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Numerical modelling of aeroelastic behaviour of an airfoil in viscous incompressible flow

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ABSTRACT

In this paper, the problem of the numerical approximation of a two-dimensional incompressible viscous fluid flow interacting with a flexible structure is considered. Due to high Reynolds numbers in the range $10^4 - 10^6$ the turbulent character of the flow is considered and modelled with the aid of Reynolds equations coupled with the $k - \omega$ turbulence model. The structure motion is described by a system of ordinary differential equations for three degrees of freedom: vertical displacement, rotation and rotation of the aileron. The problem is discretized in space by the Galerkin Least-Squares stabilized finite element method and the computational domain is treated with the aid of Arbitrary Lagrangian Eulerian method.

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1. Introduction

The interactions of fluid flow and an elastic structure motion are important in a wide range of technical applications in many technical disciplines (e.g. airplane design, civil engineering), cf. [1]. However, in practical applications typically only special problems of linear aeroelasticity or hydroelasticity are solved. The reality is usually much more complicated. The significant role play viscous effects of the flow, changes of the flow domain in time, nonlinear behaviour of the structure, etc. During last years, significant advances have been made in the development of computational methods for fluid–structure interaction problems. In order to properly approximate the mutual interaction between fluid and structure, various strategies are used, cf. [2].

This paper focuses on the mathematical modelling and the numerical approximation of interactions of a simplified problem of the two-dimensional flow and a flexibly supported airfoil section with control section. Aeroelastic behaviour of such a problem was previously studied theoretically by different approaches (see, e.g. [3,4]). The nonlinear aeroelastic behaviour of three degrees of freedom aeroelastic system was treated experimentally in [5], where also the system response was determined numerically by time marching algorithm with the classical linear aerodynamic models for approximation of the aerodynamical forces. The solution of the Euler equations for approximation of aerodynamics and application on aeroelastic analysis for airfoil with flap in transonic regime was studied e.g. in [6]. The numerical solution of the averaged Navier–Stokes equations equipped with the turbulence $k - \epsilon$ model applied on two-dimensional flow around square cylinder was applied, e.g. in [7], where also the two-dimensional aeroelastic stability analysis was performed.

Here, the aeroelastic system consisting of the structure with three degrees of freedom that interacts with a turbulent viscous incompressible flow. The flow is modelled with the aid of Reynolds equations together with the $k - \omega$ turbulence model, cf. [8]. For the approximation of Reynolds equations the stabilized finite element method is used, cf. [9]. Moreover, the computational mesh is adaptively refined in order to allow an accurate resolution of time oscillating thin boundary

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layers, wakes and vortices, cf. [10]. The time-dependent computational domain is taken into account by the Arbitrary Lagrangian–Eulerian method, cf. [11,12].

The results presented in this paper are an extension of author's previous works. The simulations of aeroelastic system with divergence type of instability was studied in [13], where the nonlinear behaviour of the system was observed. Turbulence models were included and applied on different aeroelastic systems in [14,15]. Further, the developed numerical technique was tested on an aeroelastic system of the double circular profile and a channel flow and compared with the experimental measurements, cf. [16].

The main attention in this paper is paid to the inclusion of an additional degree of freedom for the aileron, to the energy conservation in a simplified aeroelastic system and the application of two equations turbulence model approximated by finite element method. The method is applied on a benchmark problem studied previously by Lošík [17,18].

The paper is structured as follows: In Section 2 the mathematical model of a coupled fluid-structure problem is presented. In Section 3 the weak formulation of the considered coupled problem is derived. In Section 4 the numerical approximation by finite element method is described. Section 5 shows numerical results.

2. Mathematical model of a coupled problem

The mathematical model consists of fluid flow description, structure motion equations and the interface conditions, which couple both models. The structure motion described by the equations of motions (system of ordinary differential equations). The flow is governed by Reynolds equations. In order to capture the motion of the computational domains the Arbitrary Lagrangian–Eulerian (ALE) method is employed, cf. [12] or see also [13]. Further, the kinematic and dynamic coupling conditions need to be satisfied.

2.1. Structural model

In this paper a simplified problem is considered. The whole airfoil (A) is assumed to consist of two parts – the front part (B) and the aileron part (F). Following this notation the time-dependent boundary Γ_{Wt} is divided into the aileron boundary Γ_{Ft} and into the front boundary Γ_{Bt}, see Fig. 2. The motion of the structure is described by the system of linear ordinary differential equations (cf. [1]) for vertical displacement $h = h(t)$ (downwards positive), angle of rotation of the airfoil $\alpha = \alpha(t)$ of the whole airfoil around the elastic axis (EA) (clockwise positive), and the angle of rotation of the aileron $\beta = \beta(t)$ around the elastic axis of the aileron (EF) (clockwise positive), see Fig. 1. The equations of motion for small displacements read (see e.g. [1])

$$\begin{pmatrix} m & S_\alpha & S_\beta \\ S_\alpha & I_\alpha & \widetilde{\Delta} S_\beta + I_\beta \\ S_\beta & \widetilde{\Delta} S_\beta + I_\beta & I_\beta \end{pmatrix} \begin{pmatrix} \ddot{h} \\ \ddot{\alpha} \\ \ddot{\beta} \end{pmatrix} + \mathbb{K} \begin{pmatrix} h \\ \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} -L \\ M \\ M_\beta \end{pmatrix}, \tag{1}$$

where $\mathbb{K} = \mathrm{diag}(k_h, k_\alpha, k_\beta)$, m is the mass of the airfoil, S_α is the static moment of the airfoil around the elastic axis EA, I_α is the inertia moment of the airfoil around EA, S_β is the static moment of the aileron around the elastic axis of the control section EF, I_β is the inertia moment of the aileron around EF, T is the center of gravity, $\widetilde{\Delta}$ is the distance of EF from EA, see Fig. 1. Further, L, M, M_β are the aerodynamical lift force, moment and moment of the flap section, respectively.

2.2. ALE method

For the application of ALE method the ALE mapping $\mathcal{A}_t$ of the reference configuration $\Omega_{\mathrm{ref}} = \Omega_0$ onto the current configuration Ω_t is used. We assume that the ALE mapping is defined for all $t \in [0, T]$ and $\xi \in \Omega_0$, has continuous first order deriv-

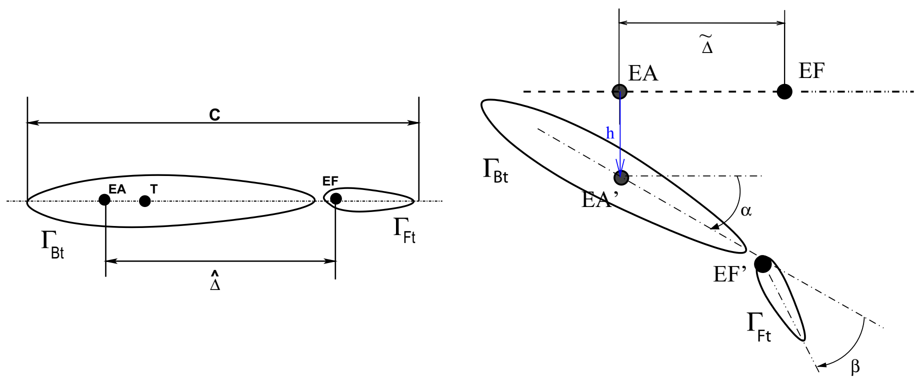

Fig. 1. The airfoil with aileron in underformed (left) and deformed position (right).

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