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PROPOSITION DE SUJET DE THESE

Intitulé : Real-time digital twin for flight dynamics in wind tunnels : combining reduced-order models and experiments via on-the-fly Data Assimilation

Référence : **MFE-DAAA-2025-11**
(à rappeler dans toute correspondance)

Début de la thèse : 01/10/2025	**Date limite de candidature :**

Mots clés

Flight dynamics, Online learning, Data assimilation, Ensemble Kalman Filters, Digital twin, Machine learning.

Profil et compétences recherchées

Student with a Master or an Engineering diploma with some skills in the following fields :

- Fluid mechanics
- Dynamical systems
- Data science

Context:

Flight dynamics is the field of study focusing on the prediction of the trajectory and of the attitude of an aircraft. For a given geometry, the knowledge of the forces and moments from the fluid on the aircraft is needed to perform the simulations. The aerodynamic coefficients, the dimensionless forces and moments from the fluid on the aircraft, depend on different quantities as the angle of attack, the angle of sideslip, the rotation rates of the aircraft, and on the different control parameters, as the angular deflection of the control surfaces. Aerodynamic coefficients, angle of attack α and angle of sideslip β are represented on Figure 1.

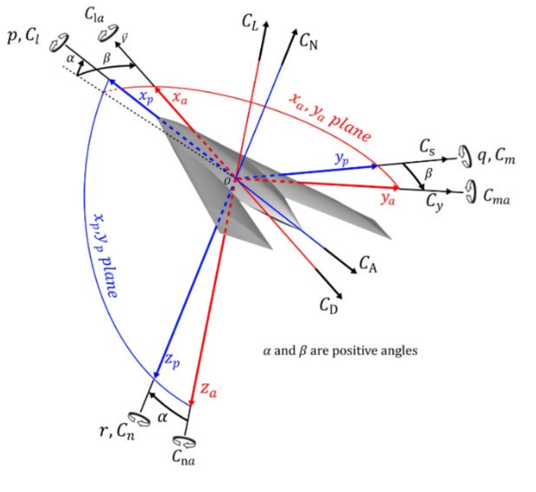

Figure 1 – Schematic representation of an aircraft and of the frames of study of Flight mechanics (from [1])

The aerodynamic loads can be calculated analytically, calculated from computational simulations, or a simplified mathematical model of the coefficients can be constructed through data-driven methods [2]. Analytical calculations rely on strong simplifications and assumptions on the flow around the system and are not accurate for complex flows. Computational simulations permit to have a precise description of the flow around the surfaces of the aircraft and therefore of the aerodynamic loads, but their cost can be prohibitive. Therefore, the thesis focuses on data-driven methods. Data-driven methods aim to build a simpler mathematical model with a set of input-output data. This model traduces the dependences of the aerodynamic coefficients on the state variables and on the control variables. Data can come from experiments in wind-tunnel on a scale model, from computational simulations or from free flight. Models can be of two types: non-parametric models (black-box) or parametric models (grey-box). Parametric models have a given structure relying on partial prior knowledge of the phenomena. To learn the parameters, offline methods or online methods, can be used [3,4]. Offline methods aim at determining the parameters of the model once the complete set of data is obtained. Online methods aim to construct a model as the data becomes available. In the literature, the latter are usually used on free flight data [4].

In the post-stall flight domain, at high angle of attack, free flight data is risky to collect. Classically, a grey-box model for the aerodynamic coefficients, consisting on a sum of subfunctions, is used. When the model is used in simulations, every subfunction values are obtained from interpolations in databases constructed from experiments in wind-tunnel [5,6]. The design of experiment, the list of different configurations (angle of attack, angle of sideslip, rotation rate, angular position of the control surfaces) realised in the experiments, have therefore to be decided a priori. This design must be large enough to be able to capture all phenomena which will have an impact of the aircraft attitude. However, in the post-stall domain, at high angles of attack, flows around surfaces of the aircraft are highly complex and the need of having a guide in the design of experiment is expressed. Figure 2 is a picture of the scale model of a light aircraft mounted of the rotary balance in the vertical wind-tunnel SV4 of ONERA Lille.

Figure 2 – Scale model of a light aircraft on the vertical wind-tunnel SV4 of ONERA Lille ©Onera

Objectives of the thesis:

The goal of the thesis is to develop an online method to guide a wind-tunnel experiment in real-time. As the experiment is running, the online model will act as a “digital-twin” to predict next configurations of interest [7] and to identify the parameters of the model on-the-fly. This coupling will permit to anticipate the occurrence of interesting and/or disadvantageous events with the digital twin and therefore to control the behaviour of the “physical twin”. It will also permit to optimise and to train the model. As online methods need to be fed by data coming from dynamic responses, the wind-tunnel experiments will mimic dynamic responses with a number of degrees of freedom permitted by the kinematics constraints of the experimental rig. Concretely, this “pseudo-dynamic” response will be performed by measuring forces and moments at each time step and then using the Flight Dynamics equations of motions (potentially considering the kinematics constraints) to get the kinematics parameters on the next time step. These experiments will therefore be in real-time or will be composed of a sequence of experimental runs according to the possibilities. To identify the parameters of the considered aerodynamics model, data assimilation methods can be considered.

At first, the online methodology will be developed and tested on numerical simulations of free-flight and on simulations of the experiments described above. An existing model developed at ONERA will be used for these simulations. According to the progress of work, the development and setup of more concrete experiments using experimental rigs in L1 and/or SV4 wind-tunnels of ONERA Lille will be considered.

One family of online methods, Kalman filters, are adapted to these types of applications. Among these methods, a new online method developed by the ENSAM (École Nationale Supérieure des Arts et Métiers) team of the LMFL (Laboratoire de Mécanique des Fluide de Lille) relying on the Ensemble Kalman Filter method [8] seems promising. Figure 3 is a schematic view of the Ensemble Kalman Filter algorithm as it is used in the context of [8].

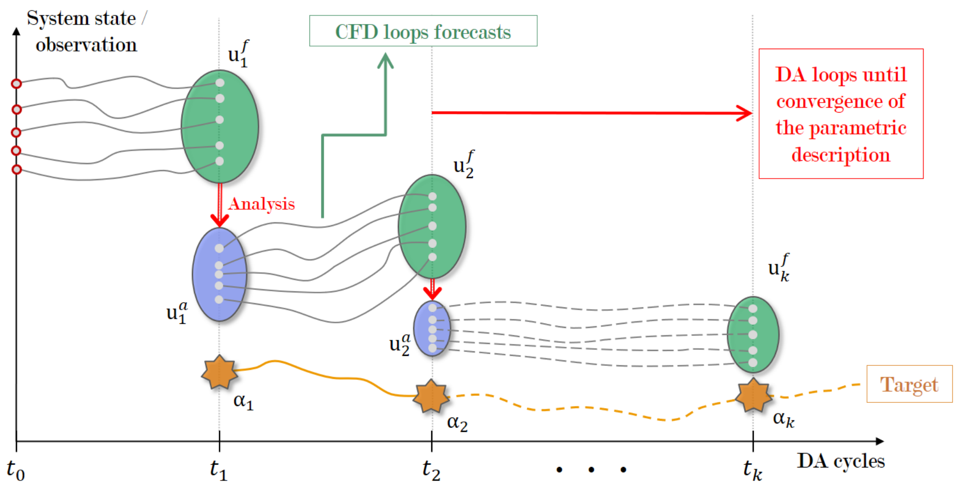

Figure 3 – Schematic representation of the Ensemble Kalman Filter algorithm used in the context of the study of [8]

Several online methods, including the one developed in [8], will be benchmarked to meet the aim described above and the most optimal one will be selected. In order to get an accurate model, the hyperparameters of the selected online method have to be tuned. One of the main objectives of the thesis is therefore also to study methods for optimising the hyperparameters of the selected method, notably with the use of modern machine learning methods [9].

Acquired skills:

The PhD student will acquire scientific skills in the following fields:

- Flight dynamics and Dynamical systems in general
- Data assimilation
- Machine learning

References:

[1] Isnard, B., Tanguy, G., Farcy, D., Dugeai, A., Garnier, E., & Foucaut, J. M. (2023). Comparison of Numerical Reduced Order Models of a Generic UCAV Configuration using a New Displacement Grid Method. In *AIAA AVIATION 2023 Forum* (p. 3269).
[2] Kou, J., & Zhang, W. (2021). Data-driven modeling for unsteady aerodynamics and aeroelasticity. *Progress in Aerospace Sciences*, *125*, 100725.
[3] Koley, B., & Alexandra, C. A. (2021, August). Recent Trends in Aerodynamic Parameter Estimation: a Review of Different Methods along with Their Advantages and Disadvantages. In *2021 2nd International Conference on Range Technology (ICORT)* (pp. 1-5). IEEE.
[4] Chowdhary, G., & Jategaonkar, R. (2010). Aerodynamic parameter estimation from flight data applying extended and unscented Kalman filter. *Aerospace science and technology*, *14*(2), 106-117.
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[6] Farcy, D., Khrabrov, A. N., & Sidoryuk, M. E. (2020). Sensitivity of spin parameters to uncertainties of the aircraft aerodynamic model. *Journal of Aircraft*, *57*(5), 922-937.
[7] Rasheed, A., San, O. & Kvamsdal, T. Digital Twin: Values, Challenges and Enablers From a Modeling Perspective. IEEE Access 8, 21980–22012 (2020)
[8] Villanueva, L., Valero, M. M., Glumac, A. Sarkic & Meldi, M. 2023 Augmented state estimation of urban settings using intrusive sequential data assimilation, arXiv: 2301.11195
[9] Luo, X. & Xia, C. Continuous Hyper-parameter OPtimization (CHOP) in an ensemble Kalman filter. Front. Appl. Math. Stat., 28 October 2022

Collaborations envisagées

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