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# 1 Cavitation control using passive flow control techniques

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## 12 Abstracts

13 Passive flow control techniques, and particularly vortex generators have been used successfully in  
14 a broad range of aero- and hydrodynamics applications to alter the characteristics of boundary  
15 layer separation. This study aims to review how such techniques can mitigate the extent and  
16 impact of cavitation in incompressible flows. This review focuses first on vortex generators to  
17 characterize key physical principles. It then considers the complete range of passive flow control  
18 technologies; including surface conditioning and roughness, geometry modification, grooves,  
19 discharge, injection, obstacles, vortex generators, and bubble generators. The passive flow control  
20 techniques reviewed typically delay and suppress boundary layer separation by decreasing the  
21 pressure gradient at the separation point. The literature also identifies stream-wise vortices that  
22 result in the transfer of momentum from the free stream to near-wall low energy flow regions. The

23 area of interest concerns hydraulic machinery, whose performance and life span are particularly  
24 susceptible to cavitation. The impact on performance includes a reduction in efficiency, and  
25 fluctuations in discharge pressure and flow, while cavitation can greatly increase wear of bearings,  
26 wearing rings, seals and impeller surfaces due to excessive vibration and surface erosion. In that  
27 context, few studies have also shown the positive effects that passive controls can have on the  
28 hydraulic performance of centrifugal pumps, such as total head and efficiency. It is conceivable  
29 that a new generation of design in hydraulic systems may be possible if simple design features can  
30 be conceived to maximize power transfer and minimize losses and cavitation. There are still  
31 however significant research gaps in understanding a range of impact factors such as  
32 manufacturing processes, lifetime, durability, and essentially how a static design can be optimized  
33 to deliver improved performance over a realistic range of operating conditions.

34 Keywords

35 Passive flow control, Cavitation control, Vortex generator, Boundary layer separation

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Nomenclature

ACL	Anti-cavitation Lip	Ra	roughness
c	Hydrofoil chord	Re	Reynolds number
CGs	Cavitating bubble Generators	Re <sub>θ</sub>	Reynolds number based on momentum thickness
CCGs	Cylindrical Cavitating bubble Generators	R-T	Rayleigh-Taylor
C <sub>D</sub>	Drag coefficient	S	Hydrofoil Span
C <sub>pmin</sub>	Minimum pressure coefficient	TLV	tip-leakage vortex
GEMS	gas entrapment by micro-textured surfaces	U <sub>∞</sub>	Free-stream stream-wise velocity
h	Device height	VG	Vortex generator
h/δ	Device height to boundary layer thickness ratio	X <sub>VG</sub>	Distance between the leading edge and vortex generators
K-H	Kelvin-Helmholtz	z	distance between two Doublet Wheeler or Wishbone Wheeler vortex generators
l	Device chord length	α	Angle of attack
L	Distance between two counter-rotating vortex generators' ends	β	Device angle of incidence
LSB	laminar separation bubble	δ	Boundary layer thickness
m	Vortex Generators spacing in the span-wise direction between two pair of counter-rotating vortex generators	Δh	height of the cavity
mVG	Micro Vortex Generator	Δs	distance between the leading edge roughness and the re-entrant jets
n	Gap ratio of between two counter-rotating vanes	ΔX <sub>VG</sub>	Distance between the vortex generators trailing edge and

			baseline line	separation line
NPSH	Net Positive Suction Head	$\lambda$	Distance between two co-rotating vortex generators	
OHG	overhanging grooves	$\sigma$	Cavitation number	
PIV	Particle image velocimetry			

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## 45 Introduction

46 Cavitation is defined as the appearance of vapor cavities due to phase change in a liquid medium  
 47 <sup>1</sup>. Hydraulic machinery in industries have been experiencing many challenges which are associated  
 48 with the cavitation phenomenon include noise <sup>2</sup>, vibration <sup>3</sup>, material damage <sup>4</sup>, and reduced  
 49 efficiency/performance <sup>5</sup>.

50 Since the initial investigation of Reynolds<sup>6</sup>, there have been many studies that have attempted to  
 51 improve our understanding of the nature of the phenomenon; focusing, amongst others, on  
 52 processes involved in the formation of cavitation vapor, the dynamics of bubble detachment, the  
 53 behavior of boundary layers, and more recently, on how the strength, extent, dynamics, and impact  
 54 of cavitation may be controlled or mitigated. The two essential prerequisite conditions needed for  
 55 cavitation to develop are the presence of favorable bubble inception sites and the opportunity for  
 56 the liquid pressure to fall below the saturation pressure. Dissolved gas in the liquid medium can  
 57 also play a role in the activation of nucleation sites. These prerequisites commonly occur in  
 58 hydraulic machinery. Sudden pressure drops over impellers and blades occur as energy in the flow  
 59 is transferred to kinetic energy in the volute and around impeller blades <sup>7</sup>.

60 Initially, the bubbles in the oncoming stream on a hydrofoil or generally a surface were assumed  
 61 to be micron-sized nuclei in the liquid and they would move along the streamline close to the solid

62 surface. Observable bubbles of 1 mm or larger were deemed to initiate cavitation. Nuclei present  
63 in incident-free streams are a primary source of these bubbles. Nuclei passing close to the front  
64 stagnation point will experience large fluid accelerations and pressure gradients since the  
65 streamlines encountering the low-pressure region are close to the surface. The initial growth phase  
66 in all cases was characterized by a spherical cap. Bubbles are separated from walls by thin layers  
67 of liquid of a thickness equal to the boundary layer. Once the bubble enters an area of adverse  
68 pressure gradient, it begins to be pushed inward, resulting in a wedge-shaped profile. Thus, the  
69 bubble collapse begins on the exterior frontal surface, often resulting in the bubble breaking into  
70 forward and aft bubbles. This phase is called bubble travelling cavitation<sup>8-10</sup>.

71 As the bubble grows, it develops substantial span-wise vorticity as it interacts with the boundary  
72 layer. As a result, the cavitating vorticity within a bubble is concentrated as the collapse proceeds,  
73 transforming it into one (or several, or even more) cavitating vortex with a spanwise axis. When  
74 the vortex bubbles collapse, they reappear as a cloud of small bubbles. There is an occasional  
75 occurrence where bubbles pass the point where the laminar separation occurs and subsequently  
76 develop locally attached cavitation streaks at the lateral or span-wise extremities of the bubble.

77 This trailing edge of attached cavitation, which is attached to the solid surface, eventually extends  
78 out behind the main bubble. Consequently, the main bubble collapses first, leaving the tails to  
79 persist for a fraction longer. At this point an attached cavity is generated which can evolve to other  
80 type of cavitation such as cloud cavitation or supercavitation (Table 2)<sup>9,11</sup>.

81 Once formed, cavities will eventually collapse or release clouds that will collapse resulting in a  
82 shock wave<sup>12</sup>, and a focus of energy toward walls which typically lead to cavitation erosion and  
83 noise. Over the past four decades, significant research effort has been dedicated to investigate how

84 cavitation may be controlled. This work has tended to focus on extruded profiles from hydrofoils,  
85 propellers, pumps, and turbine blades.

86 Stabilizing cavity resonance or reducing volume of wall and near wall cavities are two solutions  
87 to control, reduce or eliminate cavitation. The presence of nuclei and micro-bubbles within liquids  
88 and at solid surfaces, surface characteristics, and Reynolds number are some factors that affect  
89 cavitation<sup>13-17</sup>. Adjustment or modification of one or all of these parameters can allow for effective  
90 cavitation control. However, the most important parameters which impact cavitation have been  
91 linked to the control of boundary layer separation<sup>1, 18, 19</sup>.

92 The laminar separation can be generated downstream of an adverse pressure gradient and make a  
93 low pressure region. The separated layer can then shelter the oncoming flow and generate an  
94 attached separation cavity with low pressure at the core. It was found that suppressing or  
95 eliminating this separation can effectively delay or suppress the formation of an attached cavity<sup>20</sup>.  
96 The higher momentum of the turbulent flow improves its ability to resist adverse pressure gradient  
97 over convex surfaces and hence limit the incidence of separation<sup>1, 21</sup>. Compared to turbulent  
98 boundary conditions, a laminar boundary flow is more likely to separate, resulting in a higher drag  
99 penalty. The control of boundary layer separation achieved by triggering an early transition to a  
100 turbulent boundary layer is therefore beneficial both in terms of its effect on drag and on cavitation.  
101 Other solutions have been considered and have shown varying degree of effectiveness.

102 Flow control techniques can be defined as tools to change the natural state of fluid flows and their  
103 transition into more controlled and desired flow conditions<sup>22</sup>. Flow control strategies are divided  
104 into two types: passive and active. Passive solutions include devices that do not rely on the  
105 controller or energy sources needed for active control<sup>23</sup>. Passive and active can be effective  
106 techniques to manipulate and change wall-bounded or free-shear flows. This change can be made

107 by delaying or inducing advanced transition, suppressing or boosting turbulence, and provoking  
108 or suppressing separation. These changes can increase lift, decrease drag, suppress flow-induced  
109 noise, and induce vortex mixing. Devices and structures that can manipulate the fluid dynamics of  
110 a system without an external power source include vortex generators (VGs), tailored surface  
111 roughness, injection and discharge channels, and surface obstacles, as well as grooves to redirect  
112 flow and change vortices regime.

113 Active controls include wall temperature increase, dynamic surface modification by deformation  
114 or movable parts, and injection or flow oscillation using blowing, suction, and synthetic jets <sup>24</sup>.

115 This article aims to review studies focused on passive flow controls applied to cavitation. Amongst  
116 these, VGs are regarded as the most effective and simplest technique and have been used in many  
117 applications such as airfoils, wind turbine blades, swept wing, and heat exchangers <sup>25</sup>. Apart from  
118 their effectiveness on boundary layer separation, their simple design, low cost, and lower drag  
119 make them an effective tool in a broad range of applications <sup>26</sup>. Because of this, while other passive  
120 flow control technologies are also reviewed, a particular emphasis has been placed on VGs.

121 The application of passive flow control in compressible external aerodynamics has a significant  
122 history. Although there is a noticeable difference between compressible and incompressible flows  
123 in the behavior boundary layer separation <sup>27</sup>, passive flow control studies in compressible flow can  
124 be a good guide and pattern for incompressible flow cavitation. It is possible to correlate the  
125 compressible flow boundary layer behavior to the incompressible flows using three assumptions:  
126 1) the boundary layer is regarded as thermally insulating, 2) the viscosity changes with absolute  
127 temperature, and 3) the flow Prandtl number is unity <sup>28</sup>. The first section of the article reviews the  
128 literature on compressible single-phase flow studies. In the next section, different passive flow

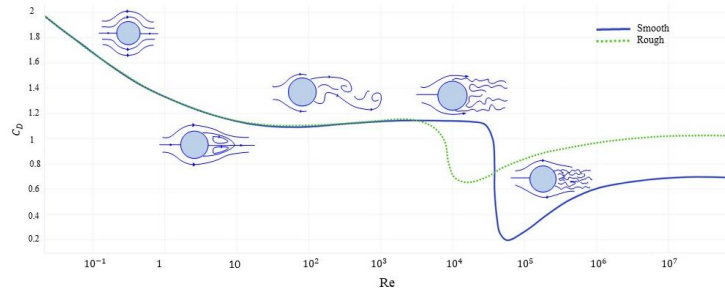


129 controls are reviewed in the context of cavitation. The last section concludes on key results and  
130 promising open research topics.

## 131 1. Passive flow control techniques in single-phase flow

132 In most aerodynamic applications, such as external flow over aircraft and ground vehicles, and  
133 internal flows such as diffusers, boundary layer separation is typically an undesirable phenomenon.  
134 Depending on the nature of the wake, separation induces periodic or random pressure variations.  
135 Boundary layer separation also leads to weaker lift, increased drag, and energy losses. Finding  
136 ways to control separation and, if possible, prevent it <sup>29</sup> is clearly desirable assuming the applied  
137 control method has no impact on efficiency or energy consumption.

138 The idea of using passive flow control and vortex generation in hydro- or aerodynamic applications  
139 is well established and has led to a broad range of studies. Since the late 1990s, several  
140 investigations have been focused on the effectiveness of using different passive flow control  
141 methods on boundary layer separation and aerodynamic performance <sup>25</sup>. According to the analysis  
142 of drag coefficients for various Reynolds numbers on a smooth sphere compared to a rough sphere  
143 or one with an obstacle, a drag crisis occurs at lower Reynolds numbers, also affecting boundary  
144 layer separation (Figure 1) <sup>30,31</sup>.



145

146 *Figure 1 - Dependency of drag coefficient on Reynolds number for a smooth and rough sphere.*

147 The results of these studies guide the implementation of passive control methods in cavitation  
 148 studies. Vortex generators, distributed roughness, leading-edge slats<sup>32,33</sup>, flow vanes<sup>34</sup>, leading-  
 149 edge serrations<sup>35</sup>, slotted airfoils<sup>36</sup> and suction and blowing techniques<sup>24,37,38</sup> have all been  
 150 considered for application in external aerodynamics .

151 There is ample evidence that increased surface roughness can be harnessed to induce vortex  
 152 shedding, insert energy into the boundary layer, and trigger an early transition to turbulence. This  
 153 has been shown to delay boundary layer separation and increase the extent of the attached flow  
 154 region<sup>39,40</sup>. Effects reported include lift recovery and noise reduction<sup>41,42</sup>. Surface roughness is  
 155 also effective in postponing stall phenomena and improving an airfoil's aerodynamic performance  
 156<sup>40</sup>.

157 VGs were initially introduced as small aerodynamic devices attached to a part of an aerodynamic  
 158 vehicle. They are able to generate a small vortex downstream. VGs can have a similar effect  
 159 transferring momentum from the free stream to the near wall region. They can provide one of the  
 160 most practical means to control flow separation over airfoils because of their small size<sup>43</sup>. Benefits  
 161 include increased lift, delayed stall and drag reduction. Most of the published research in this field  
 162 concentrates on finding a design that optimizes the vortex generators' height, geometry and

163 location upstream of the separation line. The most important parameters are the geometry, the  
164 height  $h$ , the height to pitch ratio,  $h/\delta$ , the array layout,  $\Delta X_{VG}$ ,  $l/h$  and  $\beta$ . Different VG designs  
165 and their important parameters are shown in Figure 2.

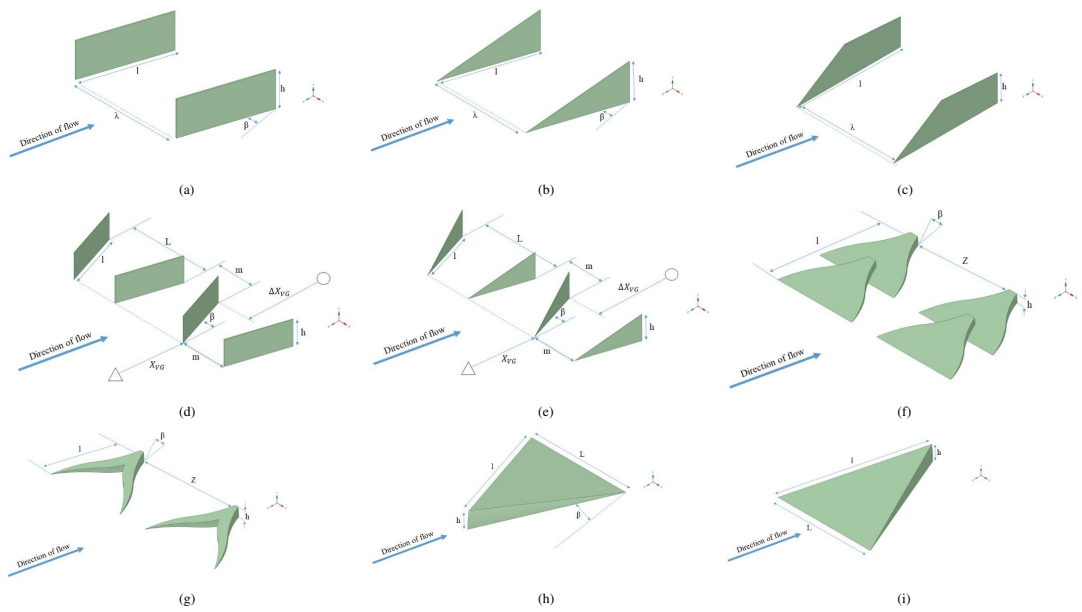


Figure 2 - Schematic of vortex generators with key design parameters, (a) Co-rotating Rectangular Vortex generators, (b) Co-rotating Delta-shaped Vortex Generators, (c) Co-rotating Goring Vortex Generators, (d) Counter-rotating Rectangular Vortex Generators ( $m=0$  joined vanes and  $m>0$  spaced vanes), (e) Counter-rotating Delta-shaped Vortex Generators ( $m=0$  joined vanes and  $m>0$  spaced vanes), (f) Doublet Wheeler Vortex Generators, (g) Wishbone Wheeler Vortex Generators, (h) Forward Wedge (Micro-ramp) Vortex Generators, (i) Backward Wedge (Micro-ramp) Vortex Generators, which  $h$ =Device height,  $l$ = Device chord length,  $m$ =Vortex Generators spacing in the span-wise direction between two pair of counter-rotating vortex generators,  $\beta$ =Device angle of incidence,  $X_{vg}$ = Distance between the leading edge and vortex generators,  $\Delta X_{vg}$ =Distance between the vortex generators trailing edge and baseline separation line,  $L$ =

*Distance between two counter-rotating vortex generators' ends,  $\lambda$  = Distance between two co-rotating vortex generators and Z = distance between two Doublet Wheeler or Wishbone Wheeler vortex generators*

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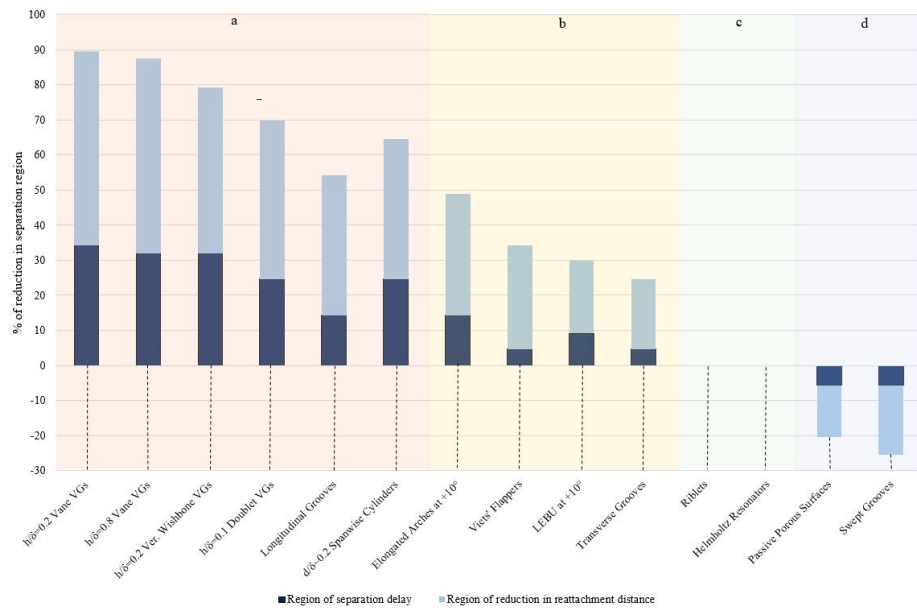
167 Inducing stream-wise instabilities and vortices is one of primary ideas for suppressing the  
168 boundary layer separation. In the 1970s, Kuethe<sup>44</sup> observed a type of centrifugal instability called  
169 Taylor–Goertler that can lead to the formation of arrays of stream-wise vortices over a concave  
170 surface. They tested wave-type VGs and with  $h/\delta$  in the range 0.27 to 0.42. They observed that  
171 VGs caused stream-wise vortices in the boundary layer because of a Taylor–Goertler instability.  
172 VGs were used to suppress the Kármán vortex stream and to reduce acoustic disturbances in the  
173 wake area. They could also confine the velocity deficit region in the wake resulting in improved  
174 performance.

175 Rao and Kariya<sup>45</sup> investigated so-called submerged VG where the VG height was kept smaller  
176 than the boundary layer ( $h/\delta \leq 0.625$ ). A comparison with conventional VGs ( $h/\delta \sim 1$ ) showed  
177 that a much lower parasitic drag and better performance in boundary layer separation could be  
178 achieved by confining the VG in the boundary layer. Since this seminal work, research has focused  
179 on these so-called submerged VGs <sup>45-49</sup> which have also been called micro-VGs <sup>50-53</sup>, sub-  
180 boundary-layer VGs <sup>54,55</sup>, and micro-vanes <sup>56</sup>. It has been shown in particular that VGs with  $0.1 \leq$   
181  $h/\delta \leq 0.5$  could provide sufficient momentum transfer towards the wall and over extended  
182 downstream region. With a smaller footprint, submerged VGs have also proven to be more  
183 versatile for a wider range of applications.

184 Research on micro-vortex generators (mVGs) has targeted two main research questions; how  
185 effective are mVGs at delaying boundary layer separation and what type of vortical flow is  
186 generated downstream. A summary is presented in Table 1 where studies are classified based on  
187 the VGs characteristic parameters such as geometry and location for effective flow control <sup>26</sup>.

188 Lin et al. conducted important experimental studies on the mVGs effectiveness on boundary layer  
189 using a 2D backward-facing curved ramp at low speed at NASA Langley Research Center <sup>46, 47, 49</sup>.

190 <sup>50</sup>. They tested numerous mVGs and other passive flow control methods. Their performance  
 191 measured in terms of the relative reduction in the extent of the separation region is shown in Figure  
 192 3, with the VG geometries defined in (a, d, f and g). The most effective methods, such as mVGs  
 193 and large longitudinal surface grooves, were shown to generate stream-wise vortices. mVGs  
 194 (counter-rotating and co-rotating vane-type VGs with  $h/\delta \sim 0.2$  and  $h/\delta \sim 0.8$ ) and Wheeler VGs  
 195 (wishbone and doublet) were found to have almost the same effects on separation delay.  
 196 Other methods such as span-wise cylinders and transverse grooves generated higher form of drag and  
 197 proved less effective <sup>47, 49, 50</sup>.



198

199 *Figure 3 - Effectiveness of micro-vortex generators and other passive flow control methods on the extent of the separation region.*  
 200 *(a) A group of devices that generates stream-wise vortices and proved most effective at suppressing boundary layer separation;*  
 201 *the submerged vortex generators being the most effective, and longitudinal producing the lowest effect (b) Devices that generate*  
 202 *transverse vortices, which are still effective; span-wise cylinders and transverse grooves having the highest and lowest effect*

203 respectively (c) The drag reducing riblets and Helmholtz resonators have no actual effect on boundary layer separation, (d) passive  
204 porous surfaces and swept grooves have the potential to enhance boundary layer separation <sup>50</sup>.

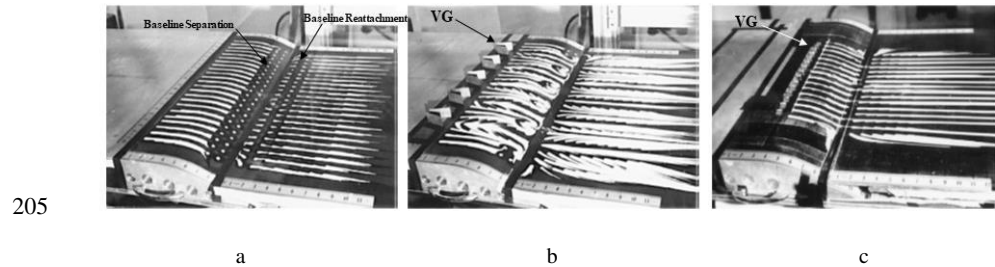


Figure 4 - Oil-flow visualizations of the effect of vortex generators for flows over a backward-facing ramp for the (a) baseline case without vortex generators which produces an obvious two-dimensional separated flow (b) Counter-rotating conventional vane-type vortex generators ( $h/\delta=0.8$ ) placed  $5\delta$  upstream of a baseline separation which could produce an attached flow downstream of the ramp albeit with strong three-dimensional features including a visible recirculation zone downstream of the separation baseline, (c) Vane-type counter-rotating vortex generators ( $h/\delta=0.2$ ) placed at  $2\delta$  upstream of baseline separation which could suppress the boundary layer sufficiently with lower three-dimensional variations in the span-wise pressure at the shoulder region of the ramp <sup>50</sup>. From Control of turbulent boundary-layer separation using micro-vortex generators, J. Lin, American Institute of Aeronautics and Astronautics, Inc, In the public domain.

206 In Figure 4, Visualization of oil flow separation downstream of the baseline surface (without VGs)  
207 (Figure 4 (a)) were compared with conventional counter-rotating VGs with flow at  $6h$  and  $10h$   
208 upstream of baseline separation (Figure 4 (b) and (c)). The results of the study found that vortices  
209 generated by conventional VGs are stronger than needed and yet are not suppressing separation,  
210 while the mVGs achieved close to a 90% reduction in separation and did not generate pockets of  
211 recirculating flow. Measurements of surface pressure along the stream-wise direction and at three  
212 span-wise locations shown in Figure 5, clarified the role of mVGs in eliminating separation. Most  
213 notable is the lower three-dimensional variability in pressure distribution along the span-wise  
214 direction on the shoulder region of the ramp.



215 Lin et al. <sup>49</sup> examined the impact of further reduction in  $h/\delta$  from 0.2 to 0.1 and observed a  
 216 deterioration in the mVG effect on separation. These results confirmed that mVGs can be more  
 217 effective in controlling flow separation than larger VG but care must be taken in determining an  
 218 effective height to boundary layer thickness ratio to avoid.  
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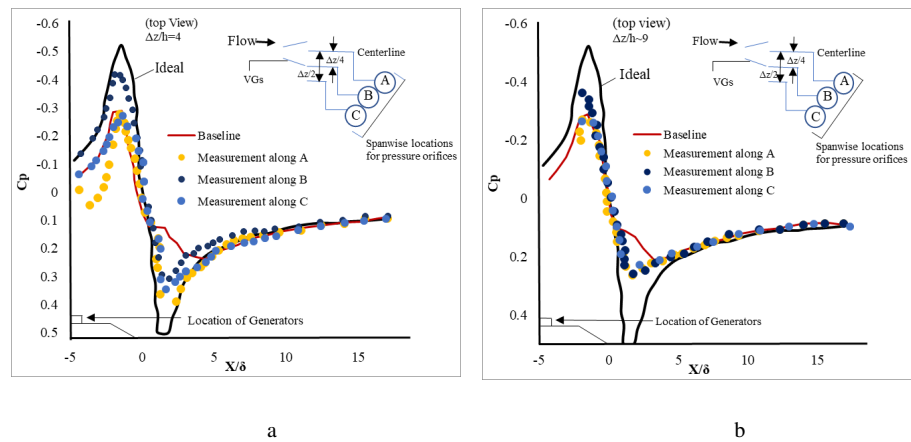
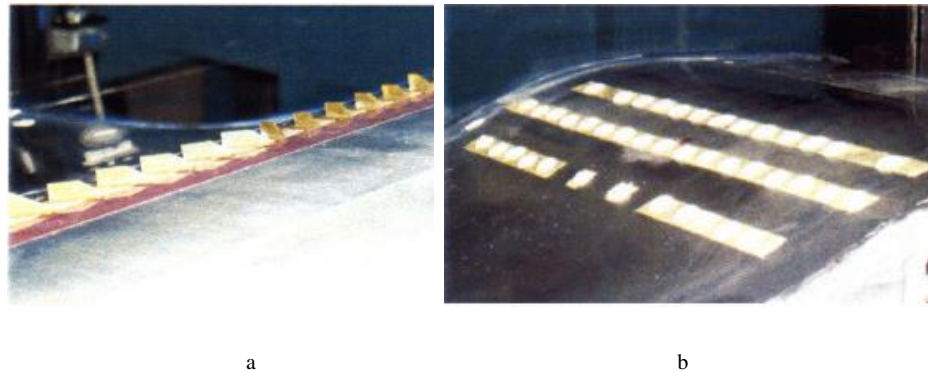


Figure 5 - Span-wise variations in the stream-wise pressure distribution with (a) conventional vane-type counter-rotating vortex generators ( $h/\delta=0.8$ ) placed at  $5\delta$  upstream of baseline separation, which shows noticeable differences between the three span-wise positions, (b) Counter-rotating vane-type micro-vortex generators placed  $2\delta$  upstream of the baseline separation, which show a lower span-wise pressure variation compared to conventional vortex generators<sup>50</sup>. From Control of turbulent boundary-layer separation using micro-vortex generators, J. Lin, American Institute of Aeronautics and Astronautics, Inc, In the public domain.

220  
 221 Ashill et al. <sup>55</sup> performed a comparative study on wedge type and counter-rotating mVGs located  
 222  $52h$  upstream of the baseline separation line. The counter-rotating mVGs (Figure 2 (e)) with a  $1h$   
 223 span-wise gap proved most effective at suppressing boundary layer separation.

224 Gorton et al.<sup>51</sup> studied the effects of mVG profile changes (Figure 6) in suppressing separation  
225 from a backward-facing ramp with co-rotating Goring VGs (Figure 2 (c)). The study relied on  
226 oil-flow visualization illustrated in Figure 7. Figure 7 (a) shows two large spiral nodes and a central  
227 reverse flow at the ramp in the baseline case. The mVGs proposed by Gorton et al.<sup>51</sup> with  
228  $h/\delta \sim 0.2$  is shown in Figure 7 (b) to alter the direction of near-wall flow sufficiently to suppress  
229 separation.

230



*Figure 6 - (a) Co-rotating Goring micro-vortex generators configured at an angle of 23 degrees to the onset flow were created by Gorton et al.<sup>51</sup>, which resulted in significant pressure gradient reduction, and (b) Installation of micro-bump arrays on the ramp with a maximum height of 10% of the boundary layer thickness<sup>51</sup>. From Flow control device evaluation for an internal flow with an adverse pressure gradient, S. Gorton, L. Jenkins, and S. Anders, American Institute of Aeronautics and Astronautics, Inc, In the public domain.*

231 Ashill et al.<sup>54, 55</sup> also studied the flow characteristics of mVGs at the UK Defense Evaluation  
232 Research Agency Boundary Layer Tunnel. They performed tests for a range of mVGs with  
233  $h/\delta \sim 0.5$ , including the single vane, counter-rotating vane-type, forwards, and backward wedges  
234 shown in Figure 2. The generated vortex strength was estimated from flow field measurements

235 using a laser doppler anemometer up to  $15h$  downstream of the mVGs <sup>55</sup> and up to  $50h$   
 236 downstream of the mVGs <sup>54</sup>. They proposed a correlation for the non-dimensional circulation and  
 237 used the concept of a mVG sufficient height <sup>55</sup>. The correlation provides a prediction of the VG  
 238 vortex strength downstream and is applicable for a wide range of Reynolds numbers. No relation  
 239 is provided, however, between the sufficient height and a physical dimension of the mVGs. The  
 240 study found that forwards-wedges and the joint-vane mVG create counter-rotating vortices sharing  
 241 a mutual interface <sup>55</sup>. Measurements indicated that this led to reduced vortex strength. The vortices  
 242 generated by backward wedge mVGs were found to be always closer to the wall impacting on wall  
 243 shear.

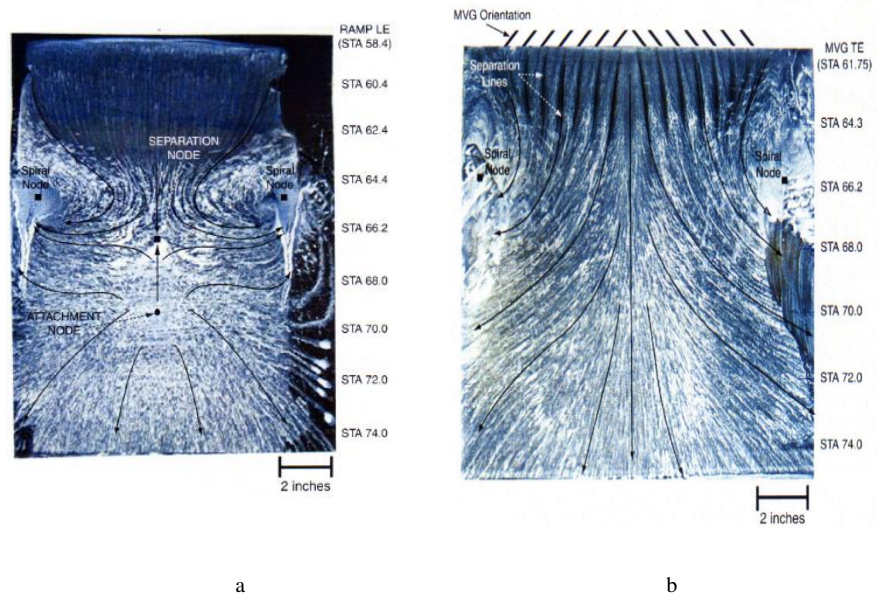


Figure 7 - (a) Oil flow visualization of baseline case for flow over a backward-facing ramp with vortex generators and at an onset velocity of 42.7 m/s. The image provides evidence of large spiral nodes and a central reverse flow. (b) Oil flow visualization of the effect of vane-type co-rotating Gothing micro-vortex generators with  $h/\delta \sim 0.2$  in comparison with the

*baseline case using which direction change of near wall flow and suppressing reversing flow is shown*<sup>51</sup>. From *Flow control device evaluation for an internal flow with an adverse pressure gradient*, S. Gorton, L. Jenkins, and S. Anders, American Institute of Aeronautics and Astronautics, Inc, In the public domain.

244 Counter-rotating vane mVGs were shown to double the vortex strength when tested up to 50  $h$   
245 downstream of the mVGs. The joined-vane and the forwards-wedge mVGs produced stronger  
246 vortex decay than the two 1 and 2  $h$  spaced counter-rotating vanes mVGs at a downstream distance  
247 of up to 15  $h$  . In terms of adverse pressure gradient, spaced vanes proved to be more efficient than  
248 joined vanes. In comparison to counter-rotating vanes, forward-wedge mVGs reduced drag by  
249 60%. According to the analysis of counter-rotating vanes, increasing the gap ratio can help  
250 decrease the generated drag of devices.

251 In other studies, Yao et al.<sup>57</sup> and Allan et al.<sup>58</sup> conducted an experimental and numerical analysis  
252 of single vane-type mVGs on a flat plate. A flow field measurement system was developed to  
253 characterize embedded stream-wise vortices downstream of mVGs. Their system consisted of a  
254 3D stereo imaging and particle image velocimetry (PIV) system covered downstream vane-type  
255 mVGs. CFD and experimental results both demonstrated that downstream of mVGs, vortices  
256 decay substantially regardless of the device incidence angle.

257 The effectiveness of wedge-shaped and counter-rotating vane mVGs interaction with shocks and  
258 boundary layer at Mach numbers of 1.5 and 1.3. was also investigated by Holden and Babinsky<sup>59</sup>.  
259 They observed that both types of mVGs affected the separation bubble under shock and the vortex  
260 intensity. Although the vane type mVGs were shown to have a stronger effect because of the higher  
261 vortex strength closer to the surface, both types of mVGs can create a wave pattern consisting of  
262 shocks, re-expansions, and shocks. Wave drag and pressure losses increase due to this pattern. It

263 was also observed that wedge-shaped mVGs generated vortices that lifted off the surface more  
264 quickly.

265 Babinsky et al.<sup>60</sup> and Ghosh et al.<sup>61</sup> conducted experimental and CFD analyses of forward wedge  
266 type mVG. The formation and evolution of multiple pairs of counter-rotating stream-wise vortices  
267 were observed downstream of the mVGs as shown in Figure 8. A low-momentum region forms in  
268 the wake of the wedge along the centerline between consecutive mVGs. The magnitude of  
269 momentum deficit was found to be proportional to the size of mVGs and inversely proportional to  
270 the drag induced by wedge-type while the two counter-rotating vortices act to transfer high  
271 momentum from the boundary layer peripheral region to the surface. Despite the strongest effects  
272 and greatest drag caused by the largest mVGs, the smallest mVGs ( $h/\delta = 0.3$ ) had similar effects  
273 on separation with lower induced drag . The results also indicated that mVGs should be located  
274 closer to the adverse pressure gradients region than traditional VGs.

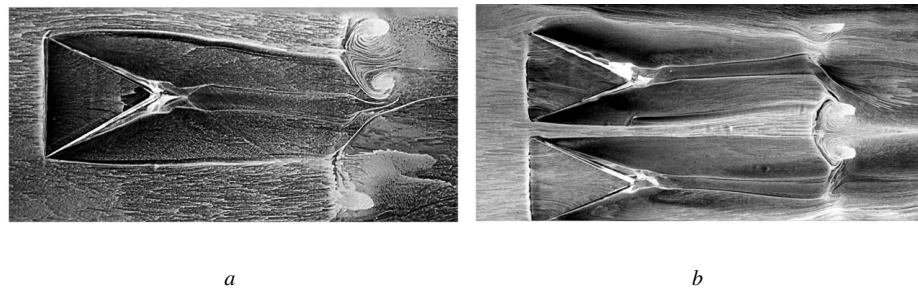
275 Dong et al.<sup>62</sup> proposed a new slotted ramp-type mVGs and numerically investigated their effect  
276 on the flow separation in supersonic flow. A more complicated wake structure was observed,  
277 including two confluent counter-rotating stream-wise vortices and an increase in number of  
278 stream-wise vortices. The interaction of these vortices with the primary counter-rotating vortex  
279 pair could increase the lifetime of vortices and boost the vortex intensity. These slotted mVGs also  
280 decrease the generated drag compared to standard micro-ramps and improve the separation control  
281 performance.

282 Sun et al.<sup>63</sup> developed a conceptual description of the evolution of the vortical structures in the  
283 wake of the micro-ramps in supersonic flows as illustrated in Figure 9. Based on Li and Liu<sup>64</sup> and  
284 Sun et al.<sup>65</sup>, velocity shear and, consequently, pressure gradients downstream of micro-ramps  
285 induce swirling vortices in an arc or ring shape. The mechanism of vortex generation can be linked

286 to Kelvin-Helmholtz (K-H) instabilities. The model of Sun et al.<sup>63</sup> depicts the dynamics of  
287 vortices in stages of K-H evolution. Initially, the stream-wise vortices generated as focused  
288 filaments which quickly lose their stability and change into arch-shape K-H vortices. The  
289 wavelength of the instability starts to increase due to shear velocity and vortex pairing increase.  
290 As the legs of the arch-shaped K-H vortices grow and merge with neighboring vortices, vortex  
291 rings are eventually formed. As a result of stream-wise vortices, downward motion is induced at  
292 this stage. Turbulent distortion eventually causes the ring vortices to break down.

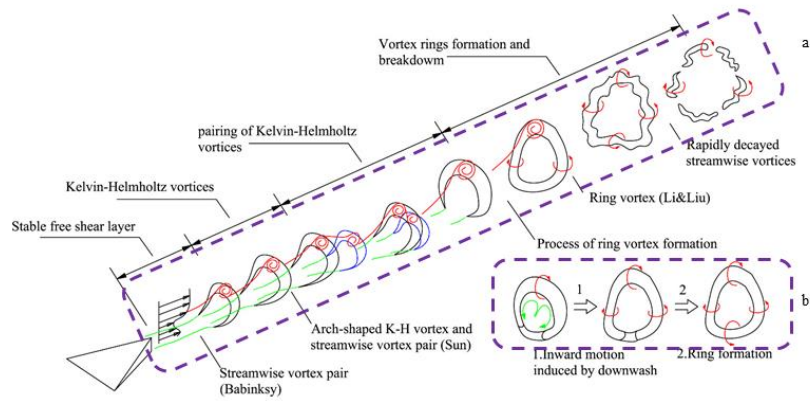
293 Sun et al.<sup>66, 67</sup> also conducted a numerical modelling to analyze the wake of micro-ramp VGs  
294 under hypersonic conditions. They observed a type of arch-type vortices that grow moving  
295 downstream and breaking the primary vortices. They found that these mVGs can generate span-  
296 wise structures caused by the impinging of the arc-like vortices. Their result showed that drag and  
297 heat flux was reduced after applying mVGs to change the cortical structure pattern.

298 Other applications of passive control in compressible flows not in the scope of this article are  
299 reviewed in detail by Akhter and Omar<sup>68</sup> and Genç et al.<sup>25</sup>.



300 *Figure 8 - A surface oil-flow visualization for flow over micro-ramp developed by Babinsky<sup>60</sup> et al. Implementation of micro-ramps*  
301 *generate a region of attached flow in its immediate downstream centerline and break down the overall separation region into small*  
302 *individual separation areas. The generation of stream-wise vortex pairs is shown to develop in both individuals and array of micro-*

303 ramps. From *Micro-ramp Control of Supersonic Oblique Shock-Wave/Boundary-Layer Interactions*, H. Babinsky, Y. Li, and C. W.  
 304 P. Ford<sup>60</sup>; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.



305  
 306 *Figure 9 - Conceptual model of vortical structures created by micro-ramps*<sup>63</sup>. (a) *The stream-wise vortex pairs are initially*  
 307 *generated immediately downstream of the micro-ramp. As a result of the instability of the curved free shear layer around the wake,*  
 308 *these vortexes developed into arc-shaped Kelvin-Helmholtz vortices. Kelvin-Helmholtz vortices pair with each other, and mean*  
 309 *shear velocity increases which cause the instability wavelength to increase. Kelvin-Helmholtz vortex rings are formed by the leg*  
 310 *portions of arch-shaped vortices extending to the bottom side of the turbulent wake. These vortex rings break down downstream as*  
 311 *a result of turbulent distortion.* (b) *process of vortex ring formation.* Republished with permission of American Institute of Physics,  
 312 *from Decay of the supersonic turbulent wakes from micro-ramps*, Z. Sun, F. Schrijer, F. Scarano, and B. Oudheusden, *Physics of*  
 313 *Fluids* 26, 025115 (2014); permission conveyed through Copyright Clearance Center, Inc.

314 Table 1- Summary of research for effectiveness of micro-vortex generators on boundary layer separation <sup>26</sup>

Investigator (s) (Year pub.)	Test condition	$U_{\infty}^i$ [m/s]	Re ( $Re_{\theta}^{ii}$ )	Mach	$\delta^{iii}$ [mm]	VG type	VG parameters					Comments
							$h/\delta^{iv}$	$l/h^v$	$m/h^{vi}$	$\beta^{vii}$ [° deg]	$\Delta X_{VG}/h^{viii}$	
Lin et al. <sup>46</sup> (1990)	Wind-tunnel test low speeds Backward-facing ramp	40.2	( $9 \times 10^3$ )	NA	32.5	Doublets	0.1	~13	8	$\pm 25$	20	Most effective Doublet VGs in separation control: $h/\delta=0.1$ .
Lin et al. <sup>47,49</sup> (1990-1991)	Wind-tunnel test Backward-facing ramp	40.2	( $9 \times 10^3$ )	NA	32.5	Wishbones	0.2	~3	4	$\pm 23$	10	Most effective Reverse Wishbone VGs in separation control: $h/\delta=0.2$ .
Lin <sup>50</sup> (1999)	Wind-tunnel test Backward-facing ramp	40.2	( $9 \times 10^3$ )	NA	32.5	Counter-rotating rectangular vanes	0.2	4	9	$\pm 25$	10	Most effective counter-rotating vanes VGs: $h/\delta=2$ . ↑ Embedded stream-wise vortices
Ashill et al. <sup>55</sup> (2001)	Wind-tunnel test Bump	20	$19 \times 10^6$ ( $35 \times 10^3$ )	0.68	33	Counter-rotating delta vanes	0.3	~10	12	$\pm 14$	52	Counter-rotating vanes VG with 1 h spacing have more potential for control boundary layer separation.
						Forward wedges	0.3	10	12	$\pm 14$	52	
Ashill et al. <sup>54,55</sup> (2001-2002)	Wind-tunnel test and CFD	10 – 40	NA	NA	60	Counter-rotating vanes	0.5	~10	NA	$\pm 14$	15	Vortex strength has been correlated with



	Flat plate					Forward wedge	0.5	10	NA	±14		device Reynolds number.
						Backward wedge	0.5	10	NA	±14	50	↓Interference between mutual vortices caused by the spacing between counter-rotating VGs.
						Single vane	0.5	10	NA	10, 20, 30, 45		↓Vortices and drag.
Gorton et al. <sup>51</sup> (2002)	Wind-tunnel test Backward-facing ramp	42.7	NA	NA	22.1	Co-rotating trapezoid vanes	0.2	4	4	23	12&9	Most rotating Co-rotating trapezoid vanes VGs: Low profile VGs induced a pair of juncture vortices.
Yao et al. <sup>57</sup> (2002)	Wind-tunnel test Flat plate	34	NA	NA	35	Single rectangular vane	0.2	0.7	NA	10, 16,	100	↑Embedded stream-wise vortex.
Allan et al. <sup>58</sup> (2002)	CFD Flat plate	34	$7.2 \times 10^6$	NA	45	Single trapezoid vane	0.2	7	NA	10, 23	15, 27, 102	CFD underestimated the peak vorticity near the VG.
Holden and Babinsky <sup>59</sup> (2004)	Wind-tunnel test Backward-facing ramp	NA	$28 \times 10^6$ ( $26 \times 10^3$ )	1.3 & 1.5	1.5	Wedge-type	1	10	12	NA	33	Both type of mVGs effects on the separation bubble under shock and vortex intensity.
						Vane-type counter-rotating	0.83	10	12		40	Vane type mVGs have stronger effect because of stronger vortices close to the surface Wave patterns that result from either mVG contain shocks, re-expansions, and shocks.

												The pressure losses result in an increase in wave drag.
Ghosh et al. <sup>61</sup> ; Babinsky et al. <sup>60</sup> (2009-2010)	Wind-tunnel test-blowdown supersonic tunnel	NA	$40 \times 10^6$	2.5	6.67	Micro-ramps	0.3 - 0.9	7.2	7.5	±24	13.3 - 16.	<p>↑The number of counter-rotating stream-wise vortices</p> <p>The largest mVGs have the strongest effect, while it also has the greatest drag.</p> <p>mVGs should be located near the adverse pressure gradients than traditional VGs</p> <p>Device height is likely to affect optimum location</p>
Dong et al. <sup>62</sup> (2017)	Wind-tunnel test-Continuous supersonic tunnel	NA	$(3.137 \times 10^4)$	1.5	1.125	Slotted Ramp-type	1.78	7.2	NA	±24	21.1	<p>↑Complex wake structure comprised of a confluent counter-rotating stream-wise vortex pair and additional stream-wise vortices</p> <p>↑ Life time, and strengthen the vortex intensity of primary vortex pairs</p> <p>↓Generated drag</p> <p>Improving the separation control performance</p>
						Ramp-type	1.78	7.2			±24	

Sun et al. <sup>66, 67</sup> (2019-2020)	Wind-tunnel test	NA	2.3 $\times 10^3$	5.0	5.17	Micro-ramps	0.25, 0.58, 0.77	7.2	NA	$\pm 24$	16.6	↓ Drag and heat flux Changing the cortical structures pattern generating span-wise structures which are caused by the Impinging of the arc-like vortices
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315 <sup>i</sup> Free-stream stream-wise velocity

316 <sup>ii</sup> Reynolds number based on momentum thickness

317 <sup>iii</sup> Boundary layer thickness

318 <sup>iv</sup> h=Device height

319 <sup>v</sup> l= Device chord length

320 <sup>vi</sup> m=Vortex generators spacing in the span-wise direction

321 <sup>vii</sup>  $\beta$ =Device angle of incidence

322 <sup>viii</sup>  $\Delta X_{VG}$ =Distance between the vortex generators trailing edge and baseline separation line

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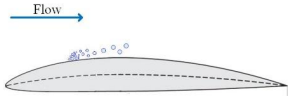
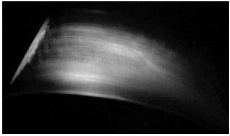





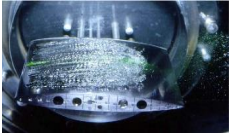
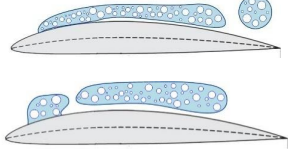
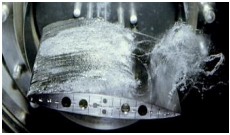
325 As a conclusion of this section, the results show that mVGs can effectively control flow separation  
326 over airfoils. The most important effects relate to boundary layer separation. The generation of  
327 stream-wise vortices in the boundary layer, transfers momentum toward near the wall, delaying  
328 and suppressing boundary layer separation, increasing lift and decreasing drag and pressure  
329 recovery downstream of VGs. The mVGs are quite efficient in suppressing shock-induced  
330 separation in supersonic flow and reducing the reverse flow region. The highest effectiveness has  
331 been observed in cases with fixed boundary layer separation by locating the VG closer than  $100h$   
332 distance upstream of baseline separation.


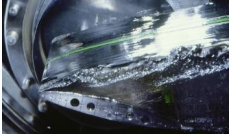


333 The geometry and arrangement of mVGs are critical parameters. The best performances have  
334 generally been reported with  $0.2 < h/\delta < 0.5$ , but effective flow separation is still possible with  
335  $0.1 < h/\delta < 0.2$ . The counter-rotating mVGs have demonstrated better efficiency in 2D flow  
336 separation tests, whereas co-rotating mVGs have been found more effective in 3D separation tests.  
337 From the literature reviewed here, the most effective distance between the upstream mVGs and  
338 the baseline separation is in the range of  $5h$  to  $30h$ .

## 339 2. Passive flow control studies in cavitation

340 In this section, we focus on passive techniques to control cavitation. Several methods, including  
341 geometry modification, injection, drainage, surface conditioning, obstacles, grooves, and VGs,  
342 have been proposed to attempt to passively control the boundary layer and cavitation instability  
343 effects. Table 2 summarizes the different types of cavitation to understand better the analyses  
344 reviewed in this article. The following sections present a review of studies of these different  
345 methods and their effects on cavitation. The summary overview of the methods and key results  
346 are presented in Table 3, Table 4, and Table 5.

347 Table 2 - a brief definition of different type of cavitation with schematics and experimental observations (a) Reprinted by permission  
 348 from Springer Nature Customer Service Centre GmbH: Springer Nature, Acta Mechanica Sinica, Global cavitation patterns and  
 349 corresponding hydrodynamics of the hydrofoil with leading edge roughness, Q. Chen, Y. Liu, Q. Wu, Y. Wang, T. Liu, and G. Wang,  
 350 Copyright (2020), (b),(d),(e),(f), (g) Courtesy of GRENOBLE UNIV<sup>69</sup> and (c) Reprinted from Journal of Fluids and Structures, 39,  
 351 O. De La Torre, X. Escaler, E. Eguisquiza, and M. Farhat, Experimental investigation of added mass effects on a hydrofoil under  
 352 cavitation conditions, 173-187., Copyright (2013), with permission from Elsevier.

Cavitation Regime	Definition and characterization	Schematic	Experimental observation <sup>69-71</sup>
(a) Incipient Cavitation	Beginning stage of cavitation where pressure reaches a level at or below saturation pressure and nuclei sites start to grow		
(b) Traveling Bubble Cavitation	Growth and collapse of isolated bubbles close to the surface		
(c) Attached or sheet Cavitation	Large-scale cavitation structures that form as a result of the transition from traveling bubble cavitation to one vapour-filled wake		
(d) Partial Cavity	An attached cavity which covers only a part of the foil		
(e) Cloud Cavitation	A shedding cavity that develops when a re-entrant jet emerges from the closure region of the attached cavity and sheds by an unsteady partial cavity		

(f) Super Cavity	An attached cavity that extends over the entire suction side of the foil and closes downstream of the foil trailing edge		
(g) Tip Vortex Cavitation	Due to the rotating motion, the static pressure at the centre of vortices drops much lower than that in the freestream, resulting in a swirling cavitation stream		

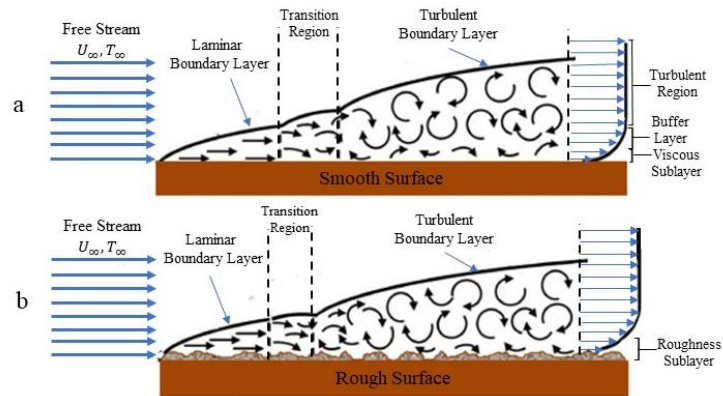
353

354

### 355 2.1. Surface condition and roughness

356 The properties of a solid surface, coatings, and roughness influence boundary layers, affecting heat  
 357 transfer and momentum transfer through the fluid-surface interface and influencing cavitation. The  
 358 boundary layer flow over smooth and rough surfaces is shown in Figure 10.

359 The flow over the leading edge of a smooth surface is laminar, and at some point, it becomes  
 360 turbulent as a result of a flow instability. A thin layer of laminar flow forms along the length of a  
 361 smooth surface after transiting into a turbulent boundary layer (Figure 10 (a)). Figure 10(b)  
 362 illustrates how roughness on the surface of a flow can cause flow instability upstream, resulting in  
 363 increased turbulence disrupting the viscous layer, causing the roughness layer to form, affecting  
 364 pressure drop and heat transfer <sup>72</sup>. Therefore, Boundary layer separation and cavitation can be  
 365 controlled by transitioning to turbulent boundary layers earlier and increasing momentum near the  
 366 surface.



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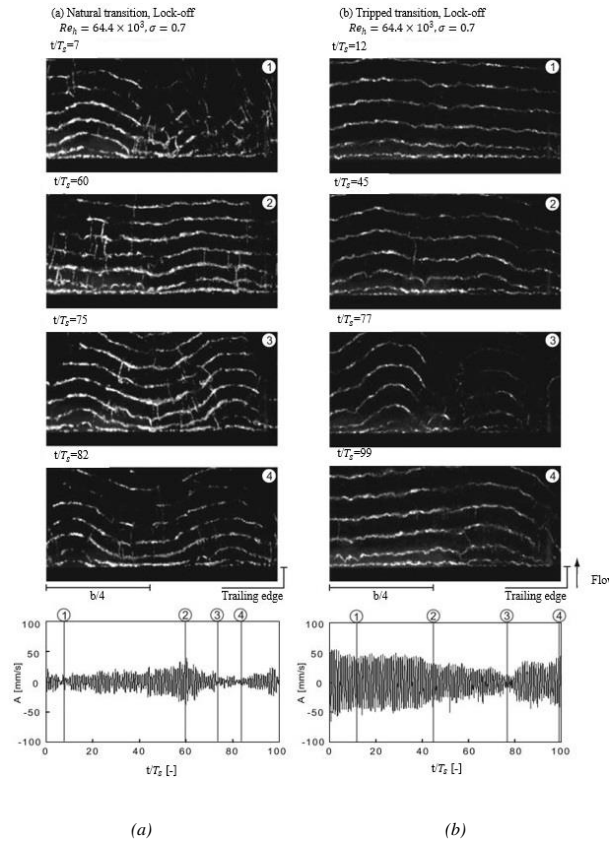
368 *Figure 10 - Boundary layer behavior over (a) smooth surface and generating a viscous sub-layer (b) rough surface where transition*  
 369 *to turbulent boundary layer flow happens over a shorter distance from the leading edge and with increases in instabilities and*  
 370 *momentum transfer compared to a smooth surface* <sup>72</sup>.

371 The first studies which considered leading-edge roughness to investigate its effect on boundary  
 372 layer separation was conducted by Dryden<sup>73</sup> and Kerho and Bragg<sup>74</sup>. Authors observed the  
 373 roughness induced boundary layer transition from laminar to turbulent flow has a completely  
 374 different mechanism than a natural transition in the smooth airfoil and, the roughness moved  
 375 trigger of transition to, or very close, the trailing edge of the roughness. Stutz<sup>75</sup> investigated the  
 376 influences of the roughness and divergent geometries located beneath the internal two-phase flow's  
 377 cavity. The study concluded that the roughness could not significantly affect the void fraction  
 378 distribution, cavity area, and time-averaged velocity. Other findings included that cavity roughness  
 379 does not impact skin friction drag.

380 Coutier-Delgosha et al. <sup>76</sup> focused on the wall roughness and its effect on the unsteady behavior of  
 381 the cavity flow. They observed a significant rise in the frequency of oscillations and a decline in

382 the intensity of pressure fluctuations. A significant reduction in the cavity length was also  
383 observed. A study by Ausoni et al.<sup>77, 78</sup> examined the effects of tripping the turbulent boundary  
384 layer on the wakes of blunt trailing edge symmetric hydrofoils in one specific condition. The  
385 leading-edge transition was shown to promote a more organized vortex shedding with decreased  
386 vortex shedding frequencies. In Figure 9, a top view visualization and measurements of vortex-  
387 induced vibrations are shown. As well as confirming the tripped transition, the study also revealed  
388 a significant increase in vortex-induced hydrofoil vibration and wake velocity fluctuations. The  
389 span-wise organization of vortices was strengthened, as was the strength of the vortices. This  
390 reduction in span-wise non-uniformities over the boundary layer was linked to the boundary layer  
391 turbulent transition at the leading-edge of the hydrofoil. The study also showed how the roughness  
392 induced transition led to the generation of small bubble clouds with potentially detrimental erosive  
393 properties.





394 Figure 11- Cavitation vortex street and vortex-induced vibration signal on the hydrofoil at  $Re=64.4 \times 10^3$  and  $\sigma = 0.7$ . (a)  
 395 Natural transition (smooth surface) and (b) tripped transition (with roughness). A direct relationship existed between span-wise  
 396 vortices and vortex-induced vibration level, and with the rough surface, the span-wise vortices considerably increased in intensity  
 397 and promote a re-establishment of organized vortex shedding<sup>78</sup>. Republished with permission of American Society of Mechanical  
 398 Engineers ASME, from the Effects of a Tripped Turbulent Boundary Layer on Vortex Shedding from a Blunt Trailing Edge  
 399 Hydrofoil, P. Ausoni, A. Zobeiri, F. Avellan, and M. Farhat, *Journal of Fluids Engineering* 134, (2012); permission conveyed  
 400 through Copyright Clearance Center, Inc.

401 The application of  $15 \mu m$  sandpaper roughness on NACA 66 hydrofoil using decreased the  
 402 characteristic lift and momentum coefficients and increased the drag coefficient<sup>79</sup>. Petkovšek et

403 al.<sup>80</sup> investigated hydrodynamic cavitation behavior from laser-textured surfaces and found major  
404 effects on the characteristics of cavitation with sensitivity to the type of micro-structuring. By  
405 comparison against highly polished cases, the extent of cavitation was reduced with some of the  
406 laser-textures.

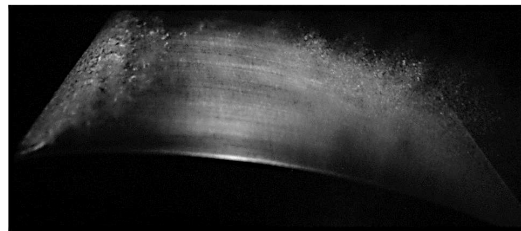
407 Emelyanenko et al.<sup>81</sup> implemented a super hydrophobic coating on stainless steel operating under  
408 cavitation in heavily loaded hydraulic systems. Micro- and nano-textures were developed by a  
409 nanosecond Infra-red laser and studied under long-term continuous contact with water. The  
410 hydrophobic properties and chemical stability were confirmed. Additional tests under prolonged  
411 exposure to abrasive wear and cavitation loads showed significant improvement to the functional  
412 durability.

413 Cavitation inception and development was investigated using hydrofoils with smooth and rough  
414 (0.4  $\mu\text{m}$ ) leading edges by Tao et al.<sup>82</sup>. According to their research, cavitation inception was  
415 enhanced by roughness when incidence angles are below  $2^\circ$ . The roughness element decreases  
416 wettability and traps more gas which can enhance surface nucleation and increases the risk of  
417 cavitation. In their studies of hydrofoils with high incidence angles ( $>3^\circ$ ), roughness significantly  
418 delayed cavitation incipience while developed cavitation was almost the same between smooth  
419 and rough hydrofoils. Based on their argument, this unexpected incipient delay was caused by the  
420 boundary layer structure changes due to roughness.

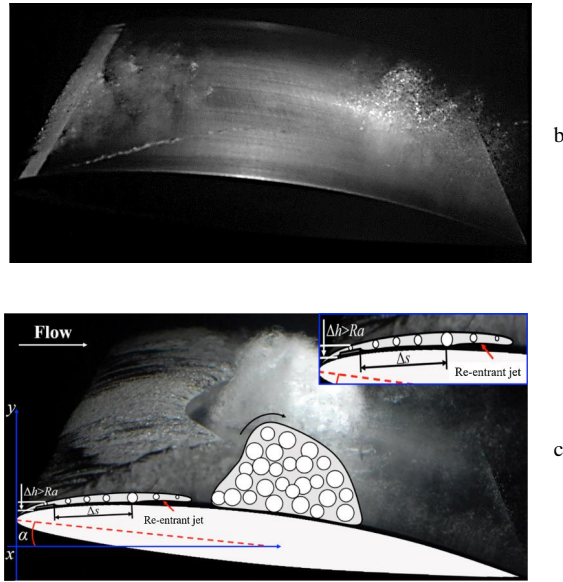
421 Churkin et al.<sup>83</sup> also conducted a study to determine how wall roughness impacts the cavitation  
422 structure. Under specific conditions, it has been demonstrated that varying the surface roughness  
423 type and characteristics can control the formation of cavities. Onishi et al.<sup>84</sup> studied the effects of  
424 hydrophilic and hydrophobic coatings on cavitation of tidal turbines and also observed that  
425 hydrophilic coating could reduce the incipient cavitation number. A lower growth of cavitation

426 was linked to the hydrophilic of textures, especially at small angles of attack. Issues related to the  
427 coating lifetime with loss of effectiveness after 210 seconds of exposure to cavitation were  
428 reported. Hao et al. <sup>85</sup> also used high speed PIV to analyze the cavitation mechanism after the  
429 addition of surface roughness over the hydrofoil's entire surface. The results show that the cloud  
430 cavitation mechanism changes significantly compared to smooth hydrofoil surfaces. Over a rough  
431 hydrofoil, cloud cavitation appears as attached subulate cavities while cavitation over smooth  
432 surfaces form finger-structured cavities. The roughen hydrofoil also experienced a longer cloud  
433 cavitation period and higher cavitation growth rate.

434 Chen et al. <sup>70</sup> focused on the effects of localized roughness modification concentrating on the  
435 hydrofoil leading edge. They observed that both lift and drag coefficients were increased by  
436 surface roughening. The lift-to-drag ratio was also slightly increased and the incipient cavitation  
437 number could be reduced by generating higher turbulent kinetic energy and lowering the minimum  
438 surface pressure at the leading edge. The roughness did not affect however the formation and  
439 transition to cloud cavitation. The change in cavitation patterns in this study is shown in Figure  
440 12.



a



441 *Figure 12- Cavitation patterns over a hydrofoil (a) without leading-edge roughness, with  $Re=0.8 \times 10^6$ ,  $\sigma = 2.5$  and  $\alpha = 8$ , and*  
 442 *observation of sheet cavitation, (b) with leading-edge roughness, with  $Re=0.8 \times 10^6$ ,  $\sigma = 2.5$  and  $\alpha = 8$ , showing incipient*  
 443 *cavitation and (c) with leading-edge roughness at  $Re=1.0 \times 10^6$ , showing the formation of cloud cavitation. High-pressure*  
 444 *gradients initiated the formation of reentrant jets toward the leading edge of the cavity during the initial stage. Thereafter, the*  
 445 *cloud cavity characterised by a high vapor fraction, rises away from the surface when the height of the cavity ( $\Delta h$ ) is greater than*  
 446 *the roughness ( $Ra$ ). Furthermore, there is enough distance between the leading edge roughness and the re-entrant jets ( $\Delta s$ ), and*  
 447 *therefore the local pressure distribution on a leading edge is greatly affected by the leading edge roughness <sup>70</sup>. Reprinted by*  
 448 *permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Acta Mechanica Sinica, Global cavitation*  
 449 *patterns and corresponding hydrodynamics of the hydrofoil with leading edge roughness, Q. Chen, Y. Liu, Q. Wu, Y. Wang, T. Liu,*  
 450 *and G. Wang, Copyright (2020).*

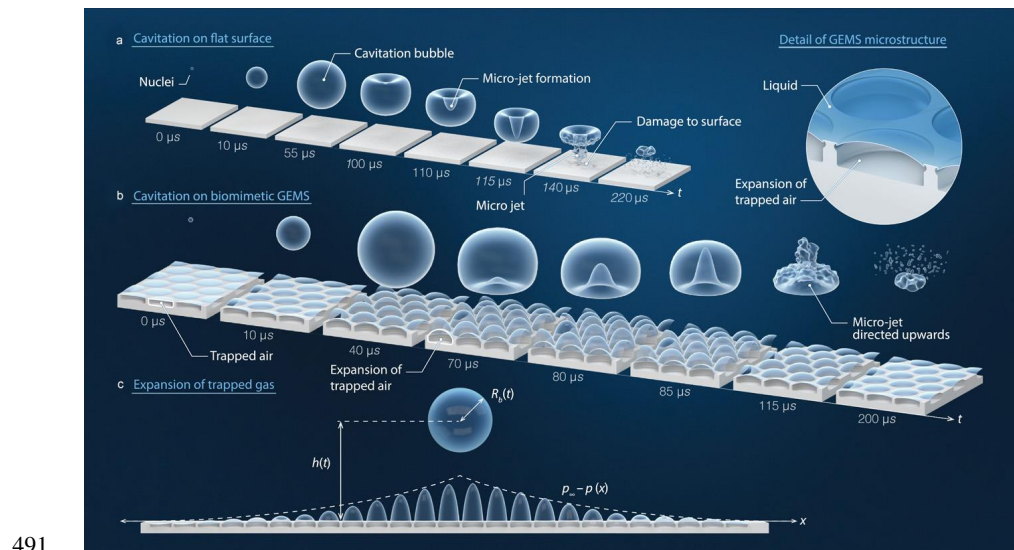
451 The efficacy of a range of artificial roughness types on propeller tip vortex cavitation was also  
 452 investigated by Asnaghi et al. <sup>86</sup>. Both of their numerical and experimental analysis showed that  
 453 in the case of optimum roughness, tip vortex cavitation inception decreased around 33%, while  
 454 drag force increased less than 2 % compared to the smooth hydrofoil. It is found that compared to

455 the smooth foil, the roughness separation line induces more distribution of vorticity over the tip,  
456 which led to the vortex strength reduction.

457 Svennberg et al.<sup>87</sup> tested two configurations of uniform and non-uniform roughness patterns of  
458 230  $\mu\text{m}$  height applied over an elliptical foil. The roughness has been shown to result in lower  
459 angular momentum one chord length downstream of the tip without notable change to the radius  
460 of the vortex core. The study found that the cavitation number for tip vortex cavitation inception  
461 can be reduced by 33 % for a 2% increase in drag by optimizing the roughness pattern. No obvious  
462 differences were noted when comparing the effect of uniform and non-uniform roughness  
463 distributions on cavitation inception properties. Non-uniform roughness distributions did,  
464 however, have a detrimental effect on drag. Also while the application of surface roughness did  
465 not increase the risk of the foil sheet cavity, it was found to impact on the small scale nuclei  
466 production. This was explained by the hydrophobic nature of the roughened surfaces, as roughness  
467 elements create nano- and micro-sized residual air pockets from which small nuclei are  
468 continuously produced as a result of local degassing.

469 The study of cavitation extends beyond inception and a significant research effort has been  
470 dedicated to the study of the follow on growth and collapse stages of cavitation. Published studies  
471 <sup>88-90</sup> have considered the effect of shock waves <sup>91-94</sup>, refraction waves <sup>91 95-100</sup>, thermal growth <sup>101</sup>  
472 <sup>95 102-109</sup>, fluids properties <sup>107, 110, 111</sup>, and in particular liquid compressibility and viscosity <sup>110 112</sup>  
473 <sup>113-117</sup> and the presence of non-condensable gas <sup>118-120</sup>. Not many studies however have focused on  
474 the effect of passive flow control on bubble growth and collapse. The most likely reason for this  
475 is the clearer role played by surface modification in controlling boundary layer separation than  
476 bubble growth and collapse. One notable exception is the work of Kadivar et al.<sup>121</sup> who recently  
477 used a rigid aluminum plate with shark skin-inspired micro-structured riblets to investigate the

478 effects of regular surface roughness on the bubble dynamics of a single cavitation bubble. A micro-  
 479 structured V-shaped riblet was used to study the dynamics of a single laser-generated cavitation  
 480 bubble. During the first collapse, microbubbles formed between the bubble and the riblet surface  
 481 were shown to reduce the momentum of the micro-jet produced by the collapse. The micro  
 482 structured riblets were then linked to a reduction in extent of cavitation-induced erosion. A recent  
 483 study by Gonzalez-Avila et al.<sup>122</sup> also proposed a biomimetic gas entrapment by micro-textured  
 484 surfaces (GEMS) derived from the mushroom-shaped features found in hairs and cuticles of sea  
 485 skaters and springtails. The GEMS, produced by using SiO<sub>2</sub>/Si substrates and micro-fabrication  
 486 techniques, were shown to trap air when immersed in water. The entrapped air, in turn, was shown  
 487 to repel cavitation bubbles and protect against cavitation erosion. The process of formation, growth  
 488 and collapse of cavitation bubbles is illustrated in Figure 13 with and without surface topographies.  
 489 Experimental results presented demonstrated the effectiveness of the technique for a wide range  
 490 of bubble to surface distances.



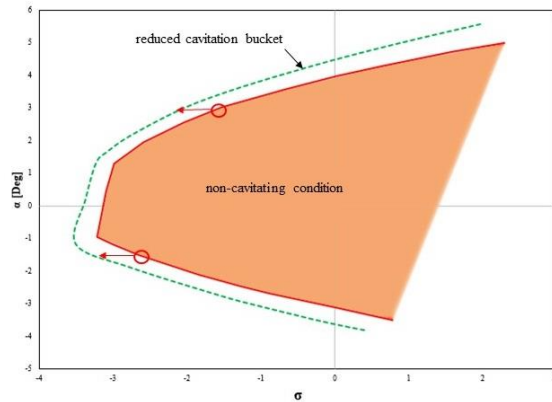
492 *Figure 13- Gas entrapment by micro-textured surfaces as a means to prevent cavitation damage showing illustrations of (a) the*  
493 *cavitation process over a flat surface with a micro-jet generated from a bubble collapsing above the substrate surface which is a*  
494 *key factor in cavitation induced erosion, (b) the cavitation process on biomimetic Gas entrapment micro-textured surfaces, showing*  
495 *the entrapped gas deflecting the liquid jet's direction upward thereby protecting the surface substrate from the cavitation bubble*  
496 *pressure jet, and (c) the expansion of entrapped gas as a result of nearby cavitation bubble pressure field* <sup>122</sup>. M. Nguyen, S.  
497 Arunachalam, E. M. Domingues, H. Mishra, and C.-D. Ohl, *Science Advances* 6, eaax6192 (2020); licensed under a Creative  
498 Commons Attribution (CC BY) license.

499 A summary of important studies for cavitation control using surface roughness is presented in  
500 Table 3.

## 501 2.2. Blade profile and geometry modification

502 Direct optimization of the blade profiles and geometries can also contribute to cavitation  
503 mitigation. Some of the earliest studies in this respect relate to efforts dedicated to the development  
504 of a series of non-symmetrical hydrofoils specifically designed to reduce the cavitation bucket in  
505 practical applications. Cavitation bucket is a diagram which can characterized the cavitation  
506 inception by presenting how minimum pressure coefficient ( $C_{pmin}$ ) vary with angle of attack  
507 (Figure 14). Results indicate that a significant delay in cavitation inception could be achieved <sup>123</sup>,  
508 <sup>124</sup>.

509



510

511 *Figure 14- The cavitation bucket diagram can predict the cavitation inception based on the cavitation number or minimum pressure*  
 512 *coefficient and angle of attack in a specific pump. Reducing or moving the cavitation bucket to a lower cavitation number can be*  
 513 *a target as it shows a delay in cavitation inception.*

514

515 Kyparissis & Margaris <sup>125, 126</sup> worked on different centrifugal pump blade designs, including  
 516 double-arc synthetic blades and different blade leading edge angles. The investigation considered  
 517 pump hydraulic performance and cavitation in tandem. The blade leading-edge angles were tested  
 518 experimentally over a range of 9, 15 and 21°. For low and high angle attached cavitation was  
 519 found to move from the pressure to the suction side respectively while cavitation could be  
 520 eliminated 15° blade leading edge angle of attack. It is because the testing condition is close to  
 521 that of the best efficiency point. Increasing the blade leading angle of attack in this study could  
 522 increase the total head and efficiency. Other studies have documented the benefit of increasing the  
 523 blade leading edge. Shi et al. <sup>127</sup> applied a biomimetic tubercle on the design of a tidal turbine  
 524 leading-edge. They observed that the appendages could constrain the extent of the cavitation  
 525 region but this was achieved at the cost of higher cavitation number and earlier onset of cavitation.



526 As the shape of the blade tips can have a significant effect on tip leakage, foils with various tip  
527 shapes, such as squealer tips<sup>128-130</sup>, thickened tips<sup>131</sup>, rounded tips<sup>132, 133</sup> and C-grooves<sup>134</sup> have  
528 been studied. The casing grooves may also serve as an effective solution for suppressing the tip-  
529 leakage vortex (TLV), according to Kang et al.<sup>135</sup>, Hah, Choi, and Dreyer<sup>136</sup>. It has been confirmed  
530 however that the effect of passive control strategies in the control of tip leakage is greatly  
531 influenced by gap size<sup>137</sup>.

532 The study by Custodio et al.<sup>138</sup> focused on the characteristics of cavitation inception with wavy  
533 leading-edge patterns. The authors found that hydrofoils with medium and large protuberances can  
534 confine the cavitation region behind the protuberance troughs. By contrast, standard hydrofoils  
535 showed sheet cavitation over the entire span. Zhao and Wang<sup>139</sup> conducted a numerical simulation  
536 to determine the effect of the bionic fin-fin structure on cavitation on a hydrofoil surface. Their  
537 results showed that these structures are able to increase the lift-to-drag ratio and decrease the  
538 turbulent kinetic energy and would be an effective passive control method for cavitation. A novel  
539 design for a hydrofoil with twin protuberances to mimic the two prominent tubercles found on the  
540 flipper of a humpback whale was proposed and studied by Kant and Bhattacharyya<sup>140</sup>. This design  
541 was characterized by its ability to limit the separation zone between the chordwise vortices shed  
542 from the two humps at high angles of attack (>20 deg). Although the pre-stall lift coefficient  
543 achieved by the modified profile was lower, the maximum lift was increased. The two  
544 protuberances were found to reduce the extent of stall separation by altering the interaction of the  
545 two chordwise vortices over the suction side, resulting in an enhanced lift after stall. At pre-stall  
546 and post-stall angles of attack, the amplitude and spacing of the two protuberances had an  
547 important impact on the lifting characteristics. It has been determined that such modifications can  
548 effectively control flow at high angles of attack and can be tailored for specific marine applications.

549 The leading-edge protuberances of humpback whale flippers were also incorporated in hydrofoil  
550 modifications by Li et al. <sup>141</sup> to study the impact on cavitation. The wavy leading edge considered  
551 improved the lift–drag characteristics, and reduced cavitation volume by around 30%. The  
552 shedding of cavitation bubbles was also stabilized by reducing the wavelength and increasing the  
553 amplitude of the shape modification. Increasing the amplitude significantly reduced the cavitation  
554 volume, decreased the amplitude of pressure, and overall enhanced the suppression of cavitation.  
555 According to a recent study of a hydrofoil with flipper protuberances on the leading edge <sup>142</sup>, the  
556 hydrodynamic performance and cavitation characteristics were significantly affected. A flow  
557 visualization illustrates how the hydrodynamics and pressure distributions of modified hydrofoils  
558 result from periodic and symmetric streamwise vortices that originate from protuberances. The  
559 location and scale of cavitation are considerably restricted by the streamwise vortices of modified  
560 hydrofoils. The relationship between pressure fluctuations and cavity evolution is also analyzed  
561 with a simplified one-dimensional model. Their results showed cavity volume acceleration is  
562 attributed to pressure fluctuations, which can be used to control cavitation oscillations in  
563 engineering designs.

### 564 2.3. Grooves

565 Grooves and riblets are defined as stream-wise channels on the surfaces and have been extensively  
566 studied for their drag reduction properties <sup>143-145</sup>. They have also shown potential benefits for  
567 cavitation control. A numerical and experimental study was undertaken by Li et al. <sup>146</sup> to examine  
568 how distributed grooves affected cavitation around the body of revolution. Numerical simulations  
569 showed that the grooves accentuated the pressure variations along the tunnel. Grooves also resulted  
570 in significant fluctuations of pressure on the surface. According to both experimental and

571 numerical results, groove width was shown to affect the amplitude and interval of fluctuation and,  
572 therefore, the cavitation distribution.

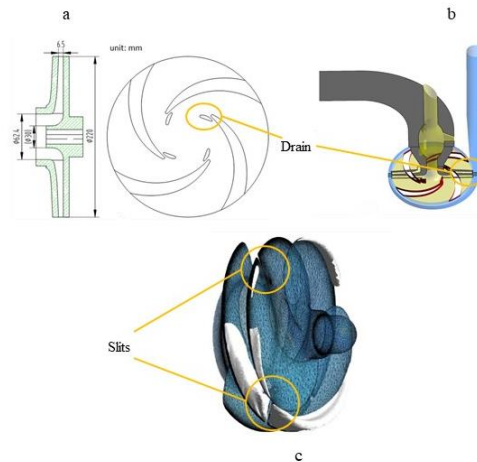
573 Following a study on the benefit of surface roughness on unsteady shedding of cloud cavitation,  
574 Danlos, Ravelet, Coutier-Delgosha and Bakir<sup>147</sup> investigated longitudinal grooves and their effect  
575 on sheet cavitation. Grooves were found to suppress cloud cavitation instabilities<sup>148</sup>. Liu and  
576 Tan<sup>149</sup> studied grooves' effects on suppressing tip vortices which are precursor to cavitation  
577 inception. The analysis confirmed the ability of grooves to suppress the leakage vortices near the  
578 leading-edge of the hydrofoil subject to careful positioning.

579 To control TLV cavitation, overhanging grooves (OHG) were fitted to hydrofoils by Cheng et al.  
580<sup>150</sup>. A significant improvement in cavitation suppression was observed with the OHG compared to  
581 the baseline, conventional grooves and anti-cavitation lip (ACL) with minimal effect on hydrofoil  
582 performance. Effective reduction in the intensity of TLVs and tip-separation vortices were  
583 achieved with small gap sizes. The OHGs were shown to increase the TLV core size when the gap  
584 size was in the medium to large range, increasing, in turn, the minimum local pressure. OHGs  
585 were also examined for their effect on hydrofoils, indicating that they can effectively suppress the  
586 fluctuation of TLV cavitation without significantly altering the time-averaged drag or lift.

#### 587 2.4. Drainage and Injection

588 Another important family of passive flow control methods relies on drainage and injection. Kato  
589 et al.<sup>151</sup> developed a method based on the water discharge from a slit from the hemispherical  
590 shaped leading edge. The momentum injection created a wavy motion in the boundary layer with  
591 a wavelength higher than the boundary layer thickness. This transitional flow motion could  
592 generate an inflection in the velocity profile and disturb the separation zone. It was shown that

593 sheet cavitation on the hydrofoil could be suppressed completely. Arndt et al. <sup>152</sup> also found that  
 594 the injection of air on the leading edge of a NACA 0015 hydrofoil minimized cavitation erosion.  
 595 The application of bleed and jet reinjection flow control on turbopumps were investigated by  
 596 David Japikse <sup>153</sup>. The auto-oscillation region on the pump impeller suction surface was  
 597 eliminated, and cavitation happened at a lower cavitation number, while also improving the pump's  
 598 total head and efficiency, and increasing the suction's specific speed.  
 599 Zhu et al. and Bing and Hongxun <sup>154, 155</sup> studied gap drainage in centrifugal pump impeller as  
 600 illustrated in Figure 15 (a) and (b). The approach was shown to act on cavitation while improving  
 601 the pump hydraulic performance. A new type of cavitation was observed due to a change in the  
 602 discharge flow due to drainage and the cavitation volume in the impeller channel.



603  
 604 *Figure 15- (a) and (b) Schematic of gap drainage impeller in Physical pump and computational region <sup>155</sup> Republished with*  
 605 *permission of American Society of Mechanical Engineers ASME, from Analysis of the Staggered and Fixed Cavitation Phenomenon*  
 606 *Observed in Centrifugal Pumps Employing a Gap, Z. Bing, and C. Hongxun, Drainage Impeller Journal of Fluids Engineering*  
 607 *139, (2016); permission conveyed through Copyright Clearance Center, Inc., (c) Modeling of inducer with slit under cavitation*

608 condition <sup>156</sup>. Y. Kamikura, H. Kobayashi, S. Kawasaki, and Y. Iga, *IOP Conference Series: Earth and Environmental Science*,  
609 240, 2019; licensed under a Creative Commons Attribution (CC BY) license.

610 The effect of water injection on cavitation suppression over NACA0066 hydrofoil was also  
611 investigated by Wang et al. <sup>157</sup>. An optimization of the position and angle of the jet were shown to  
612 have a significant effect on cavitation suppression. According to this study, this type of water  
613 injection can increase the boundary layer's velocity gradient and decrease the extent of flow  
614 separation. A decrease in the thickness of the recirculation zone and consequently of the re-entrant  
615 jets' velocity were also observed.

616 Kamikura et al. <sup>156</sup> implemented an asymmetric slit on the axial inducer's blades to observe  
617 specifically to study the effect on cavitation, as shown in Figure 14 (c). Results showed that this  
618 technique is effective on cavitation instabilities suppression while they were installed in the proper  
619 arrangement. It was observed that by viewing the flow field in a circumferential direction around  
620 the slit near the blade tip, the wave from the jet divided the cavity, which then decreased the cavity  
621 volume. Furthermore, the asymmetric arrangement of the slit in the inducer can disturb the  
622 regularity of rotating cavitation because the slit flow rates differ differently in each blade. The  
623 summary of important studies in blade profile and geometry modification, drainage and injection,  
624 and grooves and slits are presented in Table 4.

## 625 2.5. Obstacles

626 Early investigations of the effect of flow obstacles were precursors to VG studies. Kawanami et  
627 al. <sup>158</sup> studied the structure of cloud cavitation in the wake of obstacles on hydrofoils. As re-entrant  
628 jets were shown to affect the periodic shedding and generation of cloud cavitation, the obstacle on  
629 the foil was able to block the re-entrant jet off, consequently preventing the generation of cloud  
630 cavitation. In comparison with hydrofoil without obstacle, the noise intensity and hydrofoil drag

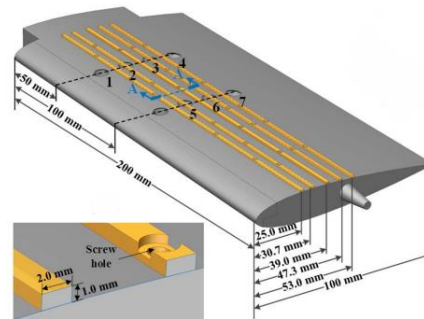
631 were remarkably reduced. After this seminal work, several studies have continued to explore the  
632 interaction between obstacles and cavitation instabilities<sup>159-162</sup>. Enomoto et al.<sup>163</sup> presented a study  
633 in which obstacle plates were attached upstream of helical inducers in order to suppress cavitation  
634 surges observed under partial flow conditions. Installing axi-symmetric and axi-asymmetric  
635 obstacle plates of ring type could narrow the range of the onset regions of oscillating cavitation  
636 surge. Obstacle plates with a blockage factor of 30% reduced cavitation surge oscillations to a  
637 negligible level. The suppression effects became greater with increased blockage factor. In a  
638 follow on study of inducer performance and cavitation surge suppression Kim et al.<sup>164</sup> considered  
639 two kinds of inducers with blade tips of 8° and 14°. The experimental study considered various  
640 axial positions of the obstacle to inducer inlet and various blockage ratios against flow passage  
641 area. A blockage of about 50% between the flow passage and the obstruction was recommended  
642 as the optimal ratio. The most appropriate axial position of the obstacle upstream of the inducer  
643 inlet must take account of the inducer blade angle with a smaller blade angle requiring a shorter  
644 distance. Axis-asymmetrical obstacles were also shown to cause vibrations even under normal  
645 operating conditions at high Net Positive Suction Head (NPSH).

646 Huang et al.<sup>165</sup> used a trip bar on an axisymmetric projectile to weaken the re-entrant jets and  
647 pressure wave propagating from the collapse of cavities. An investigation of super-cavitating flow  
648 was conducted around three different conical cavitators with wedge angles of 30°, 45°, and 60°  
649 by Kadivar et al.<sup>166</sup>. The wedge angle of the cavitator was found to be the most effective design  
650 criteria to increase the cavity length. The results have shown that as cavitation number decreases,  
651 drag coefficient decreases, and the drag coefficient of a cavitator increases with increasing wedge  
652 angle when inlet velocity is constant. The cavity length was increased both for the lower and higher  
653 supercavitation conditions studied numerically. Che et al.<sup>167</sup> focused on a span-wise obstacle

654 located on the suction side of the hydrofoil shown in Figure 16. The near-wall pressure increased  
655 in the wake of obstacles and led to suppression of sheet cavitation. The hydrofoil modification,  
656 however, had little impact under transitional cavity oscillation most likely because of the  
657 inherently unstable flow as shown in Figure 17.

658 Positioning the obstacle downstream of a flat hydrofoil was investigated by Zhang et al. <sup>168</sup>. While  
659 no significant change in the average cavity length was observed at equivalent cavitation number,  
660 the obstacle did affect the dynamics, strength and direction of re-entrant jets.

661

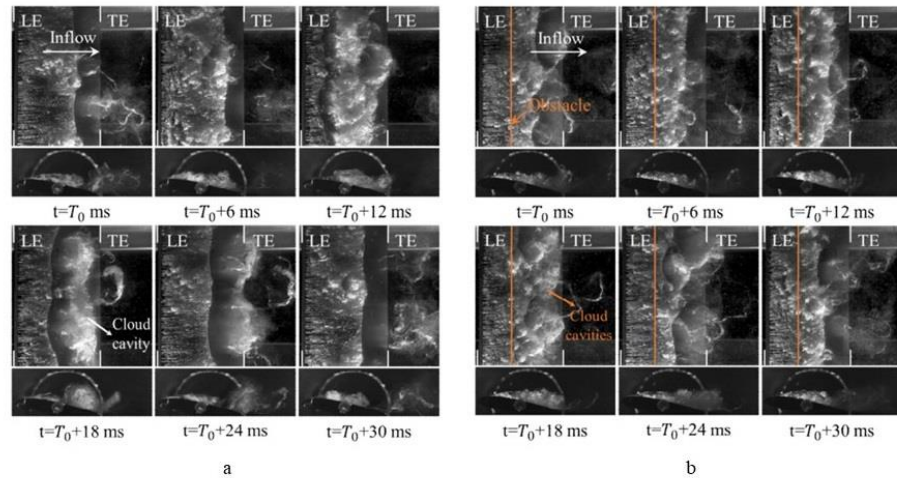


662

663 *Figure 16 - Representation of Span-wise obstacles on NACA0015 hydrofoil at different positions* <sup>167</sup>. Reprinted by permission from  
664 *Springer Nature Customer Service Centre GmbH: Springer Nature, Journal of Mechanical Science and Technology, Effect of*  
665 *obstacle position on attached cavitation control through response surface methodology, B. Che, L. Cao, N. Chu, D. Likhachev,*  
666 *and D. Wu, Copyright (2019).*

667 Using obstacles for control of baled cavitation in water jet pumps is investigated by Zhao et al. <sup>169</sup>.  
668 They implemented a pair of tandem obstacles on the suction side of the pump. It is observed that  
669 there is more resistance against the incipient and the development of leading-edge cavities after  
670 using obstacles. Although sheer energetic cavitation appears after obstacles with foamy wakes,  
671 pressure gradients analysis shows that these obstacles were effective in blade cavitation. However,

672 the hydraulic performance loss, including 6% head drop and 5.6% efficiency drop, was observed  
 673 because of violent pressure fluctuations after using obstacles on the blade.



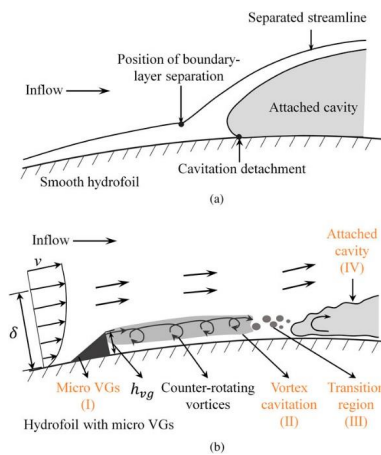
674 *Figure 17 - (a) A typical partial cavity oscillation period on a smooth hydrofoil involves the development of sheet cavitation, the*  
 675 *propagation of re-entrant jets, and the shedding and collapse of cloud cavities. (b) A hydrofoil with an obstacle in the same*  
 676 *condition. The obstacle inhibits re-entrant jets during partial cavity oscillations, thereby suppressing cloud cavitation. As a result,*  
 677 *the cavity fragments, and the cloud cavitation collapses to a non-uniform small-scale cloud*<sup>167</sup>. Reprinted by permission from  
 678 *Springer Nature Customer Service Centre GmbH: Springer Nature, Journal of Mechanical Science and Technology, Effect of*  
 679 *obstacle position on attached cavitation control through response surface methodology, B. Che, L. Cao, N. Chu, D. Likhachev,*  
 680 *and D. Wu, Copyright (2019).*

681 A recent study by Lin et al.<sup>170</sup> has analyzed the influence of arc obstacles on the evolution of  
 682 cavitation over flat hydrofoils, Experimental evidence has shown that the shedding of cavitation  
 683 and the distribution of air over the flat hydrofoils are influenced by the obstacles. The arc obstacles  
 684 were shown to stabilize the leading edge of the shedding cavity and restrict its size, which inhibits  
 685 cavitation.



686 2.6. Vortex and bubble generator

687 The ability of VGs to control boundary layer separation has been exploited on hydrofoils to  
688 destabilize attached cavities. The schematic of Figure 18<sup>171</sup> illustrates how counter-rotating  
689 vortices generated upstream of the cavity by the VG delays separation and promotes the formation  
690 of a smaller cavity with a growth and shedding behavior similar to the attached cavity generated  
691 by laminar boundary layer separation but with some important distinction. Its leading edge is  
692 observed to move dynamically, likely due to a thin liquid layer separating the cavity from the wall  
693 as conjectured by the authors and the cavity edge shows oscillations indicative of a turbulent flow.



694

695 *Figure 18-Schematic description of attached cavitation over (a) a smooth hydrofoil; a typical process of attached cavitation*  
696 *formation and (b) a hydrofoil with micro-vortex generators where (I & II) every standalone micro-vortex generators induces*  
697 *counter-rotating vortices at the end of their trailing edge and develop micro-vortex cavitation, (III) a narrow transition region*  
698 *exists between vortex cavitation and attached cavitation, which is caused by shedding of several small bubbles produced by vortex*  
699 *cavitation, and then in (IV) attached cavitation is developed without glossy and divot structures observed in smooth hydrofoil<sup>171</sup>.*  
700 *Reprinted from Control effect of micro vortex generators on leading edge of attached cavitation, B. Che, N. Chu, S. J. Schmidt, L.*  
701 *Cao, D. Likhachev, and D. Wu, Physics of Fluids 31, 044102 (2019) with the permission of AIP Publishing.*

702 The low-pressure core of the stream-wise vortices induces stable vortex cavitation which breaks  
703 down into bubble clouds upstream of the attached cavity. Similar observations were made in a  
704 study of VGs by An<sup>172</sup>. The application of VGs in control of cavitation in multi-propulsion vessels  
705 was studied by Liang-mei<sup>173</sup>. They found a significant improvement in cavitation instability and  
706 declining pressure fluctuation.

707 The application of bubble generators on cavitation control was studied by Javadi et al.<sup>174</sup> through  
708 a two-dimensional cavitation calculation. This bubble generator was actually a wedge type VG.  
709 Their numerical analysis showed that this VG can make a low pressure recirculation region (below  
710 saturation pressure) behind the VG. Bubbles then start to generate and grow in this region. By  
711 controlling this condition, the bubbly flow becomes stable and will not vanish, or in other words,  
712 interfere and stop the cavitation process. They observed that the whole cavitation process,  
713 including vaporization, bubble generation, and bubble implosion, could be affected, and lift and  
714 drag fluctuations could be reduced.

715 Vortex generators that have been optimized can also be used for TLV cavitation suppression. The  
716 experimental results of Amini et al.<sup>175</sup> have shown that the winglets could effectively increase the  
717 radius of the tip vortex, and delay the initial inception of the TLV cavitation process. The ACL,  
718 however, is the only proposed method that has actually been applied. Results showed that it is  
719 difficult for the ACL to have a satisfactory inhibitory effect on TLV cavitation and once the vortex  
720 generators are not operating under design conditions, a more intense level of cavitation will be  
721 induced<sup>137, 176</sup>.

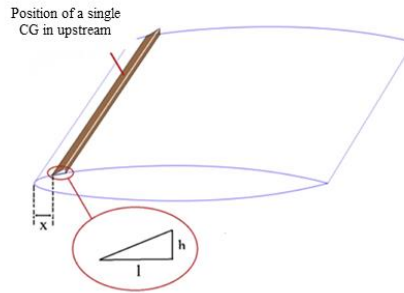
722 A recent numerical study by Kadivar et al.<sup>177</sup> proposed a new type of VG called Cavitating bubble  
723 Generators (CGs) (Figure 19). The CGs were adopted from wedge-type VGs were used before for  
724 aerodynamics application with the aim of generating cavitating bubbles at the suction side of

725 hydrofoil. They observed that high momentum fluid from free stream flow moved to the  
726 hydrofoil's near-wall low energy region. These CGs could generate vortices downstream and move  
727 higher kinetic energy flow to the vicinity of the hydrofoil surface. Consequently, quick high-  
728 pressure pulsations near the hydrofoil surface were reduced, and the resistance against pressure  
729 rise before boundary layer separation was increased. They found the vortex structures were  
730 significantly modified on the suction side and the hydrofoil wake region. This phenomenon  
731 suppresses the cyclic behavior of unsteady cloud cavitation and declining turbulent velocity  
732 fluctuation in that area. The experimental investigation of CGs proved an essential role of re-  
733 entrant jets on cloud cavity shedding structure<sup>178</sup>. Their experiment proved the reduction of  
734 pressure pulsation's amplitude in instabilities of cavitation dynamic. As a result, they can be used  
735 as a useful tool for delaying cloud cavitation formation. A comparison between hydrofoil with and  
736 without CGs is presented in Figure 20. In another study, a CG was installed adjacent to the  
737 cavitation inception on a semi-circular leading-edge flat plate to control and manipulate unsteady  
738 dynamics of cavitation surge. The CG was shown to mitigate large-scale cavities, suppress the  
739 spanwise instability of adjacent cavities, and suppress large-scale cavities over the flat plate.  
740 Passive control was observed to reduce the dominant frequency of pressure pulsations<sup>179</sup>.

741 Xu et al.<sup>180</sup> used cavitators placed at various locations on a hydrofoil's bottom surface to study the  
742 supercavitation flow around it. As their observations showed, a localized high-pressure region  
743 appears between the leading edge of the hydrofoil and the cavitator, and downstream of the  
744 cavitator, the pressure is equal to the saturated vapour pressure of water. Based on the magnitude  
745 and distribution of pressure on the hydrofoil surfaces, the lift coefficient increased as the cavitator  
746 was positioned farther away from the leading edge and towards the trailing edge. Alternatively,

747 there was a strong correlation between drag coefficients and the maximum thickness of cavitating  
748 wakes, which was used as a proxy for the drag coefficient.

749 Kadivar et al.<sup>181</sup> also examined a single span-wise row of cylindrical obstacles named Cylindrical  
750 Cavitating bubble Generators (CCGs), shown in Figure 21. Similar effects were observed such as  
751 a reduction in the adverse pressure gradient at the end of cavity, weakening of re-entrant jets and  
752 turning unsteady cavity structure to a quasi-stable cavity structure. As a result, the instability of  
753 cloud cavitation was mitigated and the near-wall high-pressure pulsation dampened. One key  
754 difference to previously studied CCGs is that only small-scale cavity structures are shed while  
755 large-scale cavitation clouds are effectively suppressed. It was also observed that vibration-  
756 induced cavitation as well as wall-pressure peaks on materials with solid surfaces were  
757 significantly reduced<sup>181 182</sup>. In another study, high-speed visualization, PIV and a hydroacoustic  
758 pressure transducer were used to analyze experimentally the effects of CCGs on turbulence  
759 behavior, the amplitude-frequency spectra of pressure pulsations associated with oscillations in  
760 the attached cavity length and cloud cavitation instabilities. This study confirmed that CCGs is  
761 quite effective at hindering the development of cloud cavitation and at decreasing the strength of  
762 middle- and side-entrant jets which are the primary mechanism that cause unstable cloud cavitation  
763<sup>183</sup>.



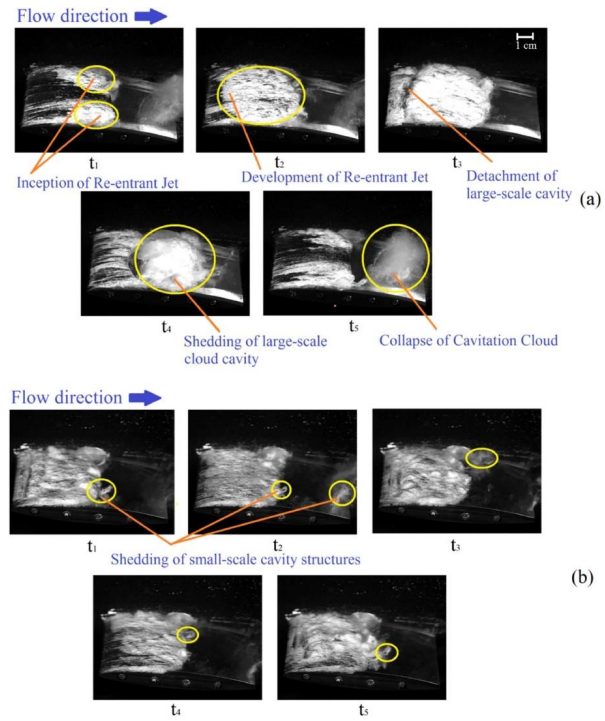
764

765 *Figure 19 - Analysis of wedge-type Cavitating bubble Generators located on the suction side of a hydrofoil was found to reduce*  
 766 *high-pressure pulsations, alter boundary layer separations, and alter vortex structures*<sup>177</sup>. Reprinted from *Applied Mathematical*  
 767 *Modelling*, 64, E. Kadivar, O. e. Moctar, and K. Javadi, *Investigation of the effect of cavitation passive control on the dynamics of*  
 768 *unsteady cloud cavitation*, 333-356., Copyright (2018), with permission from Elsevier.

769 Che et al.<sup>171</sup> considered counter-rotating delta-shaped mVGs built into a quasi-two-dimensional  
 770 NACA0015 hydrofoil (Figure 22). The type and geometry of mVG was based on designs from  
 771 Lin<sup>26</sup> and Godard and Stanislas<sup>37</sup> reviews to control boundary layer separation using VGs<sup>184</sup>. They  
 772 designed five counter-rotating delta-shaped mVGs with different  $h/\delta$  in the range of 0.5 to 2.5.  
 773 The  $\Delta X_{VG}$  were set at 2.5 mm from the hydrofoil leading edge based on the position of boundary  
 774 layer separation at the leading edge obtained from their 2D numerical modeling results. The study  
 775 demonstrated that the mVG can suppress the laminar separation under non-cavitating conditions.  
 776 MVGs located within the viscous sub-layer close to the cavitation detachment point failed to  
 777 suppress the attached cavitation. Results did show however that the transition region and attached  
 778 cavitation were affected. The authors found that at lower heights relative to the viscous sub-layer,  
 779 mVGs can generate longer counter-rotating and cavitating vortices within the boundary layer.  
 780 These mVGs could also fix cavitation inception causing more stable sheet cavitation and cloud  
 781 cavity shedding. The attached cavitation over the smooth hydrofoil showed a formation of “divot”

782 or “finger” structure as well as two-dimensional Tollmien–Schlichting waves which are shown in  
783 Figure 23. Divots are three-dimensional flow structures which appear near the cavity interface.  
784 They occur at moderately high Reynolds numbers because of local disturbances near cavity  
785 interfaces. Upstream of the detachment point, local disturbances were caused by a breakdown of  
786 the laminar boundary separation, resulting in a divot when a jet of fluid penetrated the cavity <sup>19</sup>.  
787 Tollmien–Schlichting waves are known as stream-wise instabilities that occur prior to the  
788 transition to turbulence in boundary layers. This instability initiates because of the interaction of  
789 disturbances with leading edge roughness and can be slowly intensified while moving downstream  
790 and can help with the process of turbulence transition <sup>185</sup>. In comparison with a smooth hydrofoil  
791 surface, cavitation started closer to the leading edge, eliminating classic "fingering structures" and  
792 Tollmien-Schlichting waves <sup>184</sup>.

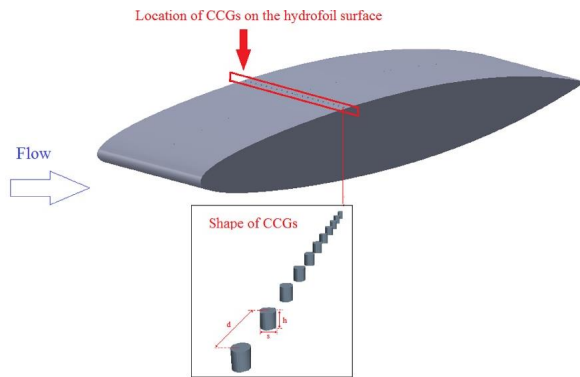
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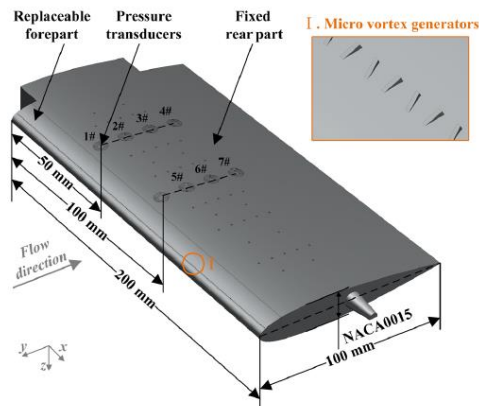
795 *Figure 20- Structure of cavitation over a hydrofoil with attack angle of  $7^\circ$ ,  $\sigma = 1.3$  and  $Re = 1.4 \times 10^6$ . (a) CSmooth hydrofoil:*  
 796  *$t_1$ & $t_2$ ) Formation and development of sheet cavities and jets,  $t_3$ ) detachment of large-scale cavities,  $t_4$ ) shedding of large-scale*  
 797 *cavitation clouds,  $t_5$ ) collapse of cavitation clouds. (b) Hydrofoil with cavitating bubble generators: inception and shedding of*  
 798 *small vortex cavitation over hydrofoil and suppressing could cavitation <sup>178</sup>. Reprinted from Control of unsteady partial cavitation*  
 799 *and cloud cavitation in marine engineering and hydraulic systems, E. Kadivar, M. V. Timoshevskiy, M. Y. Nichik, O. el Moctar, T.*  
 800 *E. Schellin, and K. S. Pervunin, Physics of Fluids 32, 052108 (2020) with the permission of AIP Publishing.*

801



802

803 *Figure 21 - Hydrofoil with cylindrical cavitating bubble generators located on the suction side where  $s$ ,  $h$ , and  $d$  are the diameters,*  
 804 *heights, and distances between cylindrical obstacles, respectively. Cylindrical cavitating bubble generators were investigated at*  
 805 *locations downstream and upstream of the hydrofoil suction surface. Using the cylindrical cavitating bubble generators, significant*  
 806 *reductions were seen in cavitation induced vibration, high wall pressure peaks, and cloud cavitation instability*<sup>181</sup>. *Reprinted from*  
 807 *International Journal of Multiphase Flow*, 115, E. Kadivar, O. e. Moctar, and K. Javadi, *Stabilization of cloud cavitation*  
 808 *instabilities using Cylindrical Cavitating-bubble Generators (CCGs)*, 108-125, Copyright (2019), with permission from Elsevier.



809

810 *Figure 22 - Schematic of the test hydrofoil with micro-vortex generators. The vortex generators are microscopic delta-shaped*  
 811 *counter-rotating vortex generators installed at the leading edge, which were shown to effectively manipulate boundary layer and*  
 812 *cavity dynamics in the test*<sup>171</sup>. *Reprinted from Control effect of micro vortex generators on leading edge of attached cavitation*, B.



813 *Che, N. Chu, S. J. Schmidt, L. Cao, D. Likhachev, and D. Wu, Physics of Fluids 31, 044102 (2019) with the permission of AIP*  
814 *Publishing.*

815 They observed a new structure for cavitation onset while the cavitation onset disappears close to  
816 the laminar separation. In the new structure, stable vortex cavitation and subsequent vortex  
817 breakdown resulted in bubbly structures, which was finally expressed as an attached cavity region.  
818 This vortex break-down was delayed when they reduced the height of mVGs. This delay resulted  
819 in a rise in cavitation vortex pattern length. This result showed the potential of mVGs in control  
820 of cavity dynamics considering the re-entrant jet penetration depth. The flow visualization of  
821 attached cavitation during cloud cavitation without and with VGs in this study is presented in  
822 Figure 23 and Figure 24.

823 In another study, Che and co-authors analyzed the instability of the attached cavitation produced  
824 with mVGs<sup>186</sup>. This study confirmed that these mVGs are an effective passive control for attached  
825 cavitation dynamics and changed the surface wall's vicinity's flow dynamics. The results also  
826 emphasized again that the mVGs could increase the cavity length and induce counter-rotating  
827 stream-wise vortices. The mVGs could change the sheet cavity structure to a uniform cavity in a  
828 span-wise direction by inducing consistent separate vortex cavitation streaks. The mVGs showed  
829 their ability to fix the attached cavitation inception line location, thereby limiting instabilities  
830 caused by span-wise disturbances.

831 In this study, Che et al.<sup>186</sup> interpret two types of Rayleigh–Taylor (R-T) and K-H instabilities,  
832 while cavity shedding and re-entrant jets interactions happened over a smooth hydrofoil and  
833 hydrofoil with mVGs. Re-entrant jets are generated by exposing cavity closure to an adverse  
834 pressure gradient. After propagating upstream, these re-entrant jets impact the cavity interface,  
835 causing the cavity to shed. It is possible to interpret the interaction of re-entrant jets and cavities

836 as an R-T. A re-entrant jet and cavity interface at the leading edge interact, generating several  
 837 cavitating vortices that are indicative of the K-H instability. The K-H instability interpretation has  
 838 been explained by different shearing velocities causing cavity shedding.

839 Che et al.<sup>186</sup> presented evidence that reverse flow beneath the attached cavities which were linked  
 840 to R-T and K-H instabilities were suppressed. The mVGs were shown to influence partial cavity  
 841 oscillations, transitional cavity oscillations, and transition between these two instabilities.  
 842 Experimentation was extended to measure cavitation erosion and analyse impulsive loading from  
 843 cavity collapse as a measure of the intensity and aggressiveness of cavitation structure with mVGs  
 844<sup>187</sup>. The study also included an analysis of the dynamic behavior of the re-entrant jet, shown in  
 845 Figure 25. The effect of the mVGs included suppression under certain condition of periodic  
 846 shedding, and reduction of the maximum pressure fluctuations and associated acoustic power. The  
 847 arrangement and geometry were shown to be an important factor in determining leading-edge  
 848 erosion which was shown to increase at lower angles of attack.

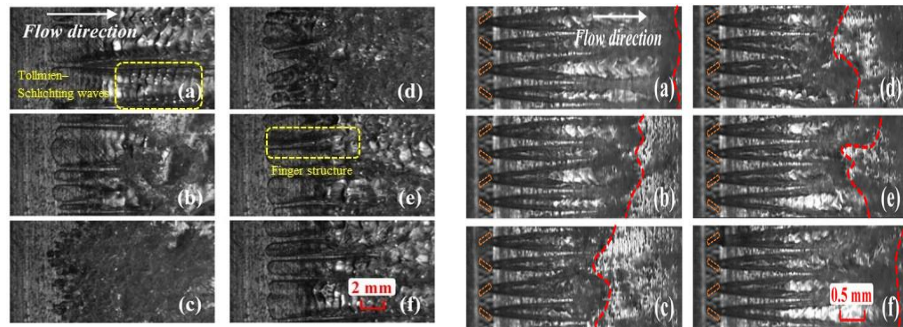
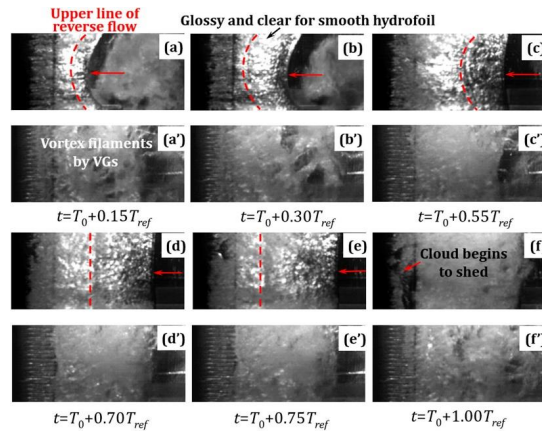


Figure 23 - (a)-(f) Dynamics of cloud cavitation shedding on a smooth hydrofoil. At the leading edge of attached cavitation, typical finger structures are visible. By observing the glossy  
 Figure 24-(a)-(f) Dynamic behavior of vortex cavitation on a hydrofoil with micro-vortex generators, with dashed boxes and dashed lines indicating the position of vortex generators

interfaces of the cavity and the Tollmien-Schlichting waves at the leading edge, laminar separation can be detected. A consistent change in finger structures resulted in cloud cavitation shedding and instability. Cavity collapse occurs when the re-entrant jet propagates upstream and reaches the leading edge.<sup>171</sup>. Reprinted from *Control effect of microvortex generators on leading edge of attached cavitation*, B. Che, N. Chu, S. J. Schmidt, L. Cao, D. Likhachev, and D. Wu, *Physics of Fluids* **31**, 044102 (2019) with the permission of AIP Publishing.

and the trailing edge of vortex cavitation, respectively. As shown in the picture, classical finger structures and Tollmien-Schlichting waves have been eliminated. The cavitation onset moved toward the leading edge, which happened at the laminar separation line for smooth hydrofoil. The onset cavitation mechanism includes stable vortex cavitation, which breaks down to a bubbly structure and accumulates in an attached cavity region.<sup>171</sup>. Reprinted from *Control effect of microvortex generators on leading edge of attached cavitation*, B. Che, N. Chu, S. J. Schmidt, L. Cao, D. Likhachev, and D. Wu, *Physics of Fluids* **31**, 044102 (2019) with the permission of AIP Publishing.



849

850 Figure 25- Behavior of re-entrant jets ( $\alpha = 8^\circ$ ,  $U_\infty = 10$  m/s, and  $\sigma = 1.7$ ) on (a)-(f) smooth hydrofoil and (a')-(f') Hydrofoil with  
 851 vortex generators. For hydrofoil with vortex generators, downstream travelling vortices break the regular movements of re-entrant  
 852 jets and suppress them. The cavity is confined and does not form a cloud, and the consequent collapse is not strong enough<sup>187</sup>.  
 853 Reprinted from *Effects of microvortex generators on cavitation erosion by changing periodic shedding into new structures*, N. Qiu,  
 854 W. Zhou, B. Che, D. Wu, L. Wang, and H. Zhu, *Physics of Fluids* **32**, (2020) with the permission of AIP Publishing.

855 The application of mVGs has started to be investigated in applications other than 2D hydrofoil.  
856 Examples include Huang et al.<sup>188</sup> study. They investigated the effects of VGs on cavitation in  
857 marine shipping. The VGs studied could lead to more uniform wake and milder propeller  
858 cavitation. These VGs could decrease pressure fluctuations and cause a more uniform distribution  
859 of energy. Li et al.<sup>189</sup> designed a delta-shaped VG to solve the vibration problem in the hull  
860 propeller and improve the ship wake quality and uniformity. The VG design was based on the  
861 ship body lines. It improved the wake uniformity in certain positions as it could generate a more  
862 moderate circumference transition and effectively increase the velocity in high wake areas.  
863 Additionally, the VGs were able to smoothly transition the unsteady cavitation of the blade in  
864 circumference direction and decrease the amplitude of pressure fluctuations. The distance between  
865 the positions of blade cavitation collapses, and ship bottom shell was increased after using VGs.

866 Teplov and Lomakin<sup>190</sup> used computation simulation to examine mVGs located at the front edge  
867 on the suction side of impeller blades in a centrifugal pump and analyzed their effect on the  
868 cavitation characteristics, efficiency, and pump head. The NPSH was significantly decreased, and  
869 the pump efficiency above the Best Efficiency Point was increased.

870 A study published recently by Chen et al.<sup>191</sup> investigated the effects on cavitation of two schematic  
871 designs of mVGs around a NACA66 hydrofoil. Two different sets of mVG were installed and  
872 positioned upstream of (mVG-1) and within (mVG-2) the laminar separation zone of the baseline  
873 hydrofoil. The experimental results indicated that the mVG-1 could promote inception of  
874 cavitation earlier than the baseline hydrofoil, while mVG-2 delayed cavitation inception especially  
875 at small angle of attack cases. Two reasons were suggested for the effect of the mVG-1. The mVG-  
876 1 modification was shown to generate fingerlike vortex at its rear which was observed before in  
877 previous studies<sup>85, 171, 184</sup> and is shown in Figure 23. These vortexes were responsible to induce

878 fingerlike vortex cavitation. In addition, the mVG-1 increases the length of the laminar separation  
879 bubble (LSB), resulting in laminar boundary layer separation with a lower pressure minimum.  
880 Since mVG-2 was located in a high pressure zone from the leading-edge, there are insufficient  
881 downstream fingerlike vortices to induce cavitation which can reduce LSB length. Smaller LSB  
882 was able to suppress cavitation at  $\alpha = 6^\circ\text{--}8^\circ$ . A summary of studies in the field of obstacles and  
883 VGs in cavitation control studies is presented in Table 5.

Investigator(s) (year)	Type of modification	$U_{\infty}^I$ (Re)	$\alpha^{II}$	$\sigma^{III}$	Coating roughness	Cavitation regime	Comments
Coutier-Delgosha et al. <sup>76</sup> (2005)	Wall roughness on a Two-dimensional foil ( $c^{IV} = 150\text{mm}, S^V = 80\text{mm}$ )	6 m/s	0–6°	0.7–1.8	100, 200, 400 $\mu\text{m}$	Cyclic Cloud Sheet cavitation	↓ cavity length ↑ oscillation frequency ↓ pressure fluctuation intensity
Ausoni et al. <sup>77, 78</sup> (2007&2012)	Blunt trailing edge on NACA 0009 Hydrofoil ( $c = 100\text{mm}, S = 150\text{mm}$ )	( $16.1 \times 10^3 - 96.6 \times 10^3$ ) ( $42 \times 10^3 - 70 \times 10^3$ )	0°	NA	125 $\mu\text{m}$ ( $\frac{\Delta x}{c} = 4\%$ ) Width = 4%	Vortex shedding	↑ organized vortex shedding ↓ vortex shedding frequency ↑ vortex span-wise organization ↑ vibrations induced by vortices ↑ vortex strength and wake velocity fluctuations generates many tiny bubbles which may be erosive in turbomachines
Onishi et al. <sup>84</sup> (2017)	Hydrophilic and hydrophobic coatings on symmetrical NACA16 – 021 ( $c = 40\text{mm}, S = 60\text{mm}$ )	$3 \frac{\text{m}}{\text{s}}$ ( $1.1 \times 10^5$ ) ,5 m/s ( $2.0 \times 10^5$ )	10°, 14°, 20°	0–4.5	3 ~ 4 $\mu\text{m}$	Tip Cavitation, Vortex Sheet Cavitation and Cloud Cavitation	↓ Incipient cavitation number ↓ Cavitation growing for in hydrophilic coating Losing Functionality after 210 seconds of cavitation condition for both hydrophilic and hydrophobic coatings
Hao et al. <sup>85</sup> (2018)	Surface roughness on Clark-Y hydrofoils ( $c = 70\text{mm}$ )	8m/s ( $5.6 \times 10^5$ )	8°	0.87, 1.02	6.9 $\mu\text{m}$	Cyclic cloud	Change in development of cloud cavitation ↑ Intensity of cavitating flow around the rough hydrofoil

Chen et al. <sup>70</sup> (2020)	Surface roughness on NACA 66 hydrofoil ( $c = 100 \text{ mm}, S = 149 \text{ mm}$ )	6 – 14 m/s (0.6 – 1.4 $\times 10^6$ )	–12 – 12 °	1– 5.5	150 $\mu\text{m}$ . $\left(\frac{\Delta X}{c} = 4\%\right)$ Width = 4%	Inception Sheet Cloud	↑Lift, drag and lift to drag ratio ↑ Minimum pressure coefficient No effect on cloud cavitation formation
Svennberg et al. <sup>87</sup> (2020)	uniform and non-uniform roughness patterns on elliptical foil ( $c=126.5\text{mm}, S=300 \text{ mm}$ )	6.8 m/s ( $8.95 \times 10^5$ )	9°	NA	$h=230 \mu\text{m}$	Tip vortex cavitation	↓Cavitation number for tip vortex cavitation inception ↑Drag force ↑Nano- and micro-sized residual air pockets

886 <sup>a</sup> Free-stream stream-wise velocity

887 <sup>b</sup> Angle of attack

888 <sup>c</sup> Cavitation number

889 <sup>d</sup> Hydrofoil chord

890 <sup>e</sup> Hydrofoil Span

891

892 Table 4- Summary of research for blade profile and geometry modification, Drainage and Injection and grooves and slits as surface methodology techniques in cavitation control

Investigator(s)	Type of modification	$U_\infty (Re)$	$\alpha$	$\sigma$	Geometry properties	Cavitation regime	Comments
<b>Blade profile and geometry modification</b>							
Custodio et al. <sup>138</sup> (2018)	Protuberances on the humpback Sinusoidal pattern	7.2 m/s (7.2 $\times 10^5$ )	–12 – 30°	$\sigma_{in}$ = 0 – 9	Protuberances amplitude= 0.025, 0.05 & 0.12 c	Sheet cavitation	Confining the cavitation to the region behind the protuberance with medium and large protuberance amplitudes Improving the sheet cavitation pattern.

	on NACA 634-021 profile (c=200 mm)				Protuberances wavelength: 0.25, 0.5 c		
Zhao and Wang <sup>139</sup> (2019)	Bionic fin-fin structure on 2D NACA 0015 (c=100 mm, S=100 mm)	10 m/s (1 × 10 <sup>6</sup> )	8°	0.8	Rectangular fins, width= 2 %c distance of the two symmetric structures = 20% C, the inclination angle is 14 front distance of the symmetrical structure is 50%	Cyclic cavitation	↓Turbulent kinetic energy of the hydrofoil ↑lift-to-drag ratio
Petkovšek et al. (2018) <sup>80</sup>	Laser-textured surfaces on stainless steel cylinders (diameter =10 mm)	Flow rate: 163 – 231 L /s	NA	1.2– 2.2	Micro-channels width: 100 μm four different angles (0°, 18°, 45°, 72°) distance between channels: 200 & 500 μm Micro-holes: diameter: 40 μm distance between holes: 200 μm	NA	↓Cavitation extent ↓Cavitation incipient number
Kant and Bhattacharyya <sup>140</sup> (2020)	twin-protuberance NACA 634-021 hydrofoil (c=100 mm, S=200mm)	2 m/s (2 × 10 <sup>5</sup> )	5-25	NA	twin-protuberance hydrofoil design mimicking the two prominent tubercles present on a humpback whale flipper	NA	limit the separation zone between the chord wise vortices shed from the two humps at high angles of attack (>20°). ↓ Pre-stall lift coefficient ↓ Stall separation, ↑Lift after stall. effectively control flow at high angles of attack
Li et al. <sup>141</sup> (2021)	Bionic NACA 634-021 hydrofoil with a wavy leading-edge (c=102 mm, S=204mm)	7.2 m/s (7.2 × 10 <sup>5</sup> )	18°	NA	Design inspired from pectoral fin of humpback whales, sinusoidal with amplitude = 0.05c & wavelength = 0.5c	Attached cavitation Cloud Cavitation	↑Improves lift–drag characteristics ↓Cavitation volume by around ↓Pressure amplitude Enhances cavitation suppression Restrains hydrofoil cavitation
<b>Drainage and Injection</b>							
Arndt et al. <sup>152</sup> (1995)	Air injection on NACA 0015	20 m/s	8°	0.5– 6	5 holes with 5 mm distance from each other and	Sheet cavitation	Effectively minimizes cavitation erosion



	(c=81 mm, half S=95mm)				0.5 mm diameter		
Zhu et al. <sup>154</sup> (2014) Bin et al. <sup>155</sup> (2016)	Gap impeller on pump's blades (Cylindrical 2D blades for a LSSCP)	17.3 m/s (45 × 10 <sup>3</sup> )	NA	0-1	Pump: 4 gad impellers Rotating speed = 1000 rpm Water head = 7 m	Cloud cavitation	↑ Pump's hydraulic performance and cavitation resistance Suppressing generating cavitation A new cavitation regime with different attack angles was developed allocated flow discharge and cavitation volume affects this new cavitation structure
Wang et al. <sup>157</sup> (2017)	Water injection on NACA0066 hydrofoil (c=150 mm)	5.33 m/s (0.8 × 10 <sup>6</sup> )	6,8°	0.55 - 1.0	Jet hole diameter: 2mm Injection position: 10-90 %c	Cloud cavitation	Water injection angle and jet angle affect cavitation suppression ↑ Boundary layer velocity gradient and enhance anti-reverse pressure gradient ↓ Recirculation zone thickness ↓ Velocity of the re-entrant jet ↓ Intensity of separation flow
Kamikura et al. <sup>156</sup> (2019)	Asymmetric slits on each blade of Inducer 335	NA	NA	0.01 - 0.3	Slit depth 30 mm Slit width 5mm Inducer speed = 6,000rpm	Vortex Cavitation	↓ Cavity volume Suppressing cavitation instabilities by rearranging the asymmetric slits
Groove and slit							
Li et al. <sup>146</sup> (2009)	Distributed grooves on MK46 torpedo (c=120mm)	25 - 30 m/s	NA	NA	Groove width: 3-10.5 mm Groove depth: 1.5 mm Number of grooves: 9-28	Cyclic cloud	Effect on the cavity clouds' position and shape depends on grooves' dimensions ↑ Pressure fluctuation ↑ Pressure drops in certain local regions which may increase the possibility of enhance cavitation inception ↓ the stability of the cavities because of pressure fluctuation
Danos et al. <sup>147, 148</sup> (2014)	Longitudinal grooved surfaces on a Venturi	~8m/s (5.2, 5.5 × 10 <sup>5</sup> )	NA	1-1.8	d= 1,2 mm h= 0.25,2 mm N= 40-124	Sheet cavitation Cloud cavitation	↓ Shedding of unsteady partial cavitation ↓ Surface erosion Suppressing the cloud cavitation shedding

							Grooves geometries affects cavitation regime One of the determining factors is depth of grooves Large depth of grooves can modify the sheet cavity structure No change in sheet cavity length with groove's depth smaller than viscous sublayer thickness
Cheng et al. <sup>150</sup> (2020)	overhanging grooves attached to the f d NACA0009 hydrofoil tip (c=100mm)	10 m/s	10 °	2	attaching several tabs, connected with each other by a slender beam with gap of 2,7&20 mm	Tip-leakage vortex	More suppression for small gaps OHGs with small gap sizes can weaken the strength of both TLV and tip-separation vortex ↑in the TLV core size ↑local minimum pressure limiting influence on the performances of hydrofoil in a large range of the gap sizes

893

894 Table 5- Summary of research for obstacles and vortex generators studies in cavitation control

Investigator(s)	Type of modification	$U_\infty$ (Re)	$\alpha$ (°)	$\sigma$	$h$ [mm] ( $h/\delta$ )	$\Delta X_{VC}/c$ ( $\Delta z/c$ )	Cavitation regime	Comments
<i>Obstacles</i>								
Kawanami et al. <sup>158</sup> (1997)	An obstacle on an Elliptic Nose Foil (c=150 mm & S=150 mm)	Propeller tunnel 5.0 m/s ( $7.2 \times 10^5$ ) For TE tunnel 7.5 m/s ( $8.6 \times 10^5$ )	6	Propeller tunnel: 1.07 TE tunnel: 1.72	2 (width 2mm)	37% c 60% c	Cyclic Cloud	Holding back the re-entrant jets ↓ Cloud cavitation ↓ Noise Intensity ↓ Cavitation drag coefficient

65

Pham et al. <sup>159</sup> (1999)	Obstacle on the flat ( $c = 150\text{ mm}$ , $S = 80\text{ mm}$ )	$8\text{ m/s}$ ( $1.2 \times 10^6$ )	3, 3.25, 3.5	0.94	2 (width $4\text{ mm}$ )	23.3% $c$	Cyclic Cloud	Cloud cavitation control Holding back re-entrant jets
Sato et al. <sup>160</sup> (2002)	Obstacle on the flat hydrofoil ( $c = 70\text{ mm}$ , $S = 70\text{ mm}$ )	$3.59\text{ m/s}$	3.8	0.8, 1.0	3 (width $3\text{ mm}$ )	33% $c$	Cyclic Cloud	No change in frequency or magnitude of oscillation
Zhao et al. <sup>161</sup> (2010)	Obstacle on the NACA0015 hydrofoil ( $c = 100\text{ mm}$ )	( $1 \times 10^6$ )	8	1.2, 1.5	1, 2 (width $2\text{ mm}$ )	32, 37, 45% $c$	Cyclic Cloud	↓ Lift and drag force ↑ lift to drag ratio ↓ Cloud cavitation Restraining re-entrant jets
Ganesh et al. <sup>162</sup> (2015)	Venturi wedge ( $c = 241.3\text{ mm}$ , $S = 76\text{ mm}$ )	$8\text{ m/s}$	22.1	1.81 – 1.94	4 (Width $4\text{ mm}$ )	26.1% $c$	Cyclic Cloud	↓ Void fraction in the cavity ↑ Cavity length
Zhang et al. <sup>168</sup> (2018)	Obstacle on the flat hydrofoil ( $c = 150\text{ mm}$ , $S = 200\text{ mm}$ )	$10\text{ m/s}$	0	0.68 – 0.76	2 (width $2\text{ mm}$ )	37% $c$	Shedding cavitation Cloud cavitation	Constant average cavity length Changing the transient re-entrant jets in terms of strength and direction
Che et al. <sup>167</sup> (2019)	Span-wise obstacle on the 2D NACA0015 hydrofoil ( $c = 100\text{ mm}$ ,	$6\text{ m/s}$	6.5 – 8	0.8 – 1.7	2 (Width $2\text{ mm}$ )	25, 30.7, 39, 47.3, 53 % $c$	Sheet cavitation Sheer cavitation	↓ Sheet cavitation ↑ Pressure in the near- wall region ↓ Energy flux, cavity length, and acoustic intensity

	$S = 200$ )								Cloud cavitation control Cannot suppress cavitation under transitional cavity oscillation
Lin et al. <sup>170</sup> (2021)	different-sized arc obstacles on a flat hydrofoil (c=100mm)	14 m/s	5	1	convexity of the arc = radius/5= 1-2.4 mm	NA	Cloud Cavitation	↓ Shedding cavity size ↑ Shedding frequency as arc radius increase Stabilize the frequency of shedding cavity on the leading edge Transforming the large-scale shedding to the small-scale shedding at the trailing edge as arc radius increase	
<i>Vortex Generators</i>									
Javadi et al. <sup>174</sup> (2017)	Artificial cavitation bubble generator on hydrofoil CAV2003 (c=100mm)	6 m/s	7°	0.4 – 4	0.367 mm	NA	Periodic cloud shedding	↓ Lift and drag fluctuations Producing low-pressure recirculating area Inducing stationary cavitation bubbles Controlling parameters: the location, shape, and size of VGs are the crucial	
Kadivar et al. <sup>177</sup> (2018)	Wedge-type cavitating bubble generators on benchmark	6 m/s ( $6 \times 10^5$ )	7°	0.8	0.25 – 0.3 mm (width 0.75 – 1.1% c)	0.6 – 21.3 %c	Cyclic Cloud	↑ Kinematic energy in the near-wall surface withstanding a pressure rise before the separation	

	hydrofoil ( $c = 100mm$ )							<p>↓ Quick surface high-pressure pulsations</p> <p>↓ Cyclic behavior of unsteady cloud cavitation</p> <p>↓ Turbulent velocity fluctuation transferring high momentum fluid into the vicinity of the wall surface</p> <p>Changing vortex structures and the hydrofoil wake region</p>
Kadivar et al. <sup>181</sup> (2019)	Cylindrical cavitating bubble generators on CAV2003 benchmark hydrofoil ( $c = 100mm$ )	6 m/s ( $6 \times 10^5$ )	7°	0.8	0.25 – 0.3 mm ( $D = 1.1 - 4\%c$ )	6–66% $c$ (1% $c$ )	Cyclic cloud	<p>↓ Adverse pressure gradient at the closure region of cavity</p> <p>↓ Re-entry jet strength</p> <p>↓ Cavitation-induced vibration</p> <p>↓ Near surface high pressure picks</p> <p>Mitigation of cloud cavitation instabilities</p>
Kadivar et al. <sup>182</sup> (2019)	Cylindrical cavitating bubble generators on CAV2003 benchmark hydrofoil ( $c = 100mm$ )	( $1.4 - 1.5 \times 10^6$ )	NA	NA	1 mm ( $D = 1 mm$ )	36% (4%)	Cyclic cloud	<p>↓ large-scale cavitation clouds</p> <p>↓ pressure pulsations at the wake region</p> <p>Shedding happened only in small-scale cavity</p>

Che et al. <sup>171, 184, 186</sup> (2017-2019)	Delta-shaped counter-rotating VGs on NACA0015 hydrofoil ( $c = 100, S = 200 \text{ mm}$ )	$7 \text{ m/s}$ ( $0.6 \times 10^6$ )	$6.5 - 8^\circ$	$0.8 - 1.7$	$0.05 - 0.25 \text{ mm}$ ( $0.5 - 2.5$ ) ( $l = 0.4 \text{ mm}, \beta = 18^\circ$ )	2.5%	Sheet Cavitation	<ul style="list-style-type: none"> <li>↑ Momentum transfer toward the surface</li> <li>↑ Cavitation length</li> <li>↓ Dominant frequency of cavitation (TCO and PCO condition)</li> <li>↑ Vortex cavitation length by decreasing height of mVGs</li> <li>↓ Flow disturbance in the span-wise direction</li> <li>Suppression of boundary layer separation</li> <li>Induce inception of vortex cavitation</li> <li>Cavity moving toward leading-edge</li> <li>Vanishing classical fingering structures &amp; Tollmien-Schlichting waves</li> <li>Creating a uniform sheet cavity in the span-wise direction</li> <li>Suppressing R-T and K-H instabilities</li> </ul>
Kadivar et al. <sup>178</sup> (2020)	Wedge-type cavitating bubble generators on	$(1.1 \times 10^6 - 1.6 \times 10^6)$	$5, 7, 11^\circ$	$0.66 - 1.3$	NA	NA	Cyclic Cloud	<ul style="list-style-type: none"> <li>↓ Amplitude of pressure pulsations</li> <li>Hampering a re-entrant jet</li> </ul>

	CAV2003 benchmark hydrofoil ( $c = 100mm$ )							Hindering cloud cavities
Qiu et al. <sup>187</sup> (2020)	Delta-shaped counter-rotating VGs on NACA0015 hydrofoil ( $c = 100, S = 200 mm$ )	10 m/s ( $1.37 \times 10^6$ )	6.5, 8	1.35&1.7	0.25 mm (2.5)  ( $l = 0.4, \beta = 18^\circ$ )	2.5%	Attached cavitation	New cavitation structure including vortex transition region-attached cavitation  Not possible to delay or suppress the attached cavitation in these conditions  More stable sheet cavitation  More shedding in cloud cavity
Huang et al. <sup>188</sup> (2020)	VGs on Ship propeller	14.37m/s	0- 45	0.2916	20mm	NA	Sheet Cavitation	↓Pressure fluctuation ↓Cavitation instability Inducing more uniform wake
Xu et al. <sup>180</sup> (2020)	A cavitator on the lower side of the NACA0012 foil ( $c=38.1 mm, S=152.4$ )	NA	1-12	0.1,0.2,0.4	5mm	3.125, 6.25, 12.5, 25%c	Supercavitation	Changing the cavitation shape and affect the pressure distribution around the hydrofoil  limitation to the effectiveness of the cavitator used for enhancing lift coefficients, since the cavity cannot grow continuously at the

								cavitator to enclose the hydrofoil in the flow.
Chen et al. <sup>191</sup> (2021)	Delta-shaped counter-rotating VGs on Aeronautics 66 hydrofoil at two different position (c=100mm, S=150mm)	1 m/s ( $1 \times 10^6$ )	4-12	0.1-5	0.1 mm	0.1%c & 0.45% c	Cavitation Inception	Vortex generators located upstream of the laminar separation point promote the earlier inception cavitation and induces the fingerlike vortex cavitation earlier  Vortex generators located in the laminar separation zone delays the inception

895



### 896 3. Conclusion

897 This study reviewed different passive flow control techniques with a focus on control cavitation  
898 application. The review of passive flow control devices in aerodynamic application showed the  
899 potential of passive flow control methods in boundary layer separation, generating stream-wise  
900 vortices in the boundary layer, transferring momentum near the wall, delaying and suppression of  
901 boundary layer separation, and pressure recovery downstream of vortex generators. The vortex  
902 generators showed a better potential for controlling boundary layer separation than other passive  
903 flow control methods. Among different types of vortex generators, counter-rotating and co-rotating  
904 with  $0.2 < h/\delta < 0.5$  and the distance of 5 to 30h from the upstream of baseline separation showed  
905 better effectiveness in controlling and suppressing boundary layer separation.

906 The review of passive flow control techniques in the hydraulic system shows the effectiveness of  
907 this method's different cavitation control types. Different studies in this field have proven the  
908 ability of passive flow control methods in suppressing and delaying boundary layer separation and  
909 reduction in cavity length and cavitation growth. Many studies observed the generation of stream-  
910 wise vortices and reduction in boundary layer span-wise non-uniformities. Besides, transferring  
911 high momentum fluid from free stream flow moved to the near-wall low energy region and moving  
912 higher kinetic energy flow to the surface's vicinity was another observation in these studies.  
913 Declining pressure gradient and intensity of pressure fluctuation at separation point and increasing  
914 resistance against pressure rise before boundary layer separation is another result of using passive  
915 flow control methods. As re-entrant jets play an important role in cavitation, the effect of passive  
916 flow control was weakening the re-entrant jets, their penetration depth, and suppressing the  
917 propagation of the pressure wave of collapse. They are also effective in declining the recirculation

918 zone thickness and consequently the velocity of re-entrant jets. In some experiments, passive flow  
919 control methods could delay cavitation inception, while there were some results with earlier  
920 cavitation onset.

921 However, there is no study comparing different types of passive flow control in the same condition  
922 in controlling cavitation. In addition to all the effects mentioned above, Vortex generators can  
923 eliminate classical "fingering structures" and Tollmien–Schlichting waves and affect partial cavity  
924 oscillation, transitional cavity oscillation, and the transition between these two instabilities. They  
925 are also effective in declining turbulent velocity fluctuation and decreasing cavitation erosion.

926 Few studies focused on the Vortex generators in micro-scale <sup>171, 174, 177, 181, 182, 184, 186</sup>. The most  
927 recent research in the field of Vortex generators and its effect on the cavitation instabilities was  
928 based on the vane-type counter-rotating vortex generator with a minimum height of 0.05mm (0.074  
929 in manufacturing) with  $h/\delta = 0.5$  <sup>171, 184, 186</sup>. According to single-phase flow studies of Vortex  
930 generators the most optimum  $h/\delta$  range for Vortex generators is  $0.2 < h/\delta < 0.5$ . Che et al. <sup>171</sup> stated  
931 that because of manufacturing limits they could not manufacture vortex generators with  $h/\delta$  less  
932 than 0.74, and 3D printing could be a solution for manufacturing vortex generators of lower height  
933 and thinner thickness and might be relatively easy to be installed in fluid machinery.

934 According to this review, the potential and effectiveness of passive flow control, and specifically  
935 Vortex generators, have been proven. However, there is great potential to optimize designs in terms  
936 of geometry, arrangement, and distance to the boundary layer separation. Since the major research  
937 in optimizing the design of vortex generators was based on the compressible single phase flow  
938 experiments and according to the different nature of compressible and multiphase flows in  
939 cavitation phenomenon, the analysis of optimized geometry criteria such as  $h/\delta$  and  $l/h$  and,  $\Delta X_{VG}/h$   
940 in hydraulic systems is necessary. Areas for additional investigation include manufacturing

941 processes including their life-time and durability. Additionally, the specific application area of  
942 hydraulic systems, and particular centrifugal pumps, requires greater investigation due to the  
943 economic and sustainability gains which might be realized from further optimization of these  
944 technologies.

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