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Technical Notes

Control of Separated Flow over Swept Missile Fin Using Pitching Oscillations

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Nomenclature

b	=	maximal span of fin
c	=	root chord of fin
f	=	frequency of pitching oscillations
F^+	=	nondimensional frequency
Re_c	=	Reynolds number based on c
u	=	longitudinal velocity
x/c	=	nondimensional longitudinal location
α	=	angle of attack
$\Delta\alpha$	=	amplitude of oscillations
ψ	=	sweep angle

I. Introduction

FLOWS over moderately swept wings (with sweep angle ψ varying from 45 to 55°) are a recent topic of interest mostly because of their application to military aircraft and unmanned combat air vehicles. In the same way as for highly swept wings ($\psi > 65°$), these flows are characterized by the formation of a leading-edge vortex that contributes to the lift [1]. Nevertheless, when increasing the angle of attack, vortex breakdown occurs. The occurrence of this phenomenon is dependent on the Reynolds number, the sweep angle, and the leading-edge shape [2]. For a sharp leading edge at a high Reynolds number, stall is expected from an angle of attack of 20°. Thus, from an industrial point of view, delaying moderately swept delta wing stall is a challenge aimed at increasing the application domain of such wings. Pitching oscillations appear to be a promising mean to control the flow over such wings. Indeed, encouraging results have been obtained experimentally at low Reynolds and Mach numbers [3,4]. The goal of this study is then to extend the range of applicability of this type of control. The chosen test case is the missile fin shown in Fig. 1. It can be considered as a 50° swept delta wing with a sharp leading edge. The root chord of the fin is $c = 0.285$ m, and the maximal span b equals 0.19 m. Moreover, in the experimental setup, the fin is mounted on a vertical plate to preserve the flow around the fin from the interaction with the boundary layer developing on the wind-tunnel lateral wall. To respect as much as possible the experimental configuration, this vertical plate is considered in the computations. Additionally, the 0.5 mm slot between the vertical plate and the fin is also accounted for.

Concerning the reference uncontrolled case, the experimental data presented in this Note were acquired in ONERA's transonic wind tunnel S3MA at operating conditions of $M_\infty = 0.7$, $U_\infty = 226.5\ \mathrm{m \cdot s^{-1}}$, $Pi_\infty = 1.5$ bar, and $Ti_\infty = 278$ K [5]. The Reynolds number based on the root chord and the freestream velocity equals $Re_c = 5.8 \times 10^6$. The angle of attack equals 25°. This study constitutes a follow up of [6], where the reference computation has been successfully validated against these experimental data. Moreover, continuous and pulsed blowing and synthetic jets have been imposed at the leading edge of the fin. It has been demonstrated, consistently with the experimental works of Williams et al. [7] in the case of a 50° sweep delta wing in the subsonic regime, that an optimal forcing frequency can be found. This nondimensional frequency F^+ (with $F^+ = f \cdot c/U_\infty$) equals 1.5 and has been identified in [6] as being the one of the natural vortex shedding. Nevertheless, such control strategies would necessitate in practice a complex pneumatic system inside the fin that is not easy to manufacture. Thus, the purpose of the current study is to exploit the existing actuators driving the fin movement to impose pitching oscillations.

The computations are performed using the FLU3M solver [8]. Implicit time integration is employed. The time integration is carried out by means of a second-order-accurate backward scheme, and the time step is set equal to 2.6×10^{-7} s. The spatial scheme is based on a second-order-accurate AUSM + (P)-type scheme [9]. The turbulent modeling, based on the zonal detached eddy simulation approach [10] with some delayed detached eddy simulation [11] ingredients, is presented in [12]. In this latter reference, the flow over the present fin has been computed without control. The agreement of the results with the existing experimental data was very satisfactory since, for example, the errors on the lift and drag coefficients were found equal to 3 and 1.3%, respectively. Furthermore, this hybrid Reynolds-averaged Navier–Stokes/large-eddy simulation approach has been successfully applied to the study of compressibility effects on the vortical flow over a highly swept wing [13] and to its control [14]. The grid is composed of 21×10^6 points. Finally, the averaging process has been performed over a physical time equal to 26 ms, which represents a duration of $20 \times c/U_\infty$.

II. Description of Control Strategy

The key point of the current study is to control the separation of the flow over the missile fin by exploiting the actuators already used to pitch the fin. It has been experimentally shown by Vardaki et al. [3] and Cipolla and Rockwell [4] that applying a sinusoidal pitching motion to a stalled moderately swept delta wing can reduce the intensity of the reverse flow over the wing and can also regenerate the leading-edge vortex. As a consequence, the wing stall is delayed and the lift force increases. In the current investigation, the sinusoidal pitching motion of the missile fin is ensured using the arbitrary Lagrangian–Eulerian formulation. The rotation axis is located at $x/c = 0.6$ (this location is the one of the fin actuator). The frequency is set equal to $F^+ = 1.5$, which corresponds to the natural vortex shedding frequency in the unforced case. It should be remembered here that Vardaki et al. [3] have shown that this control strategy is efficient in a range of F^+ varying from 1 to 2. It should be also underlined here that flexible wings self-exited at the same frequencies also delay moderately sweep wing stall [15].

Finally, two amplitudes are currently assessed: $\Delta\alpha = 0.5°$ and $\Delta\alpha = 1°$. With these amplitudes, the maximum relative speeds v/U_∞ at the apex of the fin are, respectively, equal to $3.7\ 10^{-2}$ and $7.3\ 10^{-2}$.

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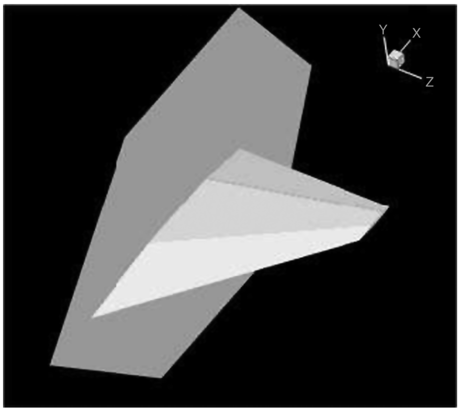

Fig. 1 Perspective view of the geometry.

III. Pitching Oscillations Effects on Flow

A. Overview On Time-Averaged Flow

The aim of this part is to study the oscillation effects on the separated flow. As a starting point, Fig. 2 presents an isosurface of the longitudinal velocity $u = 0$. This figure clearly shows that applying a sinusoidal pitching motion to the missile fin decreases the intensity of the reverse flow region over its upper surface. Indeed, one can observe at the apex of the fin in the controlled cases that reverse flow does not develop anymore, contrary to the baseline case. One can also note that the flow topology in the controlled cases differs from the one of the baseline case. Indeed, the reverse flow extends on nearly 80% of the surface of the fin suction side in the unforced case, whereas this region is split into two parts when the sinusoidal pitching motion is applied to the fin. Finally, an increase of $\Delta\alpha$ leads to an increase of the control efficiency, since the size of the reverse flow region is smaller for $\Delta\alpha = 1°$ than for $\Delta\alpha = 0.5°$.

B. Discussion

As illustrated in Fig. 3, which presents the contours of the velocity in the plane materialized by the dotted lines of Fig. 2, applying a pitching motion to the missile fin results in the acceleration of the longitudinal flow over the suction side of the missile fin. Particularly, the longitudinal velocity u becomes positive between the leading edge of the fin and $x/c = 0.05$ in the $\Delta\alpha = 0.5°$ case and between the leading edge and $x/c = 0.1$ for the $\Delta\alpha = 1°$ case.

These results are consistent with the experimental observation of Vardaki et al. [3], who have shown that applying a sinusoidal pitching motion to a 50° sweep delta wing at the same incidence as in the current study and for F^+ varying from 1 to 2 results in the acceleration of the longitudinal flow and in the reformation of the leading-edge vortex for $\Delta\alpha = 1°$. Nevertheless, in the current study, the study of the flow in transverse planes has evidenced that the leading-edge vortex is not regenerated. This difference can be attributed to Reynolds number effects on the flow over moderately swept delta wings. Indeed, it has been experimentally demonstrated that the vortical flow developing over moderately swept wings depends on the Reynolds number [16,17] contrary to slender wings ($\psi > 65°$). In fact, an increase of the Reynolds number induces a faster vortex breakdown and then the disappearance of the leading-edge vortex. In our study, the Reynolds number based on the root chord of the wing equals 5.8×10^6, whereas it ranges between 13,000 and 30,000 in the experimental works of Vardaki et al. [3]. One can then assume that the regeneration of the leading-edge vortex is more difficult in our case than in [3]. It should also be mentioned that the experimental study of Vardaki et al. [3] is free from compressibility effect, since the experiment has been carried out in water.

IV. Effects on Aerodynamic Performance of Fin

Figure 4 represents the effect of the oscillating pitching motion on the aerodynamic performance of the fin as a function of the pitching amplitude. Note that, in these figures, the case $\Delta\alpha = 0°$ denotes the

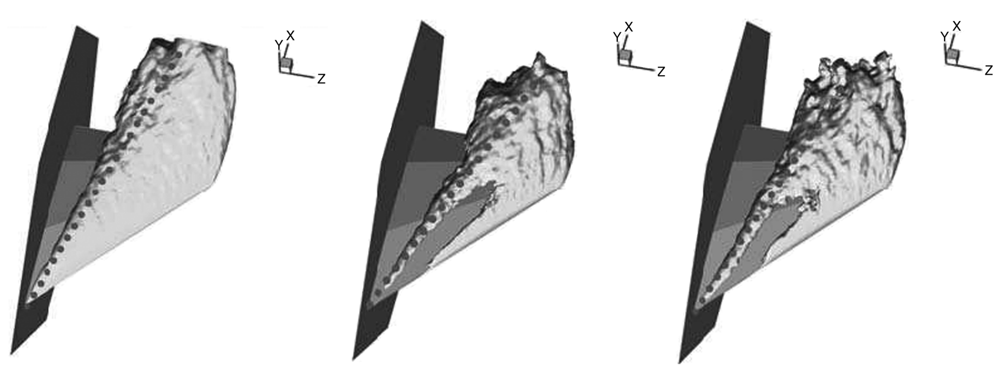

Fig. 2 Isosurface of $u = 0$: a) reference, b) $\Delta\alpha = 0.5°$, and c) $\Delta\alpha = 1°$. The dotted line represents the plane used in Fig. 3.

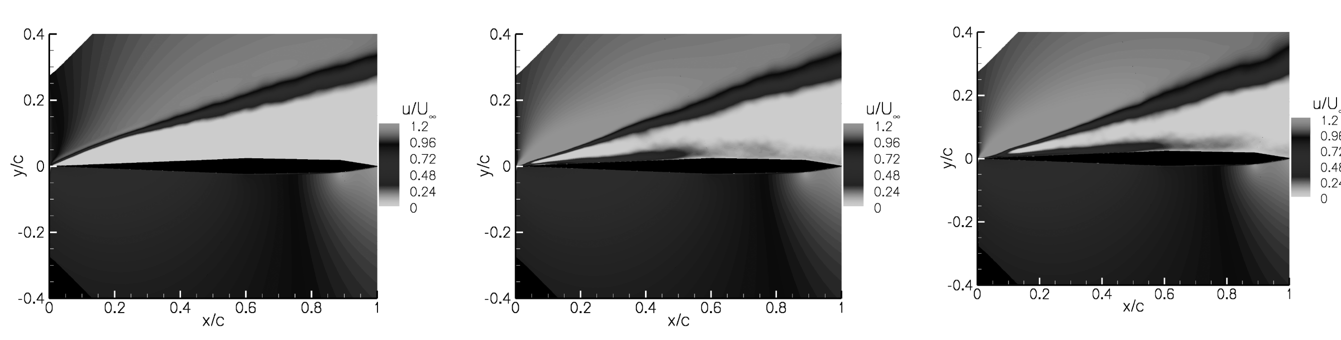

Fig. 3 Contours of u/U_∞ through the inner reverse flow region (following the dotted lines presented in Fig. 2): a) reference, b) $\Delta\alpha = 0.5°$, and c) $\Delta\alpha = 1°$.

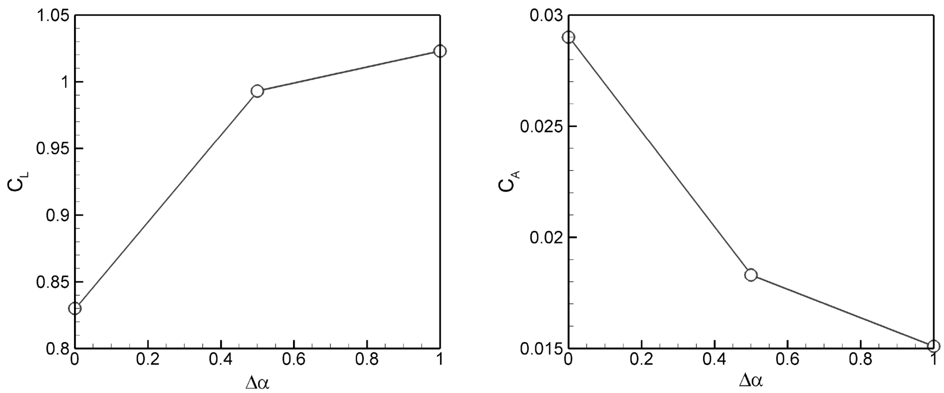

Fig. 4 Pitching oscillations effects on the performance of the fin.

Table 1 Aerodynamic performance of the fin as a function of the control strategy

	C_L	C_A	C_{Lrms}/C_L	C_{Arms}/C_A
Reference	0.832	0.029	0.01	0.04
$\Delta\alpha = 0.5°$	0.99	0.017	0.025	0.25
$\Delta\alpha = 1°$	1.03	0.015	0.05	0.5

baseline case. One can observe that the aerodynamic performances of the missile fin are improved for the two controlled cases. Indeed, for $\Delta\alpha = 0.5°$, the lift force increases by 20% and the drag one decreases by 37%. Augmenting the amplitude of the pitching oscillations still improves the aerodynamic performance, since C_L increases by 25% and C_D decreases by 48% for $\Delta\alpha = 1°$. Nevertheless, it may be noted here that the relative efficiency of the strategy is reduced with an increase of $\Delta\alpha$, and one can anticipate a saturation for larger values of $\Delta\alpha$.

To conclude, Table 1 summarizes the fluctuations of the lift C_{Lrms} and of the drag C_{Arms} in the reference case and in the oscillating ones.

As previously mentioned, applying pitching oscillations enhances the aerodynamic performance of the fin. However, one can observe in this table that it also amplifies the loading fluctuations. The most important increase concerns the drag fluctuations, which are subjected to a tenfold amplification for $\Delta\alpha = 1°$. From an application point of view, the case $\Delta\alpha = 0.5°$ might be preferable, since good performance is achieved while keeping a reasonable level of loading fluctuations.

V. Conclusions

This Note has presented a numerical study of a control strategy based on pitching oscillations that aims at limiting the separated flow over a stalled missile fin. This fin can be considered as a 50° sweep delta wing. The angle of attack is equal to 25°, and the Mach and Reynolds numbers, respectively, equal 0.7 and 5.8×10^6. The frequency of the sinusoidal motion of the fin has been set equal to $F^+ = 1.5$. This nondimensional frequency has been previously identified as being the frequency of the natural vortex shedding in the unforced case. Two amplitudes have been assessed: $\Delta\alpha = 0.5°$ and $\Delta\alpha = 1°$. The analysis of the time-averaged flows has shown that the separated flow is deeply altered by the pitching motion of the fin. Indeed, for the two forced cases, the size of the reverse flow region decreases, this effect being amplified by an increase of $\Delta\alpha$. It then results in an improvement of the aerodynamic performance of the fin, the $\Delta\alpha = 1°$ case being the most efficient. Nevertheless, considering the loading fluctuations, the lowest amplitude case may be the most attractive. Such a control strategy then seems to be a good candidate to enhance the performance of missile fins without any additional control system.

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