

Response to Reviewers

Fixed frame Control-Oriented Modeling and Characterization of Asymmetric Wind Disturbances for Advanced Individual Pitch Control Design

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Dear Editor and Reviewers,

We would like to thank the Editor and the Reviewers for their time, constructive comments, and valuable suggestions, which have helped us improve the quality and clarity of our manuscript.

Below, we provide a point-by-point response to all the comments raised by the reviewers. For clarity, our responses are presented in **blue**, while the corresponding actions taken and changes made to the manuscript are highlighted in **red**.

In addition, a tracked-changes version of the revised manuscript has been included to facilitate the review process and allow all modifications to be easily identified.

General Remarks

First of all, after internal discussion and revision of the manuscript, we have decided to implement the following changes in addition to those arising from the comments of the reviewers:

1. We have removed the term *Control-Oriented* from the original title, as it was considered somewhat redundant in the context of a title that already highlights the use of the proposed framework for IPC control design.

Reviewer 1

General Comments

Reviewer Comment: *This work derives and validates a control-oriented framework for asymmetric wind disturbances, intended for use in IPC controller design. The relevance of the contribution is made very clear, and I personally welcome this line of work, as it could improve the process of IPC controller design when using the MBC transformation. However, in its current form I recommend major revisions before publication in Wind Energy Science for two main reasons. First, the derivation of the methodology is not yet clear enough, which makes it difficult to follow the underlying steps, assumptions, and limitations. Second, I believe the paper would become substantially stronger if the authors applied their own proposed methodology to design the IPC controllers used in the validation. I will elaborate both points below, followed by more specific comments.*

Response: The authors sincerely thank the reviewer for the careful review and constructive feedback. We greatly appreciate the positive assessment of the contribution and the valuable suggestions provided. The manuscript has been revised to address all the comments raised.

The derivation of the method

Reviewer Comment: *When trying to reproduce the derivation from Eq. 10 to Eq. 13, I arrive at a different result for Eq. 13, which in the frequency domain results in: $\delta W_d^{eq}(s) = \frac{\sum_{n=1}^N G_{y,d}^n(s) \delta u_d^n(s)}{\sum_{n=1}^N G_{y,d}^n(s)}$. I suspect the authors have assumed $G_{y,d}^n(s) = G_{y,d}^n(0)$, which indeed results in the same definition of the equivalent disturbance as in Eq. 13. If so, please note that this is not consistent with the definition announced in Eq. 11. I would like to ask the authors to either correct the derivation or state the underlying assumption explicitly, together with their justification and limitations. Since dynamic amplification can be significant in wind turbine blades, I would be curious to see whether the validation results improve further if the equivalent disturbance were computed without the steady-state assumption. In addition, would it be possible to add a plot similar to Figure 5, comparing the equivalent disturbance with and without this assumption, perhaps for different output weightings as well?*

Response: The authors thank the reviewer for this insightful comment. The reviewer correctly identified that the original derivation did not explicitly introduce the approximation leading from the exact dynamic formulation to the final equivalent disturbance definition. To address this issue, the methodology has been revised to first derive the exact equivalent disturbance in the Laplace domain and subsequently introduce the steady-state approximation explicitly. This approximation is motivated by the low-frequency nature of the wind disturbances considered, while the exact dynamic formulation requires the inversion of a transfer function that may exhibit non-minimum-phase (NMP) dynamics. Consequently, the direct reconstruction using the full dynamic formulation is not straightforward and would require dedicated inversion or estimation techniques. For this reason, the comparison suggested by the reviewer could not be performed directly within the scope of the present work.

Action taken: The derivation in Section 3.2 has been revised to explicitly introduce the exact equivalent disturbance formulation in the Laplace domain before the steady-state approximation is applied. The assumption has been explicitly stated and justified together with a discussion on the limitations associated with the inversion of NMP dynamics.

Reviewer Comment: *A minor thing about the derivation is the consistency of symbols. Symbols*

seem to switch between lower and upper case while referring to the same quantity. In addition, I think it would help the reader if a single, consistent symbol were used for quantities related to the wind disturbance (rather than both u and w).

Response: The authors thank the reviewer for this helpful observation. We agree that the simultaneous use of u and w for quantities related to the wind could be confusing. Therefore, the notation has been unified throughout the manuscript. Regarding the use of uppercase and lowercase symbols, this distinction was intentionally used to differentiate transfer functions in the Laplace domain (i.e. $G(s)$) from their corresponding time domain impulse response (i.e. $g(t)$) used in the convolution formulation. With the revision of the methodology, all the convolution formulations have been reformulated in the Laplace domain, improving the consistency of the notation.

Action taken: The notation of the horizontal nodal wind inputs has been changed from $u_{0,d,q}^n$ to $w_{0,d,q}^n$ throughout the manuscript and figures to ensure a consistent representation of wind disturbances. In addition, the methodology has been reformulated in the Laplace domain.

IPC tuning procedure

Reviewer Comment: *Having tuned simple IPC controllers myself, I have wondered whether there might be a better way to choose, for example, the crossover frequency, so I am glad to see this contribution. I think the paper would benefit from a section where the proposed method is also applied to IPC controller design. While I think that applying it using quantitative feedback theory or H -infinity would be outside the scope of this paper, and is indeed a nice future work, I do think that showing some loop gains and doing some manual loop shaping using this method would greatly improve the completeness of this work.*

This point is reinforced by the fact that the design of the two IPC controllers used for validation is not discussed in the paper. The gains and controller structure are not motivated, whereas the method introduced in this paper would offer a natural way to justify their design.

Response: The authors thank the reviewer for this valuable suggestion. We agree that the original manuscript did not sufficiently motivate the design of the IPC controllers used in the validation. To address this point, a new baseline control design subsection has been added. The purpose of this section is not to present an optimized IPC design methodology, but to illustrate how the proposed equivalent disturbance framework can be used to support and justify controller tuning decisions. The equivalent disturbance spectra are now employed to motivate the selection of the controller crossover frequency. The differences between both IPC configurations are also explicitly discussed.

Action taken: A new baseline control design subsection has been added to Section 4.4. The section introduces the disturbance-aware tuning procedure used to obtain the validation controllers. The design of both IPC configurations is now discussed and a new figure illustrating the tuning process has been incorporated.

Minor Points

Reviewer Comment: *The authors do not include the azimuth offset in the reverse MBC transformation. While this is by no means mandatory, it does conflict with certain claims made in the text. Without the azimuth offset, the tilt and yaw channels remain coupled, which prevents the use of simple linear control laws, since a MIMO controller would then be required. This seems to conflict with the statement on line 130. Related to this, Fig. 9 shows that IPC1, which gives the*

strongest attenuation, does not only attenuates the loads, it also shifts the peak of the loads to a different frequency. This is a typical result of omitting the azimuth offset. See for example Fig. 16 in Mulders, Sebastiaan Paul, Atindriyo Kusumo Pamososuryo, Gianmarco Emilio Disario, and Jan Willem van Wingerden, "Analysis and Optimal Individual Pitch Control Decoupling by Inclusion of an Azimuth Offset in the Multiblade Coordinate Transformation," Wind Energy, 2019, <https://doi.org/10.1002/we.2289>.

Response: The authors would like to thank the reviewer for this observation. We agree that the original wording could suggest a tilt-yaw decoupling. The manuscript has been revised accordingly. In addition, the baseline control design section now explicitly discuss the residual coupling between the asymmetric channels and notes that more advanced IPC architectures, including azimuth offset compensation, could be employed without affecting the applicability of the proposed framework.

Action taken: The statement in Section 2.3 has been revised. Furthermore, a discussion has been added to the baseline controller design section about the tilt-yaw coupling and the potential use of azimuth offset compensation.

Reviewer Comment: *I think it would help to add some discussion and motivation around the output weighting of the equivalent disturbance. If I am designing an IPC controller for the out-of-plane loads, for example, why would I use an output weighting based on a different output? Is this simply because a single output weighting is used across all outputs of the plant, which then introduces some inaccuracy? This point is relevant to both section 3.2 and section 4.2.2. Related to this, I would suggest turning Fig. 6 into a frequency-domain plot, similar to Fig. 5, which would give more insight into the differences one might expect between the different output weightings.*

Response: The authors thank the reviewer for this valuable suggestion. We agree that the role of the reference output in the equivalent disturbance definition required further clarification. The purpose of considering different output weightings is not to identify a preferred output for a given control objective but to assess whether the proposed equivalent disturbances represent robust inflow characteristics or are strongly influenced by the selected sensitivity weighting. To address this point, additional discussion has been included in Sections 3.2 and 4.2.2. Moreover, following the suggestion from the reviewer, Figure 6 has been extended to include the PSDs obtained from different output weightings.

Action taken: Section 3.2 has been expanded to clarify the role of the reference output in the equivalent disturbance definition and to motivate the analysis of different output weightings. In addition, Section 4.2.2 and Figure 6 have been updated to include both time-domain and frequency-domain comparisons and extend the assessment conclusions.

Specific Comments

Reviewer Comment: *Line 96-97: This could perhaps be phrased more precisely. Could the authors add that the models are averaged in the fixed reference frame to obtain models suited for conventional control design.*

Response: We agree that the original wording could be made more accurate. The text has been revised to explicitly state that the transformed models are averaged to obtain a suitable LTI model for conventional control design.

Action taken: The description of the MBC transformation in Section 2.1 has been updated.

Reviewer Comment: *Paragraph starting on line 260: Could the authors elaborate what the reader is meant to take away from this result?*

Response: We agree that an additional discussion were needed. Figure 4 was added to present a time-domain example of the equivalent disturbances. The accompanying text has been expanded to highlight the stronger low-frequency component of the collective disturbance and the similar behavior of the dq disturbances, as expected from the rotor asymmetry.

Action taken: The discussion accompanying Figure 4 has been expanded to explicitly describe the main features of the equivalent disturbances.

Reviewer Comment: *Line 305: Is there a particular reason to assess the controllers with both the R^2 and NRMSE measures? If so, could you add those insights to the paper? Are both measures showing the same underlying result and reinforce each other or do we also get additional information by including both?*

Response: We agree that additional information about the selection of the indicators were needed. Both metrics were included because they provide complementary information. While R^2 evaluates how well the reconstructed signal reproduces the dynamics of the reference signal, NRMSE provides a direct measure of the reconstruction error magnitude. Therefore, the two metrics reinforce the conclusions from different perspectives and help provide a more complete assessment of the reconstruction accuracy.

Action taken: A brief discussion has been added in Section 4.3 to clarify the complementary role of both metrics.

Reviewer Comment: *Line 331: Could the authors add what the expected difference is between these controllers?*

Response: The authors thank the reviewer for the suggestion. The expected differences between both controllers are now explicitly discussed. While IPC_1 provides stronger disturbance rejection, IPC_2 results in lower attenuation and actuator activity.

Action taken: A brief discussion describing the expected behavior of IPC_1 and IPC_2 has been added to the baseline control design section.

Reviewer Comment: *Line 349: Is standard deviation the most suitable metric here? Two quite different signals can have the same standard deviation. I do not think this is actually a problem in your case, since Fig. 9 shows good agreement, but would R^2 and/or NRMSE not be a more informative metric than standard deviation?*

Response: The authors thank the reviewer for this observation. We agree that signals with different characteristics may exhibit similar standard deviations. However, the objective of Section 4.4 is to validate the spectral propagation methodology. For this reason, time-domain metrics such as R^2 or NRMSE are not directly applicable. Instead, the agreement in the frequency domain is assessed through the PSD comparisons shown in Figure 9, while the standard deviation is used as a complementary quantitative metric.

Action taken: The discussion in Section 4.4 has been expanded to clarify that Figure 9 is used to assess the agreement of the predicted and simulated responses in the frequency domain, while the standard deviation provides a quantitative metric for supporting the conclusions.

Reviewer Comment: *Line 370: Section 5 could be structured somewhat more clearly, as it currently moves back and forth between contribution and validation between the paragraphs.*

Response: The authors thank the reviewer for this helpful suggestion. The section has been revised to maintain a clearer and more coherent progression between the contributions, validation and the future work lines.

Action taken: Conclusions section has been reorganized to improved the overall flow of the discussion and to present the contributions, validation and future perspectives in a more structured and coherent way.

Technical Corrections

Reviewer Comment:

- *Line 40: Should 'the' be removed?*
- *Line 130: Should 'low-frequency' be 'steady-state'?*
- *Line 158: On first reading, it is not very clear what "the resulting state-space model" refers to.*
- *Line 191: It might be nice to elaborate on "the transfer function" (from what to what).*
- *Line 195: "being $G(0)$..." could be reformulated to "where $G(0)$..." to be consistent with the rest of the text.*
- *Line 225: Should "are" be "is"?*
- *Line 259: Should "from" be "using"?*
- *Line 271: "frecuency" $\rightarrow$ "frequency".*
- *Line 397: "grategully" $\rightarrow$ "gratefully"*

Response: The authors thank the reviewer for the careful review of the manuscript and for identifying these technical and editorial issues.

Action taken: All comments have been addressed in the revised version.

Reviewer 2

General Comments

Reviewer Comment: *Overall, I find the topic relevant to the wind turbine control community and the manuscript presents an interesting framework with potential value for disturbance-aware individual pitch control design. In particular, the reduction of a high-dimensional distributed wind input into a small set of control-oriented equivalent disturbances, followed by validation against nonlinear aeroelastic simulations, is an appealing idea. The manuscript is generally well structured and the numerical results show good agreement between the reduced linear-model responses and the OpenFAST simulations.*

Nevertheless, I believe that several aspects of the proposed methodology require further clarification and justification to better establish the scope and validity of the proposed framework. In particular, further clarification is needed regarding the conditions under which the static sensitivity-based disturbance reduction can reproduce the dynamic response of the full distributed-input model, the assumption of a diagonal spectral density matrix for the equivalent disturbances, and the positioning of the claimed novelty with respect to previous effective-wind and disturbance-oriented IPC formulations. The dependence of the proposed disturbance representation on the selected operating point and inflow conditions should be discussed more explicitly.

Response: The authors would like to thank the reviewer for the careful evaluation of our manuscript and for the constructive comments and suggestions. We appreciate the recognition of the relevance and potential value of the proposed framework. The reviewer’s observations have helped us to improve the clarity, rigor and overall quality of the paper. In the revised manuscript, we have addressed all comments and provided additional explanations, analyses and discussions to clarify the scope, assumptions and applicability of the proposed methodology.

Equivalent disturbance formulation

Reviewer Comment: *The equivalent disturbance in Eq. (13) is constructed using the static gains, while the reduced model in Eq. (12) retains the full dynamic transfer functions. The manuscript then states that this construction “reproduces the same system response as the full set of nodal wind disturbances when propagated through the linear model”. This statement seems too strong in general.*

The static weighting in Eq. (13) preserves the DC input-output mapping by construction, but exact dynamic equivalence would require additional conditions. The good agreement shown in Fig. 7 and Table 1 indicates that the proposed approximation works very well for the investigated case. However, I suggest that the authors clarify the approximate nature and validity conditions of Eq. (13). In particular, the sentence stating that the equivalent disturbance is “built so that it reproduces the same system response as the full set of nodal wind disturbances when propagated through the linear model” suggests exact equivalence. Unless the authors can demonstrate that the normalized nodal dynamics are practically identical over the relevant frequency range, I think this wording should be softened, for example by stating that the equivalent disturbance is constructed to approximate the dominant system response, or that it is based on static sensitivities to preserve the low-frequency input-output contribution.

Response: The authors thank the reviewer for this valuable observation. We agree that the original wording suggested a stronger equivalence than can be guaranteed by the static gain formulation. As correctly pointed out by the reviewer, the proposed equivalent disturbance preserves the low-frequency input-output contribution by construction, but does not ensure exact dynamic equivalence. To address this issue, the methodology has been revised to explicitly distinguish between the exact dynamic formulation and the final approximation based on static

sensitivities. The manuscript now clarifies the assumptions underlying this approximation and its intended low-frequency interpretation.

Action taken: Section 3.2 has been revised to explicitly introduce the exact equivalent disturbance formulation in the Laplace domain and the subsequent approximation based on static sensitivities. The justification for using DC gains has been added, emphasizing the low-frequency nature of the wind disturbances considered. In addition, statements implying exact response reproduction have been replaced by wording that reflects the approximate nature of the formulation and its focus on preserving the dominant low-frequency disturbance contribution.

Cross-spectral terms in the equivalent disturbance representation

Reviewer Comment: *In Eq. (19), the disturbance spectral matrix is assumed to be diagonal, which implies that the equivalent collective, tilt and yaw disturbances are mutually uncorrelated in the spectral sense. I think this assumption requires further justification. Since the three equivalent disturbances are obtained from the same spatial turbulent wind field and transformed into the fixed frame, non-zero cross-spectral terms, particularly between the two asymmetric components, cannot be excluded a priori.*

Previous stochastic multiblade formulations have explicitly shown that cross-spectral coupling can remain after transformation to the fixed frame. For example, Thomsen et al. derived stochastic wind models in multiblade coordinates including cross-spectral relationships between the transformed disturbance components (Thomsen et al., 2010), while Shan showed that the cross-spectral terms between the two asymmetric multiblade components may contain relevant information and should not generally be neglected without verification (Shan, 2017). In the latter work, the cross terms between the collective and asymmetric components were found to be small, but this was an observed property rather than a general consequence of the transformation.

I therefore suggest that the authors quantify the cross-spectral densities or coherences between the equivalent collective, tilt, and yaw wind disturbances using the turbulent simulations already available. If these terms are negligible over the relevant frequency range, the diagonal approximation in Eq. (19) would be properly justified. I would also be interested to see whether non-negligible cross-spectral terms appear, particularly between the two asymmetric components, and whether accounting for them could help explain part of the remaining discrepancies observed in the closed-loop spectral predictions.

Response: The authors sincerely thank the reviewer for this insightful comment, which significantly improved the rigor and accuracy of the spectral formulation. Following the suggestion, the coherence between the disturbances was quantified. While negligible coherence levels were found between the collective and asymmetric components, a moderate coherence was observed between the tilt and yaw disturbances around the 3P frequency. Consequently, the cross-spectrum between the asymmetric components was incorporated into the disturbance matrix, leading to improved agreement between the predicted and simulated closed-loop responses.

Action taken: The coherence between the equivalent disturbances has been quantified and included in the manuscript through a new figure (Figure 5). Accordingly, the cross-spectrum between the asymmetric disturbances has been incorporated into the disturbance matrix. Finally, the validation results have been updated.

Positioning of the novelty with respect to previous disturbance-oriented IPC formulations

Reviewer Comment: *The novelty statement in the Introduction could, in my view, be positioned more precisely with respect to the existing disturbance-oriented IPC literature. The manuscript states that asymmetric disturbance characterization and control-oriented modeling have mainly been addressed separately, and that the disturbances responsible for exciting the loads are typically not explicitly incorporated into the IPC design process. However, previous studies have already combined several of these elements.*

For example, stochastic wind disturbance models formulated in multiblade coordinates have been explicitly incorporated into model-based IPC design (Thomsen et al., 2010). Tang et al. (2022), already cited in the manuscript, also introduce blade-specific wind disturbances and transform them into fixed-frame average, d-axis, and q-axis wind components for disturbance-aware IPC design. In addition, Shan (2017) demonstrates controller evaluation and tuning based on disturbance spectra and linear models. These works do not implement the same methodology proposed here, but they suggest that the general link between asymmetric disturbances, fixed-frame representations, and control-oriented design has been explored previously.

In my view, the specific contribution of the present work is more clearly associated with the reduction of a high-dimensional distributed wind input into three equivalent fixed-frame disturbances using whole-system input-output sensitivities, together with the validation of this reduced representation against nonlinear OpenFAST simulations. I therefore suggest that the authors reconsider the wording of the research gap and clarify more explicitly how this specific contribution differs from the previous disturbance-oriented IPC literature.

Response: The authors thank the reviewer for this valuable observation. We agree that the original research gap discussion did not sufficiently distinguish the proposed contribution from previous studies. Following the reviewer’s suggestion, the introduction has been revised to better acknowledge the existing literature and to explicitly position the novelty of this work as the sensitivity-based reduction of a high-dimensional distributed wind field, together with the validation against OpenFAST simulations.

Action taken: The research gap in the introduction has been revised. The contribution of the paper is now more explicitly described around the sensitivity-based reduction and its subsequent validation through aeroelastic simulations.

Dependence on the operating point and inflow conditions

Reviewer Comment: *The proposed equivalent disturbance representation is derived and validated at a single above-rated operating point, corresponding to a mean wind speed of 19 m/s. Since both the linearized input-output sensitivities used to construct the equivalent disturbances and the disturbance spectra may depend on the operating condition, the manuscript should discuss more explicitly how the proposed framework is expected to behave away from this operating point.*

In particular, it would be useful to clarify whether the equivalent-disturbance weights are expected to remain approximately valid over a range of above-rated wind speeds, or whether they should be recomputed as the turbine operating condition changes. A similar question applies to changes in turbulence intensity or vertical shear, since these conditions may modify the spatial and spectral characteristics of the inflow.

A full multi-operating-point validation does not seem necessary for the present manuscript, but a discussion of this dependence and of a possible extension to gain-scheduled or operating-point-dependent disturbance models would help define the practical applicability and limitations of the framework.

Response: The authors thank the reviewer for the valuable observation. We agree that the operating point dependence of the proposed framework deserved further discussion. Since all the main elements involved in the application of the framework are expected to vary with operating conditions, assessing this variability and its implications for the applicability of the methodology remains an important topic for future research.

Action taken: A discussion has been added to the conclusions section highlighting the dependence on the operating point of the proposed framework and identifying operating-point-dependent disturbance models, gain-scheduled implementations and robust control formulations as relevant directions for future work.

Practical estimation of the equivalent disturbances for real-time control applications

Reviewer Comment: *The proposed framework provides a compact and potentially useful representation of the distributed wind field through the equivalent collective, tilt, and yaw disturbances. In the present study, however, these signals are obtained from the undisturbed nodal wind velocities available from the OpenFAST simulations.*

Could the authors comment on how these equivalent disturbances might be obtained in a practical wind turbine implementation, particularly for future real-time disturbance-aware control applications, including possible feedforward or preview-based architectures? A brief discussion of the main practical difficulties would help clarify the pathway from the proposed disturbance representation toward such applications.

Response: The authors thank the reviewer for this valuable recommendation. We agree that the connection between the proposed framework and the real-time applications deserved further discussion. The document now clarifies the potential use of the equivalent disturbances in such control architectures and identifies their practical estimation for real-time implementations as an open research work line.

Action taken: A discussion has been added to the conclusions section describing the potential use of the proposed disturbance representation to feedforward and preview-based control strategies and highlighting the practical estimation of the equivalent disturbances as a relevant direction for future work.

Clarification of reconstruction, prediction, and computational savings

Reviewer Comment: *The manuscript highlights that the proposed framework can reduce the need for computationally expensive aeroelastic time-domain simulations during controller design. I agree that the spectral propagation through the reduced linear model has clear potential in this regard. However, I think the distinction between reconstruction and prediction could be clarified more explicitly.*

In the time-domain validation of Fig. 7, the equivalent disturbances are constructed from the nodal wind velocities extracted from the OpenFAST turbulent simulations and are then propagated through the reduced linear model. Therefore, this test primarily demonstrates the ability of the reduced disturbance representation and the linear model to reconstruct the corresponding nonlinear turbine response for a known inflow realization.

I would suggest clarifying which quantities need to be obtained from high-fidelity simulations before the proposed framework can subsequently be reused for controller evaluation. In particular, are the equivalent disturbance spectra intended to be characterized once for a given operating

and inflow condition and then reused to assess multiple controller designs without additional aeroelastic simulations? If so, stating this workflow more explicitly would help quantify where the computational savings are obtained and avoid possible ambiguity between reconstruction of a known turbulent realization and statistical prediction using previously characterized disturbance spectra.

Response: The authors thank the reviewer for the valuable observation. We agree that the distinction between reconstruction and spectral prediction was not sufficiently explicit in the original draft. The revised version now clarifies that the computational savings arise from the spectral framework, where the equivalent disturbance are characterized once for a given operating point and subsequently reused to assess multiple controller designs without additional aeroelastic simulations.

Action taken: A more explicit discussion has been added to the conclusions section describing the intended workflow of the methodology.

Technical corrections and minor editorial comments

Reviewer Comment: *The manuscript is generally well written, but I noticed several minor typographical and grammatical errors that should be corrected:*

- Line 86: "correspondng" → "corresponding".
- Line 121: "an specific pitch variation" → "a specific pitch variation".
- Line 129: "respresented" → "represented".
- Line 271: "rotor frecueney" → "rotor frequency".
- Line 354: "demostrating" → "demonstrating".
- Line 361: "rotor spped variability" → "rotor speed variability".
- Acknowledgements: "grategully appreciate" → "gratefully appreciate".

I also recommend a final proofreading of the manuscript to identify similar minor typographical and grammatical issues.

Response: The authors thank the reviewer for the careful review of the manuscript and for identifying these editorial issues.

Action taken: All comments have been addressed in the revised version.

Fixed Frame ~~Control-Oriented~~ Modeling and Characterization of Asymmetric Wind Disturbances for Advanced Individual Pitch Control Design

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Abstract. The development of advanced load reduction strategies is becoming increasingly important for modern wind turbines, making it essential to incorporate both the dynamics and the characteristics of the wind disturbances responsible for structural loading into the control design process. In this context, this work proposes a control-oriented framework that combines the modeling and characterization of asymmetric wind disturbances. Starting from a linearized model with distributed horizontal wind inputs, the inflow is reduced to three equivalent disturbances in a fixed reference frame through a sensitivity-based aggregation of the wind field. The methodology is validated on the IEA 15 MW Reference Wind Turbine, including all relevant aeroelastic degrees of freedom, through turbulent OpenFAST simulations. The results demonstrate accurate reconstruction of open-loop time-domain responses and prediction of closed-loop output spectra, enabling control design to be directly focused on the disturbances to be rejected while reducing the reliance on computationally expensive aeroelastic simulations.

1 Introduction

The continuous growth of wind turbine size has been one of the main drivers of the reduction in the cost of wind energy. In particular, the increase in rotor diameter has enabled higher energy capture by enlarging the swept area (Henrique et al., 2025). However, large rotors are exposed to greater spatial variability in the wind field, leading to an increase in structural loads (Trigaux et al., 2024; Canet et al., 2021). As a result, advanced control strategies have become increasingly important for modern large-scale wind turbines, not only to ensure efficient power regulation but also to mitigate the structural loads arising from complex aerodynamic excitation (Bošnjaković et al., 2022).

Despite the distributed nature of the aerodynamic interaction, wind turbine control design is commonly based on lumped linear models. In these models, the inflow disturbance is typically represented by an equivalent wind disturbance which represents the homogeneous horizontal wind speed acting on the rotor (Jonkman et al., 2018). In this context, the characterization of the equivalent wind disturbance is essential, since the resulting controller is designed according to the effect of this input on the turbine response.

The most widely adopted representation of this equivalent disturbance is the Rotor Effective Wind Speed (REWS) (Schlipf, 2008). Since collective variables such as rotor speed or generated power are mainly driven by the overall aerodynamic behaviour of the rotor, REWS provides a suitable representation of the inflow for many control-oriented applications. Accordingly, it has been extensively used in wind turbine control design, specially in LIDAR-assisted control strategies (see e.g., (Schlipf et al., 2013; Miquelez-Madariaga et al., 2022; Miquelez-Madariaga et al., 2023)). For control objectives involving collective variables, the combination of REWS disturbance characterization and conventional lumped models is generally sufficient. However, when the response of interest is primarily driven by asymmetric inflow effects, a single collective disturbance is not enough to capture the spatial variability of the aerodynamic excitation across the rotor plane.

To overcome this limitation, several alternative inflow representations have been proposed in the literature. Among them, Blade Effective Wind Speed (BEWS) formulations have been introduced to provide additional information about the aerodynamic conditions experienced by each blade (Simley and Pao, 2013). Other works have addressed the estimation of physically meaningful asymmetric inflow variables, such as wind shear, wind misalignment or upflow angle, from turbine measurements and load signals (Bottasso et al., 2018; Cacciola et al., 2016; Bertelè et al., 2017, 2024). These approaches provide information about the spatial variability of the wind field and enable the characterization of asymmetric inflow phenomena. However, their primary focus remains the estimation and characterization of the disturbances themselves, rather than the development of control-oriented models describing their effect on the turbine response.

In parallel, several control-oriented wind turbine models incorporating asymmetric aerodynamic effects have also been proposed. Since the individual pitch control (IPC) is the most commonly adopted strategy for asymmetric load alleviation (Burton et al., 2021), the vast majority of studies focus on it. For example, Selvam et al. (2009), Laks et al. (2010) and Tang et al. (2022) account for asymmetric inflow effects by introducing blade-specific wind speed disturbances, where the aerodynamic excitation of each blade is represented by an individual wind speed input. Alternatively, in Yuan et al. (2020), the aerodynamic disturbances are described through horizontal and vertical wind shear components. Nevertheless, the associated disturbances are typically introduced as model inputs without an accompanying temporal or spectral characterization. As a result, the relationship between the disturbance characteristics and the corresponding turbine response remains difficult to analyze within a unified control-oriented framework.

~~Consequently, although asymmetric disturbance characterization and~~
Consequently, previous works have explored both the characterization of asymmetric inflow disturbances and their incorporation
~~into control-oriented modeling have both been addressed separately in the literature, a unified framework combining equivalent~~
asymmetric inflow disturbance modeling and their characterization for advanced IPC frameworks. Nevertheless, a methodology
enabling the reduction of a high-dimensional distributed wind field into a small set of equivalent fixed-frame disturbances using
whole-system input-output sensitivities, together with a systematic validation of the resulting representation against nonlinear
aeroelastic simulations, is still missing. Such a framework would provide a direct link between the spatially distributed inflow,
~~its temporal and spectral characterization and the resulting turbine response within a unified control-oriented applications is~~
~~still missing. As a result, the design of advanced asymmetric load reduction strategies, such as IPC, is typically carried out~~
~~by considering only the dynamic relationship between the blade pitch inputs and the controlled loads, while the disturbances~~

responsible for exciting those loads are not explicitly incorporated into the design process (see e.g. (Lara et al., 2025; Hummel et al., 2025))

framework.

60 To address this gap, this work proposes a unified control-oriented framework based on equivalent wind disturbances in the $0dq$ reference frame. This formulation exploits the Multi-Blade Coordinate (MBC) transformation (Park, 1929), which provides a fixed-frame representation of asymmetric rotor quantities and constitutes the basis of conventional IPC implementations (Bossanyi, 2003). Within this framework, an enriched lumped disturbance model is derived by post-processing the linearized models routinely provided by aeroelastic simulation tools used in wind turbine control design. The distributed inflow is thereby
65 reduced to three equivalent disturbance channels, associated with the collective, tilt and yaw inflow components, which are subsequently characterized in time and frequency domains to support advanced asymmetric load reduction strategies.

As a result, the proposed framework enables the systematic design of asymmetric load reduction strategies by explicitly incorporating both the model and the characterization of the disturbances affecting the system. In this way, the control design effort can be rigorously linked to the characteristics of the disturbances to be rejected, leading to a more transparent and
70 consistent control design workflow. Moreover, the framework enables the prediction of the spectral response of controlled wind turbine signals directly from the linear model, facilitating the comparison and assessment of different control designs, the evaluation of disturbance-rejection capabilities, and the formulation of frequency-domain design specifications. This provides an efficient basis for advanced control-oriented analyses while reducing the need for computationally expensive aeroelastic time-domain simulations during the controller design process.

75 The remainder of the paper is organized as follows. Section 2 reviews the theoretical background on linear wind turbine modeling, the MBC transformation and the conventional IPC design. Section 3 presents the proposed equivalent disturbance framework, including the distributed wind input formulation and its reduction to three equivalent disturbances. Section 4 validates the proposed methodology through time domain simulations and spectral analyses under different closed-loop configurations. Finally, Section 5 summarizes the conclusions and future work.

80 2 Theoretical Background

This section introduces the theoretical tools on which the proposed framework is built. The linearization of the nonlinear aeroelastic wind turbine model is first reviewed to establish the linear state-space model used throughout the paper. The Multi-Blade Coordinate (MBC) transformation is then briefly presented as the standard approach for mapping rotating quantities into a fixed $0dq$ reference frame, enabling time-invariant control-oriented models. Finally, the conventional Individual Pitch Control
85 (IPC) strategy is summarized, as it provides the baseline asymmetric load reduction framework used later for validation.

2.1 Linear wind turbine modeling

Let us consider the wind turbine equations of motion, expressed in state-space form as

$$\dot{\mathbf{x}}(t) = f(\mathbf{x}(t), \mathbf{u}(t), \mathbf{w}(t)), \quad \mathbf{y}(t) = g(\mathbf{x}(t), \mathbf{u}(t), \mathbf{w}(t)), \quad (1)$$

where $\mathbf{x} \in \mathbb{R}^{n \times 1}$ is the state vector, $\mathbf{u} \in \mathbb{R}^{m \times 1}$ is the vector of inputs to the system, $\mathbf{w} \in \mathbb{R}^{p \times 1}$ is the vector of disturbances of the system and $\mathbf{y} \in \mathbb{R}^{q \times 1}$ is the vector of outputs.

The nonlinear model is linearized around a steady operating condition. Since the rotor is spinning, the steady-state solution and the ~~corresponding~~ corresponding linearized dynamics are periodic with the rotor azimuth angle ψ . Therefore, the linearization is performed at several azimuth positions ψ_k over one rotor revolution.

Around each operating point, the variables are written as deviations from their steady-state values as: $\mathbf{x} = \mathbf{x}_{op} + \delta\mathbf{x}$, leading to the first-order linear model

$$\begin{cases} \delta\dot{\mathbf{x}} = \mathbf{A}(\psi_k)\delta\mathbf{x} + \mathbf{B}(\psi_k)\delta\mathbf{u} + \mathbf{B}_w(\psi_k)\delta\mathbf{w} \\ \delta\mathbf{y} = \mathbf{C}(\psi_k)\delta\mathbf{x} + \mathbf{D}(\psi_k)\delta\mathbf{u} + \mathbf{D}_w(\psi_k)\delta\mathbf{w} \end{cases} \quad (2)$$

where the system matrices $\mathbf{A}$, $\mathbf{B}$, $\mathbf{B}_w$, $\mathbf{C}$, $\mathbf{D}$ and $\mathbf{D}_w$ are the Jacobians of f and g evaluated at the corresponding azimuth-dependent operating point.

The result of the linearization is a periodic model consisting of a family of linear models describing the local input-output behavior of the wind turbine around the selected operating point. Although these models provide the basis for linear control-oriented analysis, their explicit azimuth dependence prevents their direct use as standard linear time-invariant (LTI) representations. The MBC transformation, introduced in the next subsection, is commonly used to project rotating quantities into a fixed reference frame ~~and obtain models~~, enabling the transformed models to be averaged into a single time-invariant representation suitable for conventional control design.

2.2 Multi-blade coordinate transformation

As discussed in the previous subsection, the linearized wind turbine model depends periodically on the rotor azimuth angle. This periodicity arises from the interaction between rotating components, such as the blades, and non-rotating components, such as the tower, for example. As a result, the state-space matrices obtained at different azimuth positions cannot be directly averaged while relevant state, input or output signals remain expressed in the rotating frame (Stol et al., 2009).

The Multi-Blade Coordinate (MBC) transformation $T(\psi(t))$ provides a standard procedure to express three-bladed rotating quantities in a fixed reference frame (Park, 1929). Given a generic rotating signal $\mathbf{y}_{123}(t) = [y_1(t), y_2(t), y_3(t)]^\top$, the transformation into collective (0), tilt (d) and yaw (q) axis is defined as

$$\begin{bmatrix} y_0(t) \\ y_d(t) \\ y_q(t) \end{bmatrix} = \frac{2}{3} \underbrace{\begin{bmatrix} 1/2 & 1/2 & 1/2 \\ \cos(\psi(t)) & \cos(\psi(t) + \frac{2\pi}{3}) & \cos(\psi(t) + \frac{4\pi}{3}) \\ \sin(\psi(t)) & \sin(\psi(t) + \frac{2\pi}{3}) & \sin(\psi(t) + \frac{4\pi}{3}) \end{bmatrix}}_{T(\psi(t))} \begin{bmatrix} y_1(t) \\ y_2(t) \\ y_3(t) \end{bmatrix}. \quad (3)$$

The 0 component represents the collective contribution, while the d and q components describe asymmetric contributions associated with the tilt and yaw directions, respectively.

Similarly, the inverse transformation $T^{-1}(\psi(t))$ maps non-rotating quantities back to the rotating frame as

$$\begin{bmatrix} y_1(t) \\ y_2(t) \\ y_3(t) \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & \cos(\psi(t)) & \sin(\psi(t)) \\ 1 & \cos(\psi(t) + \frac{2\pi}{3}) & \sin(\psi(t) + \frac{2\pi}{3}) \\ 1 & \cos(\psi(t) + \frac{4\pi}{3}) & \sin(\psi(t) + \frac{4\pi}{3}) \end{bmatrix}}_{T^{-1}(\psi(t))} \begin{bmatrix} y_0(t) \\ y_d(t) \\ y_q(t) \end{bmatrix}. \quad (4)$$

The MBC transformation can be applied directly to the azimuth dependent set of state space models obtained from the linearization process. By applying this transformation to rotating states, inputs and outputs, the dominant azimuth-dependent terms of the linearized model are removed or significantly reduced (Bir, 2008). The transformed system matrices can then be consistently averaged over one rotor revolution, leading to a single linear time-invariant representation of the form

$$\begin{cases} \delta \dot{\mathbf{x}}_{0dq} = \bar{\mathbf{A}}_{0dq} \delta \mathbf{x}_{0dq} + \bar{\mathbf{B}}_{0dq} \delta \mathbf{u}_{0dq} + \bar{\mathbf{B}}_{w,0dq} \delta \mathbf{w}_{0dq}, \\ \delta \mathbf{y}_{0dq} = \bar{\mathbf{C}}_{0dq} \delta \mathbf{x}_{0dq} + \bar{\mathbf{D}}_{0dq} \delta \mathbf{u}_{0dq} + \bar{\mathbf{D}}_{w,0dq} \delta \mathbf{w}_{0dq}. \end{cases} \quad (5)$$

This fixed-frame representation is particularly useful for wind turbine control, since periodic blade loads can be expressed as nearly stationary quantities in the dq frame. This principle is exploited in conventional Individual Pitch Control (IPC) strategy, which is briefly reviewed in the following subsection.

2.3 Conventional IPC framework

Individual Pitch Control (IPC) is a well-known control strategy aimed at mitigating periodic structural loads. Unlike collective pitch control, which applies the same pitch command to all blades, IPC generates ~~an~~ a specific pitch variation for each blade to counteract asymmetric aerodynamic loading (Burton et al., 2021). This is particularly important in large-scale wind turbines where spatial variations in the wind field lead to significant periodic loads, primarily at once-per-revolution and higher harmonic frequencies (nP) (Dai et al., 2022).

The primary objective of traditional IPC strategies is to reduce out-of-plane (OoP) blade vibrations. As mentioned in the previous subsection, classical implementations use the ~~Multi-Blade-Coordinate (MBC)~~ MBC transformation to express the OoP bending moments of each blade M_{123} from the rotating frame to the fixed (non-rotating) frame, following the Equation (3). In this way, the resulting signals M_{0dq} can be interpreted as virtual moments associated with the collective, tilt and yaw motions of the rotor, as depicted in Figure 1. The periodic blade loads that appear at 1P in the rotating frame are therefore ~~represented as low-frequency~~ represented as steady-state signals in the $0dq$ frame, which ~~enables the use of simple linear control laws~~ facilitates the application of conventional linear control techniques (Bossanyi, 2003).

The usual IPC objective is to reject these asymmetric load components by regulating $M_{d,q}$ towards zero, while the collective component M_0 is typically not used for IPC action. The controller generates virtual pitch commands in the fixed frame $\beta_{d,q}$, which are transformed back to individual blade pitch references through the inverse MBC transformation (Equation (4)), where β_0 denotes the collective pitch contribution, usually provided by the rotor speed loop.

This conventional architecture is summarized in Figure 2 in the Laplace domain, where $P_{0dq}(s)$ denotes the wind turbine plant expressed in the fixed reference frame. The diagram highlights that IPC is designed from the pitch-to-load dynamics

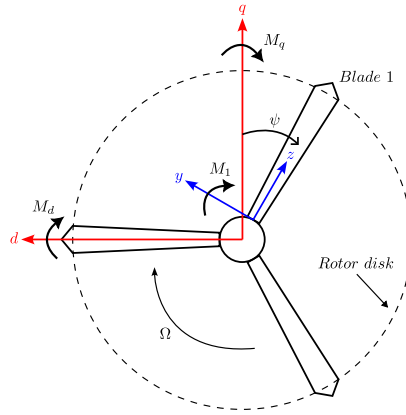


Figure 1. Definition of the blade rotating frame (blue) and the rotor fixed frame (red).

145 and the measured asymmetric outputs. However, the disturbances responsible for exciting these signals are not explicitly represented. This is precisely the enhancement that this work proposes: a design framework in which the disturbances that the IPC loop must face are accurately described and, consequently, more easily tackled.

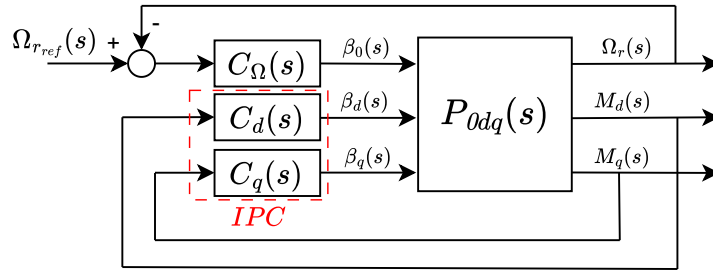


Figure 2. Block diagram used for the control baseline design.

This conventional IPC framework provides the control-oriented context for the present work, in which asymmetric loads are naturally handled in the fixed frame. The following section addresses the lack of an explicit disturbance representation by
 150 introducing a framework that models and characterizes the disturbances exciting these channels.

3 Equivalent Disturbance Framework

To address the need for modeling and characterizing the asymmetric disturbances affecting the system, this section introduces the proposed equivalent disturbance framework. The disturbance input vector of the linearized model is augmented with blade-node horizontal wind disturbances and subsequently reduced, through a sensitivity-based formulation, to three equivalent
 155 disturbances in the fixed $0dq$ frame suitable for control-oriented analysis and design.

3.1 Distributed horizontal wind input

Let $\underline{w}_b^n$ denote the horizontal wind speed at blade $b \in \{1, 2, 3\}$ and node $n \in \{1, \dots, N\}$, where each node corresponds to a discrete blade-element location along the blade span. The distributed horizontal wind disturbance vector $\delta \mathbf{w}_{dist,123}$ is then constructed as

$$160 \quad \delta \mathbf{w}_{dist,123} = [\delta \underline{w}_1^1, \dots, \delta \underline{w}_1^N, \delta \underline{w}_2^1, \dots, \delta \underline{w}_2^N, \delta \underline{w}_3^1, \dots, \delta \underline{w}_3^N]^\top. \quad (6)$$

The resulting state-space model integrates the relationship between the outputs of the system with the nodal horizontal undisturbed wind of each blade. By introducing this disturbance vector into the linearized model, the state-space representation is augmented to explicitly describe the influence of the nodal horizontal wind disturbances on the system outputs.

Although this formulation preserves the distributed nature of the wind field, the resulting disturbance vector is high-dimensional and expressed in the rotating blade frame. Following the state-space MBC formulation (Bir, 2008), the transformation is applied similarly to the distributed disturbance input. In this way, the blade-frame nodal wind disturbances are expressed in the fixed $0dq$ frame, yielding an equivalent disturbance input vector composed of collective, tilt and yaw horizontal wind components at each radial position. The transformed disturbance vector is defined as

$$\delta \mathbf{w}_{dist,0dq} = [\delta \underline{w}_0^1, \dots, \delta \underline{w}_0^N, \delta \underline{w}_d^1, \dots, \delta \underline{w}_d^N, \delta \underline{w}_q^1, \dots, \delta \underline{w}_q^N]^\top. \quad (7)$$

170 After applying the MBC transformation to the azimuth-dependent state-space model and averaging the transformed matrices over one rotor revolution, the augmented fixed-frame LTI representation is defined as

$$\begin{cases} \delta \dot{\mathbf{x}}_{0dq} = \bar{\mathbf{A}}_{0dq} \delta \mathbf{x}_{0dq} + \bar{\mathbf{B}}_{0dq} \delta \mathbf{u}_{0dq} + \bar{\mathbf{B}}_{w,0dq} \delta \mathbf{w}_{dist,0dq}, \\ \delta \mathbf{y}_{0dq} = \bar{\mathbf{C}}_{0dq} \delta \mathbf{x}_{0dq} + \bar{\mathbf{D}}_{0dq} \delta \mathbf{u}_{0dq} + \bar{\mathbf{D}}_{w,0dq} \delta \mathbf{w}_{dist,0dq}. \end{cases} \quad (8)$$

In this model, the distributed wind disturbance is represented by $3N$ fixed-frame input channels, corresponding to collective, tilt and yaw wind components at each radial node. Although this representation preserves the spatial structure of the inflow and enables the computation of fixed-frame input-output sensitivities, its high dimensionality makes it unsuitable for direct disturbance characterization and control-oriented analysis, motivating the reduced equivalent disturbance formulation introduced in the following subsection.

3.2 Equivalent disturbance definition

To address the high dimensionality of the distributed wind input, a reduced-order disturbance representation is proposed. The key idea is to replace the distributed wind inputs by a minimal set of equivalent disturbance channels defined in the $0dq$ reference frame. These equivalent disturbances are built such that they preserve the input-output behaviour of the system with respect to selected outputs, while enabling a low-dimensional and physically interpretable description of the inflow.

Accordingly, one equivalent disturbance is defined for each component of the fixed $0dq$ reference frame, yielding three disturbance channels associated with the collective, tilt and yaw inflow components. These disturbances are denoted as δW_0^{eq} ,

185 δW_d^{eq} and δW_q^{eq} , respectively. This leads to a reduced LTI representation of the form

$$\delta Y(s) = G_{y,0}^{eq}(s)\delta W_0^{eq}(s) + G_{y,d}^{eq}(s)\delta W_d^{eq}(s) + G_{y,q}^{eq}(s)\delta W_q^{eq}(s), \quad (9)$$

where $G_{y,i}^{eq}(s)$, with $i \in \{0, d, q\}$, denotes the equivalent transfer function from the corresponding equivalent disturbance to the output y .

The equivalent disturbance signals are defined by exploiting the linear superposition property of the LTI model and the
 190 spatial distribution of the input-output sensitivities, defined as the gains between the distributed wind inputs and the selected output. For a given output $y(t)$, the contribution of the distributed wind inputs in a given Odq channel (e.g. the d axis) can be expressed as

$$\delta y_d(\underline{t}) = \sum_{n=1}^N \underline{g}_{y,u_d} \underline{G}_{y,d}^n(\underline{t}) * \underline{u} \underline{w}_d^n(\underline{t}), \quad (10)$$

where ~~$\underline{g}_{y,u_d}^n(t)$ denotes the impulse response of the~~ $\underline{G}_{y,d}^n(s)$ ~~denotes the~~ transfer function from the wind disturbance $\delta u_d^n(t)$
 195 ~~$\delta w_d^n(s)$ at radial position n to the output $y(t)$. This expression highlights that the system response results from the weighted contribution of all radial elements, as determined by their respective input-output sensitivities.~~ y .

The equivalent disturbance δW_d^{eq} is then defined such that the same input-output mapping is preserved in a reduced order form as

$$\delta y_d(\underline{t}) = \underline{g}_{y,d}^{eq}(\underline{t}) * \delta W_d^{eq}(\underline{t}), \quad (11)$$

200 where ~~$\underline{g}_{y,d}^{eq}(t)$ is the impulse response of the transfer function given by~~ the equivalent transfer function is obtained as

$$G_{y,d}^{eq}(s) = \sum_{n=1}^N G_{y,d}^n(s). \quad (12)$$

This leads to the following definition of the equivalent disturbance:

$$\delta W_d^{eq}(\underline{t}) = \frac{\sum_{n=1}^N G_{y,d}^n(0) \delta u_d^n(t)}{\sum_{n=1}^N G_{y,d}^n(0)}, \frac{\sum_{n=1}^N G_{y,d}^n(s) \delta w_d^n(s)}{G_{y,d}^{eq}(s)}. \quad (13)$$

being $G(0)$ the static gains of the selected transfer functions. Analogous expressions are obtained for the collective $\delta W_0^{eq}(t)$
 205 and yaw components $\delta W_q^{eq}(t)$.

In this way, the term $\delta W_{0,d,q}^{eq}(t)$ represents a reduced-order description of the distributed inflow in the Odq axis, built so that it reproduces the same system response as the full set of nodal wind disturbances when propagated through the linear model

This definition preserves the input-output relationship of the distributed model. However, its computation requires a frequency
 dependent weighting of the distributed wind disturbances. In the time domain, the convolution process contains the inverse
 210 of the equivalent transfer function $G_{y,d}^{eq}(s)$. Since the wind turbine dynamics may exhibit non-minimum-phase zeros, the corresponding inverse system is generally unstable, making the direct reconstruction of the equivalent disturbance non-trivial and potentially requiring dedicated inversion or estimation techniques.

Nevertheless, the objective of the proposed framework is to obtain a physically meaningful disturbance representation suitable for characterization and control-oriented analysis. Since turbulent wind disturbances are predominantly characterized by low-frequency content, the frequency dependent sensitivity weighting is approximated by its steady state value. In this sense, the equivalent disturbance can be interpreted as a projection of the spatially distributed wind field onto a single control-relevant coordinate-way, the low-frequency input-output contribution of each radial wind disturbance is preserved while avoiding the inversion of the dynamic transfer function. This leads to the following approximation,

$$\delta W_d^{eq}(t) = \frac{\sum_{n=1}^N G_{y,d}^n(0) \delta w_d^n(t)}{G_{y,d}^{eq}(0)}. \quad (14)$$

Analogous expressions are obtained for the collective $\delta W_0^{eq}(t)$ and yaw components $\delta W_q^{eq}(t)$.

The formulation shows that the equivalent disturbances are resulting equivalent disturbances $\delta W_{0,d,q}^{eq}(t)$ are therefore obtained through a sensitivity weighted aggregation of the distributed wind inputs. The, where the weighting factors are directly determined by the static input-output sensitivities of the system $G(0)$, such that rotor- Rotor regions with higher influence on the selected output contribute more strongly to the equivalent disturbance. The use of static gains in this definition ensures that the dynamic characteristics of the wind signal are preserved, while the system dynamics are subsequent. As a result, the equivalent disturbances can be interpreted as low-frequency, control relevant projections of the distributed wind field onto a reduced set of coordinates. The dynamic behavior of the system is subsequently captured through the equivalent dynamic model transfer functions $G_{y,i}^{eq}(s)$.

The construction of the equivalent disturbances requires the selection of a reference output to define the sensitivity weights. Therefore, the resulting disturbances are, in principle, output-dependent. In practice, physically meaningful output pairings are selected for each Odq channel, such as a collective response for δW_0^{eq} and fixed-frame asymmetric load components for δW_d^{eq} and δW_q^{eq} . These canonical pairings provide a physically consistent definition of the equivalent disturbance channels, as each set of sensitivity weights is derived from an output directly associated with the corresponding inflow component. The performance of the resulting reduced-order formulation. Although alternative output selections may lead to slightly different sensitivity distributions, the resulting equivalent disturbances are expected to capture the dominant inflow structures at each Odq component. The sensitivity of the proposed formulation to the selected reference output is assessed in the validation section Section 4.2.2.

4 Validation

Once the methodology has been defined, the objective is to assess its capability to represent the wind turbine response using the reduced order linear model. This section presents the validation of the framework through high-fidelity aeroelastic simulations. First, the simulation setup is described. Then, the equivalent disturbances are characterized and their robustness with respect to the selected reference output is assessed. Subsequently, the reduced-order model is validated in the open-loop time domain. Finally, the characterized disturbance spectra are-is propagated through the closed-loop transfer functions to assess the ability of the proposed framework to predict the output PSDs-power spectral densities (PSDs) under different control configurations.

245 4.1 Simulation setup

The proposed method is validated using the IEA 15 MW Reference Wind Turbine in its offshore monopile configuration (Gaertner et al., 2020), with rated power 15 MW, rotor diameter 240 m and hub height 150 m. The turbine is modeled and simulated in OpenFAST (Jonkman and Buhl, 2005), which is also used to obtain the linearized models required for the equivalent disturbance formulation. To capture the dominant aeroelastic couplings for simulation and control design, the model incorporates
250 the following degrees of freedom (DOFs):

- **Blades:** First and second flapwise bending modes and first edgewise bending mode of each blade.
- **Tower:** First and second fore-aft and side-side bending moments.
- **Nacelle and Drivetrain:** Yaw motion and generator rotation.
- **Foundation:** Translational and rotational motions of the support structure.

255 The selected operating point (OP) corresponds to above-rated operation at a mean wind speed of 19 m/s, with vertical shear coefficient 0.2, blade pitch angle 16.5 deg and rated generator torque. The linear model is obtained around this OP from 36 azimuth-dependent state space linear models, computed every 10 degrees over one rotor revolution. For the distributed wind formulation, the horizontal wind disturbance is defined at $N = 50$ nodes per blade, resulting in an augmented disturbance vector of $3N = 150$ elements before the equivalent disturbance reduction.

260 Time-domain aeroelastic simulations are carried out in OpenFAST using turbulent wind fields generated with TurbSim (Jonkman, 2009). Ten independent turbulent wind seeds are considered, each with a duration of 3600s, following IEC class B Normal Turbulence Model conditions based on the Kaimal spectrum (IEC Technical Committee, 2020). For the closed-loop simulations, control algorithms are implemented through the MATLAB/Simulink interface. Hydrodynamic excitation is neglected by considering still water conditions.

265 4.2 Equivalent disturbances characterization

This subsection characterizes the equivalent disturbances obtained for the considered case study before using them for response reconstruction and spectral propagation. First, their time-domain behavior and open-loop power spectral densities are analyzed from turbulent wind simulations. Then, their dependence on the selected reference output is assessed to verify the consistency of the canonical input-output pairings adopted in the following validation steps.

270 4.2.1 Temporal and spectral characterization

The equivalent disturbances are first computed from open-loop turbulent simulations using the methodology proposed in Section 3.2. For each equivalent Odq disturbance, the sensitivity weights are obtained from physically aligned reference outputs. Rotor speed Ω_r is used for the collective disturbance $\delta W_0^{eq}(t)$, while the tilt and yaw moments, M_d and M_q , obtained from the blade root bending moments, are used for $\delta W_d^{eq}(t)$ and $\delta W_q^{eq}(t)$, respectively.

275 Figure 3 depicts the corresponding normalized sensitivity distributions along the rotor span. These distributions represent the relative contribution of each radial position to the equivalent disturbance definition. For the collective θ channel, the sensitivity associated with Ω_r remains relatively uniform over most of the blade span, indicating that rotor speed is mainly influenced by the overall collective inflow across the rotor. In contrast, the asymmetric channels exhibit a stronger contribution from the outer rotor sections, reflecting the increasing aerodynamic leverage of these regions on the tilt and yaw moments. Moreover, due to
280 the rotor symmetry, they appear practically superimposed.

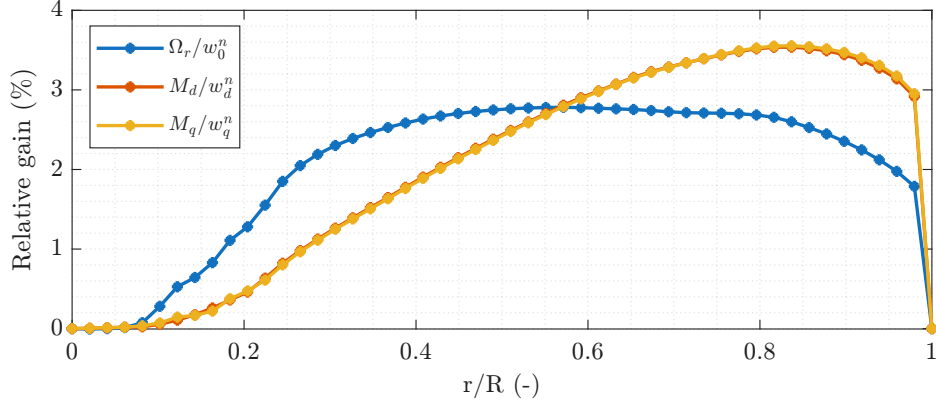


Figure 3. Normalized radial sensitivity distributions used to define the equivalent collective (blue), tilt (red) and yaw (yellow) disturbances. The gain at each radial position is expressed as a percentage of the total equivalent gain.

For each turbulent seed, the undisturbed horizontal wind speed at each blade node are extracted and processed to obtain the corresponding fixed-frame components $u_{0dq}^n(t)$ and $w_{0dq}^n(t)$. To avoid inconsistencies with the treatment of linear models, their mean values, associated with the OP, are removed before applying the reduction methodology proposed.

285 Once the radial sensitivity weights and the corresponding time-domain wind signals $u_{0dq}^n(t)$ and $w_{0dq}^n(t)$ have been defined, the equivalent disturbances $\delta W_0^{eq}(t)$, $\delta W_d^{eq}(t)$ and $\delta W_q^{eq}(t)$ are computed from using Equation (14).

Figure 4 shows a representative time-domain realization of the equivalent disturbances. The blue lines represent the instantaneous equivalent disturbances, while the red lines show a moving-average filtered version of the same signals, included for visualization purposes to highlight their underlying trends. Note that all three signals represent disturbances with respect to the operating point and therefore oscillate around zero. The figure illustrates that the equivalent disturbances capture both the low-frequency turbulent variations and the periodic components introduced by the rotational sampling of the wind field. The collective disturbance exhibits a more pronounced low-frequency component than the asymmetric disturbances, while the dq signals, based on the symmetry of the rotor, present a very similar low-frequency behavior.

290

The ~~Power Spectral Densities (PSDs)~~ PSDs of the equivalent of the equivalent disturbances are estimated from the open-loop turbulent simulations using Welch's method and averaged over the ten wind seeds. The resulting ~~spectra, shown $0dq$~~ auto-spectra are depicted in Figure 5, ~~provide the frequency domain characterization of the $0dq$ equivalent disturbances used~~

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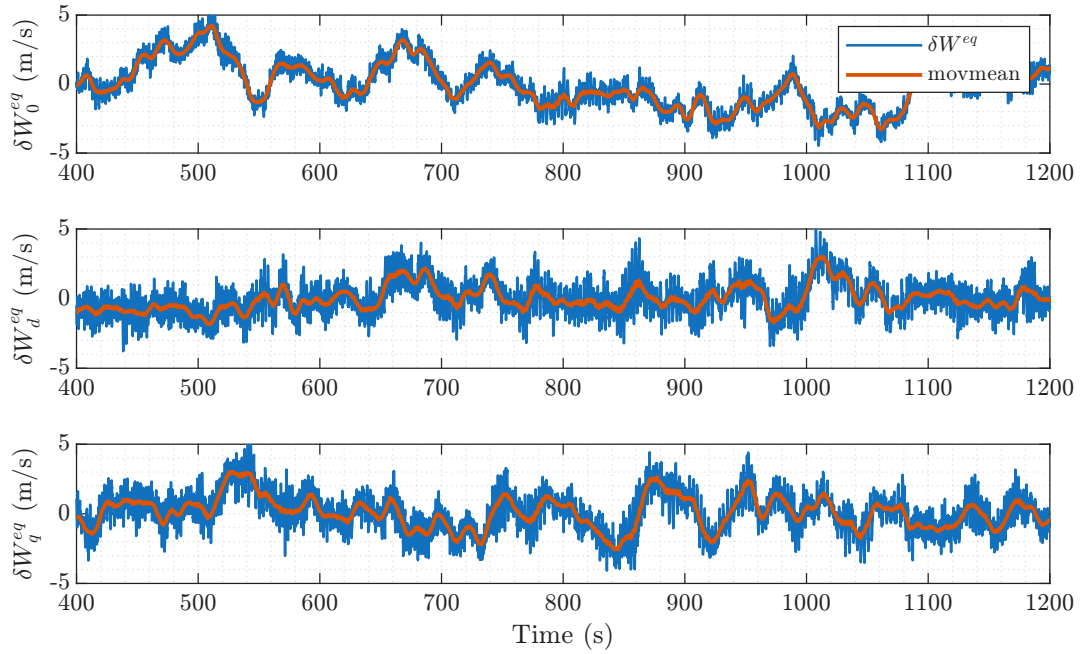


Figure 4. Equivalent wind disturbances in the Odq frame. Blue lines show instantaneous signals, while red lines indicate moving-average trends.

later for the closed-loop spectral propagation. The collective component exhibits the largest low-frequency content, whereas the dq components show very similar spectral levels due to the symmetry of the rotor.

Power spectral densities of the equivalent wind disturbances in the Odq reference frame, obtained from turbulent open-loop simulations.

Since the nodal wind velocities are obtained at blade positions that are rotating with the rotor, the equivalent disturbances inherently contain forced periodic components associated with the rotational sampling of the wind field. These components appear as harmonics of the rotor frequency nP in the blade frame. After the MBC transformation, these components appear at multiples of $3nP$. Consequently, the temporal signals exhibit the high-frequency ripple visible in Figure 4, while distinct spectral peaks can be observed around the $3P$ and $6P$ frequencies in Figure 5.

4.2.2 Output invariance assessment

In addition to the auto-PSD characterization, the spectral coupling between the equivalent disturbances is assessed through the magnitude-squared coherence. Previous studies have shown that non-negligible cross-spectral terms may remain after the MBC transformation, specially in the asymmetric components (Thomsen et al., 2010; Shan, 2017). The coherences obtained from the turbulent simulations are also shown in Figure 5. The results indicate low coherence between the collective and asymmetric components over the frequency range. In contrast, a higher coherence is observed between the asymmetric components around

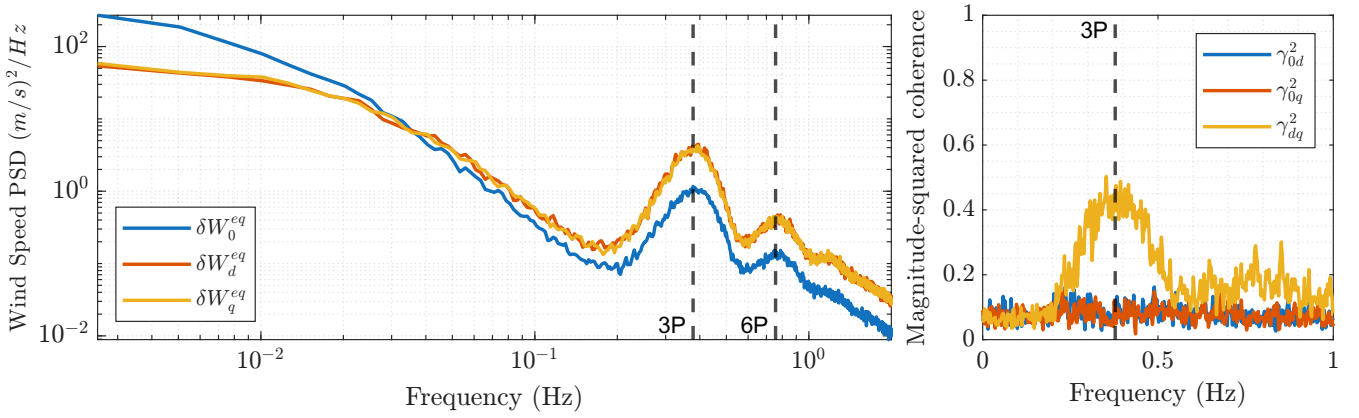


Figure 5. Power spectral densities (left) and magnitude-squared coherences (right) of the equivalent wind disturbances in the $0dq$ reference frame, obtained from turbulent open loop simulations.

the 3P frequency. This behavior suggests that, while the collective disturbance can be considered approximately decoupled from the asymmetric channels, some coupling remains between the asymmetric components, mainly associated with the periodic content introduced by the rotational sampling of the wind field.

Based on these results, the spectral matrix of the equivalent disturbances is defined as

$$S_{ww}(\omega) = \begin{bmatrix} S_{00}(\omega) & 0 & 0 \\ 0 & S_{dd}(\omega) & S_{dq}(\omega) \\ 0 & S_{qd}(\omega) & S_{qq}(\omega) \end{bmatrix}, \quad (15)$$

where $S_{00}(\omega)$, $S_{dd}(\omega)$ and $S_{qq}(\omega)$ are the auto-spectra of δW_0^{eq} , δW_d^{eq} and δW_q^{eq} , respectively, while $S_{dq}(\omega)$ and $S_{qd}(\omega)$ denote the cross-spectra between the asymmetric components. This disturbance spectral matrix will be used in Section 4.4 for the closed-loop spectral propagation and output PSD estimation.

4.2.2 Output invariance assessment

Since the equivalent disturbance weights are defined from input-output sensitivities, the resulting signals may depend on the selected reference output. To assess this dependence, the equivalent disturbances are computed using four different outputs: rotor speed (Ω_r), tilt moment (M_d), yaw moment (M_q) and tower base bending moment ($TwrMy$). The resulting time series are compared in Figure 6.

The results show that the equivalent disturbances obtained from different reference outputs are highly consistent, with both the corresponding time series and PSDs being almost superimposed for each $0dq$ channel. This indicates that the proposed methodology captures dominant collective and asymmetric inflow components that are largely independent of the particular output used for their construction.

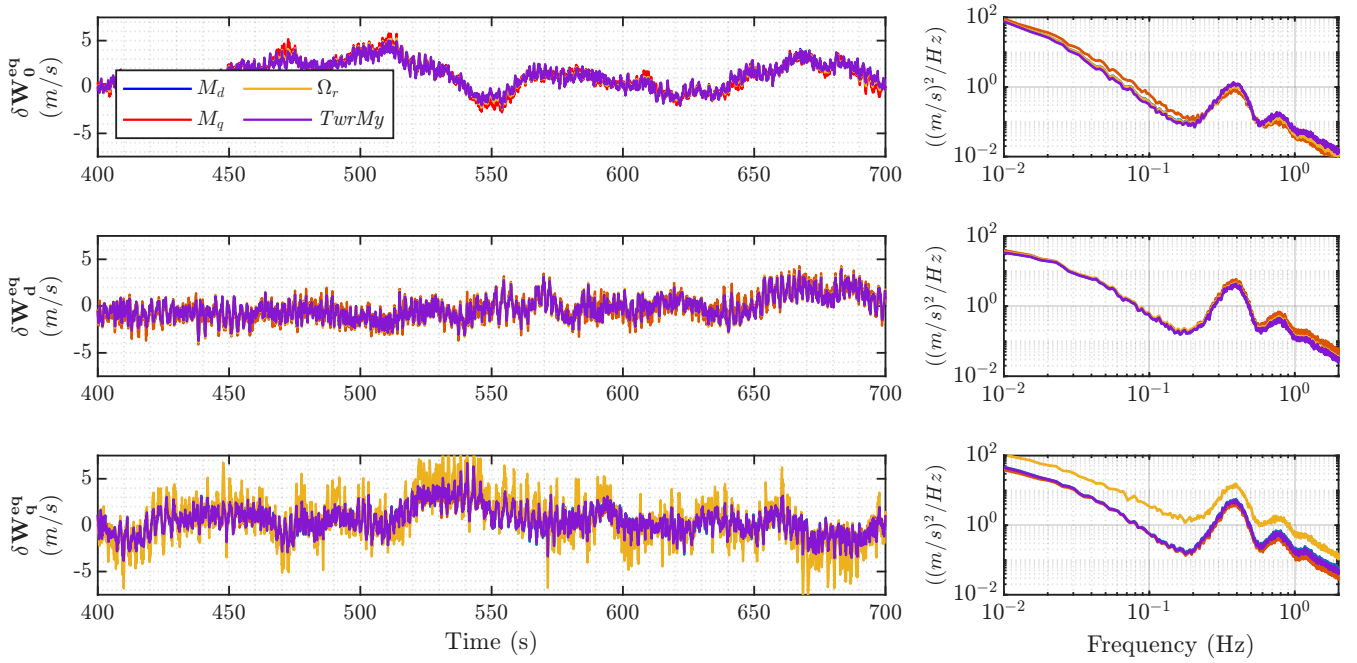


Figure 6. Equivalent wind disturbances in the Odq frame characterized from four different system outputs both in temporal and frequency domain.

Small deviations From a practical perspective, this results suggests that the reference output mainly affects the sensitivity weighting employed in the disturbance aggregation, rather than the dominant inflow structures presented by the equivalent disturbances. Therefore, although the disturbance definition is formally output-dependent, physically meaningful output selections lead to very similar disturbance characterizations.

Deviations observed are mainly associated with reference outputs whose radial sensitivity distributions present sign changes along the rotor span, leading to partial cancellations in the weighted aggregation. Therefore, based on this analysis, the canonical input-output pairings, defined in the previous subsection, are adopted for the remainder of the validation.

345 4.3 Open-loop time-domain validation

The time-domain validation assesses the ability of the proposed reduced-order linear model to reproduce the turbine response under open-loop turbulent conditions. For each wind realization, the three equivalent disturbances $\{\delta W_0^{eq}(t), \delta W_d^{eq}(t), \delta W_q^{eq}(t)\}$ are computed from OpenFAST ~~$w_{0dq}^n(t)$~~ $\delta w_{0dq}^n(t)$ measurements and used as inputs to the equivalent LTI model. The reconstructed output $\delta \hat{y}(t)$ is obtained as

$$340 \quad \delta \hat{y}(t) = g_{y,0}^{eq}(t) * \delta W_0^{eq}(t) + g_{y,d}^{eq}(t) * \delta W_d^{eq}(t) + g_{y,q}^{eq}(t) * \delta W_q^{eq}(t). \quad (16)$$

where $g_{y,i}^{eq}(t)$ is the impulse response of the transfer function between the output $y(t)$ and the corresponding equivalent disturbance input.

The outputs are also reconstructed using the conventional Rotor Effective Wind Speed (REWS) representation, defined as the horizontal wind speed averaged over the rotor disk (Schlipf et al., 2013). In this case, the standard linear model is employed, where REWS constitutes the single disturbance input of the system (Jonkman et al., 2018). This provides a benchmark to assess the benefits of explicitly incorporating asymmetric disturbance channels into the model.

The reconstructed signals are compared with the corresponding outputs obtained from nonlinear OpenFAST simulations. The selected outputs are rotor speed Ω_r , tilt moment M_d , yaw moment M_q and tower-base bending moment $TwrMy$, which provide a representative set of collective and asymmetric responses relevant for control design.

Figure 7 compares the simulated responses with those reconstructed using the proposed equivalent disturbance framework and the conventional REWS-based representation. The proposed framework reproduces the main features of all considered outputs, showing a close agreement with the nonlinear simulations. The REWS-based reconstruction also captures the dominant trends of outputs mainly influenced by the collective inflow, such as rotor speed Ω_r and, to some extent, the tower-base bending moment $TwrMy$. However, as expected, it is unable to reproduce the asymmetric responses represented by the tilt and yaw moments M_d and M_q .

A quantitative assessment is performed over the ten turbulent wind realizations using the coefficient of determination, R^2 , and the normalized root mean square error, $NRMSE$, defined as

$$R^2 = 1 - \frac{\sum_{i=1}^K (y_i - \hat{y}_i)^2}{\sum_{i=1}^K (y_i - \bar{y})^2}, \quad NRMSE(\%) = \frac{100}{y_{max} - y_{min}} \sqrt{\frac{1}{K} \sum_{i=1}^K (y_i - \hat{y}_i)^2}. \quad (17)$$

While R^2 evaluates the ability of the reconstructed signal to reproduce the variability of the reference response, $NRMSE$ provides a direct measure of the reconstruction error magnitude. Therefore, both metrics provide complementary information regarding the accuracy of the proposed framework.

Table 1 summarizes the mean (μ) and standard deviation (σ) of both metrics. The results show high reconstruction accuracy for all analyzed outputs, with R^2 values above 0.92 and $NRMSE$ values below 4%. This confirms that the three equivalent disturbances, together with the reduced-order LTI model, capture the dominant response of the turbine under distributed turbulent inflow.

For the rotor speed Ω_r , both the proposed framework and the conventional REWS-based representation provide accurate reconstructions, as this variable is predominantly driven by the collective inflow. In contrast, $TwrMy$ is reproduced significantly more accurately by the proposed methodology, indicating that asymmetric inflow effects make a relevant contribution to this response.

The reconstruction metrics obtained for M_d and M_q using the REWS-based representation are not reported in Table 1, as the resulting errors are excessively large and therefore not meaningful for comparison with the remaining results. This behavior is expected, since a single collective disturbance does not contain the information required to represent the asymmetric

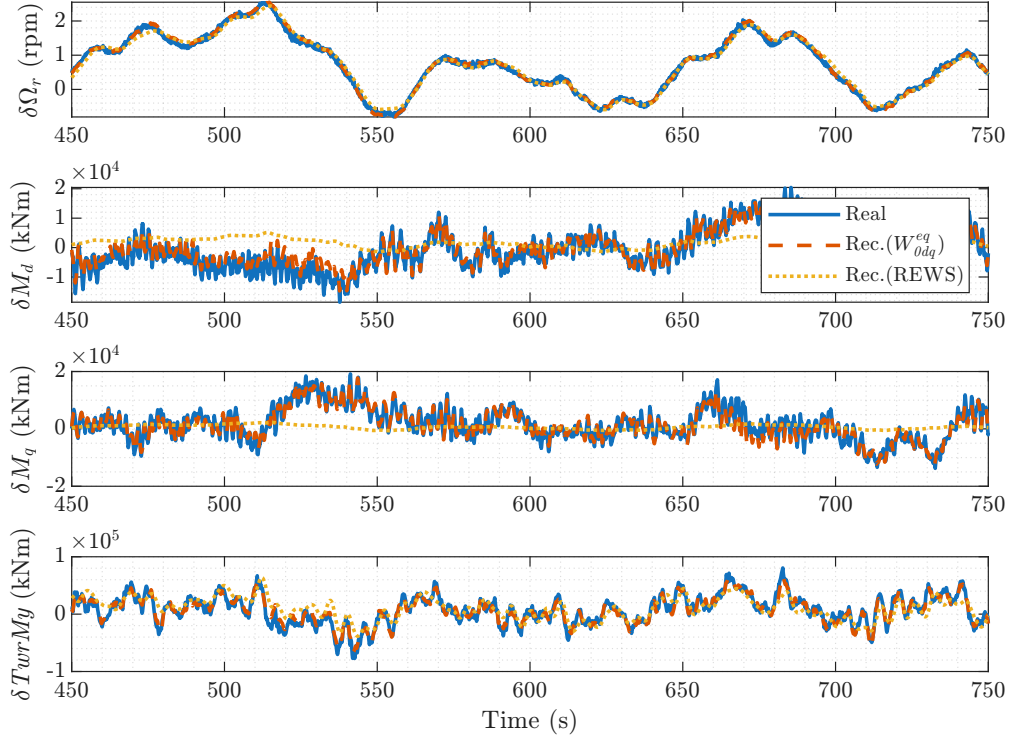


Figure 7. Comparison between simulated (solid blue) and reconstructed signals using the proposed equivalent disturbance framework (red dashed) and the REWS disturbance representation (yellow dashed) for rotor speed ($\delta\Omega_r$), tilt and yaw moments (δM_d and δM_q), and tower-base bending moment ($\delta TwrMy$).

Table 1. R^2 and $NRMSE$ (%) values obtained from the time-domain validation for rotor speed Ω_r , tilt moment M_d , yaw moment M_q and tower-base bending moment $TwrMy$. Metrics are reported for both the *REWS* representation and the proposed equivalent disturbance framework (W_{0dq}^{eq}), as mean $\pm$ standard deviation ($\mu \pm \sigma$) over 10 turbulent simulations.

Output	R^2 (<i>REWS</i>)	R^2 (W_{0dq}^{eq})	$NRMSE$ (%) (<i>REWS</i>)	$NRMSE$ (%) (W_{0dq}^{eq})
Ω_r	0.984 ± 0.002	0.996 ± 0.001	2.096 ± 0.164	1.027 ± 0.034
M_d	—	0.928 ± 0.004	—	3.539 ± 0.275
M_q	—	0.947 ± 0.004	—	3.187 ± 0.140
$TwrMy$	0.615 ± 0.023	0.943 ± 0.004	8.022 ± 0.672	3.077 ± 0.219

inflow mechanisms driving these responses. These results illustrate the limitations of conventional equivalent wind speed representations when dealing with asymmetric loads and motivate the proposed framework.

375 4.4 Closed-loop spectral validation

The final validation step ~~assesses whether the proposed framework can predict the~~ focuses on the closed-loop ~~spectral response of the controlled turbine. For this purpose~~ application of the proposed framework. First, a baseline control architecture ~~composed of rotor speed regulation and conventional IPC is considered.~~

~~Rotor speed is regulated through a collective pitch controller $C_\Omega(s)$ defined as-~~

$$380 \quad C_\Omega(s) = \frac{-0.0226(s + 0.6341)}{s(s + 2)},$$

~~while the IPC loop acts on the fixed-frame asymmetric load components M_d and M_q to reduce the corresponding tilt and yaw loads. In this work, identical controllers are used in both axes, such that the same control law is applied to~~ is introduced to illustrate how the characterized disturbance spectra can support controller tuning and to define two representative control scenarios. Then, the disturbance spectra are propagated through the d and q channels. To assess the proposed methodology
 385 ~~under different~~ resulting closed-loop ~~dynamics~~ transfer functions to assess the capability of the framework to predict the spectral response of the controlled turbine.

4.4.1 Control baseline design

The objective of the baseline control design is not to demonstrate an optimized IPC tuning procedure, but to illustrate how the proposed disturbance characterization framework can support and justify controller tuning decisions. Therefore, two IPC
 390 ~~configurations are considered,~~

$$C_{d_1}(s) = C_{q_1}(s) = \frac{-8.6 \times 10^{-6}}{s(s + 12.57)}, \quad C_{d_2}(s) = C_{q_2}(s) = \frac{-8.6 \times 10^{-7}}{s(s + 12.57)},$$

~~denoted as IPC_1 and IPC_2 , respectively~~ designed to represent different disturbance rejection scenarios and are subsequently used to validate the proposed spectral methodology.

The ~~resulting closed-loop system considered control architecture~~ is represented by the augmented block diagram shown in
 395 ~~Figure 8, where.~~ In contrast to the conventional IPC formulation presented in Section 2.3, the three equivalent disturbances $\{\delta W_0^{eq}, \delta W_d^{eq}, \delta W_q^{eq}\}$ are explicitly introduced as external inputs. This MIMO representation captures the propagation of collective and asymmetric wind disturbances to the controlled outputs and provided the basis for the disturbance-aware controller tuning described next.

~~Based on this representation, the PSDs of the equivalent disturbances, characterized in Section 4.2, are~~ Rotor speed control
 400 is common to both configurations and is achieved through a collective pitch controller $C_\Omega(s)$ defined as

$$C_\Omega(s) = \frac{-0.0226(s + 0.6341)}{s(s + 2)}. \quad (18)$$

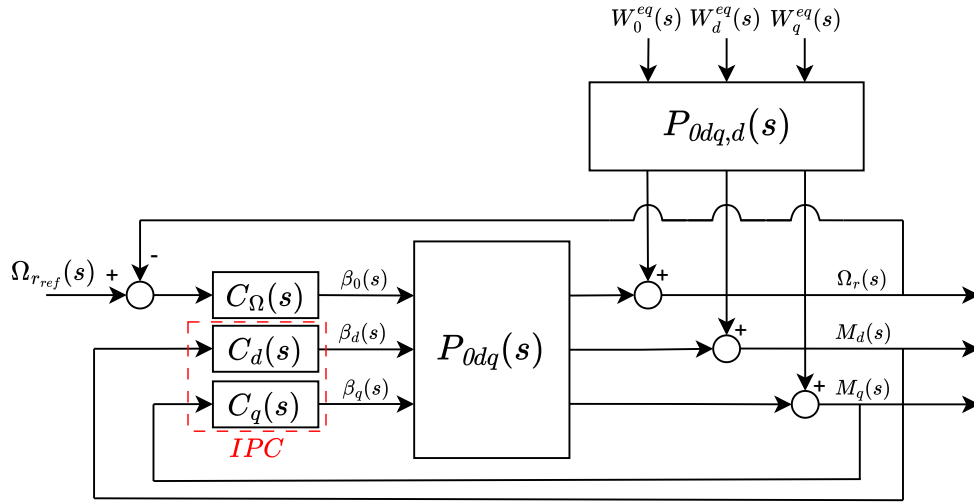


Figure 8. Augmented diagram block including the equivalent wind disturbances, used for the spectral propagation and output estimation, and proposed for advanced control designs. The perturbation notation (δ) is omitted for readability, although all signals represent deviations with respect to the operating point.

For the asymmetric channels, the controller tuning is guided by the equivalent disturbance predominantly exciting each load component. Although a residual coupling between the tilt and yaw axes remains due to the absence of an azimuth offset in the inverse MBC transformation (Mulders et al., 2019), the resulting disturbance spectra still provide a useful basis for disturbance-aware loop shaping.

Figure 9 shows an example of a tuning procedure for the d axis. The disturbance spectrum is analyzed together with the corresponding closed-loop sensitivity functions. Since most of the disturbance energy is concentrated at low frequencies, the crossover frequency $f_{c,1}$ of the IPC_1 design is selected to provide significant attenuation over the frequency range containing the dominant disturbance content. Consequently, a simple integral controller I is sufficient to achieve the desired low-frequency disturbance rejection. In addition, a low-pass filter is included to reduce the influence of high frequency components.

An analogous tuning procedure could be applied to the q axis using its corresponding equivalent disturbance spectrum. However, due to the rotor symmetry, both channels exhibit very similar disturbance characteristics and dynamic behavior. Consequently, the same controller is employed in both dq axes throughout this work.

To obtain a second validation scenario, the controller gain is reduced by one order of magnitude, yielding IPC_2 . This result in a lower-bandwidth controller with reduced disturbance rejection capability and lower actuator activity. The two controllers therefore represent distinct trade-offs between load reduction and control effort.

The resulting IPC controllers are given by

$$C_{d_1}(s) = C_{q_1}(s) = \frac{-8.6 \times 10^{-6}}{s(s + 12.57)}, \quad C_{d_2}(s) = C_{q_2}(s) = \frac{-8.6 \times 10^{-7}}{s(s + 12.57)}. \quad (19)$$

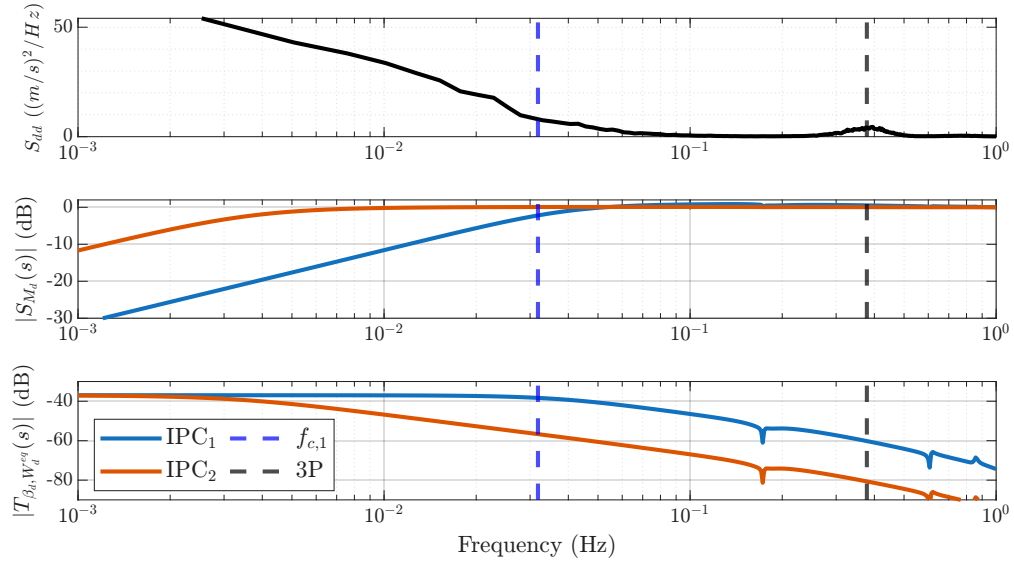


Figure 9. Equivalent disturbance PSD $S_{dd}(\omega)$ together with the sensitivity functions $|S_{M_d}(s)|$ and closed-loop transfer functions from disturbance to pitch activity $|T_{\beta_d, W_d^{eq}}(s)|$ for the IPC₁ and IPC₂ configurations.

denoted as IPC₁ and IPC₂, respectively.

420 More advanced IPC architectures could incorporate features such as azimuth offset compensation to improve the tilt and yaw decoupling or notch filters to attenuate the remaining 3P contribution. These modifications would alter the resulting closed-loop transfer functions. Since the proposed methodology relies on the propagation of disturbance spectra through those transfer functions, it remains directly applicable regardless of the specific controller architecture employed.

4.4.2 Spectral propagation

425 Once the baseline control configurations have been defined, the PSDs of the equivalent disturbances are propagated through the corresponding closed-loop transfer functions. This approach assumes that the statistical properties of the equivalent disturbances remain unchanged across the considered control configurations (Shan, 2017).

Let $\mathbf{G}(j\omega) \in \mathbb{C}^{q \times 3}$ denote the closed-loop transfer matrix from the equivalent disturbances to the selected outputs. The output spectral matrix is estimated as

$$430 \quad \mathbf{S}_{yy}(\omega) = \mathbf{G}(j\omega) \mathbf{S}_{ww}(\omega) \mathbf{G}^H(j\omega), \quad (20)$$

where $\mathbf{S}_{ww}(\omega) \in \mathbb{R}^{3 \times 3}$ is the spectral matrix of the equivalent disturbances and defined in Section 4.2.1, while $(\cdot)^H$ denotes the Hermitian transpose (Ljung, 1987). In this work, the equivalent disturbances are assumed to be statistically independent, leading to

$$\underline{\mathbf{S}_{ww}(\omega) = \text{diag}(S_{00}(\omega), S_{dd}(\omega), S_{qq}(\omega))},$$

435 where $S_{00}(\omega)$, $S_{dd}(\omega)$ and $S_{qq}(\omega)$ are the auto-spectra of δW_0^{eq} , δW_d^{eq} and δW_q^{eq} , respectively.

Figure 10 compares the PSDs of the system outputs obtained from nonlinear closed-loop OpenFAST simulations with those estimated using (20). Results are shown for the two closed-loop configurations IPC_1 (top row) and IPC_2 (bottom row). The proposed framework accurately captures the main spectral characteristics of all considered outputs, whereas the REWS-based representation only provides satisfactory estimates for rotor speed.

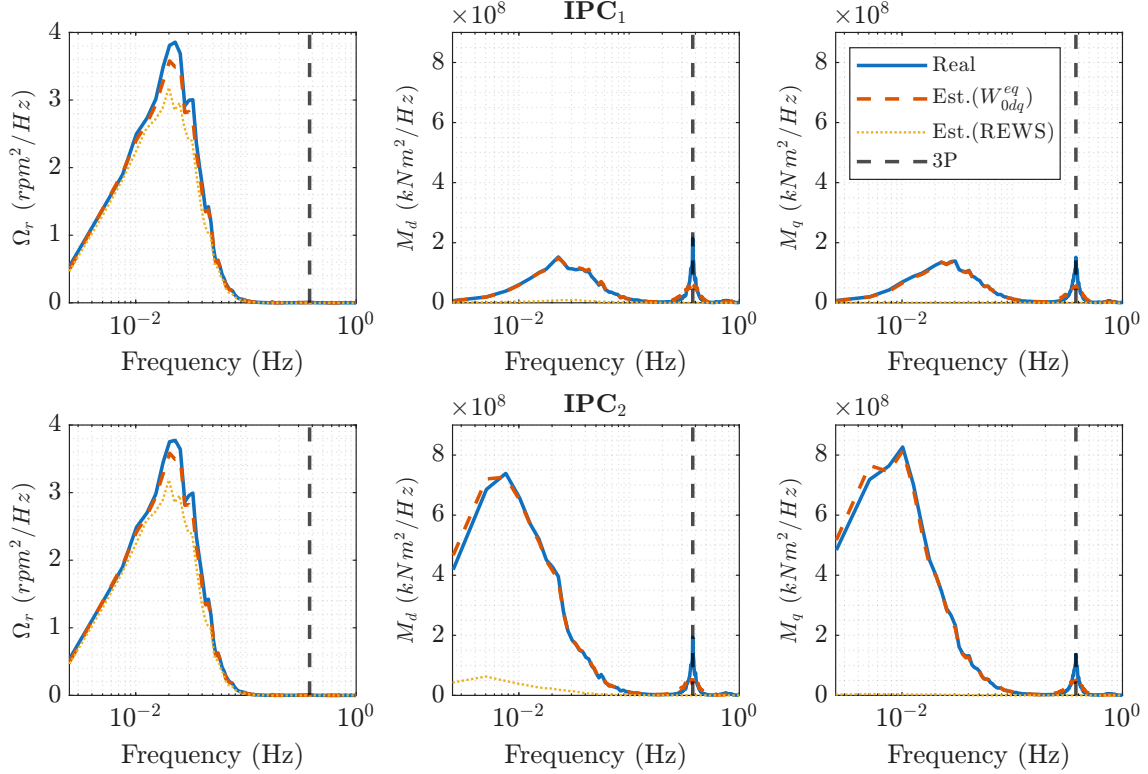


Figure 10. Comparison of simulated (blue) and estimated PSDs obtained using the proposed equivalent disturbance framework W_{0dq}^{eq} (red dashed) and REWS-based representation (yellow dotted) for Ω_r , M_d and M_q under two closed-loop configurations, IPC_1 (top row) and IPC_2 (bottom row).

440 To quantify the spectral prediction accuracy, the standard deviation σ_y of each signal is computed from both the nonlinear simulations and the estimated PSDs. For the simulated signals, it is obtained directly from the time domain data while for the estimated signals, the standard deviation is computed from the corresponding PSD as

$$\sigma_y = \sqrt{\frac{1}{2\pi} \int_0^\infty S_{yy}(\omega) d\omega}. \quad (21)$$

445 Although different signals may exhibit similar standard deviations, the objective of this section is to validate the spectral propagation framework. Therefore, the agreement in the frequency domain is assessed directly through the PSD comparisons

Table 2. Comparison between the standard deviations obtained from nonlinear simulations (real) and those estimated using the proposed spectral framework (est.) for M_d , M_q and rotor speed Ω_r , under two closed loop configurations (IPC₁ and IPC₂).

Output	Control Loop	σ Real	σ (REWS)	Rel. error (%)	σ (W_{odq}^{eq})	Rel. error (%)
Ω_r (rpm)	IPC ₁	0.363	0.328	~~9.565~~ <u>9.57</u>	0.353	~~2.762~~ <u>2.76</u>
	IPC ₂	0.361	0.328	~~9.241~~ <u>9.24</u>	0.352	~~2.418~~ <u>2.41</u>
M_d (kNm)	IPC ₁	4.307e+03	—	—	~~3.928~~ <u>4.044</u> e+03	~~8.806~~ <u>6.11</u>
	IPC ₂	5.406e+03	—	—	~~5.166~~ <u>5.210</u> e+03	~~4.430~~ <u>3.62</u>
M_q (kNm)	IPC ₁	4.103e+03	—	—	~~3.780~~ <u>3.927</u> e+03	~~7.872~~ <u>4.29</u>
	IPC ₂	5.361e+03	—	—	~~5.093~~ <u>5.222</u> e+03	~~4.996~~ <u>2.58</u>

shown in Figure 10, while the standard deviation is used as a complementary quantitative metric related to the total energy of the response.

Table 2 compares the resulting standard deviations. The absolute relative errors of the proposed framework remain below 9.7% for all outputs and control configurations, demonstrating a good agreement between the estimated and simulated variability of the signals. The load components M_d and M_q show slightly larger errors mainly due to the small underestimation of the spectral content around the $3P$ region. This effect is particularly noticeable for the IPC₁ configuration, where the controller achieves a stronger reduction of the low-frequency load variability. As a consequence, the contribution of the remaining $3P$ component becomes relatively more significant, increasing its impact on the estimated standard deviation and leading to a larger relative error. Nevertheless, the predicted values remain in good agreement with the nonlinear simulations.

For rotor speed Ω_r , the proposed framework achieves errors below 3% for both control configurations. Although the conventional REWS-based representation also provides reasonable estimates of the rotor speed variability, its errors remain around 9%. This improvement can be attributed not only to the sensitivity-based aggregation employed in the proposed framework, but also to the fact that the equivalent disturbances are constructed from the wind velocities acting directly on the blade nodes, whereas REWS is defined as a spatial average over the entire rotor disk.

These results confirm that the proposed framework can accurately estimate closed-loop output spectra by combining the characterized equivalent disturbance PSDs with the corresponding closed-loop transfer functions. The framework establishes a direct link between the characteristics of the inflow disturbances and the resulting system response, allowing control strategies to be evaluated in terms of the disturbances they are intended to reject. This leads to a more transparent and systematic control design workflow while reducing the dependence on computationally expensive aeroelastic time-domain.

5 Conclusions and Future Work

This work has presented a unified control-oriented framework that combines the modeling and characterization of equivalent wind disturbances in the Odq reference frame. Starting from a linearized model with distributed horizontal wind inputs, the

proposed methodology ~~reduces~~ uses whole-system input-output sensitivities to reduce the high-dimensional inflow ~~description to three physically meaningful representation to three equivalent~~ disturbances associated with the collective, tilt and yaw
470 components of the wind field.

~~The framework has been validated both in the time and frequency domains. In the time domain, the reduced-order model driven by the equivalent disturbances accurately reproduces the main turbine responses obtained from nonlinear aeroelastic simulations. In the frequency domain, the spectral characterization of the equivalent disturbances, combined with closed-loop transfer functions, enables the estimation of the output PSDs under different control configurations.~~

475 ~~The main main~~ contribution of the ~~proposed approach is that it explicitly incorporates both the turbine model and the characterization of the disturbances affecting the system outputs~~ framework is the integration of the disturbance modeling, characterization and turbine dynamics within a common representation. As a result, asymmetric load reduction strategies can be designed in a more systematic way, since the required control design effort can be directly related to the spectral content of the disturbances to be rejected. ~~This provides~~, providing a more transparent ~~and consistent control design workflow than approaches based only on output response simulations or uncharacterized disturbance inputs~~ basis for defining disturbance rejection requirements, comparing candidate control configurations and interpreting the resulting control effort.

~~Moreover, these findings confirm that~~ In addition, the proposed approach enables a consistent prediction of closed-loop system behavior using a reduced-order linear model, effectively separating the inflow characterization from the control-dependent dynamics. In practice, the equivalent disturbance spectra can be characterized once for a given operating and inflow condition and subsequently propagated through different closed-loop transfer functions without requiring additional aeroelastic simulations. This provides a computationally efficient alternative to simulation-based analysis ~~and facilitates the evaluation of control strategies~~, allowing multiple controller designs to be evaluated from a spectral perspective. ~~In addition while reusing the same disturbance characterization. Moreover~~, the availability of closed-loop output spectra enables the formulation of advanced control specifications directly in the frequency domain, such as fatigue-based or actuator-usage specifications (see e.g.
485 (Miquelez-Madariaga et al., 2026; Lacheta-Lecumberri et al., 2026)).

The framework has been validated both in the time and frequency domains. In the time domain, the reduced-order model driven by the equivalent disturbances accurately reproduces the main turbine responses obtained from nonlinear aeroelastic simulations with coefficients of determination R^2 above 0.92 and NRMSE below 4%. In the frequency domain, the predicted closed-loop signal standard deviation has shown relative errors below 7% for all considered outputs and control configurations.
495 These results demonstrate that the proposed reduced-order representation captures the dominant collective and asymmetric inflow effects relevant to the turbine response.

The validation results also support the use of static input-output gains to define the sensitivity weights employed in the equivalent disturbance calculation. Despite neglecting the frequency dependence of the spatial sensitivities during the disturbance construction, the resulting equivalent disturbances accurately reproduces the turbine responses and enables consistent closed-loop spectral predictions. Therefore, the static-gain approximation provides a sufficiently accurate and computationally convenient representation of the relative contribution of each nodal wind velocity.
500

It should be noted that the proposed framework has been derived and validated for a single operating point. As the wind turbine dynamics, the static gains used to define the equivalent disturbances and the disturbance spectra are all expected to vary with the operating point, the applicability of a single characterization across a wider operating range remains an open question.

505 Future work will therefore investigate the dependence of the equivalent disturbance representation on operating conditions and inflow characteristics. Possible extensions could include operating-point-dependent disturbance characterizations, gain-scheduled implementations and robust control formulations capable of explicitly accounting for this variability.

Beyond feedback control applications, the proposed equivalent disturbance representation may also support the design of feedforward and preview-based control strategies by providing a compact characterization of the disturbances to be rejected.

510 The practical estimation of these equivalent disturbances for real time implementations, for example from preview measurements provided by LIDAR systems, remains an open research topic.

Finally, future work will focus on exploiting the proposed framework for advanced control design based on frequency domain specifications, with methodologies such as Quantitative Feedback Theory (QFT) or H_∞ . In this context, the equivalent disturbance spectra could be used to define disturbance-rejection requirements, load-reduction objectives and actuator-effort

515 constraints in a unified frequency-domain design framework.

Code availability. The methods and algorithms implemented in the code are described in detail in the paper to support transparency and reproducibility.

Data availability. The data used in this study are simulated using open access tools. All models, parameters, and procedures required to reproduce the data are described in the manuscript.

520 *Author contributions.* DLL: Conceptualization, formal analysis, methodology, validation, visualization, writing (original draft preparation). IMM: Conceptualization, writing (review and editing). JE: Conceptualization, writing (review and editing).

Competing interests. The authors declare that they have no conflict of interest.

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