Authors’ Response to Reviews of

WES-2026-7: Vortex generator design for unsteady flow separation control and dynamic stall suppression on pitching thick airfoils

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RC: ***Reviewer’s Comment***, AR: Authors’ Response, ☐ Manuscript Text

We would like to thank the reviewers for their time reviewing this paper. Our responses to their comments on the paper follow. Wherever necessary, we also include parts of the original or revised manuscript within a bounding box ☐ to highlight them. The relevant changes in the revised manuscript are also highlighted in blue text.

1. Reviewer 1

RC: ***I appreciate the effort invested in this work and its focus on aerodynamic topics that are highly relevant to modern ultra-large wind turbine blades. In contemporary designs, thicker airfoils are increasingly used in the more outboard sections, and the application of vortex generators (VGs) around the 30% thick airfoil is becoming more common. With that context in mind, I offer the following suggestions to help improve clarity and strengthen the manuscript***

AR: We thank the reviewer for their time reviewing this paper and for their positive comments on the importance of this work for modern wind turbine blades.

RC: ***Clarification of unsteady flow separation in the abstract: I recommend providing a sharper and more explicit explanation of “unsteady flow separation” in the abstract. A clearer definition or brief description of the phenomenon and its relevance to the study would help readers immediately grasp the motivation and significance of the work.***

AR: We have now clarified in the abstract (quoted below) that the unsteady flow separation we discuss in this study is trailing-edge separation observed during pitch oscillations occurring on inboard and midboard blade sections. Since the word limit for the abstract is quite strict, we have added a description of the types of flow separation and stall on pitching airfoils and the relevance of trailing-edge separation to thicker airfoils in the introduction section (quoted below). We hope that these additions, along with the literature covered in the manuscript on the occurrence of pitch oscillations on wind turbine blades, will provide readers with more context about the relevance of our work.

> **Abstract**. This study experimentally investigates the performance of vortex generators (VGs) designed for steady stall control in preventing unsteady trailing-edge flow separation and dynamic stall during pitch oscillations occurring on inboard and midboard wind turbine blade sections. Surface pressure measurements are conducted in the TU Delft low-speed wind tunnel on a DU-97-W-300 airfoil undergoing pitch oscillations while equipped with VGs of various vane sizes and shapes. In steady conditions, vanes with heights smaller than the local boundary layer thickness optimally balance delaying stall following trailing-edge separation with achieving maximum lift-to-drag ratio among the tested triangular vane VGs. However, these same VGs with vane heights smaller than or equal to the steady local boundary layer thickness are insufficient to suppress the onset and upstream progression of a trailing-edge separation front ~~unsteady flow separation~~ in all pitching cycles. VGs whose vane height exceeds the local boundary layer thickness for a larger part of the pitch cycle prevent the onset and upstream progression of trailing-edge separation ~~unsteady flow separation and restrict the upstream movement of the stall vortex~~ for a larger percentage of cycles. Contrary to past literature, rectangular vanes yield a higher steady aerodynamic efficiency than triangular vanes. Rectangular vanes also suppress trailing-edge separation ~~unsteady flow separation~~ in all pitching cycles at all tested reduced frequencies, indicating more effective boundary layer energisation than triangular vanes, thus proving to be a better VG shape for steady and unsteady stall suppression on thick airfoils.

> ## 1 Introduction
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> At the airfoil level, the unsteady flow variations leading to dynamic stall are experienced as time-varying motions such as pitching, plunging, etc., which lead to cycles of flow detachment and reattachment. The works of McCroskey (1981); McCroskey et al. (1981); Carr (1988); Leishman and Beddoes (1989) detail the various flow phenomena occurring during dynamic stall. For an airfoil undergoing pitch oscillations, McCroskey et al. (1981) list three kinds of stall based on the occurrence and propagation of flow separation during the pitch cycle — leading-edge stall, trailing-edge stall, and mixed stall. Leading-edge stall is said to occur when flow separation first appears near the leading edge and moves towards the trailing edge with increasing angle of attack, while trailing-edge stall is said to occur when the separation front moves from the trailing edge towards the leading edge with increasing angle of attack. Mixed stall usually occurs either when separation fronts originating from both the leading and trailing edge move towards each other and merge somewhere near mid-chord, or when the separation front originates in the middle of the airfoil and moves both in leading-edge and trailing-edge directions. Trailing-edge stall is the most common type of turbulent stall for thick airfoils typical of inboard and midboard wind turbine blade sections and is also the type of stall observed on the airfoil section used in this work. When the unsteady angle of attack exceeds the static stall angle, flow reversal starts at the trailing edge and spreads upstream over much of the airfoil chord. At a certain angle of attack, the separated flow reaches a critical point and a strong vortex called the leading-edge vortex (LEV) forms near the leading edge and starts convecting downstream towards the trailing edge. The lift keeps increasing with increasing angle of attack during this process. Dynamic stall is observed when the LEV convects past the trailing edge into the wake.
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RC: ***Comparison and evaluation of VG shapes: The manuscript suggests that the rectangular vane shape may be a preferable option. However, as indicated in Figure 6, the rectangular or larger VG array appears to induce more abrupt separation and/or unexpected hysteresis characteristics. It would be helpful to clarify the criteria used to determine which VG shape performs better. Are the conclusions primarily based on polar curves, stall delay, hysteresis behavior, or overall aerodynamic efficiency? A more explicit definition of "better" performance would strengthen the argument.***

AR: We agree with the reviewer that denoting a particular VG array as better than another depends on the criteria which the turbine blade designer considers important. Hence, we have rewritten some parts of the discussion and conclusions (sections 4, 5, and 6) to explicitly clarify the metric on which one VG array performs better than another. To clarify briefly, the rectangular vanes restrict the upstream progression of the trailing edge separation front more effectively than the triangular vanes. In steady conditions, this leads to delayed stall, a higher maximum lift, and a higher aerodynamic efficiency before stall compared to the triangular vanes. In unsteady conditions, this leads to a disappearance of separated flow and elimination of cycle-to-cycle variability in the polar curves.

RC: ***Chordwise location of VGs: The study considers only a 30% chordwise VG location. However, for modern large blades, mid-chord placements (approximately 40–60% chord) are also commonly considered and may be more representative of practical applications. Since VG effectiveness is highly sensitive to chordwise position, the conclusions may depend strongly on this parameter. It would be valuable to discuss how different chordwise placements might influence the results and whether the current conclusions are specific to the 30% location.***

AR: We agree about the sensitivity of VG performance to chordwise location. We fixed the VG location to simplify the test matrix and picked the 30% chord location because past studies on the same airfoil [1] have shown 30% chord is the most effective VG location to delay static stall and increase maximum lift on this airfoil. We have added a line in the VG array description section (section 2.2, quoted below) to clarify the reasoning behind fixing the VG location at 30% chord. In the discussion on VG vane height selection (section 5.1 in the revised manuscript, quoted below) to prevent trailing-edge flow separation, we scale the VG height with the local boundary layer thickness in an attempt to make the conclusions more general to boundary layer characteristics and applicable to other chordwise locations.

> ## 2.2 Vortex Generator design

> The symbols used for the various VG array geometry and configuration parameters are shown in Figure 2a. All VGs tested were counter-rotating vanes with a common downwash. Previous steady measurements (Baldacchino et al., 2018) tested VGs between 10%-50% chord-wise location on this airfoil and showed that VGs at 30% chord were the most effective at delaying stall and increasing maximum lift. To simplify the test matrix by fixing the VG placement location, all ~~All~~ VG arrays were placed at the most effective location of 30% chord ~~-wise location~~ on both sides of the airfoil.
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> ### 5.1 Vane Size
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> To aid wind turbine blade designers in selecting a suitable vane height for unsteady flow separation control, we use the boundary layer thickness at the VG location as a reference length scale to compare the vane heights. In Figure 3, we calculated the steady boundary layer thickness at the VG location ($x/c = 0.3$) using RFOIL. While the cycles of flow separation and reattachment due to the pitching motion can cause the local boundary layer thickness to vary between pitching cycles, the ease of calculating the steady boundary layer thickness still makes it a useful reference length scale for preliminary VG vane height selection. Comparison of vane height with the boundary layer thickness also helps to translate the results of this study to other chordwise placement locations not tested in this study. Assuming that the incoming boundary layer upstream of the VG location does not change significantly between the no-VG and VG cases, we can divide the range of angles of attack covered in the $10^\circ \pm 10^\circ$ pitching motion into two regions based on whether the vane height is larger or smaller than the incoming boundary layer thickness. From Figure 3, the 10 mm vanes are larger than the steady boundary layer thickness till 15° angle of attack, the 5 mm vanes till 1°, and the 2.5 mm vanes are always smaller than the boundary layer thickness within the calculated angle of attack range. The flow separation results show that the greater the percentage of the pitching cycle where the vane height is higher than the incoming boundary layer height, the greater the likelihood of preventing flow separation during the pitching cycle. If a wind turbine blade designer desires to keep flow attached in all pitching cycles during unsteady conditions with VGs, the vane height should be designed to be larger than the local steady boundary layer thickness for as much of the operating angle of attack range as possible.
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RC: ***Conciseness of the conclusion section: A more concise and focused conclusion section may improve the overall impact of the paper by clearly summarizing the key findings and their practical implications.***

AR: We have rewritten parts of the conclusion section to highlight the key findings and their implications for turbine blade design more clearly.

RC: ***Minor errors to be corrected***
 # Line 5 these same VGs with vane5 heights smaller than => vane heights # Line 29 was one of the first => were one of the first to show # Line 43 dynamic angle of attack exceed the static stall angle => exceeds # Line 48 Butterfield (1989) show that dynamic stall => shows that dynamic stall # Line 54 VGs control flow separation through engergising the boundary layer. . . => energising # Line 66 etc have a significantly smaller impact => etc., have a significantly smaller impact # Line 68 is proportional on the vane height => is proportional to the vane height # Line 79 the differences in performance . . . creates an additional variable => create an additional variable # Line 91 high angles of attach => high angles of attack # Line 301 the stall vortex moves from it ultimate upstroke location => its ultimate upstroke location

AR: We have made the suggested edits.

2. Reviewer 2

RC: ***The manuscript presents an experimental investigation of vortex-generator performance for controlling steady and unsteady flow separation on a DU97-W-300 thick airfoil. The authors particularly focus on the vane height and the vane shape effects under dynamic stall conditions for pitching airfoil. The topic is relevant for modern wind-energy applications, since thick airfoils are increasingly used in large wind-turbine blades and vortex generators are widely applied as passive flow-control devices to improve aerodynamic performance under both roughness-sensitive and unsteady operating conditions. The comparison between triangular and rectangular vane geometries, together with the assessment of several reduced frequencies, provides useful experimental data in a research area where unsteady measurements remain relatively scarce. In particular, the observation that vortex-generator configurations optimized under steady conditions do not necessarily behave identically under pitching conditions is an important practical outcome for future blade-design considerations. The experimental effort is appreciated and the manuscript is generally well structured. However, some aspects of the physical interpretation require clarification, particularly where pressure-derived separation-location results are used to infer vortex dynamics during dynamic stall.***

AR: We thank the reviewer for their time reviewing this paper and their positive comments on the importance of this work and the associated experimental dataset for wind turbine blade design.

RC: ***The first point that requires clarification is about the interpretation of the dynamic stall process, particularly the repeated description that the "stall vortex moves upstream" as inferred from the pressure-derived separation location. The separation point is identified from the onset of a pressure plateau along the suction side, which can be considered as a reasonable indicator of the upstream progression of separated flow. However, this quantity should not be directly interpreted as the motion of the stall vortex itself. In the classical dynamic stall development, trailing-edge separation indeed progresses upstream as the angle of attack increases, but the dynamic stall vortex (or leading-edge vortex) forms near the leading edge once a critical separation state is reached and subsequently advects downstream over the airfoil. Therefore, the current wording appears physically ambiguous, since the pressure-based analysis more directly reflects separation-front migration rather than vortex-core motion. A clearer distinction between these two phenomena would strengthen the physical interpretation of the experimental results presented in the manuscript.***

AR: We acknowledge that the ambiguous phrasing in some parts of the discussion. Our intended interpretation was indeed to indicate the onset and upstream progression of the trailing-edge separation front and the impact of different VGs in restricting this progression. We have rephrased parts of section 4, 5, and 6 in the revised manuscript to avoid ambiguity.

RC: ***A related point concerns the repeated conclusion that rectangular vanes generate stronger streamwise vortices than triangular vanes, based primarily on the observed pressure distributions, stall delay, and separation-location behavior. While the experimental trends clearly indicate that the rectangular vane configuration performs better in delaying separation and reducing cycle-to-cycle variability under the tested conditions, the measurements do not directly quantify vortex strength, persistence, or topology within the boundary layer. Since the analysis relies mainly on surface-pressure information and force measurements, it would be more appropriate to formulate this conclusion as an indication of more effective boundary-layer energization rather than direct evidence of stronger streamwise vortices. A slightly more cautious interpretation would better reflect the capabilities of the employed measurement approach.***

AR: We have rephrased the parts involving rectangular VGs, formulating the conclusion in terms of more effective boundary layer energisation rather than vortex strength or topology. We have also added a line in the conclusions section (section 7 in the revised manuscript) to indicate that future work involving flow-field measurements would be needed to directly quantify the vortex strength and persistence with different VG shapes.

RC: ***A further point concerns the interpretation based on the ratio between vane height and local boundary-layer thickness, which is used throughout the manuscript to explain the relative effectiveness of the tested VG configurations. The comparison is made using boundary-layer thickness values obtained from steady RFOIL calculations on the baseline airfoil without VGs. While this provides a useful reference, the central conclusions of the paper concern pitching conditions involving strongly unsteady separation and reattachment, where the instantaneous boundary-layer characteristics may differ significantly from the steady baseline estimate. It would therefore be useful to discuss more explicitly the limitations of using a steady reference boundary-layer thickness when interpreting VG effectiveness under dynamic stall conditions, particularly since the*** h/δ ***argument is central to several of the manuscript's conclusions.***

AR: We have indicated in the VG design discussion section (section 5) that the boundary layer thickness values used to interpret the VG performance are based on steady no-VG RFOIL calculations. We have now added a line (quoted below) cautioning the reader that the instantaneous boundary layer evolution during continuous separation and reattachment cycles while pitching can differ from the steady reference. We have also added a line to clarify that the h/δ comparison with steady boundary layer thickness values is suggested as a practical first-estimate design guideline for turbine blade designers because of the difficulty in obtaining instantaneous boundary layer characteristics during unsteady pitching motion. In a new section on sources of uncertainty (section 6 in the revised manuscript), we discuss the limitations of our analysis as well as the limitations of the present measurement setup. In brief, we recommend wind turbine designers to use VGs which are larger than the boundary layer thickness for as much of the pitching angle of attack range as possible. Differences between the instantaneous unsteady boundary layer thickness and the steady reference can impact the exact range of angles of attack in the pitching cycle where the vane height is larger than the boundary layer thickness. However, since we base our comparison of vane heights on the percentage of separated and attached flow cycles, we expect the overall conclusions about the relative performance of different VG arrays to hold true. Overall, the recommendation of this paper is to use larger rectangular VGs considering the need for unsteady flow separation control even when smaller triangular VGs may prove sufficient for steady flow control.

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> To aid wind turbine blade designers in selecting a suitable vane height for unsteady flow separation control, we use the boundary layer thickness at the VG location as a reference length scale to compare the vane heights. In Figure 3, we calculated the steady boundary layer thickness at the VG location ($x/c = 0.3$) using RFOIL. Note that the cycles of flow separation and reattachment due to the pitching motion can cause the instantaneous local boundary layer thickness and its evolution to vary slightly between pitching cycles and deviate from the steady value. Nevertheless, the ease of calculating the steady boundary layer thickness still makes it a useful reference length scale for preliminary VG vane height selection.
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> ### 6 Sources of uncertainty
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> One of the central recommendations of this paper is that VGs selected for unsteady flow control during pitching motions should have a vane height larger than the local boundary layer thickness for as much of the pitching angle of attack range as possible. The reference used for this is the steady no-VG boundary layer thickness at the VG chordwise location calculated using RFOIL. While RFOIL calculations come with their own uncertainties quantified in literature (van Rooij, 1996; Sahoo et al., 2024a), using the steady no-VG boundary layer thickness as a reference for preliminary VG vane height selection also comes with limitations. During pitching motions, the flow around the airfoil depends on various factors like the phase of motion (upstroke or downstroke) and the pitching frequency which leads how the flow responds to the motion. Cycles of flow separation and reattachment due to the pitching motion can cause the instantaneous boundary layer thickness and its unsteady characteristics to deviate from the steady characteristics calculated from RFOIL. This can cause the exact range of angles of attack in the pitching cycle where the vane height is larger than the local boundary layer thickness can deviate from the range presented in this work. In an attempt to provide practical VG design recommendations while overcoming this limitation, our analysis is statistical in nature. We base our comparisons of VG vane height and shape on their impact on the percentage of separated and attached flow cycles. The greater the range of angles of attack in the pitching cycle where the vane height is larger than the local boundary layer thickness, the greater the likelihood of preventing flow separation during the pitching cycle. Overall, the recommendation of this paper is to use larger rectangular VGs considering the need for unsteady flow separation control even when smaller triangular VGs may prove sufficient for steady flow control.
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RC: ***One of the most interesting observations in the manuscript is the appearance of two distinct reattachment paths during the downstroke phase for some triangular VG configurations, particularly visible in the normal-force hysteresis loops and corresponding separation-location maps. Since this appears to represent genuine cycle-to-cycle variability, a quantitative indication of the fraction of cycles following each path at different reduced frequencies would further***

strengthen this result. In the corresponding discussion, the physical explanation is again formulated in terms of stall-vortex movement, whereas the presented pressure-based evidence more directly indicates differences in separation-front evolution between cycles. A clearer distinction here would help interpret the origin of the observed dual reattachment behavior more robustly.

AR: Figure 14 describing the number of separated flow cycles for different VG arrays and reduced frequencies quantifies the percentage of cycles following the late reattachment path with each VG design. Since the late reattachment path is associated with the separation front progressing beyond $x/c = 0.6$, we calculate the percentage of cycles where the flow is separated at $x/c = 0.5$ at 10° downstroke angle of attack to quantify the number of late reattachment cycles. We have added a few lines in the discussion section (section 5, also quoted below) to clarify how we calculate the percentage of cycles following the late reattachment path and how to interpret Figure 14 in terms of the percentage of cycles following the late reattachment path for different VG arrays and reduced frequencies. As mentioned earlier, we have also rephrased the discussion to trailing-edge separation front progression to remove ambiguity in the physical interpretation of the flow phenomena being described.

> ### 5 Outlook on VG design for unsteady flow separation control
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> To quantify the number of late reattachment cycles, we calculate the percentage of cycles where flow over the airfoil is separated at $x/c = 0.5$ at 10° downstroke angle of attack. As we observed in Sections 4.2 and 4.3, it is only in the late reattachment cases that the separation front goes beyond $x/c = 0.6$. 10° downstroke lies between the reattachment angles of the early and late reattachment paths for all VGs, making it a suitable angle for this comparison. Note that the early and late reattachment paths are only observed for the 5 mm triangular, 10 mm triangular, and 10 mm rectangular VG cases. Thus, the number of separated cycles for these cases represents the cycles where the VGs fail to prevent upstream propagation of the separation front resulting in the late reattachment path. For the no-VG and 2.5 mm triangular VG cases, the flow separation map and normal force coefficient polar follow only one path, and hence nearly 100% of the cycles are separated.
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RC: ***A brief discussion of finite-span effects would also be useful, considering that the tested model has an aspect ratio of approximately 1.92 and the vortex-generator arrays do not extend fully to the tunnel walls. Since both dynamic stall development and vortex-generator-induced boundary-layer modification are inherently three-dimensional phenomena, some comment on the possible influence of sidewall proximity and spanwise non-uniformity would help define the limits of the present interpretation, particularly where the results are discussed in quasi-two-dimensional terms.***

AR: While the VG arrays do not extend fully to the tunnel walls, the VG arrays still cover around 85% of the span, only leaving a small portion of the span near the tunnel walls without VGs. The pressure ports are located between approximately 20% to 25% of the span from the top wall at a slight angle with the streamwise direction to avoid downstream pressure ports being influenced by upstream disturbances. We have added a few lines in the experimental setup section (sections 2.2 and 2.4, also quoted below) to clarify this. For the steady measurements, the wake rake sweeps over a 140 mm span to capture the spanwise non-uniformity in the wake. In the new section on sources of uncertainty mentioned earlier, we discuss the potential influence of spanwise non-uniformity due to dynamic stall development and wall proximity on the results. These additional clarifying lines in the experiment setup section should help readers understand the experimental setup and its limitations better.

> ### 2.2 Vortex Generator design
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> The VGs were added across the span of the airfoil model, but leaving a gap of around 100 mm (approximately 8% of the model span) near the tunnel walls (as illustrated in Figure 1a) to avoid interactions between the VGs and the flow near the walls. Thus, the VGs cover around 84% of the airfoil model span.
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2.4 Instrumentation for data acquisition

The normal and tangential forces were calculated from surface pressures on the airfoil measured using a distribution of 102 pressure ports on the model, including 1 port on the blunt trailing edge (illustrated in Figure 4). The pressure ports are located between approximately 20% to 25% of the span from the top wall at a slight angle with the streamwise direction, as illustrated in Figure 1a. This means the pressure ports span the length of 1 VG pair for the largest 10 mm VGs and 4 pairs for the smallest 2.5 mm VGs. The angled pressure port placement ensures downstream pressure ports are not influenced by upstream disturbances. A traversable wake rake with 67 total pressure and 16 static pressure tubes was used to assess the total drag. The wake rake traversed over a spanwise distance of 140 mm spanning 2 VG pairs for the largest 10 mm VGs and 8 pairs for the smallest 2.5 mm VGs. Steady measurements were acquired at a rate of 5 Hz for 25 seconds. Unsteady measurements were acquired at a rate of 300 Hz for 150 cycles of pitching motion.

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Some other uncertainties in the data arise from the measurement setup itself. Particularly for the unsteady results, we base our analysis on quasi-2D chordwise pressure coefficient distributions. The angled placement of the pressure ports (described in Section 2.4), which covers the spanwise length of at least 1 VG pair for every VG design tested, can average over the spanwise periodic flow variations caused by the vortices from the counter-rotating VGs. However, unsteady trailing-edge separation is 3D and the spanwise variation in flow due to separation cannot be covered by the pressure ports. This can lead to some uncertainty in predicting the exact chordwise location of the separation front from the measured pressure data. The relatively low aspect ratio of the wing section means that the boundary layer growing on the top wall of the wind tunnel can also introduce spanwise variation in the flow, affecting the pressure measurements. These sources of uncertainty mean that the conclusions of this work should rather be interpreted in context of the general trends in the flow separation behaviour and aerodynamic polars in presence of different VG designs.

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RC: ***The manuscript would benefit from a clearer definition of the criterion used when stating that one VG configuration performs "better" than another, since different sections refer alternately to stall delay, aerodynamic efficiency, cycle-to-cycle variability, and suppression of separated cycles.***

AR: We agree with the reviewer that denoting a particular VG array as better than another depends on the criteria which the turbine blade designer considers important. Hence, we have rewritten some parts of the discussion and conclusions (sections 4, 5, and 6) to explicitly clarify the metric on which one VG array performs better than another. Please refer also to our response to a similar comment from reviewer 1.

RC: ***Since all VG arrays are tested only at x/c = 0.30, a brief discussion on how the conclusions may depend on chordwise placement would improve practical interpretation, especially for modern blade applications where more downstream locations are also used.***

AR: We agree about the sensitivity of VG performance to chordwise location. Briefly, we fixed the VG location to simplify the test matrix and picked the 30% chord location which has been shown by past studies like [1] to be the the most effective VG placement location. We contextualise our results and discussion in terms of the VG placement location in sections 5 and 6. Please also see our response to a similar comment from reviewer 1.

RC: ***The discussion on reduced-frequency effects could be expanded slightly, particularly regarding whether the reduced sensitivity to VG size at higher k is attributed solely to phase lag or also to modified vortex formation timing.***

AR: The main discussion about the unsteady polars and flow separation maps in section 4 is now expanded to go into more detail about the pitching frequency effects. Briefly, the separation maps indicate that higher pitching frequencies delay the onset of trailing-edge separation, but the progression of the separation front is more rapid once it appears. In downstroke, higher pitching frequencies speed up the reattachment process.

References

1. Baldacchino, D., Ferreira, C., Tavernier, D. D., Timmer, W. & van Bussel, G. J. W. Experimental parameter study for passive vortex generators on a 30% thick airfoil. *Wind Energy* **21,** 745–765. ISSN: 1095-4244 (Sept. 2018).