ANALYSIS OF COUPLING BETWEEN STRUCTURAL AND FLIGHT DYNAMICS MODES OF A FLYING DEMONSTRATOR WITH VERY FLEXIBLE WINGS

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Abstract

This work presents the development of a design and analysis framework for investigating the coupling between structural dynamics and flight dynamics in very flexible, high-aspect-ratio wings (HARW). The TU-Flex demonstrator, a composite aircraft with slender flexible wings and conventional tail surfaces, serves as the validation platform. The methodology integrates parametric modeling (ModGen), finite-element aeroelastic analysis (MSC Nastran), and flight dynamics simulations (ModSiG-FMRA) to evaluate modal interactions across the flight envelope. Results show that increasing wing flexibility reduces structural mode frequencies, leading to coupling between rigid-body and elastic modes. In particular, the short-period mode (1.73 Hz) and the first wing bending mode (1.69 Hz) occur in close proximity, confirming strong interaction between flight mechanics and structural dynamics. Subsonic flutter analysis further demonstrated that TU-Flex remains free of flutter within the operational envelope. The study highlights how the proposed procedure can be used to guide the design of very flexible aircraft and ensure the desired dynamic behavior.

Keywords

Very Flexible Wing, High Aspect Ratio Wing Aircraft, Flight dynamics /Aeroelastic coupling, subsonic flutter

1. INTRODUCTION AND MOTIVATION

The development of very flexible, high-aspect-ratio aircraft presents unique challenges for both modeling and flight control. In such configurations, the coupling between flight dynamics and aeroelastic response becomes significant and can strongly affect overall performance. Reliable prediction of both static and dynamic behavior from the preliminary design stages is therefore essential to minimize costly redesigns and ensure safe operation. Stability derivatives are particularly valuable, as they enable the development of linear aerodynamic models for early control system design, the computation of free-response modes (e.g., short period, phugoid, roll subsidence, spiral, and Dutch roll), and the prediction of load histories in complex maneuvers. A variety of methods have been developed to assess aircraft control and stability, relying on both experimental data and numerical simulations [1, 2].

Previous research has highlighted the importance of accurately capturing the interaction between structural flexibility and flight dynamics. Schoor et al. [3] investigated the aeroelastic characteristics and control of very flexible aircraft using linearized modes that incorporated rigid-body motions, emphasizing the need to account for both unsteady aerodynamics and structural flexibility for accurate dynamic modeling. Patil et al. [4] studied High-Altitude Long-Endurance (HALE) aircraft and demonstrated that large wing deformations from high-aspect-ratio structures can significantly alter aerodynamic load distributions, leading to substantial changes in the aeroelastic and flight dynamic behavior. As a result, linear analyses based on the undeformed configuration may not be valid, particularly when nonlinear dynamic motions occur. Similarly, Drela [5] and Shearer and Cesnik [6] highlighted the importance of nonlinear modeling for flexible aircraft, showing that coupling six-degree-of-freedom rigid-body motions with nonlinear aeroelastic equations is essential to accurately predict the dynamics of very flexible vehicles. Su and Cesnik [7] further demonstrated that nonlinear effects, such as torsional stiffness changes due to skin wrinkling or asymmetric gust loading, can substantially influence the response of flying-wing configurations.

Despite the advances in numerical modeling, there remains a lack of sufficient experimental data for validating models and testing control strategies for very flexible aircraft. Most existing studies rely on simulations, and available experimental data are limited to less flexible or scaled configurations. This gap in validation makes it challenging to confidently design

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flight controllers and predict the coupled aeroelastic and flight dynamics of very flexible aircraft.

To address this need, TU Berlin has developed the TU-Flex demonstrator [8], a very flexible, high-aspect-ratio wing aircraft specifically designed to investigate the interaction between structural dynamics and flight dynamics. Its wing has been intentionally designed with a low bending frequency so that its structural dynamics fall within the range of the aircraft's rigid-body modes, enabling direct coupling of elastic and rigid-body motions. Capturing this interaction experimentally is the primary motivation for the demonstrator, providing a platform to validate models, study dynamic coupling, and develop suitable flight control strategies for very flexible aircraft. The TU-Flex is shown in Fig 1. The primary objective of this study is to design a process for analyzing the coupling between the structural modes of the very flexible TU-Flex wing and the aircraft's flight mechanical modes, thereby quantifying the interactions and identifying the conditions under which these couplings significantly influence the dynamic behavior. This analysis provides the foundation for validating numerical models and informing the design of flight control strategies for very flexible, high-aspect-ratio aircraft.

FIG 1. TU-Flex-FW lateral view.

2. TU-FLEX DESIGN WORKFLOW AND VERY FLEXIBLE WING ADAPTATION

The main difference in the conceptual design of this vehicle, compared to conventional industrial processes, is the early-stage consideration of structural flexibility. The TU-Flex design enables the evaluation of how geometrical and structural design choices influence the flight-dynamics performance of the aircraft. The overall TU-Flex design process is illustrated in Fig. 2. It consists of five main blocks:

- conceptual design and geometrical definition,
- aeroelastic optimization,
- flexible aircraft dynamics evaluation,
- detailed structural design and construction, and
- experimental validation.

This research focuses on strengthening the coupling and refining the analyses between blocks 2 and 3. More details on the design process can be found in [9–12].

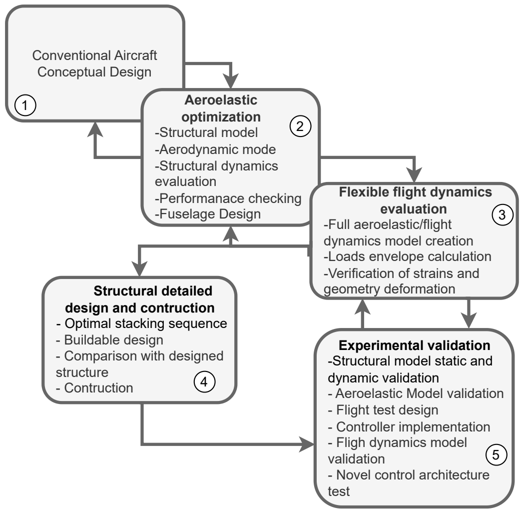

FIG 2. TU-Flex design process.

The flexible aircraft flight dynamics also include the load analysis of the aircraft. This block is closely linked to aeroelastic optimization, detailed structural design and manufacturing, and experimental validation. Simulations carried out at this stage guide the definition of static, dynamic, and flight tests, verify that the wing structures can withstand all expected loads, and assess whether the configuration exhibits the intended aeroelastic–flight dynamics coupling. Once these criteria are met, the design progresses to the structural design and construction phase.

In Block 3, the flexible flight-dynamics branch generates an aircraft model to construct a complete simulation environment. This environment is employed to analyze the vehicle's dynamics, plan the flight-test campaign, and support control design as well as real-time applications. The Modeling and Simulation Group Toolbox created by the FMRA-TUB (ModSiG-FMRA), provides a low-order methodology for modeling, analyzing, and simulating very flexible/flexible wings and aircraft [13]. ModSiG-FMRA combines nonlinear flight-mechanics equations of motion with modal superposition of the structure, and it accommodates quasi-steady or unsteady aerodynamics, including aerodynamic nonlinearities such as follower forces and/or stall effects. It further supports numerical linearization, visualization, real-time execution, and control assessment.

The underlying mathematical formulation is based on nonlinear mean-axis equations of motion together with incompressible strip theory aerodynamic models. Both quasi-steady and unsteady incremental aerodynamics can be employed, subject to specific assumptions: structural flexibility remains moderate with elastic displacements small enough for linear deformations; the wing has a high aspect ratio permitting two-dimensional strip-theory approximations;

and the aircraft operates in an incompressible flow regime [14, 15].
ModSiG-FMRA framework delivers both steady-state trim solutions and linear state-space models, complemented by a nonlinear formulation suitable for time-domain simulations in open- and closed-loop configurations. It can be linked with flight simulators such as X-Plane and FlightGear, allowing visualization of the aircraft in either rigid or flexible form [16, 17]. The tool provides dynamic responses not only for the rigid-body motion but also for arbitrary points within the flexible structure. Moreover, it generates pole–zero diagrams and Modal Assurance Criterion (MAC) evaluations over varying flight speeds. Combined with nonlinear simulation outcomes, these analyses enable verification of aeroelastic–flight dynamics interactions, guide structural or geometrical refinements, and support the development of feedback strategies to maintain stable and well-coupled dynamic behavior throughout the operational envelope. A more detailed workflow showing the interface between Blocks 2 and 3 is shown in Fig.3. Enforcing the high level of deformation together with the coupling between rigid body and structural modes allows to develope a framework able to design very flexible aircraft.

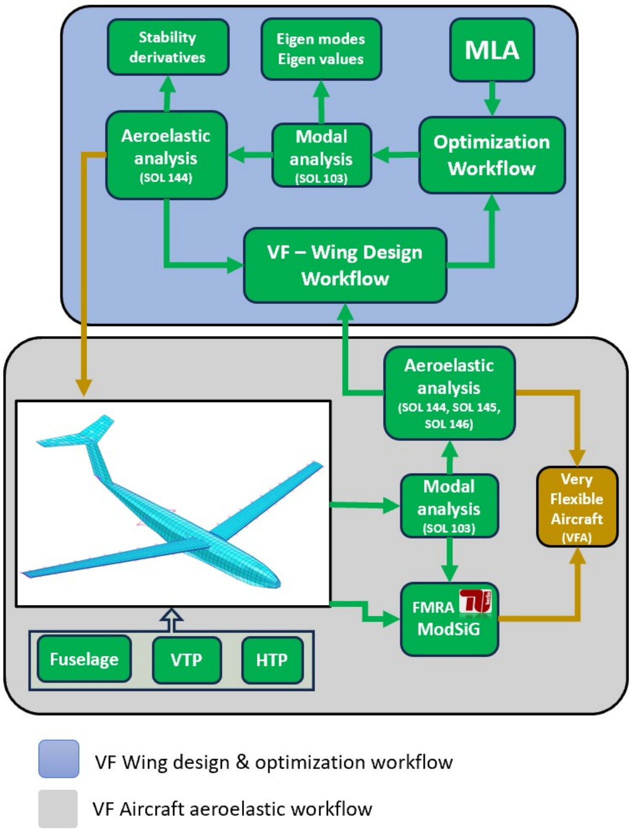

FIG 3. TU-Flex very flexible wing design workflow.

The workflow employs the complete aircraft model to evaluate structural loads, deformations, vibration characteristics, flutter boundaries, gust responses, and the coupling between aeroelasticity and flight dynamics, thereby enabling iterative design assessment. After the optimized wing from Block 2 is obtained [18], it is integrated with the aircraft fuselage for system-level analysis. Nastran and ModSiG-FMRA are then applied in combination: the modal analysis performed in Nastran provides structural mode shapes that are used in ModSiG-FMRA to build the flight-dynamics model, and they also serve as input for Nastran's aeroelastic solvers. Specifically, Solution 144 is employed for static aeroelastic response to determine divergence, trim, and load redistribution; Solution 145 is used for flutter analysis; and Solution 146 is applied for dynamic aeroelastic response to compute gust and forced-oscillation effects. The outcomes of these analyses, including flutter constraints and coupled rigid-body/structural dynamics, are fed back into the wing-design workflow to guide re-optimization. In this way, Blocks 2 and 3 are tightly integrated, ensuring that structural–flight dynamics coupling is consistently enforced while the wing and complete aircraft remain capable of sustaining all operational loads.

3. TU-FLEX-VFW AEROELASTIC ANALYSIS

The TU-Flex is a 3.6 m span aircraft with an aspect ratio of 16, featuring a high-wing configuration and a T-tail. The fuselage has three floors to accommodate instrumentation and to facilitate the installation of the wing and empennage. Its chassis is formed by two main spars, which transmit loads between the nose and main landing gears and provide primary structural support for the fuselage. The rear-mounted motors are attached to the fuselage through a series of frames and pylons, ensuring rigid structural integration. The T-tail spar consists of a boom inserted into the rear floor of the fuselage, with the horizontal stabilizer fixed to the vertical spar via two screws.
The main wing of the TU-Flex-VFW is built around two primary spars, which carry the majority of structural and aerodynamic loads. The wing skin contributes to load transfer and helps maintain torsional stiffness. The half-wings are connected through the spars using six screws, after which the complete wing assembly is installed under the fuselage main frame. This frame acts as the principal structural backbone of the aircraft, providing a rigid mechanical interface between the fuselage and the wing while distributing aerodynamic and inertial loads efficiently throughout the structure. TU-Flex´s structural topology is shown in 4.

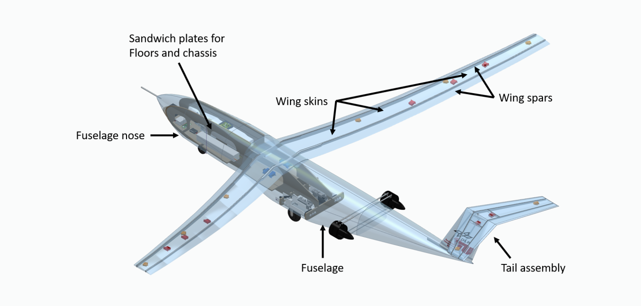

FIG 4. TU-Flex´s structural topology.

3.1. Structural Model

The fuselage and tail assembly finite-element (FE) model was created in Altair HyperMesh [19]. To reduce computational complexity, the nose and aft sections of the fuselage were omitted. An integrated wing structure, generated with ModGen [20, 21], was incorporated into the fuselage together with the vertical and horizontal stabilizers. ModGen is a parametric modeling tool for aircraft structures that produces FE models and MSC Nastran input cards for aeroelastic analysis, developed at the Institute of Aeroelasticity in Göttingen. The wing skin and fuselage were coupled using RBE2 elements, with both front and rear spars similarly connected. Additionally, the portion of the spars inside the fuselage was tied to the floor to maintain structural rigidity.
The left wing, including its aerodynamic model, was generated in ModGen, and mirrored to create the right wing. Upper and lower skins between the spars were connected across both wings to ensure continuity. The optimized, very flexible wing model [18] and the horizontal tailplane (HTP), vertical tailplane (VTP), and fuselage models from [8, 9, 18] are employed for the complete TU-Flex demonstrator modal and aeroelastic analyses. Figure 5 illustrates the full FE model and the elements used to represent each component of the demonstrator.

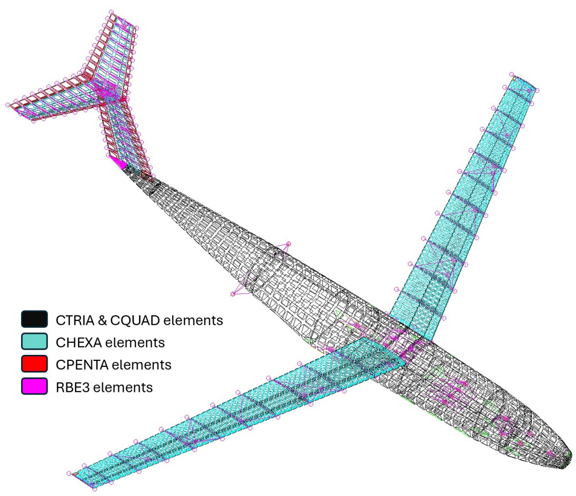

FIG 5. TU-Flex finite element structural model.

3.2. Aerodynamic Model

For aerodynamic modeling in Nastran, the Doublet Lattice Method (DLM) is employed. This method subdivides the lifting surface into small trapezoidal panels, also referred to as boxes, which are arranged in columns aligned with the free-stream direction. The panel method is widely used in aerodynamic simulations due to its balance between computational efficiency and accuracy, particularly when viscous effects can be neglected [22]. DLM enables the calculation of aerodynamic loads on the upper and lower surfaces of the wing, which are necessary to fully stress the structure, while requiring significantly less computational effort than a full Navier–Stokes solver [23].
In this study, ten panels are defined using the `CAERO1` card in Nastran. These cards specify the layout of the trapezoidal panels by defining the number of boxes in both the spanwise and chordwise directions, as well as the positions and chord lengths of the first and last rows of boxes. The aerodynamic model of the TU-Flex right wing comprises a total of 780 boxes. Among the ten panels, four trimming surfaces are defined using the `AESURF` entry, corresponding to specific aerodynamic boxes that represent the wing's control surfaces. The aerodynamic mesh of TU-Flex-VFW is presented in Fig 6.

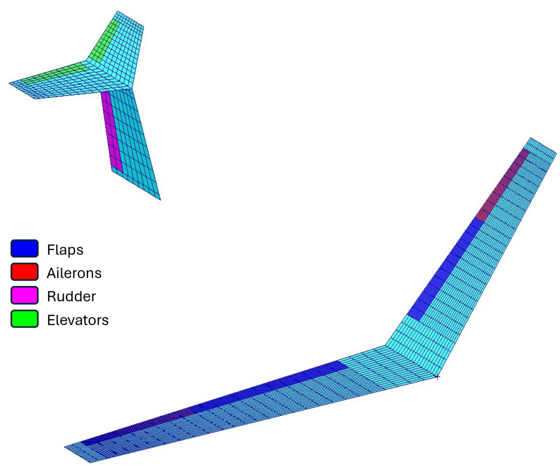

FIG 6. TU-Flex panel mesh aerodynamic model, control surfaces highlighted.

The aerodynamic discretization follows MSC Nastran guidelines [24] to ensure accurate representation of aerodynamic loads and coupling with structural modes. Box sizes and aspect ratios were selected to resolve the structural frequencies of interest, with the chordwise discretization sufficient to capture the highest frequency of 50 Hz at the cruise airspeed considered (30 m/s). This choice ensures that the reduced frequency remains within an acceptable range for the DLM assumptions, providing reliable aeroelastic loading for subsequent modal and structural analyses. The aerodynamic model is directly coupled with the FE wing model generated in ModGen, enabling the computation of aeroelastic loads and the assessment of structural response under operational flight conditions. Together, these models form the basis for the TU-Flex modal and aeroelastic analyses.

3.3. Aeroelastic Modelling

In the aeroelastic modeling framework, two key aspects are considered: the aero-structural coupling and it's verification. The aerodynamic and structural surface grids generally do not coincide due to differences in mesh density. While the structural model is typically more refined, condensation of the finite element (FE) model often results in a structural grid that is sparser than the aerodynamic grid. To reconcile this discrepancy, an interpolation scheme is employed to transfer loads and displacements between the two models. In this study, spline functions are used to map aerodynamic forces onto the structural grid and to project structural displacements back onto the aerodynamic grid.
Aero-structural coupling can be assessed by evaluating the correspondence between aerodynamic loads and structural responses at designated monitoring points. The structural monitoring points, defined in accordance with the MSC FlightLoads 2024 User Guide, serve as reference locations to verify the consistency of force transfer between the aerodynamic and structural domains. Deviations observed at these points indicate deficiencies in the coupling procedure and highlight the need for further refinement to ensure reliable aeroelastic predictions.

3.4. Flutter and Longitudinal Stability Analysis

Subsonic flutter analysis of the TU-Flex was performed using MSC Nastran SOL145 [24]. The KE-method, an efficient variant of the K-method that neglects viscous damping, was employed to compute stability curves and ensure flutter-free operation across the flight envelope. Flutter constraints were treated separately from the wing optimization process, allowing evaluation of modal frequencies and damping as a function of airspeed to identify potential aeroelastic instabilities.
Dynamic longitudinal stability was analyzed by focusing on the short-period mode about the pitch axis. The natural frequency and damping ratio of this mode were determined to characterize the aircraft's pitch response and handling qualities. These results provide a basis for assessing the dynamic behavior of the TU-Flex and for guiding potential improvements in handling performance.

4. RESULTS

This section presents the key findings of the TU-Flex aeroelastic and flight dynamics analyses. The results are organized into three main parts. First, the modal analysis of the complete aircraft is presented, highlighting the natural frequencies and mode shapes of the flexible wing and fuselage structures. Second, subsonic flutter calculations are shown, providing flutter boundaries and stability margins within the operational envelope. Finally, the coupling between structural modes and flight dynamics is examined, illustrating how aeroelastic effects influence the aircraft's dynamic response. Together, these results demonstrate the effectiveness of the integrated modeling approach and provide insight into the structural–aeroelastic behavior of the TU-Flex demonstrator.

4.1. Modal analysis

Modal analysis, a fundamental component of dynamic assessment, identifies a structure's natural frequencies and mode shapes. These inherent properties, determined by the structure's material, geometry, and boundary conditions, dictate its response to dynamic loads [25]. In this study, modal analysis was carried out using MSC Nastran SOL103.
Figures 7–10 illustrate the first two eigenmodes of the aircraft, both without and with a tip mass (TM) at the wingtip. In both configurations, the first eigenmode corresponds to the first symmetric out-of-plane bending mode of the wing (W1SBO) and the second eigenmode represents the wing second asymmetric out-of-plane bending mode (W2ABO).
Table 1 presents the eigenfrequencies of the wing with and without the TM. The addition of the TM significantly decreases the lower natural frequencies, particularly the first three modes. For example, the first mode frequency drops from 4.84 Hz without the TM to 2.07 Hz with the TM, a reduction of 58%. This decrease indicates that the wing becomes more susceptible to low-frequency oscillations, which can influence the aircraft's dynamic response under turbulent or gusty conditions. These effects must be carefully considered when balancing weight, stiffness, and the coupling between structural and flight-dynamic modes of the wing.

TAB 1. First ten frequencies of the VFW, with and without TM

Mode	Frequency [Hz]	
	Without TM	With TM
1	2.95	1.64
2	5.91	4.47
3	12.26	9.25
4	13.91	9.74
5	17.41	10.04
6	17.47	12.85
7	18.45	16.9
8	22.32	22.3
9	28.67	28.33
10	34.1	28.66

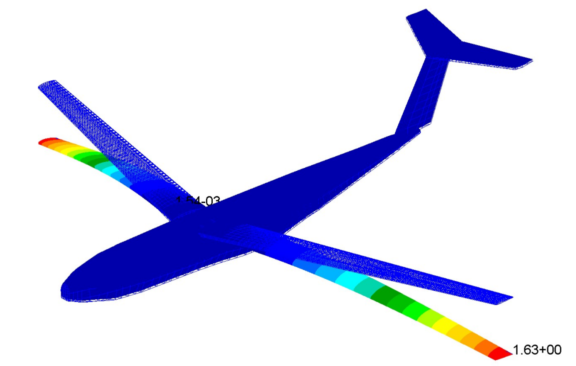

FIG 7. Mode 1 of the TU-Flex without TM: 2.93 Hz

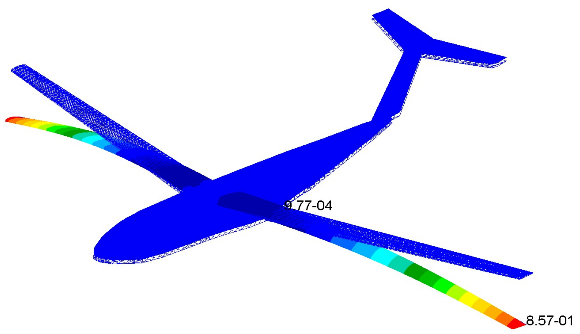

FIG 8. Mode 1 of the TU-Flex with TM: 1.56 Hz

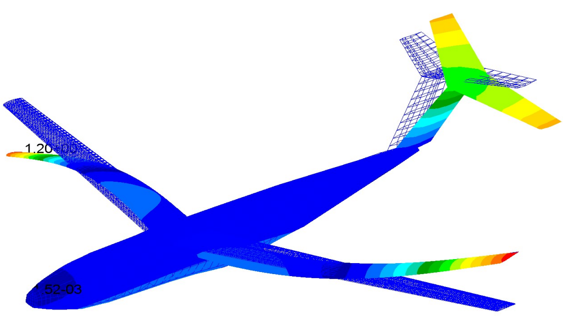

FIG 9. Mode 2 of the TU-Flex without TM: 5.33 Hz

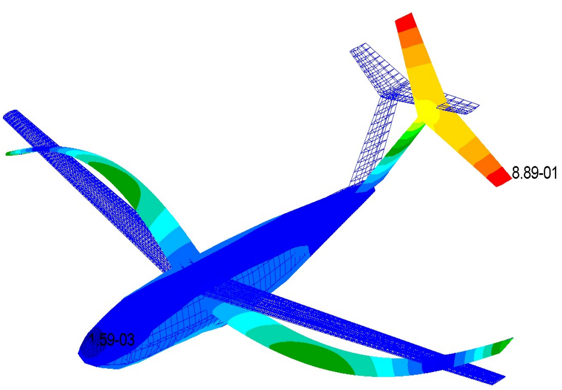

FIG 10. Mode 2 of the TU-Flex with TM: 4.13 Hz

4.2. Subsonic flutter calculation

Subsonic flutter analysis of the TU-Flex demonstrator was performed using MSC Nastran SOL145 [24], employing the KE-method for modal flutter analysis. Structural eigenmodes and frequencies were obtained from a reduced set of nodes, and aerodynamic influence matrices were calculated using standard Nastran bulk data entries. A total of 26 eigenmodes were extracted, with 20 modes included in the flutter evaluation, capturing all relevant wing, horizontal tailplane (HTP), and vertical tailplane (VTP) bending and torsion modes. The aerodynamic model was discretized up to a maximum reduced frequency of 3.0.

TAB 2. Parameters of subsonic flutter calculation on TU-Flex

Parameter	Value
Mach number, Ma	0.1749
Air density,ρ	1.225 kg/m^3
Dynamic pressure, q	2205 Pa
Calculated eigenmodes	26
Considered eigenmodes	20
Considered red. frequencies	0.01 to 3.0 with 299 sampling points

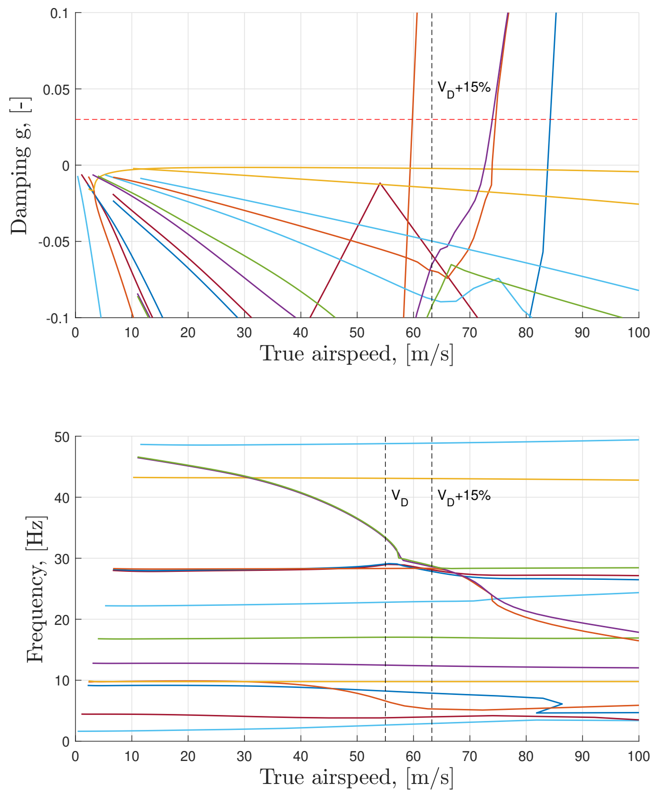

FIG 11. Flutter analysis: V-g and V-f plots of TU-Flex with TM (VFA).

Table 2 summarizes the parameters used for the selected flight condition. The analysis indicates that flutter occurs at 60 m/s, which is 5 m/s beyond the design diving speed (V_D), but still within $V_D + 15\%$, in accordance with CS25 [26]. Figures 11–13 illustrate the damping and frequency behavior across airspeeds and the key eigenmodes involved. The primary flutter phenomenon arises from the coupling between the wing torsion mode and HTP asymmetric bending, highlighting the interaction of structural components that governs aeroelastic stability. Despite the TU-Flex's high flexibility, the demonstrator remains flutter-free within the intended flight envelope.

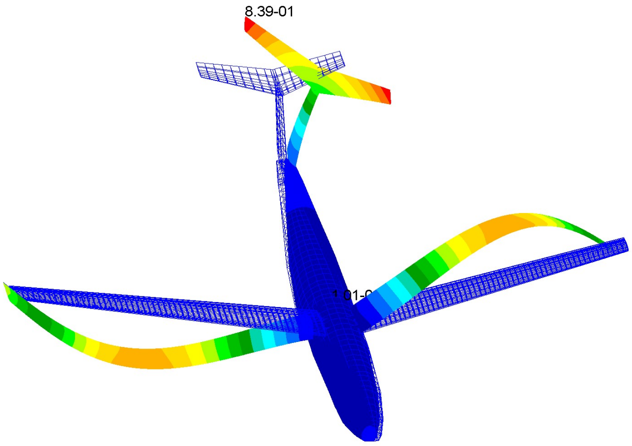

FIG 12. Mode 3: Wing second asymmetric bending out-of-plane and VTP bending mode involved in the flutter phenomenon.

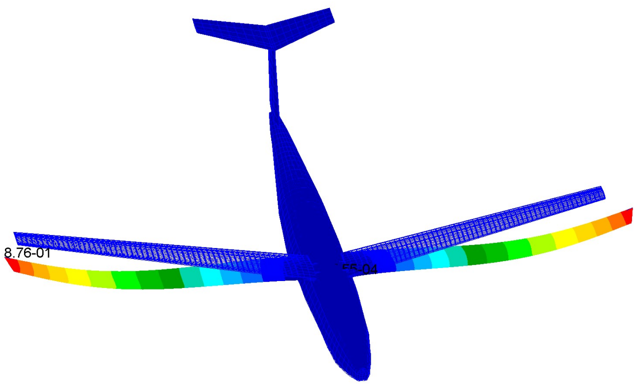

FIG 13. Mode 4: Wing second symmetric bending out-of-plane mode involved in the flutter phenomenon.

5. COUPLING ANALYSIS: STRUCTURAL DYNAMICS AND FLIGHT MECHANICS

As wing flexibility increases, the frequencies of structural modes decrease, which can lead to coupling between rigid-body and elastic modes. To investigate this effect, ModSiG-FMRA was employed. ModSiG-FMRA captures the full nonlinear equations of motion and both steady and unsteady aerodynamic effects, enabling stability analysis across the entire flight envelope.

In addition, the short-period mode was analyzed using MSC Nastran to obtain approximate natural frequencies and damping ratios. These approximations rely on linearized equations of motion and are used to evaluate the coupling between the short-period flight-dynamic mode and the lower-frequency structural modes. While Nastran provides a simplified view of the short-period dynamics, ModSiG-FMRA uses the complete nonlinear formulation, allowing the assessment of aeroelastic and flight-dynamic interactions over a wider range of operating conditions. Pole-zero maps were employed to visualize the frequencies and damping characteristics, providing insight into stability margins and the dynamic behavior of the TU-Flex-VFW configuration.

Table 3 compares the damped natural frequencies of the short-period mode and the first wing bending mode of the TU-Flex, as obtained from MSC Nastran and ModSiG-FMRA. The results show only minor deviations: 0.17 Hz for the short-period mode and 0.29 Hz for the first wing bending mode. These small differences arise from the approximation inherent in the Nastran calculation, particularly the neglect of the $C_{m_{\dot{\alpha}}}$ term in the short-period damping calculation. Overall, the close agreement demonstrates that the simplified Nastran approach provides a reliable estimate of the short-period dynamics that can be used in the wing optimization process, while ModSiG-FMRA captures the full nonlinear behavior, which can be used later for flying qualities evaluations and control design.

TAB 3. Damped natural frequency of short-period and 1st wing bending frequency of the TU-Flex from Nastran and ModSiG-FMRA

Parameter	Nastran [Hz]	ModSiG [Hz]
$\omega_{d_{SP}}$ (flexible)	1.56	1.73
1st wing bending frequency	1.98	1.69

The root loci of the TU-Flex-VFW were computed across the entire flight envelope, with velocities ranging from 18 m/s to 50 m/s at a cruise altitude of 100 m. Figure 14 shows the migration of all rigid-body modes (pure roll, short period, Dutch roll, phugoid, and spiral) alongside the first eight structural modes of the aircraft. The right side of the figure provides a zoom on the lower-frequency modes, enabling detailed observation of their interactions. Inspection of the root loci indicates that the aircraft remains dynamically stable throughout the considered flight envelope, with the frequencies of all rigid-body modes generally increasing with velocity.

The plot further highlights the coupling between structural and rigid-body modes. Twisting of the root loci reveals mode interactions, with the short-period mode crossing the wing first symmetric bending out-of-plane mode (W1SBO) and approaching the wing second asymmetric bending out-of-plane mode (W2ABO). The pure roll mode is no longer purely imaginary, reflecting the influence of structural flexibility on the overall dynamic behavior.

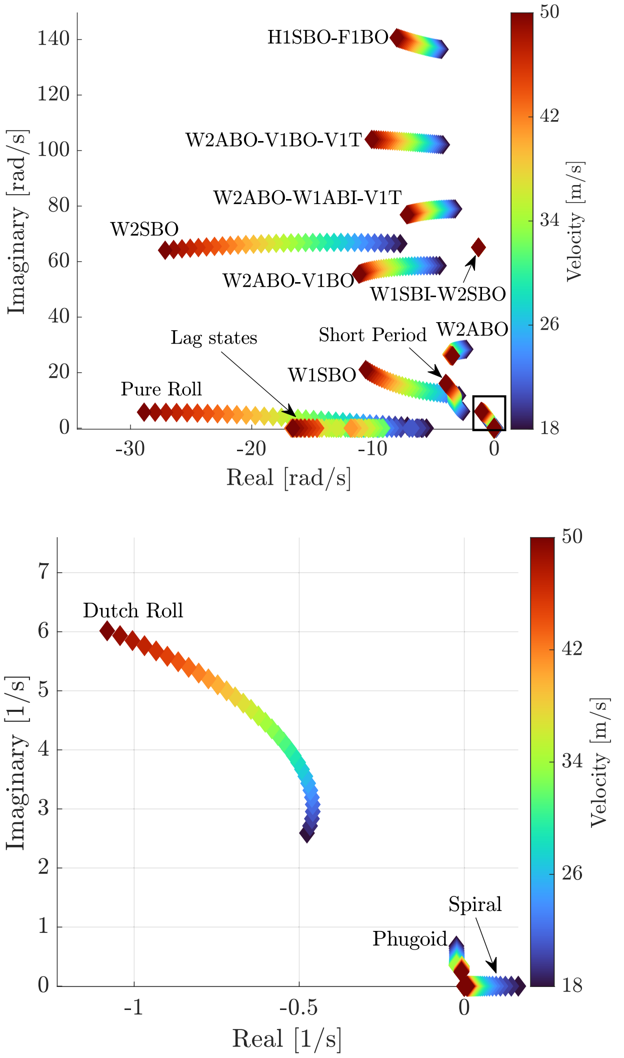

FIG 14. Full root loci varying the velocity from 18 m/s to 50 m/s at the cruise flight altitude of the TU-Flex with VFW set using unsteady linear aerodynamics model (top) and a zoomed-in view near the origin (bottom) [13].

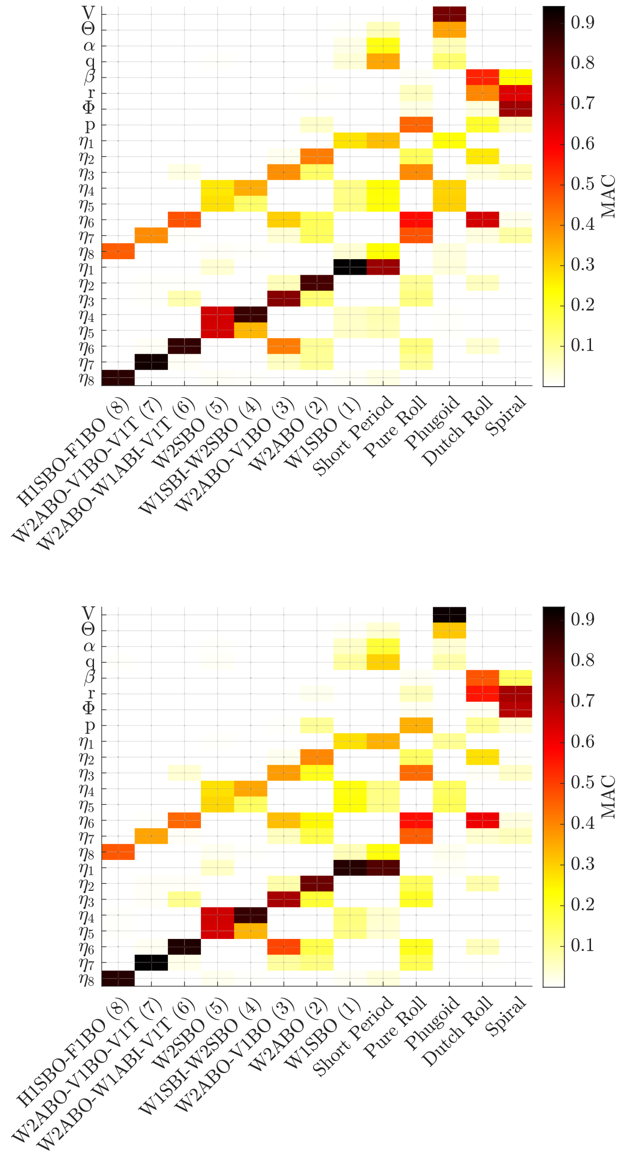

FIG 15. MAC map of the TU-Flex with VFW set at 22 m/s (top) and 30 m/s (bottom), at the cruise flight altitude (100 m) [13].

The nature of the coupling can be further analyzed using the Modal Assurance Criterion (MAC) plot shown in Figure 15, which quantifies the contribution of each state variable to the dynamic modes at a certain flight condition. While the MAC is traditionally used to compare finite element mode shapes with experimental data, it can also be applied to dynamic systems to examine modal coupling and state contributions. MAC values range from 0 to 1, with values near 1 indicating a strong influence of the state on the corresponding mode, and values near 0 indicating little contribution. For instance, inspection of the short-period mode columns reveals the typical flight-dynamic states (q and w_K) as dominant. However, due to coupling with the structure, structural states such as η_1 and $\dot{\eta}_1$ also contribute significantly to this mode, showing higher copling when increasing velocity from 22 m/s to 30 m/s. Phasor analysis of the normalized eigenvector at 30 m/s (Fig. 16) shows that q and η_1 have similar amplitudes and are approximately in phase, whereas $\dot{\eta}_1$ exhibits a significantly larger magnitude. This interaction confirms the influence of structural dynamics on the rigid-body dynamics and demonstrates that the methodology is capable of capturing the aeroelastic behavior of a very flexible aircraft.

The MAC indicators serve as quantitative measures of the level of coupling and guide the parametric study, supporting the design process to ensure that the aircraft exhibits the intended flight-dynamics/structural-dynamics interaction. Based on these indicators, it is possible to conclude that the designed demonstrator can be classified as a very flexible aircraft.

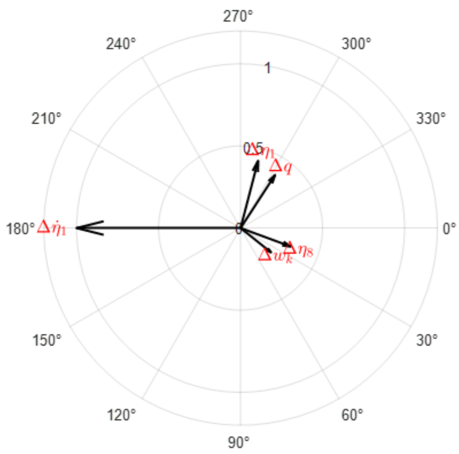

FIG 16. Short period phazor.

6. SUMMARY AND CONCLUSION

This study presents a systematic procedure for evaluating the coupling between structural modes of a very flexible wing and the aircraft's flight mechanical modes within the aircraft design process. The methodology combines parametric structural modeling with ModGen, finite-element analysis using MSC Nastran, and flight dynamics simulations via ModSiG-FMRA. By integrating these tools, it is possible to quantify the interactions between structural and rigid-body modes, identify critical coupling phenomena, and guide the design to ensure that the aircraft exhibits the desired flight dynamics while maintaining structural integrity.
The TU-Flex demonstrator, with its very flexible wings, T-tail configuration, and optimized aerodynamic surfaces, was used to validate this approach. Modal analysis revealed that the addition of a tip mass effectively reduced the eigenfrequencies, enabling significant interaction between the short-period mode and the first wing bending mode. Subsonic flutter analysis confirmed that the demonstrator remains flutter-free across the operational envelope, with flutter predicted at 60 m/s—slightly above the design diving speed but still within the allowable safety margin.
The coupling analysis shows that the short-period mode has a damped natural frequency of 1.73 Hz, while the first wing bending mode occurs at 1.69 Hz. The close proximity of these frequencies highlights the strong interaction between the flight mechanics and structural dynamics of the very flexible wing, confirming that the methodology can be used to design and assess control strategies that account for both aeroelastic and rigid-body behavior. MAC analysis further validated the coupling, providing a quantitative measure of the contributions of structural states to the flight-dynamic modes and supporting the classification of TU-Flex as a very flexible aircraft.
Overall, the developed workflow provides a robust framework for designing and analyzing very flexible aircraft, enabling engineers to evaluate structural–flight dynamics coupling early in the design process and ensure safe, stable, and well-coupled behavior throughout the flight envelope.

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References

[1] W. Su and Carlos E. S. Cesnik. Strain-based analysis for geometrically nonlinear beams: a modal approach. *Journal of Aircraft*, 51(3):890–903, 2014. DOI: 10.2514/1.C032486.

[2] A. Cea and R. Palacios. Nonlinear modal aeroelastic analysis from large industrial-scale models. In *AIAA Scitech 2019 Forum*, page 208. American Institute of Aeronautics and Astronautics, 2019. DOI: 10.2514/6.2019-0208.

[3] M. C. Van Schoor, S. H. Zerweckh, and A. H. von Flotow. Aeroelastic stability and control of a highly flexible aircraft. In *30th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Mobile, AL, Apr. 1989. AIAA. AIAA Paper 1989-1187.

[4] Mayuresh J. Patil, Dewey H. Hodges, and Carlos E. S. Cesnik. Nonlinear aeroelasticity and flight dynamics of high-altitude long-endurance aircraft. *Journal of Aircraft*, 38(1):88–94, 2001. DOI: 10.2514/2.2738.

[5] M. Drela. Integrated simulation model for preliminary aerodynamic, structural, and control-law design of aircraft. In *40th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit*, St. Louis, MO, Apr. 1999. AIAA. AIAA Paper 1999-1394.

[6] Christopher M Shearer and Carlos E.S. Cesnik. Nonlinear flight dynamics of very flexible aircraft. *Journal of Aircraft*, 44(5):1528–1545, doi: 10.2514/6.2005–5805, 2007.

[7] Weihua Su and Carlos E. S. Cesnik. Dynamic response of highly flexible flying wings. *AIAA Journal*, 49(2):324–339, 2011. DOI: 10.2514/1.J050496.

[8] Pedro J. González, Gerrit Stavorinus, Hikmat Shahi, Yasser M. Meddaikar, Sunpeth Cumnuantip, Arne Voß, Thomas Klimmek, Wolf R. Krüger, and Flávio J. Silvestre. A preliminary structural design of a flexible flying demonstrator. In *33rd Congress of the International Council of the Aeronautical Sciences (ICAS)*, Stockholm, Sweden,

Sept. 2022. International Council of the Aeronautical Sciences (ICAS).

[9] Pedro J. González, Hikmat Shahi, Yasser M. Meddaikar, Wolf R. Krüger, and Flávio J. Silvestre. Flexible-wing design process for tu-flex demonstrator. In *International Forum on Aeroelasticity and Structural Dynamics (IFASD)*, Madrid, Spain, June 2022. IFASD.

[10] P González, G Stavorinus, H Shahi, YM Meddaikar, S Cumnuantip, A Voß, T Klimmek, WR Krüger, and FJ Silvestre. A structural preliminary design of a flexible flying demonstrator. In *Proceedings*, Stockholm, Sweden, 2022. 33rd Congress of the International Council of the Aeronautical Sciences - ICAS 2022At:, ICAS. ISBN: 978-171387116-3.

[11] Pedro J. González, Gerrit Starvorinus, Flavio J. Silvestre, Arne Voß, Yasser M. Meddaikar, and Wolf R. Krüger. Tu-flex: A very-flexible flying demonstrator with a generic transport aircraft configuration. In *AIAA SCITECH 2023 Forum*, 2023. DOI: 10.2514/6.2023-1312.

[12] Pedro J. González, Guilherme C. Barbosa, Álvaro A. G. Quesada, Gerrit Stavorinus, Flávio J. Silvestre, Jonathan Hilger, Charlotte Hanke, Arne Voß, and Wolf R. Krüger. Wind tunnel testing and modal validation of tu-flex's high aspect-ratio wings. In *International Forum on Aeroelasticity and Structural Dynamics (IFASD)*, The Hague, The Netherlands, June 2024. IFASD.

[13] Álvaro A. G. Quesada, Pedro J. González, Guilherme C. Barbosa, Gerrit Stavorinus, and Flávio J. Silvestre. Influence of nonlinear aerodynamic effects on high aspect ratio aircraft model. In *IFASD 2024 - International Forum on Aeroelasticity and Structural Dynamics,*, 2024.

[14] Martin R Waszak and David K Schmidt. Flight dynamics of aeroelastic vehicles. *Journal of Aircraft*, 25(6):563–571, 1988. DOI: https://doi.org/10.2514/3.45623.

[15] Flávio J Silvestre and Robert Luckner. Experimental validation of a flight simulation model for slightly flexible aircraft. *AIAA Journal*, 53(12):3620–3636, 2015. DOI: 10.2514/1.J054023.

[16] Mauricio Armijos. *Fast Flight Dynamics Evaluator And Simulator With Visualization For HIL Applications*. Bachelor's thesis, Technische Universität Berlin, Berlin, 2022.

[17] Zeinab Eltaher. *Modelling and implementation of a real-time flexible aircraft simulation environment with animation of flight path, attitude and airframe deformation*. Master's thesis, Technische Universität Berlin, Berlin, 2024.

[18] H. Shahi, P. J. González, W. R. Krüger, and F. J. Silvestre. Model-based aero-structural design and optimization of a highly flexible high aspect-ratio wing. To be published, DLRK 2025, Augsburg, 2025.

[19] Altair Hypermesh. Altair hypermesh. [Retrieved: 18.06.2024]. https://www.altair.de/hypermesh/.

[20] Thomas Klimmek. ModGen. User's Manual. 2020.

[21] Thomas Klimmek, Matthias Schulze, Mohammad Abu-Zurayk, Caslav Ilic, and Andrei Merle. cpacs-mona – an independent and in high fidelity based mdo tasks integrated process for the structural and aeroelastic design for aircraft configurations. In *International Forum on Aeroelasticity and Structural Dynamics 2019, IFASD 2019*, Juni 2019.

[22] MSC Corporation. NAS120 - Linear Static Analysis using MSC Nastran and Patran. https://www.mscsoftware.com/session/nas120-linear-static-analysis-using-msc-nastran-and-patran?language=en, 2012. [Online class].

[23] Luis Félix, Alexandra A. Gomes, and Afzal Suleman. Topology Optimization of a Wing Including Self-Weight Load. pages 1–17, April, 2013, DOI: 10.2514/6.2013-1869.

[24] MSC Corporation. Aeroelastic Analysis User's Guide. [MSC Nastran 2021.1 student version].

[25] MSC Software Corporation. *MSC Nastran Design and Optimization User's Guide*. Hexagon MSC Software, Newport Beach, CA, 2025. Version 2025, accessed via institutional license.

[26] European Aviation Safety Agency. Cs25 - certification specifications and acceptable means of compliance for large aeroplanes - amendment 28, 2023. [Retrieved: 18.06.2024]. https://www.easa.europa.eu/en/document-library/certification-specifications/group/cs-25-large-aeroplanes#cs-25-large-aeroplanes.