MODELLING THE HEAVE OSCILLATIONS OF VERTICAL CYLINDERS WITH DAMPING PLATES

(DOI No:10.3940/rina.ijme.2016.a3.365)

A Lavrov and C Guedes Soares, Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Portugal.

SUMMARY

The laminar flow around heaving axisymmetric and three-dimensional cylinders with damping plates is numerically studied for various Keulegan-Carpenter numbers. The Navier-Stokes equations are solved using OpenFOAM, which is applied to the flow on a moving mesh. For processing of results the semi-empirical Morison equation is used. Calculations are conducted for one cylinder, one cylinder with one disk, one cylinder with two disks, and one cylinder with one pentagonal plate. The calculated values are compared against experimental data.

1. INTRODUCTION

Various offshore structures used in the last decades in oil and gas industry, have been located in deep water fields, being thus moored floaters of different geometry. Ship like shapes have been a solution for many applications of Floating Production and Storage and Offloading (FPSO) platforms. However other solutions like semisubmersibles and SPAR platforms are made of cylindrical members. In particular the SPAR geometry is basically a vertical cylinder. For floating wind turbines, several platforms of smaller dimensions but of similar shapes are adopted as discussed for example in Bagbanci, et al. [1]. To reduce the vertical oscillations of these platforms one solution often adopted is the use of damping plates attached to the platform.

In the simplest example it is possible to investigate the heaving oscillations of a vertical floating cylinder in isolation. One of the first experimental investigations of heaving oscillations of the vertical cylinder was conducted by Thiagarajan and Troesch [2], who conducted an experimental study on a small cylinder. There are two main parameters that define the characteristics of small amplitude oscillation of floating structures the Keulegan-Carpenter number *KC*:

$$KC = \frac{2\pi A}{D_c}$$

and the frequency parameter β:

$$\beta = \frac{D_c^2 \rho}{\mu T}$$

where *A*, and *T* is, respectively, amplitude and period of oscillation, and μ, ρ are, respectively, water dynamic viscosity and density. The dependence of the damping coefficient on *KC* number was investigated.

Thiagarajan and Troesch [3] conducted further experiments on a cylinder with a damping plate. It was shown that for the chosen disk diameter the damping ratio of the disk-cylinder structure increases in comparison with cylinder from 20% to 2.5 times depending on the *KC* number. In the paper of Lake, et al. [4] results of experiments for a cylinder with disk of diameters 0.15 m and 0.19 m, respectively, are presented. Comparison with experiments of Thiagarajan and Troesch [3] with other structural dimensions allowed proposing scaling laws for hydrodynamic coefficients. Recently Lopez-Pavon, et al. [5] also presented experimental data of heave oscillations of a cylinder with a disk, which is related with the design of offshore wind turbines. Unlike with other experiments these authors used a structure with large ratio of disk diameter to cylinder diameter.

The damping coefficients of solid and porous disks in the context of their use as heave dampers in offshore structures was experimentally studied in the paper of Vu, et al. [6]. Results for a solid disk agreed reasonably with previously published data, but the agreement with porous disks showed some discrepancies which need to be studied further. Damping coefficients for all disks were found to increase linearly with increasing amplitude of oscillation. The experimental work of He, et al. [7] focused on the damping coefficients parametric dependence on *KC* number and geometric dependence (thickness-to-diameter ratio).

The experimental study of Tao and Dray [8] investigated the hydrodynamic characteristics (added mass and damping) of oscillatory solid and porous disks using model scale experiments. The hydrodynamic coefficients of the solid or porous disk obtained from the force measurements were analysed. The sensitivity of the damping and added mass coefficients to both motion amplitude and the disk porosity was determined.

It is well known that numerical modelling of the flows near offshore structures allows, as a rule, to obtain necessary results quicker and with reasonable costs in comparison with experimental investigations. In line with experimental works several investigations of oscillating structures were conducted adopting methods of computational fluid dynamics.

One of the first works in the area of CFD applied to this problem was the investigation of Tao, et al. [9]. The damping forces on the cylinder were calculated by solving the Navier–Stokes equations. Different characteristics of heave damping have been found in two different regimes in the ranges of KC from 0.001 to 1.0. Tao and Thiagarajan [10] simulated an oscillation of cylinder and disk configuration using Navier-Stokes equations and a home-made code. The flow generated by a vertical cylinder with a disk was idealized as axisymmetric. Numerical results agreed well with experiments of Thiagarajan and Troesch [3]. The influence of the ratio of the disk thickness to disk diameter D_d on vortex shedding schemes is also investigated by Tao and Thiagarajan [10]. It is shown that three various regimes exist: for $t_d/D_d \approx 0.2$ there is an independent vortex shedding regime in which vortices shed from one edge of the disk don't interfere with the vortices shed from the other edge; for $t_d/D_d \approx 0.04$ there is an interactive vortex shedding regime in which vortices are convected over longer distances and the diffusion process is slower; for $t_d/D_d \approx 0.001$ there is a unidirectional vortex shedding regime in which the interaction of the vortices formed during any two successive half cycles is significantly enhanced.

A sample calculation on a classic Spar platform, see Tao and Thiagarajan [11], showed that the addition of a damping disk increased the heave damping fourfold. The hydrodynamic behaviour of a Spar prototype with a heave plate oscillating at realistic β numbers was investigated by Tao and Cai [12]. They showed that geometrical parameters have significant influence on the vortex shedding modes and associated hydrodynamic properties, e.g. hydrodynamic damping and added mass coefficients.

Numerical simulation of oscillations of a vertical cylinder with two disks was carried out by Tao, et al. [13]. The nonlinear viscous flow problem associated with a heaving vertical cylinder with two heave plates attached, in the form of two circular disks, was solved using a finite difference method. Numerical experiments were carried out to investigate the influence of the distance between disks on the hydrodynamic properties, such as added mass and damping coefficients. The paper of Tao, et al. [13] also includes results of calculation for the variant with KC=0.34, and L/D_d=0.06. It is demonstrated that in this regime the vortices induced by one disk are able to reach the edge of the other disk and interact directly with the vortices generated by the other disk.

Modelling of the disk oscillations near the seabed was demonstrated in the work of Garrido-Mendoza, et al. [14]. Analysis was performed using the OpenFOAM software. The validation for that simulation was carried out by comparing the calculated damping ratio with the experimental results of Thiagarajan and Troesch [3] for a cylinder with disk. A good agreement was obtained between the experimental data and simulations. Systematic calculations were conducted for various amplitude of oscillations and elevations of the disk from the seabed. Lavrov and Guedes Soares [15] investigated the laminar flow around various heaving oscillating axisymmetric structures at different Keulegan-Carpenter numbers using Navier-Stokes equations.

Two papers were devoted to the numerical investigation of the oscillation of rectangular plates based on CFD: one of the first papers devoted to numerical modelling of heave oscillations of 3D structures was the investigation of Atluri, et al. [16]. The authors used AcuSolve software based on the Finite Element method. Oscillations of a single square plate were calculated and the dependence of the KC number on the drag coefficient was investigated. Heave oscillations of the straked cylinder was also modelled by the authors. Wen-Jun, et al. [17] used FLUENT for modelling the oscillations of a square plate with the tapered edges. RANS equation with standard k −ε turbulent model and mesh with 510000 cells were used. The values of drag and added mass coefficients for plates with different forms of the edges were estimated.

It is seen from this review that there are only a few papers where 3D structures are investigated.

In the present paper the open source OpenFOAM software (http://www.openfoam.org/) is used for modelling the laminar flow near axisymmetric and 3D offshore structures oscillating in the vertical direction. The modelling is based on solving the Navier-Stokes equations using the pimpleDyMFoam solver of OpenFOAM. This solver is intended for solving the equations of flow of incompressible isothermal fluids using mesh motion including re-meshing. Calculations are conducted for the cylinder, the cylinder with one disk, the cylinder with 2 disks, and the cylinder with pentagonal plate. Keulegan–Carpenter number varies between 0.1 and 0.7. Results of calculations for cylinder, cylinder with disk, and disk are compared with experiments. Good agreement between the present calculations and experiments results allows to extend the model to offshore structures with various dimensions.

2. PROBLEM FORMULATION

For modelling the heaving oscillation of the various offshore structures in water the computational fluid dynamics code OpenFOAM is used. The schemes of the calculation domains are presented in Figure 1.

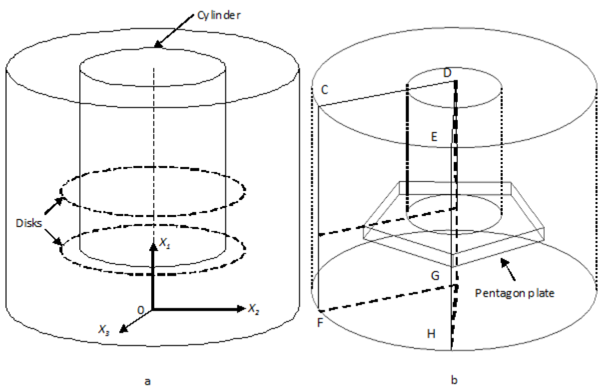

Figure 1: Schemes of the flow configurations for the structures in water (not in the scale). a: cylinder with 2 disks attached on the bottom region. b: cylinder with pentagon plate attached on the bottom.

The structure in water that consists of the vertical cylinder with 1 or 2 disks or with a pentagonal plate attached to the bottom has sinusoidal oscillations in the vertical direction. The cylinder has radius R, the distance between the centre of the pentagonal plate and its corner is R_p. Calculations are also conducted for the heave oscillations of the disk. Following Tao, et al. [13] calculations are conducted assuming that the flow is laminar. In accordance with Loitsanskii [18] the Navier-Stokes equations for the time-depended unsteady incompressible flow in Cartesian coordinates are written as:

$$\nabla(\vec{U}) = 0 \tag{1}$$

$$\frac{\partial \rho \vec{U}}{\partial t} + \nabla(\rho \vec{U} \otimes \vec{U}) = -\nabla \tau \tag{2}$$

where t is time, $\vec{U}$ stands for velocity vector with components u_1, u_2, u_3 in x_1, x_2, x_3 directions, ∇, Δ are, respectively, the gradient and Laplacian operators, the tensor τ_{ij} is the stress tensor in a Newtonian fluid and it general form is:

$$\tau_{ij} = -\delta_{ij} p + \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \tag{3}$$

where p is the pressure.

The structure is subjected to vertical sinusoidal oscillations:
$X_1 = X_1(0) + A sin(\omega t) \; for \; t > 0$

where $\omega = 2\pi/T$ is the circular frequency of the oscillations.

The vertical velocity of the structure is,

$$U_1 = \dot{X}_1 = A\omega cos(\omega t).$$

No-slip boundary conditions are set at the structure surface.

For the case of axisymmetric flow equations (1 - 3) may be transformed to axisymmetric form with velocities, u_1, u_2, respectively, in the axial and radial directions x_1, x_2, as for example in Tao and Thiagarajan [10].

Experimental results of Thiagarajan and Troesh [3] have shown that for used parameters ($A/D_c \leq 0.1$) disturbance of free surface is small. It allows do not include free surface wave contribution in numerical model, see also Tao, Thiagarajan, and Cheng [9].

Boundary conditions for axisymmetric case are:

B1: On the axis of symmetry, (Tao and Thiagarajan [10]), it is:

$$u_2 = 0, \frac{\partial u_1}{\partial x_2} = 0, \frac{\partial p}{\partial x_2} = 0.$$

B2: The experiments of Thiagarajan and Troesch [3] have shown that for the small vertical oscillations of the structure the disturbances on the water surface are small. It allows supposition that on the free surface the pressure is constant and the velocities are:

$$u_2 = 0, \frac{\partial u_1}{\partial x_1} = 0.$$

B3: At the far bottom boundary that is situated at the distance of $H_{max} = 10R$ from the structure, (see Tao and Thiagarajan [10]), it is also supposed that the velocities are:

$$u_2 = 0, \frac{\partial u_1}{\partial x_1} = 0.$$

B4: At the external boundary (see Figure 1a) that is situated far from the structure ($x_{2max} = 11R$, see Tao and Thiagarajan [10]) it is supposed that velocities are:

$$\frac{\partial u_2}{x_2} = 0, u_1 = 0.$$

From the geometry of the cylinder with pentagonal plate, see Figure 1b, it is obvious that the flow picture has rotational periodicity about the coordinate axis x_1. Accordingly, it is necessary to solve the Navier-Stokes equations in the block C, D, E, F, G, H, (Figure 1b), that is one/fifth of the whole domain.

For the cylinder with pentagonal plate the boundary conditions are:

BB1: Cyclic boundary conditions are used in the planes C, D, G, F and E, D, G, H.

BB2: On the free surface the pressure is constant and the velocities are:

$$u_2 = u_3 = 0, \frac{\partial u_1}{\partial x_1} = 0.$$

BB3: At the far bottom boundary that is situated at the distance of $12R_p$ from the structure, it is also supposed that the velocities are:

$$u_2 = u_3 = 0, \frac{\partial u_1}{\partial x_1} = 0.$$

BB4: At the external cylindrical boundary C, E, H, F (see Figure 1b) that is situated at the distance $12R_p$ from the coordinate axis x_1 it is supposed that velocities are:

$$u_1 = 0, \nabla(\vec{U}) = 0$$

The numerical grids for calculations were created using BlockMesh facility of OpenFOAM (axisymmetric case) and Pointwise (3D case). The views of the numerical grids for axisymmetric and 3D cases are presented in

Figure 2. In accordance with the recommendations of Tao and Thiagarajan [10] the grid spacing near the sharp edges of the cylinder, disks, and pentagon plate in x_1, x_2, x_3 directions is about $0.0005R$. In total the numerical grid has 22800, 27500, 29100 cells, 536800 (or 1029700 cells) respectively, for the cylinder, cylinder with 1 disk, cylinder with 2 disks, and cylinder with pentagon plate.

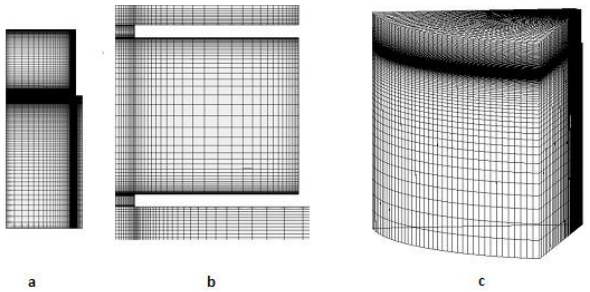

Figure 2: The grids for computations. a: General view of axisymmetric case. b: Cells distribution near the disks for axisymmetric case. c: General view of 3D case.

PimpleDyMFoam solver of OpenFOAM is used for solving the Navier-Stokes equations. It uses the PIMPLE algorithm on a moving mesh. The PIMPLE algorithm is based on the merging the PISO algorithm of Issa [19], and the SIMPLE algorithm of Patankar and Spalding [20].

Usually the Reynolds number *Re* for heave oscillations of cylinders with damping plates is calculated using as a characteristic values the diameter of the cylinder or plate and the maximum velocity of oscillations as in Tao et al. [9]. For the laboratory experiments of Thiagarajan, and Troesch [3] $Re \sim 10^4$–10^5, the boundary layer is laminar or in transition and it is possible to use Navier-Stokes equations. For real spar column, $Re \sim 10^7$ [13] and significant turbulence may develop [21]. But separation of boundary layer, as it is emphasized by Garrido-Mendonza et al. [21], takes place at the plate edge, the size of vortexes is big enough, it is approximately equal with the motion amplitude *A*. Taking into account all of the above it can be concluded that calculations in turbulent approach will not lead to significant differences. Nevertheless in future it is supposed to develop turbulent modelling of oscillations of spar column.

3. VERIFICATION OF RESULTS

For analyzing the heaving sinusoidal oscillations of the cylinder structure the semi-empirical Morison equation, e.g. Sarpkaya and Isaacson [22], is usually used. It has the form:

$$F(t) = \frac{1}{2}\rho S C_d u_1 |u_1| + \rho C_m \forall \dot{u}_1$$

where $F(t)$ is the force acting on oscillating structure, S is cross section area of cylinder or disk or pentagonal plate depending the structure components, C_d denotes the drag coefficient, $C_m = 1 + C_a$, C_a is added mass coefficient, $\forall$ is immersed volume, and $\dot{u}_1$ is structure acceleration.

The structure is subjected to sinusoidal oscillations and the Fourier average over the period allows getting equations for drag and added mass coefficients as

$$C_d = -\frac{3\omega}{4\rho S U_{1m}^2}\int_0^T F(t)\cos(\omega t)\,dt,$$

$$C_a = -\frac{1}{\pi\rho\forall u_{1m}}\int_0^T F(t)\sin(\omega t)\,dt$$

where $U_{1m} = A\omega$ is the maximum of velocity of oscillating structure, $\forall$ is immersed volume of the structure. The force *F(t)* is obtained using the formulations included in OpenFOAM.

Using the equivalent linear damping coefficient B it is possible to express drag force as

$$F_d(t) = BU_1(t)$$

In accordance with Sarpkaya and Isaacson [22] the equivalent linear damping coefficient may be presented as

$$B = \frac{1}{3}\mu\beta D_d (KC) C_d$$

In accordance with Tao, et al. [13] the non dimensional damping ratio Z for the cylinder with 1 disk (or the cylinder with 2 disks) can be presented as

$$Z = \frac{1}{3\pi^2} C_G \frac{C_d}{C_m}(KC)$$

and the geometric constant is

$$C_G = \frac{D_d^3}{(D_c^2 T_d + n D_d^2 t_d)}$$

where t_d is the thickness of the disk, and *n* is the number of the disks.

Thiagarajan and Troesch [2, 3] experimentally investigated the heave damping of a vertical cylinder, and one cylinder with disk. Their results are compared with the present calculations in Figure 3, showing a good agreement. The parameters of the experiments are presented in Table 1.

Table 1 Details of setup of experiments of Thiagarajan and Troesch [2, 3]

Diameter of cylinder	0.457m
Draft of cylinder	1.219m
Diameter of disk	0.609m
Thickness of disk	0.0254m
Period of oscillation	2.44s

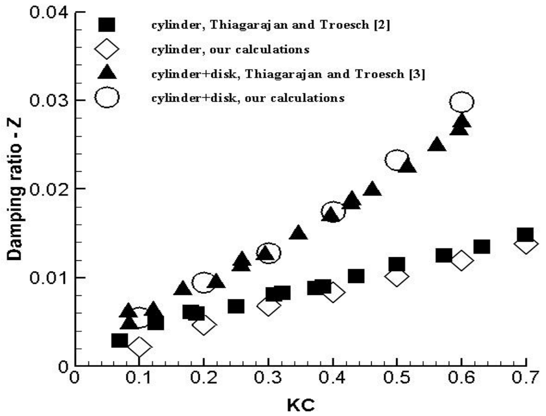

Figure 3: Comparison of experimental and numerical results for dependence of damping ratio on *KC* for cylinder and cylinder with disk.

Recently Tao, et al. [13] numerically investigated the oscillations of a spar column with 1, and 2 disks. The present calculations are compared with data of Tao, et al. [13] and hydrodynamics of oscillations for the KC numbers varying in the range of $0.1 \leq KC \leq 0.6$. The main specifications of the structures are presented in Table 2.

Table 2 Specifications of the spar column with one or two disks

Diameter of column	39m
Draft of column	198.1m
Diameter of disks, D_{d1}, D_{d2}, D_{d3}, D_{d4}	42.1, 51.2, 61, 78m
Thickness of disks	0.475m
Span (*L*)	9.15m, or 18.3m
Period of oscillation	28s

Comparison of the numerical results of Tao, et al. [13] for the spar column with 1 or 2 disks (*L*=18.3m) with the present calculations is shown in Figure 4. It is seen that the damping ratio obtained in both calculations agrees well.

Comparison of the present calculations of the force acting on the disk in the process of vertical oscillations with the experiments of Garrido-Mendoza, et al. [14] is presented in Figure 5. The disk diameter and thickness are, respectively, 0.2 and 0.002m, *KC*=0.6. It is seen from Figure 5 that the calculation agrees well with experiments.

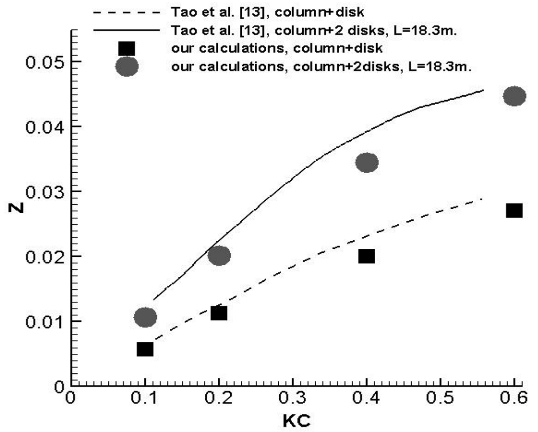

Figure 4: - Comparison of numerical results of Tao, et al. [13] and present calculations for spar column with 1 or 2 disks. D_d=51.2m.

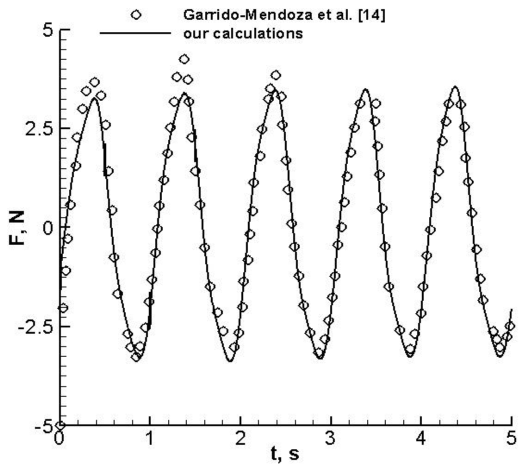

Figure 5 Comparison of experimental (Garrido-Mendoza, et al. [14]) and calculated dependence of force on time for disk, *T*=1s, *KC*=0.6

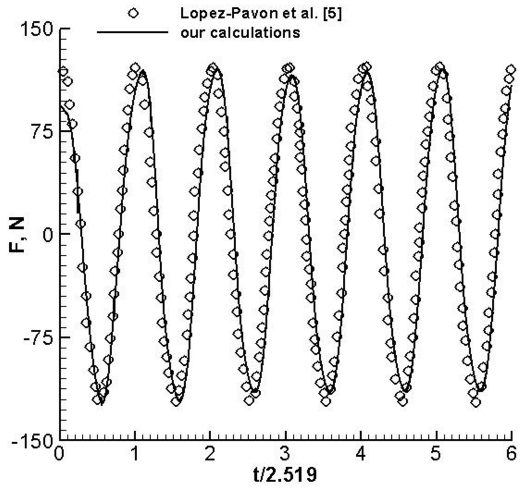

Figure 6: - Comparison of experimental, Lopez-Pavon, et al. [5] and calculated dependence of force on time for column with disk, D_c=0.35m, D_d=1m, *T*=2.519s, *A*=0.051m.

Comparison of the present calculations of the force acting on the model structure cylinder and disk in the process of vertical oscillations with experiments of Lopez-Pavon, et al. [5] is presented in Figure 6. It is seen from Figure 6 that the calculations agree well with experiments.

As a whole, the presented results of comparison of calculations with various experiments confirm that developed technique may be successfully used for investigation of peculiarities of oscillation of various structures.

4. OSCILLATIONS OF THE CYLINDRICAL COLUMN WITH ONE PLATE

Evolution in time of vortices dynamics for the cylindrical column with one plate for 28s<t≤56s is presented in Figure 7. The main parameters of the case are presented in Table 2, D_d=51.2m. Only the edge of the plate is shown in the Figure. During the first period the flow has transitory stage, and from the second period the flow demonstrates approximately a repetitive sequence of vortices incipience and movement. The calculations are started from the top dead point. For t=28s big vortices are seen in the bottom part of the picture that was created during the first period and small vortices near the disk edge. As the structure goes down (28s<t≤42s) the new small vortices are formed near the disk edge and go upward.

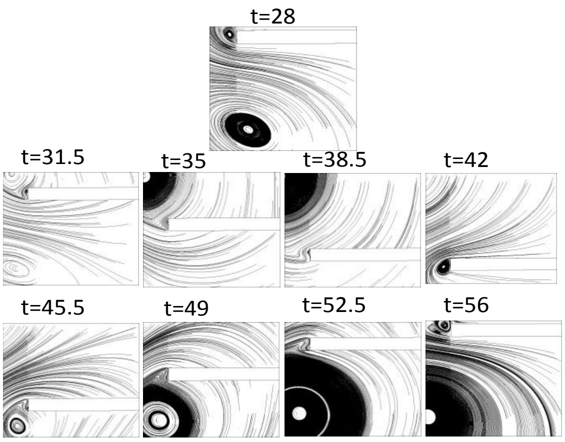

Figure 7: Evolution in time of vortices dynamic for spar column + disk. D_d=51.2m. KC=0.2.

When the disk goes upward from the bottom dead point (42s<t≤56s) the vortices that are formed near the disk edge go down. The dynamics of the vortices for other investigated disks diameters is similar to the time history shown in Figure 5. Similar time history of vortices dynamics was previously demonstrated by Tao and Thiagarajan [10] who used a home-made code. Figure 8 shows the dependence of the non-dimensional heave force on time for five periods for the cylinder with disk with various diameters. The main parameters of the structure are presented in Table 2, KC=0.2. The force is made dimensionless with the average amplitude of the force for the cylinder $< \mathrm{FF_c} >$:

$$F(t)_{nd} = \frac{F(t)}{<FF_c>}$$

In Figure 8 it is seen that the forces demonstrate a periodical character. During the first period the transitional regime is realized. For the four following periods it is seen that the force demonstrates the approximately repetitive sequence of periodical curves.

Figures 8, 9 shows that for a cylinder with disk the amplitude of the non-dimensional force varies from 1.2 to 8.9 as the D_d varies from 42.1m to 78m.

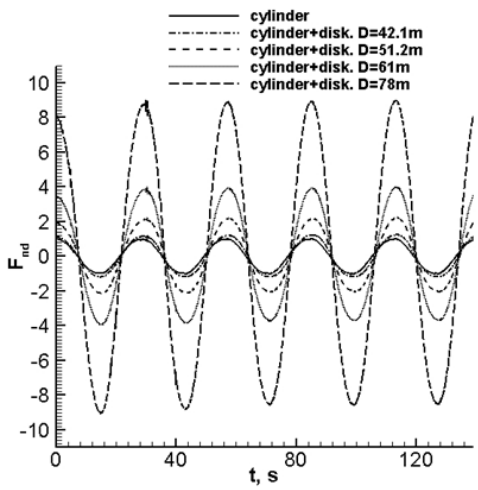

Figure 8: Dependence of non-dimensional force on time for cylinder with disk. The main parameters of the structures are presented in Table 2, KC=0.2.

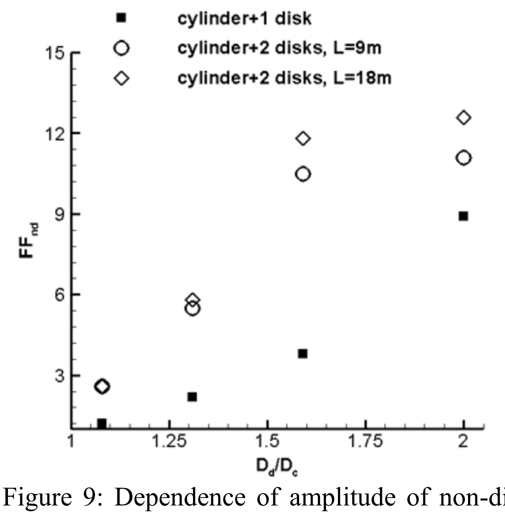

Figure 9: Dependence of amplitude of non-dimensional force on disk diameter for cylinder with 1 disk and cylinder with 2 disks.

As the disk diameter increases by 21% (from 42.1 to 51.2m) the amplitude increases 83%, and as the disk diameter increases 26% (from 51.2m to 78m) amplitude increases 134%.

The influence of the non-dimensional disk diameter D_d/D_c on amplitude of non-dimensional force FF_{nd} is illustrated in Figure 9. It is seen that this dependence has a nonlinear nature.

5. COMPARISON OF THE RESULTS FOR THE PROTOTYPE AND MODEL FOR THE CYLINDRICAL COLUMN WITH ONE DISK

It is well known that experiments for the heave oscillation of the axisymmetric structures are mostly conducted using models with the diameter of cylinder ~0.5 to 0.8m, and radius of disk ~0.6 to 1m. In the same time the real structures consists of cylinder with diameter ~10 to 40m and disks with diameter ~20 to 60m. That is why it very relevant to compare computational results for the spar column (prototype) and the model. In the present paragraph calculations for the model with the scale 1:60 are presented. Specifications of the prototype and the model are presented in Table 3.

Table 3 Specifications of the spar column and model with disk.

Magnitude	Spar column	Model
Diameter	39m	0.65m
Draft of column	198.1m	3.3m
Diameter of disks	42.1, 51.2, 61, 78m	0.702, 0.854, 1.018, 1.3m
Thickness of disk	0.475m	0.008m
Period of oscillation	28s	3.75s

The period of oscillations for the model is estimated using assumption that T is approximately proportional to the square root of draft of cylinder, as written by Tao, and Cai [12]. It is necessary also to mention that the value of T=3.75s agree well with the periods used in experiments of Thiagarajan, and Troesch [3], and Lopez-Pavon, et al. [5]. Dependence of amplitude of non-dimensional force on disk diameter for prototype and the model is presented in Figure 10.

It is seen that data for the model agrees well with data for the prototype. It is possible to conclude that the results of the experiments with models may be successfully used in process of design of spar columns.

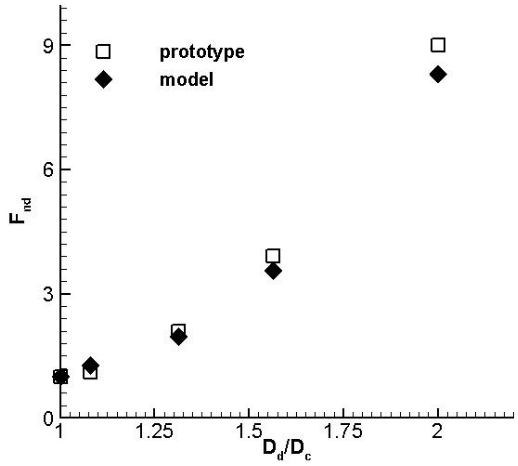

Figure 10: Dependence of amplitude of non-dimensional force on disk diameter for prototype and the model. Specifications of the prototype and model are presented in Table 3.

6. OSCILLATIONS OF THE CYLINDRICAL COLUMN WITH TWO DISKS

Evolution in time of vortices dynamics for spar column with 2 disks with D_d=78m, L=18.3m, KC=0.2 for 28s < t ≤ 56s is presented in Figure 11. Only the area near the disk edges is shown in the Figure. The main parameters of the case are presented in Table 2. During the first period the flow has a transitory stage, and from the second period the flow demonstrates approximately a repetitive sequence of vortices incipience and movement. The calculations are started from the top dead point. For t=28s it is seen two big vortices below the edges of the disks. They were formed during the first period. Also two small vortices exist directly near the disks edges. For t=31.5s these small vortices increase and move up. The new small vortices begin to form near the disks edges.

When the disk goes upward from the bottom dead point (42s<t≤56s) the vortices that are formed near the disk edge go down. Similar time history of vortices dynamics was previously shown by Tao, et al. [13].

Evolution in time of vortex dynamics for the cylindrical column with 2 disks with D_d=78m, L=9.15m, L/D_d=0.117, KC=0.1 for 56s < t ≤ 84s is presented in Figure 12. The areas near both disks and the areas near the up and down disk edges are shown in the Figure. It is seen that in this regime vortices from one disk don't interact with the vortices from another disk. It seems that regime of interaction of the vortices will be obtained if KC will increase and L/D_d decrease.

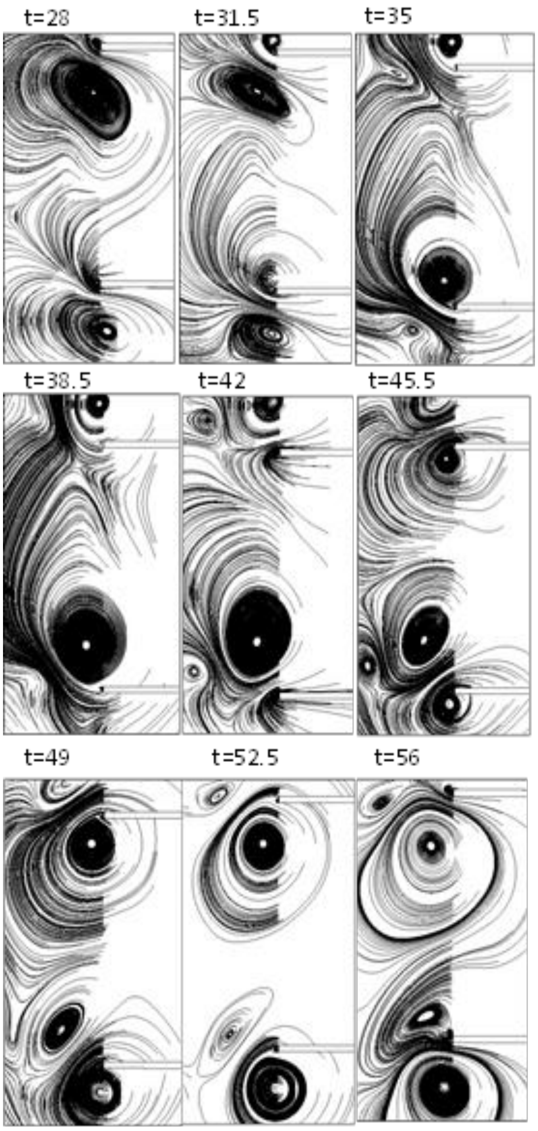

Figure 11: Evolution in time of vortex dynamics for a cylinder with 2 disks. D_d=78m. L=18.3m. KC=0.2.

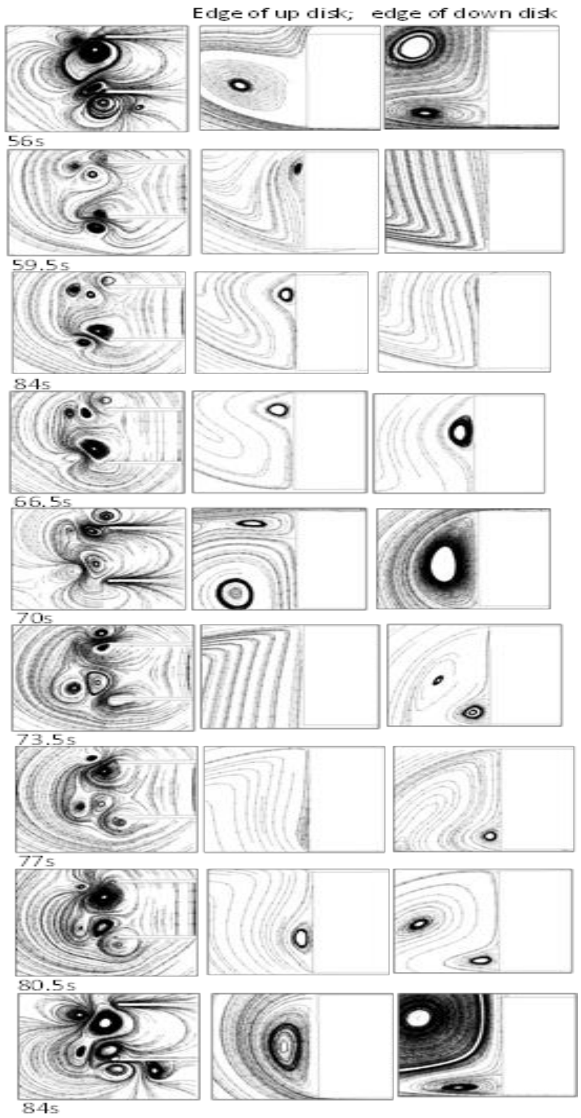

Figure 12: Evolution in time of vortex dynamics for a cylinder with 2 disks. D_d=78m, L=9.15m, KC=0.1. In the left column general view is shown. Vortices near up and down disks are shown, respectively, in the central and right columns.

Figure 13 shows the dependence of the non-dimensional heave force on time for five periods for the cylinder with 2 disks of 2 different diameters and spans. The main parameters of the structure are presented in Table 2, KC=0.2.

Similarly to the cylinder with one disk, during the first period a transitional regime exists. For the four following periods it is seen that the force demonstrates the approximately repetitive sequence of periodical curves.

It is seen from Figures 9, 13 that the amplitude of the heave force for the cylinder with 2 disks with D_d=51.2m is 2.1 times greater than for the cylinder with 1 disk. For D_d=51.2m the difference of force amplitude for L=9.15m or 18.3m is about 5%.

For the cylinder with 2 disks with D_d=78m amplitude of the heave force increases 27% (L=9.15m), and 40% (L=18.3m) in comparison with the amplitude for the cylinder with 1 disk.

Analysis of results obtained for the spar column with one or two disks shows that between the two possibilities of increasing the disk diameter or installing a second disk, it is preferable to increase the disk diameter.

Figure 9 shows the dependence of the amplitude of the non-dimensional force on the disk diameters for the cylinder with 2 disks for two values of span. It is seen that for D_d/D_c<1.3 the amplitudes of non-dimensional force are practically equal for spans 9 and 18m. As the

D_d/D_c increases the difference between results for two spans also increases.

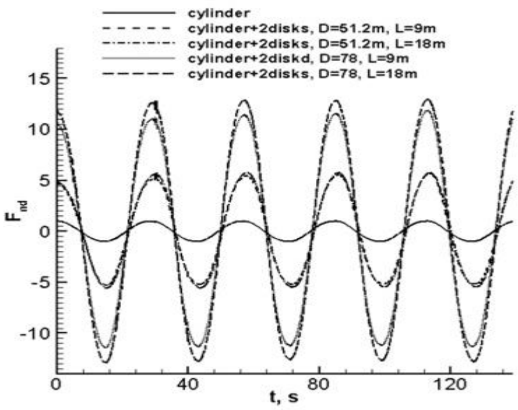

Figure 13: Dependence of non-dimensional force on time for cylinder + 2 disks. Main parameter of the structures are presented in Table 2, *KC*=0.2.

7. OSCILLATIONS OF THE CYLINDER WITH PENTAGON PLATE

Modelling of the heave oscillations of the cylinder with pentagon plate was conducted for prototype variant of Table 3. The value of R_p=11.5m was calculated taking into account that the square of the disk with radius 10m and pentagon plate are equal. The dependence on time of the force acting on the structure for the prototype variant for simulations using meshes of 536800, or 1029700 cells is presented in Figure 14. It is seen that results agree well.

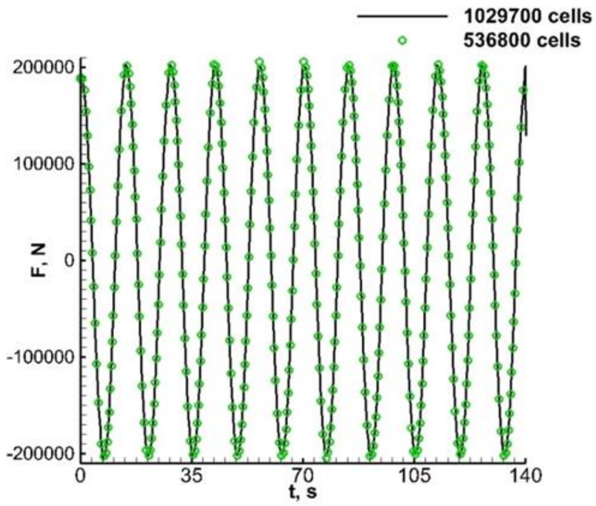

Figure 14: Dependence on time of the force for the cylinder with pentagonal plate. The main parameters of the structures are presented in Table 3.

The dependence on time of the force acting on the two structures (circle or pentagonal plate) for the prototype variant using a mesh with 1029700 cells is presented in Figure 15. It is seen that using the circle plate is preferable, but the difference of the maximum force acting on the plates is about 5%.

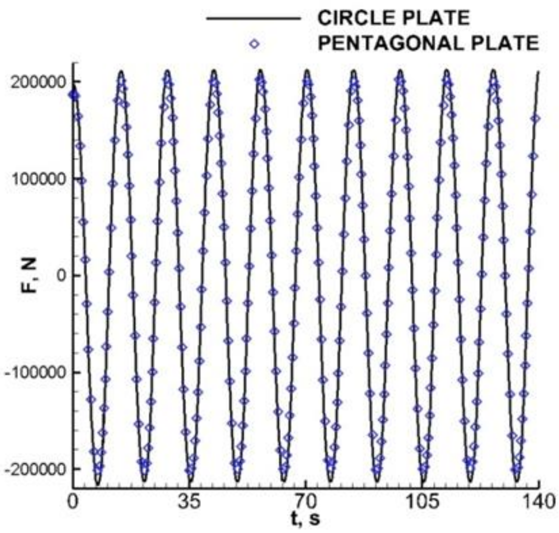

Figure 15: Dependence on time of the force for the variant using circle or pentagonal plate. The main parameters of the structures are presented in Table 3.

8. CONCLUSIONS

The open source software OpenFOAM was applied for the calculation of the heave oscillations of four structures: one cylinder, one cylinder with 1 disk, one cylinder with 2 disks, and one cylinder with one pentagon plate for various values of Keulegan-Carpenter number on the assumption that the flow is laminar. The automatic mesh motion technique included in OpenFOAM is successively used. The damping ratio for the cylinder and the cylinder with disk agrees well with the experimental data for KC numbers 0.1≤KC≤0.7. Calculations of the cylinder with 2 disks agree well with literature results. . It is possible to state that the employed solver pimpleDyMFoam is able to capture the flow fields' features for the various oscillating structures. The results obtained show that the methodology developed may be successfully used for calculation of damping ratio and forces acting on the real-scale offshore structures

The main new results may be formulated as following:

1. Calculations of heave oscillations for cylinder with big disk (D_a/D_c =2.86) are conducted. It shown that force acting on the structure agrees well with experiments of Lopez-Pavon, et al. [5].
2. Evolution in time of vortex dynamics for a cylinder with two big disks (D_a/D_c =2) is demonstrated.
3. Results of calculations demonstrate that, in general, it is preferable to increase the diameter of the single disk than to install a second disk.

4. Comparison of results for the oscillation of spar column (prototype) and the model with the scale 1:60 is presented. It is shown that data for the model agrees well with data for the prototype. It is possible to conclude that the results of the experiments with models may be successfully used in process of design of spar columns.
5. Using the pentagonal plate instead of circular disk does not cause significant change of force acting on the structure from water.

9. ACKNOWLEDGMENTS

This work was performed within the Strategic Research Plan of the Centre for Marine Technology and Ocean Engineering, which is financed by Portuguese Foundation for Science and Technology (Fundação para a Ciência e Tecnologia-FCT). The authors thank Prof. Antonio Souto-Iglesias (Technical University of Madrid, Spain) for making available the experimental data. The first author has been financed by the Fundação para a Ciência e Tecnologia, Portugal, through the grant SFRH/BPD/78137/2011.

10. REFERENCES

1. BAGBANCI, H.; KARMAKAR, D. and GUEDES SOARES, C., *Review of offshore floating wind turbines concepts*. Maritime Engineering and Technology, C. Guedes Soares, et al., editors, London: Taylor & Francis Group, pp. 553-562, 2012.
2. THIAGARAJAN, K. P. and TROESCH, A. W., *Hydrodynamic heave damping estimation and scaling for tension leg platform*. Journal of Offshore Mechanics and Arctic Engineering, 116, (3), pp. 70–76, 1994.
3. THIAGARAJAN, K. P. and TROESCH, A. W., *Effects of appendages and small currents on the hydrodynamic heave damping of TLP columns*. Journal of Offshore Mechanics and Arctic Engineering, 120, (1), pp. 37–42, 1998.
4. LAKE, M., HE, H.; TROESCH, A. W.; PERLIN, M. and THIAGARAJAN, K. P., *Scaling effects in hydrodynamic coefficient estimation of TLP and spar structures*. J. Offshore Mech and Arctic Eng, 122, pp. 118-124, 2000.
5. LOPEZ-PAVON, C., GARRIDO-MENDOZA, C. A., S.-IGLESIAS, A., *Hydrodynamic forces and pressure loads on heave plates for semi-submersible floating offshore wind turbines: A case study*. Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, OMAE2014 June 5-8, 2014, San Francisco, USA. OMAE2014-24163, 2014.
6. VU, K. H.; CHENU, B. and THIAGARAJAN, K. P., *Hydrodynamic damping due to porous plates*. *WSEAS/IASME Conferences,* August 17-19, Corfu, Greece, 2004.
7. HE, H.; TROESCH, A. W. and PERLIN, M., *Hydrodynamics of Damping Plates at Small KC Numbers*. Proceedings of the IUTAM Symposium held in Hamburg, Germany. July 23-26, Hamburg, Germany, 2008.
8. TAO, L. and DRAY, D., *Hydrodynamic performance of solid and porous heave plates*. Ocean Engineering, 35, (10), pp. 1006–1014, 2008.
9. TAO, L.; THIAGARAJAN, K. P. and CHENG, L., *On the parametric dependence of springing damping of TLP and Spar columns*. Applied Ocean Research, 22, (5), pp. 281–294, 2000.
10. TAO, L. and THIAGARAJAN, K. P., *Low KC flow regimes of oscillating sharp edges. I. Vortex shedding observation*. Applied Ocean Research, 25, (1), pp. 21–35, 2003.
11. TAO, L. and THIAGARAJAN, K. P., *Low KC flow regimes of oscillating sharp edges. II. Hydrodynamic forces*. Applied Ocean Research, 25, (1), pp. 53-62, 2003.
12. TAO, L. and CAI, S., *Heave motion suppression of a Spar with a heave plate*. Ocean Engineering, 31, (5-6), pp. 669– 692, 2004.
13. TAO, L., MOLIN, B., SCOLAN, Y.-M. and THIAGARAJAN, K. P., *Spacing effects on hydrodynamics of heave plates on offshore structures*. Journal of Fluids and Structures, 23, (8), pp. 1119–1136, 2007.
14. GARRIDO-MENDOZA, C. A.; SOUTO-IGLESIAS, A. and THIAGARAJAN, K.P., *Numerical simulation of hydrodynamics of a circular disk oscillating near a seabed*. Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering OMAE2013. June 9-14, Nantes, France. OMAE2013-11072, 2013.
15. LAVROV, A. and GUEDES SOARES, C., *On the influence of damping plates on the vertical oscillations of cylinders*. Maritime Technology and Engineering, C. Guedes Soares & T. A. Santos, editors: Taylor & Francis Group, London, UK, pp. 1169-1176, 2015.
16. ATLURI, S., MAGEE, A., and LAMBRAKOS, K., *CFD as a design tool for hydrodynamic loading on offshore structures*. Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering OMAE2009. May 31 - June 5, Honolulu, USA. OMAE2009-79502, 2009.
17. WEN-JUN, S., YOU-GANG, T., and LI-QIN, L., *Research on the hydrodynamic characteristics of heave plate structure with different form edges of a spar platform*. China Ocean Eng., 26, (1), pp. 177 – 18, 2012.
18. LOITSYANSKII, L.G., *Mechanics of Liquids and Gases*. Oxford. Pergamon Press, 1966.

19. ISSA, R. I., *Solution of the implicitly discretised fluid flow equations by operator-splitting*. J. Comput. Phys., 62, (1), pp. 40–65, 1986.
20. PATANKAR, S. V. and SPALDING, D. B., *A calculation procedure for heat mass and momentum transfer in three dimensional parabolic flows*. Int. J. Heat Mass Transfer, 15, (10), pp. 1787-1806, 1972.
21. GARRIDO-MENDONZA, C. A. THIAGARAJAN, K. P. SOUTO-IGLESIAS A. COLAGROSSI, A. and BOUSCASSSE, B., *Computation of flow features and hydrodynamic coefficients around heave plates oscillating near a seabed*. J. of Fluids and Structures, 59, pp. 406-431, 2015.
22. SARPKAYA, T. and ISSACSON, M., *Mechanics of wave forces on offshore structures*. New York: Van Nostrand Reinhold, 1981.