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MORPHING FOR SMART WING DESIGN THROUGH RANS/LES METHODS

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Abstract

This article presents numerical simulation results obtained in the context of the H2020 European research project SMS, "Smart Morphing and Sensing for Aeronautical configurations" by using among other, hybrid RANS-LES methods, able to accompany the design of the wings of the future. The morphing concepts studied are partly bio-inspired and are able to act in multiple time and length scales. They are proven efficient for the increase of the aerodynamic performances of A320 wings in reduced scale and near scale one, in synergy with the prototypes built within this project. The simulations have shown the ability of novel electroactive actuators performing slight deformation of the trailing edge region and optimal vibrations, to create suitable vortex breakdown of specific coherent structures and to enhance beneficial vortices, leading to thinning of the shear layers and the wake's width. The simulations quantified the optimal actuation ranges and the gains in lift increase, drag reduction and simultaneous attenuation of the noise sources past the trailing edge.

1 Introduction

The present article highlights the contribution of RANS-LES methods in the future wing design by means of electroactive morphing developed in the currently running H2020 European research project "Smart Morphing and Sensing for aeronautical configurations¹". This is a multi-disciplinary project that employs intelligent electroactive actuators modifying the lifting structure of an aircraft and allowing optimal shapes with respect to the aerodynamic performance (high lift and low drag). A closed-loop is accomplished for the controller design of the morphing wings in this project by using a new generation of pressure sensors using fiber optics-Bragg grating allowing distributed pressure measurements and in situ real-time optimization of the aerodynamic characteristics. The coordinator's research institutes IMFT - Institut de Mécanique des Fluides de Toulouse and LAPLACE - Laboratoire Plasma et Conversion d'Énergie, had studied since 2009 bio-inspired morphing wings thanks to electrically actuated materials able to deform and vibrate in different time and length scales, as dictated by the turbulence surrounding the wing and developed in its wake. These actuations operate in a similar way as the different classes of large hunting bird wings, winglets and feathers, able to simultaneously increase lift, decrease drag and reduce their noise when these birds hasten to the prey. By optimizing the fluid-structure interaction thanks to these novel actu-

ators, harmful coherent vortices are attenuated by means of vortex breakdown and beneficial vortices are enhanced, producing a significant increase of the aerodynamic performance and decrease of the noise sources. The studies of the research team IMFT-LAPLACE created the *hybrid electroactive morphing* [1] by simultaneously actuating different classes of smart materials in low frequencies (order of 1 Hz) but high deformations (order of 15% of the chord's length) and higher frequencies (order of 500 Hz) but low deformations (order of 1% of the chord's length), like the wings and feathers of the birds respectively. A priority of the European aeronautical industries is to make the flight safer, cleaner, greener and quieter than ever before. The bio-inspired electroactive morphing provides lighter aerostructures with a much fast response than other hydromechanical actuators and different MEMS concepts of previous studies. A first set of bio-inspired morphing prototypes of the IMFT-LAPLACE team were part of the Royal Society Annual Exhibition in 2014 in the stand: "Smart wing design through turbulence control Science imitating Nature²", in collaboration with Imperial College³.

Electroactive morphing wing prototypes of A320 have been studied by the research team IMFT-LAPLACE in collaboration with AIRBUS "Emerging Technologies and Concepts Toulouse" and in the context of the SMS project, in the subsonic wind tunnels of IMFT in reduced scale (chord of 70 cm) and near scale one (wing chord of 2.40m and high-lift flap chord of 1m), by means of Time-Resolved PIV (TRPIV), forces and pressure measurements. Following our previous studies, dynamic camber systems using Shape Memory Alloys (SMA) for low frequency-high deformation [2] and higher-frequency-low deformation trailing edge vibrations [3] by means of piezo-actuators, a new type of an A320 morphing wing was constructed, offering a simultaneous actuation at different time and length scales [4]. This prototype explored the effects of both, low frequency-high deformation by using the SMA actuators together with piezo-electric actuators of Macro-Fiber-Composite (MFC) type. By using the piezo-actuators only, a lift increase of 2 % and drag reduction of 3 % have been obtained, where by simultaneous actuation of the SMA and piezos, a lift increase of order 10 % and a drag reduction of 5% have been reached, with simultaneous reduction of the noise sources of order 20 dB, corresponding to the coherent eddies shed past the trailing edge. The experiments and simulations were ac-

¹www.smartwing.org/SM/EU

²<http://www.cnrs.fr/insis/recherche/actualites/2014/morphing.htm>

³<https://www.youtube.com/watch?v=AoAaCCvn38M>

complished at Reynolds numbers of 500,000 and 1 Million.

The numerical studies in the SMS project, [5] examined the morphing efficiency obtained by trailing-edge low deformation (order of 1-3 mm) and higher frequency vibration (order of 400 Hz) at Reynolds number of 1 Million. The turbulence modelling approach OES, Organised Eddy Simulation, [6], [7], [8] has been used, in which the resolved turbulence contains the coherent structures and the modelled turbulence contains the chaotic turbulent motion. This approach had been proven efficient for the coherent structures development and the related instabilities, even in two-dimensional approach. The numerical results have shown that the morphing produces improved aerodynamic performances and reduces the amplitude of instability modes associated to aerodynamic noise. In the context of the SMS project, The optimal frequency and amplitude of the actuations obtained by the present numerical study are in use for the closed-loop for the optimal manipulation of the embedded actuators, able to cut-off the harmful instabilities at their birth, thus showing the strong synergy between the numerical simulations and the experimental studies for the design in the SMS project. Beyond the bio-inspired context, it is worthwhile noticing that the birds do not fly at transonic speeds corresponding to the cruise phase of a real aircraft. In these regimes, the numerical approach has proven essential for the design, prior to the experiments under way within the SMS project for this regime. In [9] we investigated the electroactive morphing for an A320 type of wing in transonic regime (Mach number of 0.78, Reynolds number of order 3 Million), with the same turbulence modelling method as previously mentioned. The study revealed that a deformation with a slight upwards deflection of the trailing-edge by 2 degrees associated with a trailing-edge vibration of 300 Hz is able to attenuate the buffet instability and to enhance the life-to-drag of order 6%. This is due to the feedback effects created from the trailing edge and the wake area towards the SWBLI (Shock Wave Boundary Layer Interaction) region, produced by an eddy-blocking within the shear layers, by means of the trailing-edge vibration. This mechanism is similar to a shear sheltering one as in [10].

Frequency (Hz)	300	350	400	450	500	700
$\frac{\langle C_l/C_d \rangle - \langle C_l/C_d \rangle_{static}}{\langle C_l/C_d \rangle_{static}} \times 100$	+2.4%	+5.5%	-2.5%	-5.5%	-5.5%	+5.9%
Frequency (Hz)	720	750	800	1000	1500	
$\frac{\langle C_l/C_d \rangle - \langle C_l/C_d \rangle_{static}}{\langle C_l/C_d \rangle_{static}} \times 100$	+1.6%	+6.1%	+6%	+3.5%	+5.8%	

Table 1: Relative gain (or loss if negative) of the averaged lift-to-drag ratio for different piezo-actuation frequencies compared to the static (non morphing) case

Frequency (Hz)	300	350	400	450	500	700
$\frac{\langle C_d \rangle - \langle C_d \rangle_{static}}{\langle C_d \rangle_{static}} \times 100$	-3.5%	-8.9%	+6.1%	+12.3%	+11.9%	-9.1%
Frequency (Hz)	720	750	800	1000	1500	
$\frac{\langle C_d \rangle - \langle C_d \rangle_{static}}{\langle C_d \rangle_{static}} \times 100$	-1.2%	-9.8%	-9.6%	-4.1%	-9.1%	

Table 2: Relative gain (if negative in respect of drag reduction) or loss (if positive) of the averaged drag coefficient for different piezo-actuation frequencies comparing to the static case

Our current numerical simulations in the SMS project concerning the transonic Reduced Scale (tRS) morphing prototype of an A320 wing have determined the optimal frequency ranges able to considerably increase the aerodynamic performance presented in table 1 and 2. to decrease

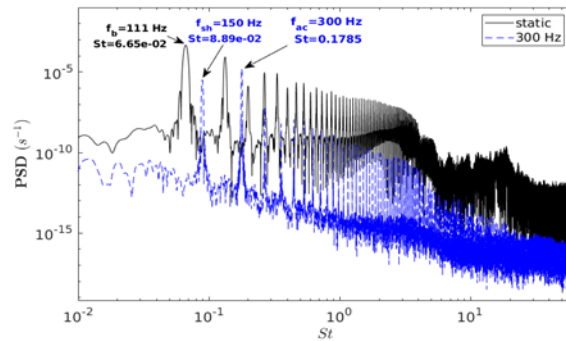


Figure 1: Attenuation of the buffet frequency f_b due to actuation and slight deformation of the trailing edge region in cruise phase, Mach=0.78, Re= 2.06×10^6 . PSD of lift coefficient, transonic morphing prototype of A320 type

the buffet amplitude as well as the overall PSD level related to the noise. This results to a constriction of the shear layers and to an attenuation of the predominant frequencies of the shear-layers vortices as shown in figure 1. These numerical simulations are in strong synergy and contribute to the experimental studies carried out in the SMS project concerning the design of the morphing prototype in cruise phase.

Furthermore, the numerical studies in the SMS project in-

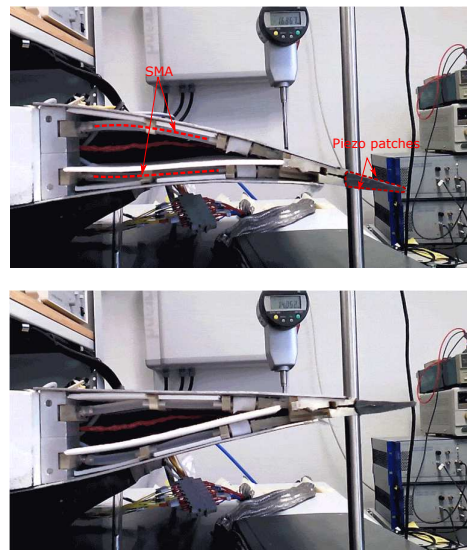


Figure 2: Reduced-Scale prototype using Shape Memory Alloys (SMA)

clude low subsonic regime simulations for the morphing wing design concerning the take-off and landing phases. In this context, the Reduced-Scale (RS) A320 prototype is considered having a chord of 70 cm and consists of a single element wing operating in clean position (at angle of attack of 10 degrees), instrumented by Shape Memory



Figure 3: Series of piezo-electric patches installed in the wing's trailing-edge

Alloys (figure 2). This design ensures high-amplitude deformations (order of 10 cm) downwards in camber control and low frequency actuation (order of 1Hz) . Moreover, piezo-electric patches allow for higher frequency actuation of order 500 Hz) and low deformations of order 1-3 mm (figure 3). In addition, numerical simulations are carried out for the Large-Scale (LS) prototype of the SMS project, having a total chord of 2.40 m and a flap's chord of 1m, (figure 4) with morphing high-lift flap near scale one, in a two-element configuration of the A320 wing operating at the take-off position. These simulations accompany the design and the experiments concerning this prototype.

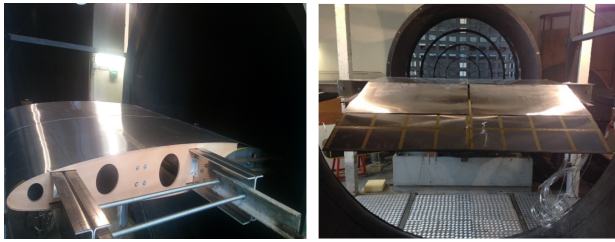


Figure 4: Morphing high-lift LS prototype of the A320 wing near scale 1 in the S1 wind tunnel of IMFT

2 Numerical methods and turbulence modelling

The NSMB code [11–13] is used to perform CFD and CFD/SM (Computational Fluid Dynamics - Structural Mechanics) simulations in the SMS project. The code solves unsteady and steady compressible Navier-Stokes equations using the finite volume method, a structured grid is used to simulate the flow around single and two-element wing-flap. This code includes a variety of efficient high-order numerical schemes and turbulence modelling closures in the context of URANS, LES and hybrid turbulence modelling. In the present study, the fourth-order central scheme and second order dual-time stepping for the temporal discretisation are selected. Artificial compressibility preconditioning was used to simulate the flow in a subsonic speed range for both Reduced and Large-Scale configurations. The NSMB code includes efficient fluid–structure coupling for moving and deformable structures. It is interfaced

with specific structural modules taking into account the prototype's deformation according to different actuations and interfaced with the CFD part of the code. The mesh movement and deformation is carried out by means of the ALE (Arbitrary Lagrangian-Eulerian) method. The Organised Eddy Simulation OES [7] and the hybrid Delayed Detached Eddy Simulation DDES-OES [14] with embedded OES approach in the statistical part of the DDES were selected to simulate the flow for both configurations. The design of the DDES grid around the wing requires a homogeneous local grid cells with $\Delta x \approx \Delta y \approx \Delta z$ following the recommendations in [15].

3 Results and discussion

3.1 Reduced Scale prototype

This part of the study focuses on the Reduced-Scale in clean configuration with a chord of 0.7 m at a $Re = 10^6$ and angle of attack 10° . Using the DDES-OES, the homogeneous ambient terms are activated as in [16]. The grid used for the Reduced Scale prototype contain 10 million cells for the OES model and 60 million cells for the DDES-OES model with a minimum local cell size less than 1 mm. A span of 0.8C (40 cells in the span direction ; C being the chord) is used for the OES model. In the DDES-OES, a span dimension of 0.3C (120 cells in the span direction) is selected as presented in the figure 6. The grids were created to respect the dimensions of the IMFT S4 wind tunnel in the vertical to the chord dimension. The streamwise numerical dimension from the inlet to the outlet is 11C and the wing is placed in the middle. Two-dimensional and three-dimensional simulations are carried out for the Reduced and the Large Scale prototypes.

A detailed parametric study has been accomplished in 2D in order to detect the optimal ranges whereas the 3D study has been performed for selected parameters only. Beyond the comparisons with the TRPIV [5], the numerical simulations are used to focus the experiments in the optimal actuation ranges. Figures 5 and 6 illustrate the flow be-

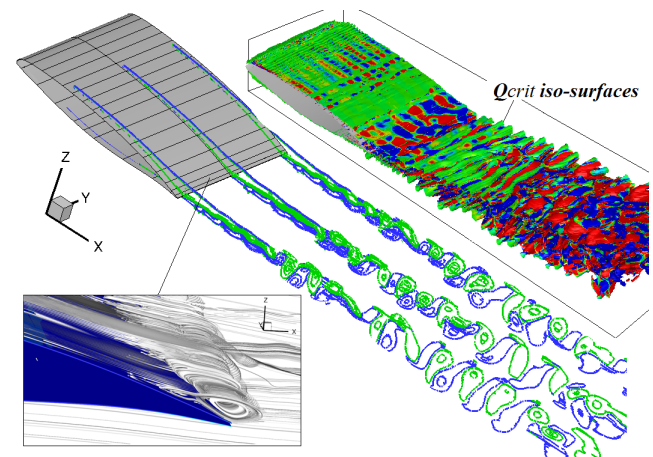


Figure 5: Presentation of the wake turbulent structures and near trailing-edge separation (recirculation) by means of the OES model

haviour around the RS prototype in static (non morphing) configuration and provide the near-trailing edge overview

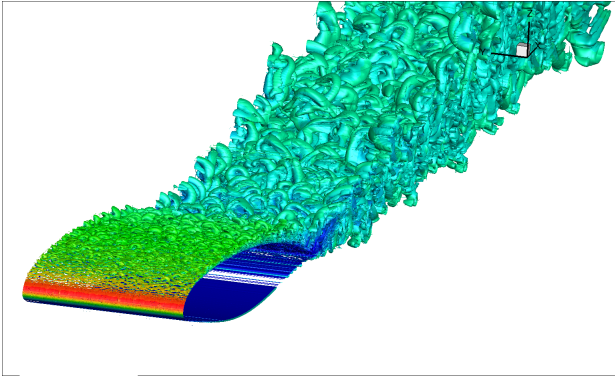


Figure 6: Q criterion (1500) colored by the velocity magnitude using the OES-DDES model

of the boundary layer detachment inducing a recirculation vortex due to the angle of attack. The separation creates a higher velocity gradient between the upper and the lower shear layers giving birth to the wake instabilities. In addition, the secondary instability appearing as a three-dimensional undulation of the coherent vortex structures according to well distinct wavelengths is highlighted by means of the Q criterion and related to the amplification of the spanwise velocity .

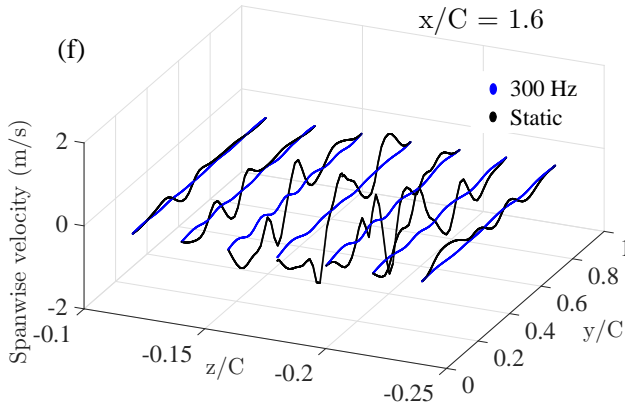


Figure 7: Extracted spanwise velocity through a vertical plane z/C along the span direction y/C

The spanwise velocity in the z direction has been extracted from different horizontal lines according to the vertical direction z in figure 7. A considerable attenuation of this is obtained, illustrating a practical suppression of the three-dimensionality. This is due to the actuation frequency by 300 Hz obtained by the piezo-patches operating monochromatically along the span in the trailing-edge region. This actuation modifies the direction of the mean shear of the von Kármán vortices, leading to a subcritical elliptic instability shape of these coherent vortices, thus attenuating the secondary instability spanwisely [17]. Consequently, the wake thickness is thinner compared to the static case (no vibration).

3.2 Large-Scale prototype

In the context of the SMS European project, the Large-Scale (LS) prototype of a morphing A320 high-lift configuration including the wing-flap two-element system was studied in accordance with the IMFT S1 wind tunnel configuration, [18], [19]. The morphing effects for the Large Scale prototype.

A subsonic regime at a Mach number $M = 0.032$ and Reynolds number of $Re = 2.25$ million is selected and an angle of attack for the fixed wing of $\alpha = 8.2^\circ$ which corresponds to the range of angles in the take-off position. A flap's deflection angle of $\delta = 10^\circ$ degrees is selected. 2D and 3D simulations have been performed for the static case, taken as reference to compare with the morphing case. The vibration frequencies vary in the range of 60 to 400 Hz with a fixed vertical actuation amplitude of 0.7 mm.

An optimal frequency range in respect of the aerody-

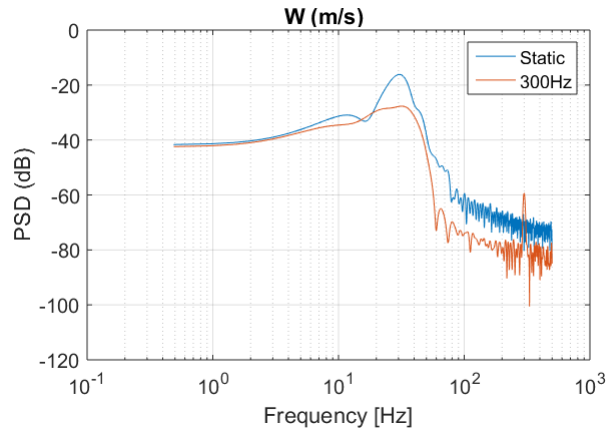


Figure 8: Power Spectral Density of the vertical velocity component at $x/C = 1.47$, $z/C = 0.04$

dynamic performance increase is found near 300 Hz. The coherent structures corresponding to low frequency instabilities are von Kármán vortices interacting with anticlockwise vortices generated from the actuation of the flap's trailing-edge. These vortices break down the existing von Kármán eddies and lead to a wake thinning. Furthermore, smaller-scale vortices are generated from the trailing edge actuation, that propagate in the wake and produce a shear-sheltering effect as in [8]. This results to a constriction of the shear layers and to an attenuation of the predominant frequencies of the shear-layers vortices as shown in Figure 8. Regarding the aerodynamic coefficient, the drag is decreased and an enhancement of the lift is noticed.

Figure 9 illustrates the Q criterion using the DDES-OES in [20]. A breakdown of the vortex rows and appearance of the three-dimensional structures in the wake is related to the high Reynolds number and the angle of attack. Vortex dislocations of the primary von Kármán vortex rows are formed in the spanwise direction, illustrated by a junction of the "spinal column" (of two adjacent vortex rows [17]), in the spanwise direction in figure 10. It is found that an actuation at 300 Hz and amplitude of 0.7mm suppresses the vortex dislocations by generating anticlockwise vortex rows, resulting to a considerable wake thinning in figure 11.

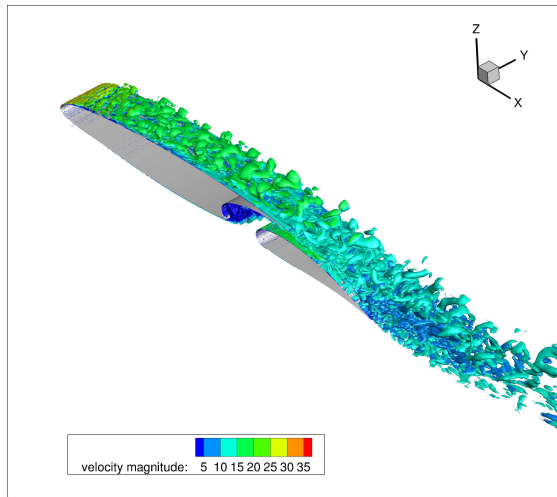


Figure 9: Q criterion (1000) colored by the velocity magnitude for the Large-Scale prototype at the take-off position using the OES-DDES turbulence model

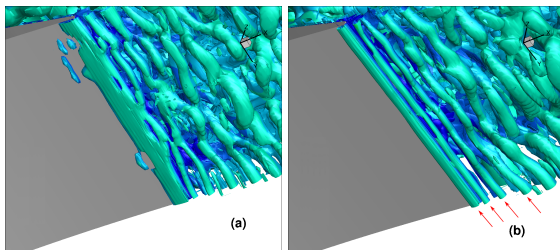


Figure 10: LS prototype, $Re= 2.25$ Million, take-off configuration. Overview of the bottom surface near trailing-edge region. Left: Static, illustrating coherent vortex rows with vortex dislocations; right: morphing with 300 Hz vibration and slight trailing-edge deformation: attenuation of the vortex dislocations and of the three-dimensional effects in the morphing configuration

Figure 12 shows comparison of the mean lift coefficient in both static and morphing configurations. The CL varies as a function of the frequency in the range of (60 Hz – 300 Hz) and the amplitude actuation in a range of (0.5mm – 1.5mm) and is found increased in all morphing configurations.

4 Conclusion

This study provides discussion based on numerical results obtained in the case of two main morphing configurations of an A320 wing in the context of the H2020 N° 723402 European project "Smart Morphing and Sensing for aeronautical configurations" coordinated by IMFT - Institut de Mécanique des Fluides de Toulouse. A single element configuration corresponding to the Reduced-Scale (RS) morphing prototype and a high-lift configuration with two-element wing-flap in take-off position corresponding to the Large-Scale (LS) prototype (near scale one) of this project are considered. In the present numerical study, the morphing is imposed in the near-trailing edge region as a slight deformation and vibration in frequency ranges (50 - 400) Hz. The simulations

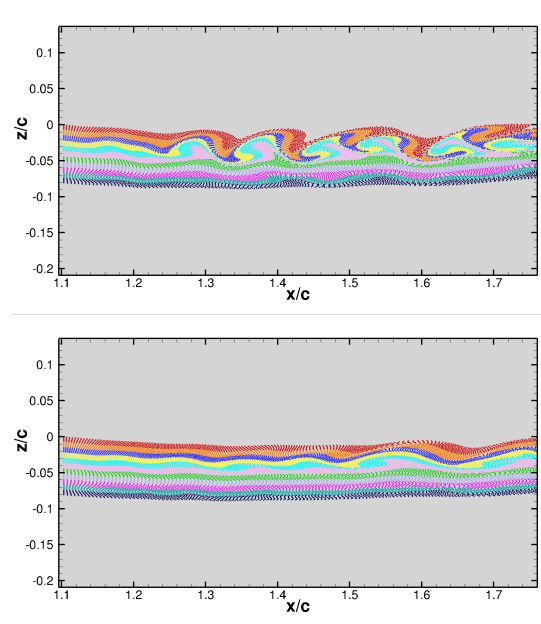


Figure 11: Streaklines illustrating the morphing effect: Top: static. Bottom: morphing with piezoactuators vibrating at 300 Hz with slight trailing-edge deformation showing the vortex breakdown of the coherent structures and the shear layers and wake thinning

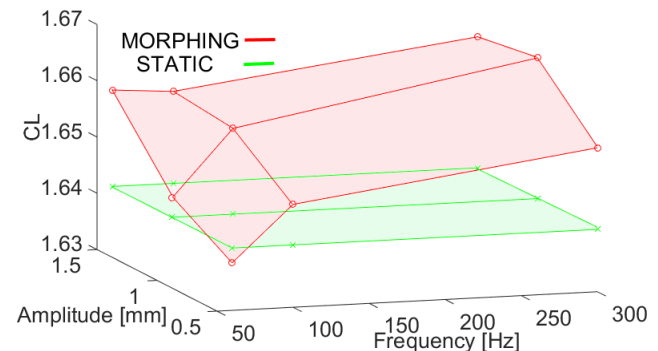


Figure 12: Mean lift coefficient at the take-off position as a function of different actuation frequencies and amplitudes compared to the static case

with high camber effects concern another part of our studies, not presented in this article. The turbulence modelling approaches OES (Organised Eddy Simulation) and the hybrid DDES-OES (Delayed Detached Eddy Simulation with embedded OES in its statistical part) have been used. It has been shown that an actuation at 300 Hz produces suitable vortex breakdown, leading to shear layer and wake thinning, as well as to an attenuation of three-dimensionality. These facts lead to a considerable increase of the aerodynamic performances for both morphing configurations of the RS and LS prototypes and attenuate the aerodynamic noise sources corresponding to the predominant frequencies generated by the coherent structures development. These benefits are produced thanks to the wake thinning through a breakdown of the coher-

ent structures in the wake, by optimal manipulation of the turbulence structures near the trailing edge and the wake regions. The turbulence modelling approaches including Hybrid RANS/LES methods contributed to this relevant performance and accompanied the prototypes design realised in the SMS project.

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