Proceedings of OMAE2006
25th International Conference on Offshore Mechanics and Arctic Engineering
June 4-9, 2006, Hamburg, Germany

OMAE2006-92140

CHARACTERISTICS OF CURRENT GENERATION SYSTEM IN DEEPWATER OFFSHORE BASIN

Lu Haining
The State Key Laboratory of Ocean Engineering,
Shanghai Jiao Tong University
Shanghai, 200030 China
Email: haining@sjtu.edu.cn

Yang Jianmin
The State Key Laboratory of Ocean Engineering,
Shanghai Jiao Tong University
Shanghai, 200030 China
Email: jmyang@sjtu.edu.cn

Peng Tao
The State Key Laboratory of Ocean
Engineering, Shanghai Jiao Tong University
Shanghai, 200030 China
Email: pengtao@sjtu.edu.cn

ABSTRACT

The current generation system in deepwater offshore basin is important for the correct modeling of ocean environment. It is generally considered to be a challenge to obtain uniform and stable current flow in the basin. As technical assurance numerical and experimental studies are performed to investigate the characteristics of the deepwater current generation in the basin. Reynolds-Averaged Navier-Stokes (RANS) equations and the standard k-ε turbulence model are adopted to simulate the current generation system numerically. In addition a 1:10 scaled model test is also performed. In both numerical and experimental studies horizontal and vertical current velocity profiles, turbulence levels and pressure losses during the current recirculation etc. are studied. It is concluded that the perforated walls are key components of the current generation system. In addition various vertical current velocity profiles can be realized in the basin.

NOMENCLATURE

u_i	Mean velocity component
$u_i^{'}$	Fluctuating velocity component
F_i	Force component
ρ	Water density
p	Water pressure
υ	Kinetic viscosity of water
μ_t	Turbulent viscosity
k	Turbulence kinetic energy
ε	Dissipation rate of the turbulence kinetic energy
υ_t	Turbulent kinetic viscosity
δ_{ij}	Kronecker delta function

INTRODUCTION

In recent years many new concepts on floating platforms, which are applied to oil and gas exploitation in deep water have been developed, including floating production, storage and offloading system (FPSO), tension leg platform (TLP), semi-floating production facility and SPAR platform etc [1-2]. These platforms are usually located in severe ocean environments. Due to the large investments and high risks [3-4], their hydrodynamic performances such as motions, environmental forces and structural responses in survival conditions need to be investigated. And reliable model tests need to be conducted based on correct modeling of wind, waves and current in deepwater offshore basin [5].

In this paper the deepwater offshore basin presently under construction at Shanghai Jiao Tong University is used as a case to be studied. The offshore basin is 50m in length and 40m in width. Its water depth can be adjusted between 0-10m. A deep pit is located in the basin with 40m in total depth and 5m in diameter. The main facilities of the basin include multi-flap wave generator, wave absorption beach, deepwater current generation system, wind generation system, towing carriage and large area movable bottom etc. The maximum current speeds in the basin are required to achieve 0.4m/s at the surface and 0.1m/s at the bottom.

Numerical simulation of the current generation system is performed based on RANS equations and the standard k-ε turbulence model. Corresponding model test is also carried out. And the model scale is 1:10. Characteristics of the flow field, such as the current uniformity, vertical current velocity profiles, turbulence levels, and pressure losses during the water recirculation etc. are considered. The calculated and experimental results are compared to each other. Conclusions and suggestions are presented, which will be helpful for the design of the current generation system.

DEEPWATER CURRENT GENERATION SYSTEM

For that the ocean current in deep water has direct loads and influences on motion behaviors of the platform. Such an effect needs to be represented properly in model tests. Therefore it is crucial to model the sea current correctly to obtain reliable results [6]. Unfortunately, there exists great difference in uniformity and turbulence levels between the flow fields in the nature and the offshore basin. To simulate ocean environment correctly, the flow field in the basin should be uniform and constant, which means stable flow directions, low turbulence level with few vortices and reversed flows. In addition various vertical current velocity profiles need to be realized in the basin.

The current in the deepwater offshore basin of Shanghai Jiao Tong University is generated by several powerful pumps and circulated outside the basin through inflow, outflow culverts, galleries and ducts. In Fig. 1 the sketch of the current generation system is presented consisting of the main part of the basin, inflow and outflow culverts, galleries, ducts and pumps. Compared with the current generation process in nature, the current in the basin is generated by pumps. These pumps will transfer a large amount of energy to the local volume of water. This process involves high current velocities, large gradients and turbulence excitations. To model the ocean current properly, disturbances such as vortices and reversed flows etc. need to be eliminated outside the basin. And it is also necessary to control the turbulence levels to ensure that the turbulence intensity is acceptable in the measuring area. Specific structures such as perforated walls, flow guiding vanes, mixing chambers and turbulence grids etc. need to be set in inflow and outflow culvert.

It is clear that the current field in the basin is quite complicated. It is necessary to study the characteristics of the current field in the basin in detail. The commercial computational fluid dynamics software (FLUENT) is used as a tool to simulate the overall current field numerically.

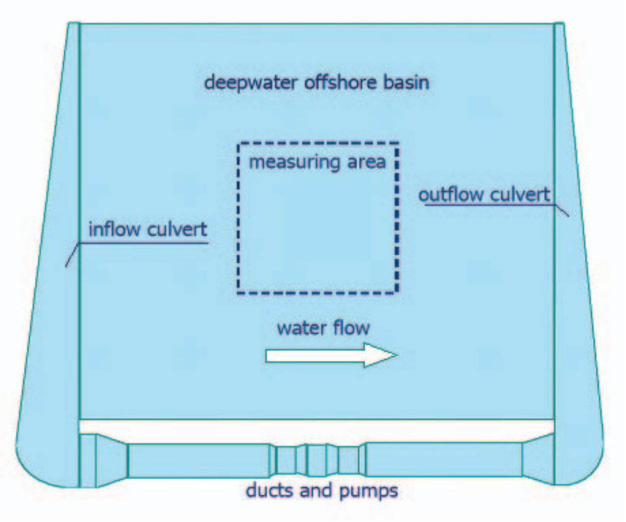

Figure1. Deepwater current generation system in offshore basin

BASIC THEORY

RANS Equations

For incompressible flows, the continuity equation and the Navier-Stokes equation can be decomposed into three components as follows:

$$\sum_{i=1}^{3}\frac{\partial u_i}{\partial x_i}=0 \qquad (1)$$

$$\frac{Du_i}{Dt}=F_i-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\upsilon\nabla^2 u_i \qquad (2)$$

Where u_i and F_i are velocity and force components respectively (i=1, 2, 3), ρ is water density, p is water pressure and υ is the kinetic viscosity of water.

Turbulent flows are characterized by fluctuating velocity fields. These fluctuations will cause the transported physical quantities, such as momentum and energy to fluctuate as well. As these fluctuations are in small scale and high frequency, they are too difficult to be simulated directly in practical engineering calculations. Instead the instantaneous governing Eqn. (1) and Eqn. (2) could be time-averaged, such as Reynolds averaging to remove all small scales [7].

In Reynolds averaging the instantaneous variables can be decomposed into the time-averaged component and the fluctuating component. For velocity:

$$\tilde{u}_i=u_i+u_i^{'} \qquad (3)$$

Where u_i and $u_i^{'}$ are mean and fluctuating velocity components respectively (i=1, 2, 3). Similarly for pressure and other scalar quantities:

$$\tilde{\phi}=\phi+\phi^{'} \qquad (4)$$

Substitute the time-averaged terms above into Eqn. (1) and Eqn. (2):

$$\rho \frac{\partial u_i}{\partial x_i} = 0 \tag{5}$$

$$\rho \frac{\partial}{\partial x_j}\left(u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \rho \frac{\partial}{\partial_j}\left[\upsilon\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i^{'}u_j^{'}}\right) \tag{6}$$

Equation (3) and (4) are the Reynolds-Averaged Navier-Stokes (RANS) equations. Where u_i and u_j are mean velocity components (i, j=1, 2, 3), p is mean pressure, υ is the kinetic viscosity of water and $-\rho\overline{u_i^{'}u_j^{'}}$ is the Reynolds stress term.

Standard k-ε Turbulence Model

In RANS equations the Reynolds stress term $-\rho\overline{u_i^{'}u_j^{'}}$ appears to represent the effects of turbulence. Therefore another new equation must be introduced to solve the RANS equations. One of the methods is to employ the Boussinesq hypothesis to close the equations:

$$-\rho\overline{u_i^{'}u_j^{'}} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_t \frac{\partial u_i}{\partial x_i}\right)\delta_{ij} \tag{7}$$

Where μ_t is the turbulent viscosity, k is the turbulence kinetic energy and δ_{ij} is Kronecker delta function.

The Boussinesq hypothesis above is widely used in Spalart-Allmaras model, k-ε model, and k-ω model (Zhang and Li, 2004). Among them the standard k-ε model is usually adopted in practical engineering computation, which is semi-empirical and based on the model of transport equations for turbulence kinetic energy k and its dissipation rate ε (Zhang, 2002).

The turbulence kinetic energy k and its dissipation rate ε can be derived from the following transport equations:

$$\frac{\partial\left(k u_j\right)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\upsilon + \frac{\upsilon_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k - \varepsilon \tag{8}$$

$$\frac{\partial\left(\varepsilon u_j\right)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\upsilon + \frac{\upsilon_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{\varepsilon 1} P_k \frac{\varepsilon}{k} - C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{9}$$

$$\upsilon_t = \frac{\mu_t}{\rho} = C_\mu \frac{k^2}{\varepsilon} \tag{10}$$

Where $P_k = -\overline{u_i^{'}u_j^{'}}\frac{\partial u_i}{\partial x_j}$, it is the turbulence kinetic energy term and υ_t represents the turbulent kinetic viscosity.

The constants $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, C_μ, σ_k and σ_ε have the following standard values:

$$C_{\varepsilon 1}=1.44,\ C_{\varepsilon 2}=1.92,\ C_\mu=0.09,\ \sigma_k=1.0,\ \sigma_\varepsilon=1.0 \tag{11}$$

COMPUTATION AND MODEL TEST

The current generation system of the deepwater offshore basin at Shanghai Jiao Tong University is investigated numerically and experimentally. Characteristics of the flow field in the basin, such as the current uniformity, vertical current profiles, turbulence levels and pressure losses during the current recirculation etc. are considered.

Computation

Based on the basic theory mentioned above, horizontal and vertical distributions of current velocities in the basin, turbulence intensities, and pressure losses during the current recirculation in the basin can be calculated.

The numerical model consists of the main part of the basin, the inflow and outflow culverts and part of ducts. In inflow and outflow culverts, perforated walls are set to control the uniformity and turbulence levels. There are over ten thousand holes distributed on these walls. And the diameter of holes is in centimeter scale. Owing to the large number and small scale of the holes, it is impossible to simulate the complicated 3D flow field in the basin. Therefore in this paper only a 2D model is adopted to simulate the current generation system. The sketch of the numerical model is presented in Fig. 2. Quadrilateral and triangular elements are used to mesh the model. And the number of panels is about 10^6.

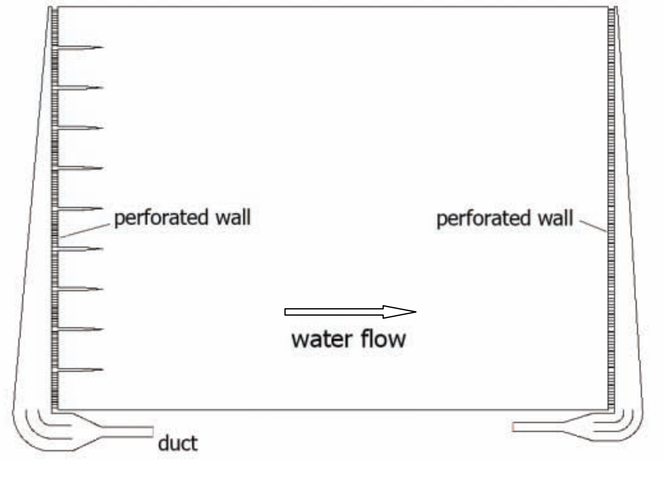

Figure 2. Numerical model of the current generation system

Model Test

A 1:10 model test is carried out in the State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University. Figure 3 shows the experimental model. In the model perforated walls, flow guiding vanes and turbulence grids are set. In the test a current meter is used to measure the current velocities at different locations and water depths in the offshore basin. And pressure transducers are used to measure the pressure losses of water flow during the recirculation. All instruments are calibrated carefully. During the model test a computer is used to record the experimental data at a sampling frequency of 20Hz. In Fig. 4 the current generation system in test is presented.

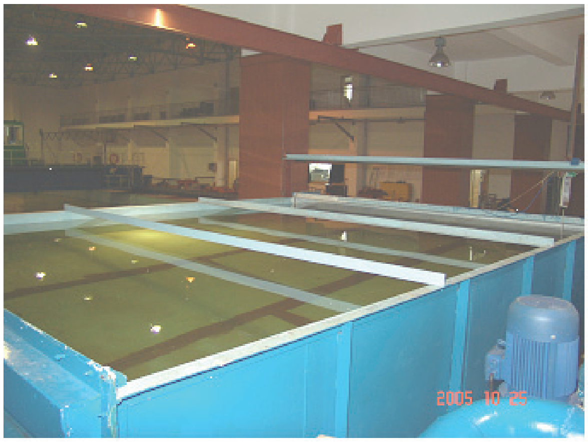

Figure 3. Experimental model of the current generation system

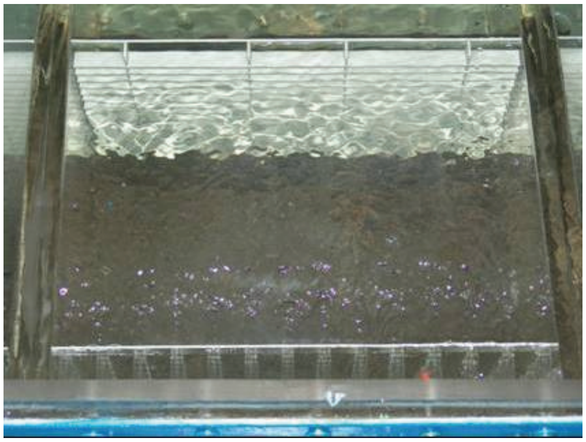

Figure 4. The current generation system in test

RESULTS AND ANALYSES

Horizontal and Vertical Current Profiles

To analyze the uniformity of the flow field in the basin, the horizontal current velocity profiles with and without perforated walls are considered. The calculated current speed distribution in the basin without perforated walls is shown in Fig. 5. It is shown in the figure that if no perforated walls are set to control the current uniformity, water will flow along the inflow culvert and enter the basin from the end with great volumes and velocities. Obviously the distribution of current velocities in the basin is far from uniform. Severe reversed flows are produced. In addition vortices are also generated between two neighboring inflow sections. It is clear that such a uniformity of current field in the basin can not reach the requirements.

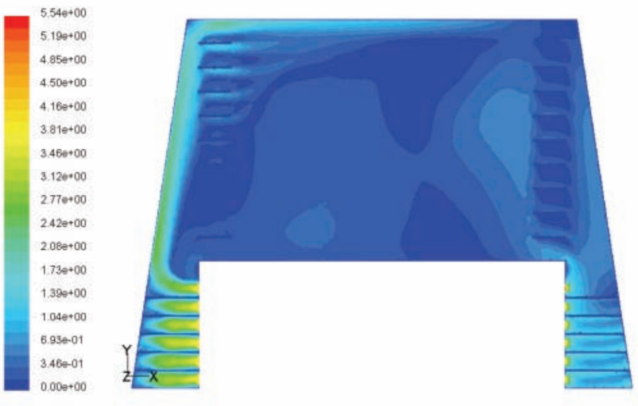

Figure 5. Speed magnitude distribution without perforated walls

To solve the problem above, perforated walls are set in inflow and outflow culverts. In addition the inlet from ducts to the inflow and outflow culverts are also modified for smooth transition of the current flow direction.

In Fig. 6 the current speed with perforated walls are presented. It can be seen from the figure that the current field in the basin is much more uniform compared with the case without perforated walls. In addition vortices and reversed flows are also seldom produced.

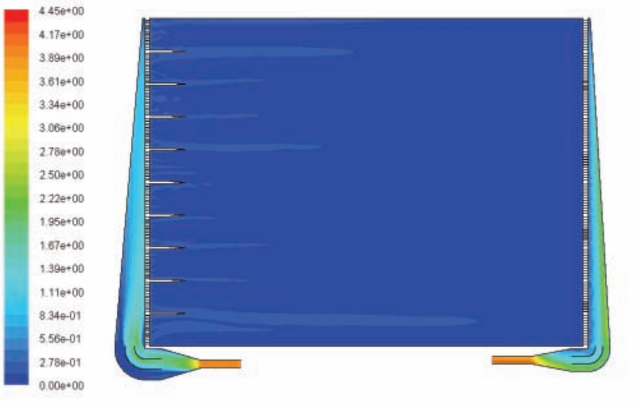

Figure 6. Speed magnitude distribution with perforated walls

Figure 7 shows the comparison of calculated and measured velocities at different locations in the basin. From the comparison between numerical and experimental results in the figure, it can be seen that the agreement is satisfactory. Both calculated and measured velocity distributions in the basin show that the flow field in the basin is generally uniform.

Consequently it can be concluded the uniformity of the flow field in the basin can be significantly improved by setting perforated walls in the inflow and outflow culverts.

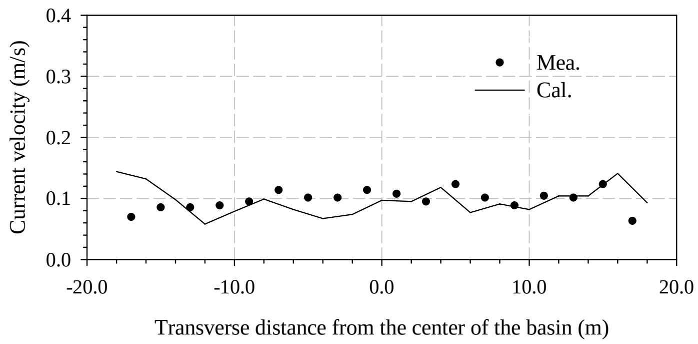

Figure 7. Comparison of current uniformity in the basin with and without perforated walls

Considering that in deep water, the current will generate great loads on mooring lines and risers. It is important to control the vertical current velocity profiles. In the model test of current generation system the vertical current velocity profiles are also measured and analyzed. Two typical vertical current profiles are presented in Fig. 8. It can be concluded that the deepwater offshore basin can simulate different vertical velocity profiles.

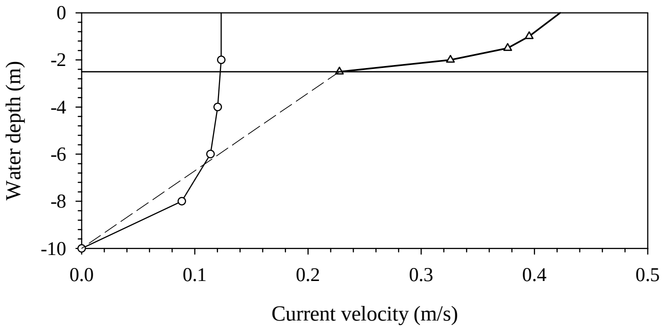

Figure 8. Examples of vertical current velocity profiles measured in model test

Besides horizontal and vertical current profiles, the turbulence level of the flow field in the basin is also important for the reliability of ocean engineering model test, it is necessary to find out whether the turbulence level can be controlled in the measuring area of the deepwater offshore basin. Therefore the turbulence intensities of the current flow in the basin are studied in the following.

Turbulence Control

In Fig. 9 the calculated distribution of turbulence intensities along the width of the basin is shown. From the comparison in the figure, it can be seen that the turbulence intensity in the basin without perforated walls is generally over 5% of the average current speed, which is beyond the required level of ocean engineering model test. However the turbulence intensity decreases significantly after the perforated walls are set. It is clear that the perforated walls have the capability to control the turbulence degree effectively.

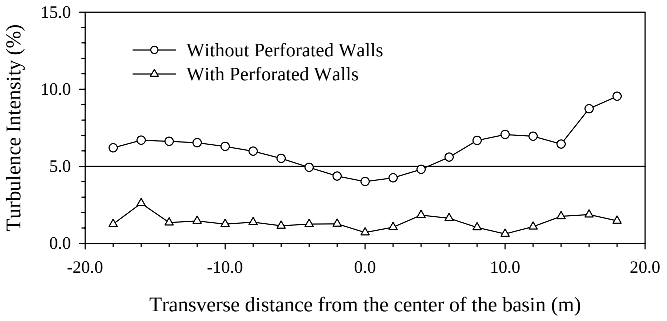

Figure 9. Effects of perforated walls on turbulence control

From the discussion above, it is concluded that both uniformity and turbulence levels of the current field in the basin can be improved significantly by setting perforated walls in inflow and outflow culverts. However the uniformity and turbulence degree are not only two factors to be considered during the design of current generation system.

Due to the small scale of holes located on the perforated walls great pressure losses will be produced during the water recirculation. Very powerful pumps are needed to drive the water flow in the basin to achieve the required current speed. It is necessary to investigate the pressure losses of current during recirculation.

Pressure Losses during the Current Recirculation

In Tab. 1 the pressure losses in the basin with and without perforated walls are listed. It is listed in the table that the pressure losses increase dramatically compared with the values without perforated walls. In addition it is also indicated that the pressure losses caused by perforated walls are over 50% (even over 90%) of the total pressure losses in the basin. In addition if additional structures are added to control the current uniformity and turbulence level, more pressure losses will be produced.

Table 1. Pressure losses with and without perforated walls

	Pressure losses in inflow culvert ($\times10^4$Pa)		Pressure losses in outflow culvert ($\times10^4$Pa)		Total pressure losses ($\times10^4$Pa)	
without perforated walls	Cal.	—	Cal.	—	Cal.	0.86
with perforated walls	Cal.	1.11	Cal.	1.02	Cal.	2.34
					Mea.	3.09

Since the experimental model includes flow guiding vanes and turbulence grids etc. And these structures are not considered in numerical simulation. Therefore from Tab. 1 it can be seen that the total pressure losses measured in model tests are relatively larger compared with the calculated result.

CONCLUSIONS

The current generation system is a challenging part in the design of the deepwater offshore basin. According to the numerical and experimental research, the characteristics of the current field in the basin are investigated, including the uniformity of the flow field in the basin, various vertical velocity profiles, turbulence control and pressure losses during the current recirculation etc.

From comparisons between numerical and experimental results, it can be seen that the agreement is satisfactory. And both results show that the perforated walls are key facilities in the deepwater current generation system. The water flow uniformity and turbulence level can be improved significantly by setting perforated walls in inflow and outflow culverts. While great pressure losses during the water recirculation will be produced by perforated walls.

In the adjustment of vertical velocity profiles in the model test, the current generation system of the deepwater offshore basin can realize various typical vertical current profiles in the basin. Therefore it can be concluded that the offshore basin has the capability to model different ocean environments in deep water.

ACKNOWLEDGMENTS

This work was financially supported by the National High Technology Research and Development Program of China (863 Program, Grant No. 2004AA617010). This support is gratefully acknowledged.

REFERENCES

[1] Li, R.P., Xie, Y.H. and Shu Z., 2003. “A Review on the Technical Development of Deep Water Offshore Platform,” *China Offshore Platform*, 18(3), pp. 1-5.

[2] Li, Y.C., 1998. “The New Development of Offshore Engineering Technology,” *China Offshore Platform*, 13(1), pp. 9-12.

[3] Ward, E.G., Robert, B.G. and Jihad, J., 2001. “Deepwater Production System Risks,” Proceedings of the 11th International Offshore and Polar Engineering Conference, Vol. 4, the International Society of Offshore and Polar Engineers, pp. 654-659.

[4] Garside, R., Snell, R.O., Cook H., 2001. “Deepwater Technology and Deepwater Developments,” Proceedings of the 11th International Offshore and Polar Engineering Conference, Vol. 4, the International Society of Offshore and Polar Engineers, pp. 1-5.

[5] Roger, C.D. and Ahllen, R.V., 2000. “The Place of Physical and Hydrodynamic Models in Concept Design, Analysis and System Validation of Moored Floating Structures” Proceedings of 20th International Conference on Offshore Mechanics and Arctic Engineering, *Ocean Space Utilization and Offshore Technology*, pp. 1-8 OMAE2000/OSU OFT-4192.

[6] Buchner, B., Wichers, J.E.W. and Wilde, J.J., 1999. “Features of the State-of-the-art Deepwater Offshore Basin” Proceedings of the Offshore Technology Conference, pp. 363-373.

[7] Liu, Y.Z. and Miao, G.P., 2000. *Advanced Hydrodynamics*, Shanghai Jiao Tong University Publishing Company.

[8] Zhang, Z.R., Li, B.Q., and Zhao, F., 2004. “The Comparison of Turbulence Models Applied to Viscous Ship Flow,” *Journal of Hydrodynamics*, Ser. A, 19(5), pp. 637-642.

[9] Zhang, Z.S., 2002. *Turbulence*, National Defense Industry Press.