Answers to reports on wes-2022-109

Paul Mella and Matteo Capaldo

February 15, 2023

Answer to anonymous referee 3

1. ROSCO will be in the introduction. In particular, we'll shortly describe the platform pitch control strategy around line 64 and we'll cite the state-of-the-art also.

2. Line 46. The difference between the two papers is related to the fact that, formally, we don't change the rated speed. In the text, to be more clear, "as introduced in this paper" will be changed by "in (Lackner et al.)". We will also explain that by modifying the rated speed as function of the platform pitch is actually equivalent to adding a compensation term to the blade pitch control that depends on the platform pitch. However, it implies a coupling between the proportional and integral gains related to the platform pitch and those related to the rotor speed control. This is different from the work presented in this paper, where those parameters are independent (moreover we consider only a proportional gain for the platform pitch control, the integral one being 0).

3. Line 193. We'll reformulate in the text. We propose to replace the sentence by "When the equation is verified, it means that: τ_a is more sensitive to blade pitch than rotational speed and F_a is more sensitive to omega than blade pitch. Therefore, by increasing blade pitch ω increases and, then, occasions F_a to decrease. Then, ϕ increases."

4. Line 220. We'll add a graphic visualization of the roots of G(s), we'll show how those roots move when m_{τ_g} varies, and that will explain how k_{τ_g} is chosen and used. We'll give more details about m_{τ_g}, including its dependency on D_t. For this, the graphical representation of zeros and poles will be useful.

5. We'll revise the references to sections, figures, and tables.

6. Tables 1, 2, 3, Figures 2, 3, 4. display each table next to the associated figure. The values are determines arbitrarily as examples, to ensure the appearance of NMPZs. This is done in the purpose of a pedagogic example to show the effects of the NMPZs. The values are purely numerical. There are not so far from the coefficients related to the IEA15MW wind turbine because we started from those physical values and we found the right coefficients, in the order of 10% or 20%, to make the system unstable. The numerical section focuses on more realistic FOWT tests.

7. In section 3. (numerical simulations) the reference strategy (refered to as $k_\beta = 0$) corresponds to a "detuning strategy" (We will develop more about this when introducing the PI controller's parameters ζ_{rot} and ν_{rot}) which already reduces the coupling effect between platform dynamics and rotor dynamics. The ROSCO toolbox, downloaded from github, implements this "detuning strategy" with interpolated gain coefficients k_P and k_I when the floating feedback is disactivated. For given turbine characteristics and operating point, one might choose wisely a fixed parameter k_β (which corresponds to Fl_kp in the ROSCO toolbox), but the toolbox does not give indications on how to choose this parameter: instead, it suggests only one value of k_β for all operating points and turbine characteristics, while we prove (see Figure 12.) that the appropriated k_β depends on the wind speed. We think this value might be obtained by linearisation (by ROSCO toolbox), similarly to what is done for the gain scheduling of k_P and k_I (but independently to the wind speed). This method is similar to what is done in (Lenfest, 2020).
   Moreover we noticed that the platform pitch controller strategy defined in the article (Abbas,

2022) (see lines 305-310, and especially equation (47) in our paper) is not implemented in the ROSCO toolbox. (Abbas, 2022) gives an explicit formula for k_β, but as we will explain in the next point (see below, point 8.) the obtained values for k_β are very different (the sign is switched) from our formula. The results obtained by (Lenfest, 2020) are closer to our formula than the one given in (Abbas, 2022).

Concerning the simulations, choosing wisely (eg. with a linearisation by ROSCO toolbox), for a given operating point and turbine characteristics, a fixed parameter k_β would give similar results to our strategy. The added value of our work is to be able to compute explicitly (without any calibration) the value of k_β for any turbine characteristics and operating point, and to give an analytical support and an explicit formula corresponding to the numerical results already observed by (Lenfest, 2020). We consider that this question is very useful and we'll clarify this point in the introduction and in section 3.

8. Comparison about ROSCO platform pitch controller strategy and the proposed platform pitch controller strategy: The main difference in the two approaches can be remarked at lines $305-310$. As it can be remarked, the two ways to define the platform pitch compensation k_β. ROSCO derives the parameter imposing the rotor dynamics and the platform pitch dynamics to be decoupled at the first order. In other words, the effect of relative wind generated by the platform pitch dynamics is, at first order, compensated by feathering. The strategy proposed in this new paper aims at taking advantage of the blade pitch control influence on the platform pitch dynamics in order to introduce an extra term in the second order dynamics equation of the platform pitch. Thus the second order dynamics equation has an explicit form involving a damping ratio ζ_{plt} whose value one can explicitly define.

   On can, then, notice that the two formulas to define k_β for ROSCO strategy and the proposed strategy are different. Also numerically, they lead to values that are opposite in sign.

   Indeed, $\frac{\partial F_a}{\partial \beta} < 0$ (for an above-rated operating point) and therefore using inequality (51), we find that
$$k_\beta = \frac{1}{h_t \frac{\partial F_a}{\partial \beta}} \left(2\sqrt{K_t J_t}\zeta_{plt} - D_t - h_t^2 \frac{\partial F_a}{\partial v} \right) < 0$$

   On the other hand, ROSCO strategy, as it is defined in (Abbas, 2022) or (Sotckhouse, 2021) derives from the equation $A_{2,4} = 0$ where A is the matrix defined in (17) ((Abbas, 2022) introduces that same matrix) and expresses the platform pitch control coefficient as
$$k_\beta = -h_t \frac{\partial \tau_a}{\partial v} / \frac{\partial \tau_a}{\partial \beta} > 0$$

   It is negative since $\frac{\partial \tau_a}{\partial v} > 0$ and $\frac{\partial \tau_a}{\partial \beta} < 0$ (for an above-rated operating point). Notice that in (Abbas, 2022), β_{comp} is defined as in (Stockhouse, 2021) but with the convention $\beta_{comp} = k_{float}\dot{\phi}$ so that $k_{float} = -k_\beta = h_t \frac{\partial \tau_a}{\partial v} / \frac{\partial \tau_a}{\partial \beta}$ is negative, but this is just a question of conventions. If one takes the same convention, the sign is actually switched in our formula.

9. Line 254. This sentence is proposed: "It is complicated to explicit[ly determine] the damping"

10. Line 374. This sentence is proposed: "which was analysed at first order in [section] 2.5"

11. we should add a paragraph explain hox k_β is defined in ROSCO (right after 2.5.2 for example) and explain why the sign is switched.

12. For test cases in section 3.3, control signals are partially reported (rotor speed). The blade pitch can be added in the text. If this is interesting, we propose to report rotor speed and blade pitch in annex.

    For numerical tests in section 3.4, we can produce the the control signals, generator speed, and platform pitch for the proposed controller. However, we suggest to send you those figure in the discussion without reporting them in the paper. They would not add any further information and, since the wind is turbulent, they will be not easy to be interpreted. Alternatively, it can be done in an annex.

13. About the wind energy verbiage: We'll do our best to improve the verbiage and adapt it to the wind energy audience. However, "wave period" is, for instance, a typical way in offshore wind to indicate the period (inverse of frequency) of the incoming waves.

14. answer to Figure 10: Section 2.5.2 shows how the proposed strategy add an extra damping in the platform pitch by coupling rotor dynamics with platform pitch dynamics. It leads to reduce the platform pitch dynamics, however, it leads also to variation in the rotor speed. There are references to this effect at line 375 and 405.

15. Line 370. "diagram 5" will be changed to "Figure 5".

16. Figures 8 and 9 report Tower base moment (load on tower), where Figure 6 and 7 report platform pitch. The idea is to show that reducing the platform movements it will reduce the tower base moment. This is something one can imagine but it is interesting to show it by results.

17. Quality factor is defined by

$$Q = \frac{1}{2\zeta}$$

As some readers might be more used to work with quality factors instead of damping ratios, we thought it was a good thing to give the quality factors corresponding to the damping ratios. It is not mandatory for the comprehension of the paper. If you prefer, we could just delete the sentence about the quality factor, or just put it in a foot note (linked to the previous sentence).

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Answer to anonymous referee 2

1. Lines 25 and 29. In the text we'll replace "oscillating stability" by "oscillating steady-state"
2. Line 27. We'll correct in the text
3. Line 37. We'll correct in the text
4. Line 40. We'll replace "However the platform pitch damping analysis is not investigated and the link with the compensation parameter is not given " by "(Lenfest et al., 2020) investigates the (coupled) platform pitch damping and parameter tuning with a purely numerical approach. In the present work, we propose an explicit formulation for the tuning parameter related to this damping which depends on the system properties."
5. Line 54 (and other occurrences). We'll add Fischer2013 to our bibliography. We'll cite it with Stockhouse for the previous works dealing with the platform pitch compensation
6. Line 107 and others. We'll correct in the text.
7. Line 120. We'll delete " $= k_I(\theta - \Omega_r)$". It didn't add info.
8. Line 129. We'll correct in the text.
9. Line 133. We'll correct in the text.
10. Line 142. We'll correct in the text.
11. Lines 165 - 175. We'll add this reference for the NMPZs definition and comprehension: Hoagg, Bernstein, 2007, IEEE Control Systems Magazine.
12. Line 177. We'll correct in the text.
13. Line 180. A graphic visualization of the roots of G(s) will be added. In particular, we'll show how those roots move when m_{τ_g} varies, and that will explain its utility. The stability margin will be discussed.
14. Line 185. We'll add the definition of WTG in the text.
15. Tables 1, 2, 3. We'll correct the errors in the units.
16. Tables 1, 2, 3. The values are determines arbitrarily as examples, to ensure the appearance of NMPZs. This is done in the purpose of a pedagogic example to show the effects of the NMPZs. The values are purely numerical. There are not so far from the coefficients related to the IEA15MW wind turbine because we started from those physical values and we found the right coefficients, in the order of 10% or 20%, to make the system unstable. The numerical section focuses on more realistic FOWT tests.
17. Figure 2. At lines 184 - 199, we explain intuitively how equation (25) can be interpreted and how it implies a flipped sign of the steady-state response. For more details at that subject, (Hoagg, Bernstein, 2007) is very clear. We will add this reference in our bibliography.

18. Figures 2, 3, 4. We'll add units for the y-axis (ϕ is in rad and ω is in $rad.s^{-1}$). The beta-step input is of size $0.02rad$. This precision will be added in the caption.

19. Line 206. for equation 28., we'll cite Stockhouse and Fischer.

20. Line 207-225. We'll give more details about m_{τ_g}, including its dependency on D_t. For this, the graphical representation of zeros and poles will be useful.

21. Line 215. Indeed, $d\beta_{comp} = -k_\beta\dot{\phi}$! (Of course this is just a typo error and doesn't affect the analytical results.)

22. Line 221. (Stockhouse, 2021) discusses equation (29) : the parameter m_{τ_g} introduces a possible saturation of generator torque (τ_g) control. We will rephrase this in order to make it clear.

23. sec.2.3.3. This section will be improved with the poles and zeros analysis.

24. Line 233. Gain scheduling approach defines a set of "set points". For each member of if, it provides a different set of pre-computed gain parameters. The hypothesis is that the system is linear close to the set point. Our approach make the same hypothesis. However, we don't need to pre-compute a set of gain parameters for each operational set point because the gain parameters are computed by the explicit formulas (equation 37). This explanation will be reformulated and added in the text for a clear understanding.

25. Line 238. We'll replace "negative damping" by "NMPZ phenomena (combined with the closed loop control)".

26. Non, generator torque parallel compensation is not implemented in the simulation because not necessary.

27. Line 328. Equation (51) will be separated into equation 51.a, 51.b, 51.c.

28. It would be good to have a section analyzing which NMPZ is verified and for which operating point, but I am not sure how we can obtain precise values for the partial derivatives that appear in the NMPZ conditions.

29. Line 352 and 354. For k_P and k_I, many preliminary simulations, without the floating compensation, have been performed in order to obtain a set of values which works already very well for this system, without using any k_β. Those values of ζ_{rot} and ν_{rot} gave the best results, which might also be due to our choice to switch off blade pitch saturation (choice motivated to better observe the effect of our platform pitch control strategy). We will add some details about this choice in the paper. This can be considered as a "detuning strategy". This remark is important because we actually compare our strategy to a "detuning strategy" which already avoids the negative damping effects. We'll reformulate and add this to the text. However, the focus of the paper is on the floating platform compensation. Since the platform pitch control ($\beta_c omp = -k\beta\dot{\phi}$) has a damping effect on the frequencies close to the natural frequency of the platform, its tuning can reasonably be considered as independent from the tuning of the PI controller. This is why, in the paper, we didn't focus on the tuning of the PI controller, which is already well assessed in literature.

30. Section 3.3. The value of the left-hand side of the third inequality in (51) varied from case to case, but was usually between 0.055 and 0.065 (so indeed lower than 0.1). This is coherent with the fact that the system is highly under-damped.

31. Fig. 6. when the platform pitch rate is compensated, the Thrust changes because of the change in the blade pitch (induced by k_β) and the mean platform rotational position changes. In fact the system slightly shifts to another operating point.

32. Fig. 8 and 9. The main result shown here is that, while the mean values changes are very small, there are big changes in min-max and standard deviation. Figures 8 and 9 actually give more precision about this statement, since all the densities are plotted. Also DELs and extreme loads are analyzed later in the paper, on a more complete simulation.

33. Sec. 3.4. This choice is to show the as much results as possible. If necessary to be homogenized, it can be done.

34. Fig. 12. blade pitch saturation is not considered to better observe the effect of our platform pitch control strategy

35. Fig. 13. Max Rotor Speed and Max Gen Power will be added in the paper. the coupling affects rotor speed, hence, around $4m/s$ the speed is close to cut-in and the variation on the rotor speed can lead to values of power close to zero. However, it is negligible with respect to the global power production.

36. bibliography will be revised and improved

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1. **Comparison about ROSCO platform pitch controller strategy and the proposed platform pitch controller strategy**: The main difference in the two approaches can be remarked at lines $305-310$. As it can be remarked, the two ways to define the platform pitch compensation k_β. ROSCO derives the parameter imposing the rotor dynamics and the platform pitch dynamics to be decoupled at the first order. In other words, the effect of relative wind generated by the platform pitch dynamics is, at first order, compensated by feathering. The strategy proposed in this new paper aims at taking advantage of the blade pitch control influence on the platform pitch dynamics in order to introduce an extra term in the second order dynamics equation of the platform pitch. Thus the second order dynamics equation has an explicit form involving a damping ratio ζ_{plt} whose value one can explicitly define.

   On can, then, notice that the two formulas to define k_β for ROSCO strategy and the proposed strategy are different. Also numerically, they lead to values that are opposite in sign.

   Indeed, $\frac{\partial F_a}{\partial \beta} < 0$ (for an above-rated operating point) and therefore using inequality (51), we find that
$$k_\beta = \frac{1}{h_t \frac{\partial F_a}{\partial \beta}} \left(2\sqrt{K_t J_t}\zeta_{plt} - D_t - h_t^2 \frac{\partial F_a}{\partial v} \right) < 0$$

   On the other hand, ROSCO strategy, as it is defined in (Abbas, 2022) or (Sotckhouse, 2021) derives from the equation $A_{2,4} = 0$ where A is the matrix defined in (17) ((Abbas, 2022) introduces that same matrix) and expresses the platform pitch control coefficient as

$$k_\beta = -h_t \frac{\partial \tau_a}{\partial v} / \frac{\partial \tau_a}{\partial \beta} > 0$$

   It is negative since $\frac{\partial \tau_a}{\partial v} > 0$ and $\frac{\partial \tau_a}{\partial \beta} < 0$ (for an above-rated operating point). Notice that in (Abbas, 2022), β_{comp} is defined as in (Stockhouse, 2021) but with the convention $\beta_{comp} = k_{float}\dot{\phi}$ so that $k_{float} = -k_\beta = h_t \frac{\partial \tau_a}{\partial v} / \frac{\partial \tau_a}{\partial \beta}$ is negative, but this is just a question of conventions. If one takes the same convention, the sign is actually switched in our formula.

   About the comparison on the numerical tests, we tried to compare to ROSCO during the work in two ways: by using the ROSCO controller as downloaded from github and also by implementing the equations explained in Abbas2022. In both cases, the obtained results not in line with the ones found in Abbas2022. Hence, we concluded that we missed some other parameters for those simulations. It is much better to compare to a strategy with $k_{beta} = 0$. This term of comparison has not been well presented in the paper, but it corresponds to a "detuning strategy". In fact, to find the right ν_{rot} and ζ_{rot} of equations (36) at line $274-279$, a lot of simulations have been tested in order to find the best values for this platform and this wind turbine generator. However, if necessary one can compare the strategies by looking at the article Abbas2022 which considers the same numerical test as the one considered in this article.

2. line 50: comment accepted and introduced in the next paper version.

3. line 64: Lenfest2020 linearizes the k_β (called k_px in his article) and the authors calibrate a scheduling of the values of k_β by testing many numerical values, instead of making an analytical studies on the platform damping to define the parameter. The proposed strategy has an explicit form involving a damping ratio ζ_{plt} whose value one can explicitly define to obtain the right parameter.
4. Line 75, the hinge point of the platform is the COG of the platform. An image will be added to make it clear.
5. 91, comment accepted and introduced in the next paper version (τ_w replaced by τ_{wave}).
6. Line 96: comment accepted and introduced in the next paper version.
7. Line 102, comment accepted: the sentence is removed in the next paper. It does not add any information.
8. Line 121, comment accepted and introduced in the next paper version.
9. Line 125, "relative speed" replaced by "infinitesimal speed" $\omega = \Omega - \Omega_r$.
10. Line 125, Yes, it is indeed the onshore standard blade pitch control.
11. Figure 1: we'll modify the scheme to remove $\dot{\Phi}_r = 0$.
12. Line 153: "closed loop" will be added to the sentence.
13. Line 155: this is the *Laplace* domain. It will be clarified in the next version.
14. Line 161: the size of the equations with matrix is too big to write it in the article. It could be done in an Annex, if necessary.
15. Line 166: corrected
16. Line 174: corrected
17. Line 174: corrected
18. Line 167: corrected
19. Line 185: "the amplitude" will be replaced by "the importance" to make it clear
20. Line 191: "with respect to the platform pitch at the operating point" will be added
21. Line 193: we propose to replace the sentence by "When the equation is verified, it means that: τ_a is more sensitive to blade pitch than rotational speed and F_a is more sensitive to omega than blade pitch. Therefore, by increasing blade pitch ω increases and, then, occasions F_a to decrease. Then, ϕ increases."
22. Line 200 Table 1. the values are determines arbitrarily as examples, to ensure the appearance of NMPZs. This is done in the purpose of a pedagogic example to show the effects of the NMPZs. The values are purely numerical. There are not so far from the coefficients related to the IEA15MW wind turbine because we started from those physical values and we found the right coefficients, in the order of 10% or 20%, to make the system unstable. The numerical section focuses on more realistic FOWT tests.
23. Line 200. Caption clarified by: "Platform pitch (ϕ) and rotor speed (ω) responses to a blade pitch (β)-step input ..."
24. Line 220. A graphic visualization of the roots of G(s) will be added. We'll show how those roots move when m_{τ_g} varies, and that will explain its utility. (Stockhouse, 2021) introduces m_{τ_g} and explains that the choice of $m_{\tau_g} = 1$ avoids any eventual NMPZ, but is not always possible because of τ_g saturation. The stability margin will be discussed.

25. 232: for the NMPZ $\omega -- > \phi$ a solution is proposed by (Stockhouse, 2020) with the introduction of the m_{τ_g}. For the NMPZ $\beta -- > \phi$, at our knowledge it is the first time to be analysed. This paper does not investigate a solution.

26. Line 259: the coupled system is 4x4 fully populated. It is very hard to be diagonalized. We tried to solve it by using symbolic software languages. However, it didn't come to an outcome, it didn't give anything usable in practice. It has been chosen to continue on 2x2 simplified systems. In this case, damping expressions are explicit. Modal dampings could be expressed but they they should be very similar to the one already expressed because the system has only 2 dofs.

27. Line 273: Indeed, this is the same equation as for a rotor with a fixed nacelle.

28. Line 283: Actually here we are not in open-loop condition. The hypothesis $Kp = Ki = 0$ is to arrive to a 2x2 system and the control is ensured by $k_\beta \neq 0$

29. Line 322: in text we'll add "disturbance and open-loop" input.

30. Line 352: $k_{\tau_g} = 0$ has already been studied by "Stockhouse" and it was not interesting to repeat the same study

31. Line 360: Quality factor is defined by

$$Q = \frac{1}{2\zeta}$$

   As some readers might be more used to work with quality factors instead of damping ratios, we thought it was a good thing to give the quality factors corresponding to the damping ratios. It is not mandatory for the comprehension of the paper.

32. Line 366: We'll add in the text: "corresponding to Table 4" as suggested.

33. Line 367: When the platform pitch rate is compensated, the Thrust changes because of the change in the blade pitch (induced by k_β) and the mean platform rotational position change. In fact the system slightly shifts to another operating point.

34. Line 367 (Figure 6): When comparing results from section 3. with Figure 5, one should keep in mind that in in section 3, the system is way more complex: Figure 5 corresponds to a 2-dimensional state-space model. Moreover, what is underlined by Figures 6 and 7 is the comparison between the damping of an input of period 11s and an input of period 28.75s. In figure 6, the gain is much lower than in figure 7 and we can, then, see a similar trend to the one of Figure 5. When comparing Figures 6 and 7, one should also keep in mind that the chosen wave conditions have same height, but this does not mean that the input's amplitude is the same. We'll try to make this clearer in the paper.

35. Line 370: Figures 8 and 9 will be better explained.

36. Line 374: section 2.5 will be replaced by equation (50)

37. Line 399: Yes, k_β changes with time. A filter is also applied to change it smoothly since it focuses on low frequencies and it is useless to have high frequency changes.

38. Line 401: "section" added in the text.

39. Line 406: The mean value of the blade pitch changes because the increase in blade pitch variations makes the rotational speed increase. Hence in order to have this variations of the rotational speed, the mean value has to slightly decrease in order to not overpass the rated rotational speed.

40. Line 415. We correct the text by removing sentence "It is interesting .."

41. Line 424 (Table 7). This question is related to the one at Line 406. Please, refer to the previous answer.

42. Line 439. We'll explain variables in the caption.

43. Line 446. We'll replace in the text "those tendencies ..." by "they keep converging to the right solution".