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Control of Pressure Gradient in the Contraction of a Wind Tunnel

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***Abstract*—**Subsonic wind tunnel experiments were conducted to study the effect of tripped boundary layer on the pressure distribution in the contraction region of the tunnel. Measurements were performed by installing trip strip at two different positions in the concave portion of the contraction. The results show that installation of the trip strips, have significant effects on both turbulence and pressure distribution. The reduction in the free stream turbulence and reduction of the wall static pressure distribution deferred signified with the location of the trip strip.

***Keywords*—**Contraction, pressure distribution, trip strip, turbulence intensity.

I. Introduction

CONTRACTION is an important part of a wind tunnel. The main effects of a contraction are to reduce both mean and fluctuating velocity variations to a smaller fraction of the average velocity and further to increase the corresponding mean velocity. Generally to design of a subsonic and supersonic wind tunnel, the contraction portion should not adverse pressure gradient in the streamwise and further the effect of adverse pressure gradient at the exit of the contraction must be minimal. Whenever a converging duct segment is attached to a constant-area segments, regions of adverse pressure gradient will occur along the wall, at its inlet and exit that may cause boundary layer separation. If separation occurs, it will degrade the flow uniformity and steadiness, both of which are essential in a test facility. Separation is usually avoided if the adverse pressure gradients are minimized which is done by making the contraction sufficiently long.

The contraction can be divided into two parts. The first part has walls of concave shape and it is very important to elongate this part as much as possible to avoid wall boundary layer separation. The streamline curvature effects on the pressure gradient in the boundary layer promote the risk of separation. Along a fair part of this section, there will be a positive pressure gradient. The second part of the contraction has convex walls that may cause flow separation in the vicinity of the test section due to existing a positive pressure gradient.

To delay separation, it is better that a longer contraction's length be chosen, but this will increase the cost and thickening the boundary layer that may enhance boundary layer and risk of separation. Furthermore, if the length is reduced, the contraction costs will reduce and it will fit into a smaller space. In addition, the boundary layer will generally be thinner due to the combined effects of increase in the favorable pressure gradients and decrease in the length of the contraction. Furthermore, it may increase the possibility of flow separation. Thus the length most be optimized. The contraction area ratio is another dominant factor that affects the extent of flow uniformity, flow separation, and downstream turbulence level.

Fang and Chen [1] investigated Flow characteristics in a square contraction numerically and experimentally. Their Measurements included the cross-sectional velocity profiles and longitudinal pressure distributions along the wall of a contraction of a wind tunnel. Chmielewsk [2] studied boundary layer in the contraction. His Calculations showed that the minimum-length contraction shapes can provide fully attached boundary-layer flow. He showed that there may exist regions of separated flow along the wall, in the inlet and exit of the contraction furthermore; he concluded that the existing adverse pressure gradient is the essential condition for the separation. Fig. 1 shows the probable separation region in a contraction.

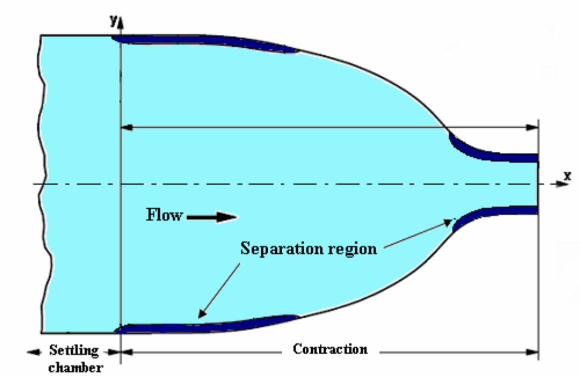

Fig. 1 Probability separation region

As noticed before, the separation can occurred in two regions, on the inlet and exit of contraction. This phenomenon occurred at the inlet of the contraction because the wall changes suddenly from a flat to a curved region, thus the

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streamline near the wall would accumulate and eventually increase the relative pressure (adverse pressure gradient) in this region. Flow study shows that a three-dimensional separation occurs in the contraction surface. In a proposed conceptual model of this phenomenon, the separation process begins with small non-uniformities in the boundary-layer flow merging from the screens upstream of the contraction. On entering the contraction, the non-uniformities are amplified by a combination of Gortler instability, lateral pressure gradient and adverse streamwise pressure gradient to form a strong counter-rotating streamwise vortex pair that detaches from the surface, Fig. 2.

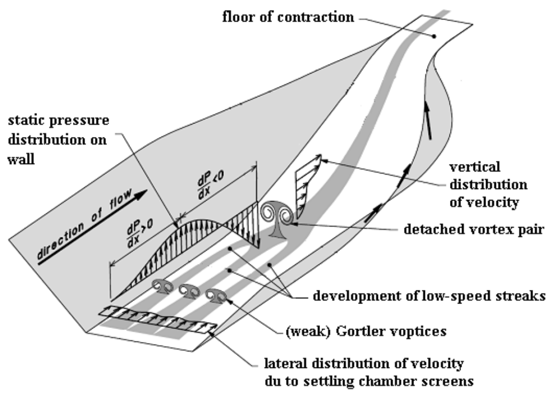

Fig. 2 Schematic diagram of a conceptual model for 3-D separation in contraction

Therefore, there are three major sources for the separation in the contraction region:

1. Initial Non-uniformity: The screens located upstream of the settling chamber has an important effect on the uniformity of the flow in the test section. However, Bottcher and Wedemeyer [3] show that small spatial variations in the mesh density are the source of low-amplitude non-uniformities in the time-averaged flow downstream of the screen. Gortler number on the concave contraction surfaces is in the range where the growth of primary Gortler instability has been observed.

2. Streamwise Pressure Gradients: Sonada and Aihara[4] examined the effects of streamwise pressure gradients on the development of secondary Gortler instability. Their measurements show that the vertical distributions of mean velocity are heavily inflected and there such two regions of high shear, one near the wall and the other near the top of the vortex-pair "mushroom", Fig. 3. They found that favorable pressure gradients tend to suppress the growth of the velocity fluctuations hence retarded the development of secondary instability. The main effect of an adverse pressure gradient is to move the outer shear layer away from the wall, with little effect on the near-wall shear layer. This increase in distance between shear-layers is interpreted as a migration of the vortex pair away from the wall.

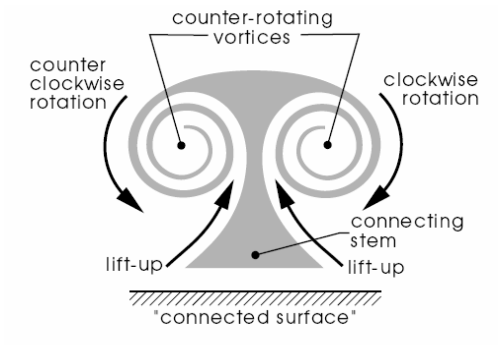

Fig. 3 Interpretive diagram of mushroom vortex-pair

3. Lateral Pressure Gradients: Bansod and Bradshaw [5] showed that the converging lateral flows generated by *lateral* pressure gradients can also produce pairs of streamwise separated vortices. This is explained by observing that, if the deflection angle of the flow is small and the viscous diffusion terms are ignored, the equation for the lateral component of the momentum can be simplified to

$$U\frac{\partial W}{\partial x} \approx -\frac{1}{\rho}\frac{\partial P}{\partial z}$$

The rate of flow deflection ($\partial W/\partial x$) in the relatively low momentum fluid of the boundary layer is significantly larger than in the free stream flow. The result is a skewed boundary layer where the lateral velocity component has a maximum value within the boundary layer. The convergence of the lateral flows near the middle of the floor provides a second mechanism for amplifying the initially very weak streamwise vortices produced by the Gortler instability. The relative importance of an adverse streamwise pressure gradient and the skew-inducing lateral pressure gradient in the production of the three-dimensional separation is indicated in Figure 4, where one vortex pair is reinforced by a skew-induced vorticity while the other less centrally located vortex pair is not.

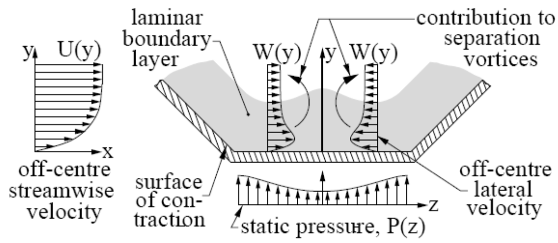

Fig. 4 Lateral velocity distribution and the effect of lateral Pressure gradient on the boundary layer deformation

Takagi, Nishizawa and Tokugawa [6] in their study found that a row of Gortler vortices developed and eventually breaks down to turbulence in the concave region of the contraction. It was observed that strong acceleration suppresses the turbulence and leads to a reverse transition in the convex region, following the concave wall. They also observed an abrupt appearance of a turbulent signal in the convex region of the contraction after the laminarization process.

Takagi and Tokugawa [7] studied the flow behavior in the contraction region of a wind tunnel. their experimental results showed that although the turbulent boundary layer in the concave region near the contraction inlet is thickened by unknown factors possibly related to the Gortler-type instability, acceleration gives rise to laminarization in the convex region following the concave wall. At the downstream, this laminarized boundary layer encountered an inflection-type instability initiated by the flow separation. This inflectional instability abruptly precipitates the transition from a laminar state to a turbulent one.

Nishiza, Takagi and Tokugawa [8] investigated experimentally the re-transition process of the boundary layer along a wind-tunnel contraction. They showed that the laminar boundary layer was distorted by an array of large-scale longitudinal vortices spanned by the Gortler instability in the concave region and the resultant turbulent boundary layer was laminarized in the convex region due to acceleration of the mean flow at a lower Reynolds number. For the higher Reynolds number, the initial boundary layer flow was already turbulent at the entrance of the contraction. This laminarized boundary layer encountered an inflection-type instability initiated by the flow separation. It is can counteract a separation in this section by using some boundary layer tripping device such as roughness elements.

The above studies showed that 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. Hence, in order to lever this drawback, the addition of suitable trip strips on the concave part of the contraction section of the tunnel is examined. An extensive subsonic wind tunnel testing was conducted to measure the pressure distribution for cases in which the trip wires were installed on the $\frac{x}{L} = 0.115 \text{ and } 0.192$ in the contraction section of the tunnel and the effect of trip strip on the pressure distribution and turbulence intensity are studied.

In this experiment, the pressure distribution along the contraction with the turbulence intensity in the inlet of the contraction for a clean case was examined. The effects of tripped boundary layer at two positions in the concave portion of contraction, on the pressure distribution and the turbulence intensity were then investigated. Furthermore, an optimum position for the trip strip, to set smooth pressure distribution is proposed.

II. Equipments

In order to measure the pressure distribution in the contraction as well as the turbulence intensity in the inlet of the test section, pressure transducer and hot wire anemometer system were used throughout the measurements.

A. Wind Tunnel

All experiments were performed in a subsonic wind tunnel in Iran. A schematic of the tunnel is shown in Fig.5. The tunnel is of closed return type and has a test section of $80\times80\times200$ cm^3 and operates at speeds from 10 to 100 m/sec. The inlet of the tunnel has a 7:1 contraction ratio with four large, anti-turbulence screens and honeycomb in its settling chamber to reduce tunnel turbulence level in the test section. The detail information about the calibration and the quality of the flow in this wind tunnel could be found in [9-10]. The presented data are digitally filtered to disregard possible noises and other disturbances. Various cut-off and transition frequencies are used to find the best frequencies to fit the original data.

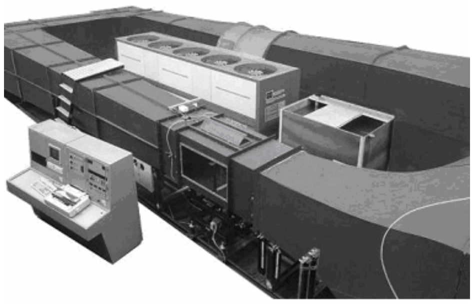

Fig. 5 Schematic of win tunnel

B. Pressure Transducer

For the pressure distribution measurements, differential pressure transducers are used. The frequency of these transducers is 1 kHz and the relative accuracy at the low of pressure differences is less than 0.1 Pa. prior to the tests, all of these transducers have been calibrated separately. Hot-wire

C. Hot-Wire

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

III. Experimental Procedure

The effect of trip strip is investigated by measuring the pressure distribution and the turbulence intensity for the following cases:

- Case 1: Clean (without the trip strip)
- Case 2: the trip strip was glued at $\frac{x}{L} = 0.115$; 30 cm from the inlet of contraction, see Fig. 6
- Case 3: the trip strip was glued at $\frac{x}{L} = 0.192$; 50 cm from the inlet of contraction, see Fig. 6

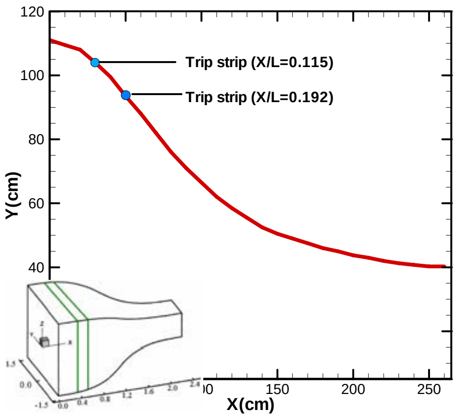

Fig. 6 Position of the trip strip in contraction

Experiments were conducted at tunnel speeds of 20-70 m/s. The data for all ranges of speeds were acquired with 27 pressure transducers along the centerline in the bottom floor of the contraction with the hot wire located at the middle of inlet of test section for both cases, with and without the trip strip. The data presented in this paper for the pressure distribution is an average of 5000 samples that has been takes in 5 seconds (A). At the first, case 1, tests were conducted with the clean tunnel for all ranges of speeds. The data for the case 1 is shown as the clean one, trip strip was then installed at two positions in the concave portion of the contraction and all tests were repeated. The contraction curvature is shown in Fig. 6.

IV. Results

As indicated, the main purpose of the present work is to explore the effect of tripped boundary layer on the pressure distribution and the turbulence intensity in a subsonic wind tunnel.

A. Results of Case 1, Clean Tunnel

The general aerodynamic performance of the contraction is given by the static pressure distribution, Cp, along the wall. Fig. 7 shows the measured static pressure distributions in the contraction region of the nozzle at various test section velocities. This plot indicates that the distributions are smooth and favorable except for the inlet and exit regions of the contraction, and for a few lvelocities this phenomenon, sudden adverse pressure at the two different low velocities are due to the sudden changes from a flat to a curved surface along the wall. That will cause an accumulation of the streamline near the wall and eventually increases the relative pressure, adverse pressure gradient, in this region. However, as the free stream velocity, increasing this adverse pressure gradient is weakened and eventually of the velocity higher than 40m/s the adverse pressure in the inlet of contraction is eliminated, Fig. 7.

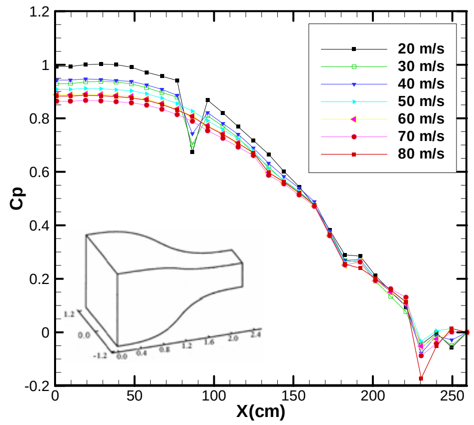

Fig. 7 Cp distribution along the contraction for all of range of velocity

from Fig. 7, it is obvious that at the entrance of the convex portion of the contraction, about $\frac{x}{L}=0.73$; 190cm from the contraction inlet, the pressure distributions is not smooth. The phenomena are caused by the reverse boundary layer transition [8].

At the exit of the contraction, the adverse pressure gradient exists too. Ito, Kobayashi and Kohama [11] also reported this phenomenon at the exit of the contraction. By increasing the velocity, this adverse pressure gradient strengthens. The unfavorable pressure gradient in this area may be due to the change from a curved wall to a flat surface along the wall. Additionally, the near wall streamline velocity is greater than the axial middle contraction velocity, when the flow arrives to the flat surface, velocity profile like to be uniform and it cause to streamline velocity near the wall decreases and consequently increase in relative pressure (adverse pressure gradient) is happened. Chmielewsk [2] reported such as this result in his studied. In higher velocities, probable of separation in the inlet of contraction is decrease and for exit of contraction, it increase.

B. Results for the Cases 2&3

The trip strips were installed at two positions in the concave portion of the contraction, Figs. 8 and 9. For the first case, the trip was located at a locate of $\frac{x}{L}=0.115$; the 30cm from the inlet of the contraction. Fig. 8 illustrates the pressure distribution for this state. This figure shows that adverse pressure gradient is presented in the inlet and exit of the contraction for all range of the speed tested here. Form this figure it is see that in the inlet of contraction, the trip strip increases │CP│ at low velocity, than 40m/s, and decreases │CP│ at higher velocity, above 40m/s. in another word the trip strip reduces the possibility of possibility of separation at the contraction inlet at low speeds. At high speeds, however the trip strip causes an adverse pressure gradient in the inlet just as the case 1; clean state, Fig. 7. At the exit of the contraction, trip strip reduces adverse pressure gradient, at all speeds, Fig. 8.

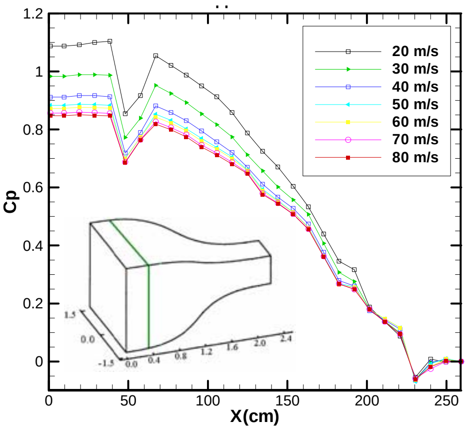

Fig. 8 Cp distribution along the contraction for case 2

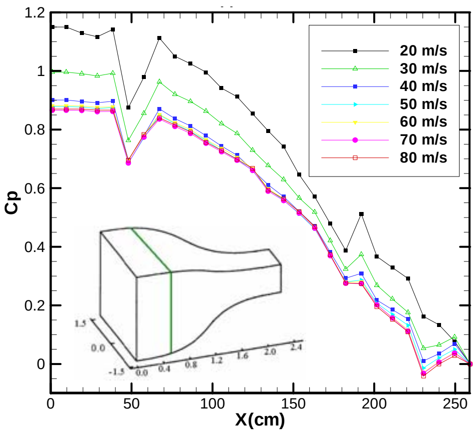

Fig. 9 Cp distribution along the contraction for case 3

Fig. 9 illustrates the pressure distribution, for this case when the trip strip was installed at $\frac{x}{L}=0.192$. As see from this figure, the effect of trip strip on the Cp distribution is similar to the corresponding case, however, at the exit area, trip strip caused a change in pressures the distribution in that place. At low speeds, adverse pressure gradient on the exit, moved to the position of the reverse boundary layer transition (190cm from the inlet). Nevertheless, at high speeds this movement is removed. Variation of the turbulence intensity with velocity measured at the beginning of the test section for the aforementioned cases are shown in Fig. 10. For this figure, it is clearly see that the trip strip reduces the turbulence intensity at the low speed, V=20-50 m/sec, for both cases, $\frac{x}{L}=0.115 \textit{ and } 0.192$. However, at high speed, V=50-80 m/sec, only the trip strip that is located at $\frac{x}{L}=0.115$ decreases the turbulence level at the beginning of the test section while for the one located at $\frac{x}{L}=0.115$, the reverse is true, Fig. 10.

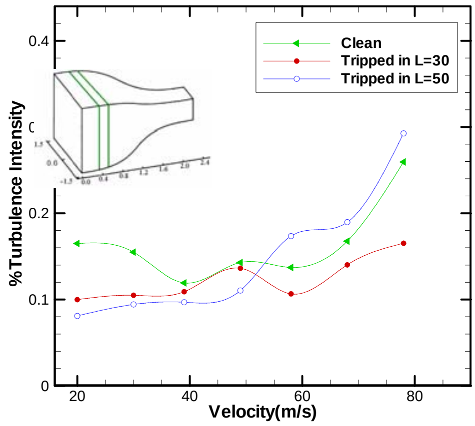

Fig. 10 Variation of the turbulent intensity with Velocity in the inlet of test section for all cases

V. Conclusion

Pressure distribution in the contraction of wind tunnel and the effect of trip strip in the concave part on this distribution and turbulence intensity in the test section is investigated. Our results show that contractions may produce adverse pressure gradient in two different positions, inlet and exit of contraction. These gradients are undesirable and can have dramatic effects on the behavior of turbulence levels in the test section. As a result, the installation of suitable trip strips on the concave part of contraction section of the tunnel is examined. The results for the trip strips indicate that the pressure distributions and turbulence level were changed compared to case without the trip strip. The results confirm the significant impact of tripped boundary layer on the control of adverse pressure gradient. The results also shows that the trip strips, cases 2 and 3, moved adverse pressure gradient to the inlet of contraction, then flow has more time and distance to be uniform in the test section. Another effect of trip strip on the pressure distribution was obvious in the exit of contraction. The trip strip in the 30 cm from beginning of settling chamber has suitable effects on the pressure distribution and reduces the turbulence in the test section for all speeds. But the installation of trip strip in the 50 cm from settling chamber has inappropriate effect on the above phenomenon and increase turbulence intensity in test section at high speeds.

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