

General review comments

Dear reviewers and commenters,

We would like to thank all three reviewers for their insightful and detailed reviews. Each of them raised important points and asked the right questions. Revising the manuscript turned out to require more than editorial changes. It called for new simulations, new derivations, and new analysis. We apologize that our response therefore took somewhat longer than usual.

In this document, we summarize the main modifications made to the manuscript. In addition, we provide a separate point-by-point response to each of the three reviews, explaining how every comment was addressed. In addition, we provide a separate version of the revised manuscript in which all changes are highlighted.

Thank you for your consideration and the valuable comments.

Hendrik Verdonck and Oliver Hach

Main corrections and improvements made to the manuscript

1. Splitting into two companion papers

Prompted by the main comment of Reviewer 1 and a comment by Reviewer 2 (*"extreme amount of information which makes it somewhat difficult for the authors to adequately cover all that gathered information"*), we decided to split the article into two companion papers: one focusing on the comparison of the aerodynamic models, and one on the analysis of the instability mechanism. Now that the comments have been addressed, this split seems even more meaningful, as the two papers comprise approximately 34 and 28 pages, respectively (preprint format, excluding appendices and reference list).

A similar split was recently made for another [WES paper](#). That paper was reviewed as a single manuscript and split during the production phase. We discussed this procedure with the handling editor by e-mail, who considered it meaningful provided that the reviewers agree.

2. (Optional) Appendices

Many of the comments requested supporting information, which was best presented in appendices. All of these appendices belong to Part 1 of the paper, and together they became very long, partly because of several large and somewhat repetitive figures. We therefore suggest including only a selection of them in the final paper, namely those that directly add insight into the results. Appendices that serve only to verify the methodology and approach would be omitted. Instead of including the corresponding verification plots, we have added a statement to the main body of the paper that summarizes which verifications were performed and which reference data they were compared against. The three optional appendices we would suggest to omit can be found separately in the pdf after Part 1.

Following appendices would be retained:

- Appendix A: Tuning of the aerodynamic airfoil parameters
- Appendix B: Detailed overview of the CFD setup
- Appendix C: Difference between a fixed or moving frame of reference
- Appendix D: Detailed view on aerodynamic transfer functions in range $0 < k < 0.25$
- Appendix E Aerodynamic transfer function comparison: FFA-W3-241 and NACA 0006
- Appendix F: Verifying the independence of the stability results on the stability analysis approach

Following appendices would be left out:

- Optional Appendix A: CFD convergence studies
- Optional Appendix B: Verification of the Theodorsen implementation
- Optional Appendix C: Verification of the methodology with classical flap-twist flutter literature data

Improvements and corrections in Part 1

3. Derivation of the potential flow theory model (Theodorsen)

The potential flow theory model was completely re-derived. The overall idea of the derivation is still the same, but the individual components of this model are now better divided and it should be easier to understand the background and theory behind each individual component. This updated derivation can be found in Sect. 2.2.2 of Part 1.

One of the main components of this model is the tilting of the steady lift vector by the unsteady variation of the angle of attack. The initial paper referenced the work by Li et al. 2022. A new preprint by the same author gives a more detailed and thorough derivation and a direct expression for this angle of attack (Li et al. 2026, preprint), given in Eq. 45 of Part 1.

4. Corrected influence of edgewise motion on the direction of the circulatory force (Greenberg terms)

The full re-derivation revealed one shortcoming of the previous version. Edgewise motion influences the angle of attack. In the initial paper, this effect was only taken into account in the frequency dependent variation of the magnitude of the circulatory lift and moment (the Greenberg terms in $L^C(k)$ and $M^C(k)$). However, this component also influences the direction in which the circulatory lift acts. This is now included correctly in Eq. 44 and 45 in Part 1 and improved the F_{xx} term (especially its imaginary part), as can be seen in Fig. 3 in Part 1. Note that this component is nevertheless small and this improvement therefore did not affect the stability analysis results significantly.

5. Correction of an additional error in the code implementation of the literature reference

Related to the previous point, an additional sign error was found in the published implementation of the literature reference model of Stäblein et al. (2017a), in the elimination of the structural accelerations from the aerodynamic lag-state equation. This part of the code was not explained in the paper itself and the error therefore affects the implementation and results only, not the equations or methodology given in that paper. This error affects F_{xx} and F_{yx} , which now match much better to the CFD reference result, as can be seen in Fig. 3 in Part 1. The error scales with the steady angle of attack, which is presumably why the discrepancy went unnoticed under the

verification performed only for 0° angle of attack. We have described the sign error in Sect. 2.3 of Part 1, corrected it in the implementation used for this work and in the GitHub repository. All results shown are based on the corrected model.

6. Better explanation of the aerodynamic parameter tuning

Unlike the Jones approximation constants, the aerodynamic profile parameters (C_{L_α} , C_{D_0} , C_{MAC} , Δa_{AC} , $\alpha_{L=0}$) were tuned based on the steady CFD results. This was mentioned in the original paper, but not discussed in enough detail. Appendix A in Part 1 now includes a detailed explanation of the approach used to tune these parameters, including pointers to where each of these tuned parameters is used.

One additional parameter was introduced compared to the original paper. The aerodynamic center of a cambered profile is not located at exactly the quarter-chord point. The location of the actual aerodynamic center can be computed based on the steady state results, as explained in Appendix A. This corrected distance is used only in the computation of the circulatory moment, Eq. 24, 28, 35-37.

7. Correction of inconsistent Jones constants

This article uses an improved version of the model originally proposed by Stäblein et al. (2017a) as its reference. The aerodynamic core of the model is based on the Jones approximation of the Theodorsen function, which relies on four empirical constants. In the original implementation by Stäblein et al. (2017a), these constants were set to values derived for a thin, flat plate. While the initial proposal for the improved model also followed this approach, the implementation mistakenly included tuned constants. This error has now been corrected. All results presented for the improved model are now obtained using the standard Jones constants for the flat-plate approximation, as originally intended.

8. Explanation of the derivation of the Stäblein et al. frequency domain forces

The literature reference result (Stäblein et al. (2017a) – improved) does not use frequency domain forces. It relies on a state-space formulation of the aerodynamics, enabled by a linearization of the Jones approximation of the Theodorsen function. To allow a direct comparison with the two methodologies in this paper, the frequency domain equivalent of the formulation in the literature reference is used. Its derivation was not explained in the initial paper, and has now been added as supporting information in Appendix F. In the same appendix, a verification is included, which verifies that 1) this construction of the frequency domain forces does not introduce additional differences or errors and 2) the difference in stability analysis approach between the paper (flutter analysis based on the g-method) and the literature reference (direct eigenvalue analysis on the state matrix) does not influence the stability result - at least not of the edgewise or other lowly damped modes (see next point).

9. Difference between the g-method results and the approach by Stäblein et al.

The updated results showed a notable difference in the damping of the flapwise mode between the literature reference and the two results obtained with the g-method, best visible in case $\gamma_x = +0.3$, $\gamma_y = 0$ in Fig. 7 of Part 1. This difference was not present in the original version due to the tuning of the Jones constants.

This case shows that the flapwise mode is critically damped, a result which cannot be represented by the g-method flutter analysis. This difference is explained in detail in Appendix F. Although it may appear substantial at first glance, it does not affect the dynamics of the system relevant to stability analysis.

10. More documented verification

The reviews requested additional verification of the methodology. Most of this verification had been done before the initial version of the paper, but had not been properly documented. This documentation is provided in the current manuscript including:

- Opt. Appendix A: CFD convergence studies of the mesh domain radius, mesh discretization, CFD computational setup; setup of the pulse excitation and identification procedure as well as an additional verification with harmonic excitation at 5 individual reduced frequencies to compare with the continuous transfer function obtained with the pulse excitation. This more detailed verification study revealed some small imperfections in the CFD setup (see next point).
- Opt. Appendix C: Verification of classical flap-twist flutter speeds. The same verification as performed in Stäblein et al. (2017a) was repeated with the potential flow theory model derived in this work. As discussed in the paper, this only verifies the parts of the model which are relevant for flap-twist flutter, but does not necessarily verify all parts relevant for edgewise flutter mechanisms.
- Opt. Appendix B: Verification of the Theodorsen function implementation. The implementation of the core Theodorsen function was verified for the aerodynamic response of a flat plate undergoing harmonic pitching and heaving motions by comparison with experimental literature reference data and an independent Theodorsen function implementation.
- Appendix E: A comparison of the frequency domain aerodynamic forces between the investigated, relatively thick, cambered FFA-W3-241 profile and a thin, symmetrical NACA 0006 airfoil was added as an appendix.

11. Updated CFD setup

The detailed verification study showed that the mesh domain radius had a small influence on the frequency domain transfer functions. This is likely caused by the reflection of disturbances from the farfield boundary and back to the profile, which resulted in small ‘waves’ in the transfer functions at low reduced frequencies. The mesh domain diameter was therefore increased from 400 m to 800 m (for the profile with 3.292 m chord length).

As a second improvement, the number of pseudotime iterations was drastically increased from 300 to 2000. The original setting of the parameter was based on best-practice values, and the convergence of this parameter was not investigated before. The dependence was stronger than expected and affected some components of the transfer functions, but did not affect the overall stability analysis results significantly.

Improvements and Corrections in Part 2

12. Improvement of the 2DOF model

Prompted by the comment of Reviewer 1 regarding the derivation of the simplified two-degree-of-freedom (2DOF) model, we took a closer look at this derivation. In doing so, we found that the original reduction could be improved in a way that is both physically more consistent and closer

to the reference results, while preserving the original idea behind it. The revised manuscript therefore uses an improved 2DOF model and contains a more detailed explanation of the methodology. Here we briefly reiterate how the original model was derived and what its limitations were and how the improved methodology is based on the same idea, but serves as a more consistent model.

The original 2DOF model was derived from the simplified 3DOF model by assuming a fixed kinematic relation between edgewise and torsional motion, $x = B\theta$. The coupling parameter B was taken from the edgewise mode shape of the structural system and assumed to be unaffected by the aerodynamic forces. This relation was substituted into the equations of motion. The flapwise and edgewise equations were retained, the torsion equation was discarded, and the structural coupling terms $k_{x\theta}$ and $k_{y\theta}$ were not retained in the reduced stiffness matrix.

In this formulation, edgewise motion and twist are rigidly connected: any edgewise displacement results in a proportional twist, which changes the angle of attack and thus the lift. This captures the essential aeroelastic path of the instability mechanism. However, the formulation has several limitations: **1)** The effect of the twist back on the bending motion is not included. In the coupled structure, part of the edgewise deformation is accommodated by twist, which lowers the effective edgewise stiffness. Because the coupling terms were dropped, the edgewise equation retains the uncoupled stiffness k_x . The edgewise frequency was therefore too high (0.93 Hz instead of 0.886 Hz at zero wind speed). **2)** Because of the simple $x = B\theta$ relation, only the edgewise motion induces twist. With flap-twist coupling ($\gamma_y \neq 0$), flapwise motion also twists the section. This is not represented, which explains the poor agreement for the cases with flap-twist coupling. **3)** The kinematic $x = B \times \theta$ relation is imposed. The justification was the observation that this ratio was constant for the cases without flap-twist coupling, but it was still an approximation.

The original model implicitly relied on two properties of the simplified 3DOF model: **1)** There is no aerodynamic moment acting on the section, which was a result of the elimination study. The torsional degree of freedom is therefore excited only through the structural coupling with bending. **2)** Torsion is much stiffer than bending (6.66 Hz vs. 0.6-0.9 Hz), which implies that on the time scale of the edgewise oscillation, the torsional degree of freedom has time to reach equilibrium continuously.

Together, these properties imply that the twist of the section is determined by the bending deflections through the structure alone, and cannot be altered directly by the aerodynamic forces. This is the physical basis of the fixed kinematic relation in the original model. The improved model is based on exactly the same two properties. However, it uses them to derive the relation between twist and bending, rather than imposing it.

The new methodology neglects the torsional inertia in the torsion equation, because the torsional frequency is well separated from the bending frequencies. The torsion equation then reduces to a static equilibrium, which determines the twist as a function of the bending deflections: $\theta = -(k_{x\theta}x + k_{y\theta}y)/k_{\theta\theta}$.

The torsional degree of freedom is condensed out with this relation, which is essentially a standard Guyan reduction (static condensation). The result is a symmetric 2DOF system in the physical edgewise and flapwise degrees of freedom, x and y . The aerodynamic model is unchanged and contains the same three quasi-steady terms as before. This formulation has the following properties: **1)** The original relation is recovered for $\gamma_y = 0$, meaning that the twist only depends on edgewise motion. **2)** Structural coupling is fully retained and therefore flap-induced twist motion is included, which is relevant for $\gamma_y \neq 0$ cases. This has also the effect that the

observed edge-torsion ratio changes with wind speed, which is, however, not directly caused by the aerodynamics, but an effect of changes in the mode shapes (caused by aerodynamics). **3)** The only assumption (with respect to the three-degree-of-freedom model with simplified aerodynamics) is the neglected torsional inertia. **4)** The only downside of this formulation compared to the initial one is that the equations of motions look a bit more involved and not as simple and clean as before (compare Eq. 43 in the original paper with Eq. 11 in Part 2 of the revised paper). Part of this simplicity is given up in favor of a wider range of validity, as the improved model now also gives good results for cases with flap-twist coupling. The revised derivation is given in Sect. 2.4 of Part 2 of the revised manuscript.

This improvement has a strong influence on some of the results and some conclusions. For cases without flap-twist coupling ($\gamma_y = 0$), the result remains the same, but the previous version of the 2DOF model also matched well with the 3DOF model for that case. However, in cases with flap-twist coupling ($\gamma_y \neq 0$) the original model failed completely, while the new methodology still matches well with the 3DOF model. The poor result of the 2DOF model was explained in the initial paper by the variation in the edge-torsion coupling, which in itself was true, because that methodology relied on it directly. However, the new methodology shows that a better 2DOF model can be obtained, which still matches well with the 3DOF model for those cases.

The original conclusion from the analysis was that this reduction to a 2DOF model exemplified the core instability mechanism. It showed that the minimal coupling needed is a coupling between a flapwise and an edge-twist coupled degree of freedom. The new methodology and new results expand and generalize this conclusion: the edgewise instability is a coupling between two bending degrees of freedom, edgewise and flapwise, each accompanied by a structurally coupled twist. For $\gamma_y = 0$ this reduces to the original picture of a flapwise and a coupled edge-torsional degree of freedom. These new results also show that torsion has no independent dynamic role, as torsional inertia is completely removed, and the model still agrees with the 3DOF model which contains it. Torsion only converts bending deflections quasi-statically into changes in angle of attack.

The discussion and conclusions have been updated accordingly in Sect. 5 and 6 of Part 2 of the revised manuscript.

13. Aerodynamic work replaced by aerodynamic damping

The original version used the aerodynamic work and its directional components to identify which contribution (flapwise, edgewise, or torsional) has the largest impact on the overall stability. The aerodynamic work is directly related to damping: positive work means that energy is transferred from the flow into the structure, i.e., a destabilizing contribution (and vice versa). However, the absolute work values are not very insightful; they only allow the relative contributions to be compared and the zero crossing to be located.

To improve on this, the aerodynamic work can be used to compute an approximate aerodynamic damping. This approach assumes harmonic motion, in the same way as the p-k method. The aerodynamic damping is obtained by relating the aerodynamic work per cycle to the total energy of the mode. The resulting quantity retains the benefits of the aerodynamic work – it is exact where the motion is harmonic (i.e., at the flutter point) and can be decomposed into its directional contributions – but has the additional benefit that its absolute value (a damping ratio in %) is directly comparable with the total damping of the system. Since the flutter analysis itself uses the g-method, which does not assume purely harmonic motion but approximates the damping through a Taylor expansion (see Sect. 2.2 of Part 1), the aerodynamic damping does not exactly

match the total damping, but it is a good approximation. A detailed derivation of the aerodynamic work and the aerodynamic damping is given in Sect. 2.5 of Part 2.

14. Detailed analysis of the contribution of the edgewise and flapwise components towards the total aerodynamic damping

The flutter mechanism analysis in the initial version of the paper relied to a large extent on the fact that the aerodynamic work performed in the flapwise direction is the dominating component in the instabilities. This argument was used to narrow down the plots shown. Emphasis was placed on the force in flapwise direction to explain the mechanisms.

This argumentation was tested by a more thorough and comprehensive analysis of the contributions of the aerodynamic damping in Sect. 3 of Part 2. A new Figure 3 shows the relative contribution of the aerodynamic damping in flap direction and in edge direction to the total damping (the torsional contribution negligible is in all analyzed cases). This analysis pointed out that some of the claims made in the initial version have to be nuanced. The original argument is true for most cases, i.e. the negative aerodynamic work is in most cases performed mostly in flapwise direction, but there are cases where the edgewise direction dominates. This finding has then also been taken into account in the detailed mechanism discussion.

15. Consistent equations of motion of the simplified models

There were two inconsistencies in the equations of motion of the model used for the instability mechanism analysis (equations 41-43 in the initial paper, equations 7, 8, 11 in Part 2 of the updated manuscript). There was still a center of gravity offset e_{cg} in the equation, but as mentioned in the text, this was not included in the model actually used. The aerodynamic equation used α_0 , but in the code, $\alpha_{0,eff}$ was used. Both inconsistencies have been corrected.