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A critical analysis of the stall onset in vertical axis wind turbines

Nidiana Rosado Hau^{a,b}, Lin Ma^a, Derek Ingham^a, Mohamed Pourkashanian^a

^a*Energy 2050, University of Sheffield, United Kingdom, S10 2TN*

^b*Facultad de Ingenieria, Universidad Autonoma de Yucatan*

Abstract

The dynamic stall phenomenon in Vertical Axis Wind Turbines (VAWTs) appears, under some operating conditions, to be not very well defined, such as at a low tip speed ratio. Some studies have focused on describing the topology of the dynamic stall but little attention has been paid to understand how all the operating VAWT parameters influence the moment of stall inception. This paper focuses on analysing the influence of the tip speed ratio, pitch angle, reduced frequency, relative velocity and Reynolds number on the stall-onset angle of VAWTs. CFD simulations with an oscillating NACA0015 describing the angle of attack and relative velocity in VAWTs were employed. The results have revealed that an increase in the stall-onset occurs anytime the operating parameters increase the value of the non-dimensional pitch rate and the Reynolds number at the moment the angle of attack approaches to the static stall angle. The stall-onset angle showed a linear increase with the non-dimensional pitch rate in the range of Reynolds number tested, namely $0.8 - 3.3 \times 10^5$. This paper has elucidated how the several parameters governing VAWTs operation effect the stall-onset angle and therefore has contributed to a much better understanding of the causes that induce the stall in these devices.

Keywords:

Vertical axis wind turbine, Stall-onset, Dynamic stall, Reduced frequency, Reynolds number, Pitch angle

1. Introduction

Vertical Axis Wind Turbines (VAWTs) have drawn much attention of research and industry due to their potential to be installed in urban and offshore regions, and in particular where the wind resource

Email address: nidiana.rosado@correo.uady.mx (Nidiana Rosado Hau)

Nomenclature

C	Constant variable		revolution, m/s
C_C, C_D, C_L	Chordwise, drag and lift force coefficients	V_{rel}	Relative velocity, m/s
C_{fx}	Skin friction, $\sigma_x/0.5\rho U_{ref}^2$	c	Chord, m
C_p	Pressure coefficient	q	Non-dimensional pitch rate
D	Rotor diameter, m	t	Time, s
L, M	Lift stall and moment stall points	x/c	Non-dimensional chord distance
R	Rotor radius, m	$\alpha(t)$	Angle of attack, ($^\circ$)
T	Period of oscillation	α_{max}	Maximum angle of attack in the upstroke
U	Incoming wind flow for the oscillating aerofoil, m/s	α_{os}	Dynamic stall-onset angle, ($^\circ$)
U_{ref}	Actual wind speed, m/s	α_{ss}	Static stall angle, ($^\circ$)
V_∞	Free stream wind velocity in the VAWTs, m/s	$\dot{\alpha}$	Pitch rate, (rad/s)
V_{inst}	Wind speed at a specific time, m/s	β	Pitch angle, ($^\circ$)
V_{mean}	Average of the relative velocity in one	κ	Reduced frequency, $(\omega c/2U_{ref})$
		λ	Tip speed ratio, $\omega R/V_\infty$
		ω	Rotational speed, rad/s

26 presents highly variable wind speed and direction [1]. In order to understand its aerodynamics, many
 27 authors have used URANS Computational Fluid Dynamics (CFD) simulations to explore qualitatively
 28 the influence of the aerofoil profile [2, 3, 4, 5], the pitch angle [6, 7, 8], Reynolds number [9, 10, 11, 12]
 29 and the number of blades [1, 13, 7, 14] on the power coefficient.

30 The aerodynamic investigations on VAWTs have confirmed that the presence of the dynamic
 31 stall phenomenon has been observed under some operating conditions and still it is not very well
 32 known except that it is being associated mainly to low tip speed ratios (TSRs). The range of TSRs

33 where dynamic stall appears has been found to be different in each case investigated [15, 16, 17,
34 18, 19, 20, 21]. In addition, the parameter c/D , that relates the chord length and diameter, have
35 been demonstrated to play a significant role in the development of dynamic stall on VAWTs and
36 according to Buchner et al. [22], the tip speed ratio alone is not sufficient to describe the dynamic
37 stall phenomenon.

38 In the VAWT, when dynamic stall takes place then this degrades its power coefficient and induces
39 high structural loads on the rotor [23]. The vortex formation and its release to the wake characterizes
40 the dynamic stall on VAWTs. If the dynamic stall is severe, multiple vortices are released, and an
41 additional decrease in the power coefficient is observed [24]. The generation of the vortices has been
42 observed to be more prominent in the upstream section of the rotor but may appear downstream of
43 the rotor [25, 16].

44 In order to improve the VAWTs performance and to regulate the dynamic stall that induces the
45 undesired unsteady loads, it is fundamental to determine the operating and physical conditions that
46 control the stall-onset in the upstream region of the VAWTs. Since previous studies have investigated
47 mostly the impact of the tip speed ratio, the present analysis addresses the need in understanding
48 the influence on the stall-inception of the several parameters governing VAWTs operation.

49 The stall-onset angle (α_{os}), represents the inception of the stalling process. Under static condi-
50 tions, this angle is recognizable by the angle where a sudden loss in the lift occurs but under dynamic
51 conditions, this is not the case [26] and attention to other aerodynamic characteristics need to be
52 made. Under dynamic conditions, stall inception occurs immediately after a laminar bubble, that is
53 concentrated near the aerofoil leading edge (LE), experiences a maximum in the pressure coefficient
54 (negative), then, a vortex is initiated and detaches from the LE [27, 28] and the presence of the vortex
55 affects the unsteady aerodynamic forces.

56 An example of the unsteady aerodynamic forces under dynamic stall for oscillating aerofoils is
57 shown in Fig.1. At the stall-onset, the lift coefficient (C_L) starts to deviate from its linear attached
58 trend and increases in value (over-lift) due to the movement of the vortex downstream along the chord;
59 the lift coefficient reaches its maximum value when the vortex is located at the mid chord position
60 and then, stalls, this point is called lift stall (L). In addition, a deviation occurs in the drag force
61 coefficient (C_D) and the pitching moment coefficient (C_M). Further, McAlister, [29] has suggested
62 that the maximum chordwise force coefficient, (C_c), is the point that is a more quantifiable criterion

63 to select for the stall-onset angle. A discussion of different techniques to define the stall-onset angle
 64 is found in [30, 31].

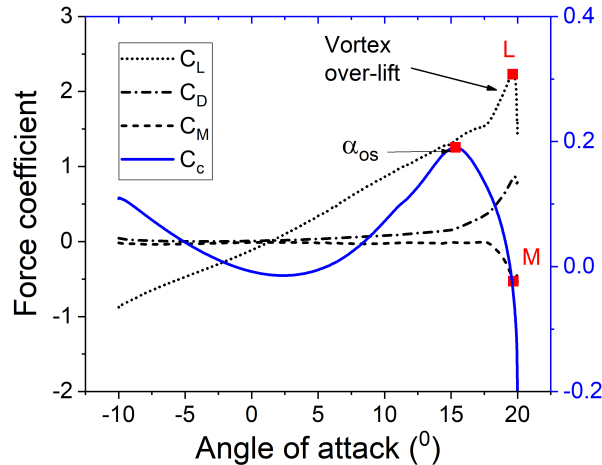


Figure 1: A typical unsteady loads coefficient as a function of the angle of attack that illustrates the lift stall point (L), moment stall (M) and stall-onset angle (α_{os}).

65 The stall-onset angle is a critical parameter in describing the dynamic stall process since it marks
 66 the inception of the leading edge vortex. Thus, the larger is the stall-onset angle then the later the
 67 vortex formation and the severity of the stall conditions may be reduced. For example, the point
 68 where the sudden loss in the lift force occurs is moved to a larger angle of attack as well as the point
 69 where a large negative pitching moment is observed [32]. In addition, the large hysteresis in the
 70 unsteady loads due to the presence of the vortex decreases, and the stall conditions change from deep
 71 stall to light stall or even non-stall conditions. Therefore, investigating how the operating conditions
 72 affect the stall-onset angle is an essential task in improving the aerodynamics and the design of the
 73 VAWTs.

74 There is a large amount of experimental and numerical investigation on the dynamic stall phe-
 75 nomenon [32, 33, 34, 35, 36, 37]. The ramp-up tests, that have a constant pitch rate $\dot{\alpha} = C$, have
 76 demonstrated this parameter as being the most crucial parameter [38, 39, 40, 41, 42, 43, 44] to define
 77 the stall-onset. In oscillating motions, where the pitch rate is a function given by $\dot{\alpha} = f(t)$, the
 78 variables that affect the inception point are less clear, since the amplitude and mean angle of oscil-
 79 lation and reduced frequency affect the angle of attack equation and hence the pitch rate function
 80 [29, 30, 45, 46].

81 Sheng et al. [30] evaluated the stall-onset angle of several oscillating aerofoils, and they proposed
82 similarly to the ramp-up tests a non-dimensional parameter called the equivalent reduced pitch rate
83 that is the product of the amplitude and the reduced frequency. This equivalent reduced pitch rate
84 was shown to be the most crucial parameter that defines the stall-onset in the oscillating motion.
85 The same equivalent reduced pitch rate was used in [47] and a similar linear trend between the
86 equivalent reduced pitch rate and the stall-onset angle was found. More recently, Mulleners et al.
87 [31] experimentally found for oscillating aerofoils that the non-dimensional pitch rate at the static-stall
88 angle was the parameter that is the most critical factor in determining the stall-onset and the previous
89 proposed equivalent reduced pitch rate in [30] did not show a clear relation with the stall-onset.

90 In the VAWTs, the number of operating conditions that may affect the stall-onset angle is larger
91 compared with the ramp-up and sine-pitching motions. For example, the stall-onset can be affected
92 by the tip speed ratio, pitch angle, rotational speed, Reynolds number and the constantly changing
93 relative velocity. Thus, despite the efforts made by several authors, defining how these operating
94 parameters affect the stall-onset angle results in a very complicated task when using a full wind
95 turbine [22].

96 This paper uses a systematic methodology to understand how the mentioned variables affect the
97 stall-onset angle and the dynamic stall in VAWTs. First, an analysis of the tip speed ratio, reduced
98 frequency and pitch angle at a constant Reynold number is performed by using CFD simulations
99 of an oscillating NACA0015 describing the angle of attack of a VAWT. Second, the relation among
100 all the mentioned variables with the non-dimensional pitch rate parameter and their effect on the
101 stall-onset angle is elucidated. Finally, the effect of the relative velocity is investigated by using the
102 oscillating NACA0015 aerofoil with a time-varying incoming flow.

103 This paper is divided as follows: In Section 2, the operating parameters employed in the simu-
104 lations are defined and the methodology to calculate the stall-onset angle is described respectively;
105 Section 3 describes the numerical techniques employed. Section 4 describes the effect of the TSR,
106 pitch angle, reduced frequency, Reynolds number, Variable wind speed at the stall-onset angle of
107 the VAWTs, and Section 5 discusses the present findings and their application in VAWTs; Finally,
108 conclusions are included in Section 6.

109 2. Methodology

110 2.1. Description of the operating parameters

111 In this paper, two-dimensional CFD simulations that agree very well with the experimental data
 112 were employed. The description of the numerical strategy is included in Section 3. In order to evaluate
 113 the effect of the operating conditions on the stall-onset angle, then two approaches were used.

114 First, an incoming wind flow U with a constant magnitude (depending on the chord-based
 115 Reynolds number under evaluation) past an oscillating aerofoil, as illustrated in Fig. 2. The os-
 116 cillating aerofoil describes a motion with the angle of attack $\alpha(t)$ for a VAWTs [23] given as follow:

$$\alpha(t) = \arctan\left(\frac{\sin(\omega t)}{\lambda + \cos(\omega t)}\right) - \beta \quad (1)$$

117 where, λ is the tip speed ratio; ω is the rotational speed; t is the time and, β is the pitch angle.
 118 β is positive outwards from the circle described by the outer edge of the rotation of a VAWT blade.
 119 For this oscillating aerofoil β positive is indicated in Fig. 2. The angle of attack represents the angle
 120 between the aerofoil-chord and the incoming wind flow U aligned all the time to the x-axis.

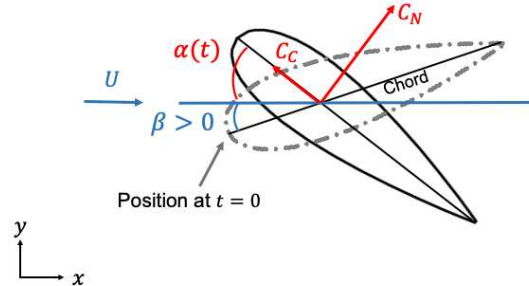


Figure 2: Sketch of an oscillating aerofoil with the VAWT angle of attack $\alpha(t)$ and an incoming flow (U). U can take a constant magnitude or a time-varying magnitude given by the relative velocity equation.

121 The value of ωt from 0 to π represents the upstream zone of the rotor, and from π to 2π the
 122 downstream zone. Positive angles of attack are associated with the upstream zone of the rotor and
 123 negative angles with the downstream zone.

124 In order to replicate the angle of attack motion given by Eq. (1) in the CFD simulations, a user
 125 defined function (UDF) was employed to control the pitching rate of the rotating mesh domain (mesh
 126 domain explained in Section 3.1.2) according to the equation:

$$\dot{\alpha}(t) = \omega \frac{(1 + \lambda \cos(\omega t))}{(1 + 2\lambda \cos(\omega t) + \lambda^2)} \quad (2)$$

127 (i) Using this first approach, at a constant Reynolds number the influence of the tip speed ratio
 128 (λ), pitch angle (β) and the angular velocity (ω) that affect the angle of attack given in Eq. (1) were
 129 investigated. The rotational speed was expressed in terms of the non-dimensional parameter, called
 130 the reduced frequency (κ) as $\omega = 2\kappa U_{ref}/c$. U_{ref} represents the actual wind speed that impacts the
 131 aerofoil. For this first approach, with an incoming wind flow with a constant magnitude, $U = U_{ref}$
 132 and takes a value of 20 *m/s* to obtain a Reynolds number base on the chord-aerofoil of 2×10^5 .

133 The tip speed ratios investigated were 2 and 3 as these are typically found to be small enough to
 134 allow the presence of dynamic stall in VAWTs. Additionally, the values of κ tested are in the range
 135 of the average reduced frequency ($c/2R$), between 0.025 and 0.1828, as found in VAWTs [13, 48, 49].

136 (ii) The non-dimensional pitch rate parameter, q , that is formulated by Daley et al. [44] is given
 137 as:

$$q = \dot{\alpha}c/(2U_{ref}) \quad (3)$$

138 It is necessary to emphasize that the pitch rate $\dot{\alpha}$ and the velocity changes constantly in VAWTs,
 139 thus, the non-dimensional pitch rate q uses the values of the pitch rate and the relative velocity at a
 140 specific time, t , as input values corresponding to $\dot{\alpha}$ and U_{ref} respectively. The expression in Eq.(3) is
 141 also used to calculate the non-dimensional pitch rate in the ramp-up motion, but because the pitch
 142 rate $\dot{\alpha}$ has a constant value then q is easily calculated.

143 In the second approach, the incoming wind flow U , as represented in Fig. 2, was a time-depend
 144 function given by the relative velocity equation of VAWTs as follows:

$$V_{rel} = V_{\infty} \sqrt{1 + 2\lambda \cos(\omega t) + \lambda^2} \quad (4)$$

145 where, V_{∞} represents the incoming free-stream wind velocity on the VAWT rotor.

146 For this approach, a user defined function was implemented to vary the incoming flow (inlet
 147 velocity) according to Eq.(4) and at the same time the pitching rate according to Eq. (2). In order to
 148 have a single value of the non-dimensional pitch rate using Eq. (3) then, the pitch rate, $\dot{\alpha}$ and U_{ref}
 149 uses the value of the Eq. (2) and Eq. (4), respectively, at the instant of time t when the angle of
 150 attack approaches the static stall angle.

151 (iii) The constantly changing relative velocity described by the Eq. (4), has been investigated in
 152 order to assess its influence on the stall-onset and to compared the existing difference on the stall-
 153 onset angle when using a constant-average relative velocity. The average relative velocity, ωR or
 154 λV_∞ , that is an approximated average of the Eq. (4) in one revolution, is typically used in VAWTs
 155 in order to simplify the analysis [17, 50]. Thus, it is interesting to investigate if a difference exists
 156 when using the actual relative velocity rather than its average value.

157 2.2. Stall-onset estimation

158 As mentioned previously, there are several techniques to identify the stall-onset angle. In this
 159 paper, the stall-onset angle, α_{os} , is calculated as the angle where a maximum value in the chordwise
 160 force coefficient is observed. This criterion is also recommended in [29, 34, 51].

161 The chordwise force coefficient, C_c , for an oscillating aerofoil is represented in Fig. 2 and is
 162 described as follows:

$$C_c = C_L \sin(\alpha) - C_D \cos(\alpha) \quad (5)$$

163 Due to the prominent influence of the dynamic stall in the upstream zone of the VAWT, [25, 16],
 164 i.e. from $\omega t = 0 - \pi$, in this paper we focus on evaluating the stall-onset angle in this range of angle
 165 of attack.

166 3. Computational fluid dynamic simulations

167 3.1. Unsteady simulations

168 The two-dimensional URANS simulations used in this investigation were validated very carefully
 169 with the available experimental data of an oscillating NACA0012 aerofoil. The Reynolds number for
 170 this data is 1.35×10^5 (chord-based); the aerofoil chord-length, $c = 15$ cm; the reduced frequency
 171 $\kappa = 0.1$, and the intensity of the turbulence was 0.08 %, similar to the experimental conditions of the
 172 wind tunnel test case [37]. This experimental data is selected since VAWTs for urban environments
 173 can experience a Reynolds number as low as 1×10^5 [10, 14] and this is the main interest of the
 174 present study.

175 Several numerical investigations of the selected experimental data in [37] have been performed
 176 in order to determine a numerical strategy that considers the mesh, time and domain independence

177 analysis for oscillating aerofoils at low Reynolds numbers [46, 52, 53, 54]. This is beneficial to verified
178 the numerical techniques performed in this paper.

179 *3.1.1. Numerical settings*

180 In the present simulations, the turbulent transitional model $\kappa\omega - SST - \gamma$ was selected due to
181 the Reynolds number being studied, namely $0.8 - 3.3 \times 10^5$, where the boundary layer flow transition
182 is likely to occur and a transitional model is recommended at such Reynolds numbers [55, 56, 57]. A
183 discussion of the influence of the turbulence models of this experimental case has been made in [57]
184 and the use of a transitional model is recommended.

185 The COUPLED method that is a non-segregate method of pressure coupling with an implicit
186 scheme was selected due to the advantages of fast convergence for coarse meshes and coarse time steps
187 as described in ANSYS FLUENT 17.2. Additionally, the COUPLED method has the capabilities of
188 detecting divergence and automatically reduces the Courant Number (CFL). The default CFL is 200
189 and a reduction to 10-50 is recommended if there are difficulties with convergence, thus a CFL=10
190 was selected. A full convergence criterion with a relative residual less than 1×10^{-5} was used with 100
191 iterations per time step. At least four oscillating cycles were run for each simulation before collecting
192 the results, and in most cases, a convergence in the lift force coefficient was achieved after the second
193 cycle. This agrees with the statistical convergence observed by Geng. et al. [57]. A second-order
194 discretization (spatial and temporal) and a hybrid initialization was set up in all the simulations.

195 *3.1.2. Mesh domain and boundary conditions*

196 The mesh topology consist of two domains: a rotating domain with an unstructured mesh shows
197 in Fig 3(a) and, a stationary domain consisting of a structured mesh, Fig. 3(b).

198 In the experimental data, a closed wind tunnel was used with the walls allocated to be three times
199 the chord-length of the aerofoil from the centre of the pitching motion. Thus, to be consistent with
200 the experimental test conditions, non-slip conditions were applied for the upper and lower bounds of
201 the domain with an original distance of 3 times the chord-length. Moreover, due to the interest in
202 studying aerofoils in an open environment, then the distance of the upper and lower boundaries from
203 the pitching position of the aerofoils ($1/4 c$) was increased to 3, 10, 15 and 20 times the characteristic
204 length, c , in order to find a domain with no influence on the forces on the aerofoil. The influence of
205 this distance is observed in the resulting lift coefficient and very similar results were obtained using

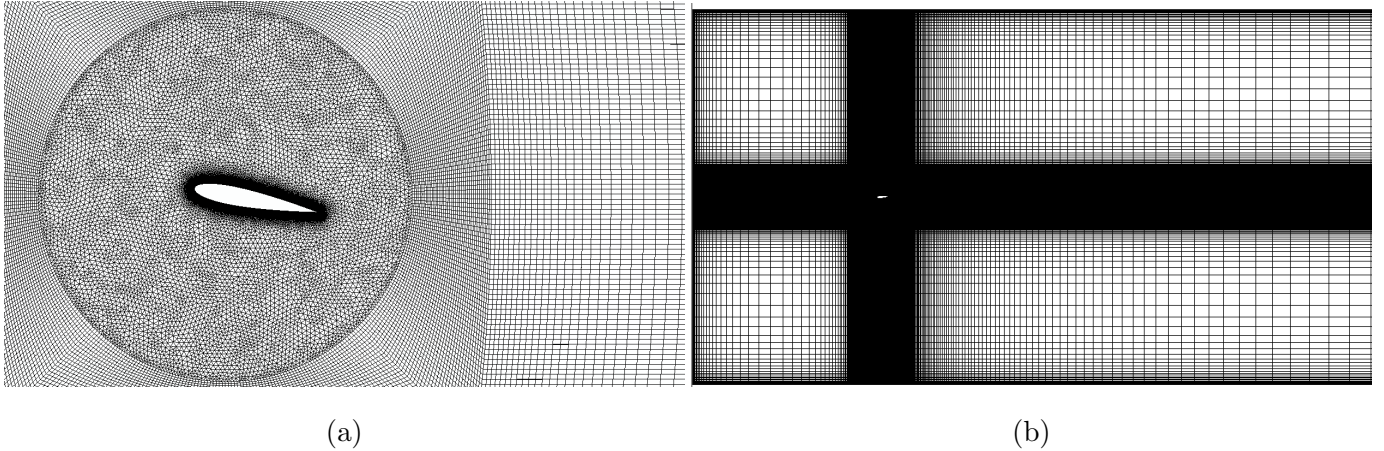


Figure 3: Mesh topology (a) around the aerofoil with 1000 nodes, and (b) for the non-rotational region with the final settings of the domain.

206 distances of 10, 15 and 20 c . Therefore, 15 c was selected as the distance from the pitching point to
 207 the boundaries (lower and upper), and this was enough to avoid the influence of the upper and lower
 208 boundaries. The pressure outlet was set to be 45 c from the pitching point of the oscillating aerofoil,
 209 and the velocity inlet was set to be 15 c from the oscillating point. Both distances are considered to
 210 be large enough to allow the development of the wake and within the recommendations of several
 211 investigations [52, 54].

212 The aerofoil profile was set as non-slip conditions and due to the importance of solving the viscous
 213 layer, then 60 layers were collocated around the aerofoil and the y^+ in the boundary layer was less
 214 than 1.2.

215 A mesh independence analysis with four grids with the parameters as given in Table 1 was per-
 216 formed. The number of nodes around the aerofoil investigated was 500, 1000, 2000 and 4000; however,
 217 no large impact was found in the force coefficients observed in Fig. 4(a) within this range of nodes,
 218 and therefore 1000 nodes were selected for the final settings.

Table 1: Characteristics of the evaluated meshes.

Parameter	G1	G2	G3	G4
Nodes on aerofoil	500	1000	2000	4000
Total mesh elements	140000	200000	300000	500000

219 A time step independence study was conducted with a non-dimensional time constant ($\tau = t/T$)

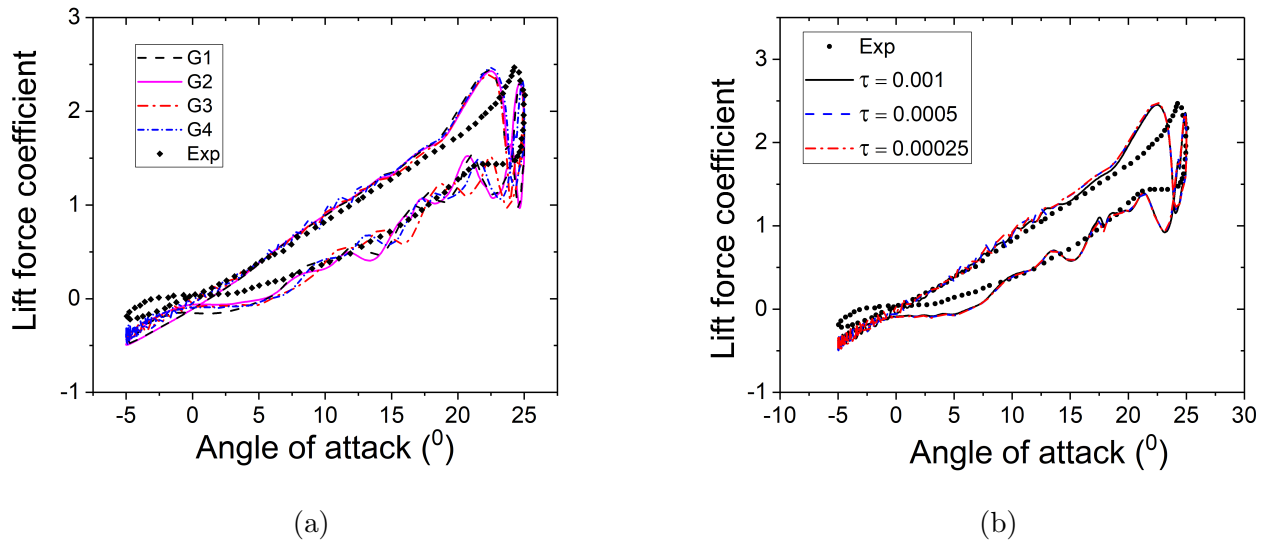


Figure 4: (a) Mesh independence study, and (b) time step independence study.

220 of 0.001, 0.0005 and 0.00025. These time steps correspond to a step increment of 0.1, 0.05 and 0.025
 221 degrees in the angle of attack, respectively. Similar results were obtained for the lift force coefficient,
 222 as observed in Fig. 4(b), for all the time steps studied and therefore, $\tau = 0.0005$ was selected as the
 223 best option.

224 3.1.3. Numerical verification

225 The present URANS simulations were validated against the URANS simulation performed by
 226 Geng et al. [54], and the Large Eddy Simulations (LES) carried out by Geng et al. [54] and Kim et
 227 al. [53], and a comparison among these four simulations is shown in Fig. 5(a). Very good agreement
 228 in the prediction of the lift force coefficient, C_L , was observed among present 2D CFD simulations,
 229 Geng et.al 2D CFD simulations [54] and Geng et al. LES simulations [54].

230 For all the numerical simulations, 2D CFD and LES, the linear region of variation of the lift
 231 force coefficient with angle of attack is in very good agreement with the experimental data. The
 232 deviation in C_L , that appears once the vortex has been released, suggests that the stall-onset angle
 233 may be predicted with the same accuracy for all the numerical techniques compared in Fig. 5 (a).
 234 Unfortunately, the significant C_L peak observed in the experimental data was not captured by any
 235 of the numerical simulations. Since this peak indicates that a vortex is located at the mid-chord of
 236 the aerofoil, thus, the accuracy in predicting the stall-onset angle is not affected and this angle is the

237 focus of this paper.

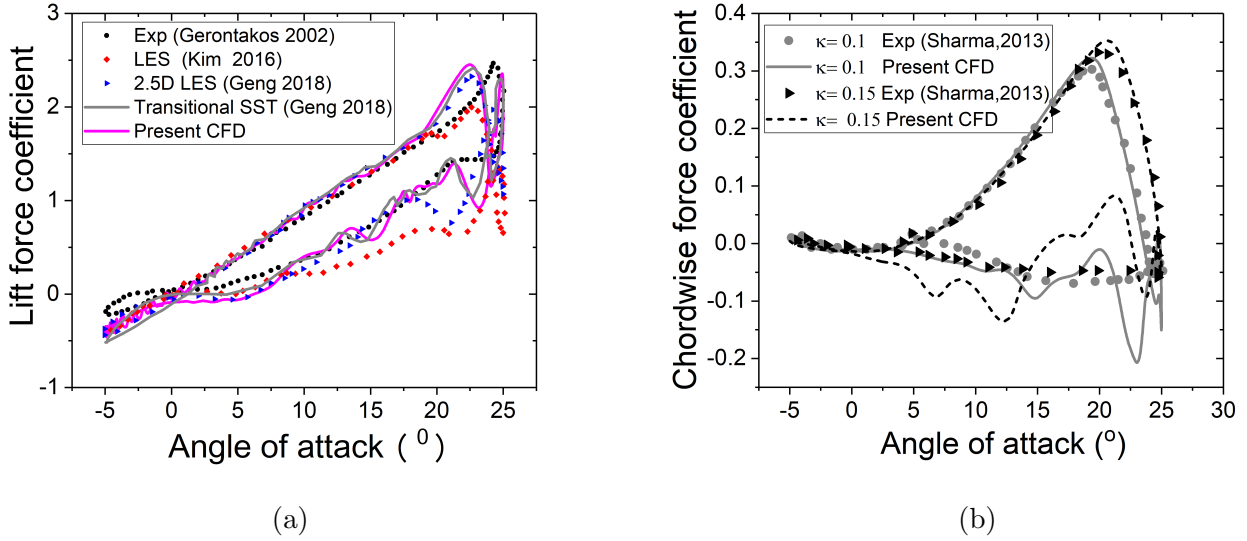


Figure 5: (a) The lift coefficient as a function of the angle of attack of the aerofoil NACA0012 at $Re\ 1.35 \times 10^5$ and the comparison with the experimental data [37]. (b) Chordwise force coefficient of the NACA0015 as a function of the angle of attack with a VAWT motion at $Re\ 2 \times 10^5$ [58].

238 Further, to demonstrate the accuracy of the present numerical methodology to capture the stall-
 239 onset angle, a second validation is performed by using the experimental data of a NACA0015 aerofoil
 240 that describes the same motion as the previous experimental case, i.e. $\alpha(t) = 10 + 15 \sin \omega t$ at
 241 $Re\ 2 \times 10^5$. The advantage of this second case results in the available data of the chordwise force
 242 coefficient. The numerical predictions of the stall-onset angle are obtained for the reduced frequency
 243 values of $\kappa = 0.1$ and $\kappa = 0.15$ and these are included in Fig. 5(b). Excellent agreement was
 244 observed in the prediction of the peak in the chordwise force coefficients. Hence, the present numerical
 245 simulations, since they capture with an excellent agreement the chordwise force with the experimental
 246 data, may be considered accurate enough to investigate the stall-onset angle.

247 3.2. Static simulation

248 Due to the interest in evaluating the static stall angle for three Reynolds numbers, namely, 0.8,
 249 2 and 3.3×10^5 , static simulations were performed by using the same mesh characteristics as those
 250 employed in the unsteady simulations. The number of iterations used was 10000 to ensure a full
 251 stabilization of the lift force coefficient and then, the static stall angle obtained for each aerofoil

252 was: 10° , 13° , 14° for the Reynolds numbers 0.8 , 2 and 3.3×10^5 , respectively. The Reynolds number
253 was changed by varying the incoming flow to 8 , 20 and 33 m/s .

254 4. Results

255 4.1. Influence of κ , λ and β at constant Reynolds number

256 The analysis of the influence of the reduced frequency (κ), tip speed ratio (λ) and pitch angle (β)
257 on the stall-onset angle by using the first approach for a constant Reynolds number has shown the
258 following results:

259 (i) With the increase in the reduced frequency (κ), the calculated stall-onset angle (α_{os}) increases.
260 For example, in the simulation with a reduced frequency of $\kappa = 0.09$, the stall-onset angle was $\alpha_{os} =$
261 20.60° . Decreasing the reduced frequency to $\kappa = 0.06$ produced the stall-onset angle $\alpha_{os} = 18.79^\circ$.
262 For both values of κ the tip speed ratio was $\lambda = 2$ and the pitch angle was $\beta = -11^\circ$.

263 The delay in the stall conditions with the increase in the reduced frequency is also observed in the
264 comparison of the pressure coefficient (C_p) and skin friction (C_{fx}) curves including in Fig. 6(a-b).
265 The skin friction at the Reynolds number 2×10^5 for two dynamic cases with reduced frequencies
266 $\kappa = 0.09$ and $\kappa = 0.06$, and one static simulation were computed at the angle of attack of 13° . At
267 the static condition, the aerofoil stalls at 13° and thus a high negative pressure coefficient is observed
268 close to the aerofoil leading edge. This is a critical point where a laminar separation bubble (LSB)
269 concentrated at the LE collapsed [34]. For the unsteady simulations, this high minimum pressure is
270 not reached, suggesting a delay in the pressure collapsed for the reduced frequency $\kappa = 0.06$ and a
271 further delay for the reduced frequency $\kappa = 0.09$.

272 Another interesting characteristic that confirms the delay in the stall is recognized by observing
273 the skin friction (C_{fx}), as plotted in Fig. 6(b). The closer the laminar separation bubble (LSB) to the
274 aerofoil leading-edge indicates an earlier collapse of the pressure coefficient and, an earlier separation
275 of the boundary layer occurs. The region occupied by the LSB is exemplified for the static case in
276 Fig. 6(b) by circular and triangular symbols; at these two points the skin friction experiences a zero
277 value. The LSB region for the unsteady cases with a reduced frequency $\kappa = 0.06$ is closer to the
278 leading edge of the aerofoil compared for the case with the reduced frequency $\kappa = 0.09$.

279 Moreover, the point where the turbulent boundary layer (formed after the reattachment of the
280 LSB) experiences $C_{fx} = 0$ is an additional parameter of reference to evaluate the magnitude of the

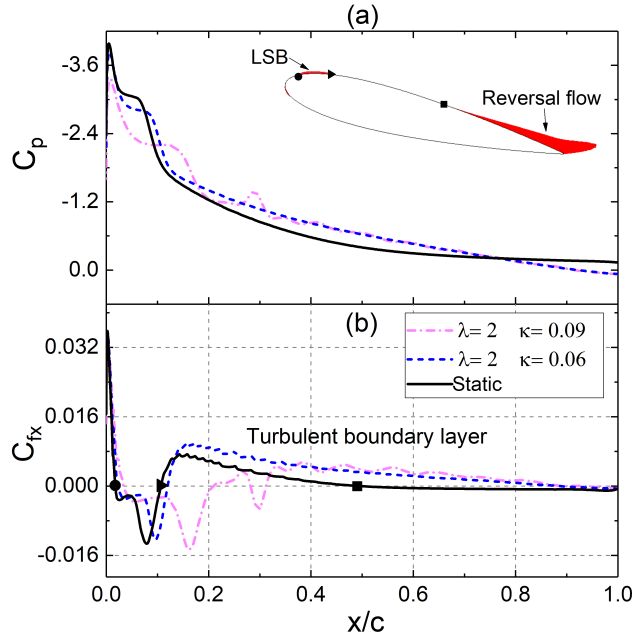


Figure 6: (a) Pressure coefficient, and (b) skin friction along the chord of an oscillating aerofoil at the angle of attack 13° . ● Laminar boundary layer separation, ► Reattachment of LSB, ■ Start of reversal flow in the turbulence boundary layer at TE.

281 delay in the stall-onset angle; closer is this point to the LE, then the sooner stall occurs. For the
 282 static case, the turbulent boundary layer experiences $C_{fx} = 0$ at 50 % of the chord, this point is
 283 indicated with a square in Fig 6 (b). For the unsteady cases with $\kappa = 0.06$ and $\kappa = 0.09$ the turbulent
 284 boundary layer with $C_{fx} = 0$ is located at 95% and 97 % from the LE. More details on the pressure
 285 coefficient and skin friction behaviours under unsteady conditions are described by Ekaterinaris &
 286 Platzer [55].

287 The increase of the stall-onset angle with the reduced frequency is confirmed by comparing the
 288 calculated stall-onset angle, α_{os} , for another two dynamic simulations with $\kappa = 0.02$ and $\kappa = 0.04$
 289 using both a tip speed ratio of $\lambda = 3$ and a pitch angle of $\beta = -11^\circ$ at $\text{Re } 2 \times 10^5$. The stall-onset
 290 angle, α_{os} , results in 14.70° and 16.22° for the reduced frequencies $\kappa = 0.02$ and 0.04 , respectively.

291 (ii) The influence analysis of the tip speed ratio (λ) has shown that with a decrease in λ the stall-
 292 onset angle (α_{os}) grows. For the tip speed ratios investigated with values 2, 2.37 and 3, the computed
 293 α_{os} were 18.82° , 17.68° and 16.56° , respectively. The skin friction for these dynamic cases is illustrated
 294 in Fig. 7 (a) and it was revealed that the lower is λ then more is the delay in the stall-onset angle.

295 For example, the position of the laminar bubble (first two locations with $C_{fx} = 0$), is closer to the
 296 leading edge aerofoil for $\lambda = 3$, followed by $\lambda = 2.37$ and finally $\lambda = 2$. Moreover, the point where
 297 the turbulent boundary layer experiences $C_{fx} = 0$, which indicates the start of reverse flow, is located
 298 at 84 % from the aerofoil LE for $\lambda = 3$, at 86 % for $\lambda = 2.37$ and 88% for $\lambda = 2$. Therefore, this
 299 indicates that the tip speed ratio $\lambda = 2$ presents the largest delay in the stall conditions. Compared
 300 with the location of the LSB in the skin friction between the two values of the reduced frequency in
 301 Fig. 6(b), the effect on the skin friction due to the tip speed ratio in Fig.7(a) is minimal.

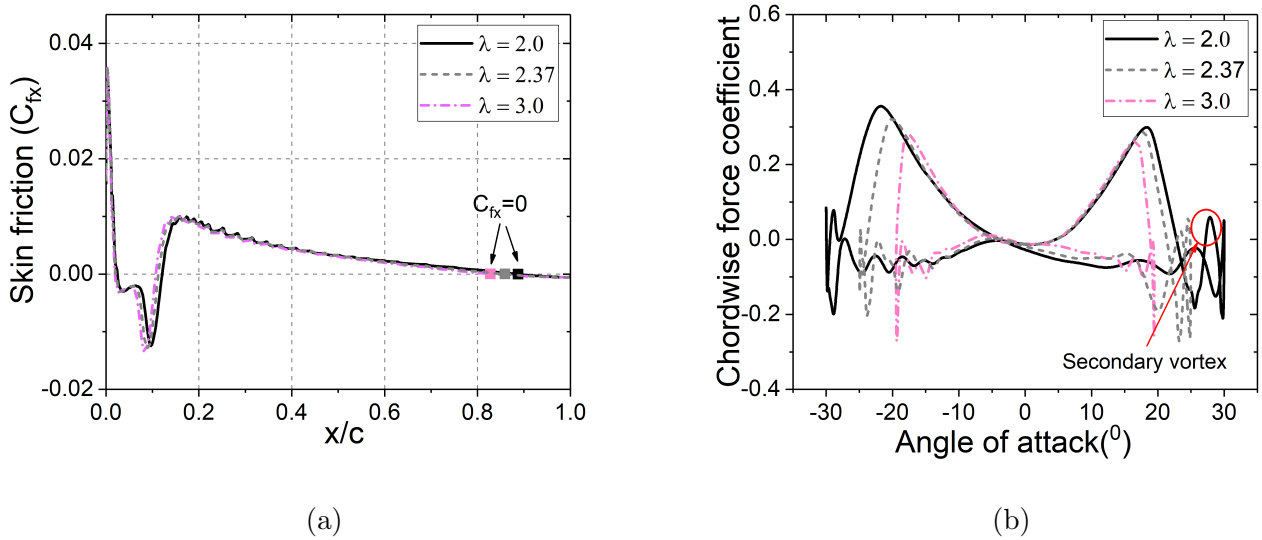


Figure 7: (a) Skin friction, and (b) chordwise force coefficient, as a function of the angle of attack for $\lambda = 3, 2.37$ and 2 with values of $\kappa = 0.06$, $\beta = 0$ and $Re = 2 \times 10^5$.

302 The tip speed ratio plays a key role that is extremely important for the VAWT operation; it
 303 substantially influences the maximum angle of oscillation (α_{max}). Larger is the difference between
 304 the stall-onset and the maximum angle of oscillation, ($\alpha_{max} - \alpha_{os}$), then secondary vortices are more
 305 likely to occur and thus deeper stall conditions are observed.

306 For the tip speed ratio $\lambda = 2$, this difference, $\alpha_{max} - \alpha_{os}$, is 11.6° . This allows the release into the
 307 wake of the primary vortex formed at the leading edge (LEV), a shear layer vortex (that if formed
 308 at the TE, and is opposite in direction to the LEV) and the formation of a secondary vortex, as
 309 indicated in Fig. 8(a). The secondary vortex is also observed in the chordwise force coefficient, C_C ,
 310 included in Fig. 7(b) where a second peak in C_C is identified.

311 In the case of $\lambda = 3$, the difference between α_{max} and α_{os} is 3.44° and hence, a primary vortex

312 is released and the shear layer vortex is formed; there is no indication of a secondary vortex in the
 313 chordwise force coefficient in Fig. 7(b), neither in Fig. 8(b). More details on the deep stall conditions
 314 can be found in [32].

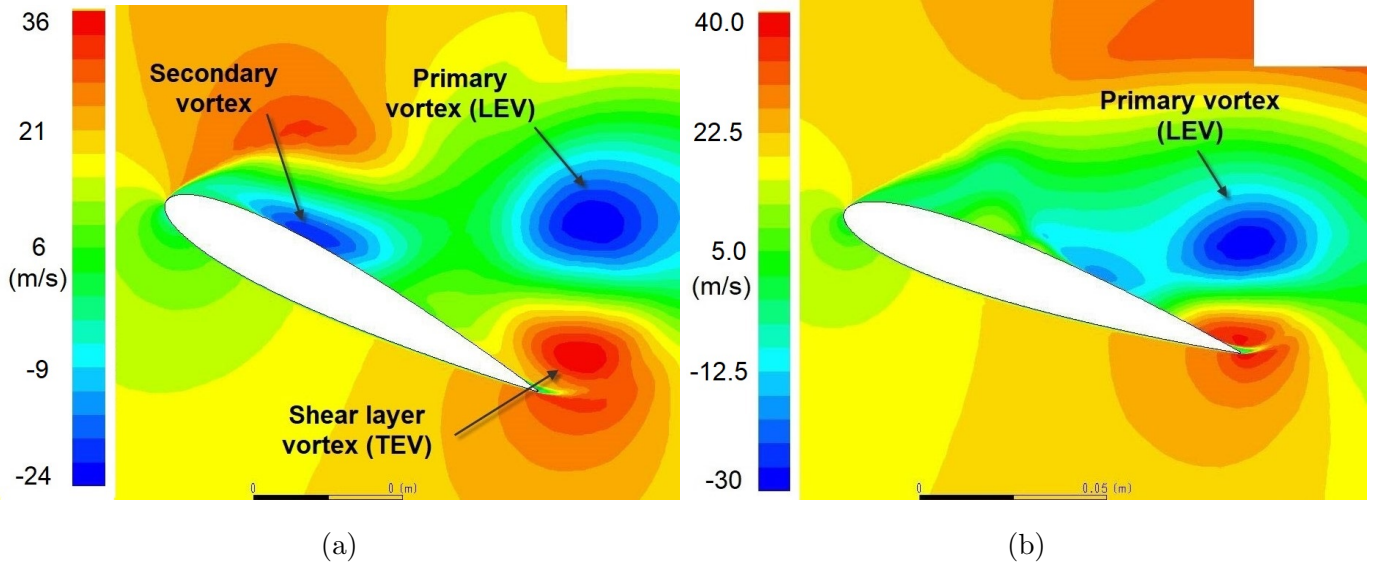


Figure 8: The x-component velocity contour for the oscillating NACA0015 with (a) $\lambda = 2$ at $\alpha = 26.8^\circ$, and (b) $\lambda = 3$ at $\alpha = 20^\circ$ at $Re = 2 \times 10^5$.

315 (iii) The changes in the values of the pitch angle (β) produce an increase in the stall-onset angle
 316 if β increases the maximum angle of attack. For example, the stall-onset angle using $\beta = 10^\circ$ was
 317 $\alpha_{os} = 17.25^\circ$ and when using $\beta = -10^\circ$ was $\alpha_{os} = 18.79^\circ$. The corresponding maximum angle of
 318 attack (α_{max}) for both pitch angles was 20° for $\beta = 10^\circ$ and $\alpha_{max}=40^\circ$ for $\beta = -10^\circ$. The maximum
 319 angle of attack, α_{max} , is calculated by performing a mathematical analysis of Eq.(1) that results in the
 320 expression $\alpha_{max} = \arctan([\lambda^2 - 1]^{-1/2}) - \beta$. Thus, the maximum angle of attack could be calculated
 321 using the corresponding pitch angle, a reduced frequency $\kappa = 0.06$ and, a tip speed ratio of $\lambda = 2$.

322 In Fig. 9(a), the skin friction for five values of β are plotted. It is observed that more positive is
 323 β thus closer is the laminar bubble to the leading edge and thus the stall occurs at a lower angle of
 324 attack. Additionally, the turbulent boundary layer point with $C_{fx} = 0$ has progressed closest to the
 325 LE for the most positive β value of 10° (Fig. 9(a)). Nevertheless, in general, the difference among
 326 the skin frictions curves for the range of pitch angles tested $[-10^\circ$ to $10^\circ]$ are minimal and the overall
 327 variation in α_{os} due to the influence of the pitch angle (β) is less than 1.54° . The impact of the pitch
 328 angle on the stall-onset angle, compared with the tip speed ratio and the reduced frequency is the

329 lowest.

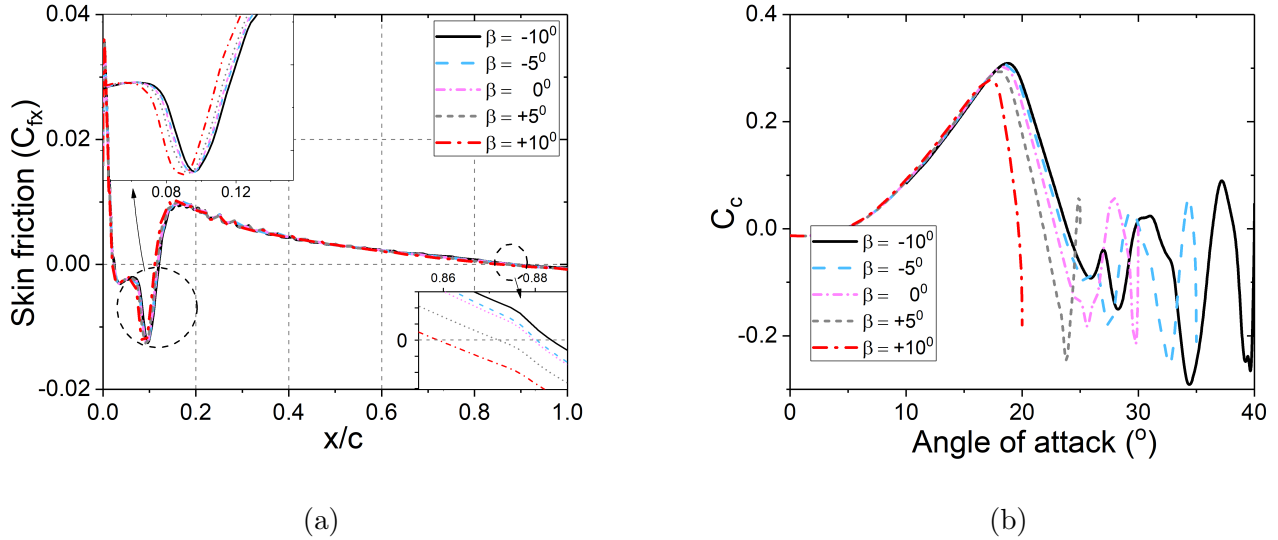


Figure 9: (a) Skin friction along the non-dimensional chord length, and (b) chordwise force coefficient for several values of β at $Re = 2 \times 10^5$.

330 Similar to the tip speed ratio, the pitch angle also influences the maximum angle of attack. Thus,
 331 the severity in the stall conditions may be affected by changing the pitch angle. In Fig. 9(b) the
 332 chordwise force coefficient for the five values of β are plotted. With a more positive β value as
 333 explained in the previous paragraph, a slight decrease in α_{os} is observed but also a decrease in the
 334 maximum angle of oscillation. Thus, as observed in Fig. 9(b) for the most positive β value there is no
 335 indication of secondary vortices. On the contrary, with the most negative β value, despite experiences
 336 the larger stall-onset angle, it also produces a very large maximum angle of attack that causes two
 337 secondary peaks in the chordwise force as observed in Fig. 9(b). Those peaks in C_C indicate the
 338 formation of multiple secondary vortices and therefore, a largest severity in the stall conditions.

339 4.2. Non-dimensional pitch rate and Reynolds number effect

340 In this section, the stall-onset angle is evaluated as a function of the non-dimensional pitch rate,
 341 q , given by Eq. (3). This parameter involves the pitch rate, $\dot{\alpha}$, given by Eq. (2). Because $\dot{\alpha}$ is a
 342 time-dependent function, its value is evaluated at the instance when the angle of attack approaches
 343 the static stall angle. Three Reynolds number (based on the chord length) were evaluated by changing

344 the magnitude of the incoming flow U_{ref} to 8, 20 and 33 m/s and obtaining the Reynolds number of
 345 0.8, 2.0 and 3.3×10^5 , respectively.

346 The analysis has revealed that the stall-onset angle, α_{os} increases linearly with the increase of the
 347 non-dimensional pitch rate, q , for all the Reynolds numbers tested, see Fig.10(a). Further, at the
 348 same q with the increase of the Reynolds number an increase in the stall-onset angle is observed.

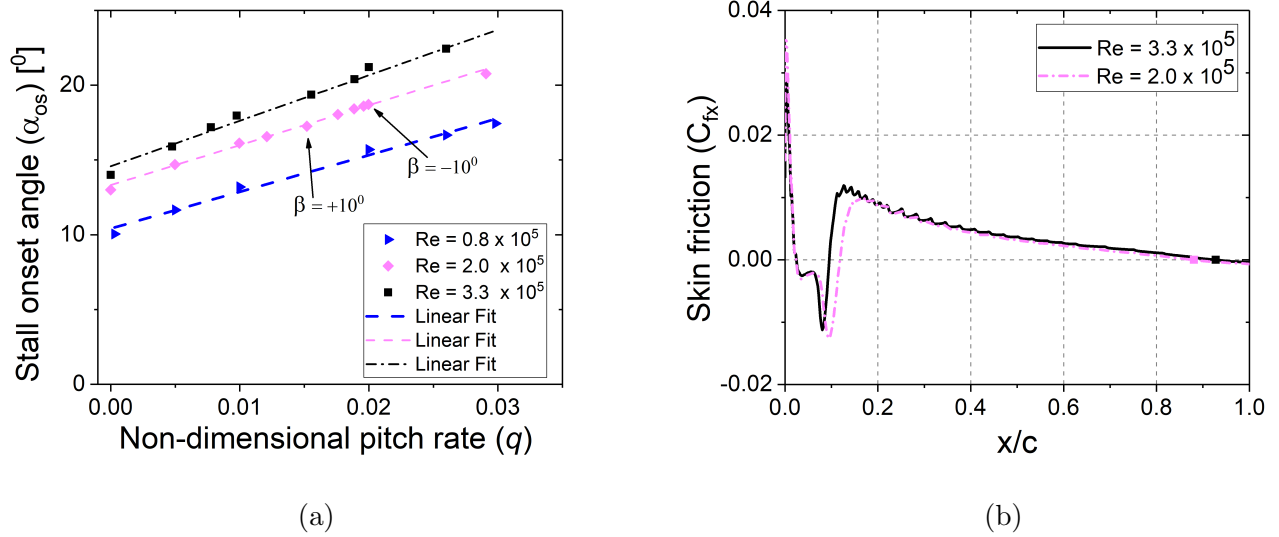


Figure 10: (a) Stall-onset angle as a function of the non-dimensional pitch rate and Reynolds number for the NACA0015 aerofoil, and (b) Skin friction along the non-dimensional chord length for two Reynolds numbers at $\alpha = 13^\circ$.

349 The increase in the dynamic stall-onset angle, α_{os} , due to the increase of the Reynolds number is
 350 consistent with the increase in the static stall angle that has been studied experimentally in several
 351 investigations [27]. The larger is the Reynolds number, the larger is the increase in the momentum
 352 exchange of the air particles from the outer boundary layer to the inner boundary layer of the aerofoil.
 353 Thus, improving the ability of the boundary layer to flow against the adverse pressure gradients and,
 354 as a consequence, longer is the time the boundary layer remains attached to the aerofoil surface.

355 The skin friction at the same angle of attack for two dynamic cases at two Reynolds number, Re ,
 356 and with the same q are compared in Fig. 10(b). The region that encloses the air bubble, due to the
 357 laminar layer separation, is reduced at the highest Re as observed in Fig. 10(b) and the reattachment
 358 point as a turbulent boundary layer, occurs at an earlier distance from the leading edge of the aerofoil
 359 at $Re = 3.3 \times 10^5$. Additionally, at the same angle of attack, the turbulent boundary layer depicts a
 360 more positive skin friction coefficient and the point where $C_{fx} = 0$ occurs later along the chord for

361 $Re = 3.3 \times 10^5$. Thus, this indicated the boundary layer persists being attached at a larger angle of
362 attack before separation occurs with an increase in the Reynolds number [59, 60].

363 Surprisingly, at the same Reynolds number, two dynamic simulations with different values of the
364 tip speed ratio, reduced frequency and pitch angle that present similar values of non-dimensional
365 pitch rate predict the stall-onset angles, α_{os} , with very similar values. For example, a simulation with
366 tip speed ratio $\lambda = 2$, reduced frequency $\kappa = 0.09$ and pitch angle $\beta = -11^\circ$ produces a stall-onset
367 $\alpha_{os} = 18.37^\circ$; for a second simulation with $\lambda = 1.5$, $\kappa = 0.075$ and $\beta = -13^\circ$ the predicted α_{os} is
368 18.32° .

369 For the mentioned-above two cases with a similar non-dimensional pitch rate, the pressure coeffi-
370 cient peaks due to the laminar separation bubbles are very similar, as shown in Fig. 11(a). Further,
371 for these same dynamic cases, their skin friction values with $C_{fx} = 0$ are encountered at similar
372 locations along the chord, thus indicating laminar separation bubbles with the same size for both
373 dynamic cases, see Fig. 11(b). Also, the turbulent boundary layer achieves $C_{fx} = 0$ at the same chord
374 locations. Therefore, present results suggest the non-dimensional pitch rate value when approaches
375 to the static stall angle is the most important parameter that defines the stall-onset angle in the
376 VAWT motion. Therefore, the effect of the tip speed ratio, reduced frequency and pitch angle on the
377 non-dimensional pitch rate (q) requires more attention when the stall-onset angle is being predicted
378 in the VAWTs.

379 The positive effect of non-dimensional pitch rate, q , on the stall-onset angle has been supporting
380 by analysing the simulations presented in Section 4.1. It has been observed that the reduced frequency
381 (κ) in the dynamic simulations increases the non-dimensional pitch rate (q) from 0.018 to 0.029 for
382 the reduced frequencies of $\kappa = 0.06$ and $\kappa = 0.09$ respectively. Thus, the stall-onset angle increases.
383 In the case of the tip speed ratio (λ), the decrease in λ increases the q values: for $\lambda = 2, 2.37$ and
384 3 , the values of q were 0.018, 0.016 and 0.0121 respectively, and the stall-onset angle decreases in
385 value. Similarly, the pitch angle β that increases the q values increases the stall-onset angle, see
386 Table 2. The increase in the stall-onset angle due to the increase of q due to the changes in the pitch
387 angles are marked with arrows in Fig. 10 (a). Therefore, it is confirmed that anytime the operating
388 parameters, individually or combined, increases the non-dimensional pitch rate, then, an increase in
389 the stall-onset angle is also observed.

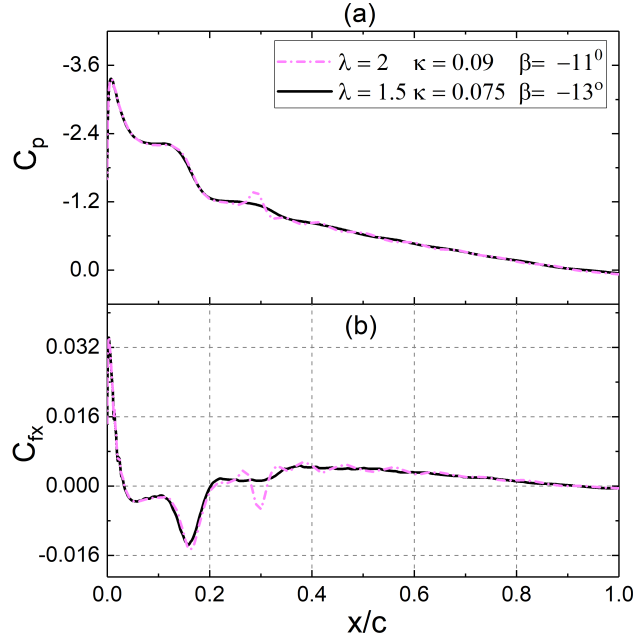


Figure 11: (a) Pressure coefficient and, (b) skin friction for two simulations with closed non-dimensional pitch rate value at $\alpha = 13^\circ$.

Table 2: Pitch angle effects on the instantaneous non-dimensional pitch rate at α_{ss} .

β ($^\circ$)	-10	-5	0	5	10
q	0.0199	0.0196	0.0188	0.0176	0.0152
α_{os} ($^\circ$)	18.79	18.59	18.40	18.04	17.25
α_{max} ($^\circ$)	40	35	30	25	20

390 4.3. Effect of the relative velocity on the stall-onset angle

391 In the previous sections, it was found that the stall-onset angle depends on the non-dimensional
392 pitch rate and Reynolds number. In a VAWT with a constantly changing relative velocity, a fluc-
393 tuation in both the non-dimensional pitch rate and Reynolds number occurs and this fluctuation
394 increases in amplitude by decreasing the tip speed ratio. Therefore, the effect of the fluctuating rel-
395 ative velocity is investigated by using a time-varying incoming flow as given by Eq.(4) and described
396 in the second approach in Section 2.

397 The fluctuation in the Reynolds number gives rise to the interest in investigating whether or not
398 a difference on the stall-onset angle exists if using an average of the fluctuating relative velocity,

399 $V_{mean} \approx \lambda V_{\infty}$, instead of the actual fluctuating relative velocity. Two cases are being analysed using
400 the fluctuating relative velocity described in Eq. (4). First, using a tip speed ratio $\lambda = 2$ and $V_{\infty} = 10$
401 m/s and, second, using a tip speed ratio $\lambda = 3$ and $V_{\infty} = 20/3 m/s$. For both cases, $\kappa = 0.06$ and
402 $\beta = 0^{\circ}$ were employed.

403 The analysis shows that the tip speed ratio $\lambda = 2$ produces a Reynolds number that fluctuates in
404 the range $1 - 3 \times 10^5$ and $\lambda = 3$ produces Reynolds number in the range $1.4 - 2.6 \times 10^5$. These two
405 cases with a fluctuating velocity maintain a similar average relative velocity, $\lambda V_{\infty} = 20 m/s$, thus
406 resulting in the same average Reynolds number 2×10^5 . In Table 3, the predicted stall-onset angle,
407 α_{os} , for $\lambda = 2$ and 3, with a fluctuating velocity V_{rel} and a constant wind velocity V_{mean} , is presented.
408 The stall-onset angle, α_{os} is included for the positive angles of attack (upstream zone of the rotor)
409 and the negative angles of attack (downstream zone). In addition, the non-dimensional pitch rate (q)
410 and the instantaneous velocity (V_{ins}) when the angle of attack approaches 13° are included for all the
411 cases investigated in the upstream and downstream zones.

Table 3: Main characteristics of the stall onset for the two cases studied and evaluated upstream (up) and downstream (dw) of the rotor.

Parameter	Case (i) ($\lambda=2$)		Case (ii) ($\lambda=3$)	
	$V_{rel}(t)$	V_{mean}	$V_{rel}(t)$	V_{mean}
α_{os} ($^{\circ}$) [upstream]	18.37	18.32	16.31	16.56
q [upstream]	0.013	0.0189	0.01	0.012
$V_{ins}(m/s)$ [upstream]	28.41	20.00	24.30	20.00
α_{os} ($^{\circ}$) [downstream]	23.97	21.80	18.14	17.63
q [downstream]	0.096	0.050	0.027	0.020
$V_{ins}(m/s)$ [downstream]	10.55	20	14.57	20

412 For the case (i) with $\lambda = 2$, the stall-onset angle predicted using a fluctuating wind velocity results
413 in $\alpha_{os} = 18.37^{\circ}$ for the upstream zone of the rotor, and this is very similar to $\alpha_{os} = 18.32^{\circ}$ when using
414 the average wind velocity, V_{mean} . For all the cases, the non-dimensional pitch rate (q) and Reynolds
415 number are evaluated at the instant the angle of attack is $\alpha = 13^{\circ}$.¹

¹ α_{ss} at $Re=2 \times 10^5$ is 13° , despite the Reynolds number fluctuation can change α_{ss} , this fluctuation is very small,

416 For the incoming flow using the V_{rel} equation, the wind velocity calculated at $\alpha = 13^\circ$ is $V_{inst} =$
417 28.41 m/s and $q = 0.013$; on the other hand, for the constant incoming wind velocity of 20 m/s case,
418 the non-dimensional pitch rate is $q = 0.018$. Since q is larger for the constant wind velocity case, then
419 it is expected to have a larger α_{os} , as explained in the previous section and illustrated in Fig. 10(a),
420 but this is not observed because of the change in the Reynolds number. The Reynolds number has
421 resulted in $Re = 2.8 \times 10^5$ for the incoming flow with the V_{rel} equation, and in contrast to the effect
422 on q , the incoming flow with the constant wind velocity produces a $Re = 2 \times 10^5$ that is lower than
423 the fluctuating velocity case.

424 For the case (ii) with $\lambda = 3$, similar results were obtained. The stall-onset angle α_{os} produced by
425 both incoming flow conditions were very close in value; the calculated α_{os} with the fluctuating wind
426 velocity was 16.31° and using a constant wind velocity, $\alpha_{os} = 16.56^\circ$. The relative velocity again
427 increases the actual wind velocity during the upstroke motion of the aerofoil, being $V_{ins} = 24.30$ m/s
428 and q reduces its value to 0.01. Then, the increase in the Reynolds number, $Re = 2.4 \times 10^5$ increases
429 α_{os} , see Table 3. On the other hand, the constant wind velocity produces $q = 0.012$ that is larger
430 than in the V_{rel} of the incoming flow, but the Reynolds number is 2×10^5 , slightly lower than the
431 V_{rel} case; thus, both incoming flow conditions, the constant-average and the time-varying velocities
432 predict similar stall-onset angles.

433 Present results suggest that for the upstream zone of the rotor, despite the fluctuations in both,
434 the Reynolds number and the non-dimensional pitch rate (due to the relative velocity fluctuation),
435 the use of average relative velocity, λV_∞ gives a good approach to the stall-onset angle.

436 Moreover, for the negative angles of attack (downstream zone of the VAWT rotor), and at a tip
437 speed ratio of $\lambda = 2$, it is observed in Fig. 12 that the stall-onset angle, α_{os} , increases to 23.97° when
438 using the V_{rel} as the incoming flow. This increase is due to the large increase in non-dimensional
439 pitch rate, q , as a result of the very low wind speed V_{ins} of 10.55 m/s, see Table 3. Using the average
440 relative velocity V_{mean} , the stall-onset angle was 21.80° and $q = 0.50$, and this non-dimensional pitch
441 rate has half the value compared to that of the non-dimensional pitch rate when using V_{rel} .

442 This difference on the non-dimensional pitch rate and in the Reynolds number between the use of
443 the V_{rel} incoming flow and the average value $V_\infty \lambda$ in the downstream region of the rotor is larger than

and the variation in q is negligible. See the influence of β on q in Section 4.2

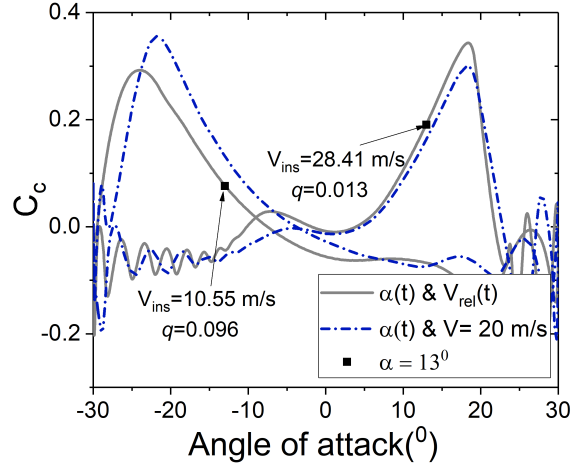


Figure 12: Chordwise force coefficient for $\lambda = 2$ using an incoming flow with: a constant velocity and with time-varying velocity given by the relative velocity Eq. (4).

444 in the upstream region of the rotor. Therefore, these findings suggest the use of an average relative
 445 velocity downstream is less convenient when evaluating the stall-onset angle in VAWTs.

446 Additionally, the computed chordwise force coefficients for the negative angles of attack, in Fig.
 447 12, do not show a secondary peak after the stall-onset angle when compared with the constant velocity
 448 case of 20 m/s . The absence of a secondary C_C peak suggests that the dynamic stall phenomenon
 449 is less severe downstream than upstream due the higher values of the non-dimensional pitch rate
 450 $q = 0.093$. Thus, this explained why the vortex shedding in the experimental tests (in previous
 451 investigations) has been observed to be more frequent upstream of the VAWT rotor (positive angles
 452 of attack) than in the downstream of the rotor.

453 5. Discussion

454 The analysis of the operating parameters that affect the stall-onset angle in VAWTs carried out
 455 in the present investigation has revealed important findings for the applications in VAWTs and for
 456 the applications in dynamic stall algorithms.

457 The increase in the reduced frequency, κ , increases the stall-onset angle and delay the separation
 458 of the boundary layer to larger angles of attack. This delay in the separation of the boundary layer is
 459 in agreement with previous investigations on the reduced frequency that have used the ramp-up and
 460 sine-pitching motion and have focused mainly on the lift stall (L) rather than the stall-onset angle

461 [29, 39, 40]). The present findings explain why other authors that have studied the full rotor have
462 found that an increment in the average reduced frequency ($c/2R$) may reduce the deep dynamic stall
463 conditions to light stall or even non-stall at the same tip speed ratio [9].

464 The tip speed ratio and the pitch angle influence the magnitude of stall-onset angle. Nevertheless,
465 their main role consists of defining the maximum angle of attack. When the maximum angle of
466 attack is further increased to be larger than the stall-onset angle, deeper stall conditions are likely to
467 occur. Hence, this means the several vortices formed upstream of the VAWT rotor can be released
468 downstream and hence, reduce the power contribution of the VAWT in this latter zone. Thus, using
469 the pitch angle as a strategy to control the maximum angle of attack can reduce the stalling degree
470 conditions upstream of the rotor. Nevertheless, the tip speed ratio needs to be considered in order to
471 select the most appropriate pitch angle, since both of them influence the maximum angle of attack
472 and the stall-onset angle.

473 The pitch angle (β) evaluated here can be seen as being equivalent to the mean angle of oscillation
474 from the sine-pitching motion. In previous investigations using the sine-pitching motions, instead of
475 the VAWT angle of attack given by Eq. (1), a parameter called the equivalent reduced pitch rate has
476 been proposed to evaluate the stall-onset angle [30, 47]. Nevertheless, in those studies an independence
477 of the mean angle of oscillation with the stall-onset angle was suggested while in this paper, the pitch
478 angle influences the stall-onset angle. Thus, the changes in the stall-onset with different β values
479 explains why changing the pitch angle in the VAWTs blades changes the azimuthal angle where stall
480 occurs and affects the severity of the stalling conditions [61].

481 The most interesting finding of this work is the influence of the typical parameters of VAWTs,
482 namely, the tip speed ratio (λ), reduced frequency (κ) and pitch angle (β) on the investigated non-
483 dimensional pitch rate (q) when the angle of attack approaches the static stall value. The larger is
484 the non-dimensional pitch rate, then the larger is the stall-onset angle.

485 The positive effect of the non-dimensional pitch rate to delay the stall and calculated here using
486 the VAWTs equations agrees with the effect of the non-dimensional pitch rate calculated with the
487 ramp-up motion in some previous investigations. For example, using a ramp-up motion, the increase
488 in the constant non-dimensional pitch rate produces an increase in the stall point (stall-onset or lift
489 stall) [38, 39, 40, 44]. In addition, the non-dimensional pitch rate, as calculated for the sine-pitching
490 motion in [31], has been shown to have a positive effect, namely increasing the stall-onset angle.

491 The confirmation of the equivalence among the non-dimensional pitch rates corresponding to the
492 angle of attack of VAWTs, the sine-pitching and ramp-up motions are very important investigations
493 that require much more exploration.

494 The increase in the stall-onset angle due to the increase in the Reynolds number observed in this
495 paper using the VAWT angle of attack agrees with the results of the ramp-up tests performed by
496 Choudhry et al. [39] where the lift-stall angle (L) as a function of the non-dimensional pitch rate was
497 investigated at three Reynolds numbers.

498 The stall-onset angle as a function of the non-dimensional pitch rate, q , has not been well inves-
499 tigated at low Reynolds numbers, such as the requirement of VAWTs to operate at low wind speeds.
500 Therefore, the obtained results for the stall-onset angle calculated in this paper, as a function of the
501 non-dimensional pitch-rate at different Reynolds number, results in an essential tool in predicting
502 the stall-onset angle for VAWTs. Also, this is very useful data that should be incorporated into the
503 semi-empirical dynamic stall methods [35, 32, 30].

504 Semi-empirical dynamic stall methods use a time-delay constant that defines the linear relation
505 of the stall-onset as a function of the non-dimensional pitch rate. This time delay constant depends
506 on the Reynolds number and has been evaluated before mostly for Reynolds number as large as 1
507 million [62, 50, 63]. Therefore, the present results can be integrated into some of the dynamic stall
508 models, such as the Leishman-Beddoes, to predict the unsteady loads in applications with a range of
509 operation of the Reynolds number $0.8 - 3.3 \times 10^5$.

510 Overall, the present analysis has revealed that the combined effect of the tip speed ratio, reduced
511 frequency and pitch angle on the non-dimensional pitch rate is an essential factor that dictates the
512 level of delay in the stall conditions. Thus, this effect explain why it has been not possible in the
513 previous studies to define a range of tip speed ratios where the dynamic stall occurs in VAWTs: the
514 resulting non-dimensional pitch rate can increase or decrease according to the combined effect of the
515 tip speed ratio, reduced frequency, pitch angle and relative velocity.

516 In VAWT analyses, it is very common to use the average of the fluctuating relative velocity to
517 investigate its aerodynamics instead of using the actual fluctuating relative velocity. The findings of
518 this paper have shown that in the upstream region of the rotor, the stall-onset angle is not significantly
519 affected when an average the relative velocity, rather than the actual relative velocity is employed.
520 In contrast, in the downstream region of the rotor, where the low magnitudes of the relative velocity

521 produce high values of the non-dimensional pitch rate and low Reynolds numbers, the prediction of
522 the stall-onset angle using an average of the relative velocity instead of the actual relative velocity
523 may have a significant impact.

524 In this paper, a single blade using the angle of attack and relative velocity equations of a VAWT
525 has been used to investigate the stall-onset angle. Although, these equations can be modified, by using
526 the full rotor due to the number of blades or the curvature effects, the effect of the non-dimensional
527 pitch rate and Reynolds number on the stall-onset angle are likely to still valid.

528 **6. Conclusion**

529 The investigations performed in this paper have revealed that the stall-onset angle in VAWTs is
530 dominated by the combined effect of the tip speed ratio, reduced frequency, pitch angle and relative
531 velocity on the two primordial parameters, the non-dimensional pitch rate (q) and the Reynolds num-
532 ber (Re), at the moment the angle of attack approaches the static-stall angle. The stall-onset angle
533 increases with the increase in the non-dimensional pitch rate and with the increase in the Reynolds
534 number. Therefore, techniques that can improve the non-dimensional pitch rate and Reynolds num-
535 ber can lead to a minimization of the dynamic stall effect on VAWTs. Moreover, the dynamic stall in
536 VAWTs can take place at different azimuthal locations if the non-dimensional pitch rate and Reynolds
537 number are affected by the changes in the tip speed ratio, pitch angle, reduced frequency and relative
538 velocity during the VAWT operation.

539 The reduced frequency has been shown to have the most substantial influence in delaying the stall-
540 onset to a larger angle of attack; this is followed by the tip speed ratio and then by the pitch angle. The
541 last two parameters, i.e. the tip speed ratio and the pitch angle, are crucial in defining the maximum
542 angle of oscillation and thus are the key to reducing the severity in the stalling conditions. Deep stall
543 conditions and secondary vortices formation may be reduced if the difference in the maximum angle
544 of attack and the stall-onset angle decreases.

545 The influence of the relative velocity on the stall-onset angle is attributed to its impact on the
546 non-dimensional pitch rate and the Reynolds number. However, overall it produces similar stall-onset
547 values in the upstream zone of the rotor than those values found using a constant average relative
548 velocity. The relative velocities in the downstream zone of the rotor have lower magnitudes than in
549 the upstream zone and, substantially higher values of the non-dimensional pitch rate than when using

550 a constant-average relative velocity. Thus, the stall occurs at a larger angle of attack, and therefore
551 the vortex shedding is less pronounced than in the upstream zone of the rotor.

552 It is important to note that although these results are based on one single aerofoil, the impact of
553 the non-dimensional pitch rate and Reynolds number on the stall-onset angle in a full rotor is likely
554 to be still valid since those are non-dimensional parameters and take into account any angle of attack
555 and relative velocity history.

556 7. Acknowledgement

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