AN OVERALL EVALUATION OF FLOW CHARACTERISTICS AND PERFORMANCE PARAMETERS OF Y-SHAPED DIFFUSING DUCT WITH SAME ANGLE OF TURN AND DIFFERENT CENTERLINE LENGTH & RADIUS OF CURVATURE

Netrapal Singh¹, Abdur Rahim², Md. Islam³

¹Research Scholar, Department of Mechanical Engineering, JMI Delhi, India
²Associate Professor, Department of Mechanical Engineering, JMI Delhi, India
³Professor, Department of Mechanical Engineering, JMI Delhi, India

Abstract
The several set of experiments have been carried out to compare the flow and performance characteristics of both Y-ducts made of epoxy resin having centerline length(300mm&600mm) and radius of curvature(382mm&764mm) for both sets of y-ducts area ratio and aspect ratio keep constant i.e. 2 with turning angle 22.5°/22.5°. The inlet shape of both limbs of Y duct is rectangular while the outlet is circular. All the experiments have been carried out for a fixed velocity ratio 1.2(suction to free stream velocity). The maximum average inlet velocity at the inlet of duct is 15.06 m/s. The flow in duct is created by suction with the help of pipeline network which directly connected at the inlet of centrifugal blower with the help of control valve followed by a sliding door. The all parameters are measured with the help of a calibrated five hole probe. The results are presented in the form of 3-D plots for longitudinal velocity at inlet, contour plots for velocity and pressure as well as vector plots for secondary velocity along with wall pressure and mass averaged pressure recovery coefficients and loss coefficients. The surfer graphic package based on finite volume method is used for all plots.

Keywords Y-Shaped Diffusing Duct, turning angle, Centerline length, Radius of curvature, Cₚ and C_Loss.

1. Introduction
The Y-shaped ducts are used as intake ducts in aircrafts, as air intake is a crucial component of the propulsion system of modern combat aircraft. From aerodynamic point of view, small and short intake is desirable to minimize the loss while maintaining the mass flow requirements and meeting the space constraint of the aircraft. These ducts fulfill the requirements of higher flow and less distortion, due to space constraints and geometrical variations, diffusion make the flow characteristics quite complex. Curvature of limbs of duct generates centrifugal forces, which get balanced by the pressure gradient in the plane of the bend. The central part of the fluid is forced outwards to satisfy the continuity resulting in generation of secondary flows.

Martin and Holzhauser (1949) have conducted experiments for pressure recovery and mass flow characteristics in a single and twin submerge intake duct system on the both side of the fuselage at various angles of the side lip. They have showed that the twin intake air induction system had unstable air flow characteristics. Intake must meet the engine mass flow requirement for a combat aircraft steady and symmetric condition over a wide range of aircraft speed and altitude ensuring higher pressure recovery and less distorted flow (Whitford, 1987). This makes the compressor more sensitive to the flow field at the inlet of the engines and hence performance of aircraft engine also depends on the flow characteristics at the end of the intake duct. Sudhakar and Ananthkshinan (1995) have explained the jump phenomenon caused due to transition from symmetric to asymmetric operation in Y-duct in supersonic flight. Ahmed and Kumar (2002) have studied the mechanism of flow instability at supersonic speed on twin intake duct. They have shown the presence of flow instability in the form of shock oscillation at moderate exit area and it is initiated when the terminal shock is expelled from the inside of the intake. An experimental study has been done by Sullery et al. (2002) to reduce the exit flow distortion and improving the total pressure recovery in two-dimensional s-diffuser using various fences and vortex generators. Their results indicate that substantial improvement in static pressure rise and flow quality is possible with judicious deployment of fences and vortex generators. Gorton (2004) also did similar experimentation along with the computational investigation on different flush mounted inlets. The reversal of the pressure recovery trend with increasing inlet mass-flow at low and high Mach numbers was predicted by CFD. However, in the CFD simulation they observed that CFD results show larger losses than experimental results. Patel et al (2005) have examined the effect of different inflow conditions on the flow characteristics of the Y-Shaped rectangular duct having 22.5°/22.5° angle of turn and AR 2.0. Their studies have shown that static pressure recovery decreases with increase of skewness and strong secondary flow exist throughout length of the diffuser. They have also observed deflection of flow toward the outer wall along the length of the diffuser.

Experimental facility & Y - duct:
Experimental investigation has been carried out to establish the flow and performance characteristics of Y-shaped rectangular duct-fuselage assembly with fixed velocity ratio (1:2) i.e. suction to free stream velocity by adjusting the control valve and inlet throttle valve (figure-1(a)). The experimental investigation has been carried out at a free stream velocity 15.06 m/s by adjusting the opening of the sliding gate provided at the suction of blower. Although higher velocities could have been obtained by the blower, it was not feasible to operate at higher flow rates. This was due to constraints of the starter unit of the blower and the noise generated at the higher flow rates. Due to these constraints, the velocity of 15.06 m/s ($R_e=6.85 \times 10^5$) was the maximum achievable in the set-up. Measurements have been made at ten planes at turning angle of $0^\circ$ (inlet), $11.25^\circ$, $22.5^\circ$, $22.5^\circ/11.25^\circ$ in both limbs (four+four) and than merger & outlet section (Singh et al, 2012) along the length of the duct (figure 1(b)). The number of measuring stations at each plane in the radial direction varies from four to ten, with at each station 19 or more measurements points in the lateral direction for velocity and pressures. At every station, the probe was inserted through the slot provided on the top wall and it was traversed along the lateral direction. Inserts made-up of Perspex with step height equal to the top wall thickness (12 mm) of the duct were used to cover the unused portion of the slots while carrying out the probe measurements (figure(c)). The atmospheric pressure and temperature were recorded twice during the run of each experiment in a day.

To obtain the different parameters, the probes were traversed at the pre-selected locations in the lateral direction. The number of measurement locations at a measurement planes were between 76 and 248. To measure the velocity and pressure distribution, the pre-calibrated five-hole probe (Bryer and Pankhurst, 1971) was first mounted with the traversing mechanism and then inserted into the duct. The five tubes of the five-hole probe & the two side tubes of the pitot static tube were connected with the multi-tube inclined manometer having an accuracy of 0.1 mm (figure 8). In addition, the two side tubes of the orifice meter were also connected across an inclined U-tube water manometer. At each point of measurement, the probe was rotated in the horizontal plane about its vertical axis such a way that the two side tubes read the same pressure that was monitored on the inclined multi-tube water manometer. The zero angle for the probe was fixed with the flow direction at the inlet. The positioning of the sensing head offset due to probe rotation was always brought back to its original position using the traverse mechanism. After the probe alignment the angular position of the probe was recorded with an accuracy of $\pm 0.5^\circ$ (resolution of the protractor) and the readings from all tubes of the five-hole probe recorded from the inclined multi-tube water manometer. From these measurements and calibration curves, velocities and pressures were evaluated using the atmospheric pressure and temperature readings. These steps were repeated at each measuring point.

The measured velocity by the five-hole probe is resolved into two components as longitudinal and cross-flow velocities. For normalization of velocity and pressure terms, the mass-averaged longitudinal velocity and mass-averaged dynamic pressure at section-inlet are used respectively. The results are presented in the form of 3-D plots for normalized longitudinal velocity and vector plots for normalized cross-flow velocity. For 3-D and vector plots, ‘SURFER’ software graphics package is used, which uses ‘Kriging’ method. Kriging is a geostatistical gridding method, which produces a regularly spaced, rectangular array of Z values from irregularly spaced XYZ data. Using the ‘XYZ’ data, the grid file is generated and thereafter ‘Cubic Spline’ method is used for smoothing the grid which is a rectangular region comprised of evenly spaced rows and columns. The grid files are used to produce 3-D and vector plots.

2. Results & discussions

Longitudinal Velocity Distribution

Both the inlets of ducts shows more or less symmetric fluid flow contours except to the walls. Due to curvature effect, fluid flow towards concave wall in the first half bend and continuously developing along the same curvature in the second half [convex wall in the second half]. The inflexion plane shows separation of flow at the convex wall. The two flow regimes mixed with each other at merger plane resulting uniform intensity of pair of vortices. Central region occupy the core flow and decay in a uniform manner from central region to outer walls. At the exit plane weak intensities pair of vortices slowly-slowly disappeared which signifies smooth merger with sufficient space along with axial length to settle the flow i.e. nearly uniform flow. The normalized longitudinal velocity ($U_{norm}/U_{ave(in)}$) contour plots of different cross-sections at $10^\circ$ & $20^\circ$ yaw for the intake duct A(Right Limb) and duct B(Left Limb). The contours of Right Limb & Left Limb of section 1, 2 & 3 shows asymmetric flow magnitudes due to $10^\circ$ & $20^\circ$ yaw at right side up to inflexion plane. These figures are not presented due to constraints on space.

Figure 2(b, c) & Figure 3(b, c) of normalized longitudinal 3-D velocity ($U_{norm}/U_{ave(in)}$) contour plots also supports this flow behavior in which skin friction of forebody/fuselage plays important role due to that flow divert its direction at both the inlets of duct.

Cross flow velocity distribution
Normalized cross flow velocity ($U_{sec}/U_{ave(in)}$) distribution at different planes for the 22.5°/22.5° Y-shaped diffusing duct also analyzed & found that there is no significant variation observed in the cross flow velocity distribution upto section (4) for 22.5°/22.5° in Y-shaped diffusing duct. The cross flow velocity pattern is nearly similar throughout, in both inlet limbs of Y-duct. At the merger, two streams are mixed with each other, centrally core flow with almost uniform intensity of pair of vortices found. The secondary flow pattern seen at the exit plane shows, presence of two pair of vortices, with central pair having weak intensity. These figures are not presented due to constraints on space.

3-D Wire Mesh Longitudinal Velocity Distribution
Figure 2(a,b,c) & Figure 3(a,b,c) shows normalized longitudinal 3-D velocity ($U_{long}/U_{ave(in)}$) contour plots at 0°, 10° & 20° yaw angles at inlet cross-sections for the intake duct A(Right Limb) and duct B(Left Limb). The 3-D wire mesh plot supports velocity distribution at both the inlets. These plots also clarifies that 0° yaw angle have better performance comparatively with 10° & 20° yaw angles in both ducts. Hence as yaw angles increases performance deteriorates. The flow uniformity is better in 600 C.L in comparison with 300 mm C.L.

Total and Static Pressure Variations
The total and static pressure distributions at the various sections, supports the velocity distribution. The variation in the static pressure distribution at the merger plane ranging between (-2.5 to -1.5), and for exit plane ranging between (-1.6 to -2.6) for 0° yaw angle, and for 10° yaw angle the merger plane range is (-3.7 to -1.7 to -3.2), and at the exit plane it is order of (-3.2 to -1.7 to -3.2) and for 20° yaw angle the merger plane range is (-1.5 to -2.5), and at the exit plane it is order of (-1.6 to -2.0 to -1.4).The total pressure distribution is almost identical to the longitudinal velocity distribution. These figures are not presented due to constraints on space.

Wall pressure distribution
The curved wall averaged static pressure coefficient variations for different locations with different yaw angles along the length of the both ducts are presented in Fig. 4 & Fig. 6. At the inlet, there is no significant variation in the static pressure coefficient for all the tapping and this supports the longitudinal velocity distribution at the inlet. Due to corner effect of curvature some drop observed initially which further increases. The wall pressure coefficient increases continuously along the outer wall of the first bend and inner wall of the second bend, whereas on the opposite side it increases up to the point of inflexion and is followed by a fall. This shows the movement of the fluid core towards the concave surface. As the flow moves downstream, the static pressure coefficient starts to increase again due to accumulation of fluid near the inner surface of the second bend.

Performance Characteristics
Variations of the mass-averaged static pressure recovery coefficient and total pressure loss coefficient with different yaw angles for both the limbs are presented in Fig. 5 & Fig. 7. For limb A, the mass-averaged static pressure recovery coefficient increases continuously in the first bend and a slight reduction in the rate of recovery coefficient is observed near to the inflexion plane due to a change in the direction of curvature, which leads to turbulent mixing. In the second bend, the fluid recovers its lost energy and the loss coefficient is nearly constant up to the exit of diffusing duct, except at X/L=0.45 & X/L=0.75,where some depression occurs. This may be due to the growth of boundary layer and increase in the losses due to rapid mixing. More or less similar trend found in limb B. It is observed that the variation of total pressure loss is almost linear along the whole length of the duct. The values of static pressure recovery coefficient and total pressure loss coefficient are 0.38, 0.37, 0.35 and 0.25, 0.24, 0.23 respectively for the yaw angles of 0°, 10° and 20° for 300mm C.L and The overall static pressure recovery coefficient for 600 mm C.L ducts with the angle of turn of 22.5°/22.5° are 0.51, 0.50 and 0.48 with respect of yaw angles of 0°,10°,20°. The corresponding values of loss coefficient are 0.39, 0.38 and 0.37, respectively.

3. Conclusions
1. The nearly uniform pattern of contours as well as 3-D wire-mesh plots at inlet signifies flow stability in settling chamber i.e. in front of both the inlet limbs.
2. The high magnitude core flow clearly depicts the reasoning of suction controlled flow.
3. From inlet to merger and further up-to exit, as curvature increases recovery coefficient also increases and it is proportionate to fluid flow from inlet to exit and the loss coefficient is nearly constant, with this turning angle.
4. The overall performance of duct with 600 mm C.L & 764 mm R.C shows better flow stabilization along with pressure recovery in comparison with duct of 300 mm C.L & 382 mm R.C with same turning angle and area ratio.

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5. The duct/diffuser effectiveness (as defined $C_p / C_{p(ideal)}$) was found 68% for duct with 600 mm $C_L$ & 764 mm $R_C$ while the duct/diffuser effectiveness (as defined $C_p / C_{p(ideal)}$) was found 50.7% for duct of 300 mm $C_L$ & 382 mm $R_C$.

6. At the merger, two streams are mixed with each other, centrally core flow with almost uniform intensity of pair of vortices found. The secondary flow pattern seen at the exit plane shows presence of two pair of vortices with central pair having weak intensity. When two streams mixed at the merger plane distortion occurs in the flows and it is finally settle down at the exit and flow distribution is uniform at the exit.

### Notations

<table>
<thead>
<tr>
<th>AR: area ratio (Outlet area of the duct / Inlet area of both limbs of the duct)</th>
<th>$U_{ave(in)}$: mass-averaged velocity at inlet, (m/sec)</th>
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<tr>
<td>$C_p$: coeff. of static pressure recovery ($=(P_{so} - P_{si})/P^{dyn(in)}$)</td>
<td>CV: convex surface</td>
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<td>$C_{Loss}$: coeff. of total pressure loss ($=(P_{oi} - P_{oo}) / P^{dyn(in)}$)</td>
<td>$P_{wall}$: wall static pressure, (N/m²)</td>
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<tr>
<td>$P_{so}$: mass-averaged static pressure at inlet, (N/m²)</td>
<td>CC: concave surface</td>
</tr>
<tr>
<td>$P_{si}$: mass-averaged static pressure at outlet, (N/m²)</td>
<td>$L$: axial length along duct, (m)</td>
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<tr>
<td>$P_{oi}$: mass-averaged total pressure at inlet, (N/m²)</td>
<td>$ρ$: fluid density, (kg/m³)</td>
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<tr>
<td>$P_{oo}$: mass-averaged total pressure at outlet, (N/m²)</td>
<td>$h$: height of duct at inlet,(mm)</td>
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<tr>
<td>$P^{dyn(in)}$: dynamic pressure at inlet (=1/2 $ρU^{2}_{ave(in)}$), (N/m²)</td>
<td>$w$: width of duct at inlet,(mm)</td>
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<td>$X$: distance along the centerline of the duct from the inlet plane, (m)</td>
<td>$C_L$: centerline length (mm)</td>
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<td>$Y$: distance perpendicular to the centerline of the duct from the inlet plane, (m)</td>
<td>$U_{long}$ :velocity in the axial direction, (m/sec)</td>
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<td>$θ$: rotation angle (angle of rotation of the five-hole probe), (deg)</td>
<td>$R_C$: radius of curvature (mm).</td>
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<td>$C_{p(ideal)} = [1-{1/ (AR)^2}]$</td>
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### References


Figure 1: Schematic layout of experimental Set-up

Figure 1 (a): Schematic diagram of divided intake duct

Figure 1 (b): Orientation of five-hole probe at a point of measurement

Figure 1 (c): Details of the five-hole probe
Fig.2(a,b,c): 3 D-Normalised Vlong Wire-mesh Plots at 0,10,20 Degree Yaw of Both Inlets.

(Velocity Ratio = 1.2) (CL = 300 mm & RC=382 mm)
Figure 3 (a,b,c) : 3 D-Normalised Vlong Wire-mesh Plots at 0,10,20 Degree Yaw of Both Inlets.
Fig. 4: Wall pressure distribution of different yaw along duct length.

Fig. 5: Variation of performance parameters along duct length.
Figure 6: Wall pressure distribution for different yaw along duct length

Figure 7: Variation of performance parameters with different yaw along duct length
Showing photographs of 300 mm & 600 mm centerline length for test Y-ducts