Modelling of wind impacts on silos and silo parks

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Abstract. This paper devoted computer modelling of wind impacts on the silos for grain storage in order to obtain their aerodynamic characteristics. This modelling was made in the system of computer analysis Ansys Workbench for various wind conditions and different layouts of silos: separately located silo and silo parks by varying their sizes and mutual arrangement at various angles of the wind pressure. Within the numerical experiment it was obtained not only a huge array of data about the aerodynamic resistance of the silos, but also developed a special technique of the mathematical modelling of the wind effects on the selected class of constructions. This technique is a single software module for the platform Ansys Workbench, which automatically forms an optimal calculation area, makes an estimation of the wind loads on the silo and exports obtained loads in the software package SCAD for calculating the strength and deformability. To achieve this goal it was made the calculation of the same tasks on meshes of different dimensions, set the dimensions of the mesh in different places of the calculation area and installed the minimum required time of computer simulations.

1. Introduction

Wind impacts on empty cylindrical grain storage silos are one of the main types of loading, which often leads to their destruction. To determine the magnitude and nature of the wind load distribution on the surface of the silo, standard methods are used [1-5]. In addition, many theoretical and experimental studies have been conducted on this issue [6-10]. However, the possibility of using these materials in the design of modern silos and silo parks raises a number of questions. This is primarily because the basic information about the wind flow of cylindrical structures was obtained for models with a Reynolds number much smaller than the corresponding value characteristic of silos. Secondly, due to the corrugated walls and the presence of a large number of ribbed stiffeners, the silos have a rather rough structure, which in turn provokes the appearance of complex wall effects that increase the load on the silo body. The third reason is the question of the absence or insufficiency in the design rules of information regarding the consideration of wind loads on cylindrical structures, which are partially or completely in the wind shadow of other objects. This is a typical situation for silo parks being part of hopper complex.

The modern development of computer technology and software implementation of the control-volume method makes it possible to perform computer modelling of wind impacts on structures, avoiding these disadvantages. In particular, it is possible to implement flow modes with high Reynolds numbers that cannot be reproduced in wind tunnels [11-13].

2. Computational aerodynamics verification tests

2.1. Choosing a computational mesh

In order to be able to verify the calculation procedure, a computer modelling of a two-dimensional flow along cylinder (2D notation) with a diameter of \( d_0 = 100 \) mm with Reynolds number \( \text{Re} = 3900 \) was carried out. These output parameters are quite commonly used for test activities [6-10], that meet...
the selected initial criteria. At Re = 3900, the airflow is characterized by a laminar separation zone, in which the transition to turbulence occurs in the shear range, which accordingly causes the appearance of large-scale vortices and complex flows in the separation zone. Unfortunately, these experiments set values of different parameters and in different zones, which caused extremely large variance of data. The representative characteristics were the means sharing of the aerodynamic coefficients along the contour and the drag coefficient.

Given that the ANSYS CFX software package does not provide for classical two-dimensional aerodynamic calculations, a pseudo-two-dimensional statement is applied when a single cell of size is generated at the height of the cylinder. The quality of the mesh (Figure 1) was taken in six variants (from A to F), and the number of points per circle was constant and equal to 180.

![Figure 1. Mark F of the computational mesh of domain (a) and its enlarged fragment (b) around the cylinder.](image)

Table 1 shows the modelling results for different variants of the calculated meshes, and Figure 1 shows a visual stratification of the cells of the computational domain and on a larger scale near the cylindrical body for meshes D and F.

The most consistent with the experimental values showed the variant of the E mesh, which was adopted as a reference for further research. Visualization of the instantaneous wind flow velocity in the flow of a single cylinder within the test task are shown in Figure 2a. In addition, Figure 2b presents a graphical comparison of the pressure coefficients for a single cylinder in the 2D formulation at Re = 3900 for the considered mesh options.

2.2. Two-dimensional flow along round cylinder
The turbulent flow around the cylinder in the 2D formulation was considered in two variants - an isolated body in free airflow and a cylinder near the obstacle, which was selected as the infinitely long rough screen [14]. The airflow model was adopted with constant physical properties. Four high-speed wind modes were selected to fit the cylinder's supercritical flow mode. Each mode was characterized by its own Reynolds number. The diameter of the silo was assumed to be 3500 mm, and the distance from its center to the screen plane was $G = 0.7D$.

The computational mesh for solving the set tasks was taken for option E. A general picture of the turbulent flow around an isolated cylinder is shown in Figure 3.

On the basis of the constructed mesh, the problem of turbulent flow around both isolated cylinder and cylinder near the obstacle, was solved in two formulations: stationary and unsteady. When solving the problem in the stationary formulation, the installed wind flow was considered, and the results of the calculation focused the aerodynamic characteristics of the cylindrical body.
Table 1. Parameters of the computational mesh for 2D flow along cylinder.

| Name/Mesh | A  | B  | C  | D  | E  | F  |
|-----------|----|----|----|----|----|----|
| $d_0 / \Delta_{\text{min}}$ | 20 | 20 | 20 | 20 | 100| 20 |
| $d_0 / \Delta_{\text{max}}$ | 2  | 2  | 2  | 2  | 2  | 2  |
| $d_0 / \gamma_0$ | 50 | 100| 200| 500| 1000| 1000|
| $\gamma_0$ | 1.05 | 1.10 | 1.10 | 1.10 | 1.25 |
| $n_f$ | 20 | 20 | 20 | 20 | 20 | 20 |
| $d_0 / y_n$ | 19.8 | 16.36 | 32.70 | 81.75 | 163.50 | 14.41 |
| $n_{\text{nodes}}$ | 40560 | 33632 | 76836 | 324352 | 1141240 | 31008 |
| $n_{\text{elements}}$ | 36627 | 29702 | 72895 | 318725 | 1130214 | 27080 |
| Orthog. Angle | 70.7 OK | 70.3 OK | 69.9 OK | 61.6 OK | 56.9 OK | 69.5 OK |
| Exp. Factor | 4 OK | 4 OK | 4 OK | 5 OK | 6 OK | 4 OK |
| Aspect Ratio | 81 OK | 74 OK | 78 OK | 77 OK | 80 OK | 89 OK |
| $C_D$ | 0.488 | 0.666 | 0.773 | 0.820 | 0.828 | 0.846 |

a, b Minimum and maximum mesh size.

c Size of the first wall cell of the boundary layer.

d number of wall cells.

e the size of the last wall cell and the mesh size of the internal volume of the computational domain.

f number of mesh points.

g the number of cells (elements) of the mesh.

h drag coefficient.

Figure 2. Visualization of the instantaneous wind flow velocity in the flow of a single cylinder in the framework of test task (a) and the pressure coefficient (b) for a single cylinder in the 2D formulation at Re = 3900.

Unsteady calculation made it possible to track the change in aerodynamic characteristics over time, and to determine a number of frequency parameters of the turbulent flow around the cylinder, such as the frequency of failure of vortices from its surface. Considering the long duration of unsteady calculation and the attraction of considerable computer resources, it was possible to switch to it only after adjusting models for tasks in a stationary setting.

Figure 3 shows a characteristic feature of the trail is the presence of transverse (Karman street) and sufficiently intense longitudinal vortices. The obtained results are in full agreement with the
experimental data known from the literature and the results of calculations of the cylinder flow by the methods of computational aerodynamics [7, 8, 9, 15].

![Cylinder images](image_url)

**Figure 3.** The general instantaneous picture of the flow around an isolated cylinder at \( \text{Re} = 2,33 \cdot 10^6 \) (a) a cylinder near an infinitely long screen at \( \text{Re} = 1,17 \cdot 10^7 \) or 50 m/s (b).

3. **Numerical experiment of vortex systems modelling**

3.1. **In the plane flow (2D modelling)**

The real design decisions of the master plans of grain terminals or hopper enterprises, involve a simple arrangement of silos in the form of small groups with parallel, perpendicular placement or some angular deviation. Preferably, silo parks include silos of the same diameter and height, which greatly simplifies their study.

With airflow, the silos in the local group interact with each other and form some velocity spectrum inside and around the formed arrangement. The nature of the silos placement is reflected in the pressure distribution on their surface and, of course, differs from those that are set for single, non-windproof structures and declared in the design standards.

Thus, the study focuses on the study of the kinematic spectrum and the evaluation of the interference interaction of group models of two, three and four silos with different geometric dimensions and distance. In the first formulation, two-dimensional (plane) numerical modelling of wind flow is performed, which does not depend on the coordinate of the normal to the plane under consideration. The cylindrical bodies of the same diameter were considered as storage capacities. Height does not matter in this experiment. The airflow direction was fixed: the cylinders were placed in a line perpendicular to the flow, with variable variations in the location of the objects within the group. The position of each body of the flow was expressed parametrically along two axes by the ratio of the characteristic distance between the centers of the cross sections to a given diameter.

Variables in these experiments were the accepted body diameters and four variants of the flow Reynolds number, which respectively determined the speed of its movement at the inlet. The main quantitative characteristics of the conducted numerical experiments were to obtain the distributions of the aerodynamic coefficient for each of the cylindrical bodies in the group and to establish the dependence of its values upon changing the size and initial parameters that determine the wind speed. In the first stage, the pairwise arrangement of cylindrical bodies was considered - parallel and perpendicular to the flow and at diagonal placement. In the following, we analyzed a group of three objects with a similar arrangement and taking into account the separated position of one of the cylinders. The third stage was to study the flow conditions of the formation of the leeward domain for a four-cylinder system. The analysis of the received results made it possible to obtain a visual representation of the spatial behavior of the airflow in the vicinity of cylindrical bodies with the help of isofields of the wind flow (Figure 4).

It is possible to observe the characteristic direction of the flow, the formation of vortex systems in the conditions of limited space, the point of flow separation on the surface of the cylindrical body, the
formation of the vortex shedding, as well as qualitative changes in the distribution of isofields in different variants of the Reynolds number values. The color spectrum of the lines characterizes the velocity field gradient - from minimum values to maximum. The illustration of the complete cycle of the flow phenomenon of groups of cylindrical bodies is very important for the possibility of aerodynamic optimization and reduction of wind loads for the silo park in real design tasks.

The graphs of the change of the aerodynamic coefficient along the perimeter of cylindrical bodies at different Reynolds numbers showed a considerable divergence of values in quantitative equivalent (Figure 5).

**Figure 4.** Visualization of the airflow around a system of two cylinders (a) and of three and four cylinders (b).

**Figure 5.** Graph of the distribution of the aerodynamic coefficient along the perimeter I (a) and II (b) of the cylinders with their sequential location and distance between the centers of body (b).

The results of a large-scale computer modeling of wind impacts on cylindrical storage tanks allow us to formulate a special aerodynamic atlas, which shows graphs of the distribution of the wind pressure coefficient over the surface of the silos for the vast majority of real silo park layouts.
3.2. 3D modelling of spatial flow around cylindrical models
Certainly, the numerous variants of silo park configurations considered cannot fully describe the actual construction in the vicinity of the storage tank (grain dryers, warehouse buildings, etc.). In addition, the process line can combine capacities of different configuration, diameter and height. In this case, it is not possible to limit the problem of numerical modeling of wind impacts only in 2D formulation. Therefore, 3D modelling of spatial flows in the vicinity of groups of cylindrical bodies (Figure 6) was performed.

Figure 6. Velocity isofields in spatial flow modeling for a group of twin-tandem cylinders.

In the future, followed by determination of the dependences of the distributions of aerodynamic coefficients, which showed that a large number of calculations and the involvement of a large number of computational devices were necessary for the exact solution of this problem. The comparisons of the results obtained prove the rationality of using a two-dimensional approach to determine the basic aerodynamic characteristics.

4. Conclusions
In the framework of the numerical experiment, not only a huge array of data on the aerodynamic drag of the silos was obtained, but also a special method for mathematical modeling of wind impacts on the selected class of structures was developed. The method is the only software module for the Ansys Workbench platform that automatically generates the optimum computational domain, performs an estimation of wind loads on the silo, and exports the resulting loads to the strength analysis programs to perform strength and deformation calculations.

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