Zig-zag tape influence in NREL Phase VI wind turbine

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Abstract. Two bladed 10 metre diameter wind turbine was tested in the 24.4m x 36.6m NASA-Ames wind tunnel (Phase VI). These experiments have been extensively used for validation purposes for CFD and other engineering tools. The free transition case (S), has been, and is, the most employed one for validation purposes, and consist in a 3° pitch case with a rotational speed of 72rpm upwind configuration with and without yaw misalignment. However, there is another less visited case (M) where identical configuration was tested but with the inclusion of a zig-zag tape. This was called transition fixed sequence. This paper shows the differences between the free and the fix transition cases, that should be more appropriate for comparison with fully turbulent simulations. Steady k-ω SST fully turbulent computations performed with WMB CFD method are compared with the experiments showing, better predictions in the attached flow region when it is compared with the transition fixed experiments. This work wants to prove the utility of M case (transition fixed) and show its differences respect the S case (free transition) for validation purposes.

1. Introduction
NREL Phase VI wind turbine experiments [1] have been extensively used by researchers to validate their models (BEM, vortex methods, hybrid methods or CFD) and investigate different phenomena. Several configurations were tested, with three different tip ends, upwind and downwind configurations, parked and pitching blades, at two different rotational speeds and inflow velocities that ranged from 5 to 25m/s. Pressure measurements were taken at 5 span-wise sections together with blade root forces and flow angle measurements performed in several configurations. The visited data-sets, to the author knowledge, were the S, H, L, V, O and X, being the S and H the most popular ones (also known as free transition). However, there is another less visited case called fix transition (M), where identical configuration was tested with the inclusion of a zig-zag tape along the span of the blade. A summary of the previous work related to the CFD predictions realised for NREL Phase VI wind turbine (R=5.029m) at a rotational speed of 72rpm, a pitch angle of 3°, a yaw misalignment of 0° and wind speeds ranging from 5 to 15m/s is presented. Note that the H, M and S cases full-fill this criteria.

Sørensen et al.[2] have performed fully turbulent steady and unsteady computations with EllipSys3D solver and the k-ω SST turbulence model for the 7, 10, 13 and 15m/s cases. They have included pressure (Cp) and force coefficients (Cn & Ct) and torque predictions. Computations were compared against the free transition average experimental torque, under-predicting it by 10% at 7m/s and for partially separated flows over-predicting by ≈ 17% at 10m/s and under-predicting by 3% and 24% for the 13 and 15m/s cases. Duque et al.[3] have performed steady computations for the 7, 10, 13 and 15m/s with the OVERFLOW-D2 V1.5D solver and the Baldwin-Barth turbulence model. Cp, Cn and power predictions were compared to free transition cases. The generated power showed good agreement having the largest under-prediction at 7m/s case (≈ 20%). Computed Cn was generally under-predicted. Le Pape et al.
[4] performed steady and unsteadily fully turbulent computations for the 7, 10, 13 and 15m/s wind speeds with elsA solver employing the k-ω SST. The comparison with the free transition case show good agreement (under-prediction of ≈ 1%) regarding the torque for the 7 and 10m/s and under-predictions of 20% and 66% for the 13 and 15m/s cases. They noted that the transition should be included in the computations. Le Pape et al. [5] revisited the problem with a low-Mach number preconditioning technique, the elsA solver and the k-ω SST. The agreement at 7 m/s was still good, and the 10 m/s was improved. Schmitz and Chattot [6] computed steadily the 7, 9, 10, 11 and 13m/s with CFX V5.6 code employing the fully turbulent approximation and the k-ω. Cp, Cn, Ct and total torque were compared against the free transition case. The local forces were over-predicted for the attached flow (7m/s) and there was also a general over-prediction on Ct. The Cn comparison varied along the span of the blade from good prediction or under-prediction towards the root to over-prediction towards the tip. The rotor torque compared well with the experiments except for the the 9 and 10m/s cases that was over-predicted by ≈ 15 and ≈ 5%. Chao et al. [7] have used OVERFLOW solver for computing the 5, 7 and 10m/s cases with steady and unsteady approaches and the Spallart Allmaras (SA) turbulence model. Results were compared with the free transition case showing Cp, span-wise Cn and torque. They noted that a reason for their under-prediction of the torque at 5m/s case could be that they performed a fully turbulent computation despite they were comparing with a free transition experiment. Respect the average torque values, under-prediction of ≈ 46% at 5m/s, acceptable agreement for the 7m/s (over-prediction of ≈ 3%) and over-prediction for the 10m/s by ≈ 34% were obtained. The span-wise Cn was generally over-predicted. Zahle et al. [8] carried out fully turbulent unsteady computations with the k-ω turbulence model on a regular and and overset grids with the EllipSys3D solver. Results contain Cn, Ct and Cp for the 7m/s case and they were compared against the free transition case. The Ct predictions along the span of the blade were under-predicted, achieving the best agreements towards the tip. The averaged Cn was under-predicted for the regular grid and over-predicted for the overset one having both also good agreement towards the tip. Gomez-Iradi et al. [9] have performed unsteady computations for the 7 and 10m/s cases with WMB solver, as fully turbulent employing the k-ω SST. Thrust, torque and Cp were compared with the S case, obtaining a match for the thrust at 7m/s and an over-prediction of 4% at 10m/s. The torque was under-predicted by 5% at 7m/s and over-predicted by 18% at 10m/s.

Yelmule et al. [10] employing the CFX 12.1 solver have computed free transition cases, covering the 5, 7, 10, 13 and 15m/s wind speeds with steady computations, k-ω SST and Gamma-Theta transition model based on Langtry and Menter correlation. Power, thrust and force coefficients along the span of the blade were compared. The average thrust values were slightly under-predicted, being of 13% the largest difference at 10m/s, however the power agreed well (≈ 1% over-prediction) for the attached flow (5 and 7m/s) regime. This work was the unique one that the authors found where the experimental free case was compared to free transition computations.

Therefore, note that the majority of the predictions collected here will improve if they were compared with the tripped cases instead of the clean cases. As an example, the blind test that was carried out with the NREL Phase VI experiments, reported by Simms et al. [11]. At attached flow case 3 CFD methods under-predicted the 7m/s case, but if they were compared with the fix transition experiment, two of them would agree well with it.

2. Experiments

Since NASA-Ames Phase VI [1] experiments are broadly studied, in this paper the focus will be on the details that are interesting for the present work. Within the experiments, the main measured quantity was the pressure distribution along the blade chord at five span-wise sections, with 22 pressure taps placed in each section. The configuration of the experiments that will be analysed is summarised as two-bladed upwind rotor with 0° cone angle, with 0° of yaw miss-alignment and 3° positive pitch at the tip. The testing conditions were at a rotational speed of 72rpm and wind speeds ranging from 5 to 15m/s. Three data-set agree with these conditions, the S, H and the M and they are described in the following lines.
S / H cases: free transition

This data-set is the most employed one in the literature for computational method validation. Note that apart from the cases mentioned above, wind speeds up to 25m/s were measured and also yawed flow cases (0° to 180°). S and H cases differentiated with the use of the five-hole probes that were used to extract the local and span-wise flow angles. They were active for the H and removed for the S cases.

M case: fixed transition

During the Transition Fixed sequence, boundary layer transition was fixed by applying self-adhesive zig-zag turbulator tape of various thicknesses to the upper and lower surfaces of the instrumented blade. All turbulator tapes used in this experiment employed a geometry like that shown in figure 1, having 60° sweep angles and extending 12 mm in the chord direction. The tapes were installed from 25% span (outboard boundary of the blade root cross-section transition), to 98% span (inboard boundary of the blade tip cap). On the upper surface, the trailing edge of the tape was positioned at 2% chord; and on the lower surface, the trailing edge of the tape was located at 5% chord. Table 1 describes the thickness of the tapes. To avoid influencing pressure measurements at the five full chord pressure tap locations, application of the tape was interrupted at a distance of 6.35 mm from each of them as shown in figure 1.

![Figure 1. Zig-zag tape on the NREL Phase VI blade M data-set.](image)

Table 1. Zig-zag Tape Radial Range and Thickness [1].

| %R     | 25 to 40 | 40 to 80 | 80 to 98 |
|--------|----------|----------|----------|
| US tape thickness | 0.85 mm  | 0.51 mm  | 0.31 mm  |
| LS tape thickness  | 0.95 mm  | 0.95 mm  | 0.65 mm  |

3. Methodology

CFD RANS computations were carried out describing the characteristics of the method and inputs in the following paragraphs.

3.1. WMB

WMB (Wind Multi-Block) is the CFD method developed together between the University of Liverpool and CENER and validated for HAWT [9, 12, 13]. It is capable of solving the compressible Unsteady Reynolds Averaged Navier-Stokes (URANS) flow equations on multi-block structured grids using a cell-centred finite-volume method for spatial discretization. The present solver was designed to account for the motion of the blades, their structural deformation, as well as, turbulent flow conditions, although for this project the blades were considered rigid. A second-order implicit method [14] was employed, and the resulting linear system of equations was solved using a pre-conditioned Generalised Conjugate Gradient (GCG) method. From the beginning, the solver was designed with parallel execution in mind and for this reason a divide-and-conquer approach was used to allow for multi-block grids to be computed on distributed-memory machines and especially low-cost Beowulf clusters of personal computers. Details about the parallel performance can be found in [15].
3.2. Computations

The input geometry, employed mesh and the computational conditions are going to be detailed next.

**Geometry:** The definition of the geometry for the Phase VI experiments [1] provides the blade chord, twist and the coordinates of its unique aerofoil, the S809; however, the tip and root sections are not defined in a unique way. Therefore geometry has been self-defined based on aerofoil shape and blade plan-form [1], featuring a sharp trailing edge and a rounded tip from the 98.2%R based on its camber line. An approximated hub and the root attachment of the blade were included due to the large effect on Cp at the 30%R station [12] of the root attachment. Neither nacelle nor tower were modelled for these computations and the geometry was created with ICEMCFD v14.0 (from ANSYS).

**Mesh:** The main grid characteristics are defined in table 2. The structured hexa cell multi-block grids were created with ICEMCFD v14.0 and the mesh around the blades had a C-type topology. The boundaries of the computed cases can be obtained from table 2. At blade surface solid or non-slip condition was applied and the first cell height was of 1x10^-5c. The chord units are based on the maximum aerodynamic chord of the blade (0.737m at 25%R). Notice that just half of the wind turbine was modelled since periodic condition has been applied for this structured grid.

**Table 2.** Characteristics of the employed mesh (I=Inflow, O=Outflow & FF=Far-Field).

| Mesh name    | Total Size (cells) | chord-wise (cells) | span-wise (cells) | Boundaries (x Radius) |
|--------------|--------------------|--------------------|-------------------|-----------------------|
| NREL steady  | 9,218,880          | 246                | 259               | I=4.4 O=FF= 8.8       |

**Conditions:** Steady state simulations based on a non-inertial frame of reference that included the centrifugal forces were carried out with the k-ω SST turbulence model of Menter [16]. These were fully turbulent, therefore, no transition modelling was included. Convergence was considered to be achieved when the total loads (torque and thrust) have varied less than 1% for the last 10,000 implicit steps. Typical computation time was of 24 hours in 108 of the 400 cores of CENER’s cluster. The post-processing was done with Tecplot 360.

4. Results

Firstly, this section discusses the differences between the free and fix transition measurements. Secondly the differences of the experiments respect the CFD predictions without entering why the predictions are like they are. It is structured to begin with an approximation that covers the total integrated loads, thrust (Th) and torque (Tq), then the local normal and tangential coefficients, and finishes with the comparisons of pressure coefficients (Cp).

The experimental values shown in the following figures, are represented by an average value and its standard deviation (σ). These values were obtained based on 35 revolutions measurements, from where data taken from 120° to 240° of azimuth were neglected. The tower was not considered for CFD simulations, therefore for the comparison with experiments it was not included. This reduced the size of the σ and increased the thrust and torque average values. As an example, for the 7m/s case the increments of the torque and thrust are smaller than 1.6% and 4% respectively [9]).

It is also interesting to mention that the variation of Reynolds number based on the local chord, from root to tip and for 5 to 15m/s cases can be significant, and for some cases could add an extra influence to the tripped or clean flow. So mention that the lowest Reynolds was achieved at 30%R station and 5m/s
(615k) and the highest at 80%R and 15m/s (1,076k). The variation of Reynolds number in each of the five sections, just varying the inflow wind speeds, are of 34% at 30%R, 21% at 46.6%R, 13% at 63.3%R, 9% at 80%R and 7% at 95%R. So the outer region will be less influenced in this study than the inboards ones for the variation of Reynolds number.

The experimental loads of thrust and torque are shown in figure 2. There can be seen that the thrust values for the M case (tripped) are in general smaller than the ones for the S case (clean). The relative differences are larger for the speeds ranging from 5 to 7m/s, where the differences are of 7-10%. The summary of the differences is shown in table 3. For wind speeds of 8m/s and above, the differences in thrust are of 1-4%, being larger for all S cases. Another interesting parameter to check is the \( \sigma \), and from table 3 can be said that when the flow along the blade is almost attached (5-9m/s) the \( \sigma \) related to the thrust for the tripped case is larger than for the cases where the flow is more separated (10-15m/s). When differences in averaged torque are analysed, regions of larger or smaller discrepancies between S and M cases cannot be distinguished. However, at 13m/s case, the difference is large, of 15% despite the thrust differs just by 2%. The reason behind the small difference in thrust values will be explained a bit later when force coefficients are discussed. On the other hand, the trend to have larger \( \sigma \) for the tripped case than for the clean case in attached flow conditions is maintained.

![Figure 2. Thrust and torque values of M (tripped) and S (free transition) data-sets and CFD (fully turbulent). M cases are shown as red diamonds, S cases as hollow black circles and CFD with blue line and x symbol.](image)

| Wind speed (m/s) | Thrust [N] | Torque [Nm] |
|------------------|------------|-------------|
| 5                | 500        | 500         |
| 6                | 1000       | 1000        |
| 7                | 1500       | 1500        |
| 8                | 2000       | 2000        |
| 9                | 2500       | 2500        |

Table 3. Summary of the differences in average thrust and torque between M and S experiments.

| Wind speed (m/s) | \( \text{Th}(\text{avg}) \) % (S>M) | \( \text{Th}(\text{std}) \) x (M>S) | \( \text{Tq}(\text{avg}) \) % (S>M) | \( \text{Tq}(\text{std}) \) x (M>S) |
|------------------|------------------------------------|------------------------------------|------------------------------------|------------------------------------|
| 5                | 10% 10% 10% 10% 10% 10% 10% 10% 10% 10% 10% 10% | 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 | 3% 3% 3% 3% 3% 3% 3% 3% 3% 3% 3% 3% | 5.3 5.3 5.3 5.3 5.3 5.3 5.3 5.3 5.3 5.3 5.3 5.3 |
| 6                | 7% 7% 7% 7% 7% 7% 7% 7% 7% 7% 7% 7% | 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 | 6% 6% 6% 6% 6% 6% 6% 6% 6% 6% 6% 6% | 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.8 |
| 7                | 6% 6% 6% 6% 6% 6% 6% 6% 6% 6% 6% 6% | 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 | 5% 5% 5% 5% 5% 5% 5% 5% 5% 5% 5% 5% | 3.1 3.1 3.1 3.1 3.1 3.1 3.1 3.1 3.1 3.1 3.1 3.1 |
| 8                | 5% 5% 5% 5% 5% 5% 5% 5% 5% 5% 5% 5% | 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 | 4% 4% 4% 4% 4% 4% 4% 4% 4% 4% 4% 4% | 1.9 1.9 1.9 1.9 1.9 1.9 1.9 1.9 1.9 1.9 1.9 1.9 |
| 9                | 4% 4% 4% 4% 4% 4% 4% 4% 4% 4% 4% 4% | 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 | 3% 3% 3% 3% 3% 3% 3% 3% 3% 3% 3% 3% | 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 |
| 10               | 3% 3% 3% 3% 3% 3% 3% 3% 3% 3% 3% 3% | 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 | 2% 2% 2% 2% 2% 2% 2% 2% 2% 2% 2% 2% | 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 |
| 11               | 2% 2% 2% 2% 2% 2% 2% 2% 2% 2% 2% 2% | 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 | 4% 4% 4% 4% 4% 4% 4% 4% 4% 4% 4% 4% | 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 |
| 12               | 1% 1% 1% 1% 1% 1% 1% 1% 1% 1% 1% 1% | 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 | 6% 6% 6% 6% 6% 6% 6% 6% 6% 6% 6% 6% | 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 |
| 13               | 2% 2% 2% 2% 2% 2% 2% 2% 2% 2% 2% 2% | 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 | 5% 5% 5% 5% 5% 5% 5% 5% 5% 5% 5% 5% | 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 |
| 14               | 4% 4% 4% 4% 4% 4% 4% 4% 4% 4% 4% 4% | 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 | 7% 7% 7% 7% 7% 7% 7% 7% 7% 7% 7% 7% | 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 |
| 15               | 2% 2% 2% 2% 2% 2% 2% 2% 2% 2% 2% 2% | 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 | 5% 5% 5% 5% 5% 5% 5% 5% 5% 5% 5% 5% | 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 |

Prior to analyse CFD results, note that the computations were done as fully turbulent, therefore, no transition was taken into account. Due to this, the logical comparison should be against M case (tripped flow) instead S case (free flow). Then, comparing the CFD predictions respect to experimental values,
two clear differences can be seen from figure 2, the prediction regarding thrust and torque. It can be said that the thrust predictions of CFD fall for the majority of the cases within the σ of the experiments. Table 4 shows the differences respect average value of the thrust when CFD is compared to M and S cases. For attached flow (5-8m/s), where the CFD predictions should be better than for the separated flow, the difference between CFD and M case is of +4% to -2% and respect to S case +14% to 1%. As expected, the CFD compares better with M case than with the S case. Similarly, but not as clear as, the torque prediction also compares better with M case than with S case for attached flow region (see table 4). When predictions of the stalled regions are compared, the thrust predicted with CFD agrees with experiments (M and S) with similar trend and differences of +/-7% for M and +9% to -3% for S. On the other hand, torque values of the CFD showed a general over-prediction, not being able to predict it within the limits established by the σ. As mentioned in the computation section, fully turbulent steady computations with Menter’s k-ω SST turbulence model have been employed, which could be considered the most popular turbulence model for wind turbine applications, but the results of the stall region shown that still there is room for improvement in these predictions. The CFD is closer to S than M case, but still the fair comparison should be with the tripped case.

Table 4. Summary of the differences in average Thrust and Torque between experiments and CFD.

| m/s | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 |
|-----|----|----|----|----|----|----|----|----|----|----|----|
| Th% (M>CFD) | 4% | 2% | 0% | -2% | -5% | -7% | -2% | 0% | 3% | 5% | 7% |
| Th% (S>CFD) | 14% | 9% | 7% | 1% | -3% | -3% | -1% | 1% | 5% | 9% | 9% |
| Tq% (M>CFD) | 13% | 8% | 3% | 1% | -11% | -30% | -28% | -24% | -36% | -16% | -26% |
| Tq% (S>CFD) | 15% | 14% | 10% | 1% | -4% | -24% | -22% | -17% | -15% | -8% | -20% |

Taken a step in from total loads, now the force coefficients are analysed. Could be derived from the integrated loads, that the M case presents in general smaller Cn values than the clean case (S), highlighting the relevance of the laminar flow. However, as the inflow speed or the local geometrical angle increases, the reduction of Cn due to the zig-zag tape decreases in percentage, being for some inboard cases (30%R and 46.6%R) similar to the clean case. Respect Ct, the trend is similar but less clear due to the smaller values of the coefficients that are compared. Some particular cases will be shown in the following lines.

Figures 3 and 4 show the Cn and Ct values for attached flow (6 & 7m/s) cases and partially separated cases (11 & 13m/s) respectively. As was seen from figure 2 and table 3, the experimental average thrust and torque were 6-7% larger on attached flows for the clean case than for the tripped case. The behaviour of the experimental force coefficients also are clear since they do not cross each other avoiding the compensating errors as shown in the top part of the figure 3. The experimental values are closer to each other towards the “geometry ends” of the blade than in the more 2D region. This also occurs for the average torque measurements. Regarding the σ, at the two station closest to the root the M cases bars are much larger than the S case ones. This, as it is going to be shown when Cp are visited, is directly related to the location of the zig-zag tape at the 2% chord of the upper surface of the blade, where the suction peak plays a significant role in these low loaded cases.

The CFD predictions of the normal force coefficient are very good in all the span-wise stations related to the M case and there is a general trend to under-predict the torque. The figure 3 shows that the largest differences occur at inboard stations where the flow is more complex and can be more affected by Reynolds effects. Despite this trend, notice of the zoom scale of the figures and remember that for these sections the predicted thrust and torque were 0-2% lower and 8-3% lower than experimental average values of M case.
Figure 3. Cn & Ct comparisons between M and S data-sets and CFD for the 6 & 7m/s.

The 11 and 13m/s cases have been selected to see the local force coefficients at 5 span-wise stations for partially separated flows being different from each other. The figure 4 shows these two cases, where the Cn for the 11m/s cases are very similar for the M and S, being slightly larger the differences towards the blade tip. The $\sigma$ bars magnitudes differ from the attached flow cases, since they are an order of magnitude larger. At 13m/s the Cn values cross each other at the 63.3%R and 80%R stations, showing very different force behaviour. For Ct the M and S experimental values are very similar except for the 80%R station. These disagreements explained the large difference between the experiments regarding torque (15% as seen in table 3) at 13m/S and the small difference (2%) when the thrust values were compared. Another interesting aspect is that the torque values, at least when $\sigma$ is taken into account, either for 11 and for 13m/s cases reach negative values, which could be traduced as a opposite force to the torque generation. However, these values are relatively small if are compared with outer stations.

CFD predictions are also compared with experiments as shown in figure 4. The agreement is good for the normal coefficient at 11m/s despite having the 80%R station out the $\sigma$ bars. The Ct prediction shape is not far from the experimental one at this speed but in general the large offset between them provokes to have a torque over-prediction of 28% respect to the M case. The computed Cn values for the 13m/s case follow the opposite trend of the experimental M case approaching to the S case. It can be said that the majority of the stations are close to the $\sigma$ bar limits except the most inboard station, where at 30%R a totally different flow has been predicted. As seen before, the difference in thrust prediction was of 3%, and now can be said that this was obtained thanks to compensation of errors of Cn along the span of the blade. The Ct prediction, which is a more sensible magnitude to obtain, is far from the experiments at the majority of the radial stations except for the tip. The tip is also the section with the smaller $\sigma$ bars showing a less unsteady flow behaviour, as occurs with the 11m/s and contrary to 6 an 7m/s cases.

From the available 50 Cp comparisons, the most interesting ones are selected based on the results.
observed in the integrated forces and also in a particular phenomenon that is possible to observe just with Cp figures.

First of all, the attached flow cases are presented in figure 5, ranging from 5 to 7m/s. For these cases, the pressure sides for the M and S cases are very similar and the suction on the upper surface is consistently higher for the clean cases than for the tripped cases. In general, the σ bars are very small being a bit larger towards the suction peak. These are higher for the M case than the S case due to the zig-zag tape located at 2% of the chord on the upper surface. This can be seen clearly on the 5 and 6m/s cases (figure 5) if the Cp values of the leading edge and the first three stations of the upper surface are observed. For both, the 5 and 6m/s cases, on the 56% of the chord, there is a larger σ bar on the upper side for the clean case. These large variations of the Cp indicates that the station is in the transition region. Since for the M case the transition was correctly fixed upstream, this effect does not occur over there. The variation of the σ due to transition is visible from 5, 6 and 7m/s cases in the majority of span-wise sections and at 56% chord location. For the attached flow cases, there are also some consistent Cp value differences between the M and the S cases that are closest to the trailing edge.

Figure 5 shows that the Cp predictions respect to the tripped case are good. This also confirms that the good Cn and thrust predictions were based on a good ground and were not good due to cancellation of errors. In this comparison seems clear that the fully turbulent computation should be fairly compared with the tripped experimental cases instead of the clean cases. However, notice that the closest approximation to the experiments should be to perform CFD computations with laminar flow that transitions to fully turbulent flow at the experimental zig-zag tape locations.

The 11m/s case at 63.3%R station is also included in figure 5 due to a very similar experimental values of M and S cases. However, the influence of the zig-zag tape can be appreciated since a different slope

Figure 4. Cn & Ct comparisons between M and S data-sets and CFD for the 11 & 13m/s.
of the pressure gradient on the suction side that is pivoting on the 8% chord pressure tap is observed. Simulation predictions are also close to the experiments for this case, despite CFD shows a more stalled flow than the averaged experimental values, but being within the σ bars.

![Figure 5](image)

**Figure 5.** Cop comparisons at 63.3 & 80%R between M and S data-sets and CFD for the 5, 6, 7 & 11 m/s.

Two radial stations of the 13 m/s case are shown in figure 6. The 30%R station has a different trend of what have been observed in the majority of the radial stations and wind cases, since the tripped flow has a higher suction than the clean case. Hints of this were observed in figure 4 and mention that this behaviour occurs just for the same radial station and 12 m/s case and for the 63.3%R station and velocities ranging from 11 to 15 m/s. Pressure sides are similar for M and S cases as occurs with the Cp values that are closer to the trailing edge.

This time, the CFD has predicted an earlier stall despite pressure side prediction is good. However, this difference is the reason of the large differences in Cn and Ct observed at 30%R station in figure 4.

Finally, the 80%R radial station in the figure 6 shows the largest differences between the M and S values that have been found, that are only comparable to the ones occurred at the same radial station and at 14 m/s. This large difference has been also noted in figure 4, where the experimental Cn and mainly Ct were very different between them. In this case, the values obtained from CFD computation seems to follow the S case more than the tripped case. However, it can be said that the CFD was not able to predict the earlier or stronger stall that was measured at M case.

5. **Conclusions**

In this paper NREL Phase VI fix and free transitional experiments were analysed. The aim was to bring to the state of art the M or fix transition case that have not been used in the literature. However, this case is very interesting since a large amount of CFD computations that have been done and compared
for validation purposes were fully turbulent, where transition was not taken into account. Those cases normally are compared with S/H cases or free transition cases, being fairer if they were compared with the M case.

Therefore, the main target of this paper was to prove the utility of M case (transition fixed) and its difference respect the S case (free transition) for validation purposes, when fully turbulent computations are going to be compared. This has been proved for the region where CFD is more trust-able, the attached flow region. On the other hand, still there is room for improvement in the stall or post-stall region, specially related to torque predictions, that in our case were over-predicted.

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