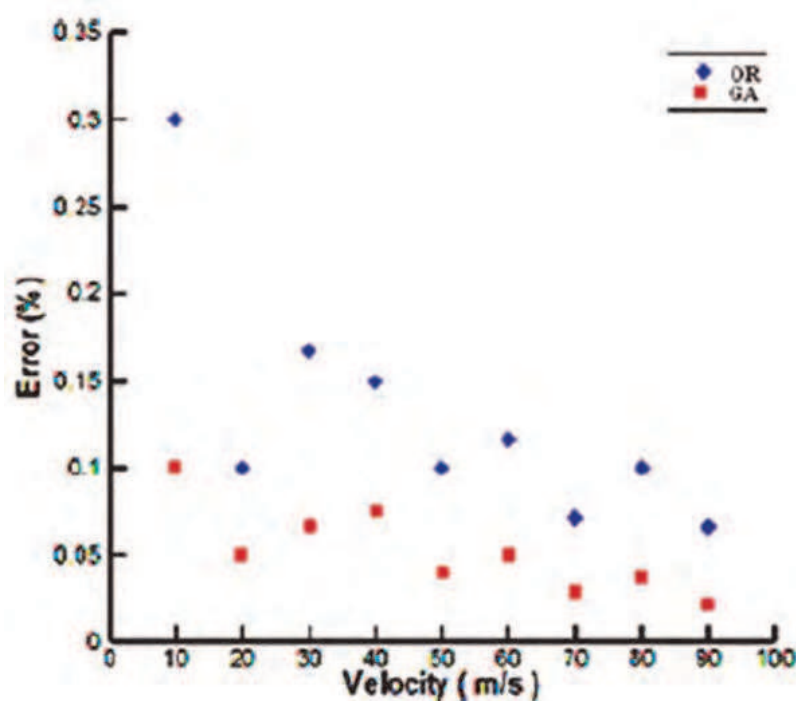

Fig. 2. Comparison of the error generated by the QR and the GA method [10].

In Fig.3 and Fig.4, the longitudinal and lateral components of the turbulent intensity, Tu and Tv, on the center line of the test section are shown against the velocity for the two aforementioned methods. The results show that considerable differences exist between the two calibration schemes. Note that the values of the longitudinal turbulence intensity for the center of the test section of the present wind tunnel are reported by the manufacturing company and it varies between 0.33 and 0.37 for the free stream velocities of V_∞ equal to 30 and 90 m/s, respectively. These two data points are shown in Fig. 3 and as seen the predicted GA method values are much closer to those reported by the company than those obtained by the QR method [10]. The reader can study the detail of above methods in [10].
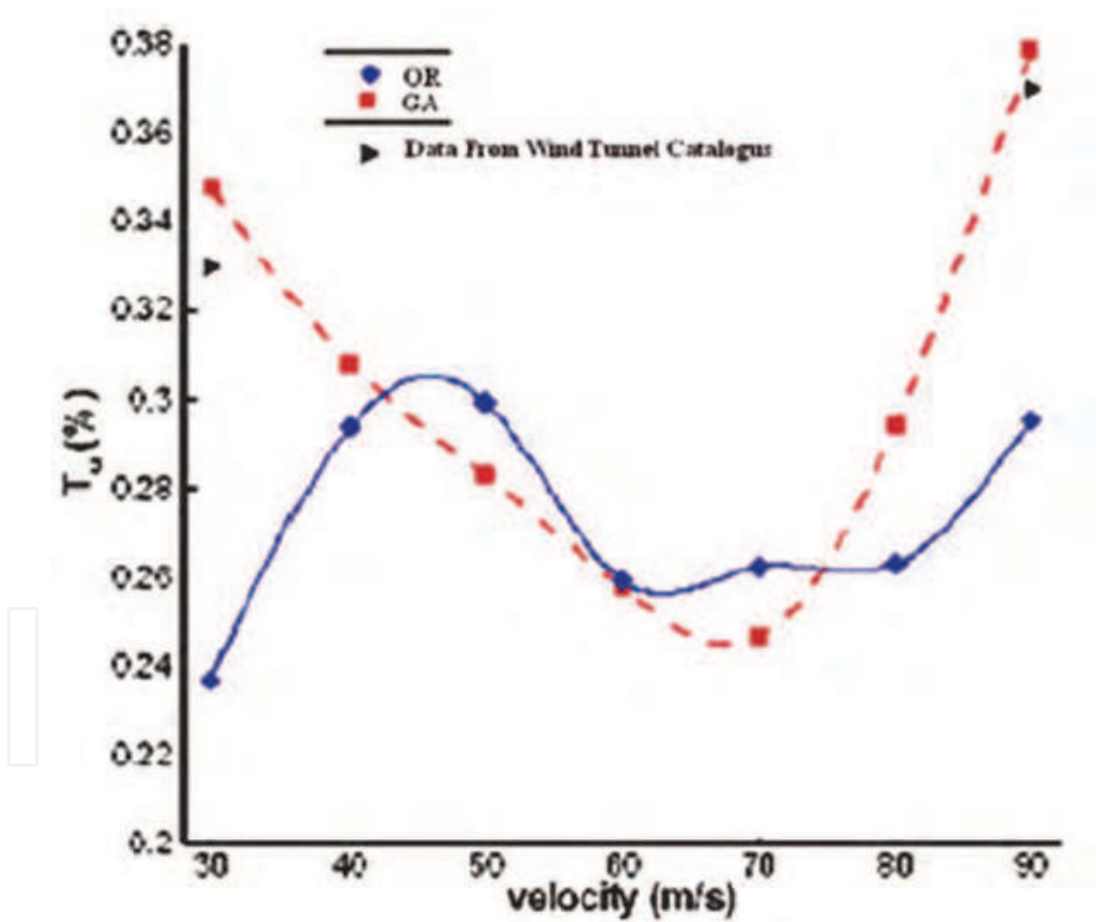

Fig. 3. Variation of T_u obtained from the two calibrations method [10]
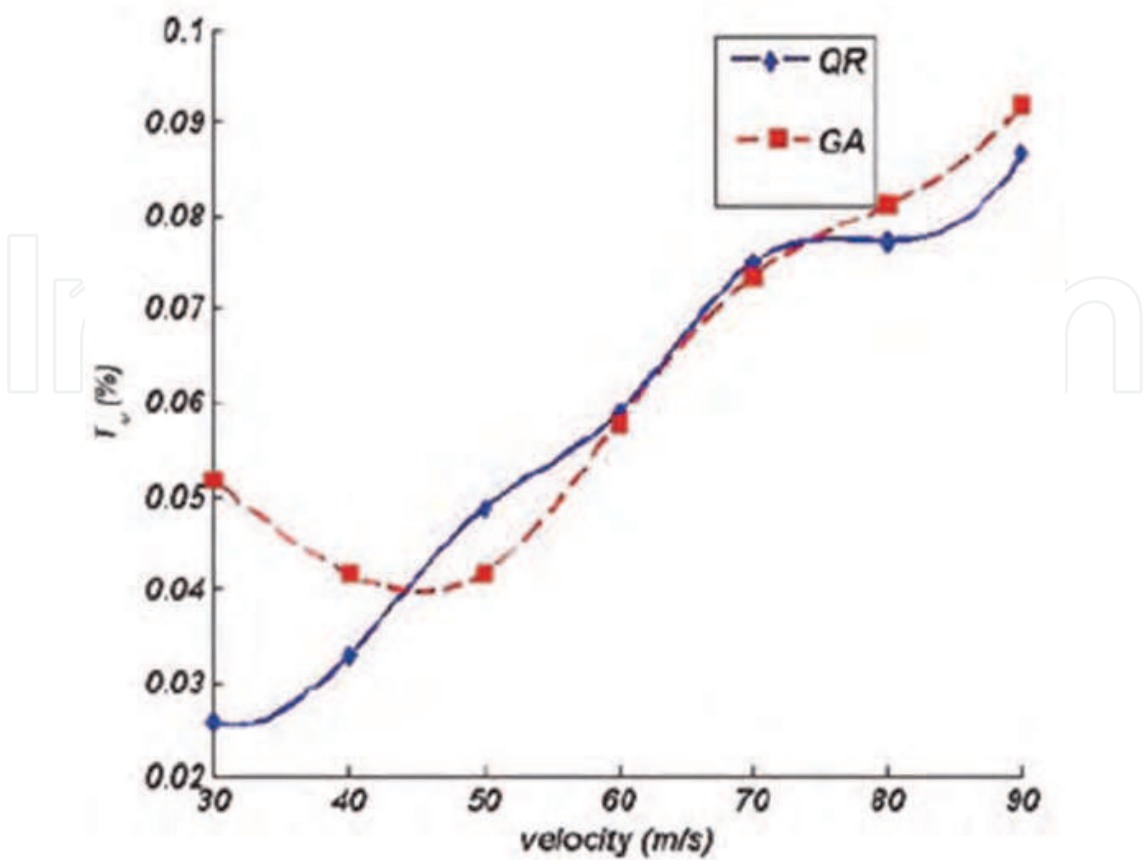
Fig. 4. Variation of T_v obtained from the two calibrations method [10]

One can find the detail of more principal of turbulence measurement by hot-wire in ref [8]. LDA, PIV and Turbulent Sphere are other devices for turbulence measurements. The measurement of turbulent sphere only can describe the feature of turbulence in wind tunnel. Further, LDA and PIV have the frequency response less than hot wire. Hot wire can responded up to 100 KHz.

5. The important parameters for turbulence measurement

All raw values of hot-wires were converted to the corresponding flow velocities using a suitable transfer function e.g., forth order polynomial. In X-probe hot wires, multi-sensor probes are decomposed into velocity components in the probe coordinate system. Then the effective velocities will determined and translate to the wire-coordinate system. As a result, the velocities component in the probe coordinate system, U and V will determine [7]. Subsequently, one may obtain the time averaged velocity, Umean and Vmean, of the flow at a particular point by taking the average of the instantaneous velocity U and V. By taking the difference of the time averaged velocity and the instantaneous velocity, the instantaneous fluctuating velocity u and v is obtained. Furthermore, the root mean square (rms) velocity at a given location has been determined as below:

$$u_{rms} = \sqrt{\sum_{i=1}^{n} \frac{\left(u_i - \bar{u}\right)^2}{\left(n-1\right)}}$$

$$v_{rms} = \sqrt{\sum_{i=1}^{n} \frac{(v_i - \overline{v})^2}{(n-1)}}$$

where n is the sample size.

Finally, the relative turbulence intensity, indicating the fraction of the total energy of the flow which resides in the turbulent regime, can be estimated. The value of relative turbulence intensity (Tu and Tv) and the total turbulence intensity (TI) has been obtained as bellows:

$$T_u = \frac{u_{rms}}{\overline{u}} \times 100$$

$$T_v = \frac{v_{rms}}{\overline{u}} \times 100$$

$$TI = 100 \times \frac{((u_{rms}^2 + v_{rms}^2)/2)^{1/2}}{(U_{mean}^2 + V_{mean}^2)^{1/2}}$$

Two simultaneous velocity time series provide cross-moments basis for Reynolds shear stresses and higher order cross moments i.e., lateral transport quantities. These moments has been defined by:

$$\overline{u'v'} = \frac{1}{N} \sum_{1}^{N} (U_i - \overline{U})(V_i - \overline{V})$$

$$\overline{u^2 v} = \frac{1}{N} \sum_{1}^{N} (U_i - \overline{U})^2 (V_i - \overline{V})$$

$$\overline{v^2 u} = \frac{1}{N} \sum_{1}^{N} (V_i - \overline{V})^2 (U_i - \overline{U})$$

Other parameters that are used for statistical analysis are skewness and flatness. The Skewness is a measure of the lack of statistical symmetry in the flow, while the Kurtosis is a measure of the amplitude distribution (flatness factor). These parameters are defined according to:

$$S_u = 1/N \sum_{1}^{N} \frac{(U(n) - \overline{U})^3}{\sigma_u^3}$$

$$S_v = 1/N \sum_{1}^{N} \frac{(V(n) - \overline{V})^3}{\sigma_v^3}$$

$$Ku = 1/N \sum_{1}^{N} \frac{(U(n) - \overline{U})^4}{\sigma_u^4}$$

$$Kv = 1/N \sum_{1}^{N} \frac{(V(n) - \overline{V})^4}{\sigma_v^4}$$

6. The source of turbulence in wind tunnels

The source of turbulence of wind tunnel may briefly divide in two parts; i.e., turbulence due to eddies (vortex shedding, boundary layer, shear stress, secondary flows) and noise (mechanical, vibration and aerodynamic) that There is a correlation between them. Manshadi et-al in [11] studied the effects of turbulence on the sound generation and velocity fluctuations due to pressure waves in a large subsonic wind tunnel. The results of this research determine that while the share due to the monopole is dominant, the share due to the dipole and quadrupole remains less important. Furthermore, it is found that sound waves have a modest impact on the measured longitudinal turbulence and is essentially generated by eddies [11].

On the assumptions that first these sound waves are of plane type and contribute only to the u component and second that the turbulence and sound are statistically independent, Uberoi [12] has shown that the spatial correlation coefficient at two different points 1 and 2 for large separation of the points is defined by:

$$\rho_{12} = \langle u_1 u_2 \rangle / [\langle u_1^2 \rangle \langle u_2^2 \rangle]^{1/2} \cong \frac{u_p'^2}{u_p'^2 + u_e'^2}$$

where u_p' and u_e' represent the velocity due to the sound and eddy turbulence, respectively, and $\langle \ \rangle$ denote a time mean value. Since the measured u component is made up u_p' and u_e', one may conclude:

$$u'^2 = u_p'^2 + u_e'^2$$

A comparison of above equations reveals that:

$$u_e' = (1 - \rho_{12})^{1/2} u'$$

The above equation states that one may determine the velocities due to the sound and eddy turbulence by calculating the correlation coefficient.

In a wind tunnel, pressure waves may be generated aerodynamically along the tunnel circuit which may be considered as plane sound waves. These pressure waves may enter the test section either from the downstream direction or through the nozzle and thus altering the test condition. Consequently, the lowest velocity fluctuation level in the wind tunnel is determined by the abovementioned pressure fluctuations [11]. i.e.:

$$\tilde{u}_p = \frac{\tilde{p}}{\rho a_0}$$

manshadi et-al in [11] investigated the effect of monopole, dipole, and quadrupole for different turbulence intensity, Fig.5. The turbulence intensity was decreased after trip installation at diffuser and contraction rather than clean condition. The less turbulence

intensity was obtained for trip in the diffuser. Figure 5 show that the shares for the clean condition for monopole, dipole and quadrupole are equal to 56%, 26% and 18% and for X/L=0.115 condition are 64%, 21% and 15% correspondingly. In addition, the shares for the case when the trip is installed in the diffuser are equal to 79%, 13% and 8% respectively. A comparison between the results of the clean condition to those for the diffuser and X/L=0.115 condition indicate that while the shares due to the dipole and quadrupole decreases, the share due to the monopole increases considerably. Recalling that the aerodynamic sources of sound for the dipole and quadrupole are generated in the boundary layer, one may state that trip strip control to some extent the unsteady behavior of the fluctuating gradients. In the next, the effect of trip installation on the turbulence reduction in the subsonic wind tunnel will discussed.
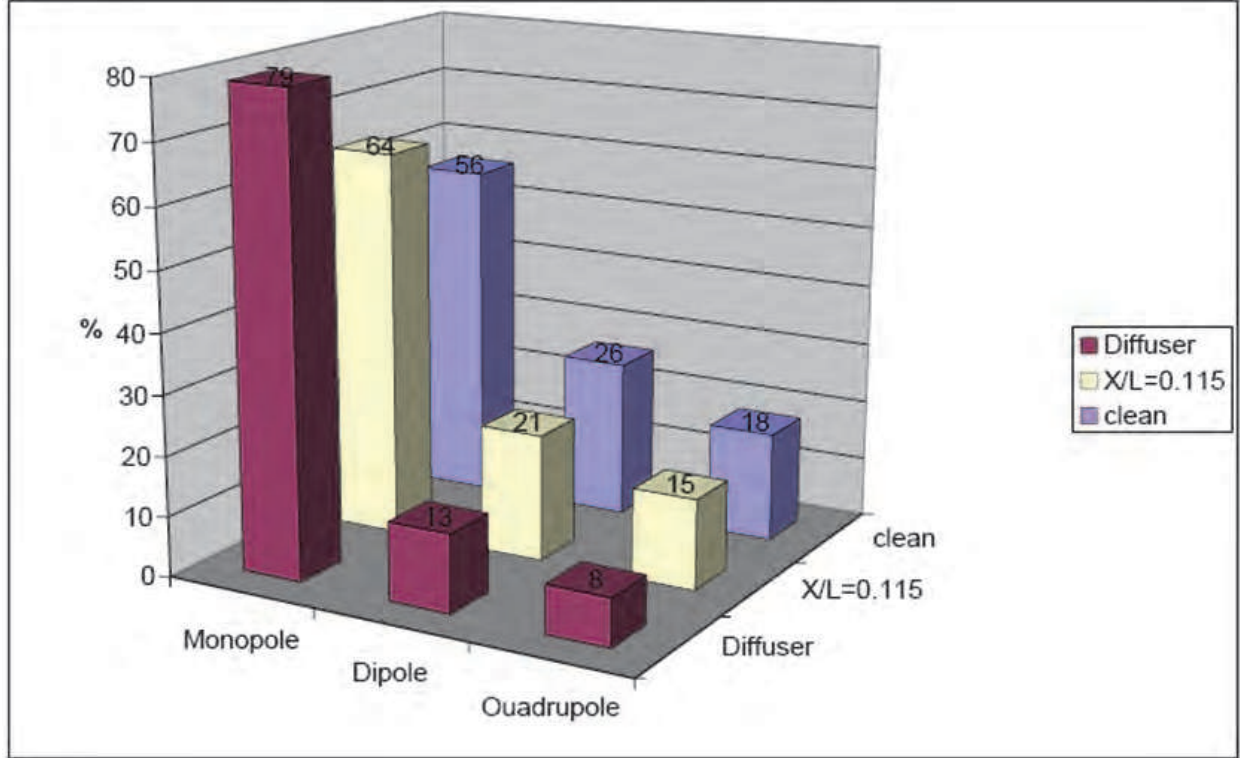

Fig. 5. Distinguished parts of each aerodynamic sound source for different conditions [11].

As abovementioned, there is a correlation between turbulence and sound. The spatial correlation for velocities equal to 60 and 70 m/s was measured at X/L=0.79 for clean and trip conditions at a subsonic wind tunnel. The results are summarized in table 1. It is evident that while the value of the correlation coefficient for the clean condition at velocities 60 and 70 m/s is 0.22 and 0.24, respectively, it is decreased to 0.16 and 0.168 for the trip condition.

Further, the table provides a comparison of u'_p as well as u'_e/u' values using sound level meter and spatial correlation measurement. It is evident that for the clean condition at the velocities of 60 and 70 m/s, sound waves have a modest impact on the measured longitudinal turbulence and over 80% of the turbulence is generated by the eddies. Furthermore, for strips at X/L=0.79 and at aforementioned velocities, the share on the

measured longitudinal turbulence due to eddies is amplified. Consequently, one may conclude that trip strip reduces the turbulence in the test section [11].

Condition	Velocity (m/s)	Correlation coefficient	$u_p^{'}$ (SLM)	$u_p^{'}$ (Correlation)	Error (%) ($u_p^{'}$)	$u_e^{'}/u^{'}$ (SLM)	$u_e^{'}/u^{'}$ (Correlation)
Clean	60	0.22	0.057	0.066	12.3	0.81	0.9
	70	0.24	0.072	0.081	12.25	0.89	0.95
X/L=0.79	60	0.16	0.035	0.030	15.7	0.88	0.98
	70	0.168	0.058	0.042	27.4	0.83	0.97

Table 1. Results for spatial correlation approach [11].

7. The methods of turbulence reduction

Aforementioned before, turbulence can have dramatic effects on the flow measurement in the wind tunnels, therefore, designers and researchers try to reduce it. Various methods such as employment of honeycombs [13,14], anti turbulence screens [15-17], and appropriate contraction ratio [18] are possible means to reduce the turbulence level in wind tunnels. In an attempt to improve the test section flow quality, sudden expansion downstream of the corner turning vanes was incorporated into the wind tunnel [19]. Further, Significant flow quality improvements were also achieved by vertical flow treatment in the diffuser and downstream of the fan. Wigeland et al used a 45 degree honeycomb flow manipulator, mounted parallel to the corner turning vanes, to improve the flow quality in the wind tunnel with little or no settling chamber length [20]. Flow quality in wind tunnels is improved through subsequent installation of acoustic baffles and dense honeycomb [19]. If one decides to remove the unwanted turbulence, he must smooth the walls, ignore sudden changes in geometry and manage the vortex stretching and separation in the entire loop of wind tunnel.

8. Turbulence reduction by using anti-turbulence screens and honeycomb

Significant devices for turbulence reduction in wind tunnels are screens. Screens are employed to even the velocity variation of flow out of the settling section. They can remove fine vortex structures and honeycombs can remove large vortex structures. They also break large vortices into smaller eddies that decay rapidly at short distances. The author in his PhD thesis shows that by utility of screens could reduce the turbulence to acceptable value [21]. Figure 6 shows variations of the turbulence intensity for one and four screens. This result exhibits that by the addition of three anti-turbulence screens located in a suitable place in the settling chamber, the tunnel turbulence was reduced for all operating speeds. Of course, the behavior of the two curves is similar and both of them exhibit humps around tunnel speeds of 20, 50 and 80 m/s. The error bar for uncertainty analysis is added for minimum and maximum velocities in Figure 6. The details of screens and their ability for turbulence reduction are reported in [15-17, 21].

Honeycomb and screens for a wind tunnel is very much dependent on the test type to which the tunnel is intended. Honeycomb may be considered as an effective mean for reducing swirl, turbulent length scales, and mean flow gradients. Further, it reduces the lateral turbulence components which are inhibited by the cells. Nevertheless, honeycombs also shed turbulence, the strength of which is proportional to the shear layer thickness in the cells. Therefore, honeycomb is supposed to break the large eddies into small ones, thus a deep honeycomb performs better than a shallow one but the pressure loss across it is larger [7]. Furthermore, the choice of appropriate screens is also difficult. Theoretically, the screens which are used for turbulence reduction should have porosity greater than 0.57 [14, 22]. Screens with smaller porosity suffer from a flow instability that appears in the test section. Whether screens or honeycombs, the obtained reduction in the free stream turbulence level is accompanied with a power loss due to manipulator pressure drop and hence reducing the maximum attainable velocity in the test section of the wind tunnel [7].
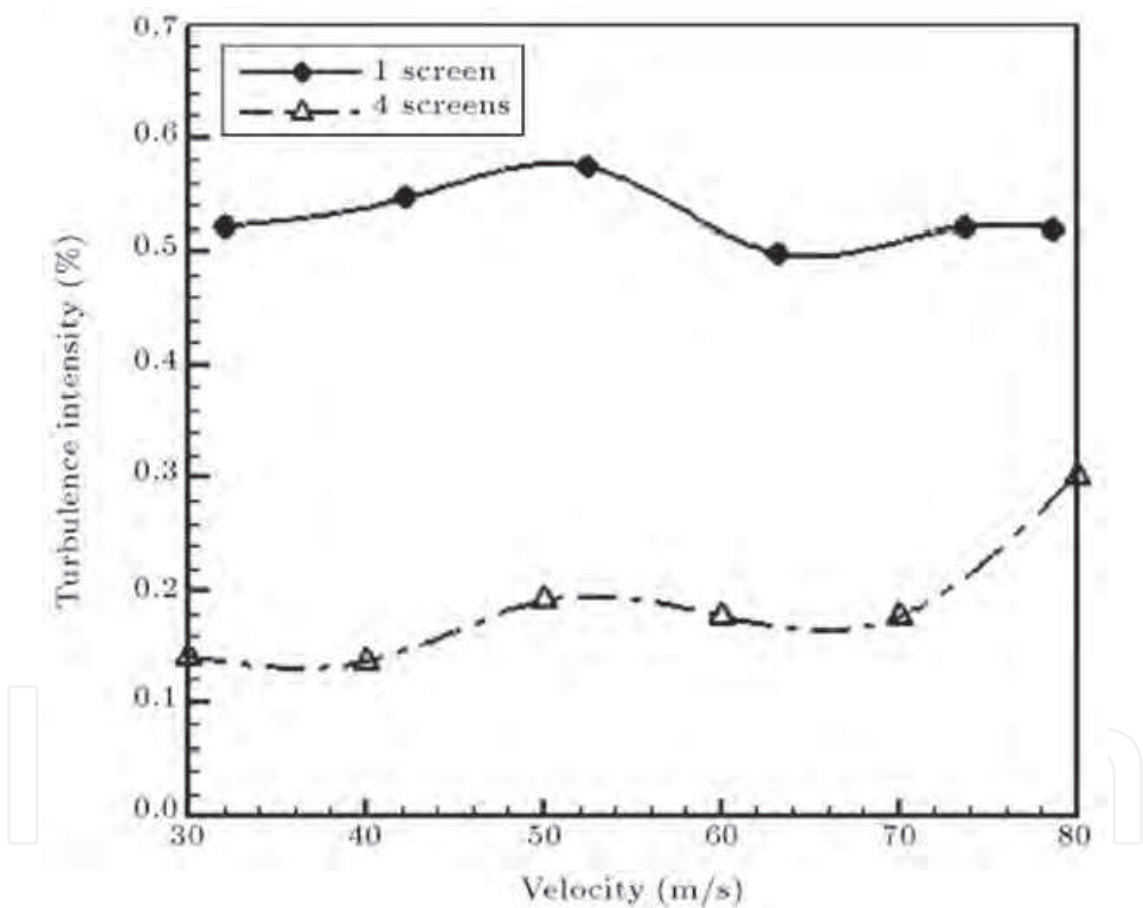

Fig. 6. Variations of turbulence intensity Vs. velocity with one screen and four screens [21]

The normal probability of outputs of hot wire at two different case, 1 and 4 screens, are shown in Fig.s 7,8. The normal probability plots indicate that for cases with screens the hot wire data may be modeled by normal distribution. However, in cases where high turbulence intensity is present, 1 screen, the data moves away from normal distribution. Consequently, in cases where the turbulence intensity has been brought back towards low levels through any means, i.e. Figure 8, one may model the data again by normal distribution [21].
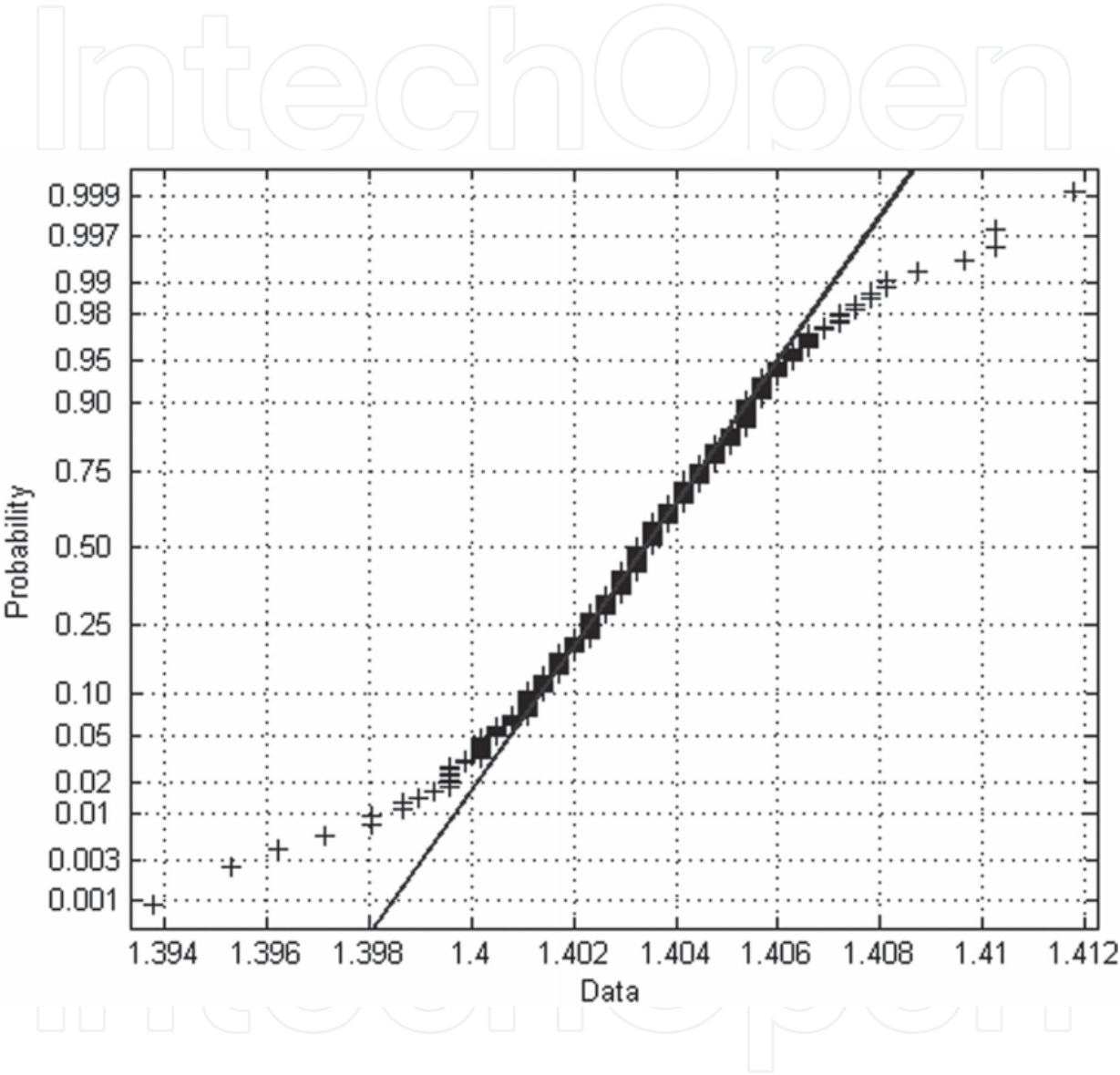
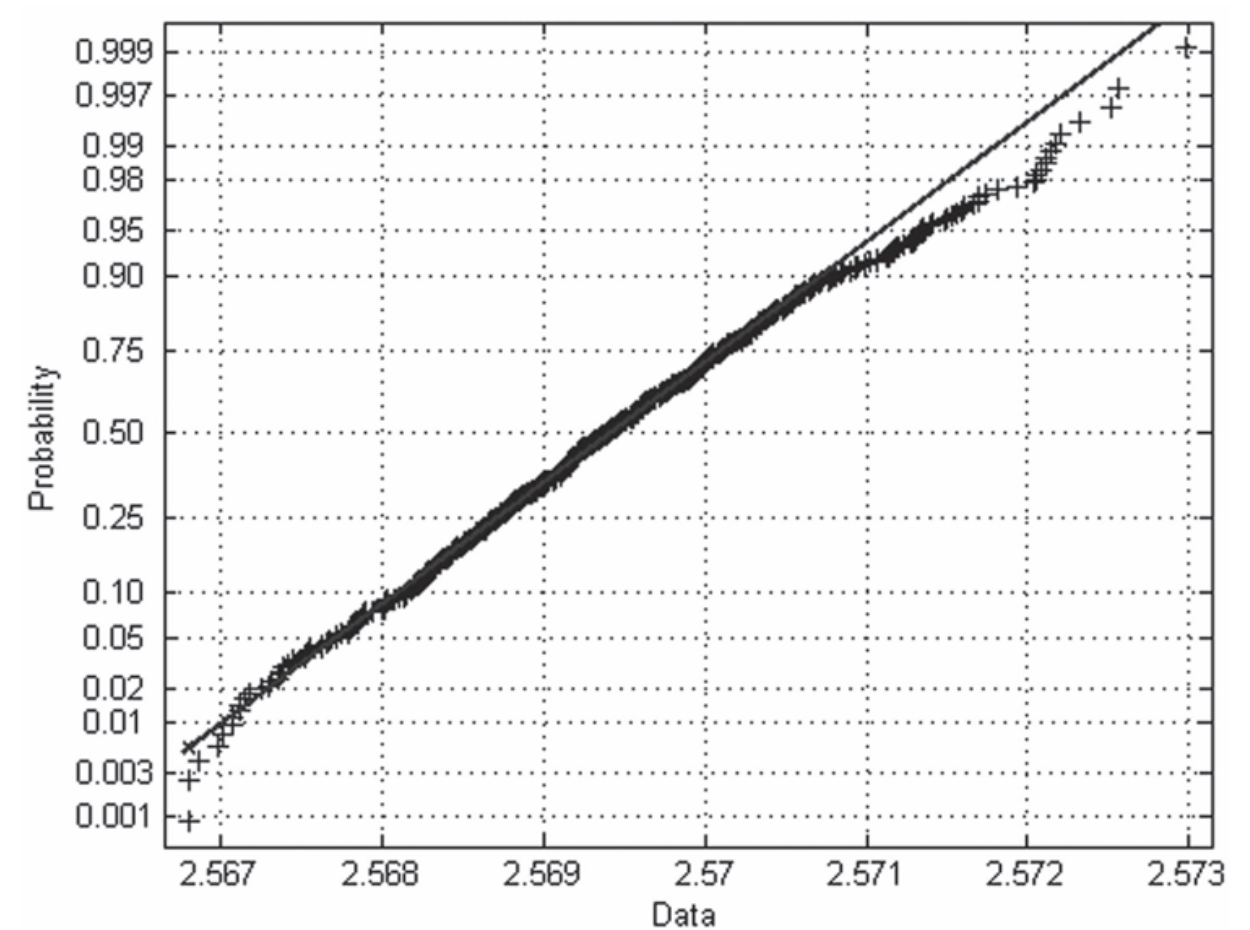Fig. 7. Normal probability plot for one screen, V1 = 80 m/s [21].

Fig. 8. Normal probability plot for four screens, V1 = 80 m/s [21].

9. Turbulence reduction by using trip strip in contraction

The contraction of the wind tunnel accelerates and aligns the flow into the test section. The size and shape of the contraction dictates the final turbulence intensity levels in the test section and hence the flow quality. Further, the length of the contraction should be kept as long as possible to minimize the boundary layer growth and reduce the effect of Gortler vortices. The flow leaving the contraction should be uniform and steady. For a finite-length inlet contraction, there exist a maximum and a minimum value for the wall static pressure distribution along the wall close to the entrance and exit, respectively. Thus, one may consider these two regions as regions of adverse pressure gradients with possible flow separation. If separation occurs, then the flow uniformity and steadiness will be degraded which may lead to an increase in turbulence intensity in the test section. In summary, contractions in the wind tunnels may produce several different unsteady secondary flows which are undesirable and can have dramatic effects on the behavior of the downstream boundary layers and turbulence intensity in test section [7, 23].

The boundary layer flow over a surface with a region of concave curvature is susceptible to centrifugal instabilities in the form of Gortler vortices [23]. Researches [24] showed that the laminar boundary layer was distorted by an array of large-scale longitudinal vortices spawned by the Gortler instability in the inlet of the contraction that can cause adverse pressure gradient. The onset of Gortler vortices can be predicted using a dimensionless

number called Gortler number. It is the ratio of centrifugal effects to the viscous effects in the boundary layer and is defined as $GO = \dfrac{U\theta}{\nu}(\dfrac{\theta}{R})^{0.5}$ that θ refers to the momentum thickness. Gortler instability occurs when the Gortler Number exceeds, about 0.3 [3].

Figure 9 shows the measured static pressure distributions in the contraction region of the tunnel at various test section velocities [23]. This plot indicates that the distributions are nearly smooth and the pressure gradient is almost favorable along the contraction wall except for the inlet and exit regions. Further, for a few velocities there exits a sharp pressure drop, reduction in Cp at distance of X = 70 to 90cm as seen from Fig. 10. It seems that this pressure drop at low velocities, V∞ = 20 and 30m/s, is due to the special behaviors of the flow. However, as the free stream velocity increases, this adverse pressure gradient weakens and eventually for velocities higher than 40ms–1 the adverse pressure in the inlet of the contraction diminishes. When flow arrives in the test section, which can be considered as a flat surface, the velocity profile becomes uniform and the streamline velocity near the wall decreases. Consequently, adverse pressure gradient increases. Pressure distribution and the locations of the adverse pressure gradient for the clean conditions show that at higher velocities probability of separation at the inlet of contraction decreases [23].

In figure 10, the above results are obtained for trip condition. The trip is glued at a location of x/L = 0.115, 30cm from the inlet of contraction. The results confirm significant impact of the tripped boundary layer on the control of the adverse pressure gradient. The trip strip installed at x/L = 0.115 had favorable effects on the pressure distribution and reduced the turbulence intensity in the test section for all range of velocity examined in this investigation. In other word, trip strip if installed at a suitable location, may move the adverse pressure gradient to the inlet of the contraction.

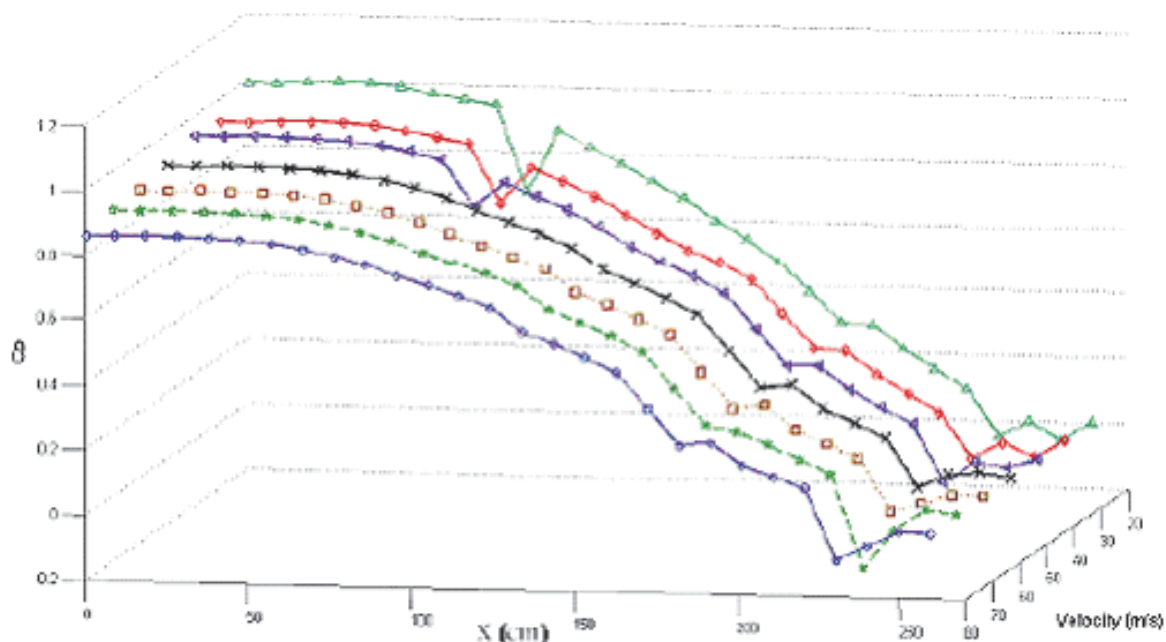This will allow the flow to become uniform in the test section as is passes along the wall [23].

Fig. 9. Cp distribution along the contraction for the clean case [23]
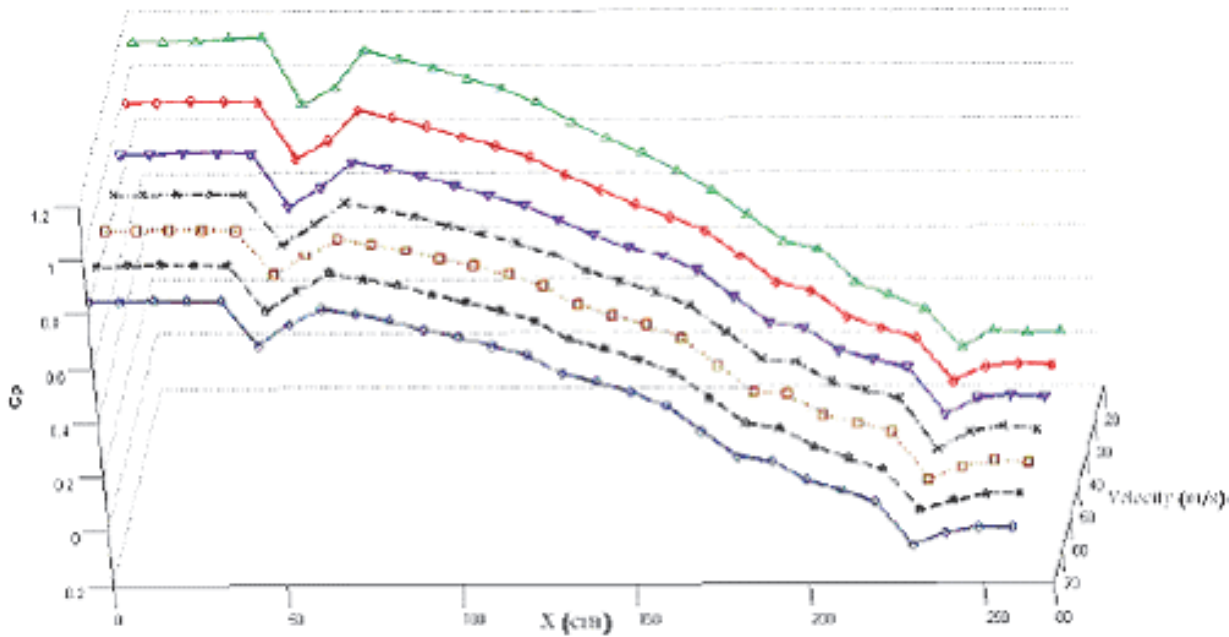
Fig. 10. Cp distribution along the contraction for the Trip case, **X/L-0.115** [23]

The studies of Takagi et al [25] showed that a row of Gortler vortices develops and eventually breaks down to turbulence in the concave region of the contraction. The resultant turbulent boundary layer was laminarized in the convex region due to acceleration of the mean flow. The details of the laminarization and subsequent re-transition of the boundary layer along the contraction and flow physics in such a process has been studied by [3]. After re-transition process in the outlet of the contraction, the boundary layer encounters an adverse pressure gradient. This unfavorable pressure gradient at the exit of the contraction may be due to the inflection-type instability, changed from a curved to flat surface along the wall [25].

Author in his PhD thesis made a series of experimental investigations on turbulence intensity reduction in the test section of four different wind tunnels [3]. While the addition of suitable trip strips on different positions of the contraction section of the tunnel is examined, the tripping of the boundary layer at its early development stage in the contraction region is also exploited. Thin wire strips were placed on the contraction walls and the turbulence intensity in the test section was measured by using hot wire.

Figure 2 summarizes the results related to the author's investigations. It is evident that for X/L=0.79 and 0.115, which are placed in convex and concave portion of the contraction, respectively, the TI has relatively the highest reduction [3, 7]. Here, L is the length of the contraction and X is from the beginning of the contraction.

The results by author in [3, 7] indicate that the installation of the trip strips has significant effects on the TI in the test section of all four wind tunnels. The magnitude of reductions in the free stream turbulence is affected by the positions of the trip strips. For one of wind tunnels, the minimum TI is obtained when a trip strip with a diameter of 0.91mm is installed at X/L=0.79 or in the wide portion of the contraction, at X/L=0.115, Fig. 2. Further, it is shown that the installation of the trip strip in a suitable location not only reduces but also smoothes the turbulence level. However, the zones between concave and convex region of the contraction, that is at X/L=0.192 and 0.615, are not proper locations for trip strips. In general, one may conclude that the TI in the test section of wind tunnels may be reduced to some degrees by simply introducing trip strip with the right dimensions at the proper positions [3, 7].
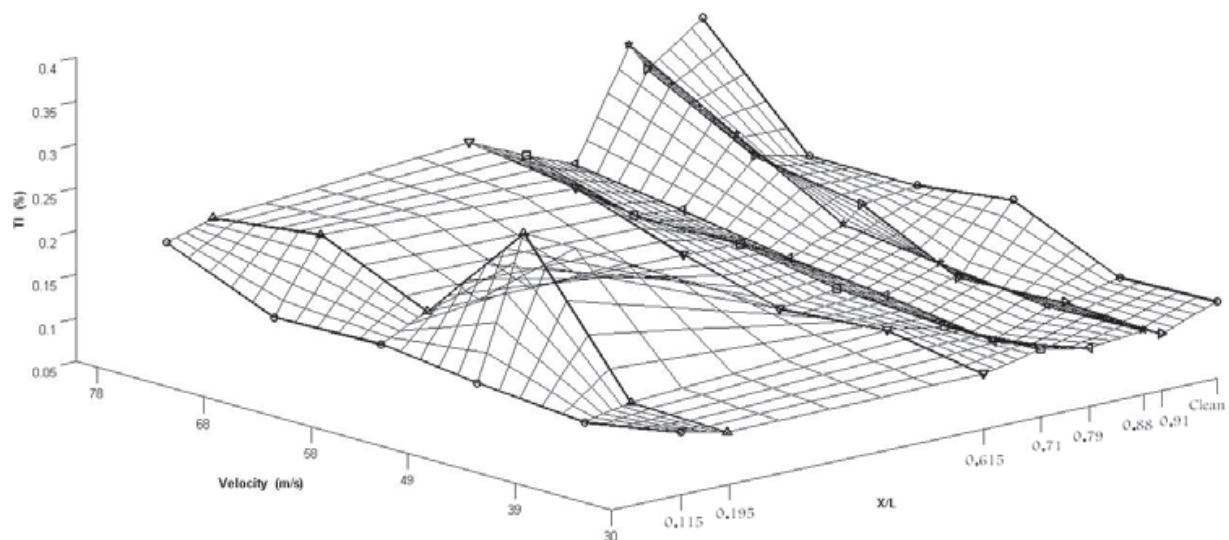
Fig. 11. Variation of TI with velocity at diameter of trip equal to 0.91mm for all various X/L at center point, WT1 [7]

10. Conclusion

In this chapter, the role of turbulence in obtaining a spatially uniform steady stream of air across and along the test section of wind tunnels considered. The study shows that the turbulence has a major character in flow quality of wind tunnel and can excite uncorrected results in experimental investigations of wind tunnels. Noise and eddy are the sources of turbulence that must try to reduce them. Screens, honeycomb, high contraction ratio and installation of trip strip at suitable portion of the contraction for handling of gortler vortices and inflection type instabilities are useful for turbulence reduction. Hot wire anemometry is a useful device for turbulence measurement that can operate at frequency up to 100 kHz.

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Edited by Prof. Jorge Colman Lerner

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