Wind Energ. Sci. Discuss.,
doi:10.5194/wes-2016-14-AC2, 2016

Interactive comment on "Wind tunnel tests with combined pitch and free-floating flap control: Data-driven iterative feedforward controller tuning" *by* S. T. Navalkar et al.

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Received and published: 8 August 2016

Response to reviewer 2

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To
The Anonymous Reviewer 2
Wind Energy Science

Dear Reviewer,

First of all, the authors would like to thank the reviewer for their positive and constructive feedback. We believe that the comments have helped us improve the quality of the paper. In our attempt to account for the comments, we plan to revise different aspects of the paper. The objective of this document is to respond to the points raised by the reviewer and to provide a detailed overview of the changes being made to the paper.

Yours sincerely,

Response to comments of Reviewer 2

1 Response to comments of Reviewer 2

1. Please precise what is new, the combination of the 2 control strategy? The real time aspect? Referring to your personal bibliography some of these aspects has already been treated. The reader should clearly be able to locate this new article in your scope.
   Thank you for this remark, the original introduction was indeed unclear regarding the precise aspect in which the paper represents an advancement of the state of the art. To answer the question, three main novelties can be found in this paper:

   (a) This is the first experimental demonstration of combined pitch and flap control.

   (b) This is the first experimental demonstration of free-floating flaps applied to rotating wind turbine blades. This is also the first time their potential has been demonstrated for load reduction in wind turbines experimentally. Further, this is the first time that free-floating flaps have been shown to induce flutter on wind turbine blades experimentally.

   (c) This is the first experiment where IFT has been devised and implemented for adaptively tuning the gain schedule of a nonlinear (LPV) system.

   Since these novelties are not clear, they will be mentioned explicitly in the introduction of the revised manuscript.

2. Line 3 page 2: please defined 1P in this chapter, the definition of this acronym comes in chapter 2 (too late),
   The term 1P will be defined as the rotor speed in the introduction of the revised version of the manuscript.

3. You affirmed that “Data-driven controller may be able to achieve greater optimality of performance without the excessive conservatism of the true robust design";

It seems you want to compare totally opposite methodology. Data-driven has no proof of robustness and/or optimality and the performance of the controller depend of the number of data-acquisition set you used to determine your controller. This methodology has advantages of deleted identification part and to be simple to use and implemented but does your non-linear system is not a linear piecewise system? Does you have some robust control methodology that you could use?
The authors agree completely with the reviewer that the data-driven strategy described in this paper has no proof of robustness or optimality, and depends strongly on the realisations of the data and wind speed during operation. In case one were to approach the controller design from a traditional robust mindset, one would be required to formulate an accurate linear parameter-varying or piecewise linear description of the system, which would undoubtedly be subject to significant parametric and dynamic uncertainties. Formulating a robust controller based on such an uncertain plant description could yield a strongly conservative controller that is perhaps not able to achieve the maximum possible load reductions. The advantage of the IFT approach is that, besides being simple, it uses input-output data to tune itself to optimise a simple user-defined criterion. Since a feedforward approach is used, the IFT controller cannot destabilise the plant; in the best case, it could perhaps achieve load reductions that a conservative robust controller may not be able to reach.

This discussion will be repeated in the revised manuscript to clearly compare the proposed control strategy with the robust control approach.

4. You must précised clearly what is new compared to your bibliography. The combination of the methodology? The real time aspect? If we read some paper of your bibliography it seems that all aspect is already treated in your previous article. Please refer to the discussion related to the first comment.

5. This chapter must be design to offer real investigation and comprehension of the design and manufacturing of blades for people that cannot be accustomed to

these topics. Why this parts is important to understand the following parts of this article?
The authors apologise for the lack of clarity in describing the aim of Section 2. In principle, this section describes the design of the experimental setup, and provides details regarding the materials, method of manufacture and assembly. The authors believe that this is important, since it is the first time that a wind turbine blade has been manufactured to incorporate free-floating flaps. Primarily, the destabilising effect of the free-floating flap is studied in detail, and the parameters are tuned such that the blade is close to, but not beyond, the flutter point in order that maximal control authority is achieved. This reasoning will be included in the introductory paragraph of Section 2.

6. Figure 3 is cited befor figure 1 and 2.
   This will be rectified by reordering the figures.

7. Line 8 page 4 : what does you mean with this word “qua"?
   “Qua" has the meaning “in terms of".

8. Line 24 page 4 :what does you mean with CAD?
   CAD stands for Computer-Aided Design, the expansion of the acronym will be included in the revised manuscript.

9. Figure 2 : can you explain where is the sample and what is around the sample?
   The top grey rectangle and the two black rectangles below it are the 3d-printed plastic samples, bonded with carbon fibre. They are placed on a sandstone-coloured desktop, this forms the background. This will be made clear in the caption.

10. You found that the blade designed using CAD software is 30% stiffer than the actual manufactured blade but doesn’t explain why. Please avoided postulated affirmation and concretely explained the difference and the consequence on the

announced gain of 70%. 30 % more stiffness of the blades does not seem to be reflected in the same way on the resonance frequency that not only down 13%. Can you explain why?

The authors retested the stiffness of the blade, and it was found that the clamp used for fixing the blade root was not ideal, but allowed rigid-body rotation of the blade. The rotation of the blade root with increasing load was measured, and compensated for in order to correctly estimate the actual stiffness of the blade. [IF THE FIGURE IS NOT VISIBLE, PLEASE REFER TO THE ATTACHED SUPPLEMENTARY PDF]. The corrected figure will be used in the revised manuscript.

stiffplotmod.png

The announced gain of 70% is an experimentally measured quantity, and has no relation to the numerical models (that do not predict load-reduction capabilities). As far as the difference between the numerical and experimental model is con-

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Discussion paper

cerned, it should be noted that the numerically calculated values are blade frequencies; the rotor modal frequencies measured in practice are also influenced by the blade connection flexibility, motor stiffness and hub flexibility, and as such are necessarily lower than the numerically calculated blade modal frequencies. These issues will be clarified in the revised manuscript.

11. Line 14 page 11 you talk about an optimal control action, where is the proof of the optimality of the control action? Do you have references that assess that the control action is optimal? It's an global optimality or an operating point optimal controller?
    The reviewer points out an important issue: IFT has no theoretical proof of global optimality. Indeed, if IFT is used for tuning a feedback controller, there is no guarantee that the closed-loop system will be stable. Since the paper discusses a feedforward controller, this is not an issue of concern. Further, if the step-size in the gradient descent algorithms is too large, the parameter tuning process may become unstable. These issues have been dealt with by Hjalmarsson in the reference “Iterative feedback tuning: an overview." This paper will be referenced in Section 5 in the revised manuscript. The “optimality" described in this section refers specifically to the optimisation in a local sense, of the user-defined cost function. This will also be made explicitly clear in the revised text.

12. Line 19 page 11, Does the plant or the controller is assumed be still LPV?
    The original statement is ambiguous. The plant, being the wind turbine, is at all times LPV. For the case where the wind conditions are held constant in the wind tunnel, an LTI controller is tuned by IFT for that specific operating point of the LPV plant. On the other hand, for the case where the wind conditions are allowed to vary in the wind tunnel, a gain-scheduled controller is tuned by the IFT algorithm developed in this paper. This schema will be explicitly mentioned in the introduction of Section 5.

13. Line 20 page 11: What is the consequence of the assumption of constant wind speed during each set of IFT experiments?
The assumption of constant wind speed implies that ordinary IFT can yield an optimal load-reducing controller only for that specific operating point. Such a controller may not achieve the highest possible load reductions, or may even increase loads, at other operating points. It is for this reason that the ordinary IFT process has to be repeated for different constant wind speeds, or an IFT gain schedule has to be generated for a varying wind speed. This will be made clear in the revised manuscript.

14. Line 32 page 11 you wrote that Ak, Bk, Ck, Dk are considered unknown so how you assess that this same matrices could be written as equation 3. What does the bracket [0] or [1] means?
A_k, B_k, C_k and D_k are all considered unknown but assumed to admit a specific LPV structure, often used for modelling wind turbines, as in the PhD thesis of Van Wingerden; a reference to this thesis will be provided in the revised text. The terms $A^{[0]}$ and $A^{[1]}$ signify the unknown components of A_k, one which is constant over time, and one that varies linearly with the wind speed. As per Van Wingerden 2008, there should be one more term that varies with V_k^2, however the influence of this term is small and it is neglected in this paper. This description will be added to the revised text.

15. Equation 5 page 12, you use qk and write line 22 page 12 that it will be described in the next section but in section 5.2 you wrote that qk is equal to zero. What the interest of this variable? This variable doesn't appear on the block diagram figure 16.
The authors thank the reviewer for pointing out this issue. While q_k is indeed zero for the reference experiment, it is non-zero for the gradient experiment of IFT, please see equation (11). As such, it is important for determining the gradient of the performance criterion with respect to the controller parameters. The authors

will update Figure 16 such that this signal is included in the block diagram.

16. Where is the global control scheme (IPC+IFC+SYSTEMS+PID...)?
A new block diagram will be included in the revised manuscript that extends the block diagram scheme of Figure 16 with the stabilising collocated PID control.

17. Line 9 page 14: μ is not defined (a residual of Sachin T. Navalkar et al. / IFAC-PapersOnLine 48-26 (2015)?)
The authors thank the reviewer for pointing out this typo, μ_* should indeed be replaced by V_*.

18. 1st paragraph Page 15 : you precise that your controller is optimal for the operating point that assess you can't compared it to robust control. What happen when the wind speed is between two operating point you use to find your controller?
The reviewer points out a shortcoming of the two control approaches used in the paper:

   - For the case where LTI controllers are devised for constant operating points, the control action for an intermediate speed is obtained by interpolating between the gains of the closest wind speeds. This is the approach followed by most industrial gain-scheduled controllers. For a highly non-linear plant, this approach is no longer optimal for the intermediate wind speeds, in common with such conventional gain-scheduled controllers.
   - For the case where a gain-schedule is automatically tuned by IFT for varying wind speeds, the control is not optimal at any operating point, but it is globally optimal for a range of operating points. However, for the case (as with IFC), where the desired gain schedule is not linear, the controller may possibly behave poorly across the entire wind speed region. This case has more parallels with an LTI robust control design, which optimises globally but may be severely suboptimal for local operating points. An LPV robust con-

trol design may be superior in general, but accuracy of modelling is critical for such an approach.

This comparison of IFT control with robust control will be included in the conclusions. Finally, the authors would like to state that the IFT approach in this paper, while interesting and novel, definitely stands to be further improved, and forms part of our future work.

19. Chapter 6 deals with results. Results are good.
We would like to thank the reviewer for their kind comments and constructive feedback.