PROPOSITION DE SUJET DE THESE

Intitulé : Airfoil flutter in transitional flow regimes

Référence : **MFE-DAAA-2022-02**
(à rappeler dans toute correspondance)

Début de la thèse : 1/10/2022	**Date limite de candidature :** 15/05/2022

Mots clés : fluid structure interaction - computational fluid dynamics - laminar separation flutter - global aeroelastic stability analysis

Profil et compétences recherchées

The candidate should have a master in Mechanics, with solid background and strong interest in Fluid Structure Interaction, Experimental and Computational Fluid Dynamics.

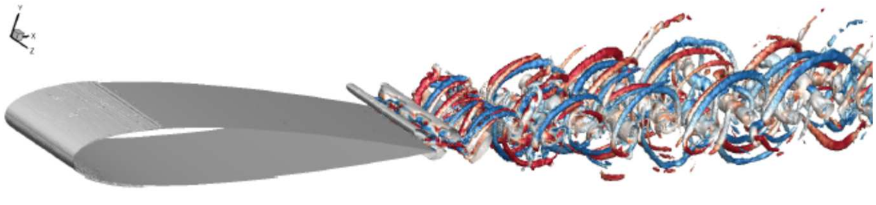
Présentation du projet doctoral, contexte et objectif

In view of diminishing the environmental footprint of civil aircrafts, the manufacturers are redesigning the wing shape to improve their aerodynamic performance. Shape of wings are optimized to delay the laminar/turbulent transition in the boundary layer and thus decrease the skin-friction drag of the wings. These aerodynamic benefits may however be mitigated by the occurrence of new aeroelastic phenomena that are still partially understood and affect the structural integrity of wings. The flutter phenomenon, which is a spontaneous wing's motion induced by its coupling with the surrounding flow, may be modified by the state of the boundary layer developing over the airfoils. For turbulent boundary layers, the flutter classically occurs by the coupling of two structural modes. But when the boundary layer is laminar over a large part of the airfoil, the flutter may appear with only one structural mode and potentially for lower critical flutter speed. The objective of this thesis is to investigate numerically and experimentally the flutter of laminar wings in subsonics flow conditions.

The flutter of laminar wings around low angle of attack in subsonic flow conditions is known as laminar separation flutter. It was first identified during experiments in a subsonic wind tunnel of NACA0012 airfoil mounted on a (single) torsional spring [1,2]. Symmetric pitching oscillations of the airfoil around the zero angle of incidence appeared for Reynolds number in the range $5.10^4 < Re < 2.10^5$ and could be suppressed by triggering the flow transition in the boundary layer developing on the airfoil. In that range of Reynolds numbers, another surprising aerodynamic phenomenon occurs for purely rigid wings: the aerodynamic lift and moment coefficients both exhibit a negative slope [7] which indicate that the flow provides a negative added-stiffness to the airfoil. When the added-stiffness is sufficiently strong to counteract the restoring torsional spring stiffness, a divergence instability occurs leading to the existence of non-symmetric state. Such non-symmetric state have yet not been observed experimentally. The first part of this project is dedicated to an experimental investigation of the competition between the laminar separation flutter and the static divergence instability. Experiments will be performed in the free-surface recirculating water channel of the Fluids Laboratory for Aeronautical and Industrial Research (FLAIR) at Monash University in Melbourne, by adapting the experimental set-up classically used for investigation on vortex-induced vibration of cylinders [8].

The second part of the PhD will be performed at ONERA to investigate numerically those phenomena. Numerical investigations of the laminar separation flutter was already performed based on two-dimensional simulations of the Navier-Stokes (NS) equations and of the Reynolds Averaged-Navier Stokes equations (RANS) in [3] as well as on three-dimensional high-order implicit large-eddy flow simulations in [4] coupled with structural dynamics. In the latter investigation, a symmetric Limit Cycle Oscillations (LCO) of the airfoil spontaneously emerge without any external distrubances for moderate Reynols numbers Re < 10^5. For the higher Reynolds number Re = 2.10^5, a symmetric Limit Cycle Oscillations was also observed only if trigerred by a large external disturbance (of the angle of attack, for instance). The oscillations of the airfoils around non-zero angle of attack as never reported.

More recently, the onset of these LCOs were investigated based on linear fluid-structure stability analysis performed around mean flows [5]. These mean flows are obtained by averaging in time as well as in the spanwise direction the unsteady flow computed by Direct Numerical Simulations for a fixed airfoil. Results for the angle of attack 0° showed that a zero-frequency mode (corresponding to a divergent instability) was unstable unlike the flutter mode that remains stable for all values of Reynolds number. This linear result cannot explain the Limit Cycle Oscillation observed in both experiments and simulations. Despite that discrepancy, it was shown in [5] that an external disturbance of the angle of attack can trigger the Limit Cycle Oscillatino of the airfoil for certain values of Reynolds numbers. More recently, the results of linear stability analysis was systemically reproduced [6] based on various flow models for computing the mean flow: two-dimensional or three-dimensional simulations of the Navier-Stokes equations as well as simulations of the Reynolds-Averaged Navier-Stokes equations supplemented with a transition model. In all cases, a divergence instability was obtained, showing that it is robust ot the flow model. Moreover, its existence suggests the existence a quasi-static equilibrium at a non-zero angle of attack for which the aerodynamic moment and the restoring elastic spring would balance. This scenario for the onset of LCO was explored in a recent PhD thesis performed at ONERA. Direct Numerical Simulations of the flow around rigid airfoils were performed for various angles of attack in the range [0°, 2°]. They showed that the time-averaged aerodynamic moment coefficient has a negative slope at angle of attack below 1° in agreement with experimental results [7]. Secondly, a fluid-structure stability analysis was then performed for mean-flows at non-zero angle of attack (using the spring stiffness value corresponding to the static equilibrium) but results did not indicate the destabilization of the flutter mode. Therefore, we revisited the linearization the governing fluid-structure equations around the mean flow and observed that the classical FSI mean flow analysis neglects the effect of the Reynolds stress tensor. In particular, by including into the linear stability analysis the variation of the Reynolds stress tensor with the angle of attack, we could obtain the destabilization of the flutter mode. This **new fluid-structure stability analysis**, based on the a-priori knowledge of the mean flow and Reynolds stress tensor, suggests that a closed form of the governing equation is crucial for explaining such phenomenon. The Reynolds Averaged Navier Stokes equations supplemented with turbulence and transition models form a closed aeroynamic flow model. But they poorly predict the flow for such low Reynolds number and angles of attack. In the second part of the project, we will improve the turbulence and transition models based on data-assimilation method [9] using the experimental data obtained during the first part of the PhD. This improved aerodynamic flow model will then be used for a parametric investigation aiming at establishing different scenari of laminar separation flutter. They will also be compared with those obtained experimentally.



Context of the PhD work: This PhD project is funded thanks to a starting collaboration between ONERA and Swinburne University of Technology. The successful candidate will spent
-18 months in Melbourne (Australia) at Swinburne University of Technology and Monash University
-18 months in Meudon (France) at the Departement of Aerodynamics, Aeroelasticity and Acoustics of ONERA.

References:

[1] Poirel, D., Harris, Y., & Benaissa, A. (2008). Self-sustained aeroelastic oscillations of a NACA0012 airfoil at low-to-moderate Reynolds numbers. *Journal of Fluids and Structures*, *24*(5), 700-719.

[2] Poirel, D., & Yuan, W. (2010). Aerodynamics of laminar separation flutter at a transitional Reynolds number. *Journal of Fluids and Structures*, *26*(7-8), 1174-1194.

[3] Poirel, D., Metivier, V., & Dumas, G. (2011). Computational aeroelastic simulations of self-sustained pitch oscillations of a NACA0012 at transitional Reynolds numbers. *Journal of Fluids and Structures*, *27*(8), 1262-1277.

[4] Barnes, C. J., & Visbal, M. R. (2018). On the role of flow transition in laminar separation flutter. *Journal of Fluids and Structures*, *77*, 213-230.

[5] Negi, P. S., Hanifi, A., & Henningson, D. S. (2021). On the onset of aeroelastic pitch-oscillations of a NACA0012 wing at transitional Reynolds numbers. *Journal of Fluids and Structures*, *105*, 103344.

[6] Sabino D., Marquet O., Fabre D., Mons V. (2021). Global Aeroelastice Stability Analysis of a NACA0012 Airfoil in Transitional Reynolds Regime, *Online Symposium on Aeroelasticity, Fluid-Structure Interaction, and Vibrations, 14–15 October 2021.*

[7] Ohtake, T., Nakae, Y., & Motohashi, T. (2007). Nonlinearity of the aerodynamic characteristics of NACA0012 aerofoil at low Reynolds numbers. *Japan Society of Aeronautical Space Sciences*, *55*(644), 439-445.

[8] Zhao, J., Hourigan, K., & Thompson, M. C. (2018). Flow-induced vibration of D-section cylinders: an afterbody is not essential for vortex-induced vibration. *Journal of Fluid Mechanics*, *851*, 317-343.

[9] Mons, V., & Marquet, O. (2021). Linear and nonlinear sensor placement strategies for mean-flow reconstruction via data assimilation. *Journal of Fluid Mechanics*, *923*.

[10] Zauner, M., Mons, V., Marquet O. & Leclaire B. Nudging-based data assimilation of the turbulent flow around a square cylinder, *in review to Journal of Fluid Mechanics.*

Laboratoire d'accueil à l'ONERA

Département : Département d'Aérodynamique Aéroélasticité Acoustique (DAAA) – Meudon, France

Swinburne University of Technology, Hawthorn, Australie

Monash Universiy, Melbourne, Australie

Lieu (centre ONERA) : Meudon

Contact : **Olivier Marquet**/Vincent Mons (ONERA)

Justin Leontini (Swinburne University)

Jisheng Zhao/Mark Thompson (Monash University)

Tél. : **0146235197**

Email :olivier.marquet@onera.fr,jleontini@swin.edu.au

Directeur de thèse

Nom : Marquet Olivier

Laboratoire : DAAA

Tél. : 0146235197

Email : olivier.marquet@onera.fr

Pour plus d'informations : https://www.onera.fr/rejoindre-onera/la-formation-par-la-recherche