Parameter Optimization of Tapered Submerged Vane

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Abstract: Submerged vanes are hydrofoils utilized to manage the sediment transport through the river by generating the turbulence in flow in form of helical currents. The vanes are placed in the flow with respect to its direction at the angle in between 10° to 40°. Many studies previously have been done on the rectangular shaped submerged vanes but a few studies have been reported on the submerged vanes having non-rectangular shaped. In the present paper, study have been conducted to optimize the parameters of tapered vane which includes its height, angle of attack, tapering angle. A model was developed based on study conducted by Wang and Odgaard (1993) by using ANSYS-CFX and k-ω turbulence model was used to model the flow downstream of tapered vane. It was observed that maximum strength of secondary currents was obtained for angle of attack, tapering angle and relative height of vane (ratio of vane of height to depth of flow) of 17°, 10° and 0.48, respectively. It was also observed that for proximity of tapered vane, secondary currents are predominated by vortex-lift while for far-reaches, the currents are dominated by potential lift. It was also observed that transverse velocity was maximum for tapering angle of 10°.

Keywords: Submerged vane, Tapered vane, Secondary currents, Vane parameters.

1. Introduction

Submerged vanes are the hydrofoils which generate the helical currents in the flow due to the difference in pressure between approaching flow side and downstream side of vanes (Odgaard and Spoljaric, 1986; Odgaard and Mosconi, 1987; Odgaard and Wang, 1991; Wang and Odgaard, 1993). The range of angle at which submerged vanes are placed in the flow with respect to flow direction varies from 10° to 40°. Submerged vanes are basically being used as sediment manager in the riverine system as suggested by Odgaard and Kennedy (1983), Odgaard and Mosconi (1987), Nakato et al. (1990), Barkdoll et al. (1999), Johnson et al. (2001), Flokstra (2002), Aware et al. (2005), Tan et al. (2005), Allahyonesi et al. (2008), Ghorbani and Kells (2008), Ouyang (2009), Gupta et al. (2010), Han et al. (2011), etc. It has been observed that all the studies enlisted above have been done on the rectangular vane but a few studies like Gupta et al. (2006), Gupta et al. (2007), Ouyang (2009), Ouyang and Lin (2016), and etc., have been done on the submerged vanes having non-rectangular shapes as shown in Fig 1.

Gupta et al. (2006) experimentally studied the optimization of parameters of double curve vane and J-type vane for generation of secondary currents of maximum strength. They obtained that for both J-type and double curve vane, the optimum angle of attack as 45° at which both type of vanes generated the secondary currents of maximum strength. They observed that as both vanes are having curvature the vortices at leading and trailing edge have opposite direction of circulations. Gupta et al. (2006) hence observed the efficiency of the double curve vane and J-type vanes to be less than that of rectangular vane of same aspect ratio, in managing the sediment erosion in fluvial channel.

Gupta et al. (2007) experimentally explored the optimal tapering angle of submerged tapered at leading edge to generate secondary currents of maximum strength for a single tapered vane. They used Moment of momentum (MOM) and loss in linear momentum (ΔLM) to optimize the tapering angle and observed that a proper optimization angle couldnot be obtained by them but they obtained a range of 33^o-45^o in which tapering angle influenced the strength of vortices at leading edge.

Ouyang (2009) studied the effect of tapering vane on sediment management in alluvial channel through numerical study. He observed that under constrain of constant surface area and height of vane, performance of vane as a sediment manager was enhanced with lower tapering ratio (tapering ratio is defined as the ratio of top width of tapered vane to its base width). Ouyang (2009) also observed that by keeping the base width of tapered vane constant and increasing the vane height, performance of tapered vane was deteriorated as sediment manager in alluvial channel.

Ouyang and Lin (2016) numerically studied the effectiveness of rectangular vane, swept vane and tapered vane arranged in a row having three vanes in it to manage the sediment. They observed that tapered vanes has raised the bed level of the bank under danger of scouring by 19% while this raise was 17% and 16% for swept and rectangular vanes, respectively. Ouyang and Lin (2016) observed that tapered vane generated secondary currents of highest magnitudes which accounted for 25.8% of longitudinal velocity while this value for swept vanes and rectangular vane was 25% and 23.5%, respectively. Ouyang and Li (2016) observed that ratio of interaction parameters between second tapered vane to first taper vane was less than 1 for small values of relative lateral spacing (ratio of lateral spacing with depth of water) and it became more than 1 for larger values of relative lateral spacing suggesting for smaller relative lateral spacing first tapered vane dominated the flow while for larger relative lateral spacing the second tapered vane overpowers the first vane. Ouyang and Lin (2016) observed that a threshold value exists for each type of vane for which dominance of each vane was equal and they deduced that for rectangular, swept and tapered vane the threshold value was 0.53, 0.68 and 0.76, respectively.

Since, the previous studies have been done for optimization of angle of attack of single non-rectangular shaped vanes but none of the study is available in literature which talks about optimization of rest of tapered vane parameters (as shown in Fig. 2) and flow around and downstream of tapered vane. Hence, in present study, parameters of tapered vanes have been optimized for single tapered vane using ANSYS-CFX to generate secondary currents of maximum strength so that tapered vanes may be used to manage the sediments effectively in the fluvial system.

2. METHODOLOGY

In the beginning, to prepare the model of a submerged vane, a volume is created of the dimensions, 10 m long, 0.910 m wide and 0.152 m deep. At 2m from the inlet of the prepared channel volume, a cuboidal volume is made having the dimensions as of 0.152 m long, 0.001

Fig.1 Tapered submerged vane being used in river Kosi in Nepal (Sharma, 2016).

m thick and where the height of this volume varied in the range of 0.038-0.114 m, as shown in Fig. 3. The smaller cuboidal volume, was thus, trimmed for different sweep angles which ranged from 10^{o} to 35^{o} while the angle of attack of this volume was varied in the range of 10^{o}-45^{o}. After finishing the geometry, process of blocking was initialized by choosing 3D blocking option. Blocking is the process to create a block or partition around the area of interest in which flow features will be captured at the microscopic level. Hence, during the blocking process, a block or a partition like structure is developed around the tapered vane to make it coincide with the vane geometry. The significance of 3D blocking initialization is that it confirms that the geometry drawn is three dimensional and hence meshing which will be done post blocking will be a three dimensional mesh. In order to develop the block around the vane, the edges of vane

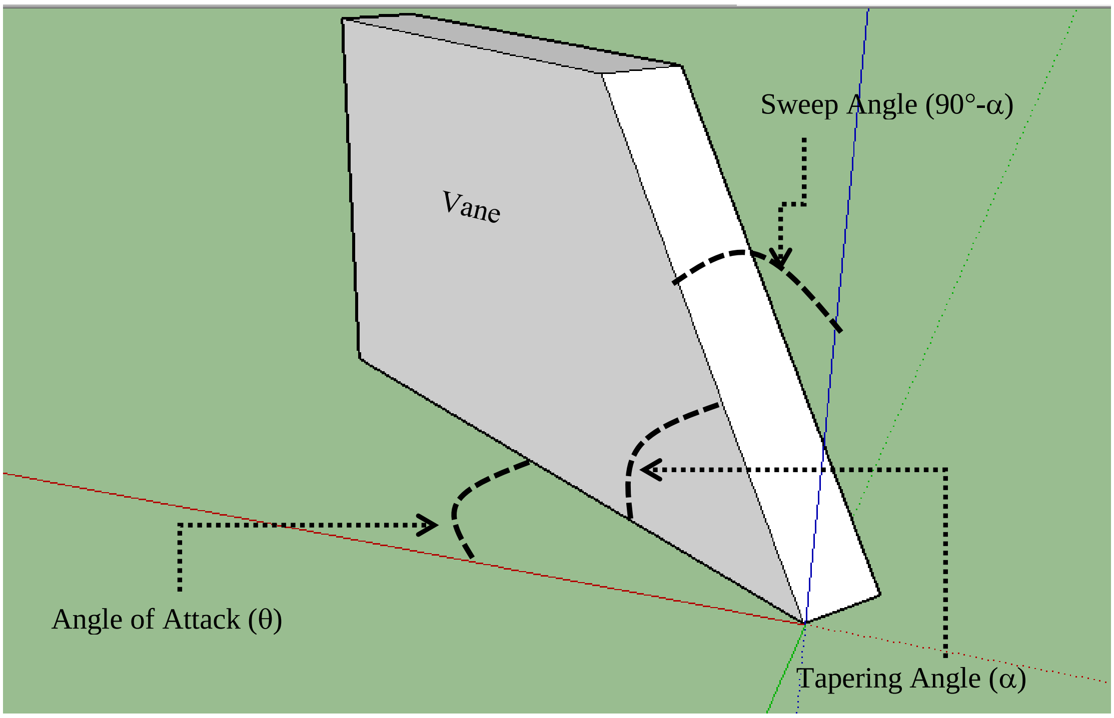


Fig. 2. Different parameters of tapered vane.

were split or bifurcated by using ‘Split edges’ option as shown in Fig. 4. As the edges were split, it leads to development of the vertices over the surface. These developed vertices remained unassociated with the points available on the geometry as their number were in excess to the points available. These non-associated vertices may lead to creation of unwarranted mesh elements during the meshing of edges. Thus, in order to associate these extra vertices, points were projected on the surfaces of channel geometry. The vertices then were associated with the projected points and thus completing the formation of blocking around the tapered vane. After the block surface is developed in the tapered vane, it is further assigned as a ‘SOLID’ boundary. The significance of providing the solid boundary to the block formed in the tapered vane is to make that block impermeable to the flow occurring in the geometrical domain as to make the flow to pass around the vane not go through it. The size of the mesh (global mesh size) element was assigned as 10 mm. One of the advantage of doing blocking is that when meshing of geometry is done then the mesh size reduces logarithmically to a lower value in the block to capture the miniscule flow features and outside the area of block mesh again regains the size which was originally assigned to it. After completion of blocking and meshing, mesh quality was checked so as to check its workability. In present study, it was observed to be within the range of 0.875 to 0.963. Since, ICEM CFD manual (2011) suggested that in order to make a mesh workable, the mesh quality value should be greater than 0.3. Hence, given mesh have a very high workability to capture the flow features in a precise manner. After saving the geometry, mesh file of geometry is imported to ANSYS CFX. After completion of geometry import, various surfaces of geometry were assigned the boundary in accordance with the role which they will serve, as below:

i. Inlet boundary condition

In the inlet boundary conditions, a normal flow (uniform flow) boundary condition is assumed. It is assumed that there is no lateral and perpendicular component to the longitudinal velocity. An average velocity of 0.24 m/s is set as an initial velocity at the inlet boundary.

ii. Outlet boundary condition

At the exit boundary plane, it assumed that there is no streamwise diffusion of velocity, so, the resulting velocity field can maintain the continuity of the model. An average velocity of 0.24 m/s is set at the outlet.

iii. Solid boundaries

All the solid boundaries were entitled to “WALL” boundary conditions, which represents that the flow cannot pass through these surfaces.

iv. Water surface

Water surface was modelled by assuming it to be a rigid lid which has no possibility of across flow. Further, it is also assumed that the water is flowing on the surface of this rigid lid having the same velocity as assigned to the flow at the inlet boundary.

3. Results and Discussions

a) Validation of CFD model

In the present study model of channel flume was developed and meshed in the ICEM-CFD platform and simulation was done with the help of ANSYS-CFX. The geometrical features of the channel section as well as flow conditions were developed and simulated for an experimental study conducted by Wang and Odgaard (1993). In order to check the efficacy of the developed model, the transverse velocity computed by model is compared with transverse velocities obtained experimentally in the study conducted by Wang and Odgaard (1993). It can be seen from Fig. 6 that modelled transverse velocities matched well with the experimental transverse velocities of Wang and Odgaard (1993). Thus, it showed the capability of ANSYS-CFX to model the flow around and downstream of a submerged vane in a satisfactory manner. Thus, ANSYS-CFX may be utilized effectively for parameter optimization of tapered vane and to capture the flow features around and downstream of the vane.

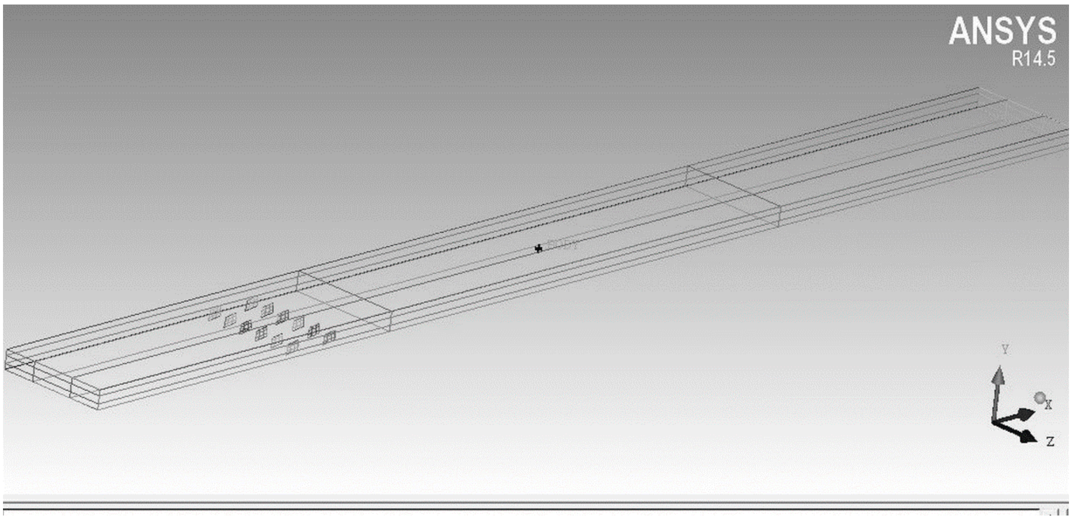


Fig. 3 Model of submerged vanes generated by ICEM-CFD.

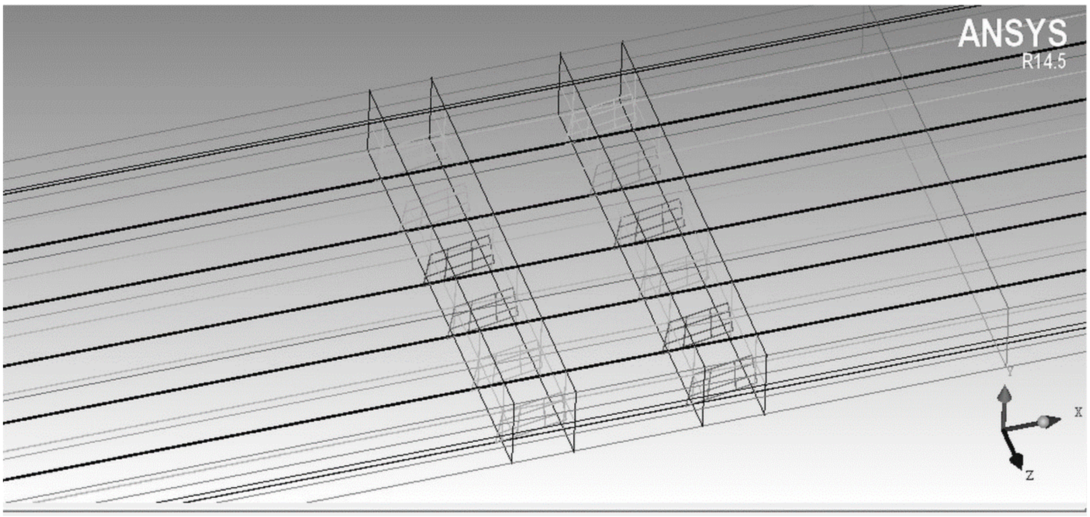


Fig. 4 Blocking of submerged vanes.

a) Sweep angle of tapered vane

Tapering angle of a tapered vane defines the inclination of the leading edge with the horizontal axis while sweep angle can be defined as the inclination of leading edge when it is measured from the vertical axis. In the present study vane of height 0.076 m, length of 0.152 m and sweeping angle varying in the range of 10^{o}-35^{o} was used. In present study, optimization of the sweep angle was done and it can be seen from Fig. 7 that for sweep angle of 10^{o}, the generated

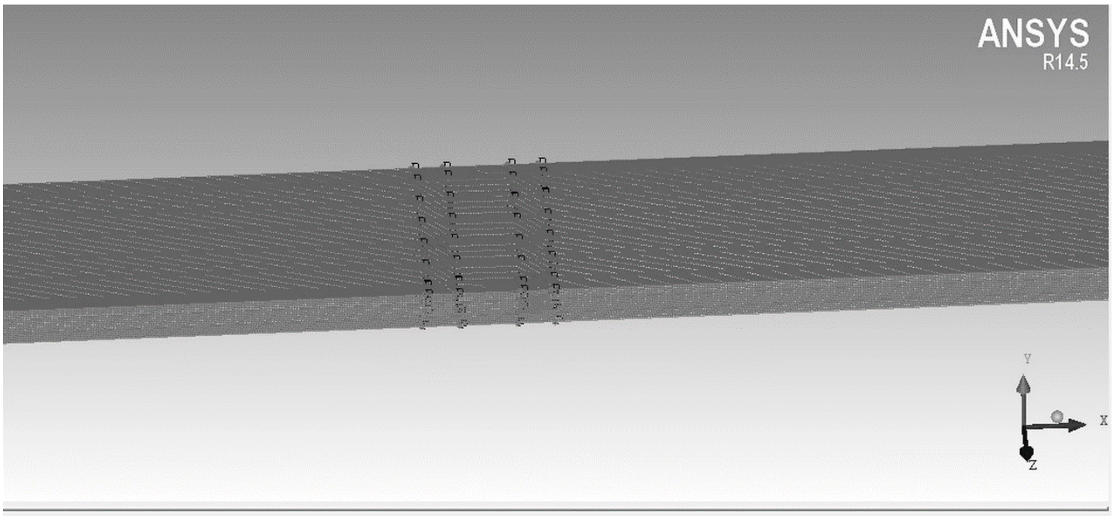
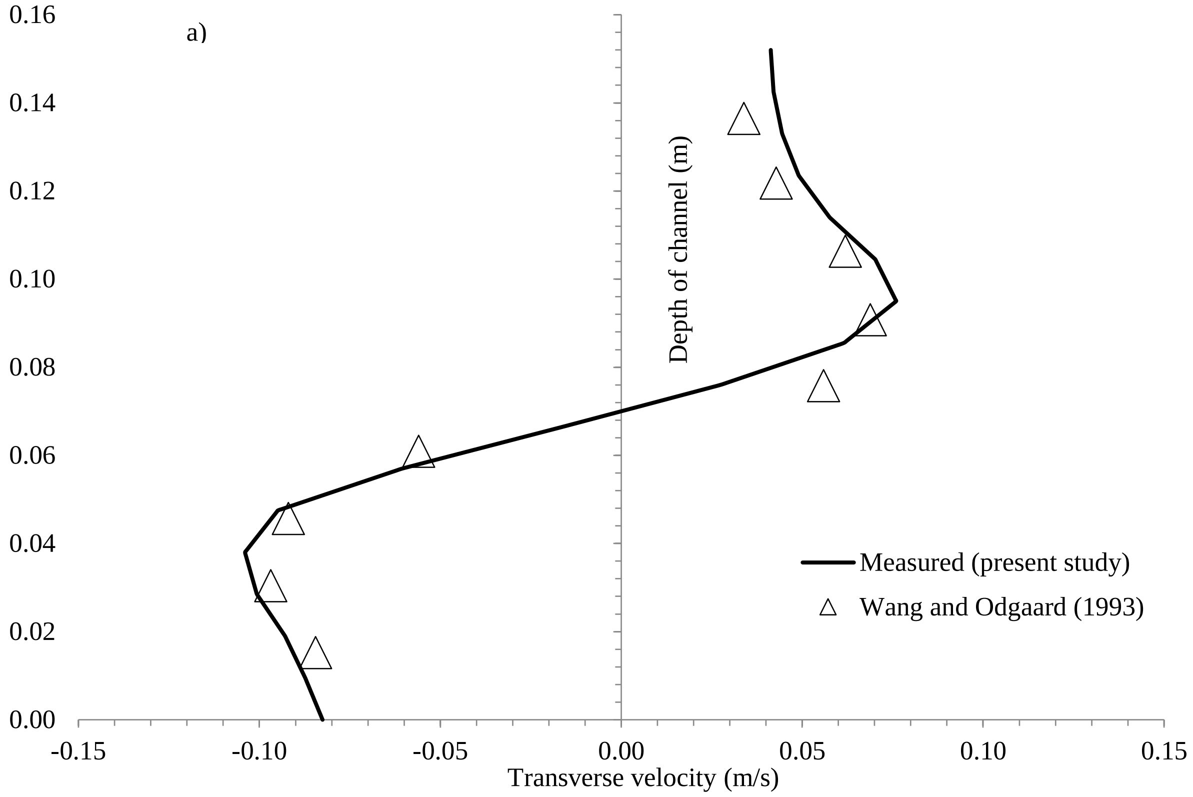


Fig. 5. Meshing of submerged vanes generated by ICEM-CFD.


a)
Depth of channel (m)
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
Transverse velocity (m/s)
Measured (present study)
△ Wang and Odgaard (1993)

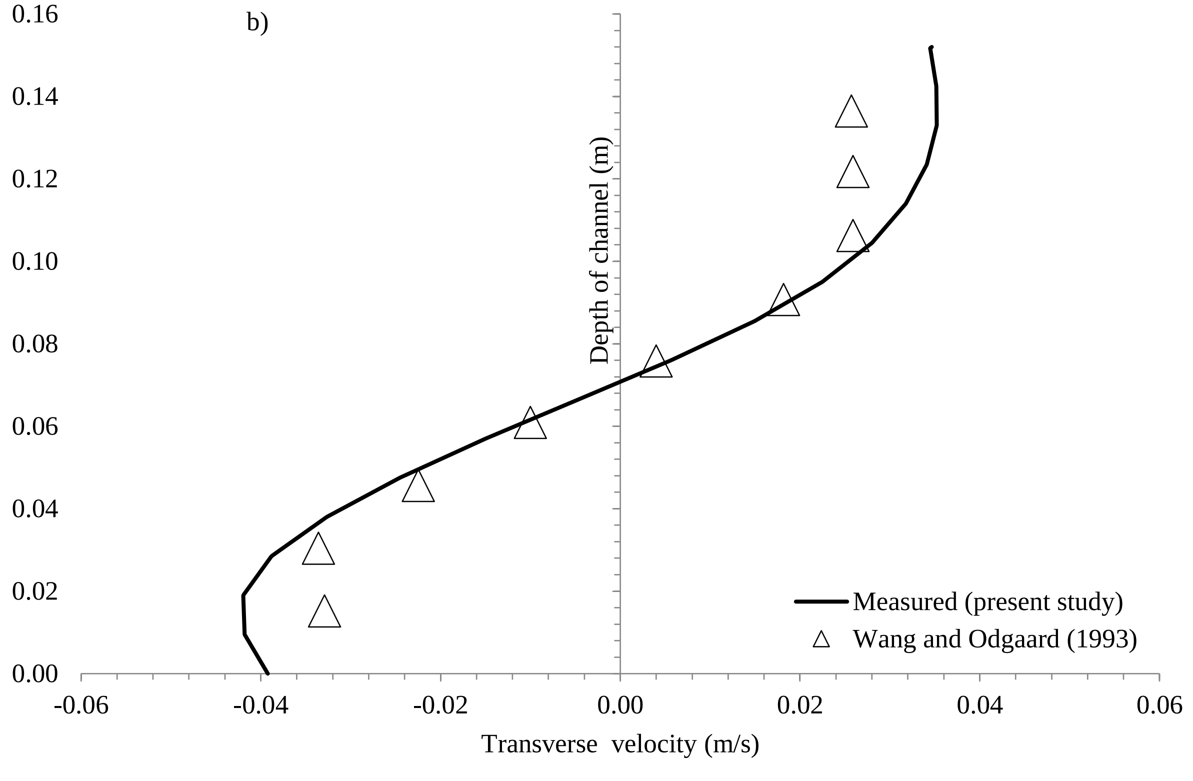

b)
Depth of channel (m)
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
Transverse velocity (m/s)
Measured (present study)
△ Wang and Odgaard (1993)

Fig. 6 Validation of model for a) x = 2H; b) x = 20H (Here, H = height of vane).

vorticity by the tapered vane is maximum and as the sweep angle was further increased, the vortcity generated by vane reduced linearly. The reason behind this reduction in vorticity with increasing sweeping angle lies in the lift force per unit length generated by vane. According to Kutta-Joukowski theorem, lift force acting over a vane is given by (Bertin & Smith, 1989; Anderson, 2007):

$$F_L = \rho U \Gamma \qquad (1)$$

Here, F_L = lift force per unit length acting over vane; ρ = density of fluid passing by vane; U = velocity of fluid approaching the vane; Γ = circulation generated by vane. It was observed to decrease causing reduction in lift force per unit length to reduce. This reduction in the lift force per unit length may be attributed to the fact that bound vortex which bound the hydrofoil is function of periphery of the hydrofoil. It will be stronger if the perimeter of the hydrofoil is bigger (Bertin and Smith, 1989). Reduction in F_L further implies reduction in the circulation and hence reduction in the induced vorticity in the flow separating from the trailing edge. Thus, it can be deduced that out of all four sweep angle 10°, 20°, 30° and 35° studied, sweep angle of 10^o induced maximum vorticity in the flow passing by the trailing edge.

b) Angle of attack of tapered vane

Angle of attack is a very essential parameter which helps in generation of secondary currents in the flow attacking the hydrofoil. Various investigators like Odgaard and Wang (1991 a), Wang and Odgaard (1993), Marelius and Sinha (1998), Sinha and Marelius (2000), Voisin and Townsend (2002), Tan et al. (2005), Sharma et al. (2016), etc., have previously investigated the rectangular submerged vane and have provided that for generation of secondary currents of maximum strength, the angle of attack should lie in the range of 2^o-40^o. For tapered vane, only Gupta et al. (2006) has proposed 45^o as an optimum angle of attack for generation of secondary currents of maximum strength while other studies have taken 20^o as optimum angle of attack as proposed by Odgaard and his associates (Odgaard and Spoljaric, 1986; Odgaard and Mosconi, 1987 and Odgaard and Wang, 1991 a).

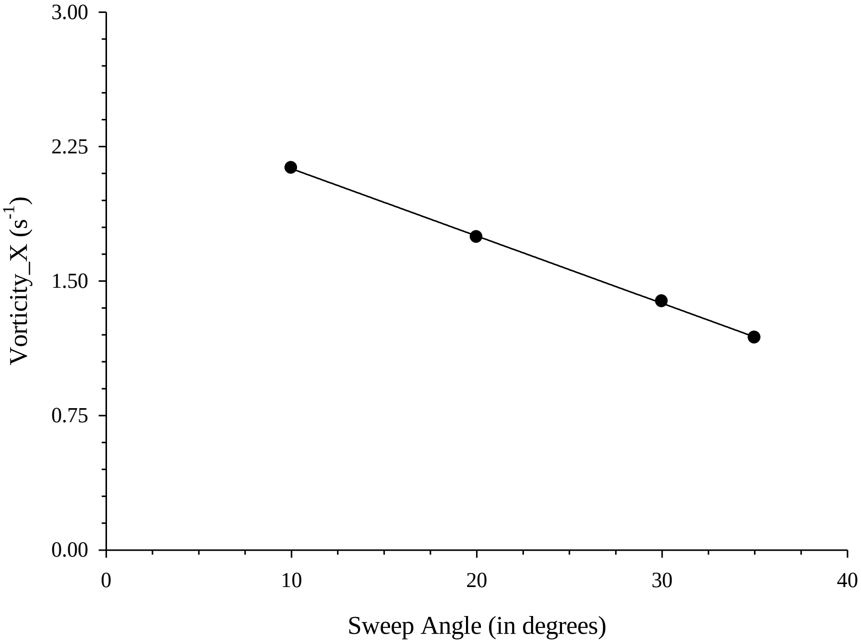


Fig. 7 Variation of vorticity with the sweep angle.

It can be seen from Fig. 8 that for the angle of attack of 17°, the vorticity generated by the tapered vane was maximum and for rest of angles of attack, the values of vorticity were reduced with increasing angle of attack. The reasoning behind the pattern attained by vorticity may be attributed to thin plate stall effect. It can be seen that as the for small angles of attack, the fluid followed the ideal potential flow pattern and hence, departed from trailing edge smoothly in order to satisfy the Kutta condition. As the angle of attack was increased, velocity gradient near the trailing edge was increased. This increment in the trailing edge velocity gradients lead to the increment in the vorticity for the flow going past the trailing edge of vane. It was observed in present study that this vortcity reached its maxima for the angle of attack of 17°. Post this angle, the large velocity gradients near trailing edge initiated the separation from trailing edge. This increment in trailing-edge separation enhanced the skin drag on the vane surface and hence, reducing the component of lift. This process is described as thin-plate stalling (Anderson, 2007). According to Anderson (2007), angle of attack of 15° is the angle after which thin plate stall starts and for the present study, this value comes out to be 17°, which is very near to the pre-described value.

c) Height of tapered vane

Height of vane defines the submergence or the depth of flow above the vane. According to Odgaard (2007) and Sharma et al. (2016), the ratio of vane height to depth of flow (*H*/*h*) is a major factor in induction of vorticity in the flow past vanes. Sharma et al. (2016) suggested that there has to be an optimum value of *H/h* for which the generated vortices induce maximum vorticity in the flow.

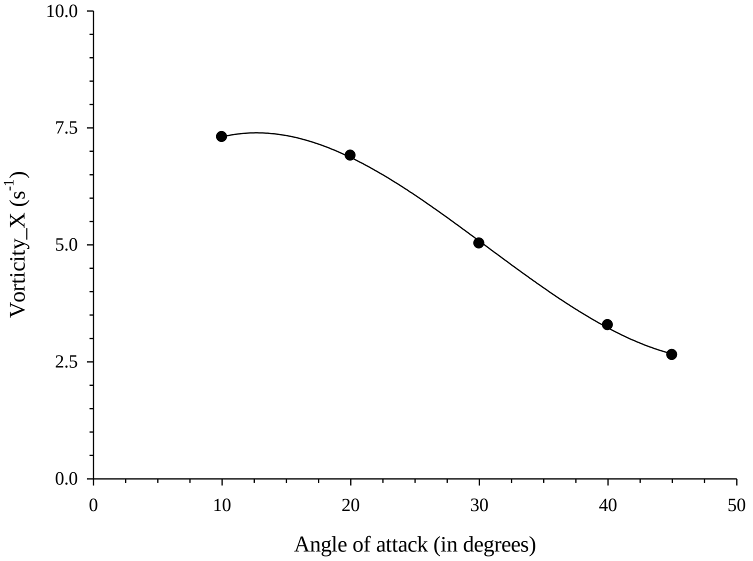


Fig. 8 Variation of vorticity with angle of attack.

In present study, it can be seen from Fig. 10, that for three different values of *H/h viz. H/h* = 0.25, 0.5 and 0.75, induced vorticity in the flow was observed. It can be seen that for *H/h* = 0.48, vorticity generated by tapered vane is maximum which is near to the *H/h* = 0.4 as proposed by Sharma et al. (2016). As suggested by Sharma et al. (2016), height of a vane is responsible for diversion of flow of core flow region towards vane and assisting to keep the vane generated vortices stable. According to Sharma et al. (2016), higher vane heights (*H/h* > 0.48) may cause hindrance of flow rather diverting it towards vanes for generation of votices and lower vane heights (*H/h* < 0.2) are small enough to attract the flow from core flow region and hence are not effective in sediment management. Thus, an optimum height is required for effective sediment management, which from present study comes out to be *H/h* = 0.48.

e) Transverse velocity downstream of the vane

Transverse velocity determines the intensity of flow being diverted in lateral direction and intensity of secondary currents (Sharma et al., 2016). Transverse velocity of flow is responsible for generation of transverse slope in a bend as studied by Zimmerman and Kennedy (1978), Odgaard (1981), Odgaard (1982), etc., which depicts the extent of bed erosion in a river bend. Odgaard and Kennedy (1983) and Odgaard and Mosconi (1987) showed that submerged vanes are effective in generating the secondary currents which have their direction of rotation in opposite direction to the bend-generated secondary currents. Thus, vane generated secondary currents nullify the effect in bend generated secondary currents and hence stall the erosion. Hence, it is a necessity to study effect of tapering angle on the transverse velocity for tapered vane which is a predominant factor affecting the generation of secondary currents from vane.

It can be seen from Figs. 11 a-b that there is a linear increase of transverse velocity from bed to a height of 0.2 times depth of flow (*h*) where maxima of transverse velocity was observed. After which an inflexion in the profile at mid-depth was observed where the transverse velocity becomes zero and again increase until surface of water is reached. It was observed that for sweep angle of 10^o, the magnitude of transverse velocity was maximum. Thus, this suggests that for sweep angle of 10^o, the magnitude of vane generated secondary currents was maximum.

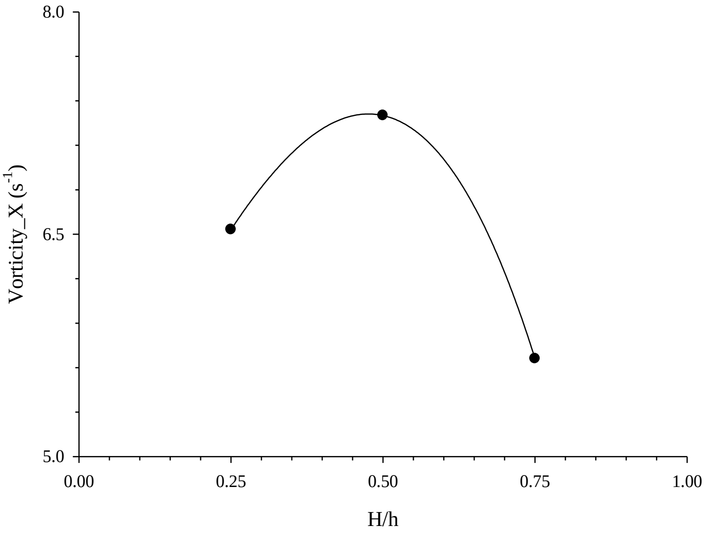


Fig. 10 Variation of vorticity with relative height of vane.

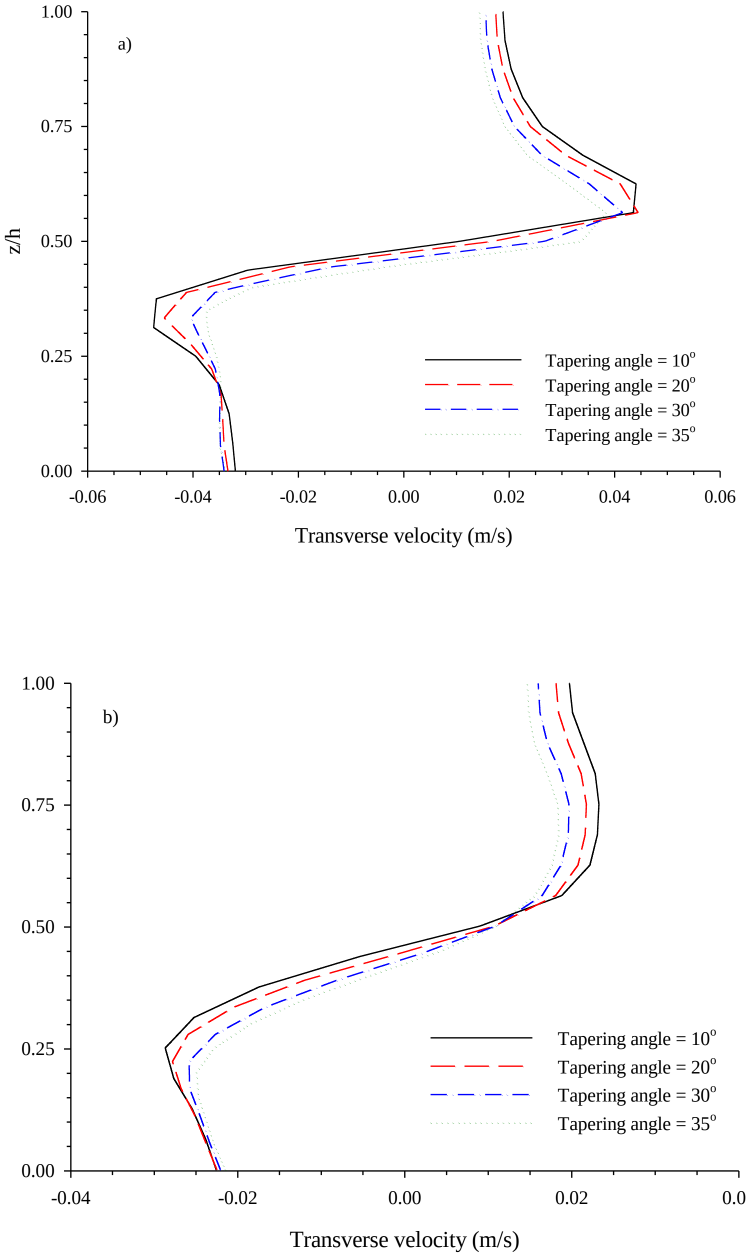


Fig. 11 Variation of transverse velocity with tapering angle for a) x = 2H & b) x = 20H.

4. Conclusions

From the present study following points can be concluded:

1. Tapered vane generates the secondary currents of maximum strength for sweep angle of 10^o due to the stronger bound vortex than other tapering angles.
2. For angle of attack of 17^o, the secondary currents generated have maximum strength. This value is near to the value of angle of 15^o post which thin plate stalling initiates causing dip in the lift generation for any hydrofoil.
3. It was observed that for relative height of vane (H/h) of 0.48, the generated vorticity in the flow downstream of vane was maximum and hence was the strength of secondary currents.

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