Transaction B: Mechanical Engineering
Vol. 17, No. 1, pp. 1–12

SCIENTIA IRANICA

Application of Screens and Trips in Enhancement of Flow Characteristics in Subsonic Wind Tunnels

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Abstract. *Subsonic wind tunnel experiments were conducted to study the turbulence level in the test section. Measurements were performed by introducing trip strip and/or damping screens on the flow field. The results indicated that the introduction of trip strips not only reduced the turbulence intensity compared to cases without it, but also flattened the variations. Further, the experiments which investigated the impact of the damping screens indicated a similar reduction in turbulence intensity; the pattern, however, remained the same. Furthermore, the results for cases wherein both trip strips as well as damping screens were placed on the contraction and in the settling chamber, respectively, showed that turbulence intensity was even more reduced than in previous cases. It is believed that the combination of several damping screens with the trip strip could be a sound method for turbulence reduction in subsonic wind tunnels.*

Keywords: *Wind tunnel; Turbulence reduction; Trip strip; Screen.*

INTRODUCTION

The subject of turbulence is of great importance in science and technology. Turbulent flows are highly complex and can be regarded as a highly disordered motion resulting from the growth of instabilities in an initially laminar flow [1]. 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].

The study of turbulence requires a firm grasp of applied mathematics and considerable physical insight into the dynamics of fluids; even in this case, there are relatively few situations in which we can make definite predictions.

An area of high importance is the turbulence level in the wind tunnels that describes the flow quality in the test section. 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 [3]. Dryden and Kuethe concluded that turbulence is a variable of some importance at all times and a careful experimenter will desire to measure and state its value so that the measured detail will be of adequate precision and can be interpreted to the free stream ones [4]. Turbulence, however, cannot be entirely avoided. Control in the turbulence of the wind tunnel is especially important in studies of laminar to turbulent transition in the boundary layers and other flows. It is widely accepted that in a wind tunnel with a high turbulence level, premature transition from laminar to turbulent flow over the model surface may occur. This phenomenon is very critical when testing laminar flow models. The differences in the experimental values obtained in different wind tunnels having similar conditions and the same Reynolds number are due to the turbulence levels in those tunnels [5-18]. Hence, the designers of wind tunnels strive to reduce the intensity of the turbulence in the test section as much as possible.

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Received 29 December 2008; received in revised form 29 July 2009; accepted 15 November 2009

Various methods, such as suitable contraction ratios and screens, are possible means to reduce the turbulence level in wind tunnels [1,5]. Screens are employed to even the velocity variation of flow out of the settling section. They also break large vortices into smaller eddies that decay rapidly at short distances. However, the most important feature for minimizing the turbulence level is the contraction ratio. A large contraction ratio makes the eventual flow smoother. The contraction itself further reduces the turbulence in terms of percentage of wind speed. This is due to the increase of the wind speed by a factor equal to the contraction ratio. However, turbulent eddies are simply carried along without any increase in their local velocities. Low turbulence tunnels usually have a wide angle diffuser just ahead of their settling chamber. The large settling chamber has honeycombs and employs several screens to damp out turbulence. In addition, a large settling chamber size allows for a larger contraction ratio to further reduce turbulence. Although the above methods are utilized for turbulence reduction in almost all wind tunnels and their outcome is excellent, the desire to have even lower turbulence levels in the wind tunnel test section has been the main drive behind researchers continuing their investigations in this field for many years.

In the present research, the authors investigated the employment of a new but simple and cost-effective method for turbulence reduction in low speed wind tunnels. In the proposed method, the tripping of the boundary layer at its early development stage in the contraction region is exploited. It is well known that contractions in wind tunnels may produce several different unsteady secondary flows that are undesirable and can have dramatic effects on the behavior of the downstream boundary layers [19,20]. Hence, in order to improve this matter, the addition of suitable trip strips on the outlet of the contraction section of the tunnel is also examined. Extensive subsonic wind tunnel tests were conducted to measure the turbulence level for various cases.

EQUIPMENT

Experiments were conducted in the subsonic wind tunnel in Iran. A schematic of the tunnel and the overall test set-up is shown in Figure 1.

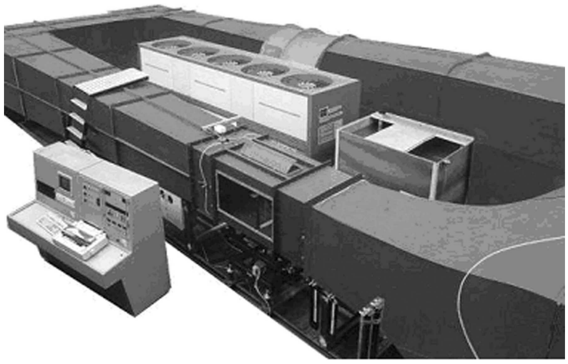

Figure 1. Schematic of the wind tunnel.

The tunnel is of a closed return type and has a dimension of $3.8 \times 6.5 \times 18$ m^3. The temperature in the test section is adjustable between 25°C to 40°C, and the Reynolds number can be varied between 5.29×10^5 and 5.26×10^6 per meter. The fan rotational speed is adjustable via a PC at an interval of 10 rpm up to 985 rpm where the wind speed in the working section reaches 100 m/s. The tunnel has a closed square test section of $80 \times 80 \times 200$ cm^3. Information about calibration of this wind tunnel is presented in [21-23].

Hot wire anemometry due to its high frequency response of up to 100 KHz [24] is used for turbulence measurement. In this study, single and X hot wire probes were used to measure turbulence intensity and RMS distribution in the tunnel working section at various wind speeds. Data were recorded via a 16 bit A/D board, capable of sample rates up to 100 KHz.

The methodology provided in [24,25] is used to quantify the experimental uncertainties. Every CTA has a temperature corrective probe that is placed in flow and applies the effect of temperature variation during turbulence measurement. The independent parameters, such as atmospheric pressure, curve fitting error in calibration, the A/D resolution uncertainty, probe positioning and humidity, are considered for uncertainty analysis. Previous uncertainty studies by the authors reveal that maximum error occurs at low velocities. The uncertainty in turbulence intensity was determined to be approximately 3%, which decreases at higher velocities. A confidence level equal to 98 percent and a related number of samples are used. The number of samples depends on the required uncertainty and confidence level of the results. The details of the uncertainty analysis and related equations are reported in [26,27].

Trip strips (guitar wires) with a diameter of 0.91 mm are glued at 54 cm before the test section (Figure 2). Proper glue with very thin thickness is used to prevent additional diameter to the wire and impeding any undesirable phenomenon in this research.

EXPERIMENTAL PROCEDURE

The effect of trip strips is investigated by measuring the turbulence intensity for the following cases:

Case 1: One screen (without the trip strip),

Case 2: One screen (with the trip strip),

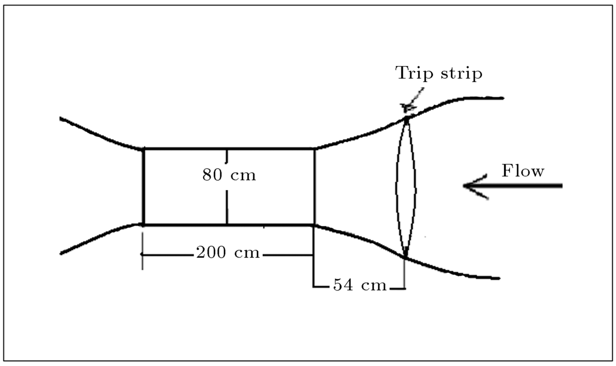

Figure 2. Location of the trip strip.

Case 3: Four screens (without the trip strip),

Case 4: Four screens (with the trip strip).

The position of the trip strip installed in the contraction portion of the tunnel (Cases 2 and 4) is shown in Figure 2. Experiments were conducted at tunnel speeds of 20-100 m/s. The data for all ranges of speed were acquired with the hot wire located in the centerline of the tunnel for both cases with and without the trip strip. The data presented in this paper for each point is an average of several tunnel runs where for each run at least 1000 samples were collected and the ensemble averaged.

RESULTS AND DISCUSSIONS

As indicated, the main purpose of the present work is to explore the possibility of a new method for turbulence reduction in a subsonic wind tunnel. The results for all cases are presented in the following sections.

Data Reduction Process

Figure 3 shows variations of the measured raw voltage from the hot wire output, filtered as well as unfiltered as a function of time. Various cutoff and transition frequencies were used to eliminate the corresponding noise of the raw data. Further, Figures 4 and 5 show the Probability Density Function (PDF) and the probability distribution function for the filtered and unfiltered data under the same test conditions. The physical meaning of PDF depends on whether the distribution is discrete or continuous. For discrete distributions, the PDF is the probability of observing a particular outcome. For the filtered data, the edges of the PDF are smaller than those of the unfiltered one. The absence of tails at the edges of the PDF is the signature of the rectification phenomena [28].

The effect of cutoff frequencies on the turbulence intensity is also shown in Figure 6. It is obvious that turbulence intensity increases with the growth of cutoff

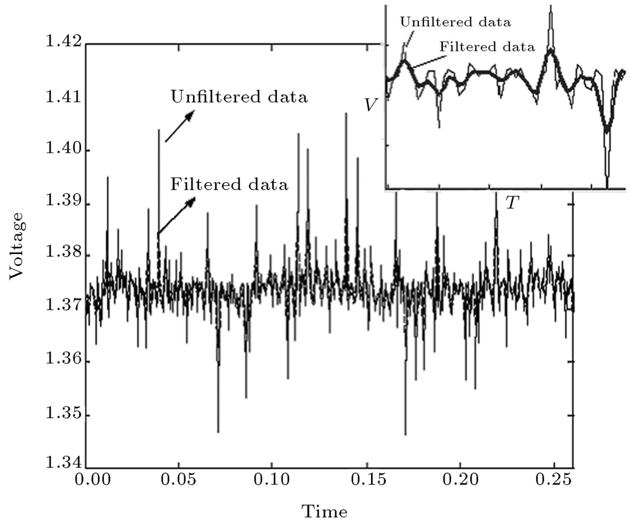

Figure 3. Variations of the unfiltered and filtered data with time.

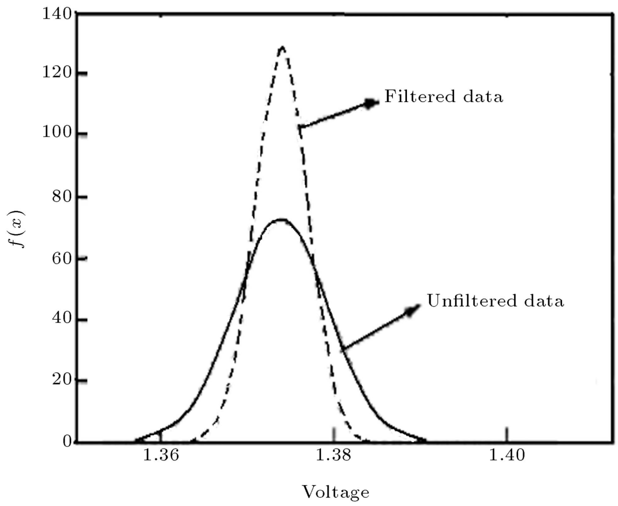

Figure 4. Probability density function for the filtered and unfiltered data.

frequency until a cutoff frequency of 1000 HZ, and remains constant beyond the frequency of 1000 Hz. Suitable cutoff and transition frequencies are used to eliminate existing noise from the raw data.

Results of Cases 1 and 2

The longitudinal component of turbulence intensity, u'/u_0, and RMS on the center line of the test section are shown against the velocity in Figures 7 and 8 for the case where one screen was installed in the settling chamber, i.e. original tunnel. The measurements were conducted at a position of 65 centimeter downstream from the outlet of the contraction and continued to the end of the test section at intervals of 10 cm apart (Figure 2).

The continuous curves shown in Figures 7 and 8

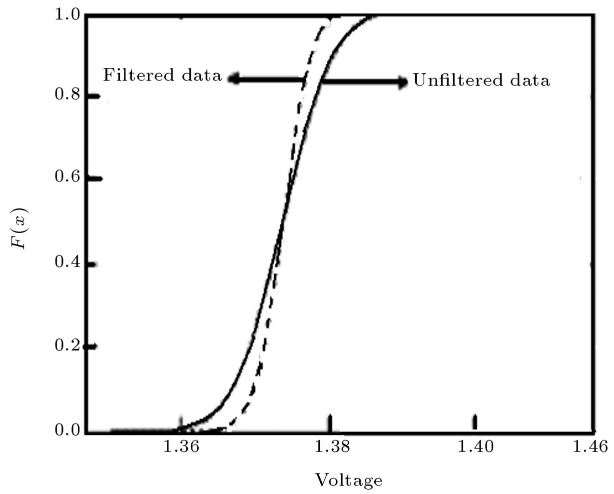

Figure 5. Probability distribution function for the filtered and unfiltered data.

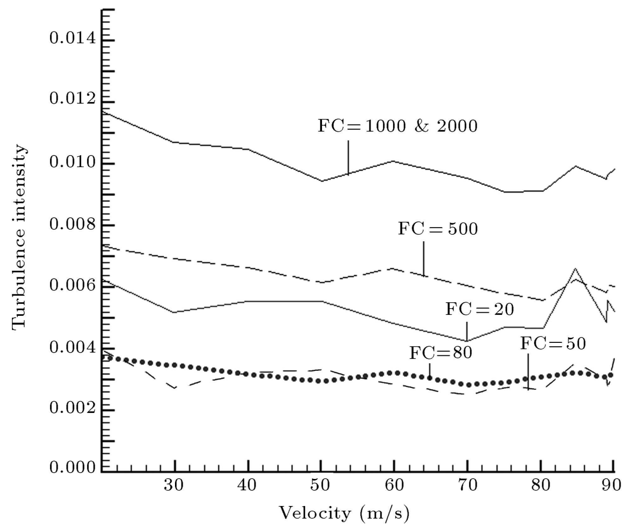

Figure 6. The effect of cutoff frequency on the turbulence intensity.

represent the results obtained without a trip strip in the contraction, while the dashed curves represent the results with the trip strip installed at a location shown in Figure 2.

In Figure 7, the continuous curve exhibits large humps around tunnel speeds of 20, 50 and 80 m/s, which may possibly be due to fluctuations of the wall boundary layer transition point near the working section. In order to remove this peculiar behavior, a trip strip was installed on the wall near the outlet of the contraction (Figure 2). Hot wire data were obtained under the same conditions as in the case without the trip strip. It can be seen by inspection that the trip strip reduces tunnel turbulence at almost all tunnel velocities. Further, the magnitude and position of the previously seen humps in Figure 7 were reduced and shifted, respectively.

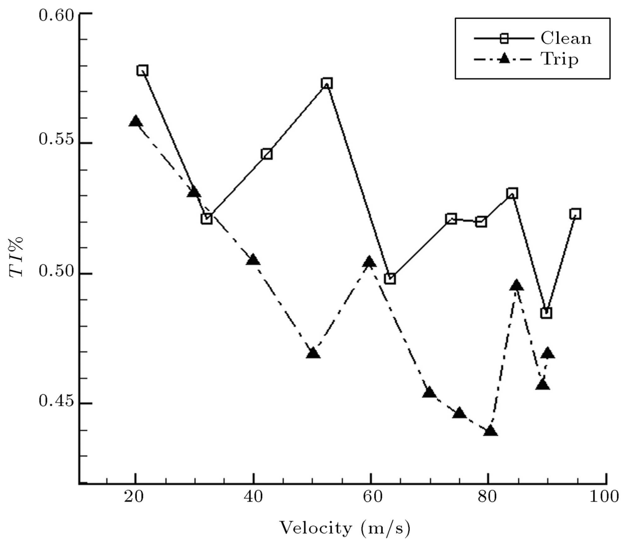

Figure 7. Variations of the turbulence intensity with speed at $X = 65$ cm for one screen.

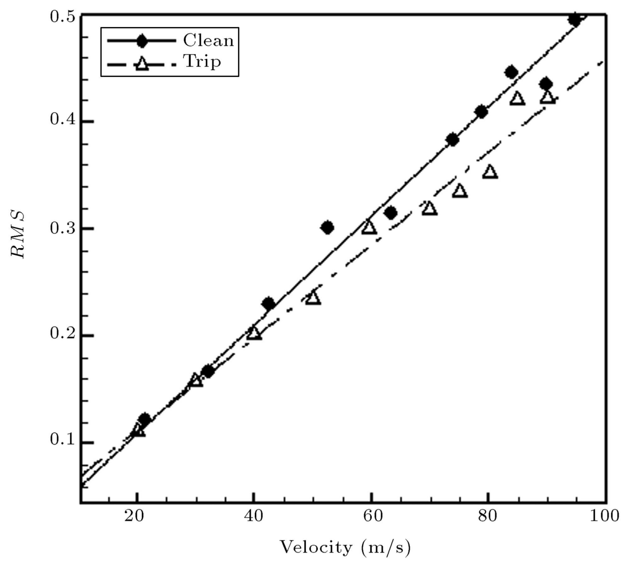

Figure 8. RMS distribution in the test section at $X = 65$ for one screen.

Turbulence level is commonly defined as the RMS of the longitudinal component of the mean value of air speed. Figure 8 shows variations of the RMS with tunnel velocity for Cases 1 and 2. It is noticeable that for all test conditions, the trip strip (Case 2) lowers the RMS, i.e. lowering the turbulence level.

Figure 9 shows variations of turbulence intensity at distances of $X = 65$ cm to $X = 115$ cm for different tunnel speeds. It should be noted that the turbulence levels shown in this figure are measured at the centerline of the test section only. This figure shows turbulence intensity for the mean velocities of 20, 40, 50, 60, 75 and 80 m/s, respectively. The dashed curves show the results associated with the

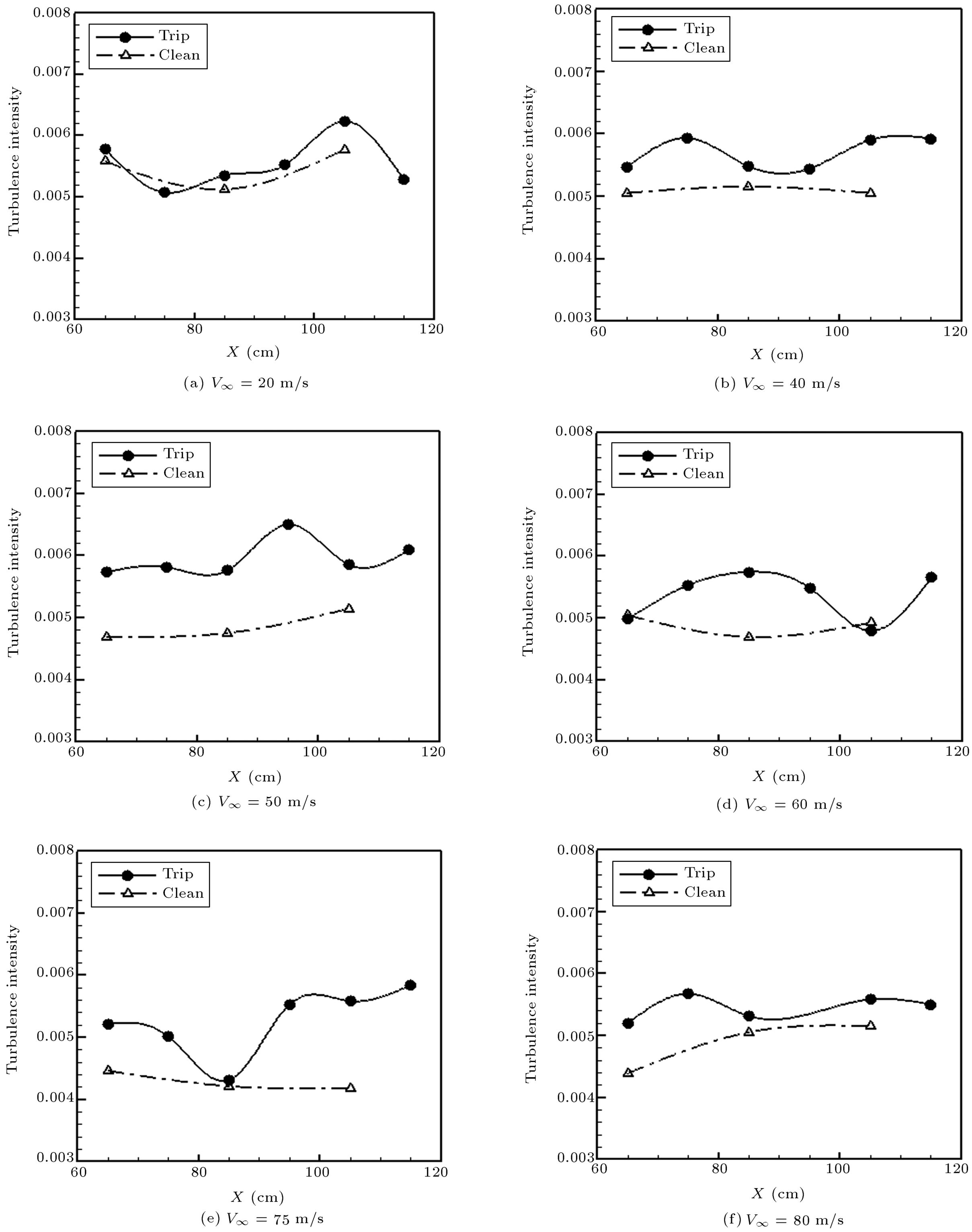

Figure 9. Turbulence intensity distribution in the test section at various velocities.

trip strip effect. From this figure, it is clearly seen that the trip strip not only decreases the longitudinal component of turbulence in the entire working section for all velocities tested in the present study but also uniforms it. Moreover, the trip strip removes the humps as observed previously in the turbulence intensity curves.

Further, Figure 9 shows that the effect of the trip strip is even more pronounced when the tunnel is operating at $V_\infty = 50 - 80$ m/sec. Additional tests for $V_\infty = 90$ m/sec (not presented in the present paper) reveals the same trend. However, at lower free stream velocities, i.e. $V_\infty =$ 20 m/s, the trip strip is not very effective (Figure 9a).

Results of Cases 3 and 4

In Cases 3 and 4, three additional screens were added to the wind tunnel and all of the aforementioned experiments were repeated. Figure 10 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 10.

The turbulence intensity is seen to have been reduced by approximately 50 percent from 0.52 percent with one damping screen to about 0.25 percent with four screens. It is apparent that the use of damping screens is very effective in obtaining low turbulence level in the test section. The utility of the screen in reducing turbulence results from the rapid decay of the fine grain turbulence. These effects are shown in detail in [29,30]. For the same isotropic upstream turbulence, screens reduce the axial turbulence component more than the lateral one [30].

The longitudinal component of the turbulent intensity, u'/u_0, and the RMS on the center line of the test section are shown against the velocity in Figures 11 and 12 for the case where four screens were installed in the settling chamber. Similar to the previous Cases 1 and 2, the measurements were made 65 centimeters downstream from the outlet of the contraction. As seen from Figures 11 and 12, the continuous curve exhibits large humps around tunnel speeds of 30, 50, 80 and 90 m/s. However, when the trip strip was installed in the contraction region, this peculiar behavior was removed and the tunnel turbulence was reduced.

Figure 12 shows variations of the RMS with tunnel velocity for four screens. Again, this figure clearly shows that for all tunnel speeds examined in this study, the case with the trip strip resulted in

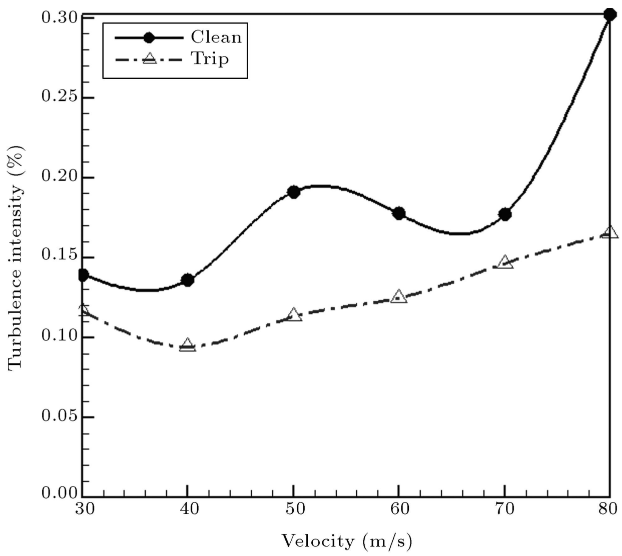

Figure 11. Variation of the turbulence intensity with speed at $X = 65$ cm for four screens.

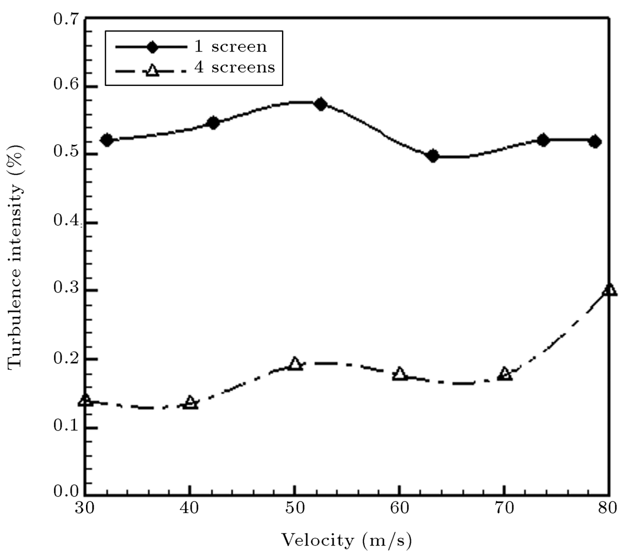

Figure 10. Variations of the turbulence intensity with speed at $X = 65$ cm for one screen and four screens.

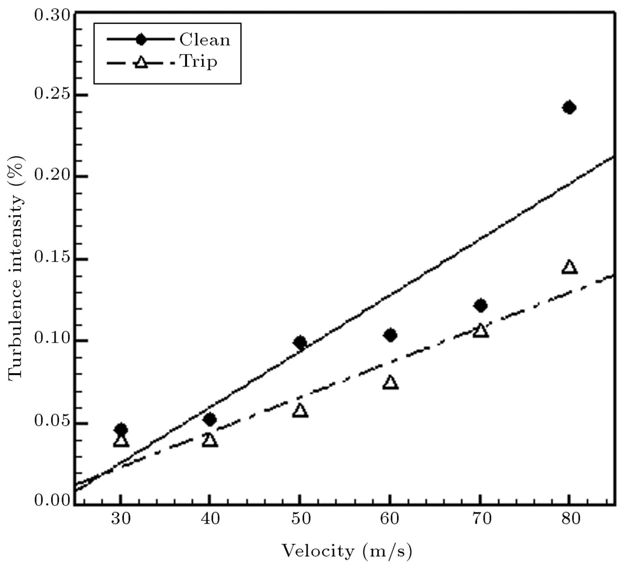

Figure 12. RMS distribution in the test section at $X = 65$ for four screens.

lower RMS, i.e. a lower turbulence level even with the addition of three screens.

Statistical Analyses

A fundamental task in many statistical analyses is to examine the location and validity of a data set. The deviation from the Gaussian distribution function can be characterized by skewness and flatness. It is due to the existence of coherency that the number of degrees of freedom in space and time are reduced locally. Skewness is a measure of symmetry, or more precisely, a lack of symmetry. Flatness is a parameter that shows whether the data are peaked or flat in comparison to normal distribution [31]. Figures 13 and 14 show variations of skewness and flatness with velocity for cases with and without the trip strip. The skewness for a normal distribution is zero, and any symmetric data should have skewness near zero. The continuous curve in Figure 13 shows that the absolute value of skewness for most velocities is less than 0.5, although at $V_\infty = 45$, 60 and 90 m/s higher values are obtained. This means that our acquired data excluding these three velocities have almost normal distribution. By installing the trip strip, the absolute values of skewness for all velocities decrease and the data are closer to normal distribution (Figure 13). The amount of skewness in this state is, however, slightly negative. The PDF is found to be positively skewed, meaning that large positive fluctuations are much greater than the expected values from a pure random distribution (Gaussian distribution) [32].

Figure 14 shows the amount of flatness or kurtosis for signals at the whole of the velocities. The flatness measures the tail's weight with respect to the core of the distribution. In the Gaussian distribution function, the flatness is 3. Positive kurtosis indicates a "peaked" distribution and negative kurtosis indicates a "flat" distribution. Figure 15 shows that these data have a peaked distribution and, with installation of the trip strip, the data are closer to Gaussian distribution.

The above results indicate that the trip strip not only decreases the longitudinal component of turbulence in the entire working section for all velocities considered in this study, but further uniforms it also. In order to explain this occurrence, the authors examined the signals and the behavior of the flow in the contraction region.

Figures 15 to 17 illustrate variations of the hot-

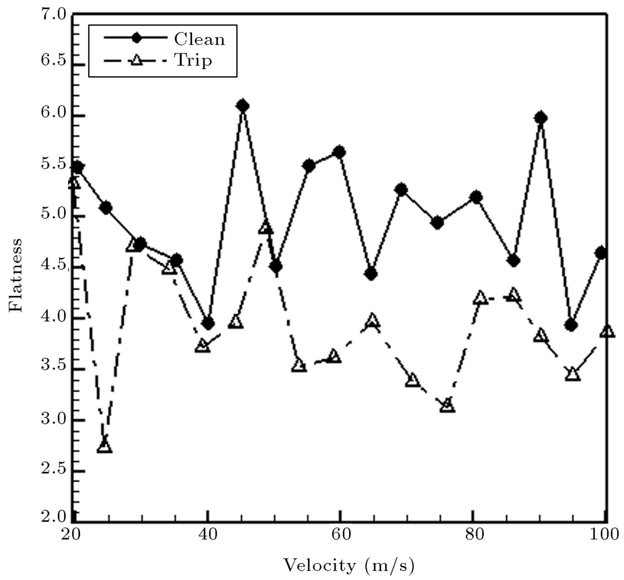

Figure 14. Variation of the flatness with speed at $X = 65$ cm for four screens.

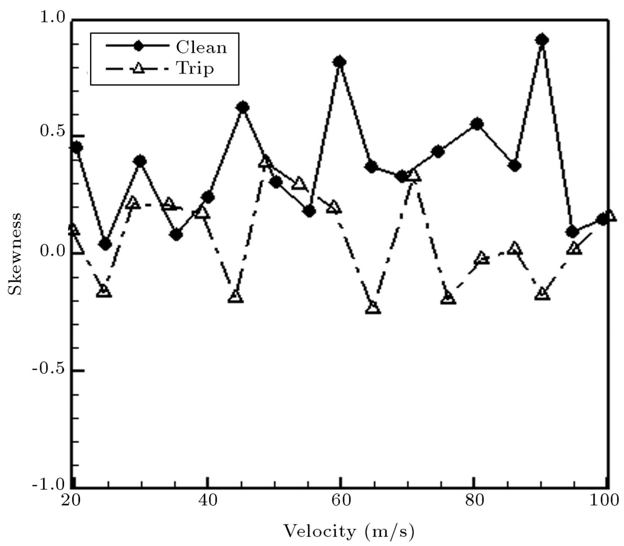

Figure 13. Variation of the skewness with speed at $X = 65$ cm for four screens.

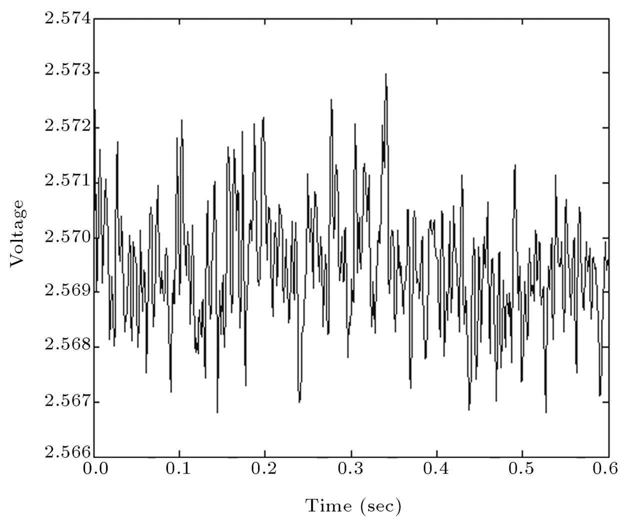

Figure 15. Time history data for four screens without trip strip, $V_\infty = 80$ m/s.

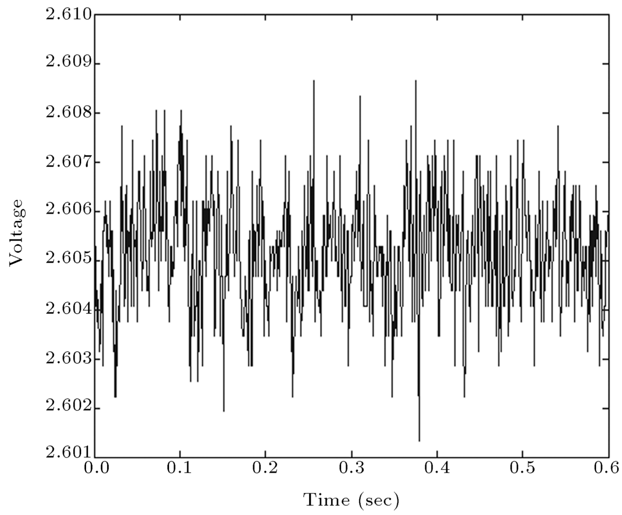

Figure 16. Time history data for four screens with trip strip, $V_\infty = 80$ m/s.

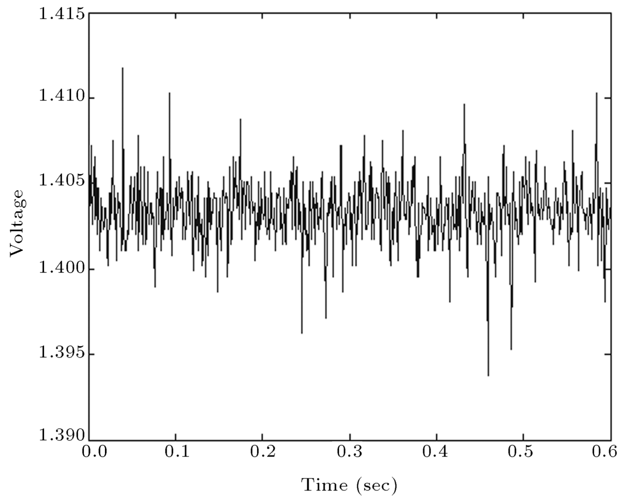

Figure 17. Time history data for one screen, $V_\infty = 80$ m/s.

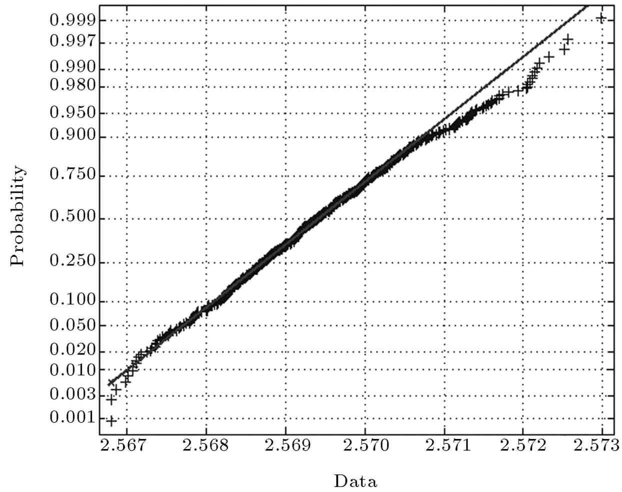

Figure 18. Normal probability plot for four screens without trip strip, $V_\infty = 80$ m/s.

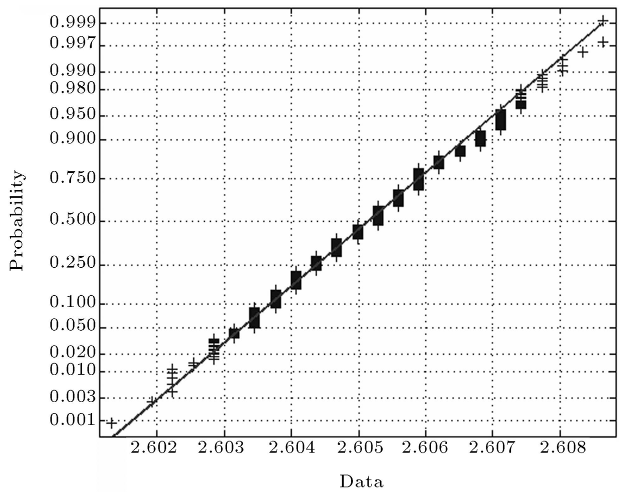

Figure 19. Normal probability plot for four screens with trip strip, $V_\infty = 80$ m/s.

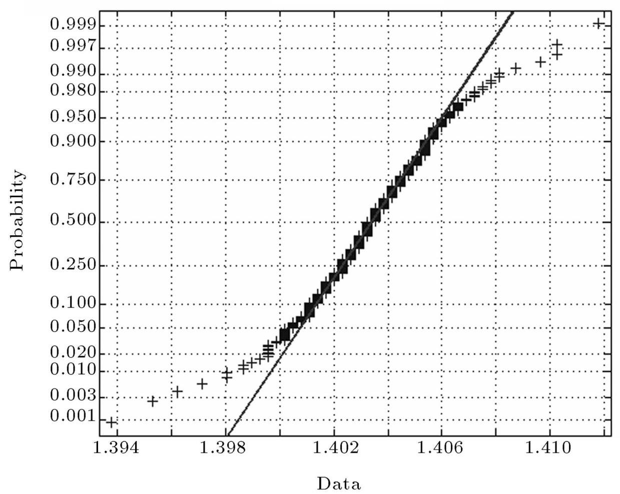

Figure 20. Normal probability plot for one screen, $V_\infty = 80$ m/s.

wire voltage with time at a constant free-stream velocity of 80 m/s for Cases 4, 3, and 1, respectively. In addition, normal probability plots corresponding to these figures are shown in Figures 18 to 20, respectively. It should be mentioned that the normal probability plot reveals whether the data are originating from normal distribution or not. In case of normal distribution, the plot appears linear and indicates that samples may be modeled by normal distribution [31-33], otherwise, the probability density function in the plot will experience some degree of curvature. The plot has the sample data displayed with the '+' symbol.

The effects of screens and trip strips on variations of the voltage with time are clearly demonstrated in Figures 15 to 17. From the normal probability plot (Figures 18 to 20), one may notice the variations of turbulence intensity in the test section through the placement of screens and trip strips. The normal probability plot in Figures 18 and 19 indicate that for cases with screens and a trip strip the hot wire data may be modeled by normal distribution. However, in cases where high turbulence intensity is present – that is, Case 1 (Figures 17 and 20), 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 19, one may model the data again by normal distribution.

Further, an attempt is also made to investigate the corresponding FFTs. As known, FFTs are useful for measuring the frequency content of stationary or transient signals and resembles the average frequency content of a signal over the entire acquisition time [33]. Figure 21 shows the FFT of the signals for the above-mentioned cases at $V_\infty = 50$ m/s. It is evident that screens decrease the amplitude of FFT, that is the energy content of the flow at almost all frequencies. However, screens may also create small initial non-uniformities after the settling chamber. In other words, one may envision small spatial variations in the mesh density as the source of low-amplitude non-uniformities downstream of the screens [34,35]. The increase of amplitude of FFT at low frequencies, i.e. 1 and 18 Hz, as seen from Figure 21, may be due to these sources. Further, Figure 21 illustrates that the trip strip decreases the amplitude of FFT more than in the other two cases.

Taking the Fourier transform of a correlation function leads to frequency-domain representation in terms of the spectral density function equivalent to energy spectral density in the case of an energy signal [36,37]. The purpose of the spectral analysis is to portray the distribution (over frequency) of the power contained in a signal, based on a finite set of data. However, the present approach is a non-parametric method, where the power spectrum density is estimated directly from the signal itself. Figure 22 illustrates the power spectra in a log/log scale for the aforementioned cases at a free stream velocity of 50 m/s. In addition, a -5/3 turbulence decay law is plotted for comparison. It is evident that the amount of energy for the cases with screens and a trip strip is less than the case with just one screen. In addition, after a trip condition with four screens, the energy of the signal is decreased further, indicating that the fluctuations of the longitudinal component of the velocity for the screens and trip strip is less than the case with one screen. The results corresponding to all cases examined in our study are in fair agreement with the decay line having a slope of -5/3.

Pope [38] has shown that the connection between the spectrum and the autocorrelation is related to the value of the spectrum at the origin. Consequently, one may conclude that the high-frequency process, that is the one-screen condition, has a smaller integral timescale than the four screens due to a smaller value of the spectrum at the origin. Also, the trip condition has a larger integral time scale compared to the four screens.

Furthermore, it is widely accepted that the main effect of a contraction is to reduce both the mean and the fluctuating velocity variations to a smaller fraction of the average velocity, while increasing the mean flow velocity. In this regard, one may identify the contraction ratio as the most important single parameter in determining these effects. For a given area ratio and cross section center, the wall shape design of a contraction influences the uniformity and steadiness of the flow at the exit. However, the boundary layer near the two ends of the contraction may separate.

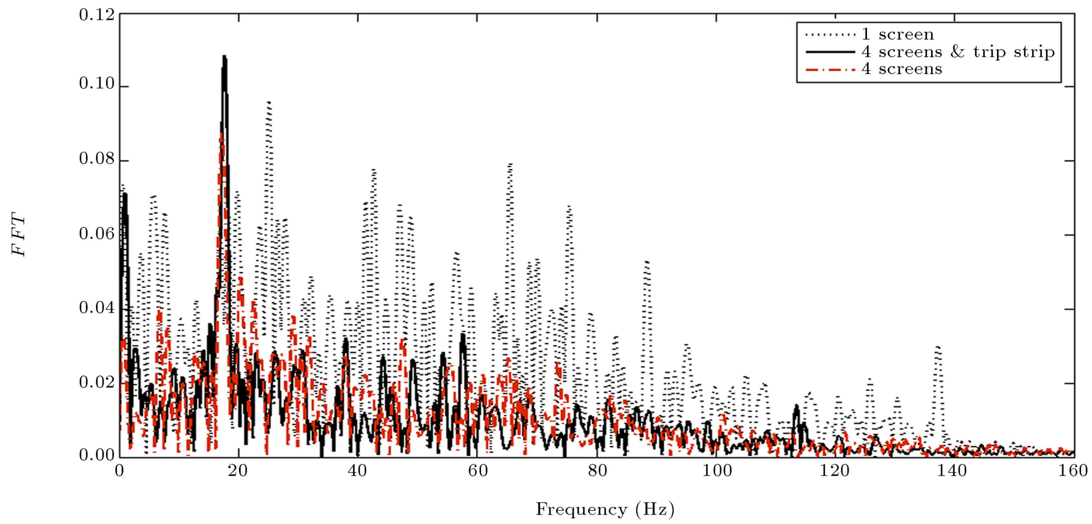

Figure 21. FFT for the signal at $V_\infty = 50$ m/s.

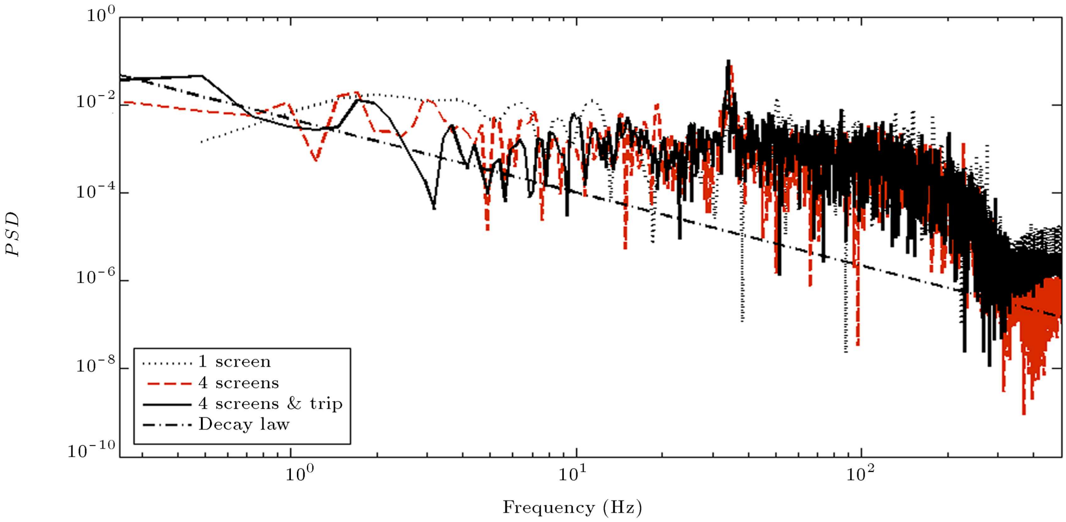

Figure 22. Power spectrum distribution for signals at $V_\infty = 50$ m/s/.

In Figure 23, pressure distribution in the contraction region of the wind tunnel at $V_\infty = 30$ m/s is shown [39]. The presence of regions of adverse pressure gradient on the curved wall near the contraction inlet and outlet are indicated by the variation in the pressure distribution or the wall velocity. This figure illustrates that the boundary layer grows rapidly in the inlet region where the effects of the first adverse pressure gradient are felt. It can be seen by inspection that with installation of the trip strip at the outlet of the contraction, the pressure gradient decreases and moves toward the settling chamber, thus decreasing the unfavorable effects of this phenomenon on the flow in the test section, and as a result the turbulence intensity will be reduced. It is also evident from the *Cp* distribution that the trip strip removes the fluctuation of pressure distribution near the test section

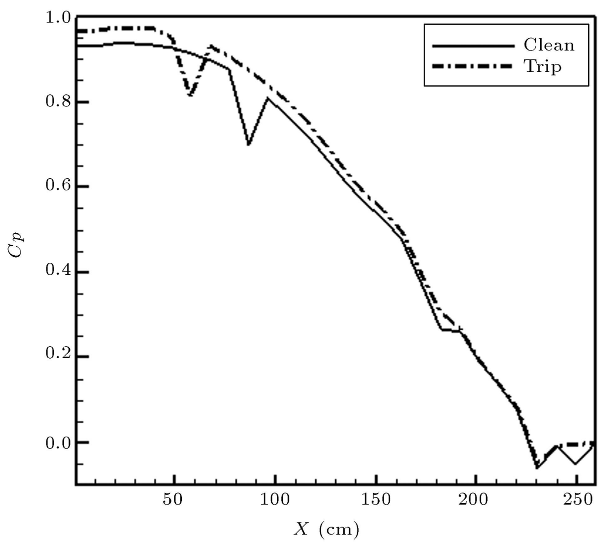

Figure 23. The pressure distribution in the contraction for clean and trip condition at $V_\infty = 30$ m/s [39].

(Figure 23). The results for pressure distribution in the contraction for a clean condition and trip strip at different positions of the contraction and at different velocities are reported by the authors in [39-41].

CONCLUSION

The employment of an innovative but simple and cost effective method for turbulence reduction in low speed wind tunnels is investigated. The tripping of the boundary layer at its early development stage in the contraction region is exploited. As known, contractions in wind tunnels may produce several different unsteady secondary flows, which are undesirable and which can have dramatic effects on the behavior of the downstream boundary layers. As a result, the introduction of suitable trip strips on the outlet of the contraction section of the tunnel is examined. An extensive subsonic wind tunnel testing was performed at different tunnel speeds, as well as at different positions, along the test section. As a next step, the trip strips were removed, screens were placed in the wind tunnel settling chamber and all the aforementioned experiments were repeated. Finally, the combination of four screens and a trip strip was also investigated.

The results for the trip strip indicate that the turbulence level was relatively reduced compared to cases without the trip strip, which might be due to the intermittent wall boundary layer interaction phenomenon, resulting in a non-uniform wall shear stress distribution on the working section. It should be also mentioned that variation of the turbulence intensity along the test section was flattened as well. However, the experiments that investigated the impact of damping screens indicated a lowering of the turbulence level, similar to the results obtained through trip strips, while keeping the pattern unlike the trip strip (Figure 10). Furthermore, the results for cases in which both trip strips as well as damping screens were placed on the contraction and in the settling chamber, respectively, show that the turbulence level was even more reduced than in the previous cases. The results also show that the screens and trip strip decrease the energy of the fluid in the wind tunnels.

Finally, one may conclude that the combination of several damping screens with the trip strip could be a sound method for turbulence reduction in subsonic wind tunnels.

NOMENCLATURE

FC	Cutoff Frequency
U	component of velocity parallel to the mean flow
$F(x)$	probability distribution function
$f(x)$	probability density function
U_0	mean velocity
TI	Turbulence Intensity
PSD	Power Spectrum Distribution
u'	root mean square value of u
u'/u_0	longitudinal component of turbulent intensity
V_∞	free stream velocity
X	distance measured parallel to mean flow
RMS	Root Mean Square
FFT	Fast Fourier Transform

ACKNOWLEDGMENT

The present work was supported by the Iranian Aircraft Manufacturing (HESA) company, Bureau of Aircraft Design. The authors would like to thank the director of the Design Bureau for the support devoted to this research.

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