The following documents contains a point-by-point response to the reviews, a list of all relevant changes made in the manuscript, and a marked-up manuscript version.

Response to RC1

Thank you for the input. The reply comments on the points are being made in order.

“The paper has a clear abstract with limited objectives enabling systematic investigation concerning VAWT rotor configurations and their influence on the cyclic bending moments seen at the base of the support tower/main shaft. In general nice connections are made in references to relevant previous work.”

Thank you very much.

“The swept area of a VAWT is in general rectangular. The configurations shown to have a height, H to diameter, D ratio of about 2.5. If the design tip speed and rated power are fixed and we compare with say height to diameter ratio, H/D of 1, the design with H/D= 2.5 has the advantage of lower rated torque but disadvantages of more blade area required and higher base moments. I don’t think this impacts too much on your study as I would expect that the results in terms of comparing loads in the K,A,B,C configurations would be similar at other H/D ratios. However this is not proven and it would be good to recognize it as another variable affecting in principle the generality of your conclusions.”

Those are very good points. The 3D validated scenario is optimized in terms of cost-efficiency, however as the materials and cost analysis were performed as part of a non-published commercial outside study, this is a troubling matter reference-wise. You are very correct that this matter has to be addressed.

“There is no mention of spiral bladed VAWTs. The idea that distributing the position of blade elements around the rotor circle will smooth torque and loads is already well appreciated and this should be acknowledged. The spiral bladed VAWT is the ultimate in that respect doing it continuously. Your study is a special case where the distribution is in only two discrete blade sets. The case for your idea could then be that while the spiral blades are structurally efficient at small scale, they would be problematic at largescale.”

Not mentioning spiral bladed VAWTs was an attempt at limiting the scope of the discussion and to avoid inadvertently leaking intellectual property too early. Right now I would love to add some content about spiral bladed VAWTs. However it must be noted that typical designs of such turbines are not optimal in smoothing bending moments – there is an effect, but as the upper sections have greater leverage than the lower ones the effect achieved is far from perfect. The solution to this, described in a soon to be published patent application PCT/PL2020/000054 lies in a non-linear twist – operating on a similar principle to the upper portion of the 2-part H-VAWT rotor being a specific different size than the lower portion. Finally, both structural concerns and increased weight of spiral blades makes the technology very interesting in small to medium scales, but far less cost-efficient than the presented scenario in the scale presented and above.

“As a general point on presentation, ahead of section 4, I find too many figures showing the configurations. In the space to the right of Fig 2 for example two vertical schematics of 3 blades for K and 6 for A,B,C would show all the configurations more clearly. Perhaps 4,5,6 could be collapsed into 1 or 2 composite figures. On the other hand, figures with graphical display of the results of Tables 1,2, 3 and 4 would be rather helpful. The model testing lacks mention of Reynolds number effects until line 209 starting the conclusions. The comment is out of place there. Its not really a conclusion and shouldbe discussed with the experimental results.”

Noted.

“How low was Re or the range of Re in the model tests?”

Around 10 000 to 50 000 – a very poor range for symmetrical NACA characteristics.

“In line 99 "started oscillating" . What kind of oscillations, bending, torsion?”

Thank you for the comment – bending.

“English in the paper is generally good but from line 114, the word "growth" is not at all wrong but reads rather strangely. Better is "increase in bending moment values". The way it is written "growth" sounds as if the increase is unusual behaviour when, until stall and unsteady effects occur most significantly, we would expect increase in moments (perhaps as square of wind speed). The graphical presentation of Table2 would definitely help here. The mention of the effects of resonance here is not telling us much with no definition of its nature or suggested explanations.”

Thank you for the corrections.

“Finally in your conclusions I think it is pushing it to say more "cost efficient". The results show how bending moments can be reduced and this is certainly useful information a designer that may assist design optimisation. In a fully engineered system it is unclear how the cross arm structures (sizes and drag impacts) for K will compare with the cross arm structures required for blades in a sense cut into two , A, B,C”

While this hypothesis has proven to be true, it is based on unpublished outside work – I am very open and thankful for pointing out the issue and possible suggestions whether itis better to make the statement weaker as I do not think we have a right to reference the validation materials; or whether it is better to solve the issue some other way.

Response to RC2

Thank you for the input. The reply comments on the points are being made in order

“Summary: The manuscript discusses a set of experiments and CFD simulationsexamining various VAWT configurations to reduce the cyclic shaft loads produced bythe standard Darreius-style, 3-bladed VAWT. The authors have spent a good deal oftime generating the experimental and numerical results which may have applicationsto VAWT design and optimization.”

Thank you.

“General Comments: The manuscript could benefit from several revisions. The first of these is to expand the introduction and review sections, as they stand the literature review is weak and incomplete. Many studies have been conducted on the twisted-blade VAWT and these should be included in the review and motivation given as to why the current geometry was chosen.” We would gladly expand on those points. If possible we would also be thankful for specific important articles that should not be missed within this part.“ There are a large number of typos throughout the manuscript (use of “effect” vs “affect” and “smoothening” instead of the correct “smoothing”).Overall, the data presentation could be improved throughout the paper. Results placed in large tables are difficult to interpret and force the reader to sift through various tables to make comparisons. These data sets should be plotted in an organized fashion. The conclusions section needs revision as well. The comments on the Reynolds number are out of place, with no other mention of the effect of Re anywhere else in the manuscript.”

Thank you for the corrections

“Furthermore, the experimental results (on which the bulk of the paper focuses) are barely discussed, which of the 4 designs performed the best?"

Truth be told which design performed the best changes depending on the criterion one might choose. For a general answer to be justified eg sets of cost-effectiveness studies of the tested designs would have to be generated. Design B was chosen as the favored one, being used as the basis for CFD validation – showing improvement in one of the desired reductions over A and no drop in the other as compared to A – like configuration C did. If that would be helpful we would explain that point in a revision of the article

“How close did the simulation and experiment data match?”As the cases in the simulation and experiment were different, being made for entirely different scales, we were concerned it might not be correct to compare them directly. It would be very interesting if one were to make a simulation in the same scale as the experiment and match the results. As the point was mainly to validate the design for large-scale

“Line Comments: The statement on line 33 stating the “high aerodynamic efficiency potential” needs to be further justified besides the Ferreira 2014 paper. Many articles have also shown the lower aerodynamic efficiency of the VAWT as compared with the HAWT, some reference should be made to these. “

The articles claiming lower aerodynamic efficiency are made in regard to small designs or low H/D ratio designs as high H/D ratios are problematic loading-wise, a problem that the tested hypothesis tries to solve. We can include the articles making statements based on less related cases, but are not sure whether it is correct to make a critical stance on the views expressed in them without a thorough shift in the article focus, to deeply explain the stance opposing some of the conflicting claims within different sources.

“There are also other benefits to the VAWT design not mentioned such as insensitivityto wind direction and the ability to mount the generator near to the ground.”

Yes.

“Line 46: What is the blockage of the model in the tunnel?”

That is a very good concern – it is not nearly optimal for many purposes. Around 16%without the step before the rotor, 20% with.

"Were any corrections made to the experimental data to account for the effect of flow acceleration?"

No.

“It appears that the simulations did not reproduce the walls of the tunnel, so some correction should be used.”

It most probably should be more clearly stated within the article that the experiment and CFD case are not trying to show the exact same case, but closest available cases to experimentally and numerically validate the overall usefulness of the special large VAWT concept showcased within the article. “Line 60: Figure 2 is very difficult to interpret. Can dimensions be added to each figure and perhaps reduce the shading of the 3D CAD models so that they show up more clearly? The figure caption should also have a brief but clear description of the 4 test-cases to aid the reader. Line 70: “For many conditions up to 6” Use specific language, what does “many conditions” mean? Also in this same sentence “momentarily” should be “momentary” and “effect” should be “affect” (there are other instances of this in the rest of the manuscript).Line 83: The use of “smoothening” is incorrect it should be “smoothing”. This should be fixed throughout the paper. Line 83: What is meant by the term “chamfering”? Again, please use technical and precise language in the discussion. “Yes, thank you for the corrections. “Line 86: The entire sentence “While the process performed has no influence on the general nature of the experiment results or conclusions unto the effectiveness of the proposed solution, it is entirely possible it has a very slight influence on the exact result values.” Is self-contradicting. How can a process have no influence on the results but have an influence on the exact result values? Did you mean that it does not change the data trends? Please clarify and re-word.”

Yes, thank you. Numerical and experimental values under specific conditions are not guaranteed to be the same in real life conditions, however they in no way invalidate the load-limiting hypothesis of the concept, rather showing very promising results. Further results based on outside non-published studies sadly cannot be referenced to further showcase this point.

“Line 90: Table 1 should be made into a plot, there is no need to have tabulated data for these comparison points in the paper (similar comment for other data tables).”Future work based on results within other authors’ articles cannot accurately be made based on plots “Line 96: Plot the data sets non-dimensionally with the tip speed ratio, what you will find is that forces/moments scale with the velocity squared so this result is not surprising.”

Yes

“Line 115: Shape of what curve?”

Please excuse us - bending moment data curve.

"Line 165: Some comments about how these results might scale up from the laboratory experiments to full-scale Reynolds numbers would be useful. Comments on the CFD Section: Why are these results (and the plotted data) not compared directly with the experimental results of the previous section? I recommend making new plots showing the comparison directly. "

That would be somewhat hard to explain as they are not related to the same case –rather they are two distortions of a large-scale real-life scenario that would be beneficial but extremely expensive to validate directly. Therefore the validation of possible advantages of the concept happens partially independently through two methods. “The section title is “CFD Validation”, but you have not validated anything becausethere is no comparison to the experiments.”

Validation refers to the turbine concept. We will try to make that goal more clear within the article.

“209: The conclusions section needs to be revised due to several issues. The first is the discussion of the Reynolds number which is not mentioned anywhere else in the manuscript (for instance, what is the Re of the experiment?) It is also not surprising that the performance of the 0018 was poor, it is an airfoil designed for high Reynolds numbers (3 million and above). Also, the conclusion section makes no mention of the4 different configurations, which one was the best?”

Thank you for the thorough review, if it would be judged that with such corrections the article could be suitable for publishing we will very gladly clarify those points.

Relevant changes:
All English mistakes pointed out the reviewers have been corrected.

Requested relevant data has been added – especially concerning literature and knowledge on spiral vertical axis wind turbines, their current status and common and diverging points as compared to the concept presented within the article. Data on experiment Reynolds numbers has been added.
Poorly structured sentences have been corrected.

Wind tunnel comparison of four VAWT configurations to test load-limiting concept and CFD validation

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Abstract. The article describes results of experimental wind tunnel testing of four different straight bladed vertical axis wind turbine model configurations. The experiment tested a novel concept of vertically dividing and azimuthally shifting a turbine rotor into two parts with a specific uneven height division in order to limit cycle amplitudes and average cycle values of bending moments at the bottom of the turbine shaft to increase product lifetime, especially for industrial scale turbines. Testing reduction effects of simultaneously including a vertical gap between turbine rotor levels, increasing shaft length but also reducing aerodynamic interaction between rotor levels, has also been performed. Experiment results have shown very significant decreases of bending moment cycle amplitudes and average cycle values, for a wide range of measured wind speeds, for dual-level turbine configurations as compared to a single-level turbine configuration. The vertical spacing between levels equal to a blade's single chord length has proven to be sufficient, in laboratory-scale, to limit interaction between turbine levels in order to achieve optimal reductions of tested parameters through an operating cycle shift between two position-locked rotor levels during a turbine's expected lifetime. CFD validation of maintaining the effect in industrial scale has been conducted, confirming the initial conclusions.

1. Introduction

Vertical axis wind turbine (VAWT) blades, unlike horizontal axis wind turbine blades, work in a high range of angles of attack within each rotation cycle (Ahmadi-Balouaki M et al., 2014). Resulting high amplitudes of bending moment values and high maximum moment values at the bottom of a wind turbine shaft in a rotation cycle (Galinos C et al., 2016) are strong deterrents to development of economically feasible large-scale VAWTs. The proposed concept for limiting those factors focuses on separating the rotor vertically into two or more parts of different lengths, shifted azimuthally in such a way as to maximally reduce maximum moment values and amplitudes at the bottom of the rotor shaft in a rotation cycle. The tested case had two rotor-levels – a longer one, closer to the bottom of the shaft, and a shorter one, further from the bottom of the shaft; in order to achieve comparable values of bending moments at the bottom of the rotor shaft from each rotor-level. Additional spacing between rotor-levels was also tested in order to limit interaction between separate rotor-levels.

The topic of lift-based large-scale VAWTs, despite the aforementioned technological drawbacks – a solution to which can be seen tested below, has been met with resurfacing interest, due to their specific advantages. While factors related to the blade tip not moving faster relative to the rest of the blade, allowing for lower noise emissions (Iida A et al., 2004), lower bird death rates and no ice block launching, in areas where the risk exists, as compared to horizontal axis wind turbines (HAWTs) are important advantages for certain siting conditions, the key factor that keeps drawing researchers to VAWTs is the high aerodynamic efficiency potential. A study by Simão Ferreira et al. (Simão Ferreira C et al., 2014), comparing 6 different methods for assessing power coefficients (Cp) for a wide range of tip speed ratio and rotor solidity, has calculated large-scale VAWT Cp for advantageous configurations for each model to be between 0.54 and 0.6. Straight bladed VAWTs specifically hold an additional advantage; that is easier manufacturing of blades (Chinchilla R et al. 2011) and lower blade weight and material use compared to VAWTs with spiraling blades.

Spiral bladed wind turbines are described in literature as having lowered amplitude changes of their aerodynamics (Guo Y et al., 2019) – specifically the time amplitude of the sum of force values affecting the entire rotor is much lower for a standard spiral VAWT compared to a straight bladed VAWT, as presented visually within the Journal of Power and Technology (Scheurich F et al., 2011). Another study gives this relationship an averaged numeric value – stating that by replacing straight blades with helical ones in a VAWT rotor, the total force fluctuation amplitude is reduced by about 50% (Marini M et al., 2010). It is important to note that these available factors do not reflect directly towards a key parameter of this study - cycle amplitudes of bending moments at the bottom of the turbine shaft, proportional to element loading and therefore determined as a parameter directly influencing turbine shaft reliability, expected lifetime and necessary material use as per use in expected lifetime for cyclic loading curves. Typical designs of spiral bladed VAWTs are not optimal in smoothing bending moments at the base of the turbine shaft – there is an effect, but as the upper sections have greater leverage than the lower ones the effect achieved cannot be perfect. The solution to this, described in patent application PCT/PL2020/000054 lies in a non-linear twist – operating on a similar principle to the upper portion of the concept that is the target of the paper, the upper portion of the rotor being a specific different size than the lower portion. Finally, both structural concerns and increased weight of spiral blades make the technology very interesting in small to medium scales, but less cost-efficient than the concept validated within this paper, in the scale referenced and above.

2. Test case description

The testing was conducted in the WUT Variable Turbulence Tunnel in the 2.5 m wide and 2 m tall environmental test section of the tunnel.

Figure 1. WUT Variable Turbulence Tunnel

Shown in Figure 1. the WUT Variable Turbulence Tunnel is a large-scale sub-sonic wind tunnel with two independent test sections allowing for testing in a range of speeds between 5 and 90 m/s. Air flow is generated by a 250 kW engine. Figure 1. shows a part of the Warsaw University of Technology including a section of the environmental part of the tunnel.

The model itself was 1.5 m high in the 2 shortest configurations, with a 57.5 cm turbine rotor diameter. The model was created with the upper level capable of shifting, in order to enable testing of different configurations. A three blade rotor design was chosen, in addition to CFD simulations by the authors a comparative analysis by Parashivoiu shows them to have better structural reliability than dual blade designs (Parashivoiu I 2002). The model used the NACA 0018 symmetrical airfoil, a classical VAWT airfoil used both in CFD based studies (Rogowski K et al. 2018) and experiments (Laneville A., Vittecoq P., 1986).

The concept tested has, in the presented version, two levels of blades within a rotor. The lower level is equipped with longer blades in order to provide similar maximum and minimum values of bending moment at the bottom of the turbine shaft as the higher level, only shifted in cycle by azimuthally displacing the upper and lower rotor-level. In order to limit interference influencing the character of aerodynamic loading on each three blade rotor level, variants with vertical spacing between rotor levels have also been tested – negatively influencing shaft length, but decreasing aerodynamic interference between adjacent rotor-levels. It is worthwhile to note that applying construction solutions reducing blade chord near the end of a rotor level (Islam M., Fartaj J., Carriveau R., 2008), should result in lower spacing needs between adjacent turbine levels.

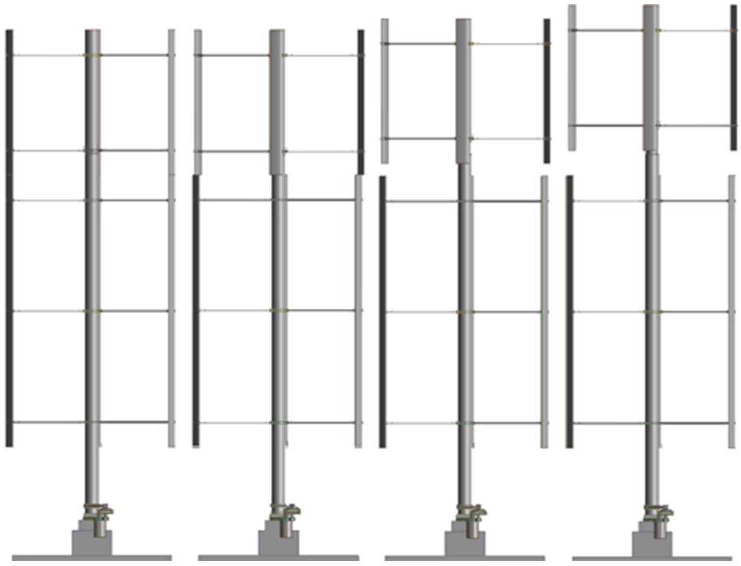

Figure 2. Chosen VAWT configurations tested in the wind tunnel.

Figure 2 displays the four configurations used for final wind tunnel testing. Configuration K is a standard single level VAWT with blade length equal to the sum of the length of both levels in other scenarios. Configuration A is a dual level wind turbine, shifted azimuthally by 60 degrees, with the second level starting at the exact height at which the first level ends. Configuration B is analogous to A, whereas there is a vertical gap between adjacent levels equal to a single chord length (3.75cm). Configuration C has a vertical gap between levels equal to two chord lengths (7.5cm).

The reason for conducting the tests was to measure the bending moment values at the bottom of the turbine tower for a laboratory-scale model of the authors' analyzed turbine concept, within a few configurations. The values were being measured for a range of inflow wind speeds between 4m/s and 12m/s while the turbine was rotating freely. Torque was not a measured parameter, as for the range of Reynolds numbers in the area of 10,000 to 50,000 within the experiment no airfoils are capable of providing characteristics comparable to ones for industrial scale blades. Each measurement consisted of 10,000 data acquisitions within the period of 10 seconds. For many combinations of inflow wind speeds and geometry configurations up to 6 measurements were taken to ensure that a momentary effect didn't influence the results. To reduce noise within the measured signal techniques from exploratory data analysis (EDA) were used (Oerlemans S. and Migliore P., 2004). Firstly a technique called hanning, or a running weighted mean, was implemented. Each data point was replaced with the sum of half the data point and one-fourth of the previous and next data points. This was used consecutively three times for better results, with 50-point median smoothing used twice afterwards for a final smoothened data set.

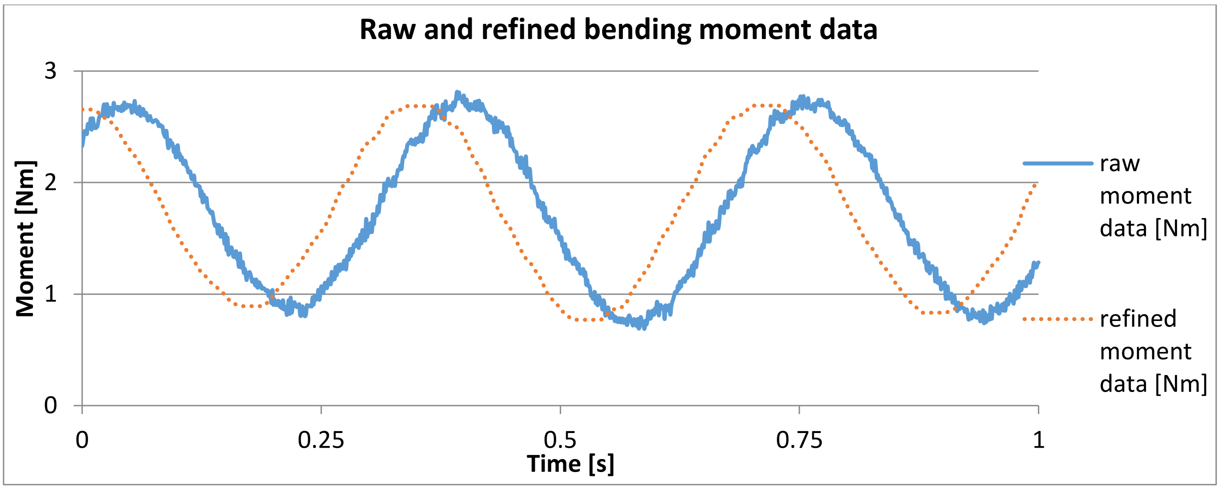

Figure 3. Sample of raw and refined bending data values from configuration A

Figure 3 presents a one second sample of raw bending moment values recorded by the tensometric scale used in the experiment, as well as the refined bending moment values achieved by a five step smoothing process used in order to eliminate signal noise. The data is from a measurement in configuration A, taken at the inflow wind speed of 11 m/s. The necessity of eliminating signal noise does, to a small extent influence experiment results. The smoothing process, if done too subtly, maintains some artificial peak value increases. If the smoothing process is too major, it leads to filtering out peak values resulting from actual physical forces acting upon the rotor. Although the smoothing was done with care, it is important to remember that, especially for comparison of tens of cycles performed for four different geometries and a range of wind speeds, it introduces risk of slightly altering peak values. The smoothing process, while aiming to recreate the values without signal noise, may have some influence on the exact result values, however the possible scale of the effect is too small to have an impact on the general nature of the experiment results or conclusions unto validating the potential effectiveness of the proposed solution.

Configuration K

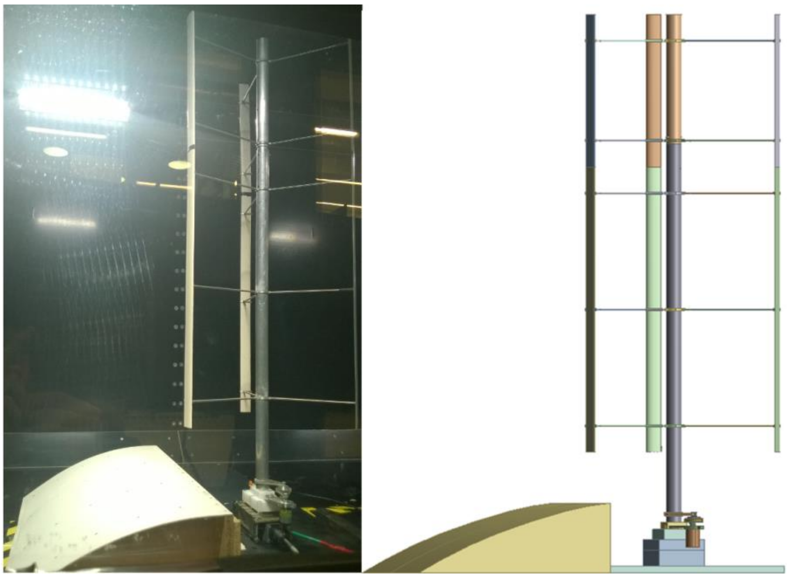

Figure 4. Model set in configuration K

Figure 4. displays the model set in configuration K. It shows a single level turbine, with straight, prolonged blades.

Table 1. Control case K testing parameters of bending moments for wind speed range

Wind speed [m/s]	4	5	6	7	8	9	10	11	12
Average moment amplitude [Nm]	0.077	0.102	0.243	0.358	0.522	1.193	7.799	3.316	1.672
Max moment amplitude [Nm]	0.118	0.183	0.389	0.604	0.809	1.529	8.249	3.762	2.326
Min moment amplitude [Nm]	0.025	0.021	0.036	0.168	0.157	0.833	7.211	2.701	1.066
Average peak value [Nm]	0.254	0.413	0.643	0.886	1.221	1.817	5.647	3.505	3.047
Max peak value [Nm]	0.270	0.509	0.753	0.994	1.363	1.976	5.941	3.727	3.414

Table 1 shows results of measuring bending moments at the bottom of the turbine tower for a range of wind speeds between 4 m/s and 12 m/s for a freely rotating wind turbine in configuration K. In general there is an increase in bending moment values and amplitudes, accompanying the growth of inflow wind speeds. The value increase, while not exactly proportional to the second power of the inflow speed, is strongly influenced by it, with two exceptions. It is noticeable from the values that at 10 m/s and 11 m/s, the turbine has started oscillating by bending. It is especially evident for 10 m/s when the moment amplitude is several times larger than for many other measurements. It is also visible that for 10 m/s the moment amplitude is noticeably higher than the moment peak values, meaning that for a part of the loading cycle the turbine is being pushed forward against the direction of the wind. That effect is, to a much smaller degree visible at the inflow speed of 11 m/s.

2.2. Configuration A

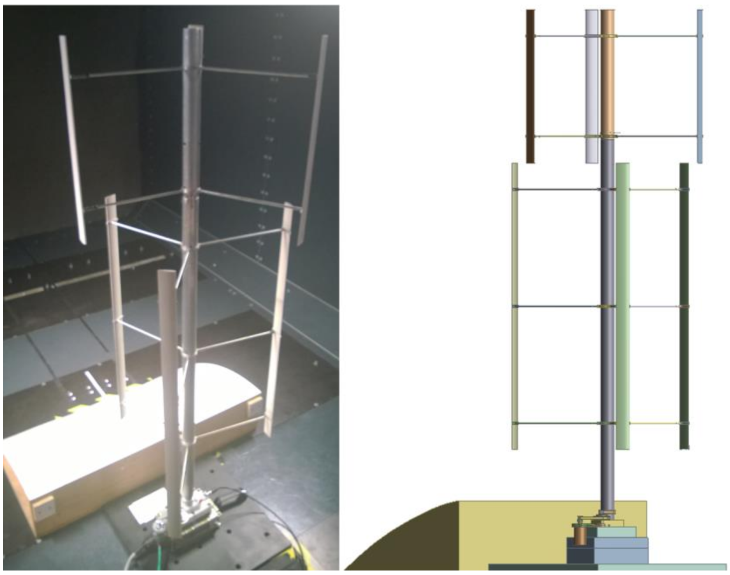

Figure 5. Model set in configuration A

Figure 5. displays the model set in configuration A. It shows a basic dual-level turbine, shifted azimuthally between levels by 60 degrees. There is no vertical displacement between levels – the upper level of the rotor starts at the same height the lower level ends.

Table 2. Case A testing parameters of bending moments for wind speed range

Wind speed [m/s]	4	5	6	7	8	9	10	11	12
Average moment amplitude [Nm]	0.058	0.133	0.133	0.170	0.179	0.258	0.521	1.917	0.721
Max moment amplitude [Nm]	0.098	0.199	0.235	0.262	0.336	0.508	0.898	2.132	1.390
Min moment amplitude [Nm]	0.025	0.084	0.052	0.084	0.043	0.108	0.214	1.710	0.188
Average peak value [Nm]	0.248	0.401	0.564	0.762	0.978	1.278	1.708	2.730	2.455
Max peak value [Nm]	0.278	0.441	0.612	0.833	1.145	1.394	1.922	2.893	2.854

Table 2 shows results of measuring bending moments at the bottom of the turbine tower for a range of wind speeds between 4 m/s and 12 m/s for a freely rotating wind turbine in configuration A. In general there is an increase in bending moment values and amplitudes, accompanying the growth of inflow wind speeds. At the inflow speed of 11 m/s, the shape of the bending moment data curve as well as the fact that both moment amplitudes and peak values are greater than for 12 m/s, suggest that for 11 m/s resonance occurs. The increase of values due to resonance is much smaller than in the single-level configuration K.

2.3 Configuration B

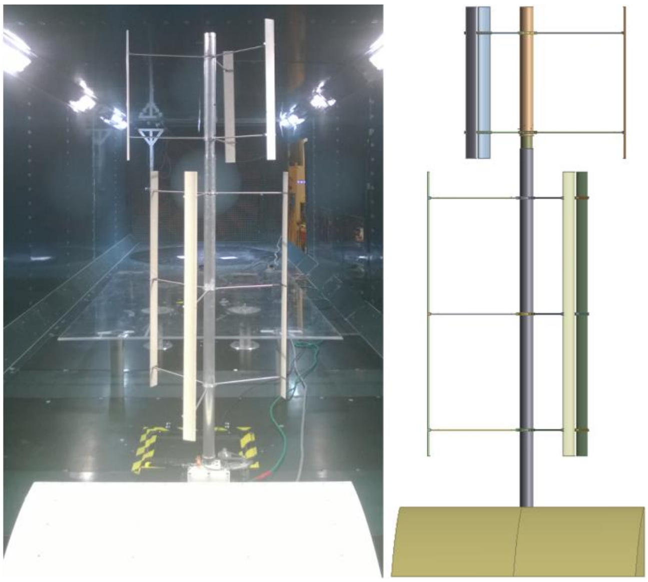

Figure 6. Model set in configuration B

Figure 6. displays the model set in configuration B. It shows a dual-level turbine, shifted azimuthally between levels by 60 degrees. The height of the vertical gap between rotor levels is equal to 3.75cm – 1 chord length.

Table 3. Case B testing parameters of bending moments for wind speed range

Wind speed [m/s]	4	5	6	7	8	9	10	11	12
Average moment amplitude [Nm]	0.059	0.065	0.097	0.145	0.177	0.411	0.399	1.223	0.595
Max moment amplitude [Nm]	0.088	0.113	0.157	0.259	0.274	0.645	0.664	1.480	0.891
Min moment amplitude [Nm]	0.025	0.022	0.030	0.043	0.066	0.185	0.164	0.895	0.128
Average peak value [Nm]	0.246	0.365	0.544	0.775	1.002	1.399	1.659	2.401	2.448
Max peak value [Nm]	0.262	0.397	0.575	0.844	1.063	1.562	1.820	2.498	2.583

Table 3 shows results of measuring bending moments at the bottom of the turbine tower for a range of wind speeds between 4 m/s and 12 m/s for a freely rotating wind turbine in configuration B. At the inflow speed of 11 m/s, the shape of the curve as well as the fact that both moment amplitudes and peak values are greater than for 12 m/s, suggest that for 11 m/s resonance occurs. The growth of values due to resonance is much smaller than in the single-level configuration K, and also lower than for configuration A, which has no vertical spacing between levels.

2.4. Configuration C

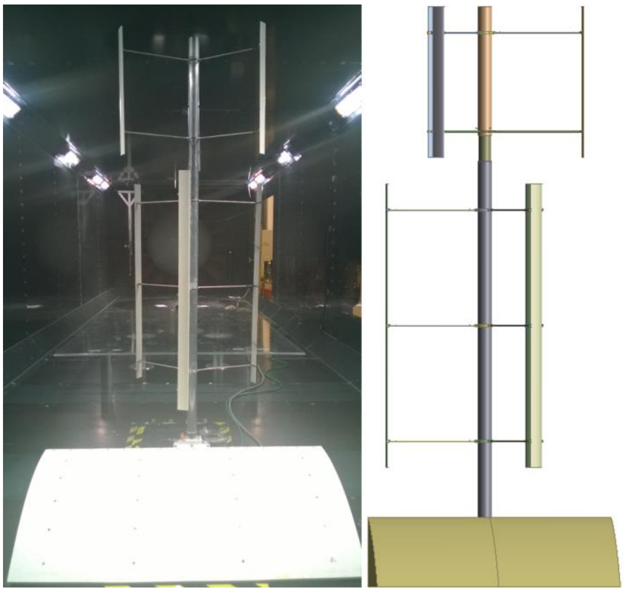

Figure 7. Model set in configuration C

Figure 7. displays the model set in configuration C. It shows a dual-level turbine, shifted azimuthally between levels by 60 degrees. The height of the vertical gap between rotor levels is equal to 7.5cm – 2 chord lengths.

Table 4. Case C testing parameters of bending moments for wind speed range

Wind speed [m/s]	4	5	6	7	8	9	10	11	12
Average moment amplitude [Nm]	0.063	0.090	0.147	0.136	0.249	0.290	0.393	0.940	0.580
Max moment amplitude [Nm]	0.111	0.149	0.209	0.217	0.441	0.520	0.766	1.264	1.122
Min moment amplitude [Nm]	0.029	0.055	0.072	0.059	0.077	0.035	0.100	0.630	0.144
Average peak value [Nm]	0.261	0.407	0.594	0.797	1.087	1.399	1.723	2.340	2.529
Max peak value [Nm]	0.287	0.448	0.643	0.864	1.159	1.564	1.946	2.490	2.776

Table 4 shows results of measuring bending moments at the bottom of the turbine tower for a range of wind speeds between 4 m/s and 12 m/s for a freely rotating wind turbine in configuration C. At the inflow speed of 11 m/s, the shape of the curve as well as the fact that both moment amplitudes and peak values are greater than for 12 m/s, suggest that for 11 m/s resonance occurs. The growth of values due to resonance is much smaller than in the single-level configuration K, and also lower than for configuration A or B. The growth of vertical spacing between rotor levels, tested to quantify the effects of decreasing interaction between levels on bending moment values in addition to the azimuthal shift of rotor levels, helps limit the effects of the sudden moment and moment amplitude growth at certain wind speeds.

3. Experiment result Comparison

Table 5. Result comparison for different scenarios

Inflow velocity [m/s]	Average bending moment amplitude reduction				Average peak moment value reduction			
	K	A	B	C	K	A	B	C
4	0%	25%	23%	18%	0%	3%	3%	-2%
5	0%	-31%	37%	12%	0%	3%	12%	1%
6	0%	45%	60%	40%	0%	12%	15%	8%
7	0%	53%	59%	62%	0%	14%	12%	10%
8	0%	66%	66%	52%	0%	20%	18%	11%
9	0%	78%	66%	76%	0%	30%	23%	23%
10	0%	93%	95%	95%	0%	70%	71%	69%
11	0%	42%	63%	72%	0%	22%	32%	33%
12	0%	57%	64%	65%	0%	19%	20%	17%

Table 5 shows the reduction of average bending moment amplitude and average peak bending moment value results for each separate inflow speed for every test configuration as compared to configuration K. Except for 4 m/s, all average bending moment amplitude reduction levels for configuration B are greater than for configuration A. Configuration C shows superior average bending moment amplitude reduction levels to configuration B for 7 m/s, and the range of 9-12 m/s. The vertical spacing between levels also increases the height of the structure as well as moves the model further from optimal level-length proportions, which were optimized for configuration A. The results show that growth of vertical spacing corresponded to a drop in average peak bending moment value reduction for inflow speeds of below 10m/s, at which point resonance begins to influence test results.

For results presented in this paper, there can be several ways of assessing the average reduction in bending moment and bending moment amplitude values. The simplest way would be to take reduction percentage values from table 5 and make a simple average of them. For purposes relating to product lifetime, a more realistic approach would be to take an average, but discard the values at low inflow speeds – too small to influence turbine lifetime, as compared to values at higher inflow speeds. For a range of relevant wind speeds set from 8m/s to 12m/s, an average reduction of bending moment amplitude in configuration A was at 67%, while the average reduction of peak bending moment values was at 32%. For configuration B, the reductions calculated thusly were likewise 71% and 33%, and for configuration C – 72% and 31%. Another simple approach would be to make an unweighted sum of all measured mean values for every configuration and quantify the reduction between those sums. A modification of this approach is weighing the results at all tested wind speeds, by probability of their occurrence. This has been done using the Weibull wind speed distribution curve for reasonable European wind farm siting conditions – a middle-of-rotor average wind speed of 5.7 m/s and k shape factor equal to 2.1 (Kiss P, Jánosi I M, 2008). For this averaging method, moment amplitudes in configuration A were limited on average by 80%, while the average reduction of peak bending moment values at the tower base was 42%, as compared to configuration K. For configuration B, the reductions were likewise 82% and 42%, and for configuration C – 84% and 40%.

4. CFD validation

A validation of the load-limiting concept in industrial scale has been performed using 3D CFD in ANSYS Fluent. Compared was a dual-level straight-bladed wind turbine with the vertical spacing between levels equal to 1 blade chord length, based on experimental configuration B – 1.5m and a single level straight-bladed turbine with identical chord, rotor length and diameter.

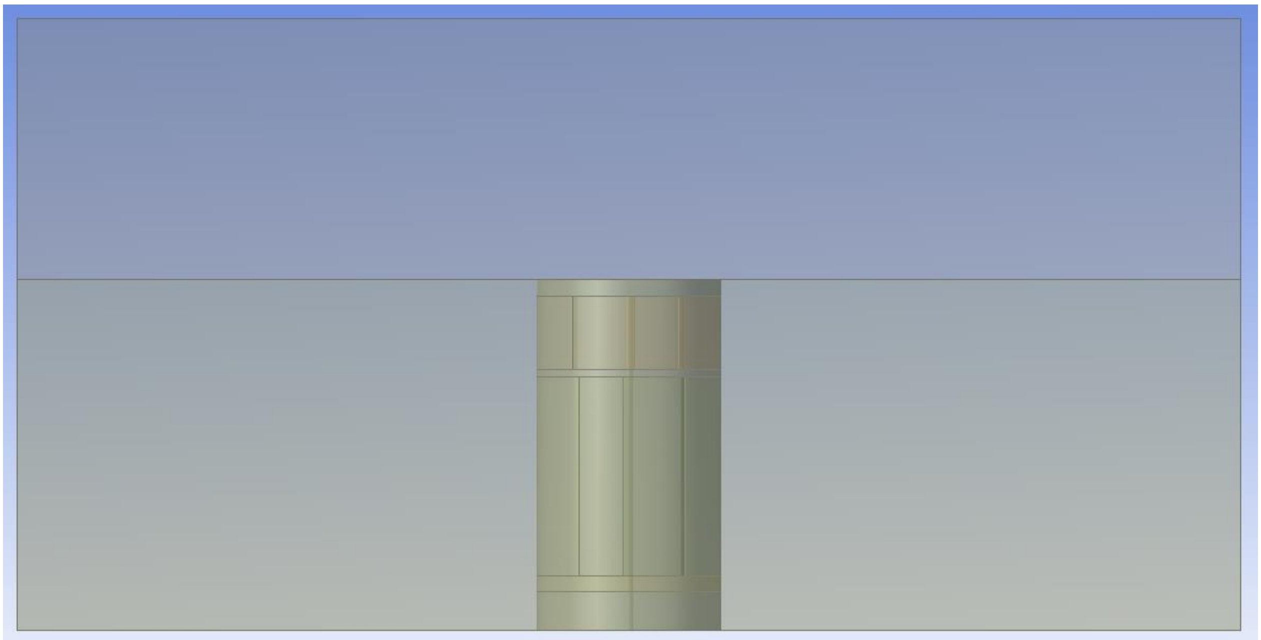

Figure 8. Computational domain geometry for dual-level scenario

Figure 8 shows a side view of the geometry used for the computational domain for the dual-level scenario. For both scenarios the blade chord, total rotor length and diameter are exactly 40 times that of the experimental cases. The blades were set 3 degrees to the outside of the rotor, relative to the blades' motion path. This parameter, and others such as the chord to diameter ratio were chosen as a result of 2D CFD production optimization. The airfoil used, after testing the influence of airfoil thickness for a range of angles of blade attachment with 2D simulations, was once again NACA0018.

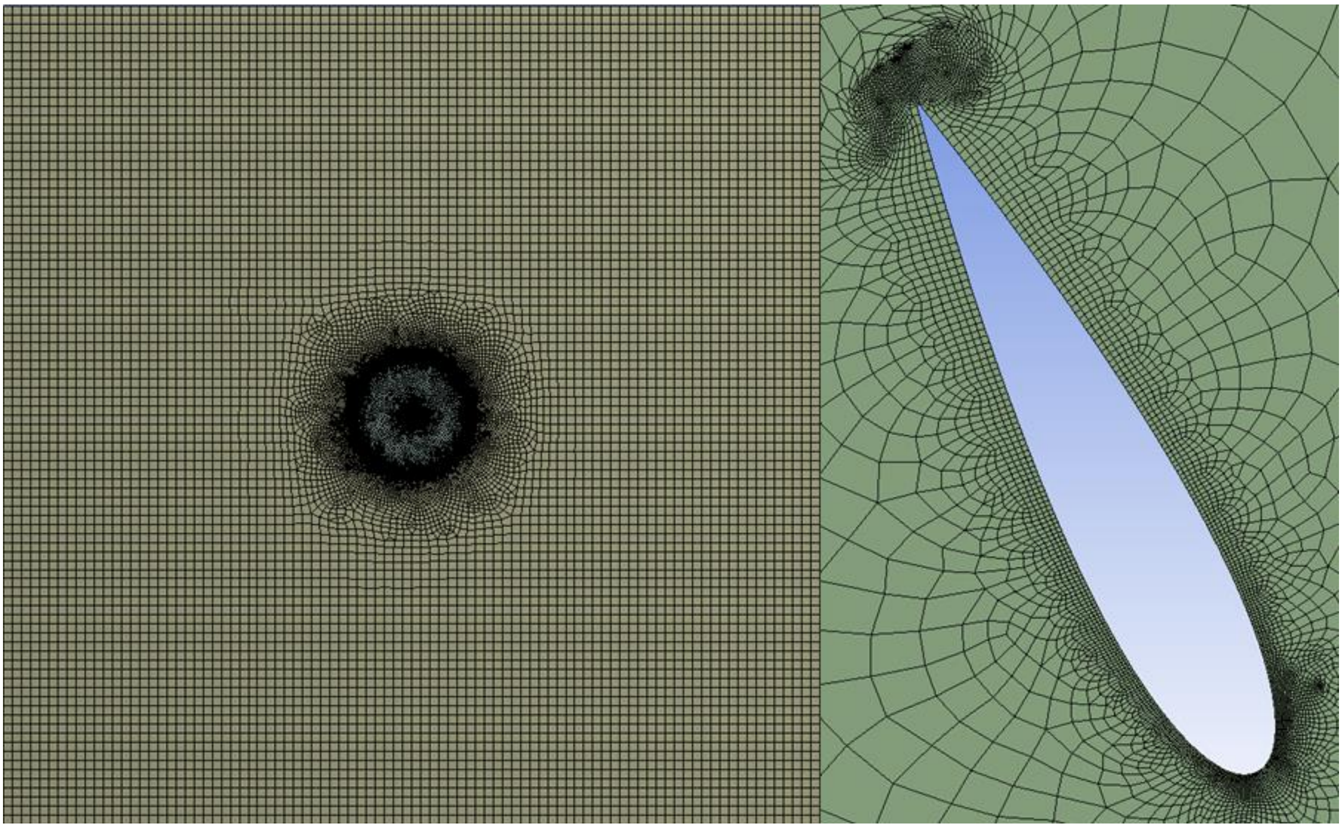

Figure 9. Bottom side view of select mesh parts

Figure 9 displays a bottom side view of the mesh for the entire domain as well as the sweepable mesh on one of the blades. The trailing edge was divided into two parts, the rest of the blade into 550 parts. Automatic boundary layer creation – as incompatible with the sweep method used, was not implemented. The simulation was conducted with the k-omega SST turbulence method, default turbulence parameters and surface roughness and a 9 m/s inflow speed, a rotational speed of 140 deg/s and 0.01s time step.

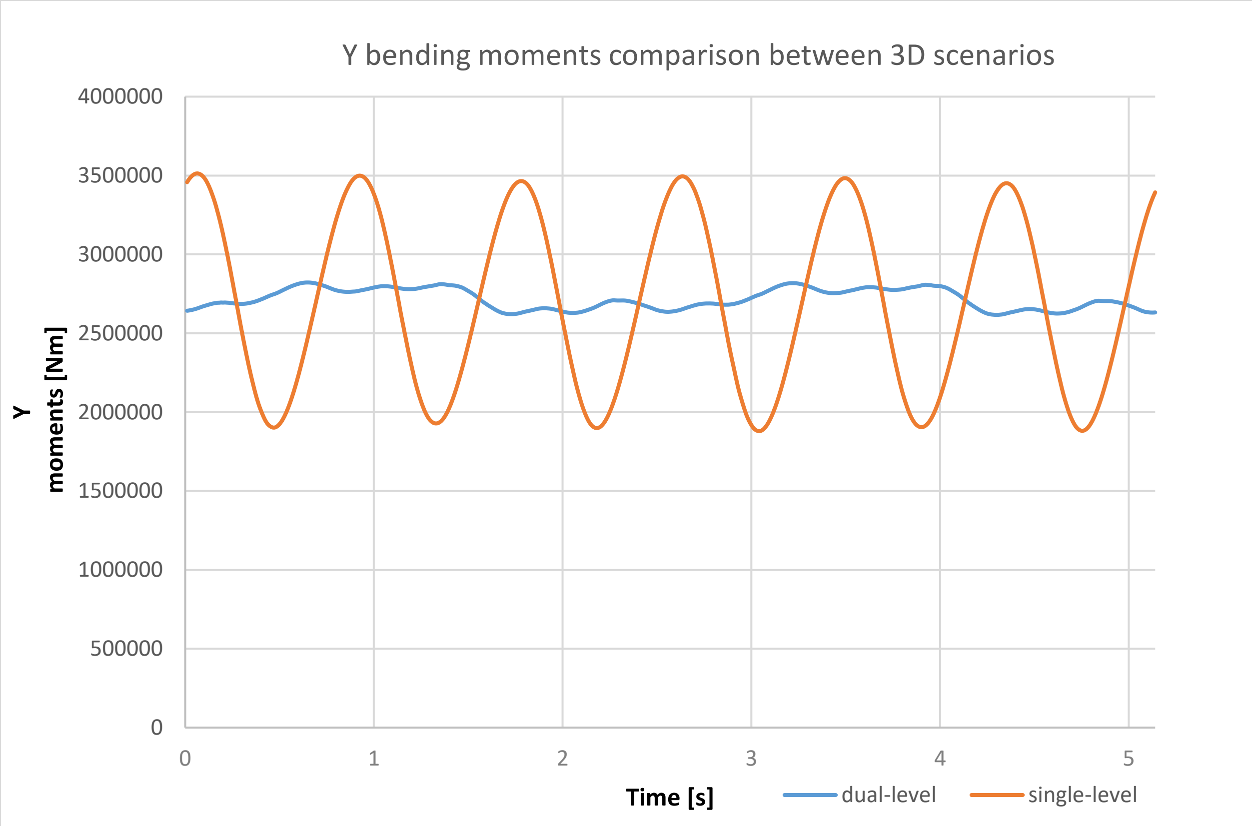

Figure 10. Y-bending moments comparison between 3D scenarios

Figure 10 shows the Y-bending moments, according to Fluent's default coordinate system, at the bottom of the rotor shaft, analogous to the moments measured during the experimental comparison in the first part of the paper. Compared to the single-level scenario, in the dual-level scenario the maximum Y-moment values within a cycle are limited by 19.7%, while the Y-moment amplitude is limited by 87.5%.

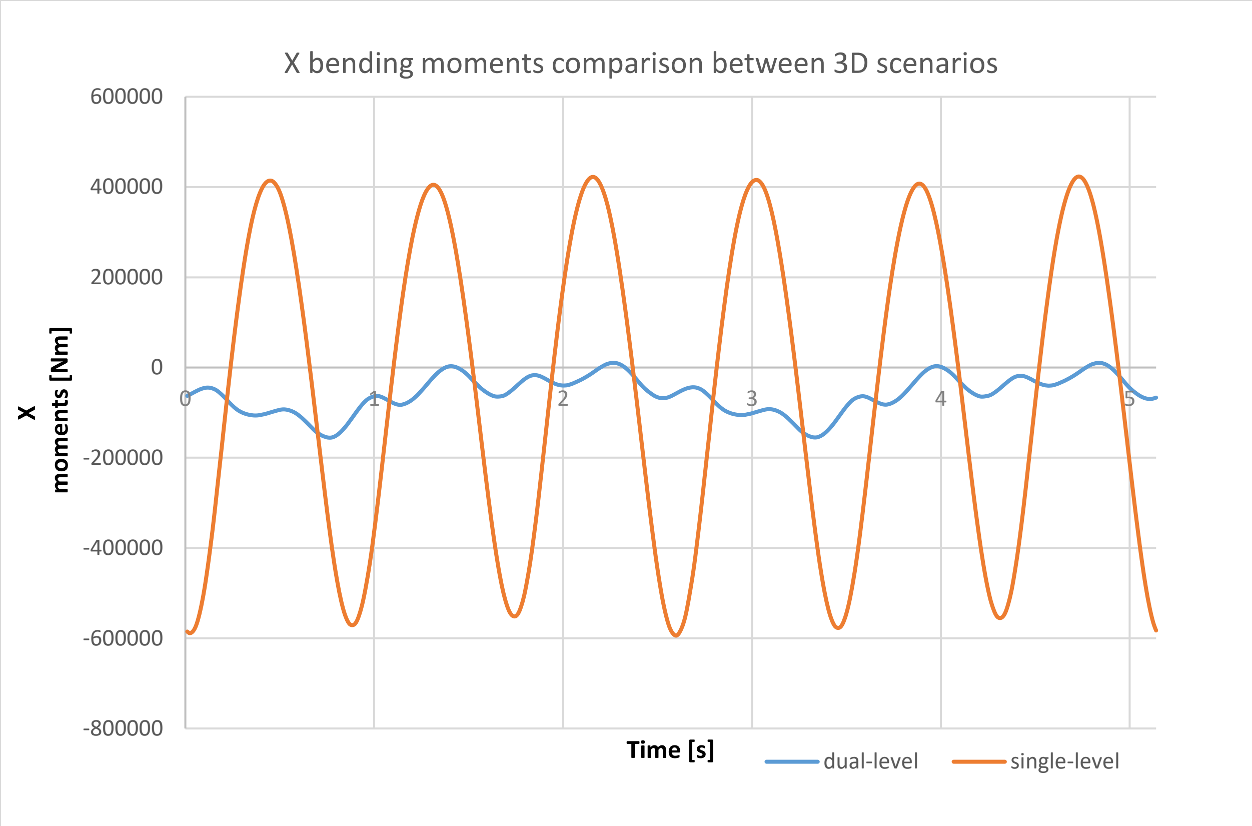

Figure 11. X-bending moments comparison between 3D scenarios

Figure 11 shows the X-bending moments at the bottom of the rotor shaft, generated due to lift. Compared to the single-level scenario, in the dual-level scenario the maximum positive X-moment values within a cycle are limited by 97.5%, the maximum negative X-moment values within a cycle are limited by 73.6%, while the X-moment amplitude is limited by 83.6%. Finally, in the dual-level scenario, the maximum total moments at the bottom of the rotor shaft are limited by 20.6%, while the total moment amplitude is limited by 87.4%.

5. Conclusions

In the laboratory scale model the lift-based bending moment component at the bottom of the turbine shaft became lost and unmeasurable among the measurement noise and a very unfavorable lift to drag ratio of the NACA0018 airfoil at low Reynolds numbers. Within the simulations, the 2.4 million to 4 million Reynolds numbers were much more advantageous in terms of airfoil lift to drag ratios resulting in a lift component taking a more distinct role in total bending moment values at the bottom of the rotor shaft. The influence of the lift based component on total moments is much lower than the Y-component even in the large scale simulation, resulting in a small increase of maximum total moment value limiting, and a slight decrease in limiting the total amplitude within a cycle. Both the experimental testing and large-scale CFD validation offered very high levels of reduction of bending moments at the bottom of the turbine shaft, proportional to cyclic loading values. The obtained results, along with prior tests, yield a high probability of the concept being applicable in creating reliable, sleeker and more cost-efficient designs than previously exploited. Further validating those assumptions with mid-scale environmental testing and a mechanical analysis of all relevant turbine elements is planned as the next research step within the topic.

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