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Trailing-edge dynamics and morphing of a deformable flat plate at high Reynolds number by time-resolved PIV

M. Chinaud [a,b], J.F. Rouchon [b], E. Duhayon [b], J. Scheller [b,a,*], S. Cazin [a], M. Marchal [a], M. Braza [a]

[a] Institut de Mécanique des Fluides de Toulouse (IMFT), UMR CNRS-INPT-UPS No. 5502, Alleé du Prof. Camille Soula, F-31400 Toulouse, France
[b] Laboratoire Plasma et Conversion d'Energie (LAPLACE), UMR CNRS-INPT-UPS No. 5213, 2 Rue Charles Camichel, F-31071 Toulouse, France

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ABSTRACT

The present paper investigates the turbulent wake structure in the near-region past the trailing edge of a deformable inclined plate. The plate is actuated by shape memory alloys. Using these actuators a significant deformation (bending) can be achieved ($\approx 10\%$ of the chord) under the aerodynamic loads corresponding to a Reynolds number of 200 000. The shear-layer dynamics as well as the mean velocity and turbulent stresses have been quantified for a reference case (flat plate inclined at 10°). The present study investigates the modification of the shear-layer and near-wake dynamics achieved by means of the dynamic deformation of the plate compared with static cases that include three intermediate positions of the deformed plate. The comparison of the static cases with the dynamic regime discusses the validity of the quasi-static hypothesis for the present low frequency actuation. It is found that the present actuation enhances the shearing mechanisms past the trailing-edge and modifies the von-Kármán mode as well as the structure of the shear-layer, Kelvin–Helmholtz eddies. Moreover, the increase of the bending enhances the appearance of the pairing mechanism between successive shear-layer eddies and the interaction between the von-Kármán and shear-layer instability modes. Furthermore, it has been found that the increase of the plate's curvature leads to an attenuation of the shear-layer amplitude and of the overall spectral energy, concerning the most deformed position.

1. Introduction

Conventional fixed wing airfoil geometries are usually the result of a design compromise that aims at optimizing the shape only for selected parts of the mission profile. Control surfaces, while modifying the aerodynamic profile of the wing and thereby extending the mission profile, are usually characterized by poor aerodynamic performance and efficiency (Ursache et al., 2007). Adaptive, morphed structures hold the potential to solve this problem and for this reason morphing has appeared as a priority item in important strategies including the ‘FP7’ and ‘HORIZON 2020’ vision of the European commission aeronautics research (Commission, 2012a,b. Therefore, studies on wing deformation receive considerable

* Corresponding author at: Institut de Mécanique des Fluides de Toulouse (IMFT), UMR CNRS-INPT-UPS No. 5502, Alleé du Prof. Camille Soula, F-31400 Toulouse, France.
E-mail addresses: maxime.chinaud@imft.fr (M. Chinaud), rouchon@laplace.univ-tlse.fr (J.F. Rouchon), eric.duhayon@laplace.univ-tlse.fr (E. Duhayon), scheller@laplace.univ-tlse.fr (J. Scheller), Sebastien.Cazin@imft.fr (S. Cazin), Moise.Marchal@imft.fr (M. Marchal), marianna.braza@imft.fr (M. Braza).

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interest in the aerospace domain. Recent advances in the field of smart-materials have renewed this interest (Weisshaar, 2013; Valasek, 2012; McGowan et al., 1998).

A variety of smart-materials and actuators have been studied for morphing applications amongst which are piezoelectric materials (Hall and Prechtl, 1999; Straub et al., 2004), shape-memory alloys (SMAS) (Jänker et al., 2006; Thill et al., 2008; Huang et al., 2010; Hartl and Lagoudas, 2007) and ferromagnetic shape-memory alloys (FSMAS) (Lagoudas, 2008; Sutou et al., 2004) to name a few (Cadogan et al., 2003). The 'Laboratoire Plasma et Conversion d'Energie' (LAPLACE) developed for example a piezoelectric PUSH–PUSH amplification mechanism based on piezoelectric stack actuators (Chinaud et al., 2013). This paper will focus on actuation by SMAS. SMA materials are able to achieve large deformations at low actuation frequencies (several Hz). For the last few decades SMA technology was intensively studied and is now well understood from a structural point of view. SMASs have many applications in the industry including medical and aerospace (Kakubari et al., 2003; Song and Ma, 2007). The characteristics of this actuator make it especially suitable to optimize the shape of the wing and to control the flight in order to increase aerodynamic performance. The SMA actuators are activated in this study using the Joule heating. This mechanism is well understood and was for example implemented by Barbarino and Manzo in order to modify the shape of an airfoil. Whereas Barbarino focussed on chordwise bending of an airfoil using SMA wires (Barbarino et al., 2009) and rods (Barbarino et al., 2010), Manzo (2006) applied SMA actuators in a pulley mechanism in order to deform the wing in the spanwise direction. Senthilkumar et al. (2013) used SMA springs in order to control the trim of an airfoil. The developed SMA spring actuator achieved a displacement of 31° (≈ 16 mm) during wind-tunnel tests of the airfoil. Similarly Brailovski et al. (2010) implemented SMA springs under the skin of an airfoil in order to the change the camber. Strelec et al. (2003) showed that by correct positioning of single SMA wires a modification of the lift coefficient of the order of 0.03–0.05 can be achieved. Faria provided an accurate model of the behavior of SMA actuated airfoils on the example of an airfoil made out of individual segment linked by rotational joints. The developed model was capable topredict the deformation of the airfoil yet the hysteresis effect of the SMAS was an issue (Faria et al., 2012). This issue was addressed in a recent article by Chinaud who demonstrated that the resistance of the wire is an accurate control parameter (Chinaud et al., 2012). Similar results were found by Lan who additionally investigated the pre-stress dependence on the accuracy of the control parameter. His results showed that by applying proper pre-stress the positioning error due to hysteresis can be reduced to 3%. The majority of these studies focus on the structural aspects of the SMA actuation. There exists little knowledge regarding the fluid-mechanic and aerodynamic behavior of SMA actuated structures.

The present paper aims at investigating the large deformation ability and the consequences in the aerodynamic behavior of the solid structure, especially the modification of trailing-edge instabilities and vortex dynamics. Although the SMA technology itself is quite well known, it is the first time, to our knowledge, that the aeroelastic coupling is investigated by advanced experimental techniques (high-frequency time-resolved particle image velocimetry (TRPIV)), in order to analyze the actuation effects on the fluid-dynamics flow structure under turbulence, in a realistic Reynolds number range (order of 200 000), corresponding to the low subsonic phases of the aircraft's manoeuvrability during take-off and landing. The present study especially focuses on the modification of the instability modes (von-Kármán and Kelvin–Helmholtz) during actuation. It is well known that the first instability mode is associated with lift and drag fluctuations, whereas the second is related to aerodynamic noise. This study is useful regarding the fact that control devices that aim at reducing noise are usually unsuccessful in reducing drag. In the present study, an analysis of the trailing-edge near-region past the electro-actively deformed plate will be performed. To this end the flow dynamics of the unactuated plate are discussed and subsequently compared to three static cases with different radii of curvature. Finally, the dynamic case where the plate's radius of curvature is progressively changed during the measurement interval, thanks to SMA actuation, will be presented and compared to the static cases. This comparison aims at examining the validity of a widely used 'quasi-static' hypothesis in aeroelasticity of low-frequency wing deformation. A similar behavior between successive dynamic regimes compared to the static regimes is not systematically a fact in aeroelasticity: it depends on the deformation rate and frequency of actuation, even in the case of low frequency operation. Therefore, it is useful to discuss the validity of the quasi-static hypothesis concerning the trailing-edge dynamics in which this quasi-static hypothesis is valid.

The present work is developed as follows : in Section 2 the experimental setup of the TRPIV measurements, carried out in the wind tunnel S4 of 'Institut de Mécanique des Fluides de Toulouse' (IMFT), is described. In Section 3, the plate's actuation and the fundamental structural properties of the SMAS used in this study are described. In addition, we present the instrumentation and control of the SMA actuators for this configuration, with forces solicitation corresponding to high Reynolds number regimes of order 10^6. In Section 4 the results of the TRPIV measurements are presented. The discussion of the results includes the analysis of the vortex dynamics past the plate at the reference case (inclination: 10°), followed by the results on intermediate static positions of the plate up to the maximum radius of curvature. Comparison of the intermediate static deformations is performed with the fully dynamic deformation by performing a phase-averaged analysis. Furthermore, the impact of the deformation on the turbulence spectrum and on the predominant frequency modes is analyzed for the different states. Finally, a discussion of the actuation effect on the vortex structures and on the instability modes is carried out.

2. Experimental set-up

The experiments have been performed in the closed-loop horizontal wind tunnel S4 of IMFT. The dimensions of the test-section are 670×715 mm. The deformable plate has been mounted on the transverse axis of the wind tunnel at 10° of