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Numerical study of trailing-edge dynamics of a two element airfoil-flap with morphing flap at high Reynolds number

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Abstract. This article examines the morphing effect of trailing-edge flap of high lift configuration at the take-off position. It includes vibrations with different frequencies and amplitudes around the supercritical Airbus A320 wing-flap. The Reynolds number is 2.25million and the angle of attack 8.2° which corresponds to take-off and landing phases. The flap deflection angle from its initial position is 10° and translated with 30cm horizontally from the main wing. The results have been validated with numerical data (Weishuang LU [1]) that worked on a similar two-element wing named GA (W) 2. In the present study, we show through spectral analysis and Proper Orthogonal Decomposition (POD) the influence on the wake's width and on the aerodynamic performances, on the predominant frequencies and instabilities.

Key words: electroactive morphing, vibration, trailing-edge, simulation, wings, aerodynamic.

1. Introduction

Trailing-edge high-lift devices have been widely used on many kinds of aircraft previously. The structure-deformation technology has also been regarded as promising in the field of aircraft design. Traditional high-lift devices have a precedent of using the concept of deformation, which is mainly applied to the rear of wing, in order to improve the performance of takeoff and landing and this concept enables the manipulation of the near-region turbulence enhancing specific beneficial structures in the wake. In this way and thanks to the introduction of smaller-scale chaotic turbulent vortices, breaking down or suppression of preexisting predominant instability modes can be achieved. This study is a part of electroactive morphing activities in the context of the SMS (Smart Morphing and Sensing) European project (www.smartwing.org/SMS/EU). It includes numerical simulations and physical analysis issued from the hybrid morphing, operating different time scales and associating different smart actuation approaches. This article focuses on the high-lift flap in take-off configuration of Airbus A320 at high Reynolds number, using adopted turbulence modelling. This design using smart material properties in interaction with fluid flow aims at simultaneously increasing the lift, reducing the drag and the aerodynamic noise of the aircraft wings of the future. The morphing applied is partly bio-inspired. Optimal vibration and slight deformation of the trailing edge region by using smart piezo-actuators have been studied. The camber control is achieved by shape memory alloys operating at low frequencies (order of 1 Hz), whereas the trailing-edge vibration are of higher order

(100-500 Hz). The association of both actuations concerns the hybrid morphing (G. Jodin et al 2017 [2]). The actuation of MFC (Micro-Fiber Composite) piezo-patches in the trailing edge region [2] is simulated by using an amplitude of the vibration at 0.35 mm and a frequency range of [20-500 Hz]. The access to ongoing experimental studies in our research team contributes to the understanding of the physics and the performance of morphing. The study uses advanced numerical simulation approaches implemented in our research team and used elsewhere in the European research institutes and aeronautical industry. A first part of the study concerns simulations of the two-element A320 wing-flap in the take-off configuration with vibrating trailing edge is performed which optimal actuations will be accessed in relation to the fixed objectives in association with the experimental large-scale morphing prototype of the SMS project in full scale.

2. Numerical method and turbulence modelling:

2.1 Flow configuration

The subsonic flow over the A320 wing in the Take-off position is investigated numerically at a free-stream Mach number in the range of 0.032 and a chord-based Reynolds number of 2.25 million. The A320 has a main wing and a flap, the total chord for the large scale is 2.72m. An angle of attack is chosen $\alpha = 8.2^\circ$ that corresponds exactly to high angles of taking-off configurations. The wind tunnel properties have the same properties as the numerical. The wing was mounted wall-to-wall in the wind tunnel S4 of IMFT by (Y. Bmegapche Tekap). We simulated the flow in 2D domain and compared the numerical results to numerical results of GA(w)-2 airfoil (Weishuang LU [1]) which is a similar wing as the A320.

2.2 Numerical methods

The simulations of the A320 airfoil in the Take-off position have been carried out with the Navier-Stokes Multi-Block (NSMB) [3] solver. The NSMB solver is the fruit of a European consortium that included Airbus from the beginning of '90s, as well as main European aeronautics research Institutes, as KTH, EPFL, IMFT, ICUBE, CERFACS, Univ. of Karlsruhe, ETH-Ecole Polytechnique de Zurich, among other. This consortium is coordinated by CFS Engineering in Lausanne, Switzerland. NSMB is a structured code that includes a variety of efficient high-order numerical schemes and of turbulence modelling closures in the context of LES, URANS and of hybrid turbulence modelling. A first reference of the code description can be found in Vos et al. (1998) concerning the versions of this code in the decade of '90s. Since then, NSMB highly evolved up to now and includes an ensemble of the most efficient CFD methods, as well as adapted fluid-structure coupling for moving and deformable structures. These developments can be found in Hoarau (2002) regarding URANS modelling for strongly detached flows,

Martinat et al. (2008), in the area of moving body configurations, Barbut et al. (2010) and Grossi et al. (2014) allowing for Detached Eddy Simulation with the NSMB code. NSMB solves the compressible Navier–Stokes equations using a finite-volume formulation on multi-block structured grids.

2.3 Multiblock grid

Two 2D normal and finer multiblock grids built in our research team have a C-H topology and a size of 0.5 M and 0.6 M cells approximately. The grids have been tested in NSMB. A comparison of these two grids for the pressure coefficients with the experimental results is provided in Figure 4. The results are very similar for the two grids. The refined grid has been used for this study.

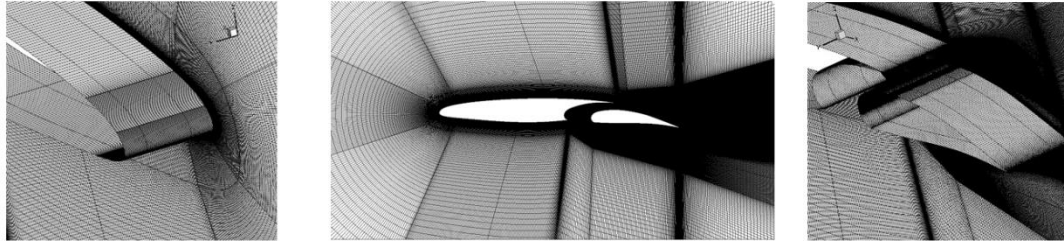


Figure 2: Presentation of the refined grid.

In addition, a Chimera grid that contains two independent grids, the first grid is the fluid domain including the wing and the second one is around the flap Figure 4. The Chimera is used for optional configurations of Take-off and Landing where the flap changes its deflection angle from 10° to 40° degrees.

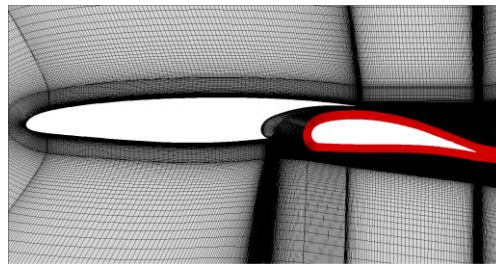


Figure 3: Presentation of Chimera grid.

The y^+ length regarding the turbulence modelling near the wall is smaller than 0.5 in the whole domain.

In order to take into account, the movement of the geometry or the deformation over time, the ALE (Arbitrary Lagrangian Eulerian) formulation was introduced into the Navier-Stokes equations. The ALE formulation is particularly well suited for taking dynamic meshing into account [4]. The formulation adopted in the NSMB code adapts to discretized conversational equations using the finite volume method. The motion and slight deformation of the near-trailing edge region with a frequency of the vibration f and the amplitude

2.4 Results validation

Different cases have been studied and investigated to find the right approximation to experimental results, different grids, time stepping for a low Mach number (compressible schemes).

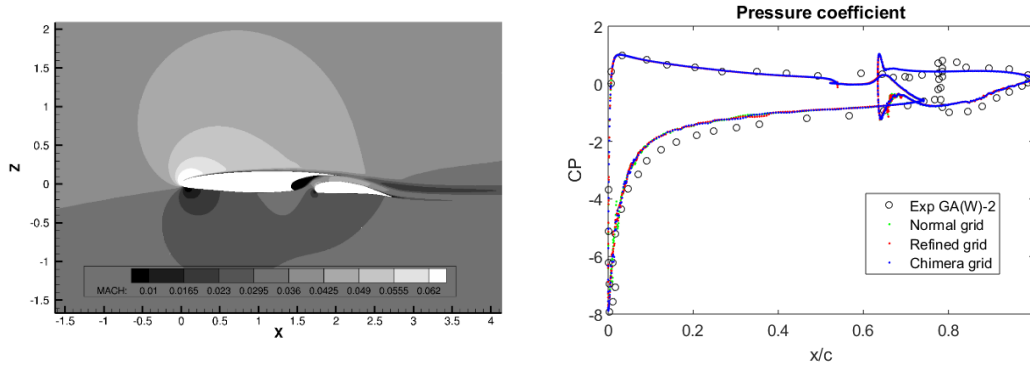


Figure 4: a) Schematic diagram of the non-dimensional velocity Mach number. b) presentation of the pressure coefficient for different grid and experimental data.

A study of the time step has been carried out for the 2D grid. After testing values of $\Delta t = 10^{-3}, 10^{-4}$ and 10^{-5} seconds, we continued the simulations with 10^{-5} that was an optimal time for the independence of the solution in an adopted implicit method. A typical number between 60 and 100 inner steps Runge-Kutta was sufficient for the convergence in each time step. The grid independency is demonstrated in the Figure4 by comparing both of normal and refined meshes, and the numerical solution is very approximate to the experiment data of GA (w) 2 airfoil Figure 4, the only difference between both of A320 airfoil and GA (W) 2 is the thickness of the wing and the GA (W) 2 has a smaller flap.

2.4 Turbulence modelling

Based on previous studies in our research group which examined the predictive ability of various turbulence models [5] [6], it was shown that the two-equation $k-\varepsilon$ model (Chien model 1982) was not able to produce the instability and the

unsteadiness at the present incidence value. The OES (Organised-Eddy Simulation), Bourguet, Braza *et al* J. Fluids & Structures 2008) provides a quite good flow detachment dynamics including the separated shear layers and wake the vortex dynamics. In the present study this turbulence modelling approach has been used and shown a clear appearance of the shear layer instability, the Kelvin-Helmholtz and von Karman vortices past the trailing edge at a first time to our knowledge concerning the two-element configuration involving a large gap between the main wing and the flap. These aspects are crucial for the modification of these dynamics thanks to morphing and are well captured by the present approach. The refined mesh has around 250 cells in 2 chords in the wake, to capture small eddies with a size around 1.5cm~2cm, it explains the presence of wake instabilities shown in [Figure5](#) for the static case.

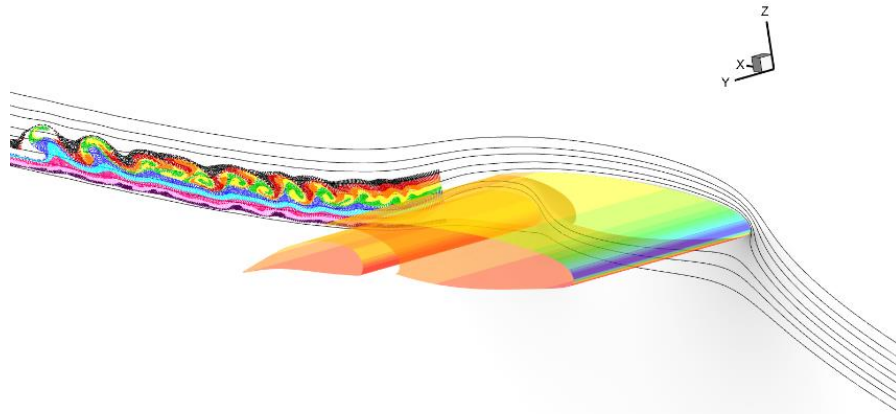


Figure 5: Presentation of streaklines on the wake + pressure on the surface of the A320 wing.

3. **Static configuration versus Morphing**

The electroactive morphing applied in the experimental set-up creates vibrations of small piezo-actuators disposed long the span near the trailing edge region and able to provide small deformations (order of cm) with frequencies in the range of 100-300 Hz. It is shown in the present study that this kind of vibration has a prominent effect on the development of vortical structures in the wake, on the wake's width and on the aerodynamic forces, as shown in the following section. The effects of the actuating case (with vibrations) compared to the static case are shown for different frequencies from a low range of 30Hz up to a higher range of 400Hz. The optimal results have been analysed concerning the higher-order range of the vibration frequency.

3.1 Wake instabilities

To a better understanding of the flow around the two wing-flap elements at the take-off position, we distinguish 3 elementary attached flow regions due to the presence of two objects in the flow (wing and flap), a separating area is noticed due to the presence of the gape [Figure6](#). The presence of two different natural frequencies in the wake, a higher frequency of 80 ~ 90 Hz which corresponds to the turbulent structures created near to the flap and a lower frequency which is the half of the first 30Hz that represents the bigger instabilities and structures created by the presence of the main wing [Figure7](#). Drawing the streaklines [Figure4](#) it is clearly seen that this frequency corresponds to Kelvin Helmholtz instability.

The understanding of the operation of vortex shedding allows their control by means of morphing. The trailing edge vibration triggers eddy blocking effects that change the wake. We compared the wake instabilities in the static and morphing cases, vibration in low frequencies and near to the natural frequencies gave a slight modification of the flow. Actuation at high frequencies has shown an interesting results [Figure6](#) the vibrating the trailing edge influences the shear layer instabilities, there is an interaction between flow coming from the flap, the gap and the main wing, the actuations at 300Hz [Figure6](#) and 400Hz can delay and suppress almost completely the formation of the Kelvin Helmholtz instabilities wake.

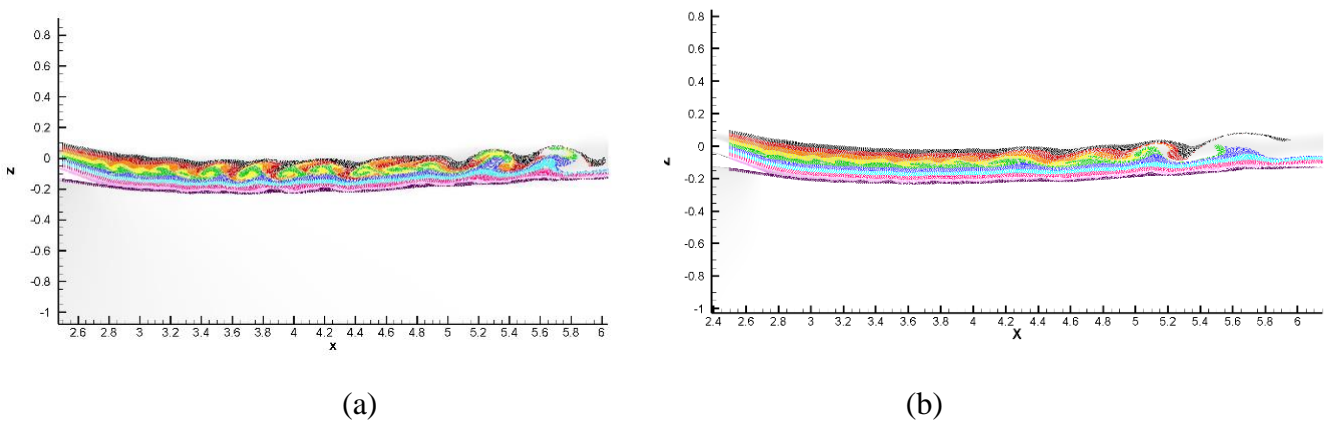


Figure 6: Streaklines in the wake region, (a) : Static case. (b) : morphing case 300Hz.

The signal of the crossflow velocity component is extracted for 5 points from the static and morphing cases. The [Figure7](#) shows the wake crossflow velocity field, that exhibit the vortical structures. The monitor points are located in the wake close and far from the flap trailing edge.

3.2. Modal analysis

The POD is applied to study the coherent structures developed in the flow and the wake specially. It was introduced at the first by Karhunen and Loweve and applied in Fluid Mechanics by Berkooz et al [8]. The flow solution is decomposed into spatial ϕ_i modes and α_i temporal coefficients sorted by their relative energy in the flow.

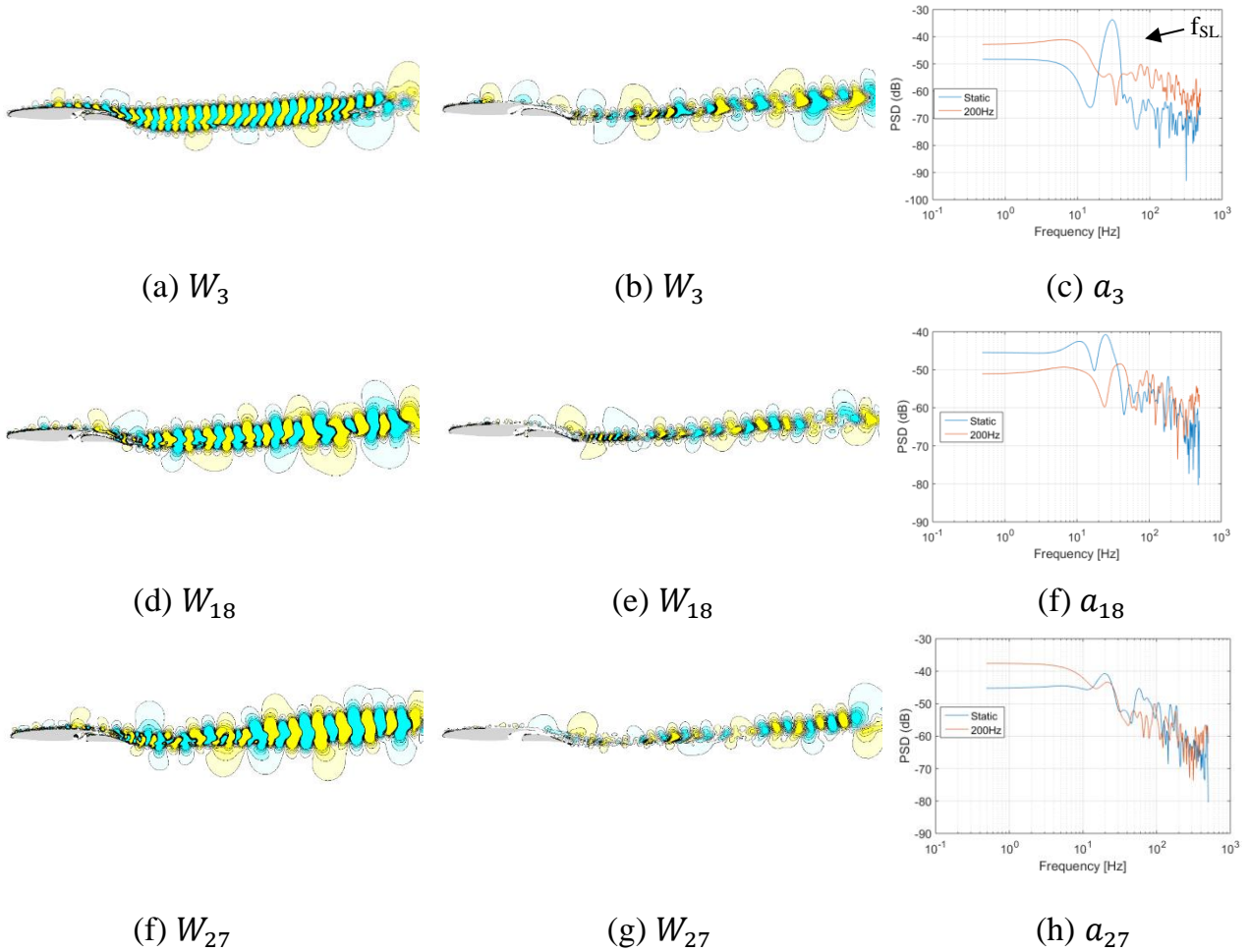


Figure 7: Spatial modes and PSD for the temporal modes computed for the crossflow velocity, the static (a), (d) and (f) and the morphing case (b), (e) and (g) at 200Hz.

The POD is applied for the crossflow velocity, the modification of the flow is highlighted when comparing the first and higher modes of the unactuated case in Figure 7 to the cases at actuation frequencies of 200Hz, it has shown the most prominent effects in the wake. The time step of the sampling is $10^{-3}s$ which is less than inverse of the highest natural frequency on the wake. A constant number of snapshots (300) were used to construct the POD correlation matrix.

The spatial modes (shown in Figure 7) for the unactuated and actuating case is significantly different from first to higher modes. The effect of the actuation is seen where the energy of the coherent structures in the wake is decreased, the actuation introduces additional modes which supersede the frequency of the shear layer, that was also shown by (Johannes et al [9]). In addition, the temporal coefficients (shown in fig.7) and their PSD such as a_3 underline this behaviour.

3.3. Mean Fields in the wake

The profiles of the mean axial velocity are compared for different x/c positions placed respectively on the wake $x/c=1.05$, $x/c=1.15$, $x/c=1.20$, $x/c=1.40$, for the comparison of the unactuated and actuated cases (shown in Figure 8)

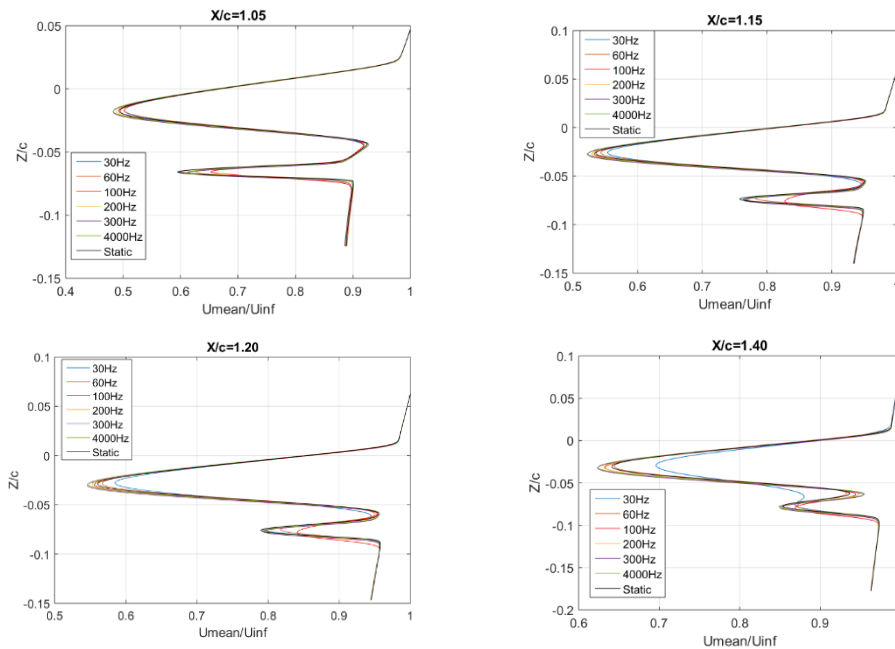


Figure 8: The mean longitudinal velocity profiles along the wake for various actuating frequencies.

The adjacent layers coming from the flap, the gap and the main wing of fluid move parallel to each other with different speeds, it creates a shear layer due to the difference of the velocity. With an actuation frequency we can modify the behaviour of the shear layer, as shown in Figure 10 a slight modification of the velocity profiles is visible at early x/c stations for low frequencies actuations as 30 Hz (near to natural frequency), but in the station $x/c=1.40$, the region of the gap is suppressed and a mixing between the two shear layers coming from the flap and the wing. With an actuation frequency 100 Hz the changes are important and the

deficit of the velocity decreases $U - U_{inf}$. Reducing this quantity causes the diminution of the shear stress $\tau = \mu \cdot \partial u / \partial y$.

4. Conclusions

In this study the morphing studied by High-Fidelity numerical simulations introduces optimal vibration frequencies with a slight deformation of the flap trailing edge region. The wake dynamics are significantly affected by the application of morphing when acting in frequencies higher than the natural frequencies of the separating shear layers. The POD has showed new modes replacing the existing of the unactuated case and the PSD that shows clearly the attenuation of the global instabilities in the wake. The aerodynamic performance are increased for some actuating cases such as for 60 Hz , the mean value of the ratio lift/drag is increased up to 1.54%, some frequencies gave higher values of lift and drag.

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