Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2023) 840-849

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X ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2023
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THE BERLIN RESEARCH TURBINE – A TESTRIG FOR ACTIVE FLOW CONTROL OF FATIGUE AND EXTREME LOADS

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Abstract. This paper presents the active flow control capabilities of the Berlin Research Turbine that are investigated within the large wind tunnel of the TU Berlin. This setup allows to assess fatigue and extreme load controllers under reproducible inflow conditions. The wind tunnel was recently redesigned to create inflow gusts and the turbine is mounted on an electrically controllable turn-table, which allows for dynamic direction changes during operation. Thereby, the turbine can be exposed to steady and dynamic inflow scenarios. Within the current setup, active trailing edge flaps are installed on the three blades of the turbine and strain gages are employed to measure the flapwise blade root bending moment. Analyzing steady conditions with yawed inflow, it could be shown that a repetitive model predictive controller outperforms an individual flap controller by 15% in terms of load control with a limited increase of flap travel. In order to perform extreme load control, the turbine is further equipped with three-hole probes and surface pressure ports for measurements of angle of attack and relative velocity as well as an accelerometer. Thereby, sudden changes of the inflow can be detected. These sensors are included into the controller architecture and thereby, a specialized extreme load controller is activated during such conditions. During the deterministic, EOG type extreme load experiments the maximum flapwise blade root bending moment could be reduced by 20%.

Key words: Active Flow Control, Fatigue Loads, Extreme Loads, Trailing Edge Flaps

doi: 10.7712/150123.9837.443170

1 INTRODUCTION

Wind turbines operate in the earth's boundary layer and are therefore exposed to changing inflow conditions. This leads to periodic and slowly changing fatigue loads on the one hand and to fast changing inflow conditions that can lead to extreme loads on the other hand. Controlling these loads is an essential task for wind turbine designers. Generally, fatigue loads are successfully alleviated by individual full-span blade pitch [1]. Furthermore, comprehensive research was conducted at various institutes into spanwise distributed *smart rotor control* [2]. Such devices are categorized into active and passive flow control devices. The latter include vortex generators, gurney flaps, leading edge flaps / slats and back flow flaps [3]. The former comprises active blowing, active leading edge slats, plasma actuators and trailing edge flaps [3]. Trailing edge flaps are among the most efficient active flow control devices for fatigue loads [2] and it was shown that they can achieve the same load reduction as full-span blade pitch [4]. However, the disadvantage of employing trailing edge flaps for fatigue loads is the high actuator duty, which potentially increases the maintenance costs [5]. Furthermore, the high actuator bandwidth is not exploited [5]. Therefore, the research focus is shifted to extreme load control [6, 5, 7]. Thereby, trailing edge flaps are only deployed when extreme inflow conditions are detected, leading to low actuator duty and their superior actuator bandwidth in comparison to full-span blade pitch is exploited [5]. Thus, maximum / minimum load peaks can be reduced, which allows to build lighter blades and thereby, lowers the cost of energy [8]. Furthermore, also edgewise loads are reduced as they are driven by gravitational 1p loads [8].

This papers presents the capabilities of the test facility of the TU Berlin to investigate fatigue and extreme loads. In particular, load control performance of trailing edge flaps are analyzed on the Berlin Research Turbine (BeRT) within the large wind tunnel of the TU Berlin. The remainder of this paper is structured as followed: Section 2 presents the test rig, in Section 3 a brief overview of the controller is given, fatigue and extreme load control results are presented in Section 4 and the paper is concluded in Section 5.

2 EXPERIMENAL SETUP

This paper presents the large wind tunnel of the TU Berlin (GroWika) and the Berlin Research turbine. The focus is on the enhancement of the wind tunnel to perform sudden changes in inflow velocity and on the implementation of trailing edge flaps on the research turbine.

2.1 LARGE WIND TUNNEL OF THE TU BERLIN (GROWIKA)

The large wind tunnel of the TU Berlin was built in the 1970s to perform steady aerodynamic experiments. Therefore, the tunnel was not designed to allow for sudden inflow velocity changes, which are necessary to investigate extreme inflow conditions. As the transient time for rotational speed changes of the wind tunnel fan is large, sudden changes of inflow velocity can only be realized by a change of pressure loss inside the wind tunnel. This was accomplished by installing a filter mat mechanism upstream of the turbine [7]. Thereby, the filter mat inside the wind tunnel can be retracted allowing for extreme operating gusts (EOG) and, in combination with intentional yawing of the turbine, extreme coherent gusts with direction changes (EDC) [7]. The wind energy test section has a cross-section area of $A = 4.2\,\text{m} \cdot 4.2\,\text{m}$ and a length of $5\,\text{m}$. The rated inflow velocity is $u_\infty = 6.5\,\text{m/s}$ with a turbulence intensity of 1.2% and $u_\infty = 7.5\,\text{m/s}$ with a turbulence intensity of 2.6% when the filter mat is fully deployed or fully retracted, respectively [7]. The BeRT is installed on an electrified turn-table that allows for direction changes. Resulting gyroscopic moments can be accounted for by multi-blade transformation [7]. The turbine is mounted such that the rotor plane aligns with the center of the turn table, which ensures the same blade tip to tunnel wall distance on both sides in each yaw configuration.

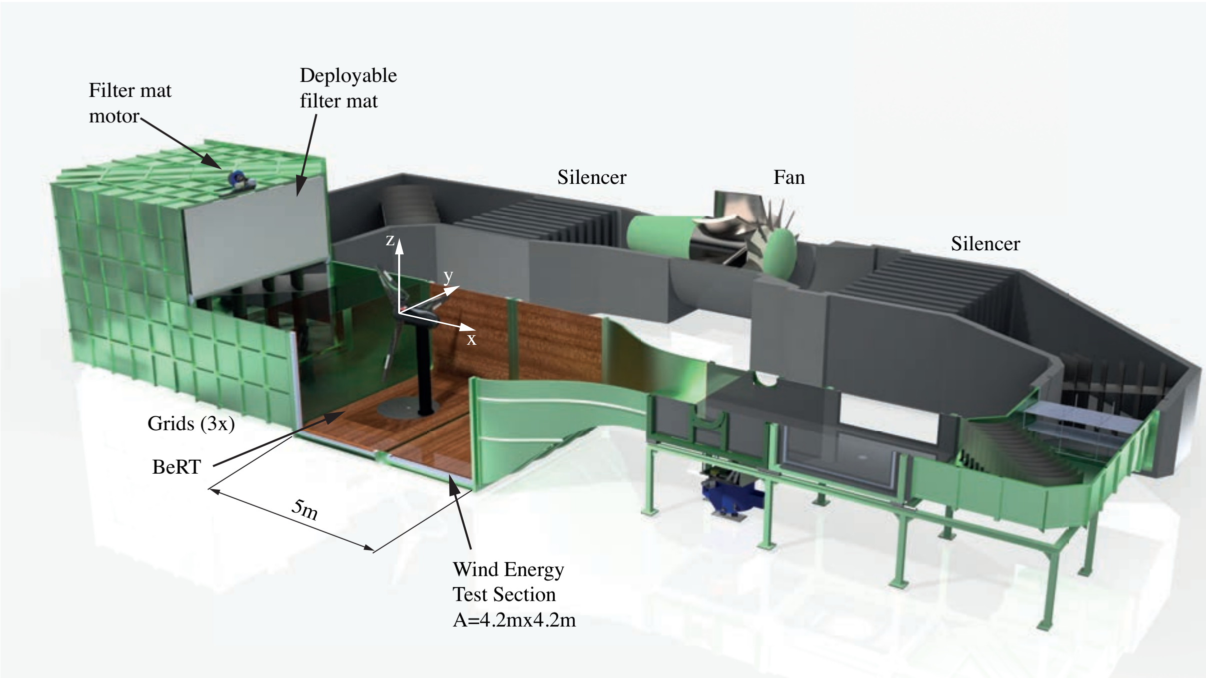


Figure 1: Large Wind tunnel of the TU Berlin. The turbine is mounted on top of an electrified turn-table. Inflow velocity changes are created by an electrified filter mat mechanism [7].

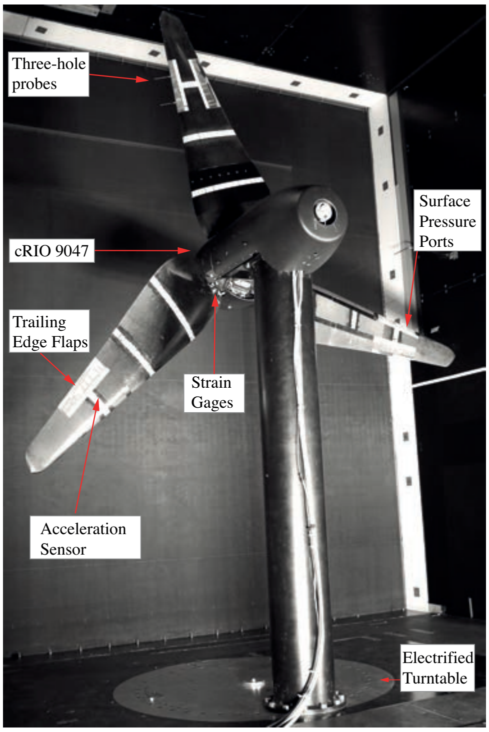
2.2 BERLIN RESEARCH TURBINE

The BeRT is a three-bladed, fixed-pitch, upwind horizontal axis turbine, Figure 2. The turbine has a tower height of $2.1\,\text{m}$ and a rotor diameter of $3.0\,\text{m}$. The rated rotational speed of the turbine is $180\,\text{rpm}$, which results in a Reynolds number of $290,000$ at the 75% spanwise position. The blades employ Clark-Y airfoils over the complete span.

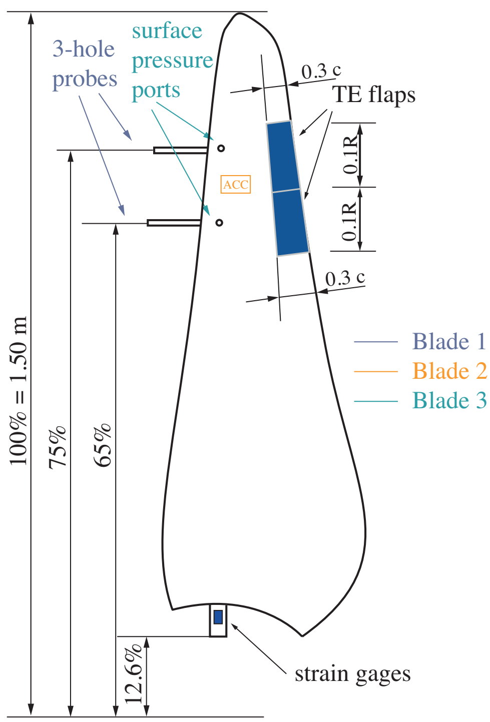
The measurement setup consists of a National Instruments cDAQ 9188 in the non-rotating domain and a cRIO 9047 inside the rotating hub. The latter samples all data in the rotating domain, such as signals from pressure sensors, strain gages for blade root bending moments and acceleration sensors. Furthermore, it comprise the control logic for the trailing edge flaps and acts as an ethercat master for Faulhaber motion controllers, which control the servo motors for the trailing edge flaps.

Each blade comprises two trailing edge flaps at spanwise positions of $60-70\%R$ and $70-80\%R$ with a chordwise extension of $30\%c$. The flaps on each blade are considered as one single control surface. A close-up of the trailing edge flap implementation is shown in Figure 3. The leading edge nose cover is removed, which allows a view on the servo motors, which are connected by lever arms to the trailing edge flaps. The mechanical structure is removable and therefore allows also an integration of other flow control devices. Furthermore, the payload bay for the pressure sensors is shown. Thereby, a short tubing length is achieved, which reduces the attenuation / amplification effects.

Besides the strain gage measurements, three-hole probes on blade 1, surface pressure ports on blade 3 and an acceleration sensor on blade 2 are employed for the detection of sudden inflow changes, Figure 2. These sensors are vital in the current setup for extreme inflow detection.



(a) The Berlin Research Turbine, view from downstream to upstream, adapted from [9]



(b) Sketch of the rotor blades, adapted from [9]. Different colors indicate which sensor is installed on which blade.

Figure 2: Berlin Research Turbine mounted inside the wind wind tunnel and sensor setup of the rotor blades [7].

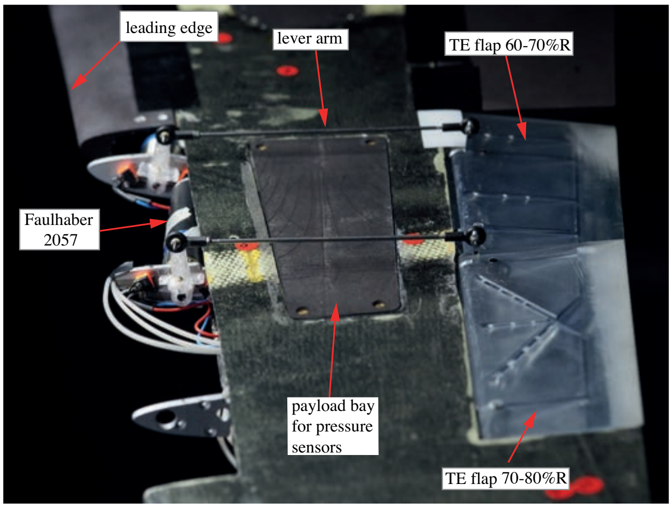


Figure 3: Close up of the Trailing Edge Flap implementation on blade 3. Adapted from [10]. Photo credit: Simon Köhn.

3 Controller

As the BeRT is a fixed pitch turbine, the trailing edge flaps are not only used for extreme but also for fatigue load control. In this section, the blended controller is presented that switches between a dedicated fatigue and extreme controller depending on the inflow situation [7], Figure 4. The fatigue controller is a repetitive model predictive controller (RMPC) in this study [9]. This multiple-input multiple-output controller adjusts its control command based on the remaining error, state deviation and the control commands of the previous cycle [9].

Generally, at rated conditions of the turbine the fatigue controller is active. At each time instant ($f_{\text{control}} = 99\,\text{Hz}$), besides the blade root bending moments, the angle of attack and velocity are measured by three-hole probe and surface pressure measurements on blade 1 and 3, respectively. Furthermore, the local acceleration at the $75\%R$ is measured on blade 2. Each measurement is compared to phase dependent running mean values. If the difference between the current measurements and the running means exceed pre-defined thresholds, an extreme event is detected which leads to a deployment of all flaps on all blades to their most negative position. Thereby, the maximum blade root bending moments can be reduced. The extreme controller is activated for 9 rotations and if no additional extreme event is triggered, the extreme controller is faded out and the fatigue controller is faded back in [7].

4 RESULTS

The results section is divided into a presentation of pure fatigue and into extreme load cases.

4.1 FATIGUE LOAD CONTROL

The fatigue load test case considers a static yaw misalignment of $\gamma = -15°$. In this study a state-of-the-art individual flap controller (IFC) for 1p and 2p loads [4] and an extended IFC

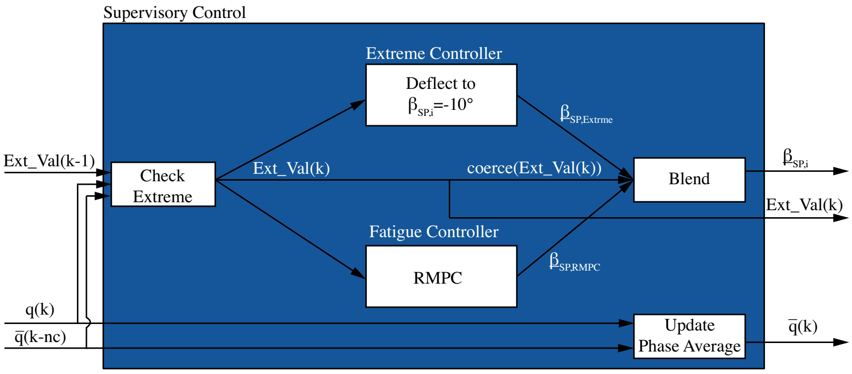
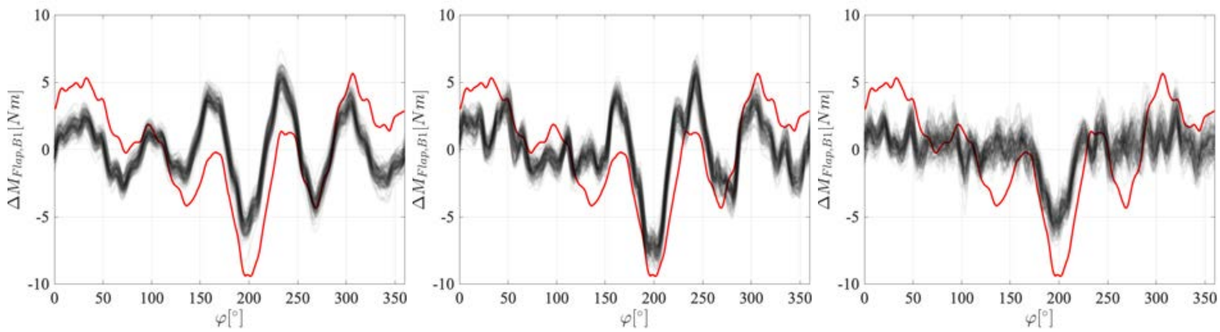


Figure 4: Blended controller architecture for fatigue and extreme load control [7].

that also targets 5p disturbances are compared to the RMPC. The 5p load is a particularity of the current test rig that is caused by the interference of the a forward whirl mode with the 5p excitation line [9]. The performance of each controller is compared to the uncontrolled baseline, Figure 5 red line.



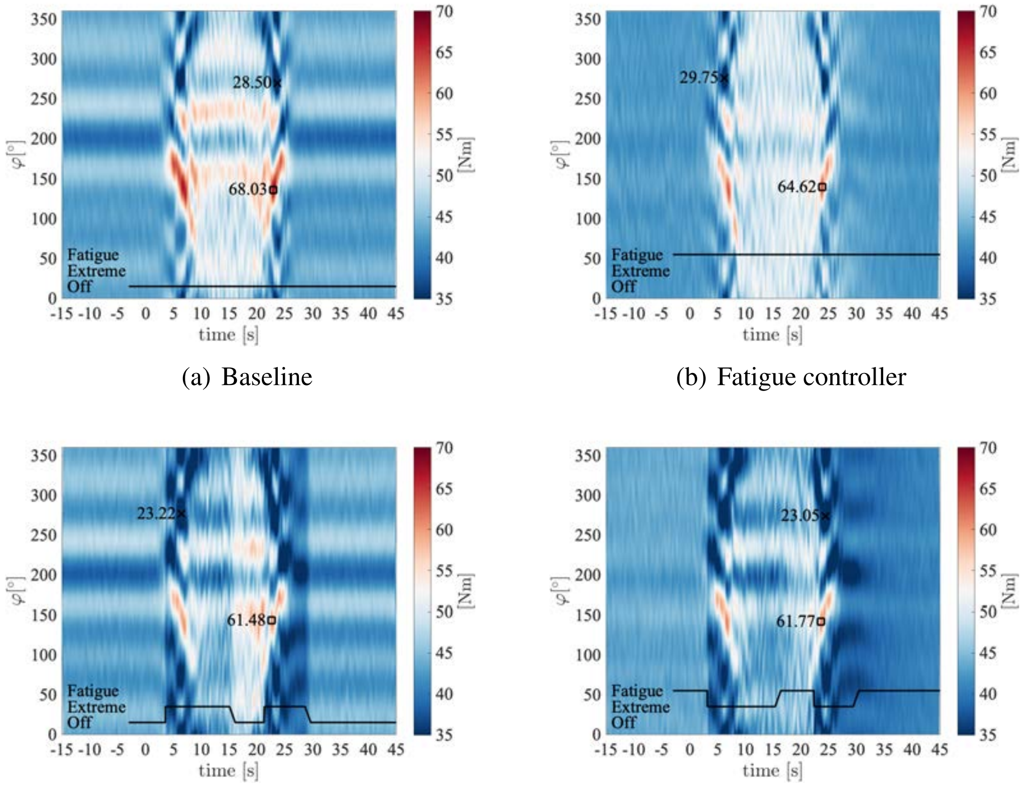
(a) *1p2p* IFC at $\gamma = -15°$ (b) *1p2p5p* IFC at $\gamma = -15°$ (c) RMPC $\gamma = -15°$

Figure 5: Flapwise blade root bending at $\gamma = -15°$ for three different control strategies [9]. Red lines show the uncontrolled baseline case (flaps fixed). Grey lines corresponds to 100 rotations.

The 1p2p IFC is successful in alleviation of the loads at the targeted frequencies, Figure 5(a). This can be seen be the removal of the dominating 1p amplitude that the baseline (red line) shows for this yaw situation. The 1p2p5p IFC additionally removes the 5p amplitude to a certain extend 5(b). Besides the simplistic structure of the IPC controllers, a drawback is that for each targeted frequency, two individual PI controller and a phase lead angle have to be tuned [9]. Furthermore, the assumption of independence of each controller might be questioned the more frequencies are targeted. In contrast to model free IFC controllers, RMPC is a model based controller that relies on a previously identified system. The load reduction is significantly larger in comparison to the previous controllers, Figure 5(c). The only major remaining error of flapwise blade root bending moment is the tower shadow, which cannot be compensated due to the limited static gain of the actuators. When comparing the short term damage equivalent loads (DELs) the 1p2p IFC achieves a reduction of 12%, the 1p2p5p IFC of 23% and the RMPC 38% [9]. Therefore, the performance of the RMPC is significantly higher in comparison to the IFC controller options with comparable travel rates of the flaps [9].

4.2 EXTREME LOAD CONTROL

Due to the superiority of the RMPC, this controller is employed as a baseline fatigue controller for the extreme load experiments. The results for four different controller options are shown in Figure 6.



(a) Baseline (b) Fatigue controller

(c) Extreme controller (d) Blended controller

Figure 6: Flapwise blade root bending moment of blade 3 for the EOG test case [7]. □ and X indicate the maximum and minimum value, respectively. The black line at the bottom indicates, which controller is active: Fatigue or Extreme controller or uncontrolled (switched off).

The uncontrolled baseline case is depicted in Figure 6(a). In this figure, the flapwise blade root bending moment is mapped over time (x-axis) and azimuthal angle (y-axis). The color levels indicate the flapwise blade root bending moment of blade 3. The previously seen 5p oscillation dominates this test case, as the turbine is unyawed, hence $\gamma = 0°$. For the EOG test case the filter mat curtain is retracted creating a localized gust at the bottom of the swept area of the turbine, followed by spreading out over the complete swept area. Consecutively, the filter mat is deployed and after creating a new localized gust the previously seen rated conditions are attained again, Figure 6(a) $t = 30\,\mathrm{s}$.

Employing the RMPC, which is a dedicated fatigue controller, for this load case shows the significant reduction of the 5p amplitudes before the extreme event happens, Figure 6(b) $t < 2\,\mathrm{s}$. Furthermore, as the transient time of the extreme event in comparison to the rotor rotational frequency is fairly high, the RMPC adopts to EOG test case and achieves a reduction of normalized maximum blade root bending moment of 8%.

The dedicated extreme controller that is only activated at extreme events and besides that keeps the flaps in their neutral position, achieves a reduction of 17%. The flapwise blade root bending moment for this controller option is shown in Figure 6(c). The black line at the bottom of the figure indicates, when the extreme controller is activated and when it is faded back out.

The blended controller achieves about the same reduction of normalized blade root bending moment of 20%. The flapwise blade root bending moment for this case is depicted in Figure 6(d). Again, the dominating 5p oscillation is significantly reduced before the extreme event happens. Once the extreme event is triggered, the maximum bending is reduced but the 5p oscillation can be seen again. At $t = 15\,\mathrm{s}$ the extreme controller is faded out and the fatigue controller is faded back in. Once the filter mat is deployed again the renewed gust is detected and the extreme controller is activated. This is followed by a fading out of the extreme controller at $t = 30\,\mathrm{s}$ and fading back in of the fatigue controller. The lower flapwise blade root bending level is due to a low-passed reference value for the fatigue controller, which recovers slowly.

5 CONCLUSIONS

This paper presents the capabilities of the large wind tunnel of the TU Berlin and the Berlin Research Turbine to investigate fatigue and extreme loads under reproducible, controlled conditions. The tunnel was extended by a filter mat mechanism to rapidly change the inflow velocity. Furthermore, an electrified turn-table allows for rapid direction changes.

Currently, trailing edge flaps are employed to alleviate the resulting fatigue and extreme loads. A repetitive model predictive controller was shown to outperform state-of-the-art individual flap controllers for fatigue loads.

Therefore, this controller was employed within a blended controller that switches between dedicated extreme and fatigue controllers. During the presented extreme load experiment, the blended controller achieved about the same load reduction as the pure extreme controller.

One drawback of the current setup are fairly large gust transient times and low gust amplitudes. This will be overcome in follow-up numerical studies.

Nonetheless, the presented test facility offers the possibility to investigate active flow control devices under reproducible inflow conditions for fatigue and extreme load control. As the turbine blades are modular, other active flow control devices can be implemented in the future and may be analyzed for their load control performance.

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