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Design of a Wind Turbine Swept Blade Through Extensive Load Analysis

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Abstract

The main focus of this work is to offer an extensive investigation regarding the use of backward swept blades for passive load alleviation on wind turbines. Sweeping blades backward produces a structural coupling between flapwise bending towards the tower and torsion towards feathering. This coupling mitigates loads on the wind turbine structure due to a decrease in the angle of attack. The load alleviation can be achieved by changing the blade geometry according to three parameters: starting point for the change of shape along the blade span, blade tip sweep, and blade forward sweep. A parametric study is carried out on a 10 MW wind turbine with the purpose of outlining the relation between load variations and three geometric parameters used to introduce passive control on wind turbine blades. The objective is to estimate and analyze extreme and fatigue loads, formulating suggestions for the design of a wind turbine that employs backward swept blades. From the investigation, it is concluded that mildly and purely backward swept shapes are the best option because they allow the wind turbine to achieve load alleviations without a large increase of the blade root torsional extreme and life-time equivalent fatigue moment. The efficacy of the design procedure provided with this work is proved through its application on a 5 MW wind turbine design.

Keywords: Wind Energy, Blade Design, Passive Load Alleviation

1. Introduction

1 Reducing the cost of energy is a key concern for wind energy research and the ultimate goal
2 for both academia and industry. An effective path to achieve this goal is to manufacture
3 components that are lighter as the wind turbines capacities and dimensions increase [1].
4 According to “The Economics of Wind Energy” [2], the rotor blades of a 5 MW onshore
5 wind turbine contribute to the overall turbine cost with a share between 20 and 25%. For
6 this reason, blade manufactures have taken up the challenge to scale down the increase in
7 total mass of the blades, when designing and manufacturing rotors with increasing energy
8 yield. In this context, the capability to mitigate loads on the structure during operation
9 becomes an attractive characteristic for the design of modern wind turbine blades [3]. To
10

11 this end, different techniques have been exploited in the last two decades to achieve load
12 reduction on wind turbines, and they can be generally categorized in two branches: ac-
13 tive and passive control methods. The first consists of technologies able to reduce loads
14 by actively controlling the machine, e.g. blade pitch actuators [4], moving flaps [5], etc.
15 The second is based on the idea of designing a structure that, without any additional
16 components, deforms so as to induce a load reduction when it is loaded [6]. The work
17 presented in this paper focuses only on passive control methodologies and, in particular,
18 on the employment of swept blades. Sweeping blades backwards is considered a load al-
19 leviation technique. This methodology produces a structural coupling between flapwise
20 bending towards the tower and torsion towards feathering. This coupling mitigates loads
21 on the wind turbine structure due to a decrease in the angle of attack. Opposite effect is
22 obtained sweeping the blade forward. For this reason, purely forward swept shapes are not
23 taken into account in this work.

24 In the last two decades, several studies, both numerical and experimental, were conducted
25 to show the potential of swept blades. The most complete study on the subject is called
26 Sweep-Twist Adaptive Rotor Blade (STAR) and it was conducted by the Knight & Craver
27 Wind Group in the SANDIA National Laboratories between 2004 and 2010 [7, 8, 9]. The
28 project started after two feasibility studies: one by Ashwill et al. [10] and the other by
29 Zuteck [11]. The STAR constitutes a complete study for swept blades involving aeroelastic
30 simulations, manufacturing, and testing. The project showed that a swept-bladed turbine,
31 with a wider rotor area compared to a straight-bladed baseline, increases the amount of
32 annual energy captured undergoing similar or higher flapwise root bending moments. The
33 implementation of this passive control methods and their potential on multi-mega watt
34 wind turbines was not investigated. Parametric and conceptual studies were carried, but a
35 full overview of the relation between different geometric parameters for the blade planform
36 shape and load alleviations is missing. On a final note, the project cannot provide a "fair"
37 comparison between the swept-bladed turbine and the baseline machine because of the
38 substantial difference in rotor diameter and blade aeroelastic properties.

39 A detailed parametric study involving geometric parameters for swept blades was con-
40 ducted by Verelst and Larsen [12]. This study is based on several swept blade configura-
41 tions involving variations on both sweep curvature and sweep offset at the tip. The authors
42 showed that flapwise fatigue and extreme loads can be reduced up to 10% and 15%, re-
43 spectively, for a backward swept blade, whereas the edgewise fatigue and extreme loads
44 can increase up to 6%. Verelst and Larsen also mapped the blade root torsional moment,
45 which registered an increase up to 400%. This parametric study is based on a simple load
46 case (10-minute time series with fixed turbulence intensity of 0.18 and no wind shear), and
47 it does not consider a full design load basis (DLB). Consequently, the work can provide
48 only a rough estimation of load variations brought by the employment of swept blades.
49 Instead, a load analysis based on full a DLB would have allowed observations focused on
50 standard requirements for wind turbine design. Furthermore, Verelst and Larsen do not
51 apply any method to compensate the loss in AEP below rated wind speed, and they do
52 not take into account the interaction between the employment of swept blades and the
53 dynamics of the pitch controller.

54 Hansen [13] investigated aeroelastic properties of backward swept blades, computing fre-
55 quencies, damping, and mode shapes of the aeroelastic blade modes. The aeroelastic
56 properties of backward swept blades were deeply investigated, but only a quality estima-
57 tion of the load alleviations brought by the employment of geometric bend-twist coupling
58 is provided.

59 Previous studies proved the potential for load alleviation of wind turbines that employ
60 backward swept blades. The focus of the current numerical study is to investigate the
61 design of swept blades through an extensive load analysis based on standard requirements
62 for wind turbines construction and operation. The changes in blade geometry are classified
63 through three parameters: location of the first control point of the Bezier polynomial used
64 to implement the swept shapes, maximum blade tip backward sweep, and blade forward
65 sweep. To ensure a "fair" comparison based on passive-controlled wind turbines with sim-
66 ilar AEP and controller dynamics comparable to the baseline, the first part of this study
67 is a pre-processing phase involving aero-servo-elastic modal analysis for controller tuning
68 and aerodynamic twist optimization. Subsequently, a DLB is carried with the purpose of
69 obtaining extreme and fatigue loads used for a realistic wind turbine design. The trends
70 associated to the loading due to the variation of each geometric parameter are analyzed.
71 The general observations provided are applied to the NREL 5 MW RWT [14] to prove the
72 efficacy of the proposed extensive-load-analysis approach.

73 In the paper, the first section describes the parametric study architecture including details
74 of the geometric parameters used and the workflow that each blade design is subject to.
75 An extensive load analysis and a discussion of the results obtained through the parametric
76 study follows in the next section. The last part of the paper is the application of the
77 outcome of the parametric study on a different blade design, specifically, the blade of the
78 NREL 5 MW RWT.

79 **2. Parametric Study Architecture**

80 This section shows the architecture of the parametric study, starting with a description
81 of the different blade geometries considered. A detailed explanation of the models used is
82 provided. At last, a description of the workflow and the DLB used are reported.

83 *2.1. Swept Blades Shapes and Geometric Parameters*

84 The blade shapes are obtained using Bezier polynomials [15], which provide the necessary
85 flexibility to obtain the desired backward swept geometries. The control points for the
86 polynomials are placed to avoid curves with very large sweep angles.

87 Three parameters are selected to describe the shape of the swept blades. Each of these
88 parameters is associated to a letter (s , b or f) and a sequence of numbers having three (in
89 this case, all three digits represent the integer part of the number) or four digits (three
90 digits for the integer part and one for the fractional). The cataloguing system helps the
91 classification of each blade shape, which can be described through a mix of three letters
92 and three numbers representing the combination of the three parameters. The parameters
93 are described as follows:

- 94 • *sxxx*: location of the first control point on the centerline; it roughly describes the
- 95 spanwise length where the sweep starts;
- 96 • *bxxxx*: backward sweep at the tip in percentage of the total blade length;
- 97 • *fxxxx*: maximum forward sweep in percentage of the total blade length.

98 For example, the swept blade classified as *s080-b0025-f0005* has a shape where the sweep
 99 starts approximately at 80% of the blade length from the blade root, the backward sweep
 100 at the tip is 2.5%, and the maximum forward sweep is 0.5% of the total blade length.

101 The parametric study involves a total of 25 blade geometries, divided according to the
 102 spanwise location where the first control point for the polynomial is placed. The considered
 103 swept shapes are listed as follows:

- 104 • Family 1, the first control point for the Bezier function is placed on the pitch axis at
- 105 25% of the total blade length from the blade root;
- 106 • Family 2, the first control point for the Bezier function is placed on the pitch axis at
- 107 50% of the total blade length from the blade root;
- 108 • Family 3, the first control point for the Bezier function is placed on the pitch axis at
- 109 80% of the total blade length from the blade root;
- 110 • Family 4, the first control point for the Bezier function is placed on the pitch axis at
- 111 90% of the total blade length from the blade root;
- 112 • Family 5, the shapes are characterized by a different location of the maximum forward
- 113 sweep along the blade span.

114 The only exception is the last family of shapes (Family 5), where the geometries are selected
 115 varying the location of the maximum forward swept part. Family 5 is included in the study
 116 to investigate whether the location of the maximum forward sweep has an influence on the
 117 variation of the blade root torsional moment.

118 Figure 1 shows a sample of shapes that belongs to the Family 1, where the x-coordinate of
 119 the centerline are specified according to the coordinate system defined in the aeroelastic
 120 software HAWC2 [16].

121 *2.2. Numerical Tools and Models Descriptions*

122 In this work, linear and nonlinear models are implemented. Linear models are used in the
 123 pre-processing phase for the tuning of the controller of the swept-bladed wind turbines,
 124 and for the aerodynamic twist optimization needed to compensate the loss in AEP (see
 125 the next section for detailed explanations). The nonlinear models are used to perform the
 126 extensive load analysis that represents the core of the study.

127 Specifically, linear models are implemented in HAWCStab2 [17] and used for both closed-
 128 loop aero-servo-elastic eigenvalue analysis and aerodynamic twist optimization. The latter

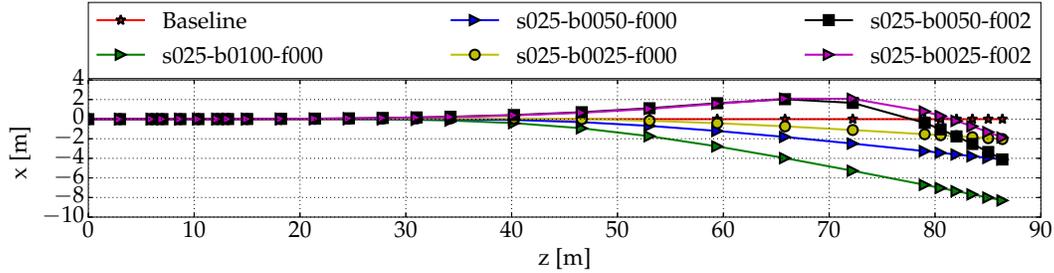


Figure 1: Backward swept shapes of Family 1. z is the coordinate along the blade centerline, whereas x is the coordinate oriented in the edgewise direction. The first control point is located at 25% span of the total blade length.

129 is carried out in the multi-disciplinary wind turbine analysis and optimization tool HAW-
 130 TOpt2 [18, 19, 20, 21]. A detailed description of the HAWCStab2 architecture is provided
 131 by Hansen [13], and its validation can be found in [22]. A full description of the HAWTOpt2
 132 framework and its application on aeroelastic optimization of a wind turbine is provided
 133 in [23].

134 The nonlinear models are implemented in the time-domain aero-servo-elastic code HAWC2
 135 [16]. The description and the validation of the multi-body formulation used by the struc-
 136 tural part of HAWC2 are reported in [24]. The validation of the unsteady BEM method
 137 used by the program can be found in [25, 26, 27].

138 The DTU 10 MW RWT [28] coupled with the Basic DTU Wind Energy Controller [29] are
 139 used as the baseline turbine.

140 2.3. Workflow and Simulations Set-Up

141 Two negative effects are associated with backward swept blades:

- 142 • due to the geometric structural coupling, turbines with backward swept blades have a
 143 lower AEP compared to a turbine with a straight-bladed rotor because of the decrease
 144 in the angle of attack along the blade span during operation [30];
- 145 • due to the changes in the structural and aerodynamic response of the blade, i.e.
 146 bend-twist coupling effect and change in the angles of attack, respectively, frequencies
 147 and damping ratios of the speed regulator mode of turbines with swept blades are
 148 significantly different compared to a baseline with straight blades [31].

149 Each blade design is pre-processed to overcome these two undesired outcomes.

150 To compensate the loss of AEP below rated wind speed, the aerodynamic twist of each blade
 151 design selected is optimized using the HAWTOpt2 framework. The numerical optimization
 152 problem is defined as:

$$\begin{aligned}
 & \max_{\mathbf{x}_p(\beta)} f(\mathbf{x}_p(\beta), \mathbf{p}) \\
 & \text{s.t.} \quad \mathbf{g}(\mathbf{x}_p(\beta)) \leq \mathbf{0}
 \end{aligned} \tag{1}$$

153 The cost function f depends on a set of variable $\mathbf{x}_p(\beta)$ and a set of constant parameters
 154 \mathbf{p} . For this simple optimization, the design variables are exclusively the parameters that
 155 describe the aerodynamic twist of the blade β . A free form deformation spline (FFD)
 156 with 5 control points is used to parametrize the aerodynamic twist as a design variable.
 157 The parameters \mathbf{p} , including the blade planform, the layups of the blades, and the other
 158 components of the wind turbine, are kept constant throughout the optimization. The
 159 design variables are normalized, such that when they are equal to zero they correspond to
 160 the baseline value.

161 The cost function, defined in Equation 2, is subject to a set of nonlinear constraints \mathbf{g} .

$$f(\mathbf{x}_p(\beta), \mathbf{p}) = \frac{AEP(\mathbf{0}, \mathbf{p})}{AEP(\mathbf{x}_p(\beta), \mathbf{p})} \quad (2)$$

162 $AEP(\mathbf{0}, \mathbf{p})$ is the annual energy production of the baseline design.

163 The constraints \mathbf{g} include:

- 164 • the rotor thrust, so that the swept-bladed turbines cannot exceed the operational
 165 rotor thrust of the baseline;
- 166 • the operational lift coefficients that, along the blade span, are limited to avoid stall.

167 To face the second constraint, after the optimization loop, the controller of the turbines
 168 with swept blades is tuned. The tuning of the PI loop of the controller in Region 4 (con-
 169 stant power, torque, and rotational speed) is performed with a pole placement technique.
 170 HAWCStab2 is used to perform this tuning adopting a method documented in [32] and [33].
 171 The target damping ratio and the target frequency for the pole of the speed regulator mode
 172 at 12m s^{-1} are 70% and 0.1Hz, respectively, for all the wind turbines that take part to the
 173 parametric study. The frequency of the pole placement for the tuning is changed according
 174 to a procedure reported by the authors [31].

175 A description of the workflow is shown in Figure 2. On the left side of the figure, the tools
 176 and a summary of each step of the process are reported. On the right side, a description
 177 of the optimization loop explained above is shown.

178 Simulating the DTU DLB [34] for the design chosen is the last step of the parametric study
 179 workflow. The DTU 10 MW RWT was designed based on the IEC 61400-1 load basis [35],
 180 disregarding the controller dependent load cases. Therefore, the following modifications
 181 are made to the DTU DLB to have a load basis similar to the one used to design the
 182 baseline turbine:

- 183 • the controller dependent design load case DLC 2.2 is disregarded;
- 184 • the extreme values of the loading from DLC 1.1 are not determined using any statis-
 185 tical extrapolation because of the uncertainty related to the choice of an appropriate
 186 method; instead, the GL approach [36], which requires a partial safety factor of 1.35,
 187 is adopted.

188 Finally, a load analysis for each wind turbine configuration is carried. Extreme and life-
 189 time equivalent fatigue loads (LTEFL) for the blade root are analyzed, along with AEP

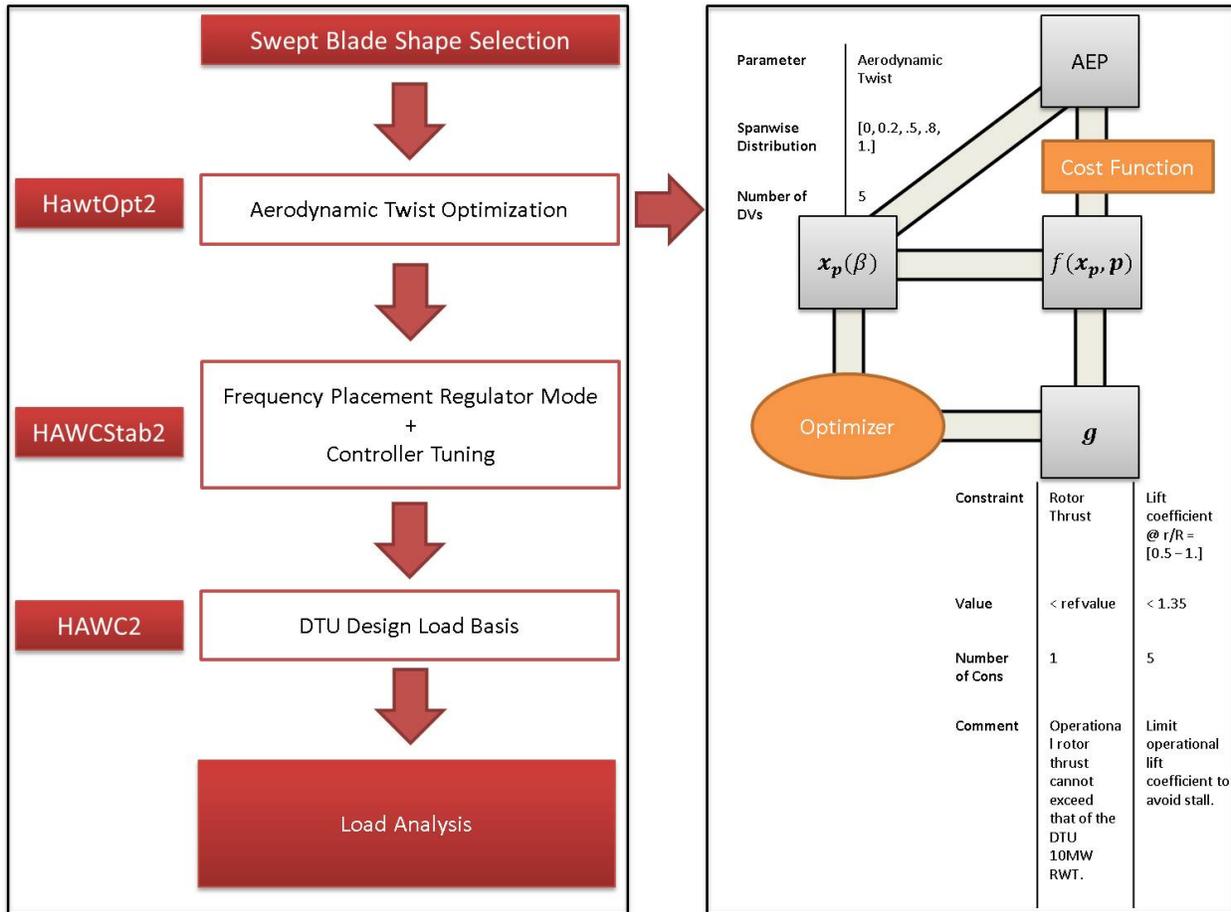


Figure 2: Description of the workflow. The tools and a summary of each step of the workflow are listed on the left side of the figure. On the right side, the optimization loop for the aerodynamic twist is shown.

190 and tower clearance. The trends associated with the variation of each of the geometric
 191 parameters are discussed in the next section, and conclusions on the design of backward
 192 swept blades are outlined.

193 3. Load Analysis Results

194 Numerical results from the load analysis depending on the swept geometries are reported
 195 and discussed in this section. In the first part of the section, the blade root extreme and
 196 fatigue loads are analyzed, with the purpose of investigating the impact of each geometric
 197 parameter of a swept blade. In the second part, AEP and tower clearance are analyzed.

198

199 3.1. Effects of the Location of the First Control Point, Parameter "sxxx"

200 The first geometric parameter analyzed is the first control point location along the center-
 201 line. This parameter is associated to the location along the blade span where the centerline

202 shape starts to change. To examine the impact of this parameter on the extreme loading,
 203 the blades with the tip swept backward by 2.5% of the total blade length, *b0025*, and
 204 with no forward sweep, *f0000*, are taken into account. Four backward swept blades are
 205 considered: *s025-b0025-f0000*, *s050-b0025-f0000*, *s080-b0025-f0000*, and *s090-b0025-f0000*.
 206 The blade centerline of each design chosen is shown in Figure 3.

207 Figure 4 shows the normalized absolute maximum blade root bending moment distribu-
 208 tions in the blade flapwise (left plot), edgewise (center plot), and torsional (right plot)
 209 direction, respectively. The distributions, shown in boxplots, include all the time-series
 210 considered in the DLB. To facilitate the comparisons, the loads are non-dimensionalized
 211 by the median of the respective baseline distribution. The lower edge of the blue box repre-
 212 sents the first quartile, whereas the upper edge is the third quartile. The whiskers delimit
 213 the 5th and the 95th percentiles, respectively. Blue crosses are the outliers. The width of
 214 the blue box (the interquartile range, IQR), the location of the whiskers ($1.8 \cdot \text{IQR}$), and
 215 the spread of the outliers give an estimation of the statistical dispersion of the distribution.
 216 The uppermost values, highlighted with a green dashed line in Figure 4, are the ultimate
 217 loads. The trend of these loads depends on the geometry of the blade selected. However,
 218 the ultimate loads are extracted from a single time-series, referring to a single point in the
 219 distribution shown in Figure 4. Hence, a comparison between ultimate loads from different
 220 designs is deterministic, and it does not take into account the stochastic nature of the
 221 turbulent load cases. For example, it is not possible to establish whether the variation on
 222 the ultimate loads is caused by the change in blade geometry or the fact that the rotor sees
 223 a different turbulence field due to the changed structural and aerodynamic responses or
 224 due to tuning of the controller. Therefore in this study, the analysis of the extreme loads
 225 is based on the comparison of distributions of the absolute maxima instead of the ultimate
 226 loads. Specifically, the extreme load analysis focuses on:

- 227 • the medians, which retain information concerning the probability of a certain design
 228 having higher or lower absolute maxima across the DLB compared to the baseline;
- 229 • the IQR, which provides information on the variability of the absolute maxima across
 230 the DLB.

231 In Figure 4, the median of the distribution is highlighted in red. The trend of the medians
 232 is described by a black dashed line.

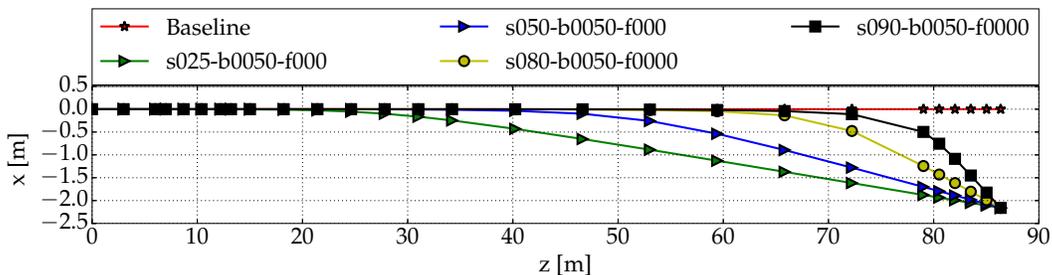


Figure 3: The four backward blade shapes chosen to study the location of the first control point parameter.

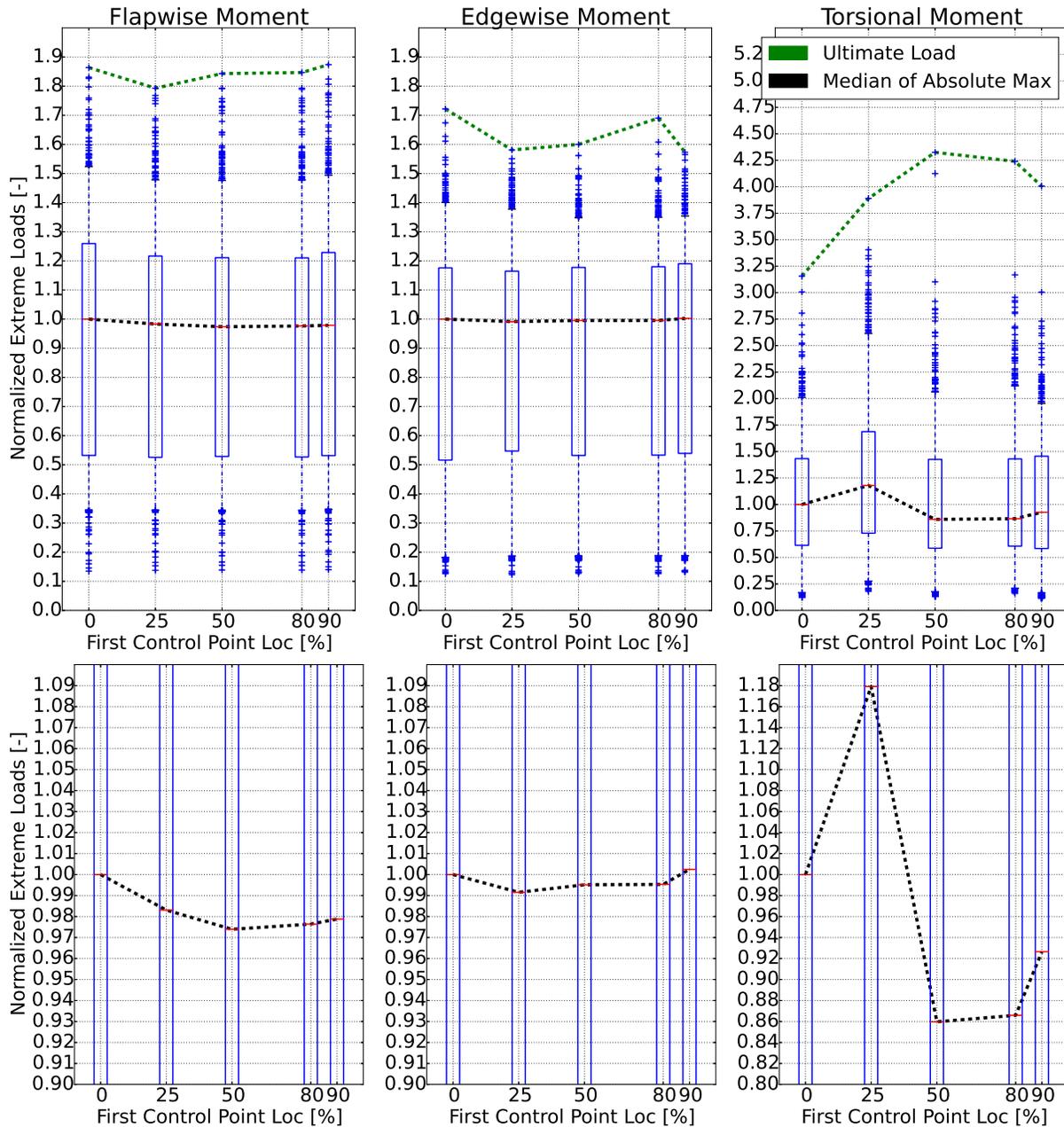


Figure 4: Normalized absolute maxima distributions for baseline and swept blades with ascending first control point location along the blade span. Extreme flapwise, edgewise, and torsional moments are plotted on the left, center, and right, respectively. Bottom plots show a close-up on the medians of the distributions. The loads are non-dimensionalized by the median of the respective baseline distribution.

233 One can notice the differences between the trend of the ultimate loads and the trend of
 234 the medians, especially for the extreme torsional blade root moment. To have a clear view
 235 on the medians, the boxes of the absolute maxima distribution are zoomed and reported
 236 in the bottom part of Figure 4.

237 The "aggressive" shapes, i.e. with a change in geometry closer to the root (*s025-b0025-*
 238 *f000* or *s050-b0025-f000*), have a higher flapwise load alleviation potential because a larger
 239 portion of the blade is affected by the change in geometry resulting in the bend-twist
 240 coupling. The median and the IQR of the flapwise blade root moments decreases for the
 241 *s025-b0050-f0000* and *s050-b0050-f0000*, but it gets closer to the baseline for the shapes
 242 that have the first control point close to the blade tip (see Figure 4, left plot). The decrease
 243 in IQR for the absolute maxima of the flapwise moment proves that the backward swept
 244 blades are able to reduce the peaks of the extreme blade root flapwise loads.
 245 The median and the IQR of the distributions of the blade root edgewise moment are not
 246 significantly changed compared to the baseline (see Figure 4, central plot). Furthermore,
 247 the variations of the medians in the edgewise direction are lower in value compared to the
 248 variations of the medians in the flapwise direction (compare bottom central and left plots
 249 of Figure 4). Therefore, the variation of the first control point location parameter does not
 250 affect the blade root edgewise extreme loads.
 251 As already shown in previous studies [9, 12], "aggressive" blade sweeps introduce the
 252 largest extreme blade root torsional moments. This effect is clearly shown in the right
 253 plot of Figure 4: the medians and the IQRs are getting larger for more "aggressive"
 254 swept blades compared to the baseline. The first control point location parameter has a
 255 consistent influence on the blade root torsional extreme loads. Different conclusions can be
 256 drawn looking at the ultimate torsional loads, where the most "aggressive" shape (*s050-*
 257 *b0025-f000*) has the lowest ultimate torsional load. The latter observation highlights the
 258 importance of comparing extreme loads distribution instead of analyzing ultimate loads.
 259 To investigate the impact of the parameter "sxxx" on LTEFL, a different set of four
 260 backward swept blades, with the blade tip swept backward is fixed at 5.0 %, is considered
 261 (see Figure 5): *s025-b0050-f0000*, *s050-b0050-f0000*, *s080-b0050-f0000*, and *s090-b0050-*
 262 *f0000*. In this study, the computation of the life time equivalent fatigue loads is based on
 263 a life-time of 20 years.

264 Figure 6 shows the LTEFL blade root moments in the flapwise, edgewise, and torsional
 265 direction for the considered blade shapes shown in Figure 5. The flapwise LTEFLs (blue
 266 circle dashed line) for the all swept blades are lower than the baseline. The edgewise
 267 LTEFLs are increased for all the shapes analyzed (red triangle dashed line), as opposed to
 268 the flapwise cases. The increases for the edgewise LTEFLs are caused by the increment in

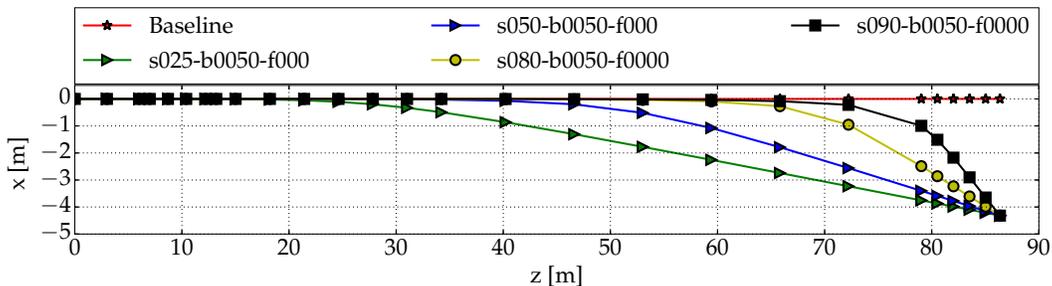


Figure 5: The four backward blade shapes chosen to study the location of the first control point parameter.

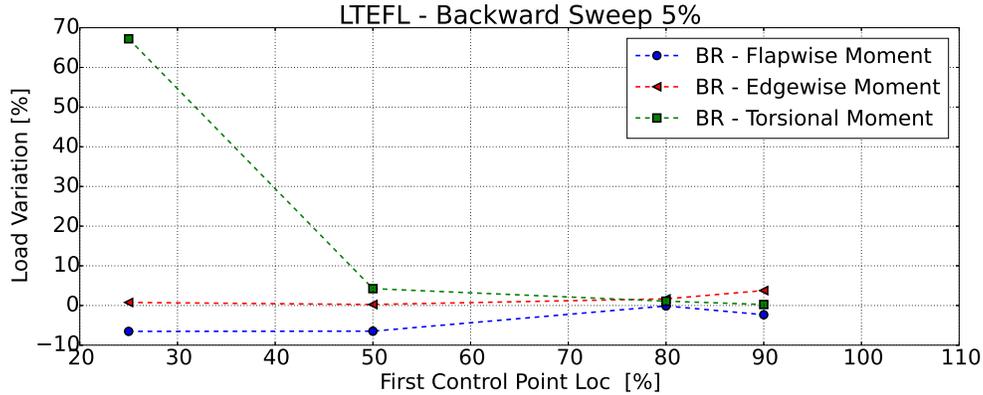


Figure 6: LTEFL blade root moments deviations in percentage from the baseline straight blade (blue circle - flapwise, red triangle - edgewise, green square - torsional). The backward sweep parameter at the tip is fixed at 5% of the blade length. No forward sweep is considered. Different blade radius along the span are taken into account.

269 the total mass of the backward swept blades because the swept blades are longer than the
 270 baseline. The increase in curvilinear length results in more materials added, producing a
 271 design heavier than the baseline blade. An overview of the blade mass increase for all the
 272 designs analyzed with respect to the baseline is reported in Table 1. Table 1 shows that
 273 the *s090-b0050-f0000* has the largest increase in blade mass (1.22%) between the shapes
 274 selected and, consequently, the largest increase in edgewise LTEFL (approximately 3%).
 275 The trend of the torsional LTEFL (green square dashed line) is similar to the one observed
 276 for the medians of the extreme loads distributions in Figure 4, right plot. The highest
 277 torsional LTEFL is observed from the most "aggressive" shape, *s025-b0050-f0000* blade
 278 (approximately 68% LTEFL increase).

279 In conclusion, the main problem with the choice of the first control point location parameter
 280 to design an effective backward swept blade is the large increase in extreme and fatigue
 281 blade root torsional moments. Blade shapes that have a change in geometry that starts
 282 closer to the root are longer and heavier than the others and, consequently, present an
 283 increase of the edgewise LTEFL.

284 3.2. Effects of Maximum Blade Tip Backward Sweep, Parameter "bxxxx"

285 The second parameter considered is the maximum blade tip backward sweep, "bxxxx".
 286 The other two parameters, "sxxx" and "fxxxx", are fixed to 80 and 0, respectively. Figure
 287 7 shows the considered swept blade geometries, that can be categorized as Family 3.
 288 The absolute maximum load distributions of the considered swept blade geometries are
 289 reported in Figure 8. In the figure, the medians and the IQRs of the flapwise bending mo-
 290 ments for the swept blades show a marginal load alleviation effect. The edgewise moment
 291 distributions are substantially unchanged, even though it appears that larger sweeps in-
 292 crease the medians due to the total weight increment (see Table 1). Moreover, as shown in
 293 Figure 8 on the right plot, increasing the maximum backward sweep at the tip of the blade
 294 produces higher medians and IQRs on the absolute maxima distributions of the blade root

Table 1: Blade total mass variations for the designs analyzed. The baseline blade mass is reported in the second row of the table. The swept blades mass are reported as variation in percentage with respect to the baseline. The identification sequence for the swept blades is reported in the first column.

Shape	Blade Mass
BASELINE	41716 [kg]
s025-b0025-f000	0.2 [%]
s025-b0025-f002	0.9 [%]
s025-b0050-f000	0.3 [%]
s025-b0050-f002	1.6 [%]
s025-b0100-f000	1.0 [%]
s050-b0025-f000	0.2 [%]
s050-b0025-f002	1.0 [%]
s050-b0050-f000	0.5 [%]
s050-b0050-f002	2.0 [%]
s050-b0100-f000	1.5 [%]
s080-b0010-f0005	0.3 [%]
s080-b0025-f0000	0.2 [%]
s080-b0025-f0005	0.6 [%]
s080-b0050-f0000	0.5 [%]
s080-b0100-f0000	1.7 [%]
s090-b0005-f0000	0.1 [%]
s090-b0005-f0002	0.2 [%]
s090-b0010-f0000	0.2 [%]
s090-b0025-f0000	0.4 [%]
s090-b0050-f0000	1.2 [%]
spe1-b0008-f0005	0.2 [%]
spe2-b0010-f0005	0.2 [%]
spe3-b0010-f0005	0.2 [%]
spe4-b0008-f0005	0.2 [%]
spe5-b0005-f0002	0.1 [%]

295 torsional moment.

296 Figure 9 shows the blade root LTEFLs. As the blade tip backward sweep increases, 1) the
 297 flapwise LTEFLs are reduced due to the higher load alleviation effect brought by larger
 298 sweeps, 2) the edgewise LTEFLs are increased due to increment of the total blade weight,
 299 and 3) the torsional LTEFLs are increased due to the increasing torque except the *s080-*
 300 *b0025-f0000*. In the latter case, the decrease in blade root torsional fatigue loading, not
 301 typical for backward swept blades, can be explained as a consequence of the annual energy
 302 production maximization and the change in aerodynamic twist.

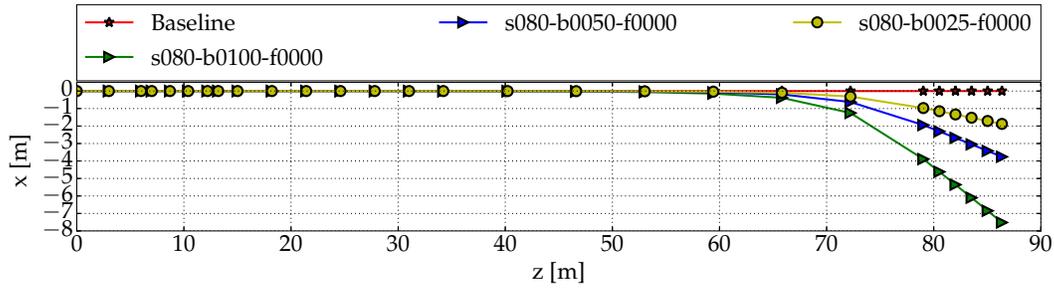


Figure 7: Swept blade shapes of Family 3. First control point for the Bezier polynomial is located on the pitch axis at 80% of the total blade length.

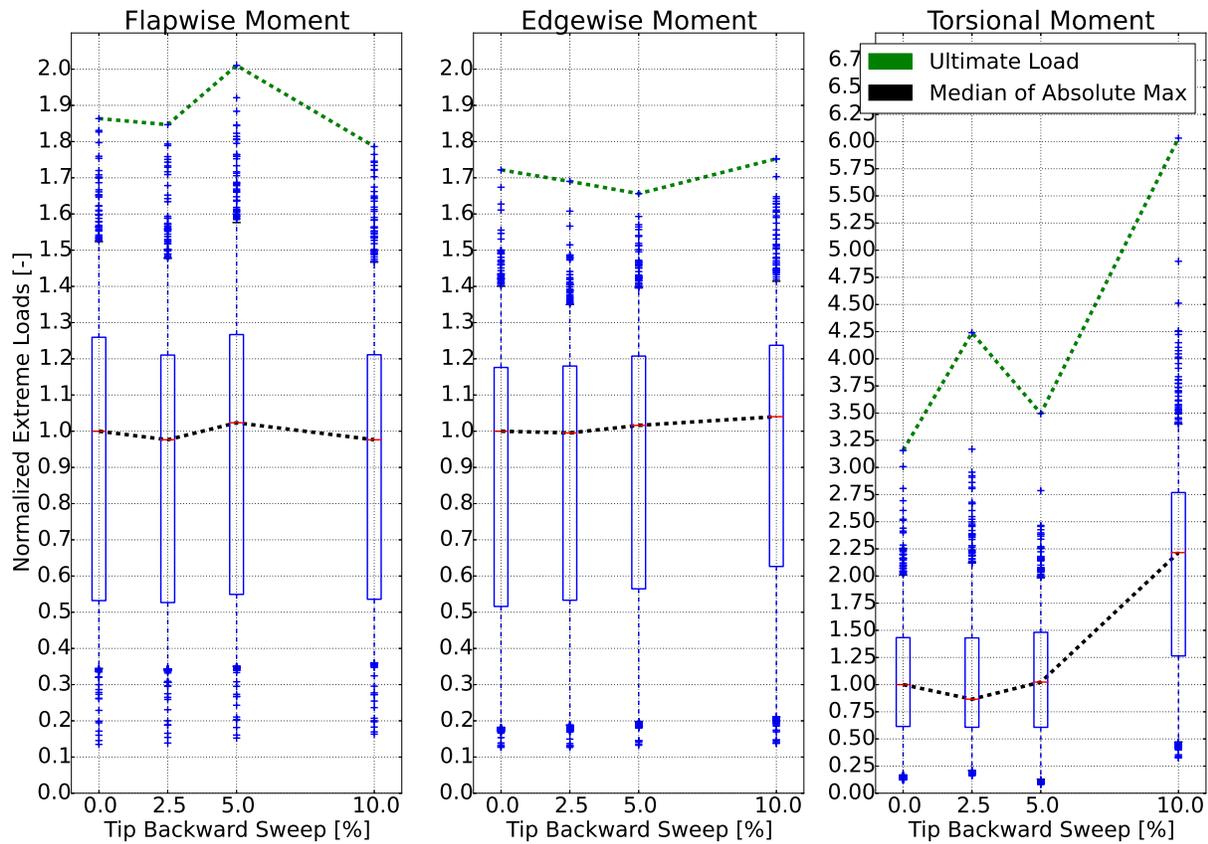


Figure 8: Normalized absolute maxima distributions for baseline and swept blades with increasing maximum backward sweep at the tip. Extreme flapwise, edgewise, and torsional moments are plotted on the left, center, and right, respectively. The loads are non-dimensionalized by the median of the respective baseline distribution.

303 The variation of the optimized twist along the blade span affects the distribution of the
 304 loading. For very mild swept shapes and very large variations of the aerodynamic twist
 305 (see the red curve in Figure 10, where the largest variation of the twist is around 5°), it
 306 is possible to obtain a design that shows alleviations for both flapwise and torsional blade

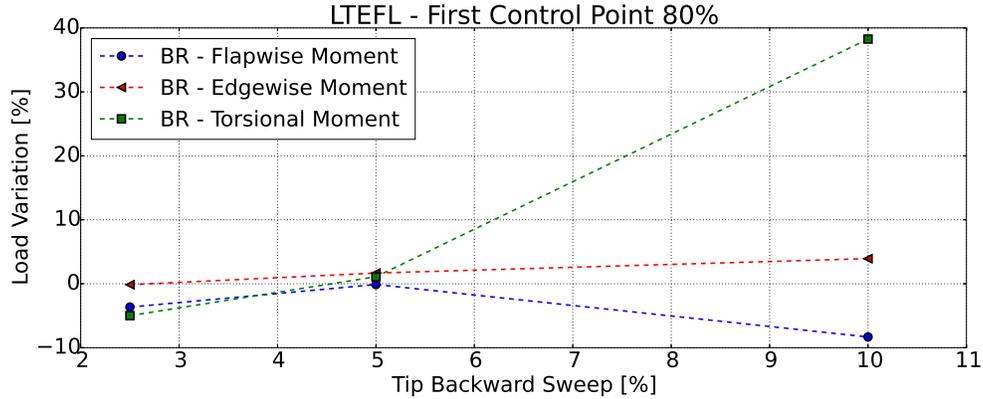


Figure 9: Life Time Equivalent Fatigue Load blade root moments deviations in percentage from the baseline straight blade (blue circle - flapwise, red triangle - edgewise, green square - torsional). All the shapes belong to Family 3. No forward sweep is considered. The variation of the amount of backward sweep at the blade tip is taken into account.

307 root fatigue loads. This property is difficult to exploit through a parametric study, and it
 308 will be the subject of future work. Very large variations of the aerodynamic twist can also
 309 have an impact on the flapwise load alleviation potential of some designs. For example,
 310 the design *s080-b0050-f0000* shows no extreme and LTEF load alleviations compared to
 311 the baseline, the *s080-b0025-f0000*, and the *s080-b0100-f0000* (see Figures 8 and 9). The
 312 distribution of the flapwise loading is heavily affected by a large variation of the optimized
 313 aerodynamic twist, which shows an absolute difference of 7° at the tip compared to the
 314 baseline (see the green curve in Figure 8). The changes in the distribution of the flapwise

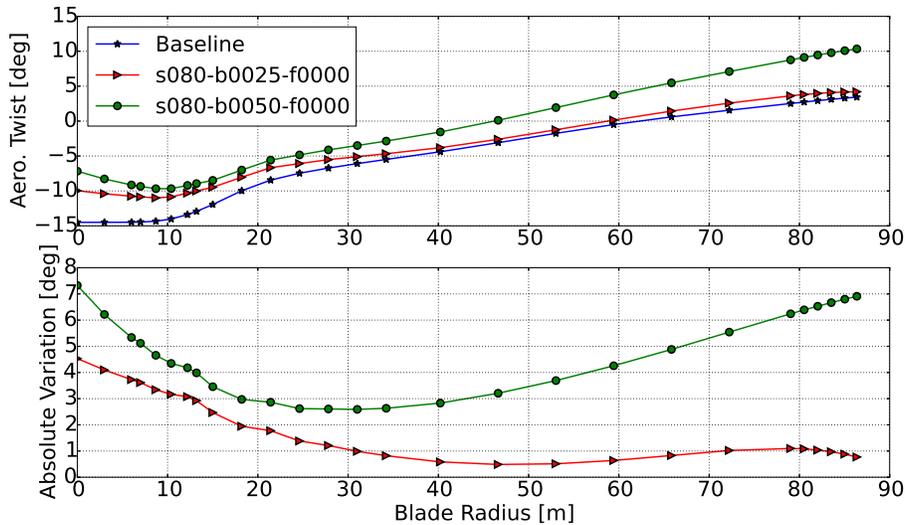


Figure 10: Comparison of the aerodynamic twist of two blades: Baseline (blue star) and *s080-b0025-f0000* (red triangle). Top plot shows the aerodynamic twist in degree, while the bottom one shows the absolute value of the variation of the twist of the two swept blades with respect to the baseline blade.

loading along the blade span have also an effect on the tower clearance. The latter problem is discussed in details in Section 3.4.

Conclusions regarding the analysis of the blade tip backward sweep parameter are similar to the ones reported in the previous section: the parameter has to be chosen considering the minimum increase in torsional extreme and fatigue loading, and taking into account the increase in blade mass due to the increment in blade length brought by the swept shape. Furthermore, it is important to consider that the aerodynamic twist optimization has an impact on the distribution on the aerodynamic loading along the blade span, which can result in a reduction of the blade root torsional moment. Future studies will be carried on the possibility of generating a design that shows alleviations for both flapwise and torsional blade root fatigue loads, as in the case of *s080-b0025-f0000*. Large variations of the optimized aerodynamic twist can also result in blade designs that show no load alleviation potentials in the flapwise direction.

3.3. Effects of Blade Forward Sweep, Parameter "fxxx"

The last parameter considered is the presence of forward sweep and its location on a swept blade, "fxxx". For this purpose, two swept blade shape families, Family 1 and Family 5, are used (see Figures 1 and 11). The main reason to implement the forward sweep on a backward swept blade is to reduce the large torsional moment at the root.

Figure 12 shows the extreme blade root moment distributions for the shapes of Family 1 where the forward swept blades (*s025-b0025-f002* and *s025-b0050-f002*) are illustrated with red color.

In general, the inclusion of forward sweep in the backward sweep jeopardizes the load alleviation effect on the extreme flapwise loading (compare medians of the blue and red boxes of the left plot of Figure 12). The reason for this negative outcome lies behind the passive control mechanism used by swept blades. The benefits come from the increase in torsion along the blade length, and the consequent increase in twist towards feather to reduce the angle of attack. The efficacy of this mechanism is reduced if the shape is more "balanced" with a forward sweep. Moreover, the blades with forward sweep are longer and heavier than the respective purely swept shapes, generating an increase in extreme edgewise blade root loading (see medians of the red boxes of the central plot of Figure 12). The torsional

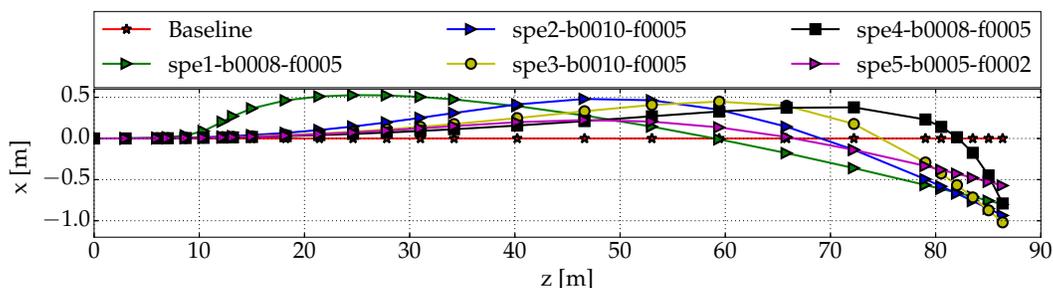


Figure 11: Swept blade shapes of Family 5. Special set of shapes characterized by different locations of the forward swept portion of the blade.

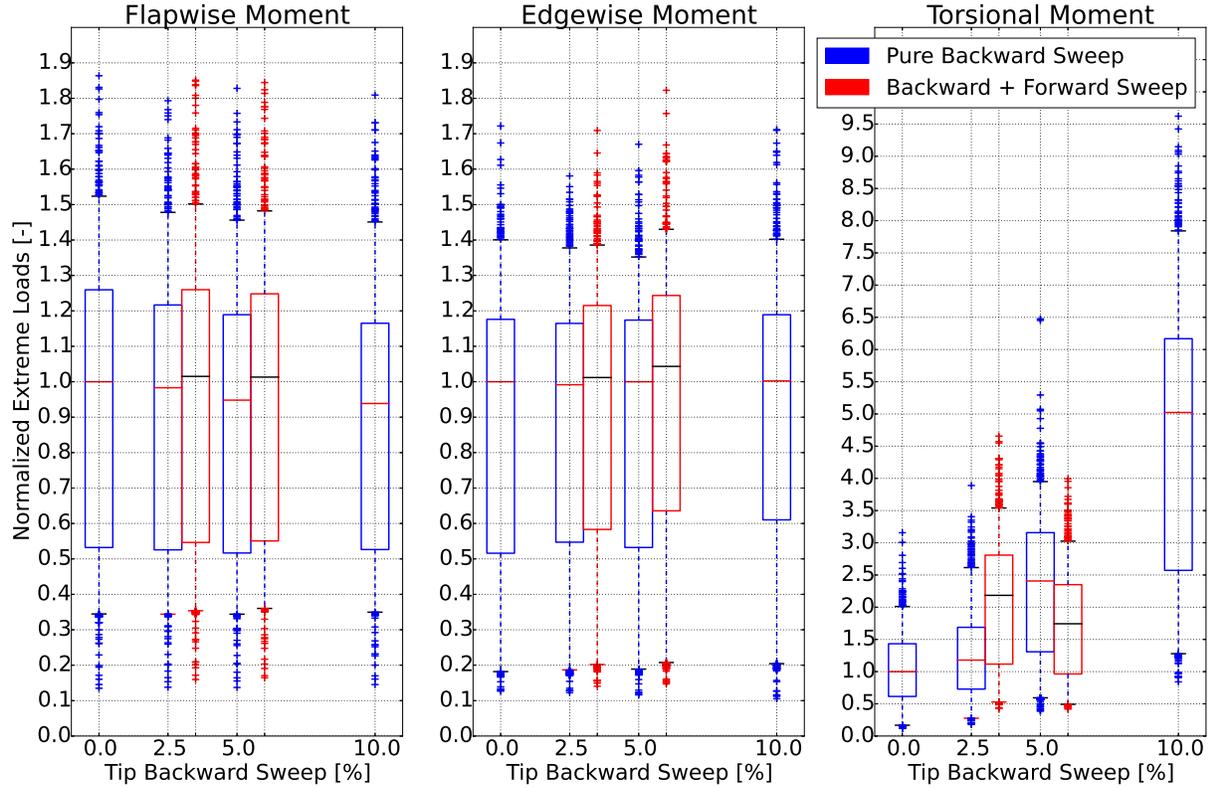


Figure 12: Normalized absolute maxima distributions for baseline and swept blades of Family 1. Extreme flapwise, edgewise, and torsional moments plotted on the left, center, and right, respectively. The loads are non-dimensionalized by the median of the respective baseline distribution. Purely backward swept shapes are denoted using the blue colour. The shapes with forward sweep are highlighted in red.

345 moments are also affected by the forward sweep. The right plot in Figure 12 shows that
 346 the median and the IQRs can be reduced compared to the purely swept back blades (*s025-*
 347 *b0050-f000* and *s025-b0050-f002*).

348 Figures 13 and 14 show the blade root extreme and LTEFLs for the shapes of Family 5,
 349 respectively. The analysis of these figures is focused on the understanding of the impact
 350 that changing the location of the forward sweep has on the blade root loads.

351 The blade root flapwise extreme loads and LTEFLs are reduced, even though substantial
 352 forward sweep variations are introduced. The amount of LTEFL reductions is lower com-
 353 pared to the alleviations achieved varying the other two geometric parameters, "sxxx" and
 354 "bxxxx". The blade edgewise extreme loads and LTEFLs are not significantly affected
 355 by the forward sweep because the variation of blade mass for the shapes of Family 5 is
 356 very limited, as shown in Table 1. The torsional extreme and LTEFLs are increased for
 357 all cases, as shown on one side by the medians of the absolute maxima distributions (see
 358 Figure 13, right plot), and on the other side by peaks between approximately 13 and 17%
 359 for the LTEFL (see Figure 14). The amount of the increment is not significant compared
 360 to the previous geometric parameters variations analyzed (see Figures 4, 6, 8, and 9).

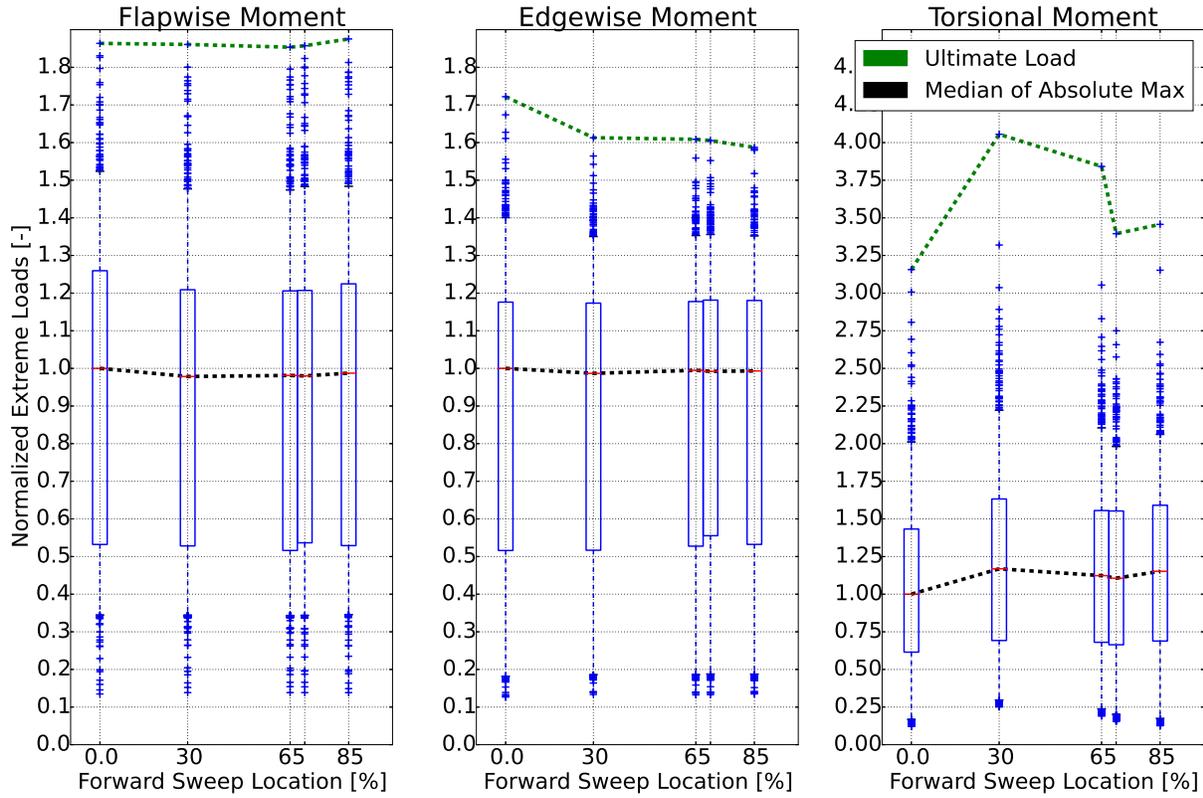


Figure 13: Normalized absolute maxima distributions for baseline and swept blades of Family 5. The loads are non-dimensionalized by the median of the respective baseline distribution.

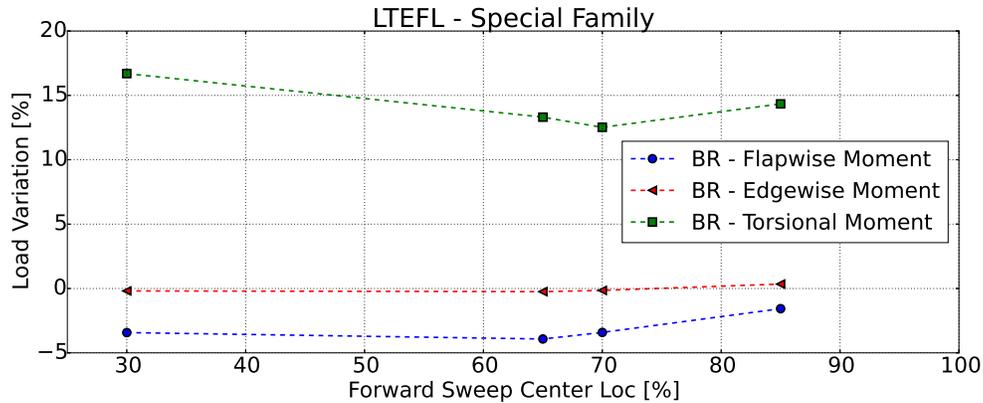


Figure 14: Life Time Equivalent Fatigue Load blade root moments blade root moments deviations in percentage from the baseline straight blade (blue - flapwise, red - edgewise, green - torsional). All the shapes belong to Family 5. Load variations from the baseline are plotted against the location of the forward sweep.

361 The conclusion is that there is a benefit in introducing forward sweep on backward swept
 362 blades. The blade torsional extreme loads and LTEFLs can be less affected by the back-
 363 ward sweep. On the other hand, the load alleviation benefits for the blade flapwise extreme

364 loads and LTEFLs are reduced due to the forward sweep.

365 *3.4. AEP and Tower Clearance*

366 The annual energy production (AEP) and the tower clearance of all considered swept blades
 367 are reported in this section. Table 2 shows the AEP and the tower clearance in percent
 368 difference from the baseline values.

369 The AEP of the backward-swept-bladed turbines are kept very close to the baseline value

Table 2: AEP and tower clearance of the blade designs analyzed. The identification sequence for the swept blades is reported in the first column. The tower clearance results include also the identification sequence for the simulation that showed the minimum tower clearance: "dlc" denotes the Design Load Case, "wsp" the wind speed, "wdir" the wind direction and "s" the turbulence seed realization. The tower clearance takes into account the safety factors assigned by the DLB used.

Shape	AEP	Tower Clearance
BASELINE	48.497 [GW h]	dlc13 wsp12 wdir350 s3005 3.656 [m]
s025-b0025-f000	0.0 [%]	dlc13 wsp12 wdir350 s3005 4.5 [%]
s025-b0025-f002	0.5 [%]	dlc13 wsp12 wdir000 s1005 -4.8 [%]
s025-b0050-f000	-0.5 [%]	dlc13 wsp12 wdir350 s3005 6.0 [%]
s025-b0050-f002	0.8 [%]	dlc13 wsp14 wdir000 s2006 -7.3 [%]
s025-b0100-f000	0.5 [%]	dlc13 wsp12 wdir350 s3005 1.3 [%]
s050-b0025-f000	-0.2 [%]	dlc13 wsp12 wdir350 s3005 1.5 [%]
s050-b0025-f002	0.7 [%]	dlc13 wsp12 wdir350 s3005 -1.0 [%]
s050-b0050-f000	0.1 [%]	dlc13 wsp12 wdir350 s3005 -4.6 [%]
s050-b0050-f002	1.0 [%]	dlc13 wsp14 wdir000 s2006 -4.1 [%]
s050-b0100-f000	0.7 [%]	dlc13 wsp12 wdir350 s3005 -1.6 [%]
s080-b0010-f0005	0.8 [%]	dlc13 wsp12 wdir010 s6005 -9.3 [%]
s080-b0025-f0000	-0.2 [%]	dlc13 wsp12 wdir350 s3005 1.8 [%]
s080-b0025-f0005	0.5 [%]	dlc13 wsp12 wdir350 s3005 0.1 [%]
s080-b0050-f0000	0.9 [%]	dlc13 wsp12 wdir350 s3005 -10.1 [%]
s080-b0100-f0000	0.8 [%]	dlc13 wsp12 wdir350 s3005 -5.8 [%]
s090-b0005-f0000	-0.3 [%]	dlc13 wsp12 wdir350 s3005 -3.3 [%]
s090-b0005-f0002	-0.3 [%]	dlc13 wsp12 wdir350 s3005 -3.9 [%]
s090-b0010-f0000	-0.3 [%]	dlc13 wsp12 wdir350 s3005 -2.2 [%]
s090-b0025-f0000	0.0 [%]	dlc13 wsp12 wdir350 s3005 -2.7 [%]
s090-b0050-f0000	0.8 [%]	dlc13 wsp12 wdir350 s3005 -3.1 [%]
spe1-b0008-f0005	-0.3 [%]	dlc13 wsp12 wdir350 s3005 4.1 [%]
spe2-b0010-f0005	-0.3 [%]	dlc13 wsp12 wdir350 s3005 4.5 [%]
spe3-b0010-f0005	-0.2 [%]	dlc13 wsp12 wdir350 s3005 3.0 [%]
spe4-b0008-f0005	-0.2 [%]	dlc13 wsp12 wdir350 s3005 3.3 [%]
spe5-b0005-f0002	-0.4 [%]	dlc13 wsp12 wdir350 s3005 2.7 [%]

370 due to the aerodynamic twist optimization scheme implemented at the pre-processing phase
 371 (see Figure 2). The variations of AEP are always below 1%, and the drops for the turbines
 372 with worse performances are never greater than 0.5%.
 373 The tower clearance is calculated as the distance between the blade tip and the closest
 374 outer section of the tower. The measured tower clearance window is between 175° and
 375 185° azimuth, for a blade pointing upward at 0° azimuth. All the swept blade designs
 376 analyzed satisfy the requirement for tower clearance demanded by the IEC standard [35].
 377 The load alleviation effect brought by the sweep reduces the flapwise displacement of the
 378 tip. Consequently, a higher tower clearance is expected from all the turbines that takes
 379 part to the parametric study, but some of the designs show a substantial decrease of the
 380 minimum tower clearance. The reason lies behind the optimization process where the
 381 optimizer might need to significantly increase the aerodynamic twist at the blade tip to
 382 maximize the AEP, causing an increase in the angle of attack around rated wind speed. The
 383 change in angle of attack introduces higher loads at rated wind speed where the minimum
 384 tower clearance is registered. Figure 15 shows the aerodynamic twist distributions for two
 385 different swept blade cases and their comparison with the baseline design. On one hand,
 386 the *s080-b0050-f0000* blade (plotted in circle with green color) has a significant increase
 387 of the aerodynamic twist at the blade tip (approximately 7° at the blade tip, as shown
 388 in the bottom plot of Figure 15) which results in a decrease of the tower clearance of
 389 approximately 10%. On the other hand, the *s025-b0050-f000* blade design (plotted in
 390 triangle with red color) shows an increase of tower clearance of approximately 6% whereas
 391 the aerodynamic twist at the tip of the blade is not significantly increased (approximately
 392 1° at the blade tip shown in the bottom plot of Figure 15).

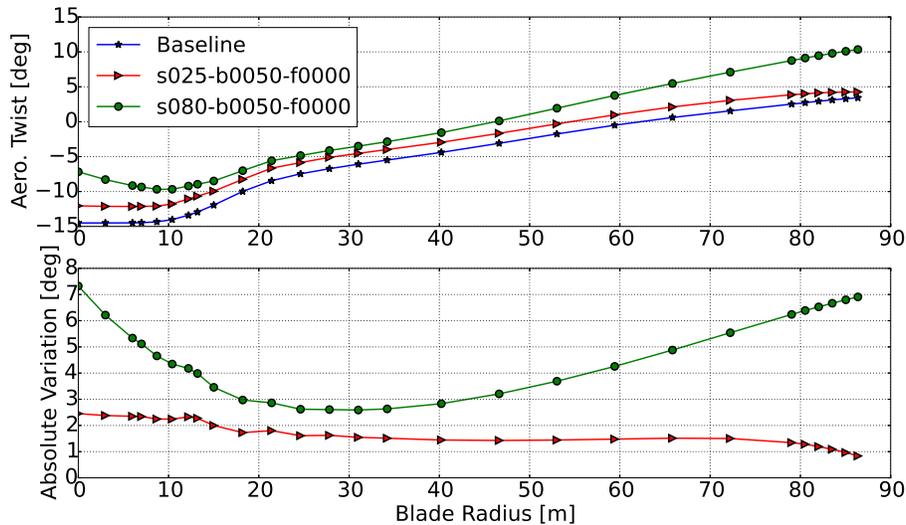


Figure 15: Comparison of the aerodynamic twist of three blades: Baseline (blue star), *s025-b0050-f000* (red triangle), and *s80-b0050-f0000* (green circle). Top plot shows the aerodynamic twist in degree, while the bottom one shows the absolute value of the variation of the twist of the two swept blades with respect to the baseline blade.

393 To keep or increase the tower clearance, the aerodynamic twist should be constrained
394 during the optimization. An alternative is to pitch the blade towards stall below rated
395 wind speed, to compensate for the reduction in the angle of attack generated by the
396 sweep [30]. The latter solution has the advantage of being less computationally expensive
397 than the optimization routine. Particular attention must be paid to avoid stall along the
398 blade span below rated wind speed.

399 **4. Swept Blade Design Application: the NREL 5MW RWT**

400 In this section, one of the obtained swept blade designs from the DTU 10 MW RWT is
401 applied to a different class turbine blade to verify its performances. In this study, the
402 NREL 5 MW RWT is used [14] with the Basic DTU Wind Energy Controller [29].

403 The *s080-b0025-f0000* backward swept blade is selected for this study based on the inves-
404 tigations made in the previous sections:

- 405 • avoid forward sweep in any part of the blade because it reduces (or completely elim-
406 inate) the load alleviation effect;
- 407 • let the backward sweep start closer to the blade tip (80% or 90% of the total blade
408 length) to avoid an excessive increase in blade root torsional moment;
- 409 • contain the maximum backward sweep at the tip within 5% of the total blade length
410 to avoid a very large blade root torsional moment;
- 411 • optimize the aerodynamic twist or pitch the blade towards stall below rated wind
412 speed to compensate the loss in AEP due to the decrease in the angle of attack; be
413 aware of the risks of the two strategies: the optimization of the aerodynamic twist
414 to maximize the AEP can increase the loading at the blade tip around rated wind
415 speed reducing the tower clearance; pitching the blade towards stall below rated wind
416 speed can drive part of the blade into stall.

417 The considered blade is pitched towards stall below rated wind speed to compensate the loss
418 in AEP compared to the baseline design. This approach is preferred to the aerodynamic
419 twist optimization because it does not have the negative impact on the tower clearance
420 described earlier, and it is computationally cheap.

421 The same design load cases based on [34] with the modifications reported in Section 2.3
422 are considered.

423 *4.1. AEP and Tower Clearance*

424 Table 3 shows the comparison of AEP and tower clearance between the baseline wind
425 turbine and the swept-bladed one. The passive-controlled wind turbine has approximately
426 the same annual energy production of the baseline, registering a very small loss of 0.04%.
427 An increase in tower clearance can be observed (3.5%).

Table 3: AEP and tower clearance of the NREL 5 MW RWT with straight and backward swept blades (*s080-b0025-f0000*). The AEP and tower clearance for the baseline blade are reported in the second row of the table. The tower clearance results include also the identification sequence for the simulation that showed the minimum tower clearance: "dlc" denotes the Design Load Case, "wsp" the wind speed, "wdir" the wind direction and "s" the turbulence seed realization. The tower clearance takes into account the safety factors assigned by the DLB used.

Blade Design	AEP	Tower Clearance
NREL 5MW RWT	24.197 [GW h]	dlc13 wsp12 wdir010 s5005 1.767 [m]
s080-b0025-f0000	-0.04 [%]	dlc13 wsp12 wdir010 s5005 +3.5 [%]

428 *4.2. Extreme bending and torsional loads*

429 Figure 16 shows the blade root load comparisons between the baseline and the considered
 430 swept blade. The extreme blade root flapwise load is decreased, as median and IQR of the
 431 distribution of *s080-b0025-f0000* highlight. This reduction is qualitatively in agreement
 432 with the variation observed for the DTU 10 MW (see Figure 8).

433 The median of blade root torsional moment distribution increases whereas the torsional
 434 moment distribution for the respective swept blade design of the DTU 10 MW is more
 435 similar to the its baseline (see Figure 8), with a slightly lower median. The differences
 436 between the extreme blade root torsional loading of the NREL 5 MW and the DTU 10 MW
 437 are due to the different strategies used to compensate the loss in AEP. The choice between
 438 the aerodynamic twist optimization and the pitching towards stall has an impact on the
 439 distribution of the loading along the blade span, as already remarked in Section 3.2 (see
 440 Figure 10).

441 The median of the edgewise loading increases due to the increase in blade mass, reported in
 442 Table 4. The *s080-b0025-f0000* of the DTU 10 MW RWT benefits less from the backward
 443 sweep due to the optimization of the aerodynamic twist which affects the blade loading
 444 at the tip to compensate for the loss in AEP. The *s080-b0025-f0000* of the NREL 5 MW
 445 RWT shows improved load alleviation characteristics on the flapwise direction compared
 446 to the 10 MW, driven by a larger extreme torsional loading (compare Figures 8 and 16).

Table 4: Blade mass of the NREL 5 MW RWT with straight and backward swept blades (*s080-b0025-f0000*). The mass of the swept blade loads is reported as variation in percentage from the baseline.

Blade Design	Blade Mass
NREL 5MW RWT	17740 [kg]
s080-b0025-f0000	+0.19 [%]

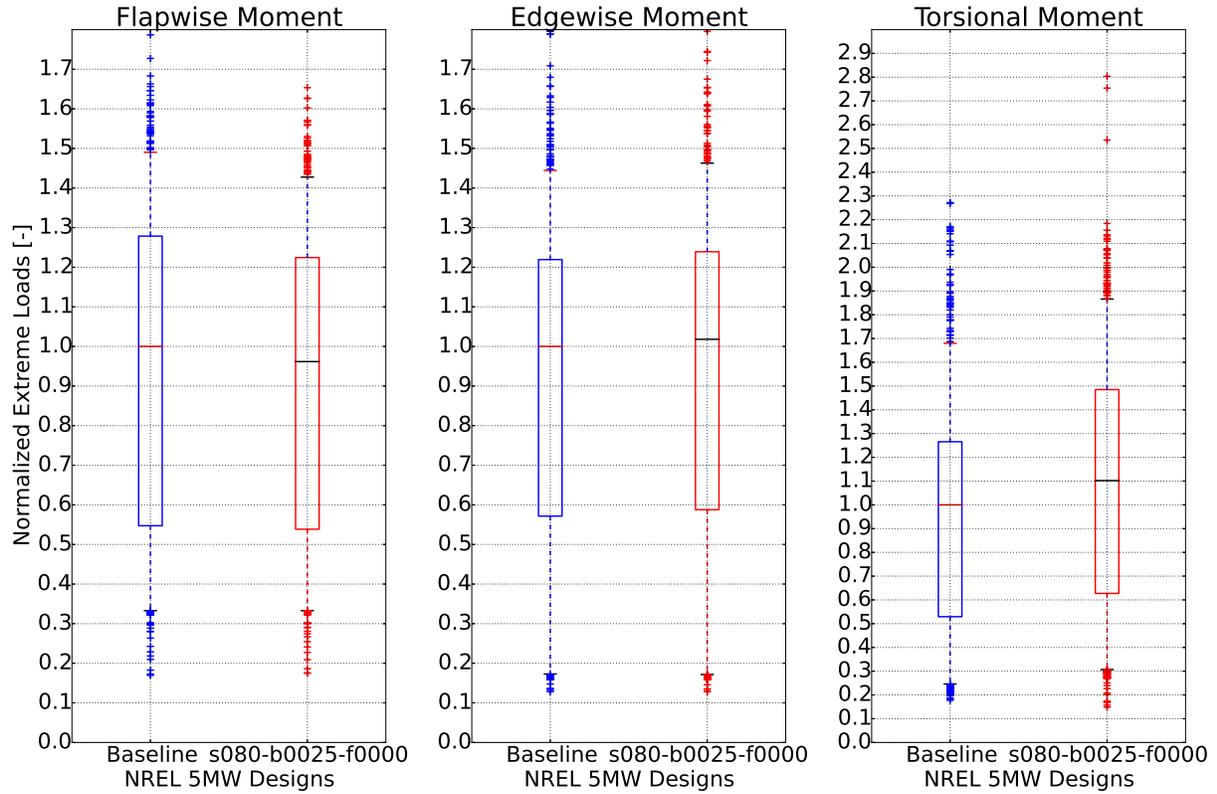


Figure 16: Normalized absolute maxima distributions for baseline and swept blade of the NREL 5MW. The loads are non-dimensionalized by the median of the respective baseline distribution.

447 *4.3. LTEFL bending and torsional loads*

448 Table 5 shows the comparison of the blade root LTEFLs for the two designs. The loads for
 449 the baseline are reported in absolute value, whereas the LTEFLs for the *s080-b0025-f0000*
 450 are reported in percent variation. The variations of LTEFLs reported for the swept blade
 451 design of the NREL 5 MW are in agreement with the observations made from Figure 9
 452 where the LTEFLs of the flapwise and torsion directions are reduced while the edgewise
 453 LTEFL is increased.

Table 5: LTEFL blade root moments of the NREL 5 MW RWT with straight and backward swept blades (*s080-b0025-f0000*). In the three rightmost columns, the blade root flapwise moment, the blade root edgewise moment, and the blade root torsional moment are respectively reported. The fatigue loads for the baseline blade are reported in absolute values in the second row of the table. The fatigue loads for the swept blade are reported as variation in percentage from the baseline.

Blade Design	LTEFL BR Flap	LTEFL BR Edge	LTEFL BR Tors.
NREL 5MW RWT	10092.379 [kN m]	7218.318 [kN m]	184.232 [kN m]
s080-b0025-f0000	-6.3 [%]	+0.2 [%]	-2.8 [%]

454 From the investigation with the NREL 5 MW RWT, it can be concluded that the outcomes
455 of the extensive load analysis of the DTU 10 MW RWT can be applied to other wind
456 turbines, ensuring the creation of a swept blade design able to provide beneficial passive
457 load alleviations.

458 5. Conclusions

459 This paper studies extensive load analyses to investigate the backward swept blade designs
460 for passive load alleviation on multi-megawatt wind turbines. To introduce various swept
461 geometries, three representative parameters are considered:

- 462 • position along the blade span where the sweep starts;
- 463 • maximum backward sweep at the blade tip;
- 464 • maximum forward sweep.

465 Based on these three parameters, 25 shapes divided in 5 families were selected. The blade of
466 the DTU 10 MW RWT was used as baseline. In general, the backward swept blades produce
467 less electrical energy compared to the straight blade. Therefore, all the considered swept
468 blades were pre-processed to provide the same amount of the annual energy production
469 (AEP). An optimization approach was introduced. The aerodynamic twist was updated
470 for each swept blade design to maximize the annual energy production, compensating the
471 AEP loss below rated wind speed. After that, the tuning of the controller according to a
472 specific frequency placement of the regulator mode was performed as well. A full design
473 load basis was adapted and analyzed for each of the swept designs selected.

474 The variation of each geometric parameter was analyzed separately producing the following
475 observations:

- 476 • "sxxx": the choice of the first control point location parameter is driven by the large
477 increase in extreme and fatigue blade root torsional moment, and the increase of the
478 edgewise LTEFL due to the increase in blade length more pronounced as the sweep
479 starts closer to the root;
- 480 • "bxxxx": the parameter has to be chosen considering the minimum increase in tor-
481 sional extreme and fatigue loading, and taking into account the increase in blade
482 mass due to the increment in blade length brought by the swept shape;
- 483 • "fxxxx": the presence of forward sweep helps compensating excessive increments of
484 the torsional moment, but it also reduces or cancels the beneficial effects due to the
485 sweep; moreover, the location of the forward sweep along the blade span does not
486 have a relevant influence on the loading.

487 To summarize, mildly and purely backward swept shapes are the best option for the de-
488 sign of passive-controlled wind turbines because they can achieve load alleviations without
489 causing large increases in blade root torsional moment.

490 Annual energy production and tower clearance were monitored as well. The optimization
491 of the aerodynamic twist to maximize AEP produces negative effects on the tower clear-
492 ance of some of the designs analyzed. The optimizer increases the aerodynamic twist at
493 the blade tip to fulfil the loss in AEP below rated wind speed, resulting in higher angles
494 of attack and higher loads at the tip around rated wind speed compared to the baseline
495 design. This process causes a reduction of the tower clearance with respect to the RWT
496 and a different distribution of the loading along the blade span.

497 The observations obtained through the load analysis of all the DTU 10 MW RWT were ap-
498 plied to a different wind turbine, specifically, the NREL 5 MW RWT. From this study simi-
499 lar trends between the DTU 10 MW RWT and the NREL 5 MW RWT were observed. The
500 outcome of the parametric study can be generally applied to produce a passive-controlled
501 wind turbine with reduced flapwise extreme and fatigue loads, and inevitable increase in
502 extreme and fatigue blade root torsional moment.

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