The Analysis of Wave Effects on Offshore Objects

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Abstract. The article discusses the approach of analyzing external influences on a wide class of marine structures. An analysis algorithm using the CosmosFlovWork CAD is proposed, which allows both visually and numerically to estimate the size of the loads as a result of external influences. A semi-submersible platform is considered as an example.

1. Introduction
The widespread use of autonomous underwater vehicles requires solving a whole range of tasks. Such vehicles autonomy increasing is one of them. Semi-submersible platforms for recharging autonomous underwater vehicles are one of the solutions to solve this task for an autonomous underwater vehicle with a limited operating radius. The work of such vehicles will take place in deep-sea areas. Such platforms developing task is arising thereby. Ocean engineering installations designing modern methods are based on the recommendations adopted in a particular state or on industry standards. The calculations are based on empirical dependencies that are unknown for new offshore platform configurations, including deep-sea platforms. In this regard, some calculations result from significant uncertainty and the risk of creating an unsuccessful design. To overcome these difficulties, a fundamentally new approach to the problem of assessing the impact of the marine environment is required. In the monograph, this is carried out based on the widespread use of modern numerical hydrodynamic calculations of wave and constant currents effect on structural elements of deep-sea platforms of various types with subsequent experimental verification of the results in an experimental wave pool [1–3]. These factors determine work relevance and its results in effective use prospects.

Research works on the creation and use of various types of offshore drilling platforms cover the period from the last century's 50s. In [4–10] carried out the works devoted to the design, stability, and strength of such structures. Such installations hydrodynamics studies could be found in the works [11 – 16].

2. External forces acting on platforms
Modern deep-sea platforms are expensive installations. The key point in the design of such platforms is to determine hydrodynamic forces acting on installation structure in extreme storm conditions. We will consider features of such impacts on a TLP type platform below, since they are among the main deep-sea platforms configurations and have a relatively complex three-dimensional structure, and alternating wave loads can exceed 10³ ... 10⁴ kN (fig.1).
Interaction of wave and stationary currents with various obstacles on the seabed has been considered in many publications [17, 18, 19]. Simple forms are considered, and calculations are performed in a two-dimensional setting in most of these works.

For the first time, the hydrodynamic loads on a stationary cylindrical column were investigated by Morison, according to whose model the wave load \( f_T \) per unit length of the column is determined as follows [11]:

\[
f_T = 0.5 \rho C_{ck} V_x |V_x| + 0.25 \rho \pi D_{kol}^2 C_i \alpha_x ,
\]

where \( \rho \) - density of water, kg/m\(^3\), \( D_{kol} \) - diameter of the column, m; \( C_{ck}, C_i \) - resistance coefficients of wave and inertial load components, respectively. The values of these coefficients depend on the dimensionless Kulegan-Carpenter numbers (\( K = \frac{V T_w}{D_{kol}} \), here \( V \) - amplitude of the wave velocity of the current, m/s, \( T_w \) - wave period, m, \( D_{kol} \) - diameter of the column, m), \( V_x, \alpha_x \) - horizontal wave velocity of the current and the wave acceleration, respectively [20].

Experimental data amount establishing drag coefficients dependence on the dimensionless Kewlegan-Carpenter numbers is very limited, and therefore, both coefficients assumed to be constant for simplicity of calculations in engineering practice. The velocity resistance coefficient value is in the range of 0.5 ... 0.75 for the MODU support base elements and 1.0 ... 2.0 for prisms with a rectangular section. The resistance coefficient for rectangular elements is in the range of 1.1 ... 1.44, according to the model test results. Thus, there is significant uncertainty in the values of the indicated resistance coefficients, which are determined mainly in laboratory conditions on simplified models of structural elements. In this case, the similarity conditions are not met in terms of the Reynolds, Froude, and other numbers. Also, it is not possible to take into account in laboratory conditions such significant factors of real flow impact, as complex forms of three-dimensional platforms structures; different directions of wave flow; effect of gaps between structural elements; seabed influence. Meanwhile, when these factors are taken into account, the available reference data on the aerohydrodynamics of bluff structures give complex dependences of the drag coefficients.

Thus, presented external forces estimates are inaccurate and incomplete since the following factors are not taken into account:

1. Field change in the natural wave currents during their interaction with the platform structure;
2. Complex (generally nonlinear) relationships between hydrodynamic forces and wave characteristics, the direction of their propagation, and design features of the platform.

All the above mentioned is the reason for significant uncertainty and, often, inaccuracy of hydrodynamic loads calculations results and overturning moments acting on platforms.

Navier-Stokes equations averaging according to Reynold is used to solve non-stationary tasks associated with the interaction between various flows and streamlined objects, and turbulent effects are considered as flow parameters or large-scale time-dependent effects. In this case, the well-known subgrid stress tensor parameterization problem exists. In the simplest case, the Boussinesq hypothesis is used, according to which this tensor is expressed in terms of the gradients of the averaged components.
of the flow velocity and a constant value - the coefficient of turbulent viscosity $\mu_t$. It makes it possible to formally replace the coefficient of kinematic viscosity with a constant value $\mu_k$, which, in essence, is ambiguous and, as a rule, is chosen from the condition of obtaining a stable solution under the given boundary conditions, computational grid, and time step.

One of the modern programs for calculating hydrodynamic loads is the COSMOSFloWorks application package. The system is fully integrated into the SolidWorks parametric design platform, which made it possible to create a 3D model, and not to recalculate the impact forces taking into account the scale.

When solving a problem using COSMOSFloWorks, the following stages are distinguished:

1. Creation of a 3D model of the investigated structure. A three-dimensional model can be created based on SolidWorks or imported in one of the formats supported by the program;
2. Project creation. When creating a project, a three-dimensional model is imported into the COSMOSFloWorks computational area, a system of units of measurement is specified for further calculations.
3. Setting the boundary and initial conditions. The density of the acting medium, the initial velocity of the flow, the effect of gravity, and other defining parameters are set.
4. Regulation of the computational grid. The computational mesh is generated automatically with a slight refinement at the fracture points of the structure, for a more correct description of the flowing flows in the near-wall zones. The step of the computational grid can also be set manually.
5. Setting the size of the computational domain. The computational domain has a parallelepiped shape, the length, width, and height of which can be adjusted.
6. Management of the calculation process. The calculation was performed automatically until convergence was obtained.
7. Viewing and interpreting the results.

3. Mathematical model of three-dimensional flow around the structure of a deep-sea platform in the COSMOSFloWorks environment

A prerequisite for working with the COSMOSFloWorks program is the creation of a mathematical model, based on which all further calculations will be made. Since the systems of differential and / or integral equations used in the mathematical model usually do not have an analytical solution, they are reduced to a discrete form and solved on a certain computational grid. To perform discretization in space, the entire computational domain is covered by a computational grid, the faces of the cells of which are parallel to the coordinate planes of the Cartesian model used in the computation in SolidWorks. Since COSMOSFloWorks uses the finite volume method, the values of independent variables are calculated at the centers of the cells, and not at the nodes of the computational grid, the computational grid used by COSMOSFloWorks is described by its cells, and not nodes, as in the finite difference methods.

Accordingly, the cells of the computational grid have the shape of parallelepipeds. The area in which this grid is built also has a parallelepiped shape that is uniform for all tasks.

When solving external problems, i.e. when the fluid flows around a solid, the computational domain is automatically constructed in the form of a parallelepiped-shaped area, whose faces are parallel, like the computational cells, to the coordinate planes of the Cartesian coordinate system of the model in SolidWorks and are located at a certain distance from the solid.

The process of constructing a computational grid begins with constructing a base grid - it is obtained by dividing the grid generation space into layers by planes parallel to the coordinate planes of the used Cartesian coordinate system of the model. The number of these planes defining the base grid, i.e. the number of cells of the base grid along each of the coordinate axes, are set based on the specified settings and were corrected manually in the process of setting up the calculation scheme.

Since the faces of the computational cells do not approximate the surfaces of solid bodies in contact with the fluid medium, to resolve the computational grid relatively small geometric features of these surfaces (areas of increased curvilinearity, protrusions, depressions, holes, surfaces of thin bodies
surrounded by a fluid, etc.) the procedures of appropriate local subdivision of the grid cells near these surface areas are used before the start of the calculation. So, each cell of the base mesh, crossed by the surface of a solid at the interface with a fluid medium, is divided into 8 identical, geometrically similar cells of a smaller size (in COSMOSFloWorks they are called child cells). If the cell division criterion used in the construction is not yet satisfied, then those of the 8 cells that are intersected by this solid surface, i.e. are partial, in turn, are similarly divided into 8 even smaller cells, etc., until the given crushing criterion is satisfied by the size of the resulting cells, but no more than until the size is 27 times smaller than the base cell.

In COSMOSFloWorks, the movement of a fluid medium is modeled using the Navier-Stokes equations, which describe the conservation laws of mass, momentum, and energy of this medium in a nonstationary setting. Also, the fluid components state equations are used, as well as the empirical viscosity dependences and thermal conductivity of these medium components on temperature. These equations simulate turbulent, laminar, and transitional flows and the transition is determined by the critical Reynolds numbers. To simulate turbulent flows, the Navier-Stokes equations are averaged over Reynolds, i.e. the effect of turbulence on the flow parameters averaged over a small time scale, is used, and large-scale time changes in the components of the dynamic flow parameters (pressure, velocities, temperature) averaged over a small time scale are taken into account by introducing the corresponding time derivatives. As a result, the equations have additional terms - Reynolds stresses, and to close this equation system in COSMOSFloWorks, turbulence and its dissipation kinetic energy transfer equations are used in the k-ε turbulence model framework.

The system of equations for conservation of mass, momentum, and energy of unsteady spatial flow in a Cartesian coordinate system \((x_i, i = 1,2,3)\) has the following form:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0, \quad (2)
\]

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_k - \tau_{ik})}{\partial x_k} + \frac{\partial P}{\partial x_i} = S_i, \quad (3)
\]

\[
\frac{\partial (\rho E)}{\partial t} + \frac{\partial ((\rho E + P)u_k - \tau_{ik}u_i)}{\partial x_k} = S_k u_k + Q_H. \quad (4)
\]

where \(t\) is time, \(u\) is the fluid velocity, \(\rho\) is the density, \(P\) is the pressure, \(S_i\) are the external mass forces acting on the unit mass of the fluid, \(S_k\) porous is the action of the porous body resistance, \(E\) is the total energy of a unit mass of the fluid, \(Q_H\) is the heat released by a heat source in a unit volume of the fluid, \(\tau_{ik}\) is the tensor of viscous shear stresses, \(q_k\) – diffusion heat flux, subscripts mean summation over three coordinates.

The kinetic energy of turbulence \(k\) and the dissipation of this energy per unit volume \(\varepsilon\) are determined by solving the following equations [2]

\[
\frac{\partial \rho k}{\partial t} + \frac{\partial (\rho u_k k)}{\partial x_k} = \frac{\partial}{\partial x_k} \left( \mu_l + \frac{\mu_l}{\sigma_k} \frac{\partial k}{\partial x_k} \right) + S_k, \quad (5)
\]

\[
\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial (\rho u_k \varepsilon)}{\partial x_k} = \frac{\partial}{\partial x_k} \left( \mu_l + \frac{\mu_l}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_k} \right) + S_\varepsilon,
\]

where: \(S_k = \tau_{ij}^R \frac{\partial u_i}{\partial x_j} - \rho \varepsilon + \mu_l P_B\),

\[
S_\varepsilon = C_\varepsilon \frac{\varepsilon}{k} \left( f_1 \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + \mu_l C_B \rho P_B \right) - C_{\varepsilon f_2} \varepsilon^2 - \frac{\varepsilon}{k}, \quad (6)
\]

\[
\tau^{R}_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_l}{\partial x_l} \delta_{ij} \right) - \frac{2}{3} \mu_k \delta_{ij} P_B = - \frac{g_i}{\sigma_B} \frac{1}{\rho} \frac{\partial \rho}{\partial x_i},
\]

\[
\tau_{ij}^R \frac{\partial u_i}{\partial x_j} - \rho \varepsilon + \mu_l P_B,
\]

\[
S_\varepsilon = C_\varepsilon \frac{\varepsilon}{k} \left( f_1 \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + \mu_l C_B \rho P_B \right) - C_{\varepsilon f_2} \varepsilon^2 - \frac{\varepsilon}{k}, \quad (6)
\]

\[
\tau^{R}_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_l}{\partial x_l} \delta_{ij} \right) - \frac{2}{3} \mu_k \delta_{ij} P_B = - \frac{g_i}{\sigma_B} \frac{1}{\rho} \frac{\partial \rho}{\partial x_i},
\]
$g_i$ - component of gravitational acceleration in the coordinate direction $x_i$, $\sigma_B = 0.9$, $C_B = 1$ when $P_B > 0$ and $C_B = 0$ for $P_B \leq 0$, $f_1 = 1 + \left( \frac{0.05}{f_B} \right)^3$, $f_1 = 1 - \exp \left( -R_B^2 \right)$, $C_{e1} = 1.44$, $C_{e2} = 1.92$.

Laminar and turbulent boundary layers of the flow near the surfaces of a solid, as well as the transition of a laminar boundary layer to a turbulent one and, conversely, a turbulent to a laminar one, are modeled with high accuracy using modified universal near-wall functions.

The solution of the equations (2 - 4) is executed at given border conditions. The general design scheme for solving the boundary value problem is shown in Figure 2. The coordinate axes form a Cartesian system in which the axis is directed along the diametrical plane of the platform, the axis is across this plane, and the axis oz is directed vertically upward from the sea surface.

Border conditions.
1. The velocity profile of the steady flow $u_s(z)$ is set following the Prandtl model for the boundary layer $u_s(z)$ at $z \geq \Delta$ and at $u_s(z) = U_s[(H - z)/\Delta]^{1/7}$; with $-H \leq z \leq -H + \Delta$ where $\Delta$ is the thickness of the bottom boundary layer, equal to:

$$\Delta = [0.045 \frac{U_p}{f} \left( \frac{\nu_m}{U_p} \right)^{0.25}]^{0.8},$$

(7)

where $f$ is the Coriolis parameter; $\nu_m = 1.0 \cdot 10^{-6}$ m$^2$/s – molecular viscosity.

![Figure 2. Estimated flow diagram of the TLP platform underwater structure.](image)

2. From the external (input) Flow $L_{y1}$ profile wave flow with a potential rate equal to:

$$F(x, y, z, t) = \frac{\alpha \sinh [k(H + z)]}{k \sinh (kH)} \cos (\alpha x - k x \cos \alpha - k y \sin \alpha)$$

(8)

where $\omega = 2\pi/T$ is the circular frequency of wave oscillations, $T$ - a period of wave oscillations, $k = 2\pi/\lambda$ - wave number, $H$ - sea depth, $a$ - wave amplitude, $\alpha$ - the angle between the longitudinal axis of the platform and the direction of wave propagation.

A linearized dynamic condition is set on the sea surface:

$$\omega^2 w + g \frac{\partial w}{\partial z} = 0,$$

(9)

where $w$ is the vertical wave velocity, $\omega = 2\pi/T$ - circular frequency of wave oscillations, rad/s; $g$ - free-fall acceleration.
3. Defined geometry board forms and related system of Cartesian coordinates. On the surface of the structure and the seabed, the adhesion condition is set (the components of the current velocity vector are equal to zero, i.e., \( u = v = w = 0 \)).

4. From the side of the outgoing flow, the Sommerfeld condition or the condition of non-reflection of perturbations of the form is set \[ \frac{\partial u}{\partial t} + C \frac{\partial u}{\partial x} = 0, \] where \( C \) is the average velocity of propagation of perturbations (flow velocity, the phase velocity of surface waves).

To solve the problem, it is also necessary to set the initial conditions. In the case under consideration, at the initial moment, a uniform flow with a constant velocity and a wave flow profile is specified, and also, taking into account the turbulent nature of the flow, the turbulence intensity \( I_t \) and mixing path \( l_p \). These parameters can be set by default with subsequent automatic correction in the process of solving the problem. In some cases, they can be calculated by solving the boundary layer equation for specific parameters of the streamlined structure.

The numerical solution of the problem is performed by the finite volume method, in which discrete solutions are determined as the average value over the cell volume and these values are assigned to its center.

### 4. Velocity and pressure fields numerical calculation under the influence of wave and stationary flows on the TLP platform

Two three-dimensional models of TLP platforms of various configurations in full size were created to carry out calculations in the application package COSMOSFloWorks.

Parameters of surface waves, corresponding to the speed of the storm wind in the range of 20 ... 40 m/s (presented in Table 1) were used in calculations.

| \( W, \text{m/s} \) | \( h, \text{m} \) | \( T, \text{s} \) | \( \lambda, \text{m} \) |
|----------------|---------|---------|---------|
| 20             | 2.16    | 9.39    | 137.00  |
| 30             | 3.70    | 10.49   | 171.70  |
| 40             | 5.40    | 13.47   | 283.00  |

The coordinate axes form a Cartesian system in which the axis \( ox \) is directed along the diametrical plane of the platform, the axis \( oy \) is across this plane, and the axis \( oz \) is directed vertically upward from the sea surface.

The fig. 3 – 6 show velocity and pressure fields numerical calculation results under the influence of a stationary flow on the TLP platform. Hydrodynamic calculation of the flow around the platform base support showed the following: at a wind speed of \( W = 20 \text{ m/s} \) and \( \alpha = 0^\circ \) near the surface of the support base, there is a sharp increase in speed to 1.35 m/s, with a background value of 0.8 m/s. Zones of an increase in speed to 1.3...1.5 m/s are formed near the lateral surface on the waves approach side at \( \alpha = 45^\circ \), followed by areas of a decrease in speed to 0.05 m/s.

The calculation results showed that significant inhomogeneities of the natural wave field \( p(x, y, z) \) are observed due to the interaction of the structure with the background field of wave and constant velocities. These deformations are manifested in increasing and decreasing pressure drop of 30...40 kPa zones formation.
Figure 3. Results of numerical calculation of the current velocity field when flowing around the
support base of TLP platform at wind speed $W = 20$ m/s and $\alpha = 0^\circ$ (a - view from the side, b - a top
view).

The hydrodynamic calculation of the flow around the support base of the platform showed the
following (fig. 5). At a wind speed of $W = 20$ m/s and $\alpha = 0^\circ$ near the surface of the support base, there
is a sharp increase in speed to 1 m/s with a background value of 0.5 m/s. At $\alpha = 45^\circ$, near the lateral
surface on the side of the approach of the waves, zones of an increase in velocity to 1.3 ... 1.5 m/s are
formed, followed by areas of a decrease in velocity to 0.05 m/s.

Figure 4. Results of the numerical calculation of the current velocity field when flowing around the
support base of TLP platform at wind speed $W = 20$ m/s and $\alpha = 45^\circ$ (a - side view, b - top view).

Figure 5. a) Results of numerical calculation of the spatial distribution of pressure when flowing
around the support base of the TLP platform. Wind speed $W = 20$ m/s, current propagation angle $\alpha = 0^\circ$; b) Results of numerical calculation of the spatial distribution of pressure when flowing around the
support base of the TLP platform. Wind speed $W = 20$ m/s, current propagation angle $\alpha = 45^\circ$.

At a wind speed of $W = 40$ m/s and $\alpha = 0^\circ$, the current speed near the surface of the support base
increases to 1.4 m/s, behind the pontoon, a shading area is formed at a speed of 0.1 ... 0.3 m/s. At $\alpha = 45^\circ$ adjacent to the side surfaces of the base region are formed alternately decreasing and increasing
flow speed of 0.6 ... 1.8 m/s.

The results of the numerical calculation of the velocity and pressure field of a steady flow are
presented in fig. 6.
Figure 6. a) Spatial distribution of flow velocity components in the flow around the TLP platform supporting base. Wind speed $W = 20$ m/s, wave propagation angle $\alpha = 0^\circ$; b) Spatial distribution of flow velocity components in the flow around the TLP platform supporting base. Wind speed $W = 20$ m/s, wave propagation angle $\alpha = 45^\circ$

5. Conclusion
The hydrodynamic calculation of the stationary flow around the support base of the TLP platform with the lower pontoon showed the following. When the wind speed is $W = 20$ m/s and $\alpha = 0^\circ$ near the surface of the support base, there is a sharp increase in speed to 1...1.25 m/s with a background value of 0.5 m/s. At $\alpha = 45^\circ$, near the lateral surface on the side of the approach of the waves, zones of an increase in speed to 0.75 ... 1 m/s are formed, followed by areas of a decrease in speed to 0.05 m/s.

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