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Comparison of computational approaches for the efficient analysis of airfoil dynamics

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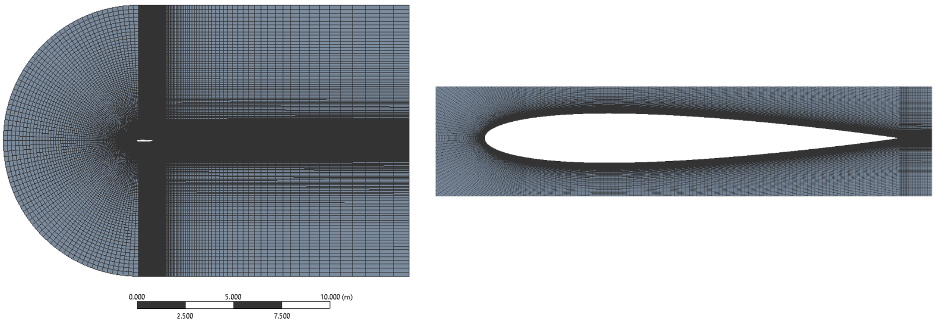
The analysis of the interaction of the flowing fluid with the enveloped body became of great importance, since it can induce structural instability. The most typical example of this type of instability is the so-called flutter representing a self-excited oscillation of the structure due to fluid flow, which in the extreme case can lead to the structural destruction. The problem is very complex and even with the current computational power it cannot be solved efficiently using the commonly available computational tools. From this point of view, there is still a motivation to find an efficient tool that would allow real-time optimization of structures with respect to flutter safety. This paper deals with the first step of the methodology and aims to compare different approaches to investigate the effect of forces acting on the stationary airfoil geometry and also the airfoil vibration response to flow field excitation.

The first performed analysis is a comparison of the force effects acting on a stationary and a fully rigid airfoil geometry in 2D. The main analysis tools chosen were the panel method represented by the XFoil software [2] and the complex CFD analysis implemented in the ANSYS Fluent software. The XFoil combines a potential flow panel method and an integral boundary layer formulation for the analysis of the flow around thin airfoils. The code is suitable for low Reynolds numbers and its convergence is reached through the iteration between the inner and outer flow solutions on the boundary layer displacement thickness. The CFD analysis was carried out using ANSYS Fluent software for comparison, which is based on solving the



Measured quantity	Value	Measured quantity	Value
Elements	96400	Orthogonal quality (avg)	0.99531
Skewness (avg)	0.03313	y^+ (max)	7.17

Fig. 1. Illustration of the computational domain, including mesh detail in the encircled airfoil and an overview of the basic mesh quality indicators

nonlinear Reynolds-averaged Navier-Stokes equation (RANS) system using the Finite Volume Method (FVM). In the case of this analysis, the pressure-based solver was chosen. Two types of turbulent models were chosen to define the viscous behavior of the flow field, namely the two-equation Shear-Stress Transport (SST) $k-\omega$ and the one-equation Spalart-Allmaras (SA).

The analysis of force effects was performed for two types of airfoils, specifically for symmetric NACA0012 (see Fig. 1) and non-symmetric NACA4412 (see for example [5]), different values of Reynolds number in the range $\mathrm{Re} \in \langle 5\times 10^5, 6\times 10^6\rangle$ and different values of angle of attack ($\theta \in \langle -15^\circ, 15^\circ\rangle$). In all cases, the flow medium was atmospheric air with density $\rho = 1.225\,\mathrm{kg.m^{-3}}$ and dynamic viscosity $\mu = 1.789\times 10^{-5}\,\mathrm{Pa.s}$. The air flow was modeled as incompressible and the airfoil was then modeled as a fixed solid. In particular, the lift force L and drag force D were analyzed and converted into the dimensionless form of force coefficients C_L and C_D based on the following relations for comparison with experimental data $C_L = \frac{L}{qcs}$, $C_D = \frac{D}{qcs}$, $q = \frac{1}{2}\rho U_\infty^2$, where U_∞ is the flow speed, c is the airfoil length and s is the considered wingspan, and for both these quantities in all tested cases $c = s = 1\,\mathrm{m}$ is assumed. The dependence between Re and U_∞ is then described by the expression $\mathrm{Re} = \frac{\rho U_\infty c}{\mu}$.

As can be seen from the results summarized in Fig. 2 (for NACA0012, Re $= 5\times 10^5$), all analyzed approaches achieve good agreement with the experimental data, especially on the interval $\theta \in \langle -10^\circ, 10^\circ\rangle$. Outside this interval, the turbulent character of the flow becomes more evident and the accuracy of the numerical approaches decreases slightly. However, the difference between experiments also increases.

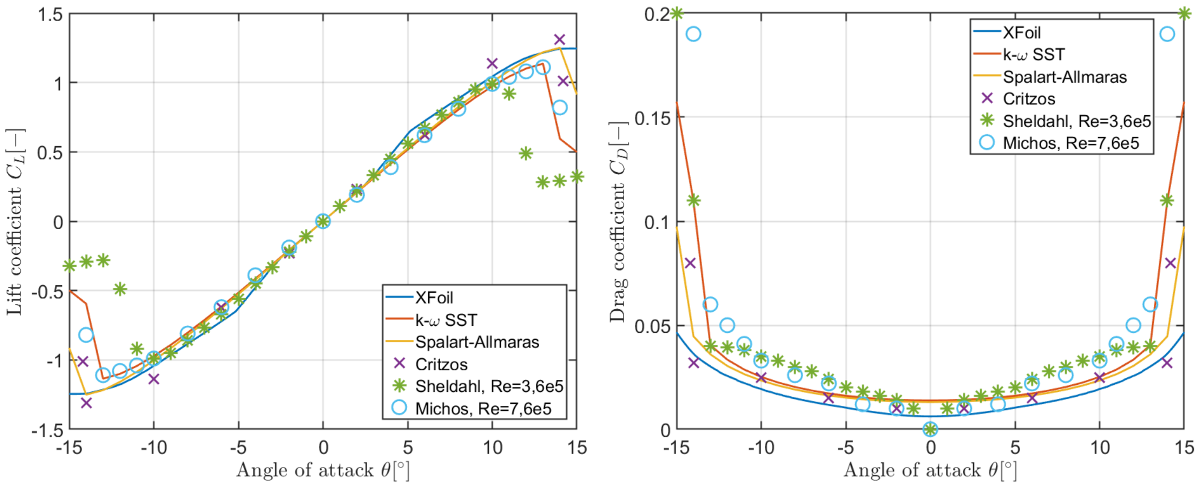


Fig. 2. Comparison of the aerodynamic force effects on a stationary airfoil for test mode No. 2 (i.e. NACA0012, Re $= 5\times 10^5$). The experimental data are taken from the literature [1, 3, 4]

It can be concluded from the presented results that all the analyzed approaches represent a comparably accurate tool for defining the force effects acting on a stationary 2D airfoil in a flow field. In terms of computational complexity (the computation of a single test mode interval at identical sampling 0.1° would be $10\,\mathrm{h}$ for Fluent and $30\,\mathrm{s}$ for XFoil), XFoil proves to be a very efficient tool that can be used to solve a given type of real-time problem with minimal loss of output accuracy.

The second analysis shown in this paper deals with the comparison of the system response in time domain for an elastically suspended rigid airfoil geometry with one or two degrees of freedom wrapped with fluid (Fig. 3). The elasticity of the system is represented by torsional and translational springs, and the system is further considered without direct material damping.

The shear center of the geometry is chosen at a distance of 18.6 % leading edge of the airfoil. The investigated approaches are an analytical method (implemented in MATLAB) based on the calculation of the forces from Quasi-Steady theory (with term $\frac{\mathrm{d}C_L}{\mathrm{d}\theta}$ calculation using XFoil or thin airfoil theory) and a fully non-stationary solution calculated using ANSYS Fluent software. The defined initial condition are the initial pitch angle (identical to the initial AoA) θ_0, the heave h_0 or the initial velocities $\dot{\theta}_0$ and $\dot{h}_0$. In terms of outputs, the force effects over time and the kinematic quantities of the position and velocity of the mass center of the profile are mainly investigated.

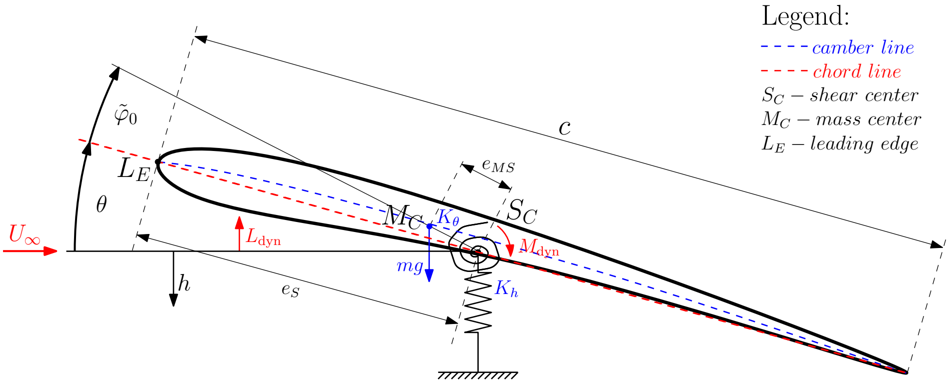


Fig. 3. Scheme of the analyzed airfoil profile with two DOF including the marked force effects acting on the system

In case of the analytical approach with force effects based on Quasi-Steady theory, the solution of the ODE system was based on the explicit Runge-Kutta formulation with the Dormand-Prince pair. Concerning the solution in ANSYS Fluent, the used mesh, solver settings and turbulent models were identical to the first analysis comparing force effects on a fixed body. Regarding the newly chosen parameters, an implicit solver of second-order of accuracy was chosen in terms of time discretization. A sensitivity analysis was carried out to adjust the time step Δt appropriately, which showed that the choice of the time step has a negligible effect on the accuracy of the results when the condition $\Delta t \leq \frac{T}{80}$ is satisfied, where T is the period length of the oscillating motion of the airfoil, thus also satisfying the basic assumption on the sampling frequency given by the Nyquist-Shannon sampling theorem. For larger values of the time step Δt, the system exhibited some degree of numerical dissipation. The stop condition for convergence at each time step was again set by the maximum size of the residual in the continuity equation, namely, to a value of 3×10^{-5}, or a maximum number of 150 iterations.

The analysis of the time response of the system was carried out on asymmetric profile NACA0012 with one DOF, with the absence of gravitational acceleration ($g = 0\,\mathrm{m.s^{-2}}$), for the value of Reynolds number Re $= 0.94 \times 10^5$ ($U_\infty = 8.802\,\mathrm{m.s^{-1}}$) and different initial conditions (non-zero θ_0, $\dot{\theta}_0$, h_0 or $\dot{h}_0$). In all cases, the airfoil was modeled as a rigid body with length $c = 0.156\,\mathrm{m}$, and the assumed span was $s = 1\,\mathrm{m}$. The force term C_L was approximated by a polynomial of 5th degree when solved with XFoil software. A total of four regimes were tested. As can be noted from the graphical outputs in Fig. 4, the outputs of all models are similar. The greatest agreement is achieved by the two models computed with Fluent software, and the highest dissipation in all cases tested is achieved by the analytical model combined with XFoil. Bigger differences between the approaches are generally detectable in the case of longitudinal oscillations, but mainly in the amplitude domain, with little effect on the value of the frequency f from the different modelling approaches. In terms of computational efficiency, the calculation of one presented time response in the Fluent software corresponded to approximately 3 h, while

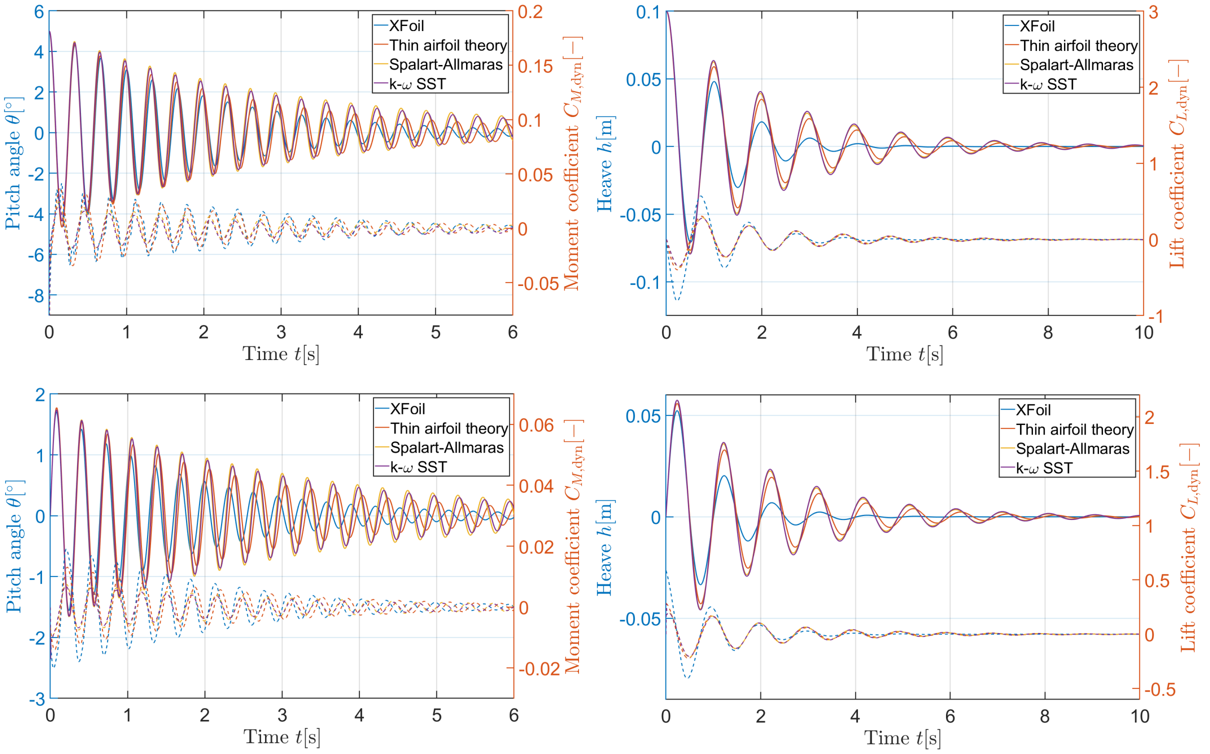


Fig. 4. Comparison of the response of a rigid airfoil with one DOF to IC and flow field excitation. Graphical dependencies of position and force coefficients over time are plotted. The evaluated oscillation frequency corresponds to values $f = 3\,\mathrm{Hz}$ for rotation and $f = 1\,\mathrm{Hz}$ for longitudinal deflection

the analytical calculation took about 10 s.

Two analyses presented in this paper show that despite the currently available computational power in combination with complex numerical software, analytical methods based on semi-empirical assumptions still have their indispensable place in FSI problems. These methods offer a high level of computational efficiency while maintaining sufficient accuracy of the generated outputs, especially at the level of one-sided interaction.

Acknowledgements

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