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

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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 hydrofoil have a NACA66, 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. After validation of the DNS-1DOF model with lower Reynolds number test cases, 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. This profile have a laminar section, which can induce large transitional regimes, even at relatively high Reynolds numbers and is often used to design marine propeller blades to maintain laminar boundary layer at the blade surface, and hence reduce the friction.

The main characteristics of transition over lifting profiles is well known. It is usually triggered by a laminar separation and a reversed flow, due to an adverse pressure gradient. 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 and on small scales devices, where the transition takes a large portion of the chord and govern the boundary layer flow, see [2]-[4] for experimental works and [5] for numerical works. From the author’s knowledge, there is only one numerical study that considered laminar to turbulent transition at relatively high Reynolds number i.e., \(Re=400,000\), see [6], for aircraft applications. This work showed the ability of the spectral element method to predict the transition, and the development of turbulence. 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. These studies concerned the NACA66 hydrofoil. Under relatively high Reynolds numbers (\(Re=300,000\) to \(1,000,000\)), highly transitional flows has been observed for this profile. It was shown that a very strong and localized transition to turbulence occurs inside the boundary layer, which induces intense pressure fluctuations ([7]). This physic have a strong influence on hydrodynamic performances [8]. Moreover, it has been demonstrated that this type of transition can induces important structural vibrations in the case of flexible hydrofoils (i.e. when the structural properties are modified to enhance fluid structure interaction). [9] showed that there could be a strong interaction between these vibrations and the physic of LSB vortex shedding. In particular, additional frequencies around the frequency of LSB shedding and structural modes, as well as a global increase of amplitude were observed in the vibration spectra in transitional flows, which could be the result of a complex fluid structure interaction phenomenon. This work also showed that when the frequency of LSB vortex shedding get close to a natural vibration mode, resonance with the blade natural frequencies can be obtained.

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To understand the physics 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 [10][11]. 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. The objective is 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 hydrofoil geometry is taken from experiments that have been carried out in the cavitation tunnel at IRENav, France. The test section is 1 m long and has a \( h = 0.192 \text{m} \) 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% [12]. It is mounted horizontally in the tunnel test section. The hydrofoil is in plastic material \((E = 3 \times 10^8 \text{Pa})\) 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 \( c = 0.150 \text{m} \) and the span is \( b = 0.191 \text{m} \). 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 \( \alpha = 4^\circ \) and a Reynolds number of \( Re = 450,000 \). Vibration measurements are performed on the hydrofoil pressure side using a Laser Vibrometer. It is a class II He-Ne laser of wavelength = 632.8 nm. The vibrometer sensitivity ranges between 10 mm/s/Volt up to 1m/s/Volt. The reader should refer to [9] for more detail about the experimental setup. It has to be noted that wall pressure measurements were carried out on a previous research on a similar hydrofoil section. It was in steel material, so that the hydrofoil is considered as rigid, and piezo-resistive transducers were placed for various locations along the chord. This setup was used to validate the DNS method, and to be able to characterize the wall pressure response due to transition, on a fixed hydrofoil configuration (i.e not submitted to any motion), see [10] for more details.

3 COMPUTATIONAL METHODS

3.1 NEK5000

The Navier-Stokes equations are solved using the flow solver Nek5000 developed at Argonne National Laboratory by [13]. 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 \( Re = \frac{u_{\infty}c}{\nu} \), where \( \nu \) is the kinematic viscosity of the considered fluid, \( c \) is the chord length and \( u_{\infty} \) is the upstream velocity.

This solver is based on the spectral elements method (SEM), introduced by [14], which provides spectral accuracy in space while allowing for the geometrical flexibility of finite element methods. Spatial discretization is obtained by decomposing the physical domain into spectral elements within which the velocity is defined on Gauss-Lobatto-Legendre (GLL) nodes and the pressure field on Gauss-Legendre (GL) nodes. The solution to the Navier-Stokes equations is then approximated within each element as a sum of Lagrange interpolants defined by an orthogonal basis of Legendre polynomials up to degree N. The results presented in this paper have been obtained with a polynomial order between \( N = 6 \) and \( N = 12 \), depending on the Reynolds number considered. The convective terms are advanced in time using an extrapolation of order 3, whereas the viscous terms use a backward differentiation of order 3 as well, resulting in the time-advancement scheme labeled BDFK/EXTk. NEK 5000 employs the MPI standard for parallelism. For further details about the spectral elements method, the reader is referred to the books by [15] and [16].

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 simulation 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 unit chord length. The span has been reduced to 0.05c. The domain of the RANS cal-
culation 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 $Re = 450,000$, $V_{\infty} = 3\text{m/s}$, $\nabla U : x = 0$ 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.

The spectral mesh is shown in 2. It is refined close to the wall to obtain a low $y^+$ value, whereas it is almost constant in $x$ and $z$ direction, i.e. chord-wise and span-wise directions. This leads to 188,480 spectral elements, with an element order of 0(12) for $Re = 450,000$. The final resolution is set to $\Delta x_{\text{max}} = \Delta z_{\text{max}} \approx 7$ and $\Delta y_{\text{min}} = 0.2$. That is, 326 million grid points in total. To obtain the DNS, a progressive increase of the element order is performed to advance in time, up to the target mesh. As the DNS code is semi-implicit, it requires the local CFL number to be strictly $CFL = u\Delta t/\Delta x < 0.75$. The computations are carried out with $CFL \approx 0.5$. For more details about the mesh, resolution and the validation of the DNS model, please refer to [10],[11].

![Spectral element mesh of the NACA66 hydrofoil, N = 188,480.](image)

**3.2.2 Fluid structure interaction model**

To reproduce the pitch motion due to the first torsional mode of the hydrofoil, a torsional spring-mass-damper is placed at the elastic axis of the hydrofoil. The coupled system is then solved dynamically with the equation of motion that describe the free motion of the hydrofoil:

$$I_\theta \ddot{\theta} + D_\theta \dot{\theta} + K_\theta \theta = M_{EA}(t)$$

where $I_\theta$ is the moment of inertia about the elastic axis, $D_\theta$ is the damping coefficient and $K_\theta$ is the torsional stiffness respectively. The numerical values are derived from the experimental material properties and are taken from [17].

The magnitude of each parameter is set in order to reproduce the pitching motion of the hydrofoil due to torsion at 75% of the span. $M_{EA}$ is the moment exerted by the fluid, which is calculated in the DNS at each time step.

The explicit algorithm (assuming no added mass effect), goes as follows:

1. The fluid flow is computed in the domain.
2. The moment exerted by the fluid on the airfoil is computed.
3. The equation (3) is solved using Range Kutta $4^{th}$ Order scheme to obtain the angular velocity.
4. The angular velocity is fed into the mesh velocity and the mesh positions get updated then the next time step proceed.

**3.2.3 Added mass effect**

For marine applications, the added mass effect plays an important role in the stability of FSI computation. If the mass ratio (mass of the foil to fluid) is much higher than 1 (aerodynamic application for example) then there is no added mass effect and the coupled calculation is always stable. As a consequence, an explicit coupling together with explicit Runge Kutta $4^{th}$ order is used for the validation case, which is an aerodynamic case. In the present case, the mass ratio is 1.48 there is a need to stabilize the coupled solution by adding an artificial added mass to the equation (3). This method is quite popular and has been used in [18] to simulate the flow around a ship, and in [19]. In Nek5000, a Green function is solved to obtain the added mass, see more details in [20].

**3.2.4 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:

$$V_{\text{pitch}}(t) = A \sin(\omega_s t)$$

In this equation the frequency $\omega_s$ corresponds to the hydrofoil first torsional natural frequency and $A$ is the mean velocity amplitude of this corresponding mode, which are taken from Laser Vibrometer measurements.

**3.2.5 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. This method allow to take into account for the mesh deformation velocity by subtracting it to the local velocity in Equation (1). It has to be noted that the ALE formulation is not necessary in the present case, as we only consider small amplitude displacement, however it will allow to consider higher amplitudes in future studies. 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 $\Delta y_{\text{min}} = 0.2$, 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 [20]. 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.
\[ \text{base velocity} = \frac{1}{1 + \exp(d - x_{mid})/y} \]  \hspace{1cm} (5)

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 VALIDATION OF DNS - 1DOF MODEL

#### 4.1 Flow induced vibration on NACA0012

Since fluid structure interaction in transitional flows has not been tested in Nek5000, a validation case is first performed on transition induced pitching of an airfoil. This case investigated experimentally[21] and numerically[22]. It consider a NACA0012 airfoil with a high aspect ratio, which is mounted on a torsional spring, and is submitted to a low Reynolds number flow of \( \text{Re}=64,000 \) with 0° initial angle of attack. It is a 1 degree of freedom system where the foil pitch about the elastic axis, located at 0.186c from the chord. The 1 degree of freedom system is the same as in Equation (3), and the structural parameters are summarized in Table 1. The parameters are set so that the airfoil experience self sustained oscillations.

#### Table 1: Numerical parameters used for simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{\theta} )</td>
<td>0.00135 kg m²</td>
</tr>
<tr>
<td>( D_{\theta} )</td>
<td>0.002 N m/rad</td>
</tr>
<tr>
<td>( K_{\theta} )</td>
<td>0.3 N m s⁻¹</td>
</tr>
<tr>
<td>Chord</td>
<td>0.156 m</td>
</tr>
<tr>
<td>Span</td>
<td>0.61 m</td>
</tr>
<tr>
<td>( x_{ea} )</td>
<td>0.186c</td>
</tr>
</tbody>
</table>

As compared to the present case, the airfoil is not deforming, but is rigidly moving according to the torsional spring. This case is first validated by comparing the pitch oscillation obtained from the LES of [22], see figure 3. Both simulations are correctly predicted the self sustained oscillations, with the same frequency and amplitude. The present DNS converges faster to the periodic state.

#### Table 2: Comparison of results for Self-Sustained Oscillations of NACA0012

<table>
<thead>
<tr>
<th>Reference</th>
<th>Max pitch (deg)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>present DNS</td>
<td>4.8</td>
<td>2.61</td>
</tr>
<tr>
<td>Poirel et al (Exp.) [21]</td>
<td>4.0</td>
<td>2.70</td>
</tr>
<tr>
<td>Simon et al (LES) [22]</td>
<td>5.3</td>
<td>2.57</td>
</tr>
</tbody>
</table>

The instantaneous vorticity field is also observed at \( \alpha = -2^\circ \) during pitching, see Figure 4. It confirm the presence of a laminar separation bubble (LSB) at about 8cm from the trailing edge, which experience shedding that cause transition to turbulence. The corresponding frequency is locked in the natural frequency of the system so that the airfoil experience self sustained oscillations.

#### Figure 4: Airfoil vorticity results in z-direction at -2.06° angle of attack and \( t = 3.86 \) s

### 5 RESULTS AND DISCUSSION

#### 5.1 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 \( \text{Re}=450,000 \), which corresponds to the conditions obtained with the current DNS. The Figure 5 shows the signal directly extracted from the Laser Vibrometer measurements, whereas the figure 6 shows the corresponding spectra. A strong level of vibration is obtained for the second mode at \( f=173 \) Hz, 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 \( (f_{shed} = 333 \text{Hz against } f_s = 173 \text{Hz}) \). 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 is \(0.47c\), where \(c\) is the chord length.: 

1. The case \(\text{Pitching} - 1\) where \(V_{\text{pitch}} = 1.1 \times 10^{-2}\) m/s 
corresponds to the maximum amplitude obtained at the 
leading edge on the spectra on Figure 6 for mode 2, 
2. The case \(\text{Pitching} - 2\) where \(V_{\text{pitch}} = 3.0 \times 10^{-4}\) m/s 
corresponds to a lower amplitude of pitch, corresponding 
to the mean level of vibration of the first two modes ob-
tained without specific hydrodynamic excitation or lock-in.

\[\dot{\alpha} = 10.3^\circ/s\]. If we form a non dimensional pitching fre-
quency defined in [7] as \(\dot{\alpha}^* = \dot{\alpha}c/U_\infty\), we finally obtain 
the non dimensional value of 0.52, which mean that the rel-
ative influence of the pitching velocity is of the order of the 
upstream velocity (two times less), i.e. the dynamic of rota-
tion is significant. As a comparison, the \(\text{Pitching} - 2\) case 
gives a non dimensional pitching velocity of \(\dot{\alpha}^* = 0.014\), 
which is considered as quasi-static. Two instants are high-
lighted in the Figure 7 that will be taken to discuss on the 
wall pressure along the chord during the increase of pitch 
\((T1)\) and a decrease of pitch \((T2)\).

\[\text{Pitching 1} \quad \text{Pitching 2}\]

The Figure 8 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 unsta-
ble, where 2D TS waves occurs, which generates periodic 
vortex shedding at \(f_{\text{shed}} = 333Hz\), 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 \(T/T_{\text{shed}} = 3.2\) or \(T/T_{\text{shed}} = 5\) for 
instance. In the lower amplitude of pitch \((T/T_{\text{shed}} = 4.1\) 
or \(T/T_{\text{shed}} = 5.9\), the wall pressure amplitudes are de-
creased by the pitching motion.

\[\text{Pitch angle (Degree)}\]

5.2 DNS results

The primary dimensions and description about the geom-
etry has given in Section 2 and 3.2.1. The DNS simula-
tions were performed at a frequency of \(f_s = 173Hz\), and 
the two different amplitudes set by the experimental 
conditions. The pitch angle versus time is shown in Figure 7. 
The time has been non dimensionalized by the period of 

\[f_{\text{shed}} = 333Hz\]. We 
observe that the total pitch amplitude is about 0.03° , that 
confirm the small amplitude of pitch imposed by the hy-
drofoil’s vibration. However, considering the frequency of 
173 Hz, we can deduce that the pitching velocity is about 
\(\dot{\alpha} = 10.3^\circ/s\). If we form a non dimensional pitching fre-
quency defined in [7] as \(\dot{\alpha}^* = \dot{\alpha}c/U_\infty\), we finally obtain 
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ative influence of the pitching velocity is of the order of the 
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lighted in the Figure 7 that will be taken to discuss on the 
wall pressure along the chord during the increase of pitch 
\((T1)\) and a decrease of pitch \((T2)\).

\[\text{Pitch angle (Degree)}\]

Figure 5: Velocity signal as function of time at \(x/c = 0.25\) and 
and at 75% of the span from the clamped section, \(Re = 450,000\)

Figure 6: Comparison of flexible hydrofoil velocity spectra at at 
\(x/c = 0.25\) and at 75% of the span from the clamped section, \(Re = 450,000\)

Figure 7: Pitch angle versus time for the cases, Pitching 1 and 
Pitching 2

The Figure 8 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 
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ble, where 2D TS waves occurs, which generates periodic 
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fluctuations, at instant that clearly corresponds to the peak 
amplitude of pitch, see \(T/T_{\text{shed}} = 3.2\) or \(T/T_{\text{shed}} = 5\) for 
instance. In the lower amplitude of pitch \((T/T_{\text{shed}} = 4.1\) 
or \(T/T_{\text{shed}} = 5.9\), the wall pressure amplitudes are de-
creased by the pitching motion.
The Figure 9 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 still 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 $T/T_{shed} = 5.9$).

The Figure 9 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 6, 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 reference time T1 at increasing pitch (Figure 11) and at the reference time T2 at decreasing pitch (Figure 12), see Figure 7 regarding the pitching motion. As expected, the wall pressure are modified by the variation of hydrofoil’s acceleration induced by the oscillatory pitching motion. For example, a clear increases of the $C_{Pmin}$ is observed for $T_1$, where the hydrofoil’s pitch is increasing (i.e. the hydrofoil’s leading edge is submitted to a positive $\Delta C_P$), whereas an increases of $C_{Pmin}$ is observed for $T_2$ (i.e. the hydrofoil’s leading edge is submitted to a negative $\Delta C_P$).

Figure 12: Comparison of coefficient of pressure between flexible and static foils at T2 instant.

To depict the spatial evolution of wall pressure along the laminar to turbulent transition, a zoom of the pressure coefficient is shown in Figure 13, for the reference time $T_2$. 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 $x/c = 1$.

Figure 13: Comparison of coefficient of pressure between flexible and static foils near the trailing edge of hydrofoil at T2 instant.

The link between pressures and boundary layer flow can be seen by comparing Figures 14 and 15, which shows the pressure and the vorticity contours, respectively, in the LSB region ($x/c \approx 0.7$) up to the trailing edge ($x/c = 1$). The TS waves, which provoke LSB vortex sheddings at $x/c = 0.72$ (Figure 15) clearly generates large pressure waves downstream the LSB. After the break down of the LSB sheddings at $x/c = 0.78$, the pressure is mixed up, but coherent flow is maintained up to $x/c = 0.82$ after what it is progressively affected by the turbulent structures.

Figure 14: Pressure coefficient $C_P$ contours for the static case at $T_2$ instant.

Figure 15: Vorticity contours $\omega_y$ for the static case at $T_2$ instant.

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 seem 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 investigate the transition to turbulence, where the TS waves downstream the LSB generates classical pressure waves with about the same characteristic streamwise 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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