Mathematical modeling of turbulent flow in vicinity of a prism installed on a plate taking into account aeroelastic effects

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Abstract. The paper presents the results of numerical modeling of oscillations of an elastic rod of rectangular cross section set normal to external flow and fixed rigidly to a plate. The simulations are performed in ANSYS using the 2-way FSI technology [1, 2]. The modal, hydrodynamic and coupled calculations have been performed. The excitation of aeroelastic vortex induced rod vibrations is simulated. The influence of the turbulence model choice is demonstrated on the vortex shedding frequency that can significantly affect the vibration excitation process.

1. Introduction

To prevent undesired vibrations of elastic structures which can lead to their destruction, the interaction of structures with external air flow should be considered. Physical processes in which the air flow has an impact on the behavior of deformable objects (Fluid Structure Interaction, FSI) are a key element in many engineering problems of aviation and civil engineering. The aeroelasticity phenomenon should be considered when creating modern aircrafts and designing high-rise buildings and long-span structures.

Turbulence plays an important role in many industrial applications. The choice of the turbulence model significantly affects the accuracy of the prediction of aerodynamic and thermo-physical processes. It is known that the widely used Reynolds Averaged Navier Stokes (RANS) approach gives good results when solving engineering problems. However, it does not allow obtaining the real spectrum of turbulent pulsations, especially in areas of flow separation behind bluff bodies. This can lead to significant inaccuracies when solving problems dealing with heat transfer, aeroelasticity, impurity propagation, etc. At the same time, the application of the Large Eddy Simulation (LES) approach requires enormous computational resources, so more economical LES-like Scale Adaptive Simulation (SAS) and Detached Eddy Simulation (DES) models have recently been developed [3, 4]. The SAS method is an improved form of URANS allowing adapting the length scale to resolve turbulent structures.

In previous papers [5, 6], coupled calculations were performed to simulate an aeroelastic oscillation of a square rod fixed on the substrate at various incoming velocities and rod heights. The structure was
analyzed and the features of the vortex air flow in the neighborhood of the model were described. The rod stress-strain state was determined, the natural frequencies and rod vibration modes were obtained. It was shown that under the influence of an external flow, a rod first oscillates in the flow direction with the first rod natural frequency. The amplitude of the oscillations decays rapidly. Later, under the action of the periodic load due to the action of Karman vortex forming behind the rod, oscillations develop in the transverse direction. The goal of the present paper are to simulate the similar problem for the rod of the rectangular section using standard RANS and the LES-like scale adaptive turbulence models.

2. Problem setup and calculation methods
In this paper, we investigate numerically the 3D problem of an aeroelastic oscillation of a rod of \( h = 0.28 \) m height and rectangular section \((0.06 \times 0.03 \) m) under the influence of an external air flow. Problem geometry (Figure 1) presents a channel of \( 12h \times 5h \times 10h \) size, inside which the rod is rigidly fixed on the plate. The arrow shows the direction of incoming flow. In Figure 1, b, behind the model, a point (1) is shown in which the \( z \)-velocity is recorded in the transient calculation.

The air flow is described on the basis of 3D unsteady Reynolds-Averaged Navier-Stokes equations, supplemented by \( k - \omega \) SST and SAS turbulence models. The calculations are performed for air density \( \rho = 1.225 \) kg/m\(^3\) and viscosity \( \mu = 1.8 \times 10^{-5} \) Ns/m\(^2\). At the inlet, air has a velocity of \( U = 5 \) m/s.

The processes in a solid body are described by the transient elasticity equations, the conditions of compatibility of deformations and the Hooke's law. As the prism material, the isotropic material with density \( \rho = 40 \) kg/m\(^3\), elasticity modulus \( E = 12.7 \times 10^6 \) Pa and Poisson's ratio \( \nu = 0.35 \) is used. The no-slip condition is accepted on the walls of the rod and on the plate. On the top and lateral boundaries of the computational region, the symmetry condition is prescribed to ensure the absence of flow through these boundaries.

To link the hydrodynamic and structural calculations, the iterative coupling algorithm is used. At each time step, the hydrodynamic and structural equations are solved separately. Then data exchanged through the interface between air and the rod. When solving the hydrodynamic problem, the kinematic boundary condition is set on the rod walls to ensure coincidence of the velocities of the external flow and the moving wall. The movement of the boundary is defined by the displacements of the prism transferred from the structural solver. For structural equations, the pressure distribution obtained in the hydrodynamic calculation is set on the rod wall.

3. Computation results
The calculations were carried out in several stages, namely, the CFD, modal and coupled stages described below.

3.1. CFD calculations
First, CFD calculations are performed with the \( k - \omega \) SST and SAS turbulence model. The rod and the plate are assumed to be absolutely rigid. This allows us to get the external flowfield data and to
analyze the vortex shedding process. Figures 2 and 3 show the flow streamlines in vicinity of the rigid prism in time moment \( t = 5 \) sec in \( x-z \) plane (a), \( x-y \) plane (b) and isometric view (c). Analysis of the structure of the air flow shows the presence of the flow separation zones SZ1, SZ2 and SZ3, the line of flow spreading (R), the formation of Karman vortices and other flow features similar to those described in details in [7].

The instant flow pattern (Figure 3) obtained in the calculations with the SAS turbulence model is more complicated than that with the \( k - \omega \) SST turbulence model (Figure 2). In the SAS computations, the vortex wake behind the model is much wider than that obtained with the \( k - \omega \) SST model. It can be seen that in the near zone behind the rod, the vortices of various scales are generated.

During the calculation, the \( z \)-velocity is recorded at the monitor point (1) (Figure 1, b). Figure 4 presents the Fourier analysis of the data taken at the monitor point during the transient computations with the \( k - \omega \) SST (a) and SAS (b) turbulence models. The presence of eddies of different scales can be seen at the FFT plot for SAS model. The main frequency is higher and the power spectrum density is ten times more than those obtained with the \( k - \omega \) SST model.

Thus, it has been shown that an unsteady flow picture is formed in the prism vicinity, which can lead to the excitation of the rod vibration. The vortex shedding frequency essentially depends on the turbulence model choice.

![Flow streamlines in vicinity of the prism in x-z plane (a), x-y plane (b) and isometric view (c) at t=5 s obtained with k - \omega SST turbulence model.](image)

3.2. Modal analysis

At the second stage, a modal calculation is performed in the ANSYS Modal Static Structural program. As a result, the natural frequencies (Table) and the rod modes (Figure 5) are obtained. In Figure 5, the initial rod position is shown by the grey line, and the deformed body is exposed by the filled deformation contours. The first and third oscillation frequencies correspond to the bending shape in the \( z \) direction (Figure 5, a, c), the second and the fifth are the \( x \)-direction bending shapes (Figure 5, b, e), the fourth frequency corresponds to the torsional shape (Figure 5, d), and the sixth is the tensile shape (Figure 5, f).
3.3. Coupled calculation
At the third stage, a coupled calculation is performed using the 2FSI technology with the $k - \omega$ SST turbulence model. The flow streamlines are obtained in the calculations which are similar to those in the CFD calculations, although the maximum velocity amplitude is slightly lower.
Figure 6 shows the behavior of the maximum longitudinal (a) and transverse (b) displacements of the prism versus time. The picture shows that first \((t < 1 \text{ sec})\) the prism performs the longitudinal vibrations in \(x\)-direction, the amplitude of which decays rapidly (Figure 6, a). Maximum prism displacement \(\Delta u_{x,\text{max}} = 4.75 \times 10^{-4} \text{ m}\) occurs at time moment \(t = 0.006 \text{ sec}\), the frequency is \(f_x = 69 \text{ Hz}\) that is close to the second rod natural frequency which is the \(x\)-bending mode.

Later, the transversal oscillations in \(z\)-direction are observed caused by the Karman vortex shedding (Figure 6, b). The maximal transversal prism deflection is \(\Delta u_{z,\text{max}} = 2.68 \times 10^{-4} \text{ m}\), while the vibration amplitude is still increasing in a pseudo-periodic way. Three main frequencies obtained using the FFT plot analysis are as follows: the first is 0.5 Hz, the second is 11.8 Hz that is close to the vortex shedding frequency, and the third is 34.2 Hz that coincides with the rod natural frequency of the \(z\)-bending mode.
4. Conclusions
Basing on the technology of bidirectional coupling (2FSI) implemented in the ANSYS system (Fluent + Mechanical + System Coupling), the 3D calculation of the elastic rod oscillation problem is performed with $k - \omega$ SST turbulence model.

It’s shown that first the rod performs the longitudinal oscillations which rapidly decaying amplitude. The oscillation frequency coincides with the natural frequency that corresponds to the $x$-bending natural mode. Further, the transverse vortex induced rod oscillations are generated with a frequency equal to that of the vortex shedding.

The results of a CFD calculation using the SAS turbulence model are presented that gives the vortex structure behind the rod different from that obtained with the $k - \omega$ SST model. The main differences are the presence of vortices of various scales and the higher power spectrum density of the velocity pulsation. It can be expected that the process of excitation of pulsations will develop differently. Further, a two-way FSI calculation will be performed for the same model using the SAS turbulence model.

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