Direct Numerical Simulation of Transition Induced Vibration over Flexible Marine Propeller Sections

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Résumé :

Dans cet article, nous étudions l'interaction entre la transition laminaire turbulent et les vibrations d'un hydrofoil à travers un couplage numérique entre une méthode de simulation numérique directe et un couplage à un degré de liberté (couplage DNS-1DOF). L'hydrofoil NACA66 étudié a une section dite laminaire, où un écoulement fortement transitionnel a été observé lors d'observations expérimentales, même à des nombres de Reynolds relativement élevés. Dans cet article, nous utilisons le code open source Nek5000 pour résoudre l'écoulement, basé sur une méthode spectrale à ordre élevée. En parallèle, des mesures vibratoires sont effectuées sur la même section d'hydrofoil dans une configuration 3D de type encastrée-libre. Nous étudions les effets de différentes oscillations vibratoires forcées sur la transition laminaire turbulent. Les amplitudes et périodes d'oscillations sont représentatives du premier mode de torsion observé expérimentalement sous différentes conditions d'écoulement. Les résultats montrent que la transition et le champ de pression pariétal résultant sont affectés par les mouvements oscillatoires. Les résultats du couplage DNS-1DOF seront présentés lors de la conférence. Ce travail sera utile pour mieux comprendre les phénomènes d'interaction fluide structure des hélices marines en écoulements transitionnels.

Abstract :

The objective of this paper is to investigate the interaction between laminar to turbulent transition and the vibration of a hydrofoil, through a numerical coupling between Direct Numerical Simulation and a One Degree of Freedom System (DNS-1DOF). The NACA66 hydrofoil have a laminar section, where highly transitional flows has been observed by previous experimental observations, even at relatively high Reynolds numbers. In this work, we use an open source DNS code 'Nek5000' to solve the flow, which is based on a high order spectral element method. In parallel, vibration measurements in hydrodynamic tunnel are performed on the same hydrofoil section using a 3D configuration, where the hydrofoil is clamped at the root, and free at the tip. We study the effect of different small amplitude forced pitching frequencies on the behavior of laminar to turbulent transition. The pitching frequency and amplitudes are representative of the first torsional mode observed experimentally under various conditions. The results shows that the transition mechanism and the resulted wall pressures are affected by the forced vibrations. The results of the DNS-1DOF coupling will be presented during the conference. The present work will help to understand the fluid structure interaction of marine propellers in transitional flows.

Keywords : Transition, Laminar Separation Bubble (LSB), Direct Numerical Simulation (DNS), One Degree of Freedom System (1DOF), Fluid-Structure Interaction (FSI)

1 Introduction

The present paper deal with the development and the validation of a numerical model to simulate the physic of transition induced vibration over a NACA66 hydrofoil. The development of the turbulent flow, which causes a momentum transfer in the wall normal direction, allows the flow to reattach, to form a so called laminar separation bubble (LSB) ([1]). Downstream of the LSB, the flow is usually highly unsteady and periodic and is governed by complex mechanisms identified as primary and secondary instabilities that lead to transition to turbulence.

The transition is known to affect the body performances and was mainly studied for aerodynamic applications see [2] for experimental works and [3] for numerical works. As far as hydrodynamic applications are concerned, several experimental works on LSB were carried out on marine propeller sections in the past at the Naval Academy Research Institute (IRENav), France. It was shown that a very strong and localized transition to turbulence occurs inside the boundary layer, which induces intense pressure fluctuations ([4]). Moreover, it has been demonstrated that this type of transition can induces important structural vibrations in the case of flexible hydrofoils. [5] showed that there could be a strong interaction between these vibrations and the physic of LSB vortex shedding.

To understand the physic of transition induced vibration on marine propellers (i.e at relatively high Reynolds numbers), experimental works show limitations as often difficult to extract the transitional boundary layer flow from a very localized region, which is submitted to small amplitudes oscillations at the surface. Direct Simulations were recently performed on the NACA66 section at Re=450,000, and the wall pressures were successfully validated with experiments on a fixed configuration (i.e no deformation), see [6][7]. In this study, we couple the DNS with a 1 degree of freedom system that represent the change in pitch due to the deformation of the hydrofoil to its first torsional mode.

This paper aims to investigate the change in pressure distribution due to these small amplitude oscillation, and then to highlight some possible coupling effects between the transition to turbulence and the hydrofoil's pitching motion.

2 Experimental Method

The test section is 1 m long and has a $h = 0.192m$ square section. The velocity can range between 0 and 15m/s and the pressure from 30 mbar to 3bars. The hydrofoil is a NACA 66 which presents a camber type NACA a=0.8, a camber ratio of 2% and a relative thickness of 12% [8]. It is mounted horizontally in the tunnel test section. The hydrofoil is in plastic material (Polyacetate) and is clamped at the root and have a free tip section.This material was chosen in order to observe significant deformation/ vibration to the hydrodynamic loading. The chord is c = 0.150m and the span is b = 0.191m. It corresponds to a low aspect ratio $b/c = 1.3$ and a confinement parameter $h/c = 1.28$. Measurements are performed for an angle of attack of $\alpha = 4$ and a Reynolds number of $Re = 450,000$. The reader should refers to [5] for more detail about the experimental setup.

3 Computational Method

3.1 NEK5000

The Navier-Stokes equations are solved using the flow solver Nek5000 developed at Argonne National Laboratory by [9]. The dynamics of a three-dimensional incompressible flow of a Newtonian fluid are described by

$$\frac{\partial u}{\partial t} = (-\nabla p) + \frac{1}{Re}\nabla \cdot (\nabla + \nabla^T)u - u \cdot \nabla u) \tag{1}$$

$$\nabla \cdot u = 0 \tag{2}$$

where $u = (u_x, u_y, u_z)^T$ is the velocity vector and p is the pressure term. The Reynolds number is defined as $Re = u_\infty c/\nu$, where ν is the kinematic viscosity of the considered fluid, c is the chord length and u_∞ is the upstream velocity. This solver is based on the spectral elements method (SEM), introduced by [10], which provides spectral accuracy in space while allowing for the geometrical flexibility of finite element methods. For further details about the spectral elements method, the reader is referred to the books by [11] and [12].

3.2 Coupling DNS and 1 - D.O.F

3.2.1 Numerical setup

The numerical setup of NACA66 hydrofoil case is shown in Fig.1.

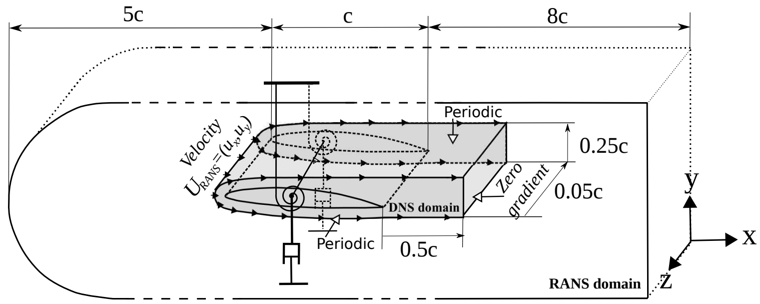


FIGURE 1 – The domain with classic support of the hydrofoil on rotational spring-damper system.

Because of the moderate Reynolds numbers considered, the DNS domain is reduced to the near wall region, and velocity boundary conditions are imposed at the domain boundaries from a transitional RANS calculation to reproduce the velocity gradient external to the hydrofoil boundary layer, which determine the circulation around the hydrofoil. Hence, the total height of the DNS domain is 0.25c and 0.5c is set in the wake, where c is the chord length. The span has been reduced to 0.05c. The domain of the RANS calculation corresponds to the dimensions of the experimental test section of the hydrodynamic tunnel at IRENav.The velocity profiles at the DNS domain boundary are extracted from the RANS calculation , for $Re = 450,000$, V_∞ = 3m/s, $\nabla U \cdot x = 0$ is set at the outlet, whereas a no slip condition is set on the wing surface. A periodic boundary condition is imposed on the vertical side planes of the domain and to know more details about the mesh, resolution and the validation of the DNS model, please refer to [6][7].

3.2.2 Forced pitching motion

In this work, we first investigate the transitional flow response to a forced/ prescribed pitching oscillation. The prescribed velocity for pitching is :

$$V_{pitch}(t) = Asin(\omega_s t) \tag{3}$$

In this equation the frequency ω_s corresponds to the hydrofoil first torsional natural frequency and A is the mean velocity amplitude of this corresponding mode.

3.2.3 Mesh deformation

After getting the displacements due to hydrodynamic loading at the hydrofoil's surface, the DNS code deform the mesh and the Arbitrary Lagrangian-Eulerian (ALE) framework is used. Concerning the mesh deformation, even for small amplitudes pitch, the mesh is set to move rigidly in the near wall region, whereas it is allowed to deform far away from the wall. The main reason comes from the DNS resolution, which impose a very fine mesh in the wall normal direction to satisfy Δy^+_{min} = 0.2, so that even a very small motion at the hydrofoil's surface can cause a change in resolution. Depending upon the topology of the mesh, different strategies can be adopted to deform the mesh [14]. In order to avoid extra computational effort a simple way is introduced. Here the mesh velocity is directly multiplied with a base velocity which satisfy the required type of deformation.

$$base\_velocity = \frac{1}{1 + exp(d - x\_mid)/y} \tag{4}$$

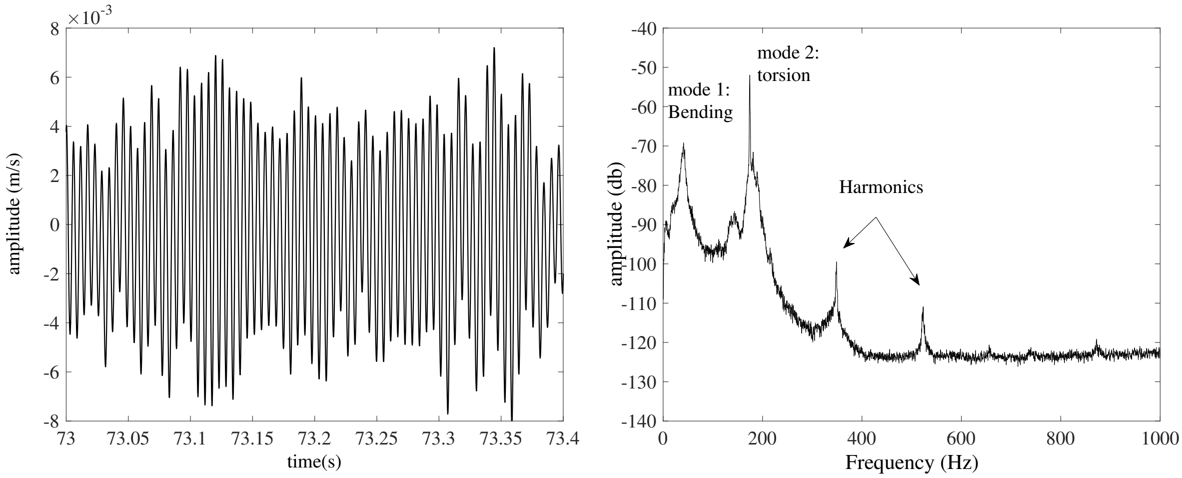
where x_mid is the mid point of the slope in x direction, d is the normal distance to the nodal points from the wall of the object and y is the slope of the base velocity.

4 Results and discussion

4.1 Experimental results

Vibration measurements were performed in hydrodynamic tunnel at IRENav, France, on the setup presented in section Experimental method. We present here new experiments, on the same NACA66 flexible hydrofoil at Re=450,000, which corresponds to the conditions obtained with the current DNS. The Figure 2a shows the signal directly extracted from the Laser Vibrometer measurements, whereas the Figure 2b shows the corresponding spectra. A strong level of vibration is obtained for the second mode at f=173Hz, which corresponds to the first torsional mode. It is suspected that the there is a resonance of this mode with an hydrodynamic excitation. The LSB shedding frequency can be locked in the torsional mode, as it is almost an harmonic ($f_{shed} = 333$Hz against $f_s = 173$Hz). The spectra also shows the harmonics of 2^{nd} mode that confirm the resonance phenomenon. The numerical results presented in this paper will aim at investigating the pressure response submitted to this level of vibration, and to analyze the effects of laminar to turbulent transition.

In order to enter realistic vibration amplitude in the DNS solver for the forced pitching motion case, we set two different velocity amplitude levels which is measured at $x/c = 0.25$. This linear velocity is converted into angular velocity at the leading edge. The distance between elastic axis and leading edge



(a) Velocity signal (b) Velocity Spectra

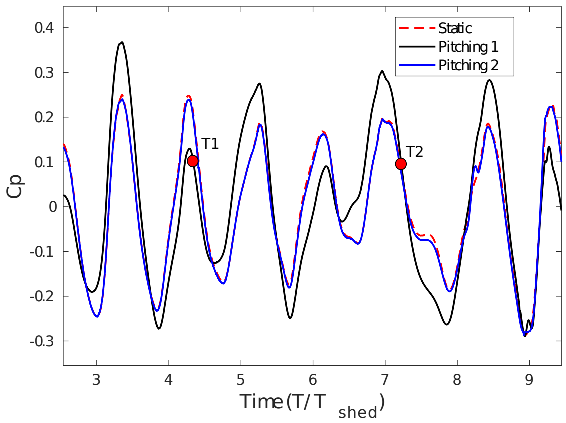
FIGURE 2 – Experimental results of flexible hydrofoil at $x/c = 0.25$ and at 75% of the span from the clamped section, Re = 450,000

is $0.47c$, where c is the chord length. :
1- The case $Pitching - 1$ where $V_{pitch} = 1.1 \times 10^{-2}$m/s corresponds to the maximum amplitude obtained at the leading edge on the spectra on Figure 2b for mode 2,
2- The case $Pitching - 2$ where $V_{pitch} = 3.0 \times 10^{-4}$ m/s corresponds to a lower amplitude of pitch, corresponding to the mean level of vibration of the first two modes obtained without specific hydrodynamic excitation or lock-in.

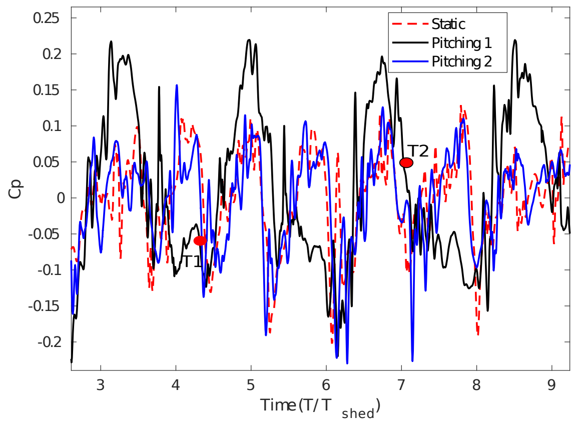
4.2 DNS results

DNS simulations were performed at a frequency of $f_s = 173Hz$, and the two different amplitudes set by the experimental conditions. The time has been non dimensionalized by the period of vortex shedding, corresponding to $f_{shed} = 333Hz$. We observe that the total pitch amplitude is about 0.03 , that confirm the small amplitude of pitch imposed by the hydrofoil's vibration. However, considering the frequency of 173 Hz, we can deduce that the pitching velocity is about $\dot{\alpha} = 10.3/s$. If we form a non dimensional pitching frequency defined in [4] as $\dot{\alpha}^* = \dot{\alpha}c/U_\infty$, we finally obtain the non dimensional value of 0.52, which mean that the relative influence of the pitching velocity is of the order of the upstream velocity (two times less), i.e. the dynamic of rotation is significant. As a comparison, the $Pitching - 2$ case gives a non dimensional pitching velocity of $\dot{\alpha}^* = 0.014$, which is considered as quasi-static. Two instants (an increase of pitch ($T1$) and a decrease of pitch (T_2)) in the simulation will be taken to discuss on the wall pressure along the chord.

The Figure 3a shows the time evolution of wall pressure fluctuation for the two pitching cases, and for the static case (no pitching) at $x/c = 0.7$. At this location, it was shown that the laminar separation bubble becomes unstable, where 2D TS waves occurs, which generates periodic vortex shedding at $f_{shed} = 333Hz$, which is the first stage that lead to transition to turbulence. It is observed that the lower amplitude of pitch have a minor effect on the wall pressure, as it is almost mixed up with the static case. The higher pitching shows significant higher pressure fluctuations, at instant that clearly corresponds to the peak amplitude of pitch, see $T/T_{shed} = 3.2$ or $T/T_{shed} = 5$ for instance. In the lower amplitude of pitch ($T/T_{shed} = 4.1$ or $T/T_{shed} = 5.9$), the wall pressure amplitudes are decreased by the pitching



(a) At x/c = 0.7



(b) At x/c = 0.8

FIGURE 3 – Comparison of wall pressure coefficient fluctuations between the pitching and static cases at trailing edge of the foil

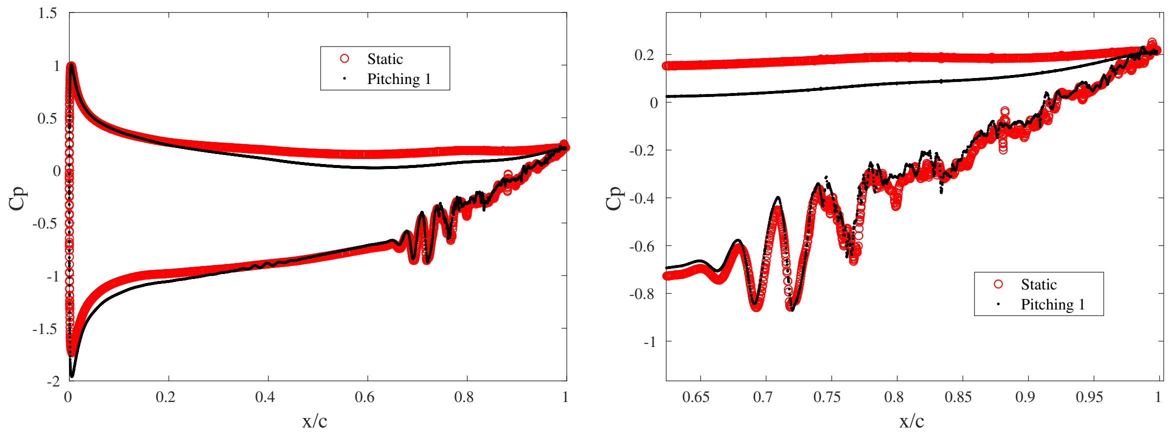
motion.

The Figure 3b shows the wall pressure coefficients downstream the LSB at $x/c = 0.8$. With the development of turbulence, which corresponds to the formation of 3D coherent structures in the boundary layer, followed by the breakdown which generates small scales structures, the pressure signal becomes more random, even if the shedding are sill highlighted by the pressure fluctuations. With the development of turbulent flow, the chaotic process makes the $Pitching - 2$ case differ from the static case, which shows that even a very small variation on the operating condition leads to two distinct physical solutions. However, the pressure fluctuations are still comparable and shows the same mean fluctuation. The higher $Pitching-1$ case shows a higher effect of the forced motion as compared to $x/c = 0.7$. This is because it is taken more far from the axis of rotation, so that the acceleration gets higher. An increase of $\Delta C_P = 0.1$ of the pressure coefficient fluctuations is observed at the higher amplitude times(see $T/T_{shed} = 3.2$ or $T/T_{shed} = 5$), whereas at the lower amplitudes of pitch, it reduces the pressure by $\Delta C_P = 0.1$(see ($T/T_{shed} = 4.1$ or $T/T_{shed} = 5.9$)).

These first results clearly showed that even for low amplitude pitching oscillation, the wall pressure can be strongly affected by the acceleration of the hydrofoil representatives of structural vibrations. The Figure 3b demonstrated that the hydrofoil's pitching can dominates the evolution of wall pressures, in particular when we moves away from the elastic axis, so that it correlates the comments on the experimental spectra in Figure 2b, where the strouhal frequency seems to be locked in the foil's vibrations.

To show the global response of the wall pressures to the hydrofoil pitching oscillations, the pressure coefficient along the chord is shown for the $Pitching - 1$ and the static cases at the at the reference time $T2$ at decreasing pitch (Figure 4a). As expected, the wall pressure are modified by the variation of hydrofoil's acceleration induced by the oscillatory pitching motion.

To depict the spatial evolution of wall pressure along the laminar to turbulent transition, a zoom of the the pressure coefficient is shown in Figure 4b, for the reference time $T2$. The transition scenario can be clearly described from this figure, where a wave length of about 0.04c is observed from $x/c = 0.65$ to $x/c = 0.75$, which corresponds to the development Tollmien Schlichting (TS) waves. Then the fluctuations progressively decreases in amplitude and become random because of the development of multi-scaled turbulent flow from $x/c = 0.8$ to $x/c = 1$.



(a) Global response (b) Near the trailing edge

FIGURE 4 – Comparison of coefficient of pressure between flexible and static foils at T2 instant

5 CONCLUSIONS

In this paper, we investigated the effect of small amplitude pitching on the behavior of laminar to turbulent transition and the induced pressure fluctuations on a NACA66, laminar hydrofoil. The simulations are performed in DNS using mesh deformations and the ALE formulation to take into account for the mesh deformation velocity in the fluid equations.

In the experimental data, the two first mode of the hydrofoil (first bending and twisting modes) are observed, with a strong peak with low damping for the torsional mode, which seems to be due to resonance with a hydrodynamic strouhal frequency. The transition frequency, observed in previous studies at $f_{shed} = 333Hz$ is not observed on the hydrofoil's vibration, and seems to be locked in the frequency in torsion or in one of its harmonics.

The DNS results shows a great influence of the oscillatory motion of the hydrofoil for the highest pitching velocity. As we move away from the axis of rotation, the pitching acceleration is increasing, which enhance the pressure fluctuations (either by increase or decrease of pressure coefficient depending on the sense of rotation) and reduces the effect of periodic fluctuations of LSB vortex shedding, whereas the boundary layer flow doesn't seems to be much affected. The spatial evolution of wall pressure coefficient along the chord confirms the general influence of the imposed pitching velocity to the pressures. The DNS also allows to investigates the transition to turbulence, where the TS waves downstream the LSB generates classical pressure waves with about the same characteristic stream-wise length, and a progressive scattering of the pressure fluctuations due to the development of multi-scaled flow.

The study will now focus on the free oscillations in pitch in the DNS solver, to investigate the coupling effects between transition and hydrofoil's torsional vibrations. Some results will be presented during the conference.

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