WATER FLOW AROUND A FLAPPING FOIL: PRELIMINARY STUDY ON THE NUMERICAL SENSITIVITY

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In this paper we focus on the water flow around a vertical hydrofoil used to generate power in micro-hydropower-units, based on the flutter phenomenon, which leads to pitching and sway oscillations of the foil. 2D computations are performed in COMSOL Multiphysics, in unsteady turbulent flow, for one-way pitch motion of the foil, with pitch angle varying over 50 degrees. This assumption precedes further studies that will point on the dynamic pitching and sway oscillations in unsteady flow. The numerical sensitivity of the results is analyzed through a grid dependency test from coarse to very fine mesh, in order to depict the trusted values of the lift and drag forces acting on the foil. The variation of the lift and drag forces during the one-way pitch motion is obtained for the studied NACA 0015 foil.

Keywords: Flapping foil, flutter phenomenon, pitch motion, numerical sensitivity.

1. Introduction

Energy generation using low pollution technologies represents nowadays a worldwide concern, in the attempt to diminish the environmental impact of the industry. Being an alternative to energy generation from fossil fuel sources [1÷4] (which raises serious environmental issues), the energy generation from renewable sources (like water/ solar/ wind/ geothermal sources, biofuel, biogas, waste and other non-combustible sources) is subjected to a sharp development.

We highlight the fact that we will denote further by "hydropower production" the power production from all water sources [5], namely from classical hydropower plants and pumped-storage plants [6], but also from tidal power plants, river/marine current power units/farms and wave power units/farms.

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According to the International Energy Agency [7], the share of renewable-based power generation in total power generation will increase from 22% in 2013, to over 26% in 2020, then up to 33% in 2040. Hydropower is the largest renewable source of energy exploited, reaching about 20% of the World electricity production. In 2010, the hydropower production was basically obtained in classical hydropower plants and pumped-storage plants, and only 0.03% of the total production was obtained from marine sources [7]. Almost 1/3 of the classical hydropower potential is already built (storage hydropower, run-of-river power, pumped-storage hydropower). Other categories of hydropower potential are not enough exploited – one can include here the tidal power, as well as the hydro-kinetic power of waves and currents (marine currents, river currents, small and medium size streams and channels, like irrigation/ headrace/ tailrace channels).

The common solution for the energy generation from the kinetic power of water currents involves for the most part rotary turbines (with vertical or horizontal axis). On one hand, such turbines encounter limitations at low flow speeds, and on the other hand, the amount of produced energy is limited by the impact of those turbines on the river/marine wildlife [8÷10]. Basically, any fish-friendly solution/technology is worth studying and could prove useful for energy harvesting, if the results are comparable to the rotary turbines solution, in terms of power production and hydropower-unit efficiency.

The technologies that extract the power from air currents and water currents to generate electricity are similar, so one can select a convenient solution already studied for wind power generation, to apply it for hydrokinetic power generation. One of these convenient solutions is the flapping foil (also called flapping wing) that operates in a power-extraction regime – this solution is based on the flutter phenomenon [11], which combines two types of oscillating motions (pitching oscillations and sway/plunging oscillations) that create oscillating aerodynamic/hydrodynamic forces on a flexible structure (e.g. airfoil, hydrofoil, tall building, bridge, iced telegraph wire, electric power line). The forces associated with the flutter phenomenon can cause destructive vibrations on flexible structures, like aircraft wings, but they proved to be useful in power generation devices. The first flapping foil wind power unit (flapping engine) was developed in 1951 by Duncan [12].

Experiments showed that a flapping foil can extract wind power with the same efficiency as a rotary wind turbine [13]. Numerical simulations on flapping foil wind power generation [14] and hydropower generation [15] showed that efficiency can be improved by controlling the motion-related parameters, thus the maximum efficiency can increase from 20% to 34% [14].

Also, the simulations revealed that non-sinusoidal foil pitching oscillations lead to better efficiencies than sinusoidal foil pitching oscillations, due to the higher pitch angles values [15].

Recently, solutions consisting of a single flapping foil [16], a cascade of two flapping foils [17] and a unit with twin-flapping foils [18] were tested in hydropower-extraction regime, in a high-speed circulating water channel at Kyushu University, in Japan. The cascade foils operating in the in-phase mode of oscillation give better results than the ones operating in the anti-phase mode of oscillation [17]. The twin-flapping foils hydropower unit was also tested in situ, in a small irrigation stream [18]. The indoor tests conducted by this Japanese team showed that the flapping foil(s) solution is suitable for hydropower generation, with a maximum efficiency varying between 18% and 32%, depending on the water velocity, amplitude of pitching oscillations and frequency. The same technology can be applied to tidal power generation [18].

Within the present paper we focus on a single flapping foil (a vertical NACA 0015 foil) used for hydropower generation. 2D computations (in a horizontal plane) are performed using the Finite Element Method software COMSOL Multiphysics, in unsteady turbulent flow, for one-way pitch motion of the foil, with pitch amplitude of 50 degrees. The numerical sensitivity of the results is analyzed through a grid dependency test from coarse to very fine mesh, to depict the trusted variation of the lift and drag forces acting on the foil during the one-way pitch motion. The present study precedes further studies that will point on the dynamic pitching and sway oscillations in unsteady flow.

2. Numerical model of the studied flapping foil

The flutter phenomenon is an aero/hydrodynamic instability consisting in self-excited oscillations, produced by aero/hydrodynamic forces on an elastic system having at least two coupled modes of vibration [11], namely: (1) the foil/wing bending, which produces a displacement of the chord normal to the fluid flow and leads to plunge or sway oscillations, and (2) the foil/wing torsion around the axis parallel to the span, which leads to pitching oscillations. The flutter phenomenon is governed by the interactions among aero/hydrodynamics, structural elasticity and inertial forces on the structure.

A flapping foil system can operate in the power extraction regime, meaning that the system extracts energy from the fluid flow, when a proper relation exists between the fluid velocity, on one hand, and the phases and amplitudes of oscillations, on the other hand. Thus, if one ensures about a quarter-period phase angle (e.g. $\pi/2$) between the pitch and the sway motions, the lift force will remain in the same direction as the foil motion during the oscillation cycle [19].

As stated before, by using COMSOL Multiphysics, a finite element method-based software, we performed 2D modelling of the unsteady turbulent flow around a flapping foil, for one-way pitch motion of the foil. In order to compare our present and further results with available experimental data [16÷18], we considered a vertical NACA 0015 flapping foil, with a chord $c = 10$ cm, a span $L = 30$ cm, and a rotation axis at mid-chord length. The upstream water velocity was set to $U = 1$ m/s and was kept constant.

The 2D computational domain, containing the horizontal cross-section of this foil, is presented in figure 1: the rectangular domain is 8 chord-length wide and 14 chord-length long; the rotation centre of the foil is placed in the origin of the *x*O*y* plane; the domain spreads around the origin by $-4c$ and $+10c$ on O*x*-axis, and by $\pm 4c$ on O*y*-axis. The foil is included in a rotational circular subdomain of radius equal to c (figure 2); thus, an open circular boundary separates the rotational subdomain from the remaining non-rotational subdomain. In figure 2, the foil pitch angle (or incidence angle) is set equal to $\alpha = 0^\circ$.

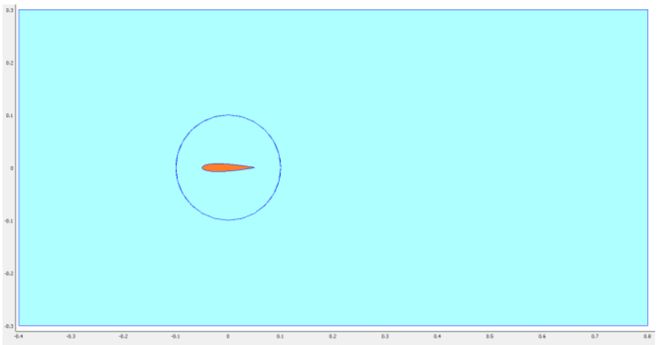

Fig. 1. Rectangular 2D computational domain: the circular rotational subdomain containing the NACA foil is surrounded by a non-rotational subdomain

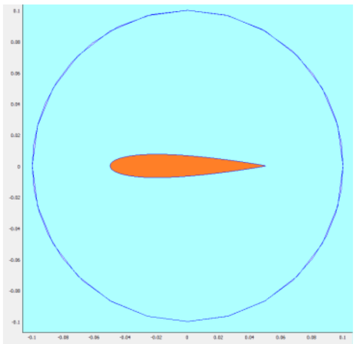

Fig. 2. Rotational subdomain containing the NACA 0015 foil at zero value pitch angle

In this paper, the following sign-rule applies for the pitch angles values: the minus sign is attached to pitch angle values starting from 0° in clockwise direction, while the plus sign is attached to angles measured from 0° in counter clockwise direction. The one-way clockwise pitch motion of the foil was studied for a pitch amplitude of 50°, starting from 2 different initial pitch angles, namely:

- starting from $\alpha = 0^\circ$, down to the maximum pitch angle value of $\alpha = -50^\circ$ (referred further as simulation ①, and containing 2 runs, one for a normal mesh and another for a fine mesh);
- starting from $\alpha = 25^\circ$, down to $\alpha = -25^\circ$ (referred further as simulation ②, and containing 4 runs, each one corresponding to a different mesh size, gradually selected from coarse to very fine mesh, e.g. coarse/ normal/ fine/ very fine mesh).

As stated before, we performed a grid dependency test using different mesh sizes, to depict the trusted values of the lift and drag forces acting on the foil. For the simulation ①, the fine mesh has the following statistics: 115380 triangular elements, 999729 degrees of freedom, 0.6126 minimum element quality and $3.22 \cdot 10^{-7}$ element area ratio, while the normal mesh has 28845 triangular elements (254682 degrees of freedom). We present in figure 3 the fine mesh around the foil at $\alpha = 0^{\circ}$.

For the simulation ②, the coarse mesh contains 7061 triangular elements (62327 degrees of freedom), the normal mesh has 28244 triangular elements (244691 degrees of freedom), the fine mesh has 112976 triangular elements (969530 degrees of freedom), while the very fine mesh has 451904 triangular elements, 3859652 degrees of freedom, 0.5773 minimum element quality and $2.27 \cdot 10^{-6}$ element area ratio. We present in figure 4 the computational mesh, namely a zoom within the rotational subdomain, around the foil at $\alpha = 25^{\circ}$, for the extreme cases: the coarse mesh and the very fine mesh.

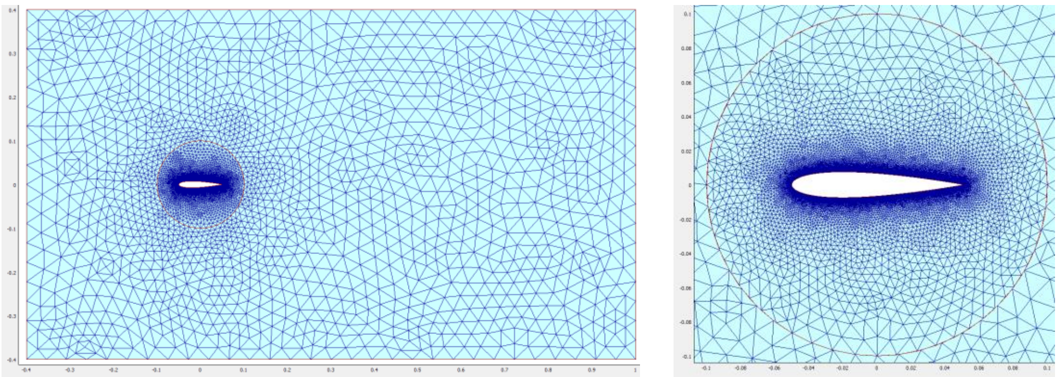

Fig. 3. Computational mesh for the simulation ①: the whole 2D domain (left frame), and zoom of the rotational subdomain (right frame) – both frames correspond to the fine mesh case

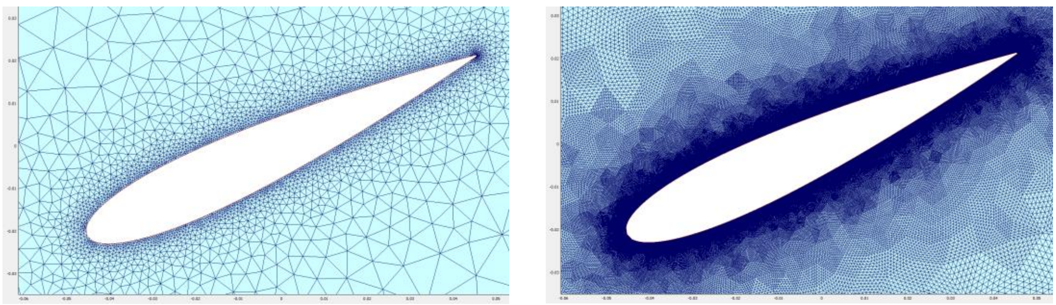

Fig. 4. Zoom around the foil for the simulation ②: coarse mesh (left), and very fine mesh (right)

The one-way clockwise pitch motion of the foil was set with a rotational speed $n = 0.1388$ rot/s, for which the foil rotates with an amplitude of 50 degrees in one second. The moving mesh cells were set with a prescribed displacement, defined upon the time t with variable $\mathrm{d}x$ and $\mathrm{d}y$ space steps as:

$$\begin{cases} \mathrm{d}x = x\cos(-2\pi\, n\, t) - y\sin(-2\pi\, n\, t) - x \\ \mathrm{d}y = x\sin(-2\pi\, n\, t) + y\cos(-2\pi\, n\, t) - y \end{cases}. \qquad (1)$$

Each run was firstly launched for a stationary flow analysis, with no displacement of the moving mesh; then, after obtaining a stationary initial solution around the foil at its initial pitch angle, the transient analysis (unsteady flow) was launched, with prescribed displacement of the moving mesh, as in equations (1).

For each run, the lift force $F_L(t)$ and drag force $F_D(t)$ acting on the foil were depicted as function of time t, using the post-processing boundary integration mode from COMSOL Multiphysics.

3. Numerical results

We present in figure 5 the velocity field for the simulation ① and the normal mesh case, at the pitch angle $\alpha = -12.5^\circ$.

For the simulation ②, the total running time was equal to: 148 seconds for the coarse mesh case, 8.87 minutes for the normal mesh, 36.7 min for the next more dense mesh (fine mesh), and 168 min (2.8 hours) for the very fine mesh case, on a workstation with 2.66 GHz quad-core processor and 16 GB of RAM memory. So it is worth checking the reliability of the results upon the mesh size.

We plotted in figure 6 the variation of the absolute errors $\varepsilon_{aL}(\alpha)$ and $\varepsilon_{aD}(\alpha)$, in N/m, on the lift force and on the drag force, acting on the foil during the simulation ①, computed as the difference between the fine mesh and the normal mesh corresponding data. The absolute error differs with a maximum of 0.11 N/m in lift force and 0.35 N/m in drag force (that force is negative), the normal mesh giving generally an underestimation of both forces (only for pitch angles from $\alpha = 0^\circ$ to $\alpha = -7.5^\circ$, the normal mesh gives an overestimation of the lift force, as one can see from figure 6).

For the simulation ②, we plotted in figure 7 the variation of $\varepsilon_{aL}(\alpha)$ and $\varepsilon_{aD}(\alpha)$, also as difference between the fine mesh and normal mesh data. The computed $\varepsilon_{aD}(\alpha)$ values vary from 0.32 N/m to 0.35 N/m, while $\varepsilon_{aL}(\alpha)$ is positive for $\alpha \le -7.5^\circ$ and $\alpha \ge 7.8^\circ$ (with a maximum value of 0.1 N/m), while it is negative for $-7.5^\circ < \alpha < 7.8^\circ$ (with a minimum value of -0.05 N/m).

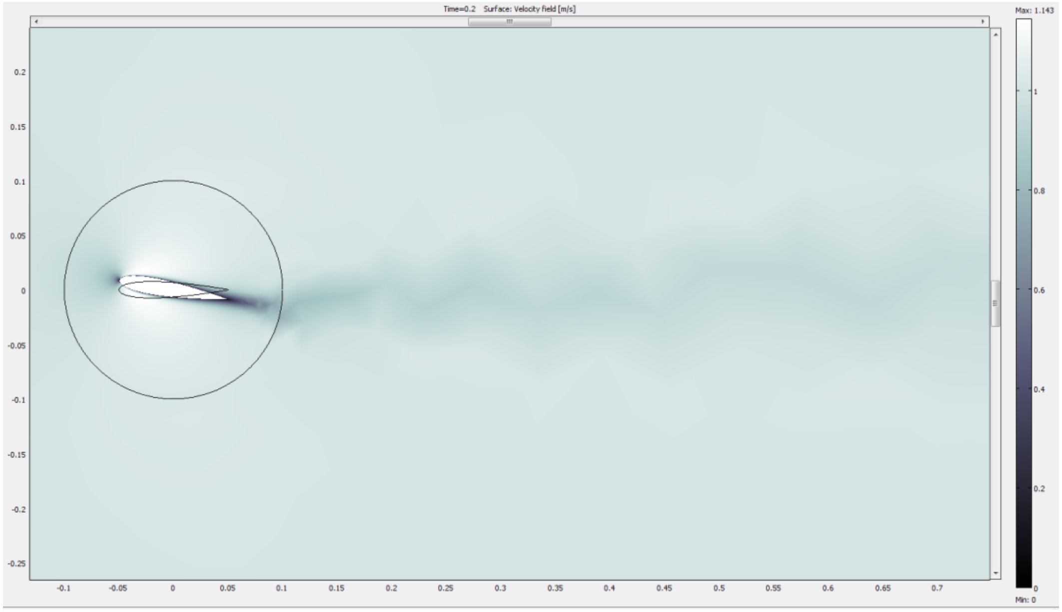

Fig. 5. Velocity field for the simulation ①: $\alpha = -12.5^{\circ}$, normal mesh case

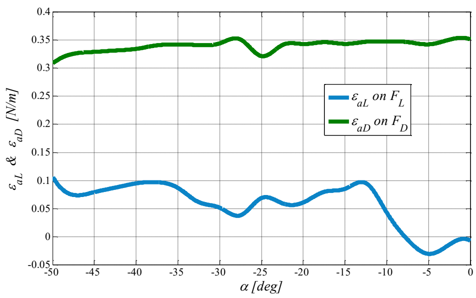

Fig. 6. Variation of $\varepsilon_{aL}(\alpha)$ and $\varepsilon_{aD}(\alpha)$, in N/m, as difference between the lift forces and drag forces obtained with the fine mesh and normal mesh, for the simulation ①

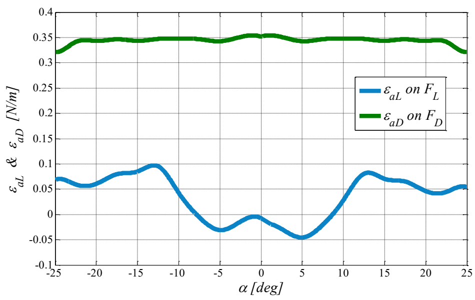

Fig. 7. Variation of $\varepsilon_{aL}(\alpha)$ and $\varepsilon_{aD}(\alpha)$, in N/m, as difference between the lift forces and drag forces obtained with the fine mesh and normal mesh, for the simulation ②

4. Conclusions

We performed 2D computations using COMSOL Multiphysics, to study the one-way pitch motion of a vertical NACA 0015 foil, with pitch amplitude of 50 degrees. The lift and drag forces acting on the foil proved to be sensitive to the mesh size. Taking into account the computed results and the running time, we recommend to set a fine mesh with about 115000 triangular elements, which ensures trusted variation of the lift and drag forces.

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