Response to RC1

July 11, 2025

We understand the challenge of the handling editor in finding reviewers for our manuscript on transonic flows in the wind energy community and, therefore, truly appreciate the efforts of the reviewers. Reviewer 1 had strong reservations to publish this manuscript based on, in particular, claims of a lack of (1) knowledge of the authors, (2) novelty of the work, and (3) relevance to the wind energy science community. In addition, some further comments were made and questions were raised. We strongly object to the main claims above, as explained in the following. Nevertheless, considering the feedback, we will make changes accordingly to improve our manuscript.

- **Knowledge of the authors**

  All authors were vested in the work carried out together and, among them, have published more than 25 scientific contributions on the topics of transonic buffet and supersonic flows including the research highlight in a leading journal in the field. This reflects decades of experience in the field, which a simple Google Scholar (or Scopus) search would substantiate. The claim of the reviewer of "a lack of knowledge on part of the authors in both compressible flow and scientific literature on transonic flows with respect to shock boundary-layer interactions (SBLI) and the physics of buffeting" is therefore surprising to us.

- **Novelty of the work**

  Transonic buffet is observed in a variety of applications and has been widely studied in aviation, where it is recognized as being an important phenomenon relevant to the operational performance. Unlike aviation airfoils, wind turbine tip airfoils are characterised by a much larger thickness-to-chord ratio and also high camber. Moreover, the buffet phenomenon on wind turbine airfoils is expected to occur at high Reynolds number Re (of the order of 10^7, similar to aviation), but relatively low subsonic free-stream Mach number Ma in combination with steeper inclinations in the opposite direction (i.e., large negative angle of attack) compared to aviation applications (De Tavernier & von Terzi, 2022). Hence, these distinct conditions under which buffeting may develop (aviation vs wind turbines) likely imply that the knowledge of one area may not be directly transferable to the other. This makes it very relevant to dedicate studies to the typical characteristics of transonic buffet produced on typical wind turbine airfoils, given the uniqueness of the geometry and operational conditions.

  An example highlighting the difference in the transonic buffet cycle produced on a supercritical airfoil for aviation applications and the wind turbine airfoil investigated in the present manuscript is shown in Fig. 1. The probability density function (pdf) of the shock location as percentage of chord for the supercritical airfoil is flatter, with a higher density towards the ends of the range of motion whereas, on the wind turbine airfoil, the density is higher towards the center of the range of motion.

  To the knowledge of the authors, this is the first time that transonic flow on any wind turbine airfoil was studied experimentally. Preceding studies had been either theoretical or numerical (URANS). The simulation tools applied are inherently limited in modeling and predicting the associated dynamics of shock occurrence, such as the amplitude and frequency of the buffet. Thus, experiments are crucial not only to investigate the physics but also to correctly model the dynamics using lower-order tools and to provide validation data.

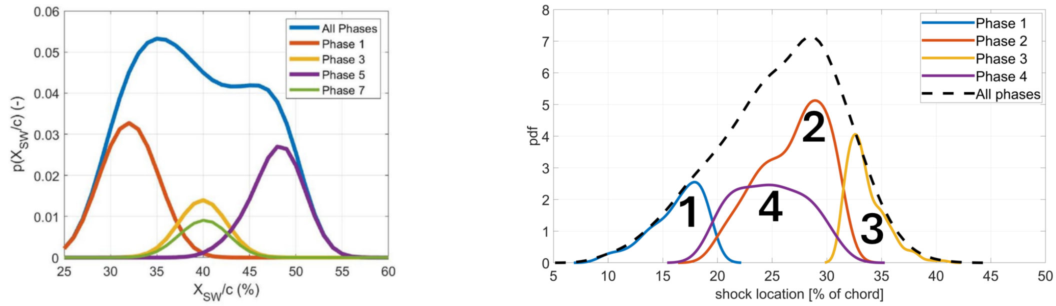

Figure 1: Probability density function of the shock location as a percentage of chord for transonic buffet. Left: OAT-15A supercritical airfoil, from D'Aguanno et al. (2021); right: FFA-W3-211 wind turbine airfoil (current study).

Contrary to the claim of the reviewer, we consider our current contribution as novel to both wind energy science and the literature on transonic flows. To support this, we will extend the introduction of the revised manuscript to provide more context on the differences in transonic buffet between aviation and wind energy applications so that the novelty can be appreciated more easily. We will include a reference to the review paper of Giannelis et al. (2017) for more literature on the aviation application.

In addition, we will expand the results section of the revised manuscript to describe the flow dynamics uncovered through our experiments in more detail. To this end, we are using a phase-averaged analysis of the flowfield based upon the shock location that builds towards the graph shown in Fig. 1. This will help address the concerns regarding both novelty in general and relevance for wind energy applications. A preview of these results is shown in Fig. 2, where the phase-averaged representation of the buffet cycle reveals the marked changes in the flowfield resulting from the motion of the shock.

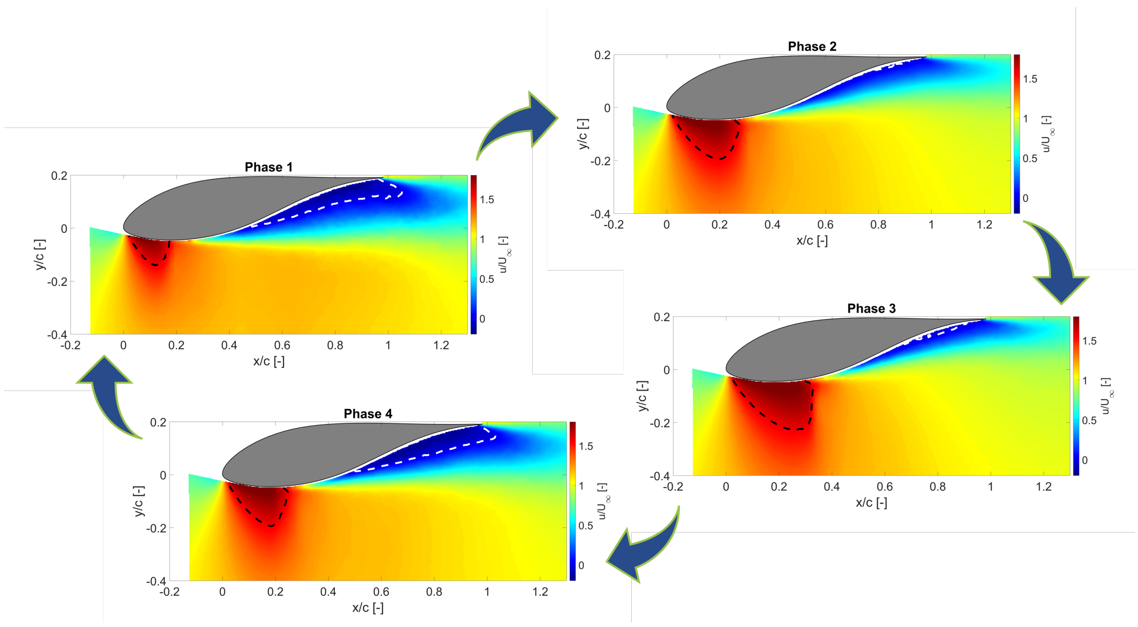

Figure 2: Phase-averaged (based on shock location) streamwise velocity fields for $Ma_\infty = 0.6$, AoA$=-10°$ of the FFA-W3-211 wind turbine airfoil (current study); black and white dashed lines identify supersonic and separated flow regions, respectively.

- **Relevance to the wind energy community**

  The investigated airfoil is used at the tip of prominent reference wind turbines, namely the IEA 15MW (see Gaertner et al., 2020) and IEA 22MW (see Zahle et al., 2024). These are widely used for scientific research in the wind energy community. However, there are very few limited datasets on polars for this airfoil, and none with compressibility effects. As the turbine was designed with polars from simulation tools, it is critical to provide insights into physical mechanisms that these tools are unable to capture.

  Regarding the choice of Ma and Re values for the experiments. As pointed out in the manuscript, these differ from the above mentioned reference turbines, in order to qualitatively capture the relevant physics expected at full scale. However, perhaps counter to expectation, Ma is not the single parameter relevant for the occurrence of compressibility effects. Vitulano et al. (2025) showed that an increase in Re plays a crucial role in accelerating the appearance of shock waves at relatively lower Ma. This is shown in the figure below. For an Re of 1.8×10^6, which is close to the Re achieved in the current experiments, shock waves occur only at a Ma of 0.6. However, at an increased Re of 9×10^6, shock waves start to occur already at a Ma of 0.45, close to an angle of attack of -9 deg. Moreover, hysteresis effects on a pitching airfoil result in shock waves being observable at an even lower Ma of 0.35, i.e. close to Mach numbers that can be observed on large turbines like the IEA 22MW reference wind turbine. However, this combination of a very high Re and a relatively high Ma is not possible to reproduce in most, if not all, experimental facilities available for wind energy research. Thus, to produce shock waves on such an airfoil experimentally, the higher Ma in our study is justified due to the limitations of achieving a Re of the order of 10^7 in the same facility, such that the physics of shock occurrence being investigated in the experiments is the same as expected for a full-scale turbine.

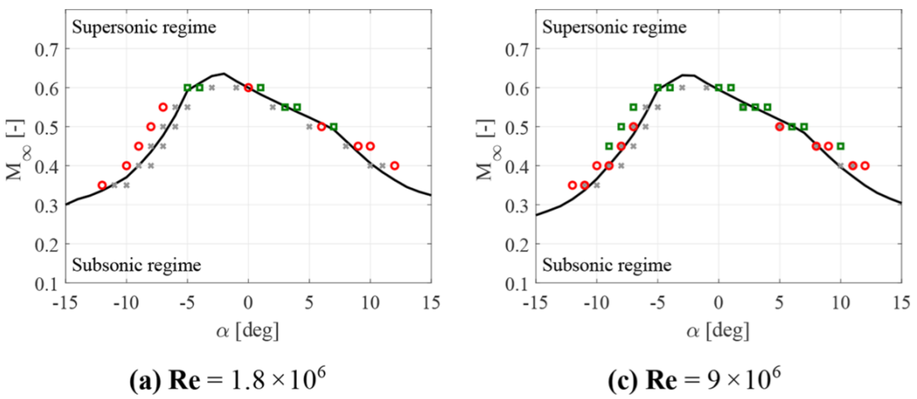

Figure 3: Subsonic-supersonic boundary for the FFA-W3-211 wind turbine tip airfoil, with symbols indicating URANS simulations showing no supersonic flow (grey crosses), supersonic regime established (red circles), and configurations in which shock waves appear (green squares); from Vitulano et al. (2025).

  In the original manuscript, we briefly alluded to the argument made above when we mention the study by Vitulano et al. (2025) on line 168. In the revised manuscript, we intend to more clearly and explicitly justify the choice of Ma and Re. It is critical to understand that in order to reproduce the same physics of shock occurrence as in full-scale, the required change in Re, for any wind tunnel, necessitates to choose the corresponding Ma and pitch angle (see Fig. 3).

Response to additional comments and questions of the reviewer:

- The reviewer is wondering why the numerical simulations of Vitulano et al. (2025) are not at the same conditions as in the experiment. In the numerical study, a range of $0.2 \leq Ma \leq 0.7$ and $1.8 \times 10^6 \leq Re \leq 9 \times 10^6$ (see also Fig. 3) were investigated to determine the threshold for transonic flow and shock occurrence. This includes all relevant Ma and bridges from the Re in an incompressible experiment used for validation to the value in full scale. In the article, more details were shown for the full-scale operation conditions due to its practical relevance. For the present experiments, a slightly lower Re of 1.5×10^6 than for the incompressible experiment was achieved and the Ma and angle of attack (AoA) were chosen to obtain similar physics as expected for full-scale considering the difference in Re as explained above.

- The reviewer suggests that some rather simple design or operational changes would "solve" transonic flow issues. Unfortunately, avoiding transonic flow, if encountered on wind turbines, may not be as straightforward as the reviewer seems to believe. The patent of von Terzi et al. (2023) (and a corresponding research article in review) delves into more detail on this. A key consideration is that the transonic operational boundaries are wind-speed dependent and, with the inherent variability of the wind resource, it is possible to end up in a challenging situation where escaping transonic flow may not be possible or, at least, the right combination of tip speed and pitch needs to be known to exit safely. Other suggestions will lead to a lower energy yield and increase the cost of energy. With a good physical understanding, it is, however, possible to navigate the "mine field" with minimal performance losses or by simply designing a better turbine pushing the boundary of transonic flow out of the operational range. Thus, it remains crucial to acquire reliable experimental data on the behaviour of wind turbine airfoils under transonic conditions.

- Regarding the use of RFOIL, we appreciate the trust of the reviewer in tools (co-)developed in our institute. Here, however, a choice was made to provide a freely accessible tool (XFOIL) for better reproducibility. While we also believe in some benefits of RFOIL, there are many versions available and no access to source code is given. Moreover, the fundamental limitations of the approach for investigating transonic flow, whether XFOIL or RFOIL, remain.

- Regarding the comments on a missed opportunity for verification and validation of the current experiments with numerical simulations from Vitulano et al. (2025), a separate publication is in preparation that stands apart from the current study (with specific experimental focus) and, in our opinion, should not be crammed together. We plan to openly publish the experimental dataset and invite other groups to carry out V&V of their numerical tools and models with our data. Also, as assumed by the reviewer and suggested in Vitulano et al. (2025), there are plans for the use of Hybrid RANS/LES methods to be applied. These efforts are beyond the scope of the present study and communication.

- Regarding the desire for lift and drag coefficients, this is understandable if the data were to be used directly in other simulation/design tools. Similarly, frequencies induced by the buffeting would be important to know for structural design. However, the present manuscript aimed in establishing qualitatively, and for the first time, the transonic flow behaviour of the wind turbine airfoil to reveal if and when shocks will occur and where they will manifest themselves. The manuscript also provides flow details to serve as a validation for future high-fidelity simulations and reduced order models. Again, the chosen operating parameters are not the same as full-scale, but chosen to match the expected physical behavior. Hence, quantitative analysis on a performance loss are less meaningful, but the qualitative behavior of the flow must be understood or attempts on avoiding buffeting risks will be fortuitous at best.

Summary

All previous literature on transonic buffet studies has focused on airfoils with low thickness-to-chord ratio (of the order of 10%), moderate camber, and a vastly different angle-of-attack regime. For the first time, a wind turbine airfoil characterized by a higher thickness-to-chord ratio, high camber and negative inclination as relevant for above-rated wind speeds, has been studied in transonic flow conditions, and the resulting buffet phenomenon was observed to be distinct compared to supercritical (aviation) airfoils. This highlights the novelty of the work.

On the full-scale IEA 15MW and 22MW reference wind turbines and similar-size turbines currently designed in industry, shocks might occur at blade tips with Re of the order of 10^7 and $Ma \sim 0.3$. However, in the transonic wind tunnel facility, it is only possible to reach Re of the order of 10^6, which would not be sufficient to produce shocks at $Ma \sim 0.3$. Recall, the appearance of shocks was shown to depend on both Re and Ma by Vitulano et al. (2025). Thus, the experiments were conducted at Ma of 0.5 and above, to study the physics of transonic flow with ($Ma = 0.6$) and without ($Ma = 0.5$) the occurrence of shocks on the wind turbine airfoil.

We thank the reviewer for valuable comments and questions that initiated amendments to the manuscript to address the aforementioned points more clearly. In addition, we will add further results to discuss in more detail the dynamics of the buffet cycle (as shown above). Overall, we want to highlight the distinct features and relevance of the possibility of transonic buffet on wind turbine airfoils. We believe that these modifications will better substantiate the novelty and relevance of our work, such that the (revised) manuscript can be considered as suitable for publication in Wind Energy Science.

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