A COMPARISON OF MODELING METHODS FOR THE SIMULATION OF FREE FLYING ELASTIC AIRCRAFT

K. Seywald[1], A. Wildschek[1], F. Holzapfel[2]

[1] Airbus Group Innovations
Willy-Messerschmitt-Straße 1, 85521 Munich
klaus.seywald@airbus.com

[2] Technische Universität München
Boltzmannstr. 15, Garching
florian.holzapfel@tum.de

Keywords: flexible aircraft dynamics, flight simulation, UVLM, GAF, mean-axis, fixed-axis

Abstract: This article deals with different methods for modeling the free-flying flexible aircraft and compares the obtained models for aircraft response simulations. A direct time domain approach which is composed of a free flying finite element structure coupled to an unsteady potential flow method was implemented. This method is used to investigate the impact of fixed-axis and mean-axis boundary conditions. Furthermore the impact of quasi-steady and unsteady aerodynamic modeling to the aircraft response is investigated. A modal truncation method is introduced which is based on the significance of modes in characteristic loadcases. Moreover a fast time capable reduced order model is generated from the original model allowing fast time simulations with similar accuracy.

1 INTRODUCTION

The exploration of future aircraft designs is evolving towards unconventional configurations and high aspect ratio wings, which show high potential for fuel efficiency improvement. For this kind of configuration aeroelasticity is becoming an increasingly important discipline since flexibility may lead to significant impacts on structural loads, response characteristics and performance. These and other possibly unanticipated effects need to be understood as early in the a/c design process as possible. Therefore a preliminary design tool is under development allowing the preliminary aeroelastic structural sizing and mass estimation for novel aircraft concepts [1]. The tool was further developed to assess dynamic loads and to perform flight simulations for aircraft handling quality and response investigations [2]. Because low frequency structural modes may interact with flight dynamics modes, an integrated flight dynamic aeroelastic model is required for this type of investigations. A number of models for the integrated flight dynamic aeroelastic simulation were developed [3], most relying on simplifications such as the mean-axis approximation which decouples the rigid body motion from the elastic deformations. Although some doubts were raised by [4] that mean axis may constitute an unrealistic simplification for certain cases, it is still widely used for the simulation of flexible aircraft. Differences between a potentially more accurate method using a nodal-fixed reference frame were investigated in [5, 6] showing minor to moderate differences. Another commonly used method for the efficient simulation of elastic aircraft is the approximation of the unsteady aerodynamic forces via rational functions. The frequency domain generalized aerodynamic forces constitute a linearization about a reference state of the aircraft and are usually obtained using a doublet lattice method (DLM), but may as well be determined using higher fidelity CFD methods [7]. High fidelity approaches for flexible aircraft dynamics which are used for accurate loads and response prediction in contrast use direct time domain aerodynamic solutions coupled to the rigid body equations of motion and the flexible structure [8, 9].

The objective of this paper is the comparison of the direct time domain method (DTM) and the possible reference frames (fixed-axis, mean-axis) against a significantly faster reduced order model using rigid quasi steady tabulated aerodynamics coupled to an aeroelastic state space system. Different cases for the maneuver response are computed, and the response characteristics of the models are compared.

2 MODELING

The elastic airframe model is composed of a structural finite element model an aerodynamic potential flow model implementing the steady and unsteady vortex lattice method (VLM, UVLM). These are coupled with respect to mesh deformation and load transfer, applying a splining algorithm [1].

2.1 Reference Aircraft

The models are compared on the example of a large flexible transport aircraft with significant flexibility contributions, shown in Figure 1.

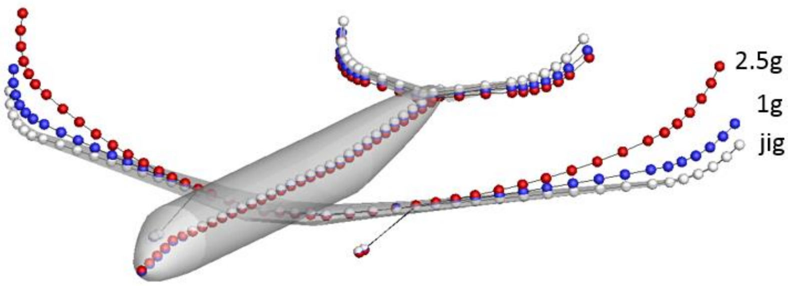

Figure 1: Reference Aircraft

The lowest structural modes of the reference aircraft are presented in Table 1.

Mode	Description	Freq.
1	1^{st} Wing bending, symmetric	0.78
2	1^{st} Wing bending, antisymmetric	1.01
3	2^{nd} Second bending, symmetric	1.89

Table 1: Frequencies

2.2 Direct Time Domain Method

The best accuracy solution for the free flying flexible aircraft applying the given model, is obtained by direct time integration of the equations of motion for the moving deformable body which is coupled to the unsteady vortex lattice time domain solution. The equations of motion for the moving deformable were derived and implemented based on [10], but were extended with nodal rotational degrees of freedom to allow the incorporation of the 3D finite element beam model which results from the applied preliminary design and sizing process [1, 2]. While other inertially coupled formulations by [11] or [12] are made using a Lagrangian formulation in terms of body quasi coordinates this formulation is based on the inertial reference frame leading to an equation of the form

$$M\begin{pmatrix}\ddot{r}\\ \dot{\omega}\\ \ddot{\delta}\end{pmatrix} + C\dot{\delta} + K\delta = F_{ext} + F_{acc} \tag{1}$$

The given formulation allows both the incorporation of nodal-fixed and mean-axis boundary conditions, for details it is referred to [10]. Using nodal fixed boundary conditions the solution must be independent of the choice of the fixed node if the deformations are reasonably small. This was confirmed through multiple simulations. Placing the fixed node in the center fuselage ensures that the deformations relative to the fixed point remain at a minimum. The overall deformations relative to the reference frame are however smaller using mean-axis frame, which is placed at the instantaneous center of mass. The transient solution of the free flying aircraft structure is found by time integration of Equation 1 using the Newmark-Beta scheme [13]. Since the stiffness matrix K and the force vectors F are a function of time a Newton Rapson subiteration is required. The free flying aircraft structure is coupled to the aerodynamic loads model using a conventional serial staggered algorithm [9] as shown in Figure 1.

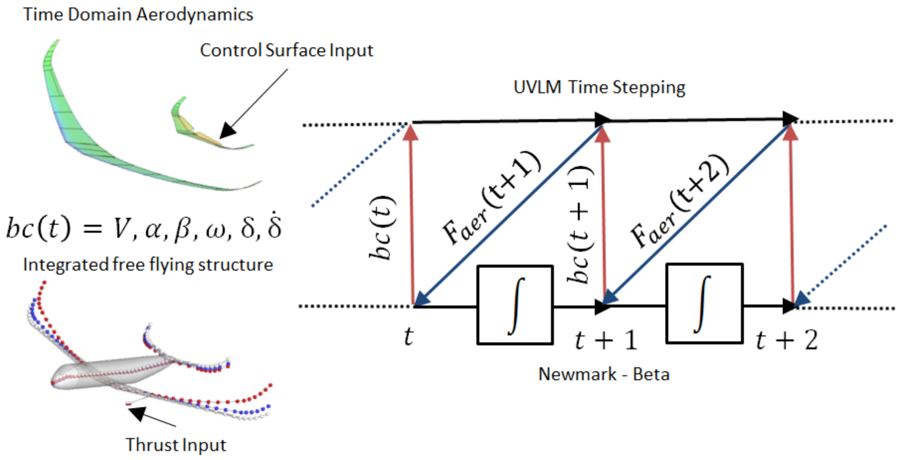

Figure 1: Direct Time Domain Method

The boundary conditions bc(t) required by the potential flow aerodynamic solver include the flight dynamic states and the current deformation, as well as the current deformation speed. These variables are passed from the structural solver to the aerodynamic solver in each timestep. These boundary conditions are used to update the aerodynamic mesh and to compute the aerodynamic forces for the next timestep. The obtained loads are then transformed back to the structural mesh which allows the computation of the movement and deformations of the structure for the next timestep. Instead of the UVLM forces the quasi steady VLM forces may be used equivalently. The thrust forces are applied as nodal forces on the finite element model.

2.3 Modal Reduction

In certain applications, e.g. the generation of linearized state space models for control systems design it is required to reduce the number of structural modes to in order to reduce system complexity. Furthermore when using CFD methods or other time domain aerodynamic methods, the computation of the generalized aerodynamic forces is computationally significantly more expensive compared to the doublet lattice method solution. The applied modal reduction technique therefore aims at the reduction of the required structural modes for accurate response simulation, without prior consideration of special input/output variables to match.

The structural mass and stiffness matrix incorporated in Equation 1 may be transformed into modal space using the unrestrained free-free modeshapes. It is assumed that the deformation of the maneuvering aircraft can be reproduced well using a relatively low amount of modes. These modes are identified by weighing the modal deformations for different characteristic loadcases. An example is shown in Figure 2. It can be seen that the deformation for the 1g cruise case is reproduced well by just considering the main wing and stabilizer bending modes.

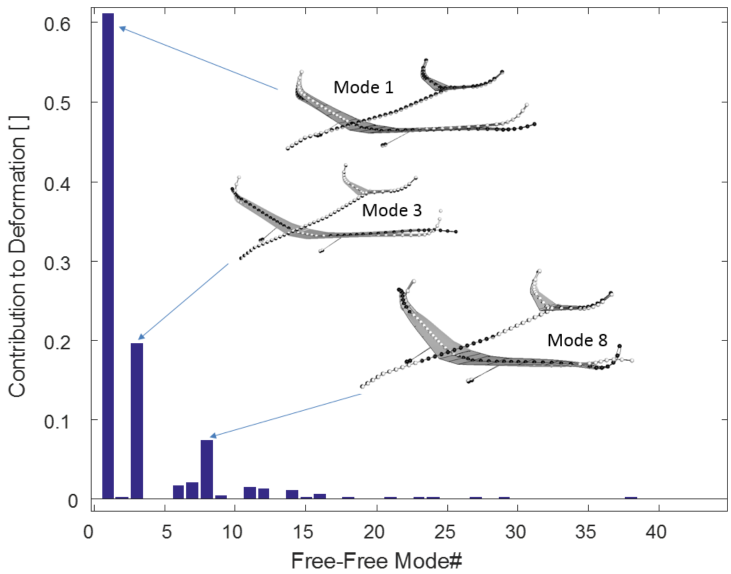

Figure 2: Significant Modes for 1g flight shape

This weighing is averaged for a number of characteristic loadcases that are available since from the structural sizing process, such as the 2.5g pull maneuver or a roll and sideslip maneuver. The modes are then ordered according to their contribution the overall deformation and the modes accounting for 99% of the characteristic loadcase deformations are kept, whereas the rest of the modes is removed. For the benchmark aircraft this was achieved with only 24 modes. This loadcase selective truncation (LST) shows good results for response investigations. This can be seen in Figure 7 and Figure 8, where the response on the pitch rate q and the roll rate p to an elevator and an aileron doublet input are compared. The direct time domain model for the unreduced case and the LST model match very closely while the difference is slightly larger using the classic modal truncation.

2.4 Fast time method

The direct time integration of the equations for the free-flying deformable body along with the time domain aerodynamic solution is computationally too expensive to be used for a fast time simulation. The fast time approach solves the 6DoF rigid body equations of motion about the mean axis reference point. The rigid body movement is assumed to be decoupled from the elastic equations of motion which are solved separately in a state space system. The aeroelastic and the rigid body equations are only interacting by means of aerodynamic and thrust forces as depicted in Figure 3. The thrust impact on deformation is considered, as is the change of the thrust vector due to deformation, although this influence was found to be minor.

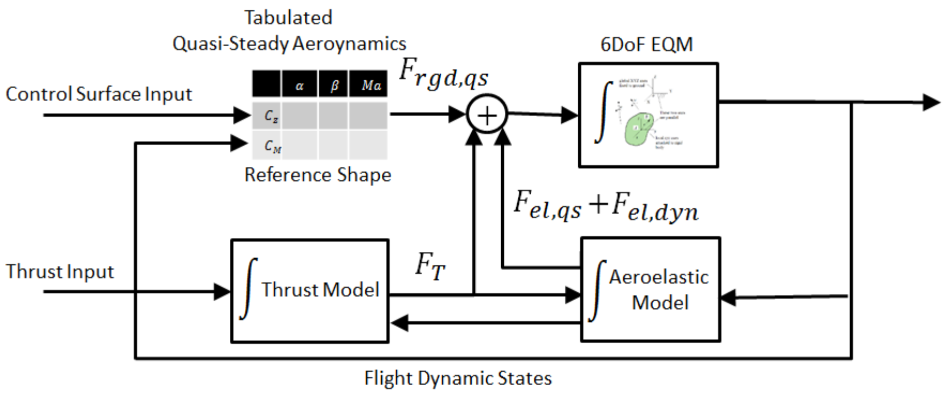

Figure 3: Fast Time Simulation Scheme

The aerodynamic forces are separated into a rigid part, a quasi-steady aeroelastic part and an unsteady aeroelastic part. The rigid aerodynamic forces are computed and tabulated for a given reference shape. In this case the table is obtained from the vortex lattice method using the equivalent mesh from the unsteady vortex lattice method used in the DTM to ensure comparability. The rigid dataset may however be replaced with higher fidelity data such as wind tunnel measurements as the design process evolves. The aeroelastic force increments result from a state space model and are added to the input forces driving the 6DoF equations of motion. This approach is known from [14, 15].

The state space model as shown in Figure 4 is obtained using Karpel's minimum state method [16]. Only the LST modes are used for the generation of the state space model. The complex generalized aerodynamic forces (GAF) are computed for these modes using the UVLM in the body fixed frame of the aircraft. The roots were not optimized but were set equal to the vector of reduced frequencies k which is ranging from k=0.01 to k=1.3. The state matrix $\boldsymbol{A}_{ee}$, the input matrix $\boldsymbol{B}_{re}$ for the rigid body states in generalized coordinates and the input matrix $\boldsymbol{B}_{ce}$ for the control states, as well as the output matrix $\boldsymbol{C}_{er}$ are scheduled with respect to the Mach number and are a function of the dynamic pressure. The aeroelastic force output is separated into the unsteady and quasisteady contribution using the minimal residual method [15]. This allows the replacement of the quasi-steady aeroelastic increments with more accurate models if available.

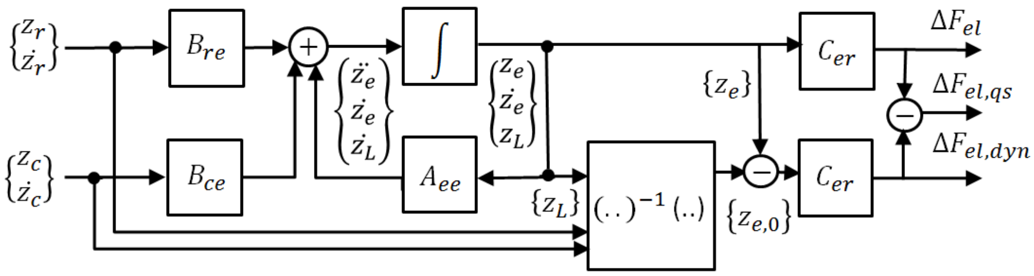

Figure 4: Aeroelastic State Space Model

Using the UVLM the GAFs can be computed as a function of the angle of attack and for different aircraft shapes. It was observed that the generalized aerodynamic forces do not vary significantly with the angle of attack. The range of variation is within the range of inaccuracy introduced by the minimum state approximation as can be seen in Figure 5. A larger variation of the GAF was found from a change of the shape which is plotted for the jig shape, the 1g flight shape and the 2.5g shape. Therefore a scheduling of the GAFs as a function of the load factor n_z can be introduced to cover this nonlinearity.

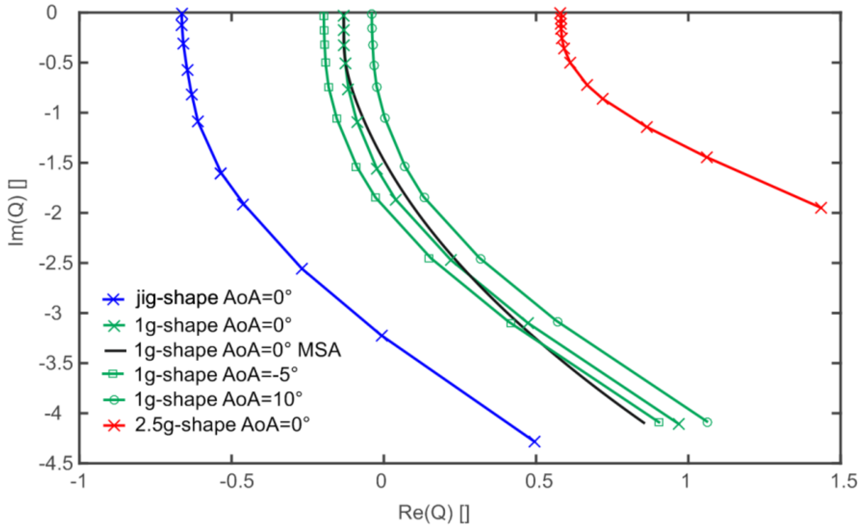

Figure 5: Self-induced aerodynamics of 1st Wing Bending Mode

3 VALIDATION

In order to ensure that all differences in the simulation originate only from flexibility effects and are not the cause of other implementation errors, the direct time domain approach and the fast time approach are compared for the rigid aircraft. The response for a doublet input on the elevator is shown in Figure 6. It can be seen that the response is independent of whether the equations for the movable deformable body or the 6DoF equations of motion are used. The same result was obtained for the roll response but is not shown here. The minor differences may originate from integration errors. This also validates the conservative force transformation because the 6DoF equations of motion are driven by the overall aerodynamic coefficient, whereas the equations of motion for the moveable deformable body are driven by the local structural loads on the finite element model.

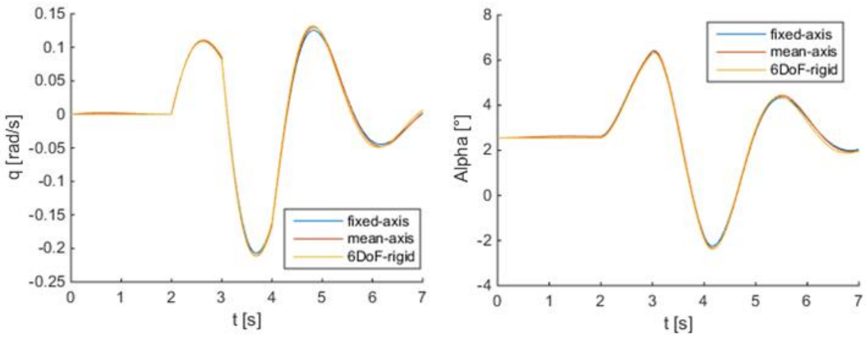

Figure 6: Validation

4 COMPARISON

The dynamic response was investigated for the pitch and roll motion due to a doublet input on the elevator and the aileron. The results are shown in Figure 7 and Figure 8, where all DTM simulations use the UVLM aerodynamic forces. All simulations were however carried out using on the one hand the unsteady vortex lattice method and the steady vortex lattice method. Slight differences in the response amplitude were found in the order of magnitude of a few percent. Since the response characteristic did not change significantly the quasi steady response plots are not shown in the Figures. The fast time model in the following simulations is using the jig shape GAFs as a reference, but considering the steady aerodynamic forces at zero deflection. The GAFs are not scheduled with respect to the shape.

A clear difference can be seen in the response between the rigid and the elastic solution both for the longitudinal and the lateral response. The elastic short period oscillation excited by the elevator doublet input shows increased damping and reduced frequency, due to the strong coupling with the wing bending mode. Both the fixed-axis solution and the mean-axis solution show a very similar response. The fast time model is able to represent the longitudinal motion relatively well. This can also be seen in the deflection of the single modes which are shown in Figure 9 for the direct time domain simulation and the aeroelastic state space system of the fast time simulation model.

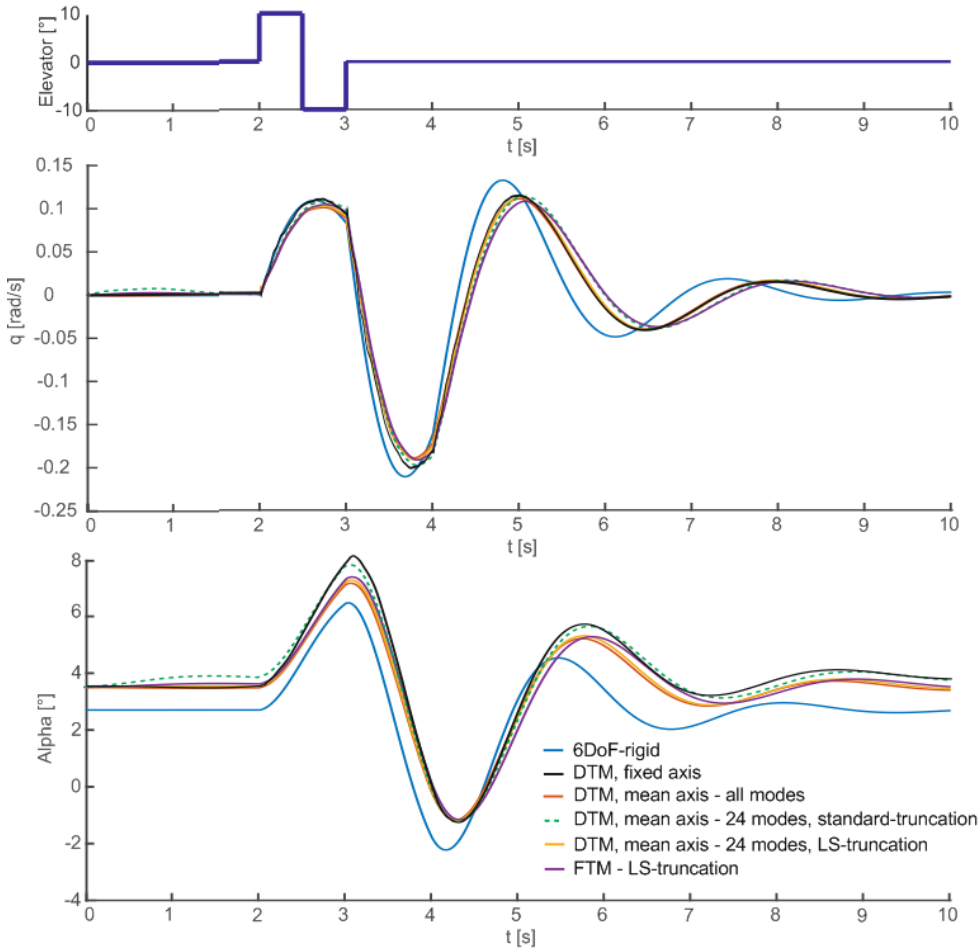

Figure 7: Longitudinal Response to Elevator Doublet, Ma=0.55, h=1000m

In the roll response it can be seen that the aileron effectiveness of the elastic aircraft is drastically reduced. A significant difference in the response between the mean-axis and fixed-axis solution can be seen for that case. All mean-axis solutions show similar results, and again the fast time model is able of capturing the elastic behavior very well. It can be seen that for both cases the loadcase selective truncation delivers slightly better results compared to a standard truncation.

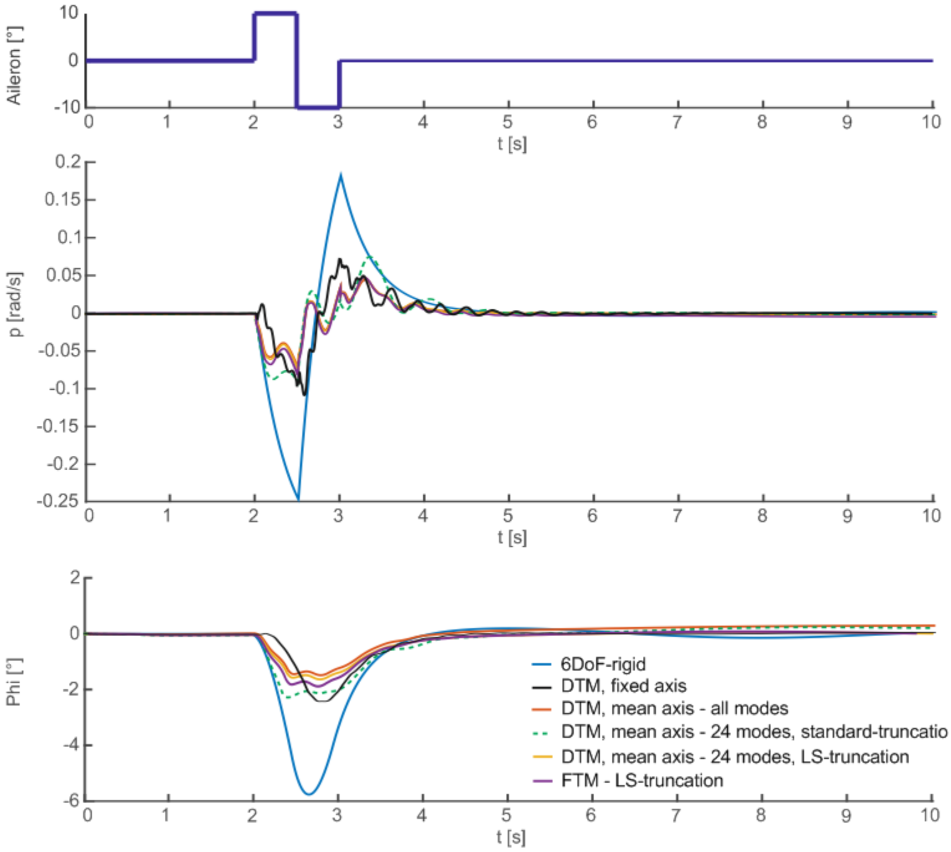

Figure 8: Lateral Response to Aileron Doublet, Ma=0.55, h=1000m

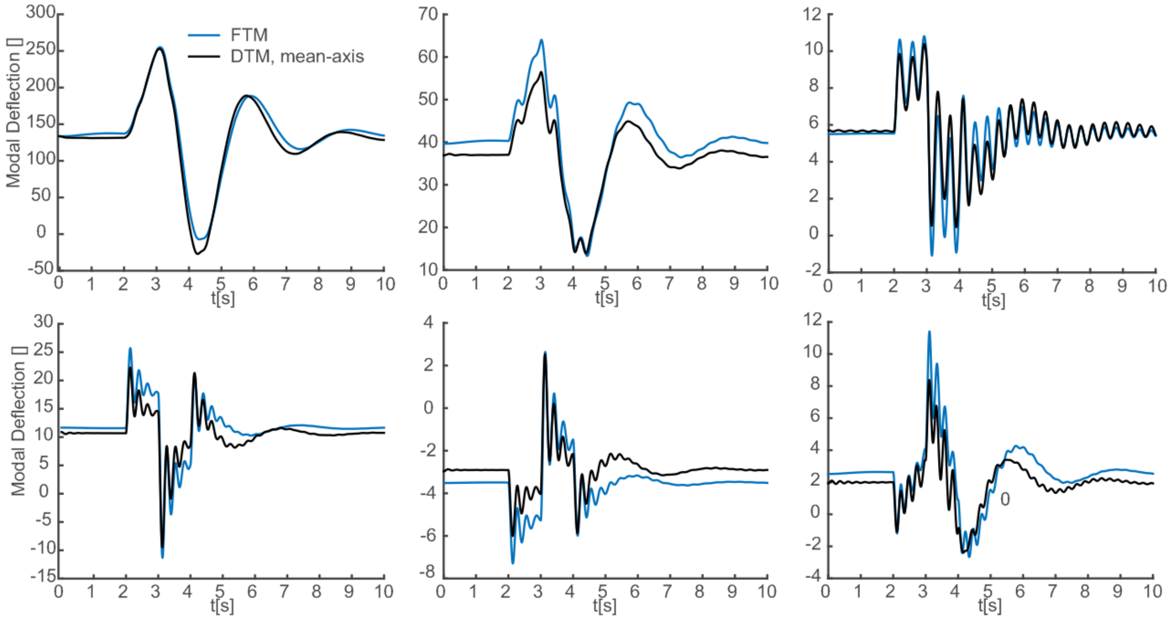

Figure 9: Modal deflections during pitch maneuver for six most significant modes

5 CONCLUSION

Different modeling approaches for the free-flying elastic aircraft were investigated, on the one hand considering the modeling of the free-flying flexible structure and on the other hand looking at different models for the aerodynamic forces.

The fixed-axis and the mean-axis approach were compared and differences could be observed. The fixed-axis solution has the highest potential to deliver accurate results, however the mean-axis approach is easier to use since it allows the decoupling of the elastic and rigid body motion as well as a simple modal reduction.

All simulations were carried out with a steady and an unsteady aerodynamic model. Changing the VLM model against the UVLM model in the DTM simulation as shown in Figure 1 did not show significant differences in the response. This however may be different for the gust response, and has to be investigated in a future step [17]. Compared to the different aerodynamic models the modeling of the free flying deformable body was showing a larger impact on the results.

It can be concluded that the mean-axis approximation is sufficient for preliminary design investigations considering large transport application scenarios, since all major impacts are covered. Although the roll response was different to the fixed-axis solution the mean-axis approach showed a similar reduction in aileron effectiveness. This may be different for larger aspect ratio configurations such as HALE aircraft, where a fixed-axis approach should be preferred.

The fast time model is able to capture the aircraft behavior very well, although slight errors are intruded during the process of the minimum state approximation. The direct time method can be used to verify the fast time model.

6 REFERENCES

[1] K. Seywald, N. G. de Paula, A. Wildschek, F. Holzapfel, C. Breitsamter, and M. Förster, "Validation of an Aeroelastic Analysis and Simulation Tool for the Assessment of Innovative, Highly Elastic Aircraft Configurations," *Deutscher Luft- und Raumfahrtkongress*, 2014.

[2] K. Seywald, F. Hellmundt., A. Wildschek, and F. Holzapfel, "Airworthiness investigation of a highly nonplanar flexible wing concept," *ICAS Conference*, 2014.

[3] M. R. WASZAK and D. K. SCHMIDT, "Flight dynamics of aeroelastic vehicles," *Journal of Aircraft*, vol. 25, pp. 563–571, June 1988.

[4] L. Meirovitch and I. Tuzcu, "The lure of the mean axes," *Journal of Applied Mechanics*, vol. 74, no. 3, pp. 497–504, 2006.

[5] H. Abbasi, P. Grant, and N. Li, "Real-time simulation of flexible aircraft: a comparison of two methods," in *Guidance, Navigation, and Control and Co-located Conferences*, pp. –, American Institute of Aeronautics and Astronautics, Aug. 2009.

[6] N. Li, P. Grant, and H. Abbasi, "A comparison of the fixed-axes and the mean-axes modeling methods for flexible aircraft simulation," in *Guidance, Navigation, and Control and Co-located Conferences*, pp. –, American Institute of Aeronautics and Astronautics, Aug. 2010.

[7] D. Fleischer and C. Breitsamter, “Cfd based methods for the computation of generalized aerodynamic forces,” *Notes on Numerical Fluid Mechanics (NNFM)*, vol. 121, pp. 43–50, 2013.

[8] G. F. P. Wellmer, *A Modular Method for the Direct Coupled Aeroelastic Simulation of Free-Flying Aircraft*. PhD thesis, RWTH Aachen, 2014.

[9] M. Ritter, “Nonlinear numerical flight dynamics of flexible aircraft in the time domain by coupling of cfd, flight mechanics, and structural mechanics,” in *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol. 121, pp. 339–347–, Springer Berlin Heidelberg, 2013.

[10] P. E. Nikravesh, “Understanding mean-axis conditions as floating reference frames,” *Advances in Computational Multibody Systems*, vol. 2, pp. 185–203, 2005.

[11] L. Meirovitch and I. Tuzcu, *Integrated approach to the dynamics and control of maneuvering flexible aircraft*. National Aeronautics and Space Administration, Langley Research Center, 2003.

[12] C. Reschke, *Integrated Flight Loads Modeling and Analysis for Flexible Transport Aircraft*. PhD thesis, Universität Stuttgart, 2006.

[13] N. M. Newmark, “A method of computation for structural dynamics,” *Journal of Engineering Mechanics*, 1959.

[14] B. A. Winther, P. J. Goggin, and J. R. Dykman, “Reduced-order dynamic aeroelastic model development and integration with nonlinear simulation,” *Journal of Aircraft*, vol. 37, pp. 833–839, Sept. 2000.

[15] G. H. Looye, *An Integrated Approach to Aircraft Modelling and Flight Control Law Design*. PhD thesis, Technische Universiteit Delft, 2008.

[16] M. Karpel, “Design for active and passive flutter suppression and gust alleviation,” tech. rep., NASA, 1981.

[17] T. M. Kier, “Comparison of Unsteady Aerodynamic Modelling Methodologies with respect to Flight Loads Analysis,” *American Institute of Aeronautics and Astronautics*, 2005.

7 COPYRIGHT STATEMENT