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Heave Plates – The Influence of the Plate-Diameter-to-Cylinder-Diameter Ratio, Holes, and Pitch on the Hydrodynamic Coefficients

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ABSTRACT

The paper presents the results of calculations of the hydrodynamic coefficients of the heave plate using RANSE-CFD (Reynolds-Averaged Navier-Stokes Equations - Computational Fluid Dynamic). The obtained values were confirmed by research results available in the literature and were used to draw new conclusions on the studied issue. The calculations were performed for a wide range of Keulegan Carpenter (KC) numbers from 0.15−6.2. Plates with different plate-diameter-to-cylinder-diameter ratios (Dp/Dc = [1.4;2;4;6]) were tested, and it was found that for a KC number < 2, the greatest damping occurs for plates with a Dp/Dc ratio > 4, while for a KC number > 4.5, the opposite situation occurs and one can observe a higher damping coefficient and a lower plate diameter ratio. The influence of holes evenly distributed in a circular array in the plate on the values of hydrodynamic coefficients was investigated; for a KC number < 2, they cause an increase in the damping coefficient, but they should be used on plates with a higher plate-diameter-to-cylinder-diameter ratio. Moreover, it was shown that in the case of the combined motion of heave + pitch, the obtained values of the damping coefficient are lower than in the case of isolated motion, and it was suggested that this could be prevented by using an additional vertical plane at the edge of the plate to prevent the vortices from sliding off the plate surface.

Keywords: heave plate, damping coefficient, floating offshore wind turbines (FOWTs)

INTRODUCTION

With the growing interest in floating wind platforms, there are also a growing number of studies on heave plates, which are supposed to increase the damping of the structure and thus reduce its movement due to waves. Initially, these elements were considered only in relation to SPAR structures. Tao et al. [1] analyzed the influence of different geometries on the vertical movement of the classic SPAR-type structure, including the heave plate, indicating that it was the best of those analyzed. The concept of additional plates can, however, be easily applied to other types of platforms. Jang et al. [2] showed the benefits of using heave plates for multi-unit floating offshore wind turbine (MUFOWT) construction. Assidiq et al. [3] examined the effect of vertical damping plates on pitch, showing that plates with holes provide better damping than solid plates. The problem of damping plates has been taken up by many researchers. Extensive analyses of damping plate effects were conducted by Subbulakshmi and Sundaravadivelu [4]. These authors examined various plate configurations, depending on their diameter and position, and double plates. Among the conclusions drawn by these authors is that the optimal plate-diameter-to-cylinder-diameter ratio Dp/Dc = 1.2–1.4, which was not confirmed by this research. Medina-Manuel et al. [5] investigated the value of hydrodynamic coefficients as a function of the Keulegan Carpenter (KC) number using forced oscillations and obtained results consistent with those available in the literature. They also noted that the values of the coefficients determined using free oscillations differed from those obtained using forced oscillations.

Rao et al. [6] examined the effect of the plate position relative to the cylinder bottom on the damping coefficient. Of the tested configurations, the best was that in which the plate was located at the end of the cylinder, but the authors noted that the configuration with two plates could be more advantageous if the distance between the plates were increased.

Turner et al. [7] compared the results obtained by different researchers, which allows an easy comparison of results. Of particular interest in their work are the graphs showing the dependence of the added mass coefficient CA (Fig. 1) and the damping coefficient CB (Fig. 2) on the KC number.

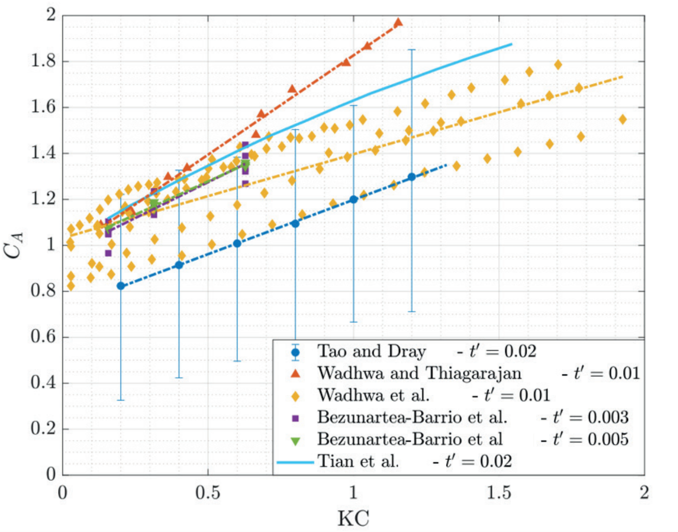


Fig. 1. Added mass coefficient from Turner et al. [7]

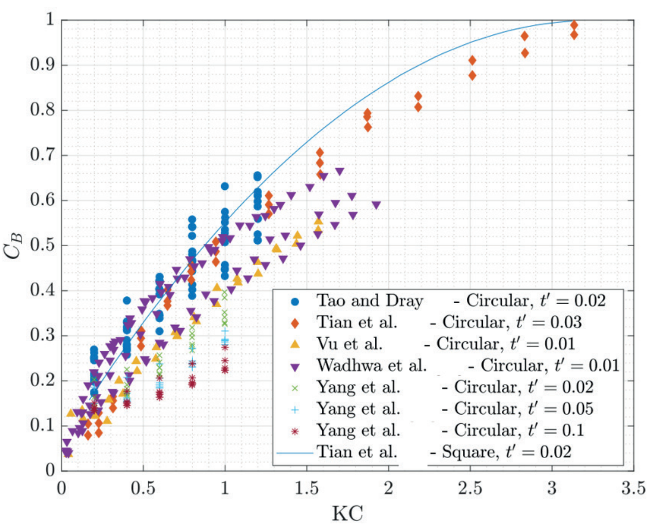


Fig. 2. Damping coefficient from Turner et al. [7]

The comparison of results was prepared based on the work of different researchers. The results of the work referred to Tao and Dray [8], who, in addition to solid plates, also tested porous plates. The research they presented shows that the damping of perforated plates is greater than that of solid plates for small KC values. They obtained the greatest increase in damping in relation to the solid plate (by 30%) for a porosity of 20% at a frequency of f = 0.1 Hz for KC = 0.2.

The results of Wadhawa and Thiagarajan [9] were obtained on the basis of experimental studies for a plate oscillating near the free surface. Meanwhile, Wadhawa et al. [10] provided the results obtained for the disk near the bottom.

Bezunartea-Barrio et al. [11], by determining the values of the hydrodynamic coefficients, showed that they depend on the KC coefficient, and the effect of scale is not significant in this case.

Tian et al. [12] also checked perforated plates. Their results show that for KC numbers < 0.75, the damping coefficient of perforated plates is slightly higher than that of solid plates. These differences are greater for lower KC numbers and decrease as the KC number increases. For KC = 0.15, they even reach 50%.

Vu et al. [13] also investigated the effect of perforation, confirming the increase in the damping coefficient for perforated plates at low KC numbers.

Yang et al. [14] examined the values of hydrodynamic coefficients in the current. They noticed that as the current speed increases, the value of the accompanying mass coefficient decreases.

A review made by Ezoji et al. [15] focused on the hydrodynamic coefficients for heave plates only at small KC numbers. They summarized the influence of many factors, such as the oscillation frequency, plate thickness, the plate's distance from the free surface and from the bottom, and the percentage of perforations on the damping value. They noticed that when the amplitude of motion is small, viscous damping from vortex shedding is proportional to the edge length. Hence, the conclusion is that cutting holes in the plate by increasing the edge length increases the damping. Ciba [16] reached similar conclusions by analyzing the motion of a cylinder with a heave plate reduced to a small edge extending beyond the cylinder outline. The results of free oscillation tests carried out for a smooth cylinder, a cylinder with a solid plate, and a cylinder with a plate with holes presented by Ciba et al. [17] confirmed these assumptions. Subsequent work presented by Ciba and Dymarski [18] based on forced oscillation tests made it possible to investigate the effect of the oscillation frequency on the values of hydrodynamic coefficients.

In connection with the above, in this work it was decided to investigate the effect of the plate-diameter-to-cylinder-diameter ratio Dp/Dc on the damping coefficient value for a wide range of KC numbers. In addition, the effect of the position and diameter of the holes on the damping coefficient value was checked for selected cases in an attempt to obtain practical design guidelines. It was also shown that in the case of the combined motion of heave + pitch, the damping coefficient values are lower than in the case of the isolated motion heave.

GOVERNING EQUATION

The coefficients are defined based on the following equation of motion:

$$F_{33} = (M + A_{33})\ddot{z} + B_{eq}\dot{z} + C_{33}z, \quad (1)$$

where F_{33} is the vertical external force applied to the structure, M is the mass of the structure, A_{33} is the additional mass in the vertical direction, B_{eq} is the damping coefficient, and C_{33} is the stiffness coefficient related to hydrostatic buoyancy.

The coefficients are defined as follows:

$$C_A = A_{33}M', \quad (2)$$

$$C_B = \frac{B_{eq}}{2M'\omega}, \quad (3)$$

where M' is the theoretical mass of water added for a cylinder of diameter D, determined based on the potential flow, and ω is the angular frequency:

$$M' = \frac{1}{3}\rho D^3. \quad (4)$$

A similar approach can be followed for the other motions. In the case of angular motions, for instance, pitch motions, the uncoupled equation of motion (now with moment terms) becomes

$$M_{55} = (I_{yy} + A_{55})\ddot{\theta} + B_{55}\dot{\theta} + C_{55}\theta, \quad (5)$$

where M_{55} is the moment about the y-axis, I_{yy} is the moment of inertia about the y-axis, A_{55} is the additional moment of inertia due to added mass, B_{55} is the damping coefficient, and C_{55} is the stiffness coefficient related to hydrostatic buoyancy

NUMERICAL IMPLEMENTATION

The values of the hydrodynamic coefficients CA and CB were determined using RANSE-CFD calculations in the Star CCM+ program. Calculations of the following oscillation tests were performed:

- Free: The dynamic fluid body interaction (DFBI) model, which allows the body to be modeled as a rigid body, is used. In this case, the mass and position of the object's center of mass, moments of inertia, and initial velocity were defined. These calculations were performed with three degrees of freedom (heave, surge, and pitch).
- Forced: A specific object trajectory (oscillatory vertical movement with an amplitude zA = 0.025 m and an oscillation period T = 2 s) is set.

In both cases, overset meshes were used, enabling the movement of the domain surrounding the object inside the stationary domain, which constitutes the object's surroundings.

The k-ε turbulence model was used.

Due to the wide range of KC numbers for which the calculations were performed, resulting in different plate diameters with the same excitation amplitude and different main cylinder diameters, the generated meshes were also different. The plate thickness was also variable, because the plate-thickness-to-plate-diameter ratio th_plate/D_plate = 0.02 was maintained.

Fig. 3 presents the mesh independence test for the case of a clean plate without a cylinder. Based on the obtained results, it can be concluded that mesh densification above 9 million elements does not significantly change the obtained coefficient values.

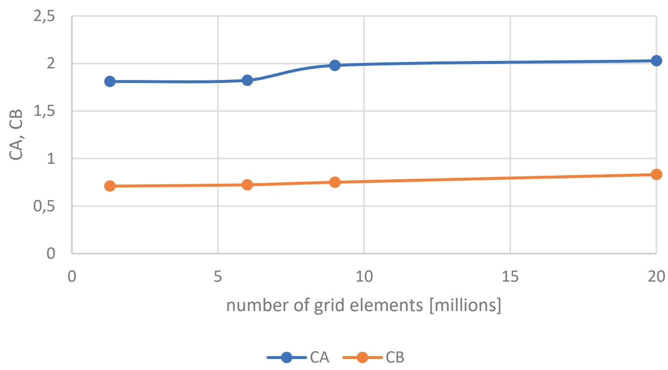


Fig. 3. Mesh independence

Calculations were performed on meshes with 9.3 million elements (Fig. 4), a time step of 0.005 s, and 5 internal substeps, achieving the residual values presented in Table 1.

Tab. 1. The values of the residuals

Parameter	Residual
Turbulent dissipation rate (Tdr)	1e-4
Turbulent kinetic energy (Tke)	1e-5
Continuity	3e-4
X-momentum	4e-3
Y-momentum	4e-3
Z-momentum	2e-4
Air	4e-4

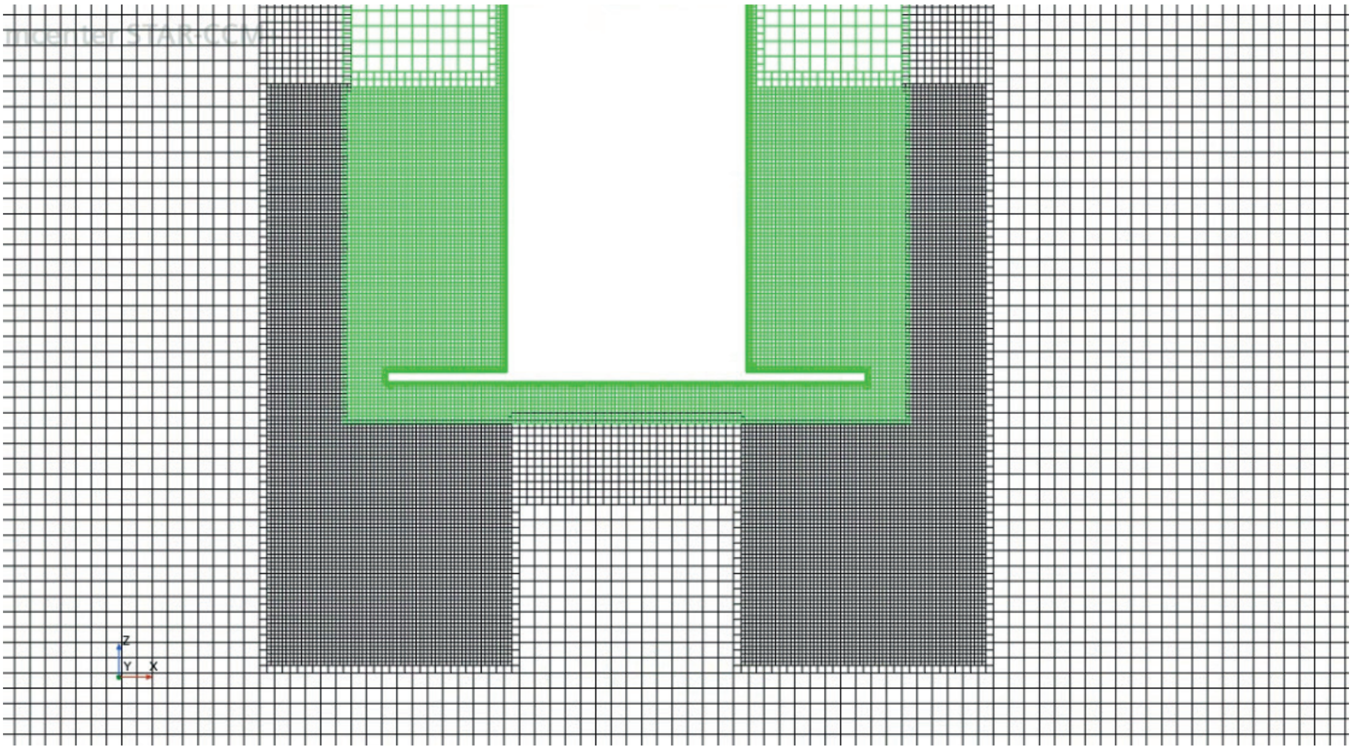


Fig. 4. Mesh used near the cylinder; moving part–green, stationary part–black

An example of a moving grid near the hole is shown in Fig. 5.

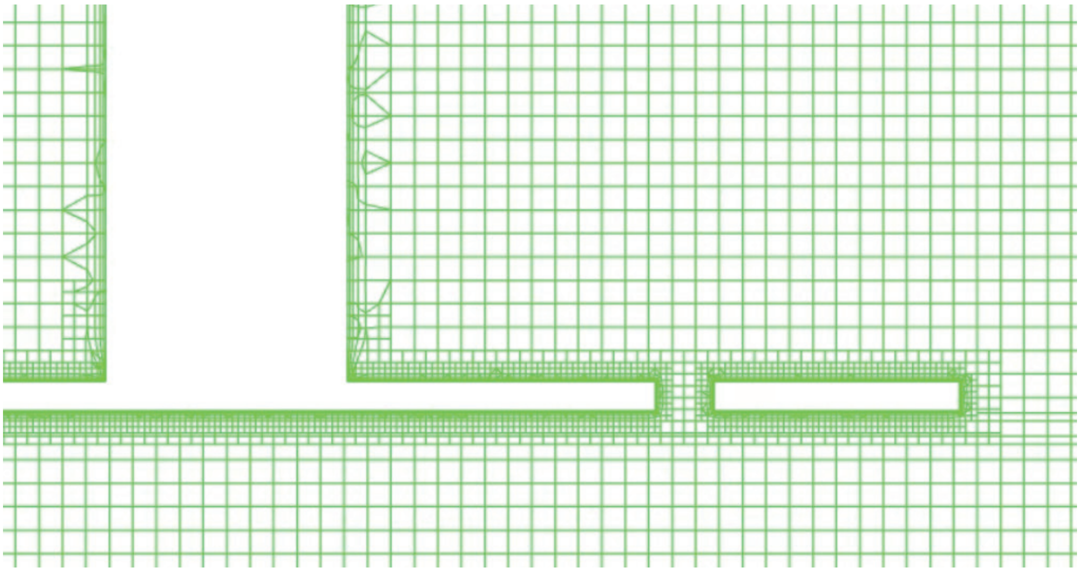


Fig. 5. View of the mesh surrounding the hole

For free-diving tests, hydrodynamic coefficients were determined according to Journee and Massie [19] based on the values of subsequent deflection amplitudes, determining the average amplitude.

In the case of forced oscillations, the coefficients were determined based on the force acting on the object integrated over time based on formulas available in the literature [18].

The forced oscillation test is carried out by causing the object to oscillate. The in-phase excitation force component is related to inertia and stiffness, while the out-of-phase component is related to damping.

VALUES OF THE DAMPING COEFFICIENT CB AND THE COEFFICIENT OF ADDED MASS CA DEPENDING ON THE PLATE-DIAMETER-TO--CYLINDER-DIAMETER RATIO DP/DC DEPENDING ON THE KC NUMBER

The obtained values for solid plates are presented in Fig. 6.

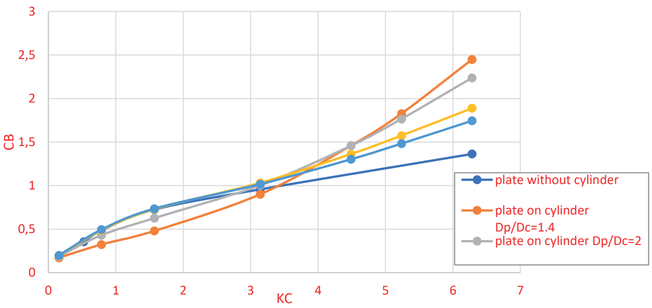


Fig. 6. The values of the damping coefficient

The first thing that can be noticed is that for KC numbers less than 2.5, the damping coefficient increases with the ratio of the plate diameter to the cylinder diameter, while for KC numbers greater than 4.5, the situation is the opposite – a higher damping coefficient appears for plates with a smaller diameter compared to the cylinder diameter. The calculations were carried out for a constant amplitude of movement, so that the increase in the KC number is related to the decrease in the plate diameter. The explanation for this phenomenon may be the fact that when the plate diameter is large compared to the diameter of the vortices generated during movement on its edges, its damping action requires a suitably large area extending beyond the cylinder edge, which can be observed by comparing the vortex structures generated for KC = 0.5 for plates with ratios Dp/Dc = 2 and Dp/Dc = 1.4 (Fig. 7). The area of the upper part of the plate in the case of Dp/Dc = 1.4 is too small to develop a vortex of the same diameter as the vortex developed in the case of a larger plate, and an additional vortex structure appears above the plate.

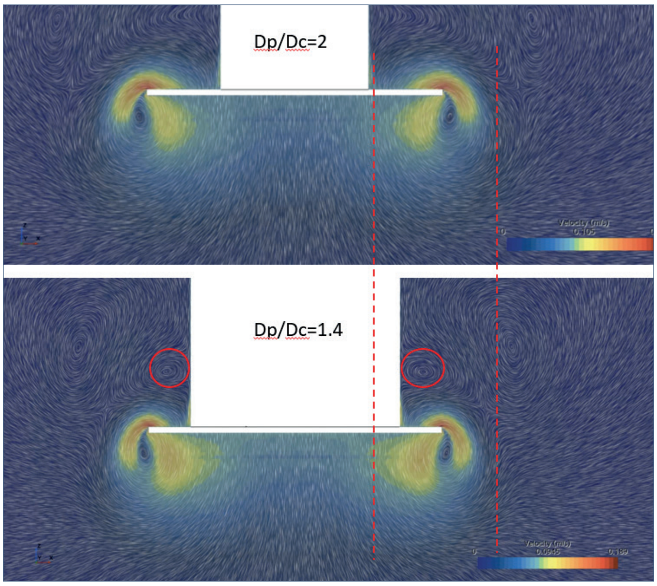


Fig. 7. Comparison of vortex structures for plates with Dp/Dc ratios of 2 and 1.4 for KC = 0.5

In the case of a small plate, i.e., for a KC number > 4.5 (Fig. 8), the main working area of the plate is its lower part, and then the situation is reversed; the presence of the vertical cylinder wall does not allow the speed to increase in this area, which results in greater damping than in the case when the cylinder has a small diameter.

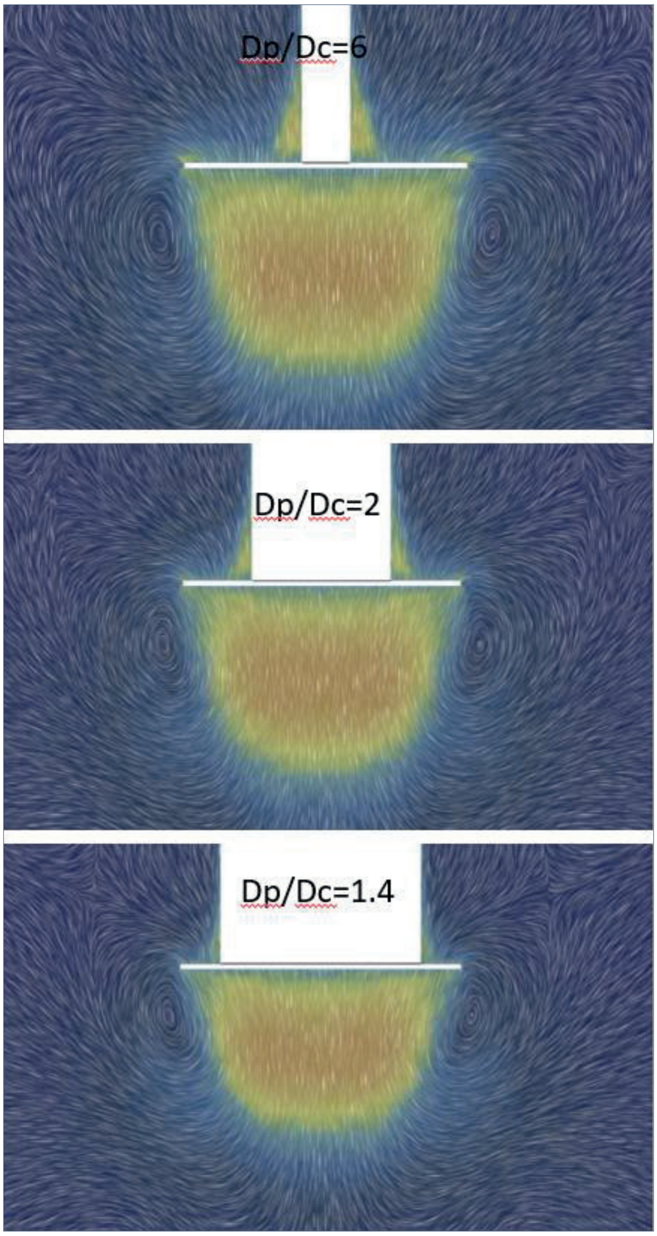


Fig. 8. Comparison of vortex structures for plates with Dp/Dc ratios of 6, 2, and 1.4 for KC = 4.5

In the case of the mass of added water (Fig. 9), the situation is similar, i.e., for a KC number < 2.5, the larger the plate-diameter-to-cylinder-diameter ratio, the larger the added water mass coefficient. Here, however, it was observed that a plate 4 times larger than the cylinder gives the same added water mass coefficient as the plate itself, without the cylinder. For a KC number > 4.5, the opposite situation occurs, i.e., an increase in the plate-diameter-to-cylinder-diameter ratio results in a decrease in the added water mass coefficient.

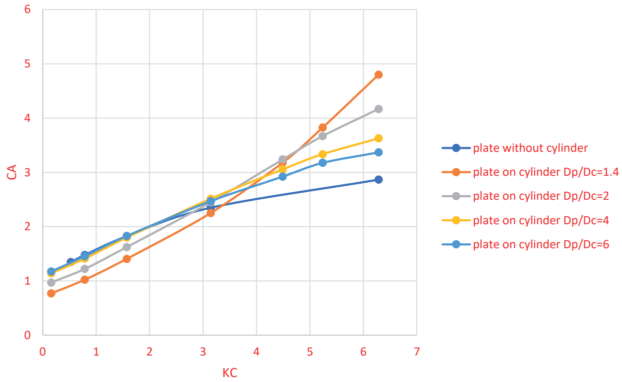


Fig. 9. The values of the added mass coefficient

COMPARISON OF THE OBTAINED RESULTS WITH THE VALUES IN THE LITERATURE

Most of the conducted studies focus on small KC numbers, because these are the most common KC values in practice. The results obtained from the presented calculations are very similar to those presented in the literature (Figs. 10 and 11).

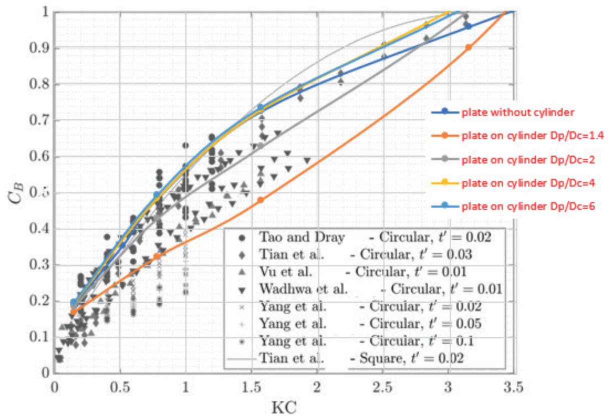


Fig. 10. Comparison of the obtained CB results with the values in the literature [7]

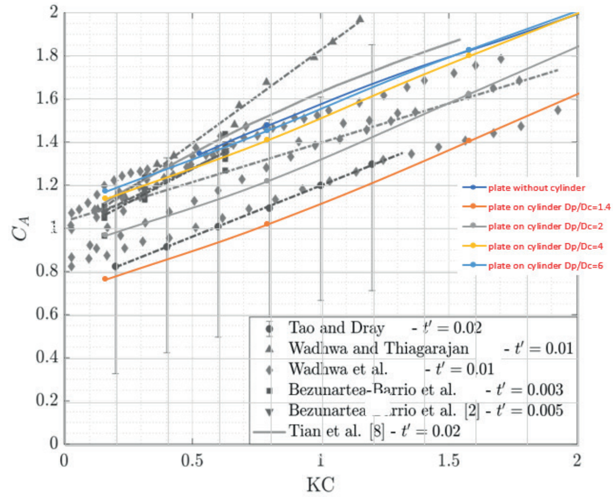


Fig. 11. Comparison of the obtained CA results with the values in the literature [7]

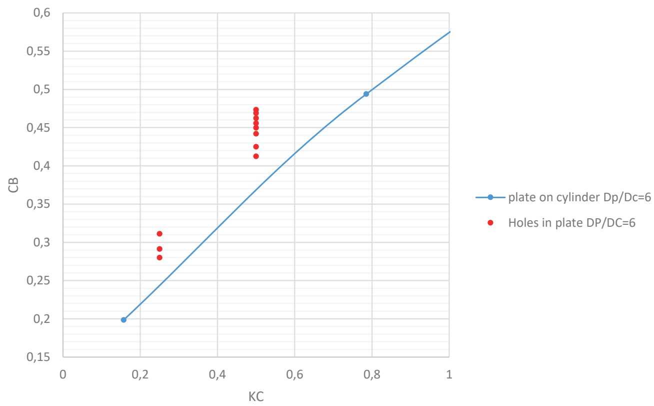


Fig. 13. The value of the CB coefficient for a plate with Dp/Dc = 6, showing the influence of holes

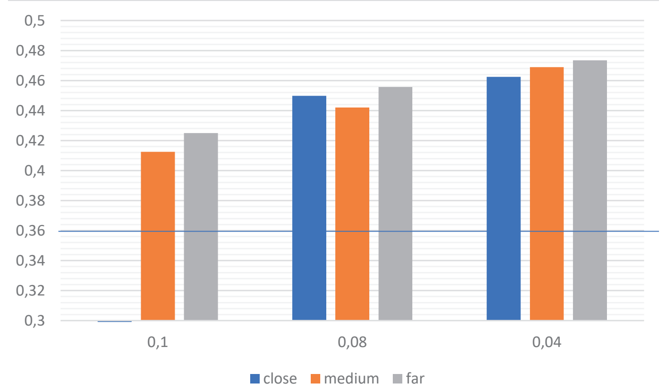


Fig. 14. The value of the Cb coefficient for a plate with Dp/Dc = 6 for KC = 0.5, showing the influence of the position of the holes

THE INFLUENCE OF HOLES ON THE VALUES OF HYDRODYNAMIC COEFFICIENTS

The concept of a perforated plate is used in the literature. In some cases, for small KC numbers, perforation increases the damping coefficient. Here, plates with holes were analyzed; they are not equivalent to perforated plates. Perforated plates have a uniform distribution of holes, while the holes analyzed here were made on the same diameter; additionally, the influence of both the size of the holes and their distance from the cylinder edge were examined (Fig. 12).

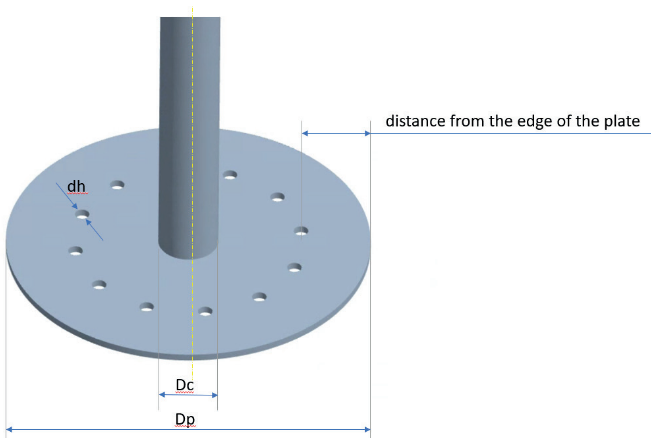


Fig. 12. Hole configuration

The influence of holes in a plate with a large plate-diameter-to-cylinder-diameter ratio Dp/Dc = 6 (Figs. 10, 11, 15, and 16) and a plate with a small Dp/Dc = 1.4 (Figs. 20 and 21) was analyzed.

The influence of the size of the hole and its position was also checked.

In the case of a larger plate, a significant increase in the damping coefficient of up to 31% was obtained for KC = 0.5.

In the range studied, the smaller the holes, the greater the damping. It can also be seen that greater damping occurs when the holes are located further from the cylinder surface. Comparing the velocity field for a plate with a ratio Dp/Dc = 6 for KC = 0.5, it can be seen (Fig. 15) that placing the holes closer to the free edge causes greater flow disturbance.

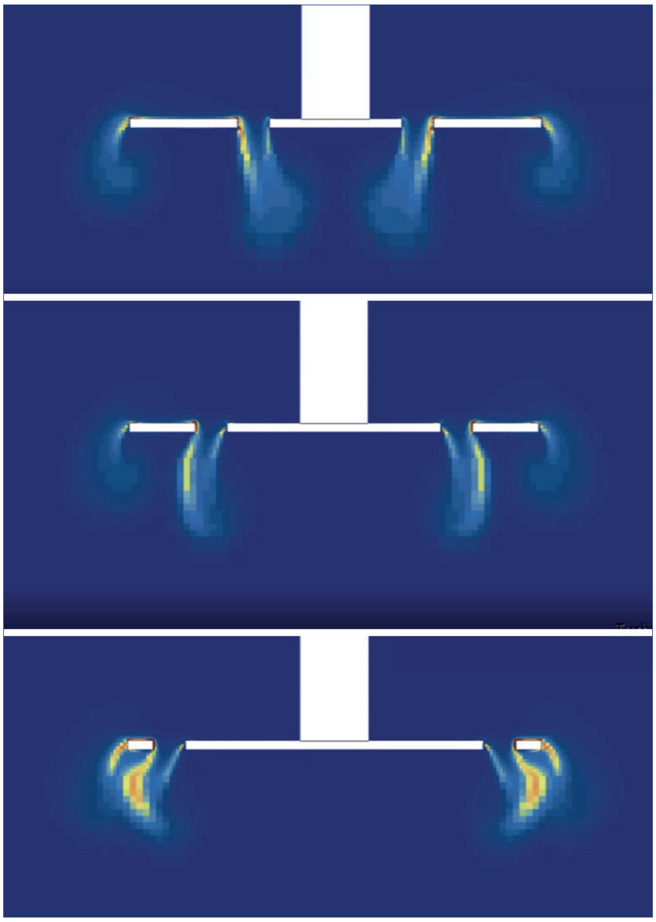


Fig. 15. Velocity field depending on the hole position for KC = 0.5

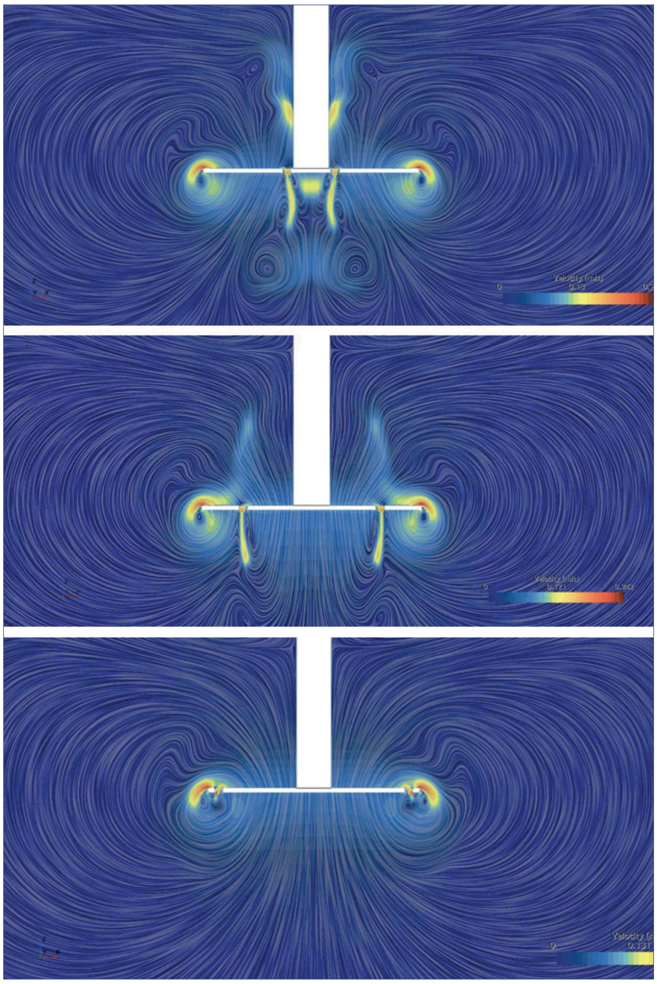


Fig. 17. Velocity field depending on the hole position for KC = 0.25

For the larger plate (KC = 0.25), the influence of the position of holes with a diameter ratio of φ/Dp = 0.04 was investigated, and here, in turn, higher values of the damping coefficient were obtained for holes located closer to the cylinder edge. Comparing the velocity fields (Fig. 17), it can be seen that the greatest flow disturbances appear in this case.

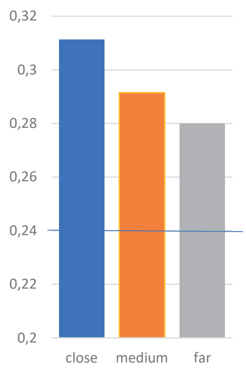


Fig. 16. The value of the Cb coefficient for a plate with Dp/Dc = 6 for KC = 0.25, showing the influence of the position of the holes

The values of the water mass coefficient for larger holes were lower than for the full plate, while for smaller holes, they were slightly higher. This is an unexpected result, but it may be due to the approximation of the value for the full plate.

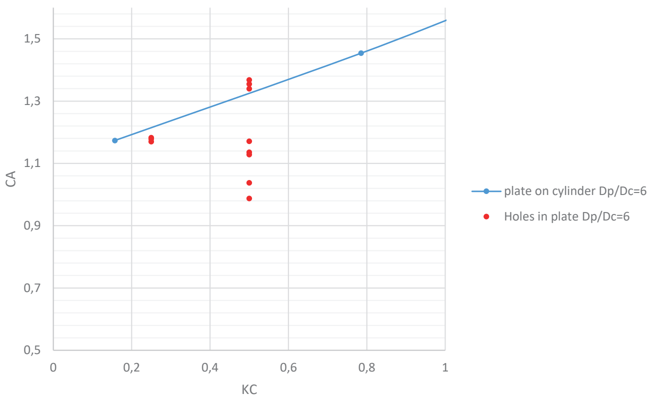


Fig. 18. The value of the CA coefficient for a plate with Dp/Dc = 6, showing the influence of holes

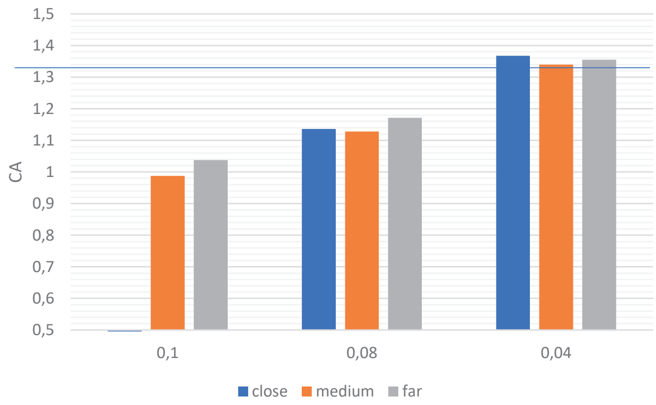


Fig. 19. The value of the CA coefficient for a plate with Dp/Dc = 6, showing the influence of holes for KC = 0.5

For a plate with Dp/Dc = 1.4, the damping coefficient assumed values similar to those for a solid plate.

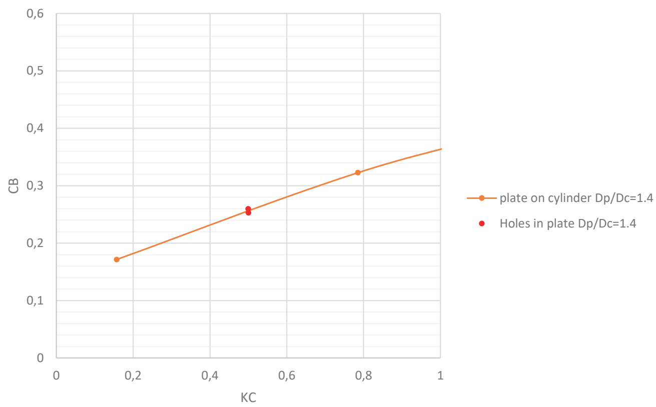


Fig. 20. The value of the CB coefficient for a plate with Dp/Dc = 1.4, showing the influence of holes

A slightly higher damping coefficient value was obtained for holes located further from the cylinder surface (Fig. 18), most likely because when the holes were cut very close to the cylinder surface, no clear vortex structure appeared at that location (Fig. 22).

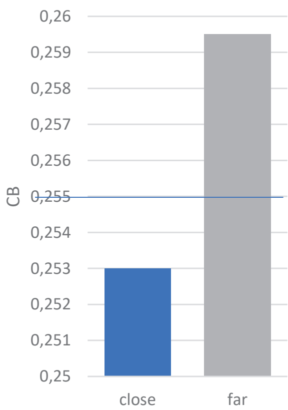


Fig. 21. The value of the CB coefficient for a plate with Dp/Dc = 1.4, showing the influence of the positions of the holes

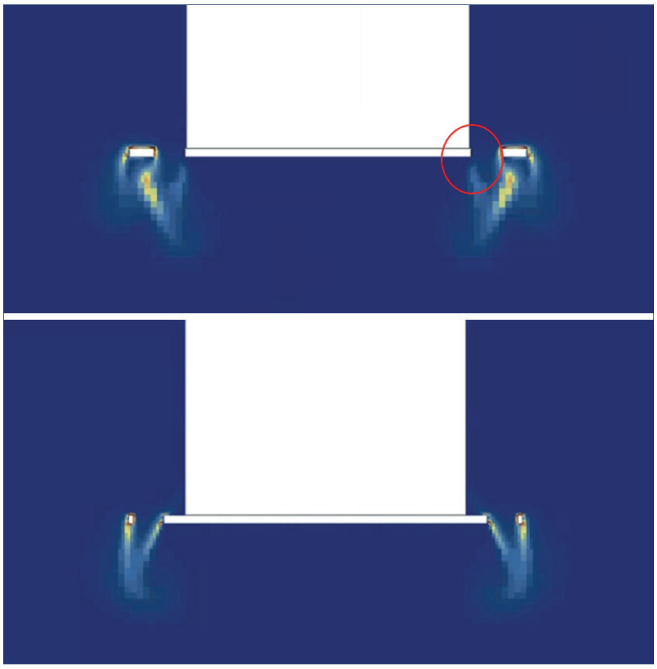


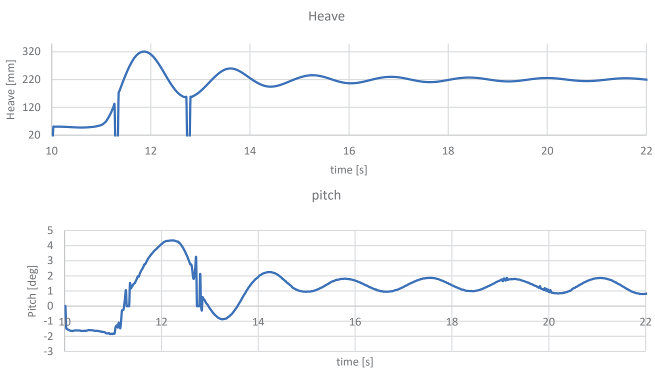
Fig. 22. Velocity field depending on the hole position for Dp/Dc = 1.4

In this case, the added water mass coefficient assumed slightly lower values than for the solid plate, and higher values were observed for the holes located further from the cylinder edge.

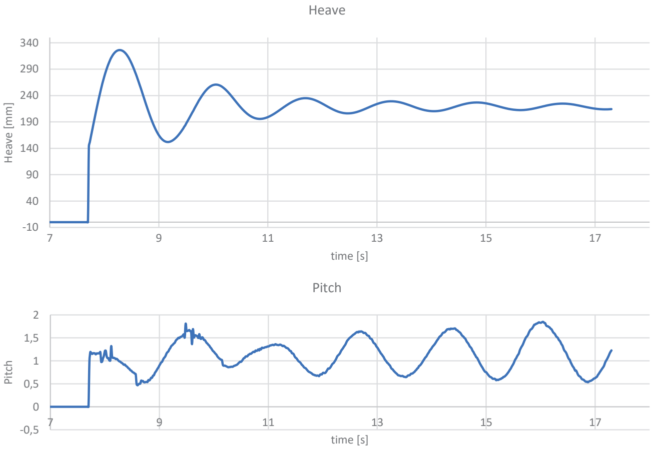
INFLUENCE OF PITCH MOTIONS ON THE DAMPING COEFFICIENT

In laboratory conditions, a free oscillation test is sometimes performed to determine hydrodynamic coefficients for floating objects. Compared to the forced oscillation test, this is a much easier test to perform, because it does not require additional devices forcing motion. However, the disadvantages of this method are that it only provides an answer for the frequency of natural oscillations, the amplitude of motion is variable, and it is almost impossible to isolate motion in one direction. For the three series of tests performed, additional swings occurred each time (Fig. 23).

Series 1



Series 2



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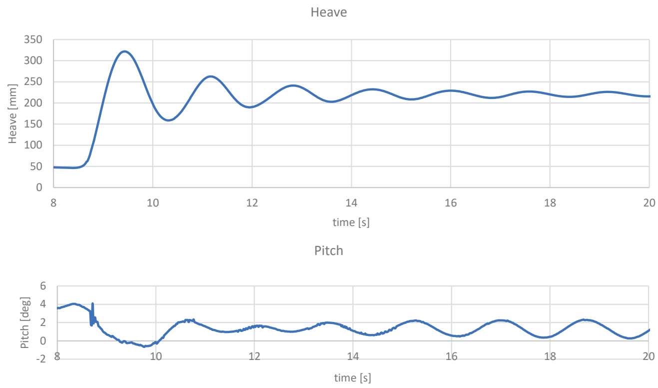
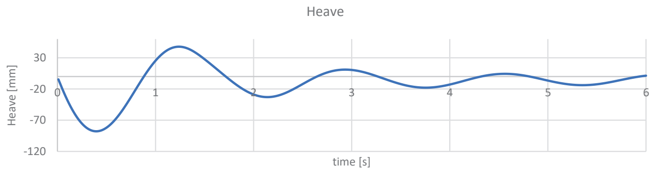


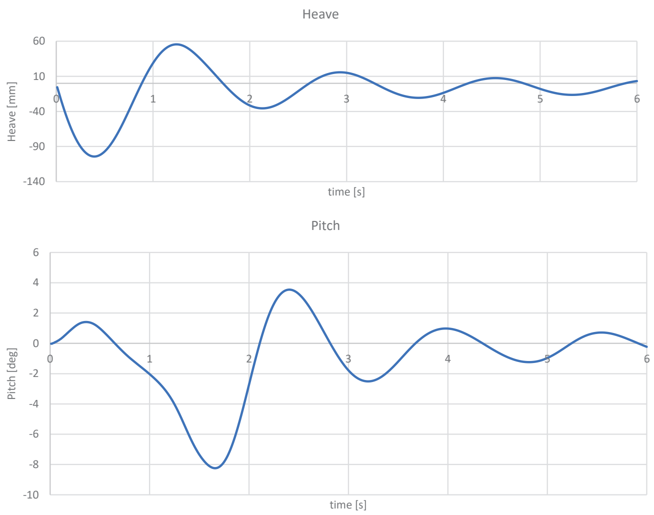
Fig. 23. Heave and pitch during FDT (experiment)

In the case where we want to examine the coefficients for a complex structure model, the limitation of conducting tests with only one period of natural oscillations can be a problem, because although this is the most important period from the point of view of the safety of the structure (the threat of resonance in sea wave conditions), it is convenient to know the values of the coefficients for a wider range of excitation frequencies. The extinction of the amplitude of motion for subsequent oscillations of the object, although it makes it possible to trace to some extent the change in the values of the coefficients depending on the KC number, has an impact on the obtained values. While the forces corresponding to a given amplitude of motion are measured, the object moves in an environment disturbed by the previous transition with an earlier, larger amplitude. This causes the obtained values of the damping coefficient to be higher than those that would result from tests of forced oscillations with a constant amplitude of motion. The occurrence of additional movements may significantly reduce the obtained values of the coefficients. In order to confirm the last assumption, RANSE-CFD calculations of free oscillations of the vertical motion of the cylinder with the plate, and the combination of heave and pitch, were performed. The results of the calculations were compared with three free oscillation tests performed on the model pool, which are discussed in detail by Ciba [17]. The calculations were performed using the DFBI model, which makes it possible to model the behavior of a rigid body, taking into account its mass, the position of the center of mass, its moments of inertia, its initial velocity, and additional forces acting on the structure. In the discussed case, for the isolated vertical motion, the initial velocity of the structure was given in the z direction, while in the other two cases, the initial velocity was also given in the x direction. Such an approach in the first case resulted in free oscillations of the object in the z direction, and in the other two cases in smaller and larger additional rotations about the y-axis (Fig. 24).

Series 1 (only vertical movement)



Series 2



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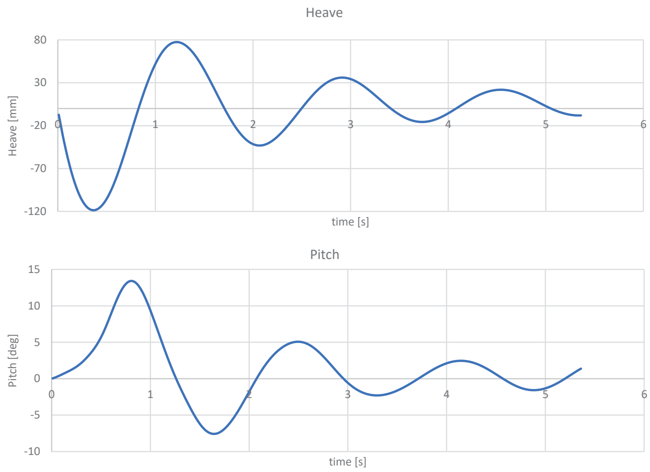

Fig. 24. Heave and pitch during FDT (RANSE CFD)

Comparing the results (Fig. 25), it can be seen that although the test results do not agree with the results of the calculations for isolated motion, when pitch is included in the calculations, the results become very similar. It can also be seen that pitch causes a decrease in the value of the damping coefficient.

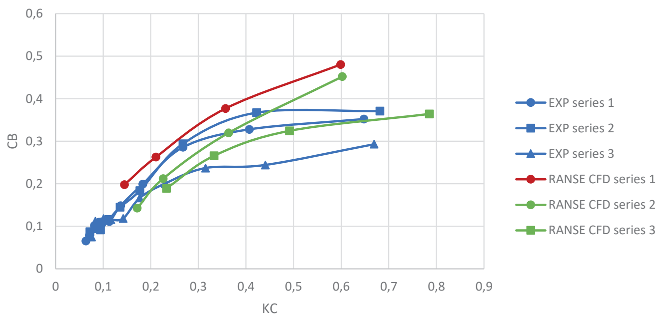

Fig. 25. The influence of combined motion on the damping coefficient value

The cause of this phenomenon can be explained by the sliding of vortices from the plate surface when it is positioned obliquely to the direction of motion, which can be observed by comparing the velocity fields in Fig. 26.

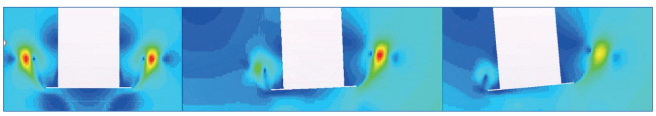

Fig. 26. Velocity field in isolated motion and in combined motion

CONCLUSIONS

The values of hydrodynamic coefficients determined in the work match those available in the literature, and some additional observations were made. It was found that for a KC number < 2, the highest damping coefficients will be obtained for plates with a plate-diameter-to-cylinder-diameter ratio Dp/Dc > 4.

For a KC number > 4.5, the highest coefficients are obtained; the higher the coefficient, the smaller the plate-diameter-to-cylinder-diameter ratio. Of course, it should be remembered that this does not mean that the damping value will be lower if, in this case, we give up additional damping plates. The value of the coefficient is being considered, and the damping value depends on the plate surface area.

Cutting holes in the plate with a KC number < 2 causes an increase in the damping coefficient and at the same time a decrease in the coefficient of added mass.

The holes should be used in plates with a high Dp/Dc ratio.

It was not possible to clearly determine the best position of the holes relative to the cylinder plane; this could be the subject of further research.

A clear decrease in damping was observed in the case of the occurrence of combined heave + pitch movement. It can be assumed that this decrease will be smaller if, in addition, a vertical edge extending below the plate is used at the edge of the plate; this could prevent the vortices from sliding down.

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