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Model reduction for flight dynamics simulations using computational fluid dynamics

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ABSTRACT

Multidisciplinary simulation involving flight dynamics and computational fluid dynamics is required for high-fidelity gust loads analysis in transonic flow. However, the main limitation to a more routine use is prohibitive computational cost involved. A promising trade-off between accuracy and low-cost is model reduction of high-fidelity methods. Thus investigation of such reduction of coupled models is presented. The reduction technique relies on an expansion of the full order non-linear residual function in a truncated Taylor series and subsequent projection onto a small modal basis. Two procedures are discussed to obtain modes for the projection. First, an operator-based identification is exploited to calculate eigenpairs of the coupled Jacobian matrix related to the flight dynamics degrees-of-freedom. Secondly, proper orthogonal decomposition is used as a data-based method to obtain modes representing the system subject to external disturbance such as gusts. Benefits and limitations of the various methods are investigated by analysing results for initial disturbance and gust encounter simulations. Overall, reduced order models based on the presented approaches are able to retain the accuracy of the high-fidelity tools to predict accurately flight dynamics responses and loads while reducing the computational cost up to two orders of magnitude.

1. Introduction

Aircraft design and certification requires an accurate prediction of gust loads for many points covering the flight envelope [1]. Multidisciplinary analyses involving, among others, flight dynamics (FD), flexible structures and aerodynamics are needed [2]. Nowadays, these simulations adopt linear potential methods as aerodynamic model and offer low fidelity at affordable computational cost. Such coupling of flight dynamics, flexible structures and unsteady aerodynamics for gust response analysis was achieved, for instance, in [3] using unsteady lifting line theory in the subsonic regime. Various approaches for coupled simulations were proposed for gust analysis of HALE (High Altitude, Long Endurance) configurations [4,5] since flight dynamics effects are essential to predict accurately those systems' behaviour. Free-flight effects can also be included directly in the linear aerodynamics equations with correction terms accounting for body acceleration, as suggested in [6, 7]. However, the work described so far exclusively relies on low fidelity aerodynamic models to perform multidisciplinary simulations.

Application in the transonic regime requires high-fidelity aerodynamics based on computational fluid dynamics (CFD), which can describe non-linear flow phenomena like shock waves, with a higher computational cost to be paid. An example of simulations for a manoeuvring aircraft in transonic flow is presented in [8], running a CFD solver alongside a structural modal solver in a closed loop. The manoeuvre was pre-defined so that time-varying flight dynamics parameters such as angle-of-attack are imposed onto the CFD solver at each time-step. A similar approach based on two distinct and interacting subsystems was also applied in [9] to cope with large static displacements in transonic flow. Although these studies provide an effective way to cope with pre-defined manoeuvres or static problems, an extension to unsteady gust simulations is needed. For such simulations, flight dynamics unknowns must be calculated at each time-step using the most recent values of aerodynamic forces which, in turn, depend also on the gust disturbance. Moreover, aerodynamics also depends on flight dynamics unknowns, leading to a two-way coupled problem. It was shown that flight dynamics effects cannot be neglected in high-fidelity gust loads analysis [10]. In addition, comparison between CFD and tools currently used in industrial practice highlighted the limitations of the latter. With feasibility for an industry-scale adoption of multidisciplinary analyses based on CFD already demonstrated, the main obstacle remains compu-

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tational cost. A first reduction of computational cost required for CFD has already been obtained using linearised frequency domain (LFD) formulations for both aerodynamic response only [11] and fluid-structure coupled simulations [12,13]. However, more rapid methods that allow for high-fidelity accuracy in transonic flow are still desirable.

Model reduction of high-fidelity methods is a good alternative to balance cost and accuracy. Owing to the fact that the flight dynamics equations are of low dimension, high-fidelity aerodynamics is typically represented as dynamic derivatives [14], possibly calculated using the LFD approach. The flight dynamics response is then obtained by integrating the equations of motion in time using rigid-body modes and an interpolation of the dynamic derivatives at each time-step. Other techniques are possible and a summary of reduction methods in the flight dynamics context is provided in [15]. These techniques usually are applied to the aerodynamics equations only. Another possible approach operates on the coupled system as a whole. It manipulates the full order, coupled non-linear residual function expanded in a Taylor series with a projection on an appropriate modal basis resulting in a monolithic reduced model [16]. The projection method produces a versatile reduced order model which facilitates a comprehensive study of the coupled system. Previous application includes the simulation of coupled structural and aerodynamic systems using linear potential aerodynamics for gust encounter analysis and robust control [16,17]. An extension to CFD is possible by calculating modes for the projection using the Schur complement method [18], and this was applied to a flexible aircraft for aeroelastic analyses in transonic flow in [13]. This formulation can also be used for structural non-linearities [19] and might be expanded to account for aerodynamic non-linearities leading to limit cycle oscillations [20].

In this paper, the model reduction technique based on modal projection is introduced for the flight dynamics problem with application to free-flight test cases in the transonic regime. Two procedures to calculate modes for the projection are investigated. First, flight dynamics modes, also known as dynamic stability modes [21,22], are identified with an operator-based method. Exact values of frequency and damping for the flight dynamics modes are unknown a priori since they depend on flow parameters and structural properties. These modes correspond to a few eigenpairs of the coupled Jacobian matrix. Calculating the complete eigenspectrum of the coupled system and applying a trial-and-error approach to find the flight dynamics eigenpairs is prohibitive even for small-sized test cases. An operator-based identification procedure is proposed instead to compute these specific eigenpairs directly. Secondly, modes for the projection are calculated with a frequency domain formulation of proper orthogonal decomposition (POD) [23]. POD was previously applied to an aerodynamics-only system for gust encounter simulations of a large civil aircraft in transonic flow [24]. Here, POD is used for the flight dynamics problem subject to external disturbances in order to obtain both flight dynamic and aerodynamic responses. It is referred to as data-based identification since the system is probed at various frequencies.

The paper proceeds in Section 2 with a description of the numerical formulation. The reduction method is derived and the two identification procedures are presented. Non-linear, time-domain simulations coupling CFD aerodynamics with flight dynamics equations of motion are adopted to provide reference solutions, whereas constructing the reduced models is accelerated by using LFD methods throughout in the paper. In Section 3 results are presented for two two-dimensional test cases. The identification of flight dynamics modes is described in detail for a NACA 0012 aerofoil in transonic flow solving the Euler equations. The size of this test case allows for an in-depth analysis of problems which can arise during the identification. Model reduction for longitudinal dynamics in transonic flow modelled with Reynolds-averaged Navier–Stokes (RANS) equations is subsequently exploited and applied to gust encounter analysis of a tandem aerofoil configuration representing the dynamics of a large civil aircraft.

2. Numerical approach

2.1. Full order model and model reduction

Rigid-body dynamics is described by the equations of motion obtained directly from Newton's second law [21]. Denoting $\boldsymbol{w}_r$ as the vector containing n_r flight dynamics unknowns and $\boldsymbol{R}_r$ as the corresponding non-linear residual function, the flight dynamics equations are formulated as a first order ordinary differential equation in time t,

$$\frac{\mathrm{d}\boldsymbol{w}_r}{\mathrm{d}t} = \boldsymbol{R}_r(\boldsymbol{w}_f, \boldsymbol{w}_r) \tag{1}$$

with the vector $\boldsymbol{w}_f$ containing the n_f fluid unknowns. Specifically, the residual vector $\boldsymbol{R}_r$ is written as

$$\boldsymbol{R}_r(\boldsymbol{w}_f, \boldsymbol{w}_r) = \boldsymbol{f}_e(\boldsymbol{w}_r) + C\,\boldsymbol{f}_a(\boldsymbol{w}_f, \boldsymbol{w}_r) \tag{2}$$

with $\boldsymbol{f}_a$ representing aerodynamic forces. The formulation of the vector function $\boldsymbol{f}_e$ depends on the reference frame (absolute or relative formulation) since it might include Coriolis effects [22] besides additional external forces such as gravity. The matrix C accounts for the coupling between the degrees-of-freedom and it contains information about geometric properties of the system. The non-linear equations describing aerodynamics are similarly written in a semi-discrete form as

$$\frac{\mathrm{d}\boldsymbol{w}_f}{\mathrm{d}t} = \boldsymbol{R}_f(\boldsymbol{w}_f, \boldsymbol{w}_r, \boldsymbol{u}_d) \tag{3}$$

where $\boldsymbol{R}_f$ is the non-linear residual corresponding to the fluid unknowns and $\boldsymbol{u}_d$ represents a possible external disturbance such as gusts. Denoting $\boldsymbol{w} = [\boldsymbol{w}_f^T, \boldsymbol{w}_r^T]^T$ as the vector of unknowns of the coupled system, the state-space equations of dimension $n = n_f + n_r$ can be combined as

$$\frac{\mathrm{d}\boldsymbol{w}}{\mathrm{d}t} = \boldsymbol{R}(\boldsymbol{w}, \boldsymbol{u}_d) \tag{4}$$

where $\boldsymbol{R}$ is the corresponding coupled non-linear residual vector. Reference solutions are obtained throughout the paper by integrating the full order model (FOM) defined in Eq. (4).

The system in Eq. (4) is expanded in a first order Taylor series around an equilibrium state with $\boldsymbol{R}(\boldsymbol{w}_0, \boldsymbol{u}_{d0}) = 0$,

$$\boldsymbol{R}(\boldsymbol{w}, \boldsymbol{u}_d) = A\,\tilde{\boldsymbol{w}} + \frac{\partial \boldsymbol{R}}{\partial \boldsymbol{u}_d}\tilde{\boldsymbol{u}}_d + O\left(|\tilde{\boldsymbol{w}}|^2, |\tilde{\boldsymbol{u}}_d|^2\right) \tag{5}$$

where $\boldsymbol{w}(t) = \boldsymbol{w}_0 + \tilde{\boldsymbol{w}}(t)$ and accordingly $\boldsymbol{u}_d(t) = \boldsymbol{u}_{d0} + \tilde{\boldsymbol{u}}_d(t)$. The Jacobian matrix A of dimension $n \times n$ is partitioned into blocks

$$A = \begin{pmatrix} A_{ff} & A_{fr} \\ A_{rf} & A_{rr} \end{pmatrix} \tag{6}$$

with

$$A_{ff} = \frac{\partial \boldsymbol{R}_f}{\partial \boldsymbol{w}_f} \qquad A_{fr} = \frac{\partial \boldsymbol{R}_f}{\partial \boldsymbol{w}_r} \qquad A_{rf} = C\frac{\partial \boldsymbol{f}_a}{\partial \boldsymbol{w}_f}$$

$$A_{rr} = \frac{\partial \boldsymbol{f}_e}{\partial \boldsymbol{w}_r} + C\frac{\partial \boldsymbol{f}_a}{\partial \boldsymbol{o}}\frac{\partial \boldsymbol{o}}{\partial \boldsymbol{w}_r} \tag{7}$$

The diagonal blocks A_{ff} and A_{rr} are fluid and flight dynamics Jacobian matrices, respectively, whereas the off-diagonal blocks describe the coupling terms. Specifically, the matrix A_{rf} describes the dependence of the aerodynamic forces on the fluid unknowns and A_{fr} represents fluid excitation due to the flight dynamics degrees-of-freedom. The term $\frac{\partial \boldsymbol{f}_a}{\partial \boldsymbol{o}}$ relates a change of aerodynamic forces