SIMULATION OF AERODYNAMIC INSTABILITY OF BUILDING STRUCTURES ON THE EXAMPLE OF A BRIDGE SECTION. PART 2: SOLUTION OF THE PROBLEM IN A COUPLED AEROELASTIC FORMULATION AND COMPARISON WITH ENGINEERING ESTIMATES

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Abstract: In this paper, we study aerodynamic instability using the example of a two-dimensional problem of flow around a simplified section of a flexible suspension bridge (on the Tacoma River, USA). A direct dynamic coupled calculation was performed to determine the critical speed of manifestation of aerodynamic instability. The results obtained were compared with the results of engineering estimates presented in [40]. This example shows that to solve such problems it is possible to use the lighter des turbulence model instead of the les turbulence model and, therefore, a coarser mesh. In contrast to existing engineering techniques, direct numerical modeling of the interaction between the structure and the air flow allows one to take into account the reverse effect of the structure on the flow, as well as the mutual influence of several types of aerodynamic instability.

Keywords: aerodynamic instability, galloping, divergence, FSI, URANS SST turbulence model, DES SST turbulence model

МОДЕЛИРОВАНИЕ АЭРОДИНАМИЧЕСКОЙ НЕУСТОЙЧИВОСТИ СТРОИТЕЛЬНЫХ КОНСТРУКЦИЙ НА ПРИМЕРЕ СЕЧЕНИЯ МОСТА. ЧАСТЬ 2: РЕШЕНИЕ ЗАДАЧИ В СВЯЗАННОЙ АЭРОУПРУГОЙ ПОСТАНОВКЕ И СОПОСТАВЛЕНИЕ С ИНЖЕНЕРНЫМИ ОЦЕНКАМИ

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Аннотация: В настоящей работе исследуется аэродинамическая неустойчивость на примере двумерной задачи обтекания упрощенного сечения гибкого подвесного моста (на реке Такома, США). Выполнен прямой динамический связанный расчет для определения критической скорости проявления аэродинамической неустойчивости. Полученные результаты сравнивались с результатами инженерных оценок, представленных в [40]. На данном примере показано, что для решения подобных задач можно использовать более «легкую» модель турбулентности DES вместо модели турбулентности LES и, следовательно, более грубую сетку. В отличие от существующих инже-

Simulation of Aerodynamic Instability of Building Structures on the Example of a Bridge Section. Part 2: Solution of the Problem in a Coupled Aeroelastic Formulation and Comparison with Engineering Estimates

нерных методик, прямое численное моделирование взаимодействия конструкции и воздушного потока позволяет учесть обратное влияние конструкции на поток, а также взаимное влияние нескольких видов аэродинамической неустойчивости.

Ключевые слова: аэродинамическая неустойчивость, галопирование, дивергенция, FSI, модель турбулентности URANS SST, модель турбулентности DES SST

1. INTRODUCTION

Long span and flexible structures such as bridges with long spans are highly sensitive to wind influences. Such structures are susceptible to aeroelastic phenomena. Over the past 150 years, many such cases have been known and described. Until the 1940s, the wind load was considered secondary and even its static component was not taken into account. This continued until the most famous destruction of the Tacoma Narrows Bridge in the United States. Almost from the very beginning of construction work, problems with the stability of the bridge began to appear, even in light winds. The bridge immediately gained a reputation as an unstable structure. Due to the fact that the windy weather of the bridge swayed, he was given the nickname "Galloping Gertie". Numerous attempts were made to stabilize the structure, but they could not solve this problem – on November 7, 1940, a collapse occurred as a result of the increasing vibrations of the bridge deck in the air stream. This disaster marked the beginning of an intensive and purposeful study of the interaction of flexible structures with wind flow. The first fundamental scientific works on this topic appeared, namely the works of Theodor von Karman [1], Alan Garnett Davenport [2–3], Barshtein M.F. [4], Simiu [5], Scanlan [5–8], Den Hartog [9]. Based on these studies, engineering methods for assessing the occurrence of aerodynamic instability were developed and introduced into regulatory documents [10–12].

In a number of cases, the issues of wind flow around unique buildings and structures during their design are solved experimentally. For this, the testing of models in laboratory conditions is widely used, as a rule, in wind tunnels (WT).

Experimental studies of the assessment of the aerodynamic characteristics of structures were carried out by such scientists as M.I. Kazakevich [11], S.M. Gorlin [12], Alan Davenport [2, 15], A. Kareem [16], B. Blocken [17] and others. The experimental approach, which was practically uncontested 20–30 years ago, has a number of serious drawbacks. A correct analysis of the mutual influence of the air flow and the structure is practically impossible in an experiment in a wind tunnel due to the difficulty of observing the similarity of a scale model of a deformable structure. Almost all modern experimental studies are based on the assumption that the structure behaves as an absolutely rigid body, and fluctuations in the flow and damping are imitated by "springs". In this case, the reverse effect of the deformed structure on the structure of the air flow has been repeatedly confirmed. Failure to take into account the reverse effect can lead to both an overestimation of the critical wind speeds (at best), and their underestimation (in the worst case). Due to the rapid development of mathematical modeling, numerical methods and implementing software systems against the background of an impressive growth in computing power, another approach has been actively developing in recent years – mathematical (numerical) modeling, free from the limitations of physical (experimental) modeling methods. Today it is possible to carry out a direct numerical solution of related problems of aero-hydroelasticity and directly simulate the phenomena of aerodynamic instability without resorting to numerous serious assumptions adopted in experimental methods. As a result, more accurate assessments of the criteria for the occurrence of aerodynamic instability of unique and especially critical flexible structures are

obtained and, as a consequence, their mechanical safety is increased. Among the works devoted to the numerical modeling of the phenomena of aeroelasticity, one can single out [18–38]. Despite the advantages of direct numerical modeling, it also has disadvantages. The main one is high computational complexity. Although, along with the further progress of algorithms and computer technology, this drawback will be more and more overcome, now it seems relevant to develop a universal and more economical approach to assessing the aerodynamic stability of structures. The purpose of this study is to develop a universal approach to assessing the aerodynamic instability of bridge structures in an unsteady wind flow using a preliminary engineering estimate and subsequent direct mathematical (numerical) modeling of the structure's behavior in a coupled aeroelastic formulation.

is considered. This problem was presented by a team of scientists from China at an international conference (The Seventh International Colloquium on Bluff Body Aerodynamics and Applications (BBAA7) Shanghai, China; September 2-6, 2012). They presented their results in [39], which describes their method for solving the problem using the ANSYS Fluent software package in a related setting with the author's software package. The geometric parameters of the section are shown in Fig. 1. When modeling the dynamic behavior of the elastic section, the scheme shown in Fig. 2. The parameters of the material are presented in Table 1. The parameters of elastic connections with linear damping are taken from [39] and are also displayed in the table. In the Ox direction, the geometric center of the section is fixed. A torsional elastic link was applied to the entire cross section on average.

2. FORMULATION OF THE PROBLEM

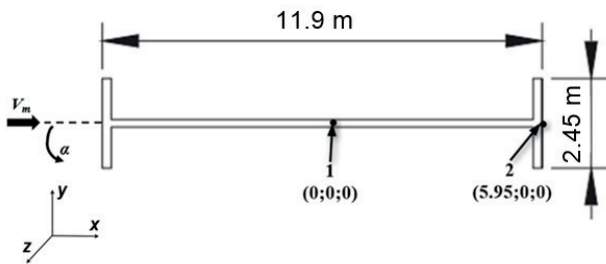The problem of interaction of a simplified section of a bridge on the Tacoma River with an air flow

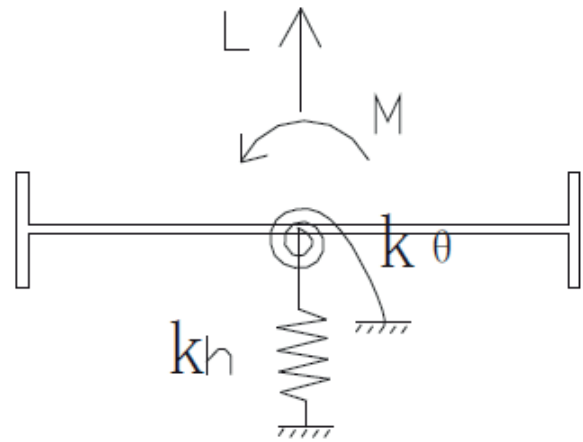*Figure 1. Geometric parameters of the section.*

Figure 2. Design model.

Table 1. Material parameters

Material parameters		Parameters of the elastic model of the bridge section	
Density ρ, kg / m³	1300	Linear weight, kg / m	4250
		Moment of inertia, kgm / m	177 730
Elastic modulus E, Pa	$2.1 \cdot 10^{11}$	Vertical relative damping	0.005
Poisson's ratio v	0.16	Relative damping by torsional degree of freedom	0.005

Air with constant properties at a temperature of 25ºC is considered.

In the course of solving the problem in a related formulation, the following parameters were determined:

• vertical displacements $y_1(t)$ of point 1 and $y_2(t)$ of point 2 (Fig. 1), the position of which changes over time due to wind action on the structure;

• angle of rotation $\theta(t)$, which is calculated as follows:

$$\theta = \arcsin\left(\frac{\Delta y}{L/2}\right) \qquad (1)$$

where $\Delta y = y_2 - y_1$ is vertical displacements of point 1 and point 2, respectively.

In order to solve the problem, the ANSYS software package was used. To simulate the fluid – structure interaction (FSI), the "2-way FSI" simulation mode was used – two-way transfer of calculated data between various independent modules in the form of displacements (on the one hand) and loads (on the other side).

3. NUMERICAL SIMULATION METHODOLOGY

3.1. Numerical CFD Setup

The entire computational air domain was divided into finite volumes using the ANSYS Meshing module. Variants of computational grids with
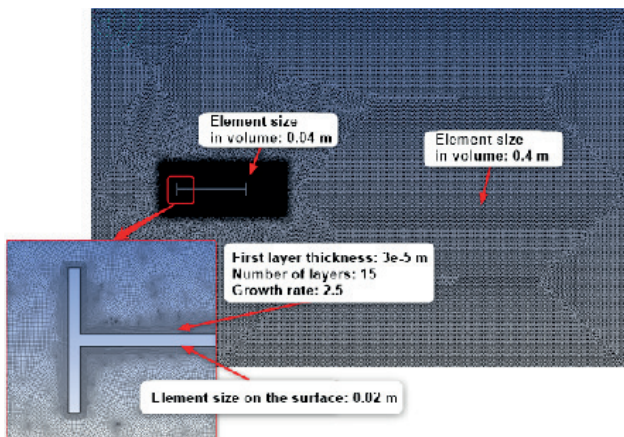

Figure 3. Calculation grid for CFD model: Model 4 (381 894 FE).

indication of the variable parameters were considered in [40]. Model 4 was chosen to simulate the behavior of air (Fig. 3).

The INLET condition ($U = V_{in}$, $V = W = 0$, where U, V, W are the components of the velocity vector, V_{in} is a given constant flow velocity) with a horizontal directional flow velocity uniformly distributed along the height is specified as a boundary condition at the input. On the face opposite from the entrance, "soft" boundary conditions "Opening" were set with the averaged relative pressure equal to zero. On the surface of the streamlined body, the "liquid-structure" interface condition was applied. Symmetry conditions were set on the other faces of the computational domain. Zero flow rate was taken as the initial conditions for the problem.

Since the flow is turbulent at typical Reynolds numbers of $\sim 10^6$ for this problem, the turbulence model must be used to close the Navier-Stokes equations. In this paper, two turbulence models are considered: URANS k-ω SST and DES SST.

3.2. Numerical CSD Setup

For the Computational Structural Dynamics model (CSD model), a structured finite element model of a bridge section with an element size of 0.05 m was created (Fig. 4).

Figure 4. Computational grid for CSD model: Model 4 (10 913 nodes).

In order to simulate the plane problem, both sides of the section are fixed along the O_z axis, which coincides with the axis of the bridge. The movements of the center point are limited along the O_x axis directed along the wind flow (there are no oscillations in the direction of the flow). The elastic vertical link was modeled by a single spring with damping, one end of which is fixed at the central

point of the section, and the other is motionless (see the parameters of the vertical link in Table 1). The elastic torsional bond is modeled through the so-called Remote Displacement mechanism, when the angle of rotation of the entire section is calculated as the average value of the angles of rotation of all mesh nodes, and, accordingly, this angle and its rate of change cause elastic and viscous components of the reactions, respectively (see the parameters of the torsional bond in Table 1).

3.3. Coupling conditions

The time step size for CFD and CSD solvers is $\Delta t = 0.02$ s. The physical calculation time is 80 s. To ensure the convergence and stability of the solution at each associated time step, it is necessary to set the following calculation parameters:
– the maximum number of iterations at each associated step (maximum number of stagger iterations);
– criterion of convergence for loads and displacements;
Is the under relaxation factor for calculating loads and displacements at each iteration of the associated step:

$$\varphi = \varphi_{pre} + \alpha(\varphi_{new} + \varphi_{pre}) \qquad (2)$$

where φ_{new} is the value of the variable calculated at the current iteration, φ_{pre} is the value of the variable calculated at the previous iteration, α is the relaxation coefficient (by default it is 0.75), φ is the corrected value of the desired value at the current iteration.
In this study, the loads were assigned a constant coefficient of lower relaxation $\alpha = 0.5$, while displacements were transferred without lower relaxation. To achieve the convergence criterion, 5 FSI sub-iterations were assigned (the maximum number of iterations at each related step) and the convergence criterion for loads and displacements was set equal to 10-3.

4. RESULTS

4.1. Results of solving the problem taking in account coupling conditions

Below are the results of solving the problem in a coupled aeroelastic formulation. In fig. 5 shows the obtained graphs of the dependences of the
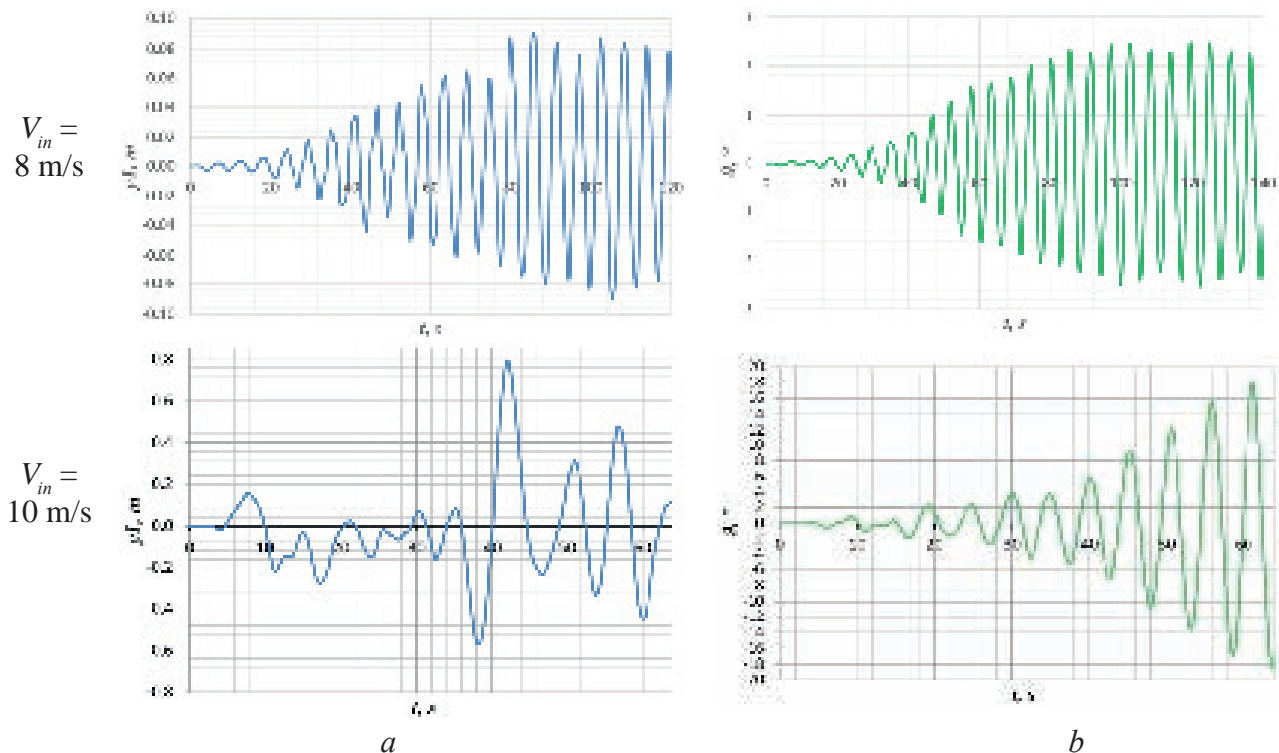

$V_{in} = 8$ m/s

$V_{in} = 10$ m/s

a

b

Figure 5. DES SST model: Graphs versus time t, s at different speeds
a - vertical movement of point 1, m; b - angle of rotation ϑ, °

vertical dynamic displacement of point 1 and the angle of rotation ϑ on time t for flow velocities of 8 m / s and 10 m / s for the DES SST turbulence model. Fig. 6 presents graphs of the dependences of the vertical displacement of point 1 and the angle of rotation ϑ on time t for flow velocities V_{in} equal to 10 m / s, 12 m / s and 15 m / s for the URANS k-ω SST turbulence model. Fig. 7 shows the velocity fields at different times for the DES SST turbulence model at a flow velocity of 10 m / s. Fig. 8 presents velocity fields at different times for the URANS SST turbulence model at a flow velocity of 15 m / s.

Based on the results of calculations in a coupled formulation for different flow rates, the vertical displacement of *point* 1 and the angle of rotation

ϑ from time t were obtained. Loss of stability was determined by an infinitely increasing displacement and / or angle of rotation. Table 2 shows a comparison of the critical velocity values in [39] (experimental and numerical simulation results) and this study.

Comparing the results, it can be noted that the value of the critical velocity for the URANS k-ω SST turbulence model is overestimated, in contrast to the results presented in [39]. This is partly due to the fact that this turbulence model can underestimate the pulsation components of aerodynamic loads, as well as thin out the frequency spectrum, which in turn did not show aerodynamic instability for speeds of 10 m / s and 12 m / s. For the DES SST turbulence model,
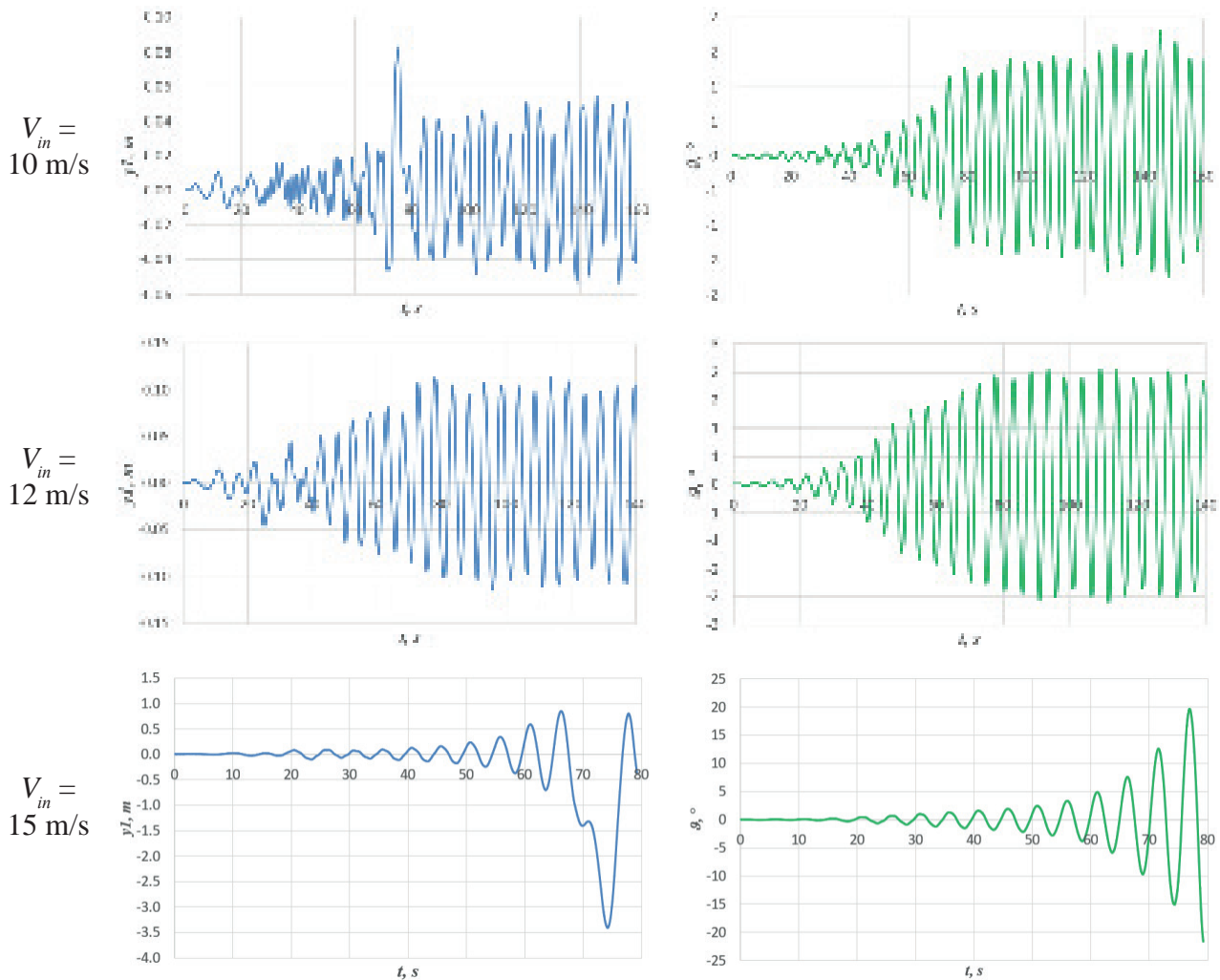

Figure 6. Model URANS k-ω SST: Graphs versus time t, s at different speeds
a – vertical movement of point 1, m; b – angle of rotation ϑ, °

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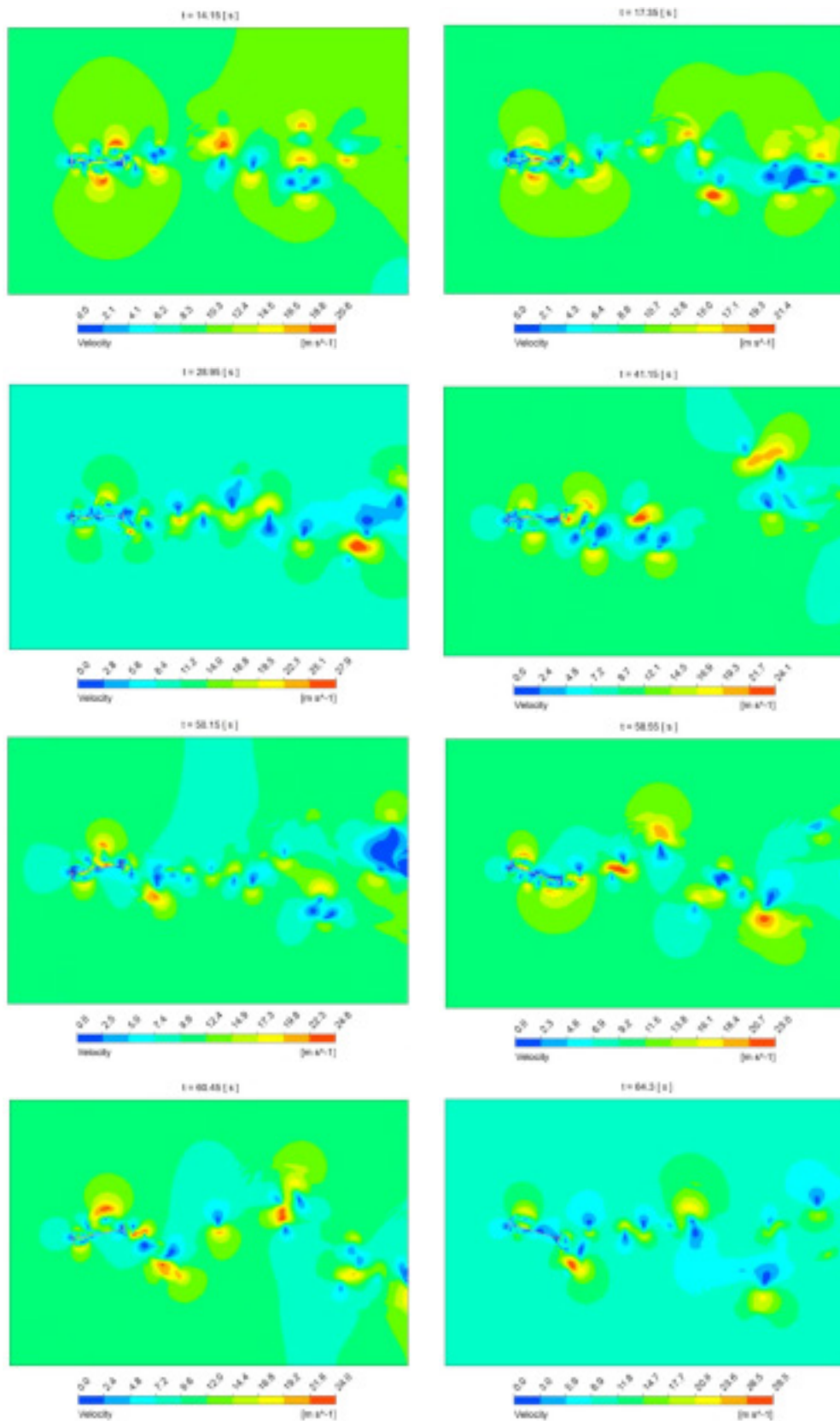

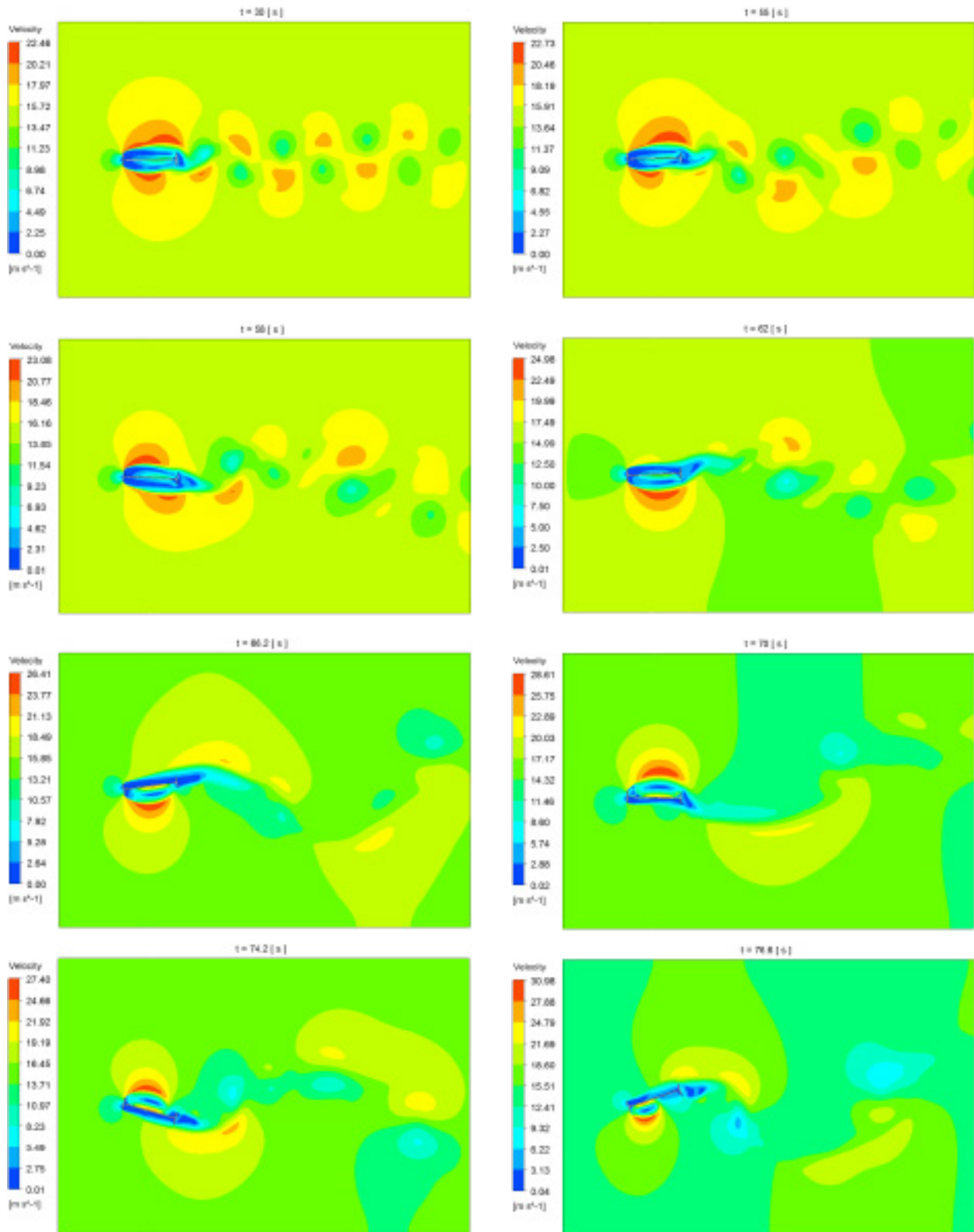*Figure 7. Velocity fields, m / s at different times t, s for a velocity V_{in} = 10 m / s (DES SST turbulence model)*

Figure 8. Velocity fields, m / s at different times t, s for a velocity V_{in} = 15 m / s (turbulence model URANS k-ω SST)

the result was similar to the numerical simulation result in [39], where the LES turbulence model was used. The critical speeds can be clarified by additional calculations, but this does not affect the conclusions of this study.

4.2. Comparison of Engineering Estimates and Direct Coupled Calculation

Comparison of the results of direct coupled calculation and engineering estimates [40] revealed the following.

For the DES SST turbulence model:
– according to the engineering estimate of the divergence occurrence [40], at 0 ° the critical speed is 7.91 m / s. The related calculation showed that at an input flow velocity of 8 m / s there was no unlimited increase in the angle of rotation of the section - it was observed at a speed of 10 m / s;
– according to an engineering assessment of the occurrence of galloping [40], this phenomenon

Table 2. Comparison of the results obtained in the related FSI setting with the results [39]

	V_{CR}, m/s
Experiment [39]	11.5
FSI [39]	10
FSI (turbulence model URANS SST)	15
FSI (turbulence model DES SST)	10

should occur at a cross-sectional angle of rotation equal to 10° at a flow velocity of 9.77 m / s. From the graphs of the dependence of the angle of rotation of the section ϑ, ° and the vertical displacement of point 1, m, on time t, s at an input flow rate of 10 m / s, it can be seen that when the angle of rotation of the section approaches 10° (time 38–47 sec) significant jump in vertical displacement. This indicates a possible galloping effect at this moment. Nevertheless, further vertical vibrations of the structure returned to a stable mode (with a rapid increase in the amplitude of the rotation angle). This indicates a complex mutual influence of two aerodynamic instabilities, in which they may not arise, taking into account the vibrations of the structure along other degrees of freedom. In this calculated variant, divergence prevails over galloping.

For the turbulence model URANS k-ω SST:
– according to an engineering estimate of the occurrence of divergence [40], at 0 ° the critical speed was 17.18 m / s. A related calculation showed that even at an input flow velocity of 15 m / s, an unlimited increase in the angle of rotation of the section was observed;
– according to an engineering estimate of the occurrence of galloping [40], at a cross-sectional angle of rotation equal to 8 ° at a flow velocity of 5.76 m / s, we should observe this phenomenon. If we look at the graphs of the dependence of the angle of rotation of the section ϑ, ° and the vertical

a   b

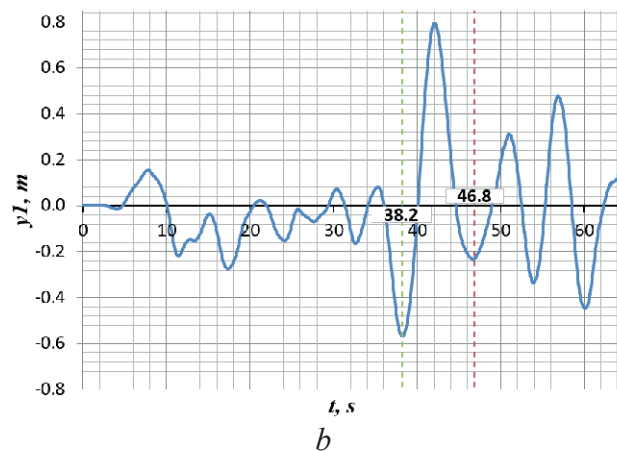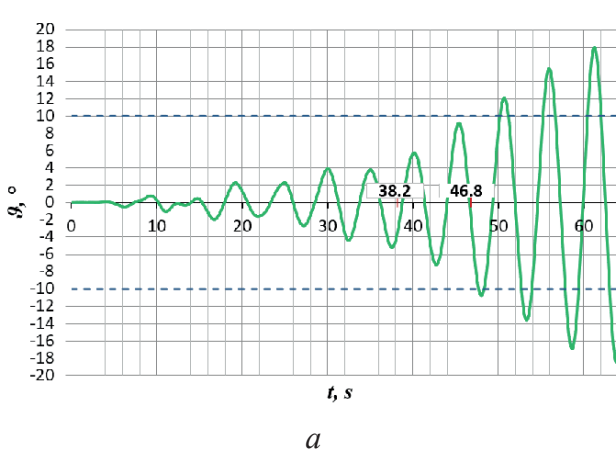*Figure 9. Turbulence model DES SST, V_{in} = 10 m / s: Graphs of dependence on time t, s (a) rotation angle ϑ, °; (b) vertical movement of point 1, m*

a   *b*

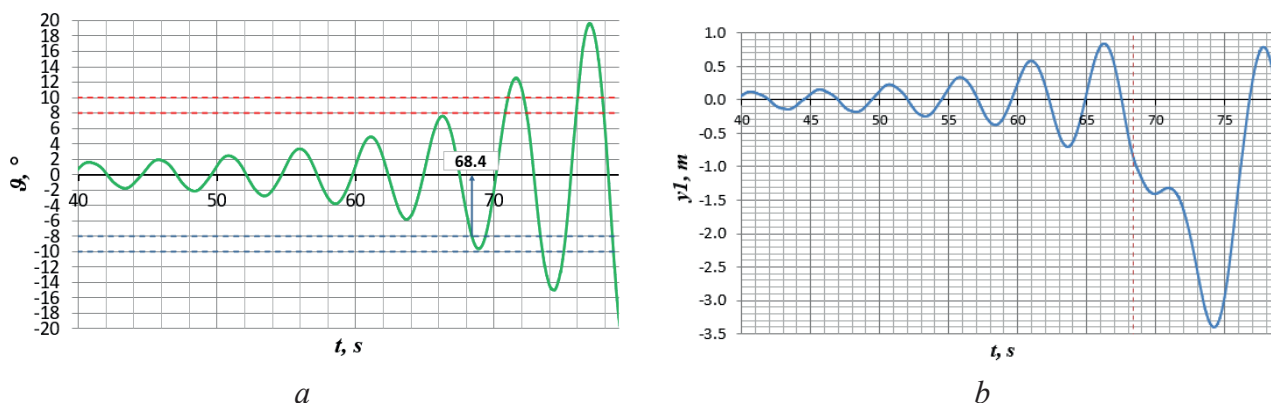*Figure 10. Turbulence model URANS k-ω SST, V_{in} = 15 m / s: Graphs of dependence on time t, s (a) rotation angle ϑ, °; (b) vertical movement of point 1, m*

displacement of point 1, m on time t, s at an input flow velocity of 15 m / s, we can see that the angle of rotation of the section equal to 8 ° is reached at the moment of time 68.4 s. Therefore, at about this point in time, galloping should be observed. Indeed, at about this moment in time, there is a sharp increase in the amplitude of the vertical displacement of point 1 (the center of the section).

5. CONCLUSION

On the considered two-dimensional problem of aeroelasticity, it is shown that it is quite acceptable to use a lighter, in comparison with LES, DES turbulence model and a coarser mesh (in comparison with "reference" numerical solutions). This will allow in the near future to take an important step towards a full 3D computational model with reasonable computing power.

Also, a test problem with a Tacoma bridge section showed that, although engineering techniques provide estimates of the possible occurrence of aerodynamic instability, they do not take into account the reverse effect of the structure on the flow and the mutual influence of several types of aerodynamic instability. Comparison of the results showed that such inaccuracies both underestimate and overestimate the calculated critical wind flow velocities, which can have detrimental practical consequences.

6. ACKNOWLEDGMENTS

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