Dynamic Analysis of A Subsea Suspended Manifold Going Through Splash Zone During Installation

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Abstract
The subsea suspended manifold designed to replace the traditional foundation structure with the buoys is a new generation subsea production system that can be suspended at a certain height from the seafloor and rapidly recycled by its own buoyancy. Due to complex environmental conditions, its hydrodynamic performance in the splash zone is extremely important for the safety of the whole installation process. In this paper, the mathematical model for the dynamic analysis of the seawater ingress process of the single-layer pre-set horizontal cabin is proposed based on the different center of gravity positions of the buoy. Meanwhile, the theoretical analysis of fiber cable is divided into infinite differential units by the discretization method, and the formulae of the horizontal displacement of the subsea suspended manifold are presented. In addition, the simulations are carried out to verify the rules of the dynamic responses on the subsea suspended manifold system with the consideration of the environmental conditions in the South China Sea. Comparing with the calculated value of the mathematical model of the cabin water ingress, the error of the simulation result by use of FLUENT is about 5.47%. Furthermore, the wave height is greater than the current impact on the lowering manifold system and the azimuth angle of the installation vessel is aligned with the direction of the environmental load.

Key words: subsea suspended manifold, lowering installation, seawater ingress, splash zone, dynamic response

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1 Introduction
The traditional subsea cluster manifold (Stock et al., 2007; Wang et al., 2012, 2014; Xu et al., 2018; Pang et al., 2021) is a large, gravity-based piece of equipment for gathering and distributing node, forming an essential part of the transportation system in subsea production systems. It is mainly used to collect oil and gas from different subsea wellheads to a separate hub pipeline to the coast and facilitate water, gas, and chemical injection, or other pigging operations. However, the traditional subsea manifold presents several challenges such as a particular topographical requirement, subsea large infrastructures with high installation investment, subsea Christmas trees with high post-maintenance cost, difficulty of release due to the guide rod connection between manifold structure, and unrecyclable foundation frame. Therefore, a new generation concept of subsea production system was presented as shown in Fig. 1.

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In the new design concept, the mixed fluid from dry wells initially processed by the high-efficiency compact separators is gathered to the subsea manifold suspended a certain 200 m depth off the seafloor (Wang et al., 2021; Liu et al., 2021), which is remarkably different from the traditional subsea manifold with the foundations. On one side, the subsea trees are replaced with the dry trees in the subsea functional chamber, which may greatly reduce the OPEX (operating expenses) in subsea wet workover operation in the future. On the other side, the subsea manifold is suspended by replacing the foundation structure with four buoys, and the multipurpose flexible jumpers can be used to transport oil and gas, as well as being a mooring system. The new system can be rapidly recycled when the connection to the manifold is unleashed and float to the sea surface through its own buoyancy. The subsea suspended cluster manifold weighing 250 tons is shown in Fig. 2, consisting of a major structure and four buoys layered design (Collu et al., 2014).

As shown in Fig. 2, the four buoys arranged around the manifold major structure that provide enough buoyancy to the subsea suspended manifold system are extremely important for the installation and recycle process. Each buoy is divided into five horizontal cabins in order to reserve enough buoyancy even if two cabins are damaged. There are three installation stages, i.e. in the splash zone, deep-water, and near the seafloor. Due to more complex environmental loads, the most dangerous stage is in the splash zone. In this stage, the external seawater keeps entering buoys’ cabins due to pressure difference between its inside and outside by adjusting the exhaust valve. As the amount of seawater in the buoy keeps increasing, the whole subsea suspended manifold system goes through the splash zone by its own weight with increment. The dynamic characteristics from the seawater ingress of four buoys and the multi-body coupling lowering system should be investigated for the safety of the installation process in the suspended manifold, which is the focus of this paper.

Recently, some scholars have been focusing on the rules of the seawater ingress of the damaged vessels (Cho et al., 2006; Gao and Vassalos, 2015; Gao et al., 2020; Kuznecovs et al., 2021). Gao et al. (2011) simulated the static and dynamic process of water inflow in a damaged cabin using CFD software by compiling N–S solver. Ruponen et al. (2013) made the time-domain seawater ingress simulation on the full-scale model hulls with different ventilation levels in a single seawater intake compartment by Bernoulli Equation. Lee (2015) proposed two new models for the seawater ingress of the damaged hull to automatically adjust the internal pressure to remove the influence of the air pressure fluctuation. Ming et al. (2018) performed a numerical simulation on the seawater ingress of the damaged hull in transverse regular waves based on a weak compressible smoothed particle hydrodynamics method, which provided a demonstration for its hydrodynamic performance. Cao et al. (2018) proposed a multi-phase model combining the virtual boundary method to investigate the effect of air on the cabin response during the process of seawater breaching the damaged hull, revealing the effect of the airflow on the breakage overflow of the cabin. Hu et al. (2019) carried out the numerical simulation on the damaged vessel based on the volume of fluid method in Navier–Stokes solver and the combination of dynamic grid technology. Zhang et al. (2020) implemented the Unsteady Reynolds-Average Navier–Stokes solver to monitor the three degrees of freedom motion, investigating the effect of symmetric and asymmetric flooding on the damage stability.

On the hydrodynamics performance of the subsea equipment, many researches have been conducted, such as the manifolds, subsea Christmas tree, submarine pipeline and the other marine structures (Tahar et al., 2006; Zeitoun et al., 2010; Zhang et al., 2015; Tommasini et al., 2018; Du et al., 2021). Koraim and Ragheb (2013) studied the hydrodynamic efficiency physical model of vertical porous structure under the action of regular waves, and conducted experimental studies on the effects of different wave parameters and structural parameters on the efficiency of breakwater. Jia and Agrawal (2014) proposed a fluid-solid coupling method of the subsea manifold to predict its motions caused by the wave loads, dynamic pressures, and deformations in the splash zone. Bai et al. (2014) established a numerical model of the subsea manifold for the drill pipe installation method based on the theory of small deformation and deduced the

Fig. 2. New subsea suspended manifold system.
stress, displacement, bending moment, and inclination angle of the drill pipe by the discrete finite element method. Nam et al. (2017) studied the coupled motion response on the floating crane vessels and super large pipe valve structures during the lowering process by combining tests and numerical calculations. Wang et al. (2018) established a numerical coupled model for the drill pipe installation of the subsea manifold and the dynamic response rules of the system on the variation stress, the lateral offset, and the bending moment under different environmental loads in the splash zone. Wang et al. (2018) studied the hydrodynamic coefficients of a double immersed inclined plate by using the boundary element method with wave terms based on the Green function and obtained the variation laws of the additional mass and damping coefficients of the device with different parameters. Gao et al. (2018) carried out the numerical and experimental studies on the hydrodynamic characteristics of the multi-column platform semi-submersible using three-dimensional potential flow theory. Zhang et al. (2021) revealed the hydrodynamic characteristics of turbulent wave boundary layer in a full-scale environment through experimental studies, and proposed an explicit formula for the thickness of rough turbulent boundary layer based on the experimental data.

Meanwhile, Wang et al. (2017) introduced the proxy model to reduce the calculation time and conduct a high-precision analysis for the design of the flying wing structure of an underwater glider, and applied the particle swarm optimization algorithm to the hydrodynamic design optimization. Hu et al. (2018) proposed differential control equations of drill pipes of different lengths based on the Keller-box method to obtain the motion response law of the subsea tree. Cong and Teng (2019) carried out a numerical study on the hydrodynamic characteristics of isolated square pendulum plates and double-square pendulum plates with openings using the immersed boundary grid Boltzmann method and obtained the relationship between the plate spacing and the hydrodynamic characteristics of double pendulum plates. Li et al. (2020) analyzed the dynamic sensitivity parameters of the wire cable installation of the Lingshi 17-2 subsea tree. Wang et al. (2020) performed numerical and experimental studies on the hydrodynamic interaction of two semi-submerged super-large floating structures in the frequency domain, revealing the influence of different wave periods on the motion response of the two modules and the wave height in the gap. Mouhib et al. (2021) used the energy method to predict the damage of the steel wire cable in the installation while describing its mechanical behavior. Fan et al. (2021) experimentally studied the hydrodynamic changes and sediment erosion characteristics near the submarine pipeline with vertical spoilers and obtained the effects of vertical spoilers on the turbulent flow energy and sediment erosion rate of the submarine pipeline.

To sum up, previous work on the hydrodynamic for the seawater ingress of the damaged single cabin is significantly different from that on the dynamic response of the four buoys with pre-set horizontal cabins. The stability analysis of roll, yaw, heave and other aspects of large vessel cabin damage is conducted by using “weight increase method” or “buoyancy loss method”. However, the investigations on the cabin water inflow process with the subsea suspended manifold as the main research object is still scarce. There are few studies on the controllable inlet area, which affects the water flow velocity and filling time, as well as the changes of the float on the unit time flow, break area and air cushion in time domain. Meanwhile, the research involving the dynamic response of the novel subsea suspended manifold in the splash zone is rarely conducted except for the suspension performance evaluation in its service life by Zhao et al. (2021). In this paper, based on each buoy’s structural design characteristics with pre-set horizontal cabins, the mathematical model of the seawater ingress process of the single-layer buoy is respectively derived with the consideration of the center of gravity position, above or below the sea level. In addition, the fiber cable is divided into infinite differential units by discretization method. The theoretical formulae of axial tension of fiber cable and horizontal displacement of the subsea suspended manifold are established based on the boundary conditions. The multi-body coupled lowering system simulations are carried out to reveal the dynamic responses of the subsea suspended manifold system in the splash zone, which can lay a foundation for the system installation in future engineering applications.

2 Mathematical modelling

2.1 Theoretical model of the seawater ingress of the cabin

Due to the symmetrical distribution of four buoys, the mathematical model of the seawater flowing into a single cabin of the buoy can be built to investigate the dynamic characteristic of the subsea manifold system. With the consideration of the increase of the seawater ingress, two mathematical models are proposed according to the positions of the center of gravity, above and below the sea surface.

2.1.1 Assumptions

During the lowering process of the splash zone, the external seawater continuously enters the five cabins of each buoy by the internal and external pressure difference on the exhaust valve. Due to the increase of the weight of the subsea suspension manifold, it is lowered to a certain depth from the seabed by its own gravity. Due to the existence of many complex events such as liquid sloshing, air cushion and so on, it is necessary to simplify the mathematical model appropriately. The following assumptions are made:

(1) The inflow mass flow rates of the five cabins are the same and the seawater sway effect on each cabin can be ignored;
(2) The fluid only flows into the cabin of each buoy at
the opening with no internal fluid flowing out;

3. The inflow seawater is assumed to be an ideal fluid and its viscosity is ignored;

4. The buoy is in a static state in the splash zone since the lowering speed of the subsea suspended manifold is far less than the seawater flow speed.

2.1.2 Center of gravity of the single-layer cabin located above sea surface

The sea level static coordinate system $xo\bar{z}$ and arbitrary dynamic coordinate system $x'oo'$ are established, respectively. Here, let the tilt angle be $\theta$, the distance between the gravity center and the sea level be $h_0$, the coordinate of the inflow position be $(x_0, z_0)$ in the dynamic coordinate system, and $(x_1, z_1)$ in the static coordinate system. Fig. 3 shows a schematic diagram of the center of gravity of a single-layer cabin located above sea level.

Fig. 3. Schematic diagram of the center of gravity of single-layer cabin above sea level.

Then, the pressure head of the single-layer cabin inflow from the sea level is:

$$H_1 = (x_0 - x_1) \cos \theta - h_0.$$  \hspace{1cm} (1)

It can be obtained from Bernoulli equation:

$$\frac{1}{2} \rho V_F^2 = \rho g H_1 + \Delta p.$$  \hspace{1cm} (2)

Therefore:

$$V_F = \sqrt{2gH_1 + \Delta p}.$$  \hspace{1cm} (3)

The seawater flow rate equation of single-layer cabin becomes:

$$Q_1 = rCA_F V_F = rCA_F \sqrt{2gH_1 + \Delta p},$$  \hspace{1cm} (4)

where $g$ is the acceleration of gravity, $V_F$ is the flow rate, $H_1$ is the pressure difference between internal and external heads, $\Delta p$ is the intensity of pressure difference between inside and outside cabin, $Q$ is the flow at the inflow, $r$ is the specific gravity of seawater, $A_F$ is the inflow area, $\rho$ is seawater density, $C$ is the shrinkage coefficient when the water flows through the inflow of the single-layer cabin, and $p$ is the intensity of pressure, see Figs. 3 and 4.

Then, the amount model of the seawater inflow of the single-layer cabin without the consideration of air cushion can be expressed by:

$$W_1 (t) = \int_0^t Q_1 (t) dt = rCA_F \int_0^t \sqrt{2gH_1 (t) + \Delta p} dt.$$  \hspace{1cm} (5)

If the air inside the single-layer cabin is not discharged in time, it may lead to the formation of a certain air cushion in the cabin. With the increase of seawater ingress, the internal air will be constantly compressed so that the intensity of pressure change in the whole physical process is not negligible. If we assume that the volume of the single-layer cabin is $V_0$ and the magnitude of pressure is $P_0$ (standard atmospheric pressure), then the volume of the gas in the single-layer cabin becomes $V_1$ and the pressure becomes $P_1$ after time $t$. We can also assume that the gas in the single-layer cabin performs isothermal compression such that:

$$P_0 V_0 = P_1 V_1.$$  \hspace{1cm} (6)

Therefore,

$$P_1 = \frac{P_0 V_0}{V_1} = \frac{P_0 V_0}{(H_1 - H_1')} A_F = \frac{P_0 V_0 r}{V_0 r - t W_1 (t)};$$  \hspace{1cm} (7)

$$P_1 - P_0 = P_0 \left[ \frac{V_0 r}{V_0 r - t W_1 (t)} - 1 \right] = \frac{P_0 t W_1 (t)}{V_0 r - t W_1 (t)}.$$  \hspace{1cm} (8)

Then, the final pressure head difference is:

$$H_1 = \left[ \frac{P_0 t W_1 (t)}{V_0 r - t W_1 (t)} + (x_0 - x_1) \cos \theta - h_0 \right].$$  \hspace{1cm} (9)

The flow equation of seawater flow rate at the single-layer cabin could be expressed as follows:

$$Q_1 = rCA_F V = rCA_F \sqrt{2gH_1 + \Delta p} = rCA_F \sqrt{2g \left[ \frac{P_0 t W_1 (t)}{V_0 r - t W_1 (t)} + (x_0 - x_1) \cos \theta - h_0 \right] + \Delta p}.$$  \hspace{1cm} (10)

The amount model of the seawater inflow of the single-layer cabin with the consideration of air cushion becomes:
The time required for the entire cabin to be filled with a specific weight can be determined by deriving and calculating the average inflow rate of a single-layer cabin. This provides a theoretical basis to be compared with the CFD calculations in Section 3.

2.2 Theoretical model of the lowering process

2.2.1 Assumptions

The stress on the fiber cable in the splash zone is extremely complex due to the influence of wind, waves, currents, and the movement of the installation vessel. Therefore, some assumptions are made as follows:

1. The mechanical analysis of the subsea suspended manifold during the lowering process is performed in a two-dimensional coordinate system.
2. The lift effects caused by waves and wind loads are ignored.
3. The fiber cable is always in the ideal state of elasticity and the subsea suspended manifold is a completely rigid body.

2.2.2 Theoretical derivation

The dynamic analysis of the fiber cable lowering installation process of subsea suspended manifold needs to be discretized (Leonard and Recker, 1972; Ma et al., 1979), as shown in Fig. 5. The global coordinate system is established by taking the crane vertex as the coordinate origin. The subsea portion of the fiber cable is divided into \( n \) differential elements, and the length of each differential element is \( L = D/n \). There are \( n + 3 \) nodes in the entire fiber cable, and the local coordinate system is established by taking node \( i - 1 \) as the coordinate origin. Therefore, the force at node \( i \) can be analyzed.

In Fig. 5, \( F_i \) is the hydrodynamic force of node \( i \), \( G_i \) is the gravity of node \( i \), \( F_{xi} \) and \( F_{yi} \) are the vertical forces and horizontal forces on node \( i \), \( D^+ \) and \( D^- \) are the lengths of the fiber cable in portions above water and in subsea. In the lowering process, the hydrodynamic forces acting on the cable mainly include the drag and inertial forces caused by the current and wave loads. Generally, the current velocity is considered a constant in engineering (Yttervik, 2003). Therefore, the inertial force caused by the current is
not considered. Generally, when the ratio of characteristic
diameter size of offshore structures with small relative scale
to the wavelength is smaller than 0.2, the wave force can be
deduced by the Morison equation. In this paper, the fiber
rope is discretized by use of the micro-element method, and
the micro-element segment is used as the research object to
carry out the force analysis, which is satisfied with the
application condition of the Morrison equation. According
to the Morison equation, the calculation formulas of $F_i$ and
$F_m$ (DNV, 1996, 2010) hydrodynamic forces of the differen-
tial elements of the fiber cable and the subsea suspended
manifold are derived as follows.

$$F_i = \frac{p}{4} C_d dL (v_i |v_i| + v_{i-1} |v_{i-1}| + u_i |u_i| + u_{i-1} |u_{i-1}|) +$$

$$\pi \rho \frac{C_M d^2 L}{8} \left( \frac{du}{dt} + \frac{du_{i-1}}{dt} \right) , i = 2,3,\ldots,n+1;$$

(19)

$$F_m = \frac{p}{4} C_D A_p (v_{n+1} |v_{n+1}| + v_{n+2} |v_{n+2}| + u_{n+1} |u_{n+1}| + u_{n+2} |u_{n+2}|) +$$

$$\frac{1}{2} \frac{C_M 2 V_D}{\lambda} \left( \frac{du_{n+1}}{dt} + \frac{du_{n+2}}{dt} \right).$$

(20)

where $d$ is the diameter of the fiber cable; $v_i$ is the current
velocity at node $i$; $u_i$ is the horizontal velocity of the water
quality point at node $i$; $C_d$ and $C_D$ are the drag coefficients
of the fiber cable and the subsea suspended manifold; $C_M1$ and
$C_M2$ are the inertial coefficient of the fiber cable and the
subsea suspended manifold; $A_p$ is the drag area of the subsea
suspended manifold; $V_D$ is the drainage volume.

According to the Airy wave theory, the horizontal velocity $u$
and acceleration of water quality point are calculated as
follows:

$$u = \frac{\pi H}{T} \cdot \cosh \left[ 2 \pi \left( 3000 - \frac{x}{\lambda} \right) \right],$$

$$\sinh \left[ 2 \pi \left( 3000 - \frac{x}{\lambda} \right) \right] \cdot \cos \frac{2 \pi}{\lambda} \left( y \cdot \frac{\lambda}{T} \right);$$

(21)

$$\frac{du}{dt} = \frac{2 \pi^2 H}{T^2} \cdot \cosh \left[ 2 \pi \left( 3000 - \frac{x}{\lambda} \right) \right],$$

$$\sinh \left[ 2 \pi \left( 3000 - \frac{x}{\lambda} \right) \right] \cdot \sin \frac{2 \pi}{\lambda} \left( y \cdot \frac{\lambda}{T} \right);$$

(22)

$$\lambda = \frac{gT^2}{2\pi} \cdot \tanh \left( \frac{2\pi \cdot 3000}{\lambda} \right),$$

(23)

where $\lambda$ is the length of the wave, $H$ is the height, and $T$
is the period.

In the local coordinate system shown in Fig. 5, the cal-
culation formulas of gravity $G_i$, vertical force $F_{ai}$, horizontal
force $F_{yi}$ of node $i$, and the effective tension $T_i$ of the fiber
cable are as follows:

$$G_i = w_d L;$$

(24)

$$F_{ai} = F_i + w_n (n + 1 - i) L ;$$

(25)

$$F_{yi} = \sum_{i=1}^{n-1} F_i + F_m;$$

(26)

$$T_i = \sqrt{F_{ai}^2 + F_{yi}^2} , i = 2,3,\ldots,n+1.$$  

(27)

If $i = 1$, then $G_1 = w_d D^*$, and if $i = n + 1$, then $F_{yi(n+1)} = F_m$. $w_d$ and $w_w$ are the dry weight and wet weight of a unit
length of the fiber cable (kg/m). $F_i$ is the wet weight of the
subsea suspended manifold (N).

The known boundary conditions (Cha et al., 2010) are as
follows:

1. The fiber cable is hinged with the winch so that $Y_0 = 0, M_0 = 0.$

2. The fiber cable is hinged with the subsea suspended manifold through the sling so that $F_x(i+1) = F_i, F_y(i+1) = F_m,$
$M_{i+1} = 0.$

3. The boundary conditions of the differential element $i$ in the local coordinate system are $y_0 = 0, M_i = M_{i-1} = 0.$

Then, the moment balance equation at node $i = 1$ in
the local coordinate system becomes:

$$M_{i+1} = F_x i L + \frac{1}{2} F_{x1} L = F_x Y_1 (L) - \frac{1}{2} G_1 Y_1 (L) = 0, i = 2,3,\ldots,n+1.$$

(28)

If $i = 1$, then $F_{yi1} D^* - F_{xi1} Y_1 (D^*) - \frac{1}{2} G_1 Y_1 (D^*) = 0.$

According to Eq. (28), the horizontal displacement of
the $i$-th differential element can be deduced as follows:

$$Y_i = \left( F_{yi} L + \frac{1}{2} F_{yi} L \right) \left( F_{xi} + \frac{1}{2} G_i \right), i = 2,3,\ldots,n+1.$$  

(29)

In the global coordinate system, the horizontal offset $Y_i$
of the fiber cable is the sum of the horizontal offset $y_i$
of each differential element of the fiber cable. Furthermore,
the horizontal offset $Y_m$ of the subsea suspended manifold is the
sum of the horizontal offset, $Y_{i+1}$ of the end of the fiber
cable and the displacement of the rigid body of the subsea
suspended manifold:

$$Y_i = \sum_{i=1}^{n-1} y_i;$$

(30)

$$Y_m = Y_{i+1} + F_m h / F_i.$$  

(31)

Then, the force analysis of the fiber rope of the subsea
suspended manifold is carried out. Through the discretization
of the fiber rope, the theoretical calculation formula of the
axial tension of the fiber rope and the horizontal displacement
of the subsea suspended manifold is deduced, which can
provide a theoretical method for the offshore engineering
simulation software Orcaflex.

3 Simulations on hydrodynamic seawater ingress of the
cabin

3.1 CFD fluid model and parameters

By simplifying the conditions of the model in Section
2.1.1, the water ingress of a certain layer of the cabin is
considered in this paper. The fluid domain of the model is
19600 mm×19600 mm×3570 mm. The bottom diameter of the
single-layer cabin of the buoy is 5600 mm, the height is
1000 mm, and the opening diameter is 170 mm. Fig. 6
shows the water-ingress simulation model of the single-
layer cabin.
The domain is divided into structured grid, which can easily realize the boundary fitting of the area and remains close to the actual model. The acceleration of gravity is set to be $-9.8 \text{ m/s}^2$. To capture the flow dynamics, RNG $k-\varepsilon$ turbulence model is employed. The density of water is set to be 1025 $\text{kg/m}^3$ and the density of solid material is set to be 2719 $\text{kg/m}^3$. The inlet velocity is 5 m/s. The turbulence intensity is set to be 5%, the hydraulic diameter is set to be 1 m, and the outlet adopts the pressure outlet boundary condition.

3.2 Distribution of velocity and mass flow

In Section 2.1, the relevant flow coefficient is chosen at an ideal state. The direction of the water flow velocity is perpendicular to the inlet of the single-layer cabin, and the thickness of the thin bulkhead of the single-layer cabin is negligible, which is different from the actual fluid flow coefficient. Fig. 7 shows the fluid flow state of the pressure ingress in Fluent and reality.

Here, a cloud diagram of the fluid velocity distribution interior and external the cabin is obtained with the simulation of the center of gravity of the single-layer cabin below the sea level. It can be seen from Fig. 8 that the maximum velocity inside the cabin is located at the pressure ingress, and the maximum velocity external the cabin is located on both sides of the cabin, and the outward velocity gradually decreases. The fluid velocity on both sides of the cabin are smaller than the fluid velocity in Fig. 8a, but the fluid velocity distribution law is basically the same. Fig. 8b is the cross-sectional velocity distribution diagram of the cabin without opening. When there is a continuous flow of fluid inside the single-layer cabin, the velocity of the fluid inside the cabin is basically the same as the velocity at the inlet.

In fact, the water ingress process of a single-layer cabin with openings in this paper is different from the flow around a cylinder. Since the ratio of the channel length of the hole to its diameter is not larger than 0.5, the hole is called thin-walled small hole. When the fluid flows through the small hole, the fluid particle can suddenly accelerate. Under the action of inertial force, the liquid flow after flowing through...
the small hole shrinks first. When it diffuses into the cabin, this shrinkage and diffusion process can cause energy loss. Hence, it can be seen from Fig. 8a that the speed at the opening of the single-layer cabin becomes smaller.

The mass flow distribution in the fluid domain is shown in Fig. 9. The value of the mass flow at the entrance of the single-layer cabin is about 261.6 kg/s and a mass flow of about 141.8 kg/s on average continuously flows into the interior cabin.

3.3 Comparison

In Section 2.1, the mathematical models of the single-layer cabin with the center of gravity at different locations were deduced. Based on Eq. (15), the initial flow at the inlet of the single-layer cabin can be calculated by Matlab as $Q = 276.75$ kg/s with the pressure head between the inlet and the sea level presented by $H = h_0 + (x_0 - x_1) \cos \theta = 0.5$ m with $h_0 = 0.5$ m, and $x_0 = x_1 = 0$. Here, the inlet area is $A_F = 0.09 \text{m}^2$, the coefficient $C$ is specified as one, and the inlet pressure is 0.3 MPa. Comparing with the simulation calculation results of 261.6 kg/s, the relative error is about 5.47%, which can be explained by the gap between reality and simulation.

In fact, the buoy equipped with exhaust valve in each cabin is designed to ensure that the gas in the compartment can be discharged in time and the internal pressure can be adjusted in single-layer cabin. Then, the seawater filling time of the four buoys can be obtained as $t = 84.5$ s considering the single cabin volume of $V = 24.62 \text{m}^3$ and the average initial flow rate of $Q = 230.625$ kg/s. We can assume that the lowering speed of the subsea suspended manifold from the air is $v = 0.2$ m/s. Therefore, the depth of seawater filled in four buoys can be calculated to be about 15 m. Based on this, the dynamic simulation analysis of the installation of the subsea suspension manifold in the splash zone using OrcaFlex can be conducted.

4 Dynamic sensitivity analysis based on OrcaFlex

During the process of the splash zone, the environmental loads will generate a large sudden load on the manifold, which may cause fatigue damage to the fiber ropes and cranes. At the same time, the installation vessel may shake under the action of environmental load changes, potentially deviating the vessel from its initial position. The tension of the fiber cable, the installation attitude of the subsea suspended manifold, and the offset in a stable state are the main factors to evaluate the stability of the whole lowering system. The discussion of the main factors should be carried out with a certain set of sea area parameters in the South China Sea.

4.1 OrcaFlex modelling and parameters

In OrcaFlex software, the vessel is regarded as a rigid body that cannot be deformed, and its motion characteristics are determined by the RAOs operator of the system. The wire rope is modeled by Line. The rope is equivalent to an inelastic spring consisting of several continuous and massless nodes. The nodes are connected by springs and dampers. The subsea suspended manifold is constructed by buoys and other floating body models. The $x$ direction is defined as the direction along the bow, the $y$ direction is perpendicular to the vessel, and the $z$ direction is perpendicular to the vessel. The connect command is used for multiple models to define the constraints between the structures, thereby constructing the multi-body coupled (installation vessel-fiber cable-subsea suspended manifold) lowering installation system model, as shown in Fig. 10. The fiber rope parameters are shown in Table 1. The main structural parameters of the subsea suspended manifold and buoy are shown in Table 2. Some environmental parameters of a certain area in the South China Sea are given in Table 3.

4.2 Effects of wave height

The dynamic response of the lowering installation system with different wave return periods is carried out. It can be seen from Fig. 11 that the wave height has different effects on the force of the fiber cable and the motion response of the subsea suspended manifold. As the wave height increases, the $x$-direction offset increases, and the $y$-direction offset first increases and then decreases. The extreme force
Table 1 Parameters of the fiber cable

| Type         | Length (m) | Diameter (m) | Dry weight (kg/m) | Wet weight (kg/m) | Rigidity (kg/m) | Drag coefficient | Added mass coefficient |
|--------------|------------|--------------|-------------------|-------------------|-----------------|-----------------|---------------------|
| Fiber cable  | 3000       | 0.087        | 6.931             | 1.4               | 148.3           | 1.2             | 1.0                 |

Table 2 Main structure parameters of the subsea suspended manifold and buoy

| Name                      | Value                                      |
|---------------------------|--------------------------------------------|
| Subsea suspended manifold | Length×Width×Height: 21.35 m×19.85 m×5.5 m |
|                           | Weight (t): 140                             |
|                           | Drag coefficient in the x/y/z direction: 2.13/2.33/2.17 |
|                           | Additional mass coefficient in the x/y/z direction: 1.72/2.00/1.22 |
| Buoy                      | Diameter (m): 2.8                           |
|                           | Height (m): 5                               |
|                           | Weight (t): 49.85                           |
|                           | Drag area in the x/y/z direction (m²): 14/14/6.15 |

Table 3 Parameters in a certain area of the South China Sea

| Essential factor | Return period (year) | 1        | 10       | 50       |
|------------------|----------------------|----------|----------|----------|
| Wave             | Characteristic wave height $H_s$ (m) | 6.3      | 9.5      | 12.3     |
|                  | Maximum wave height $H_{max}$ (m)     | 10.8     | 16.3     | 21.2     |
|                  | Average period $T_z$ (s)              | 8.0      | 9.3      | 10.4     |
|                  | Wave peak period $T_p$ (s)            | 12.1     | 13.6     | 14.4     |
| Current speed (m/s) | 0 m subsea | 1.09 | 1.46 | 1.86 |
|                  | 79 m subsea | 0.92 | 1.27 | 1.63 |
|                  | 237 m subsea | 0.74 | 1.02 | 1.26 |
|                  | 394 m subsea | 0.57 | 0.63 | 0.67 |
|                  | 500 m subsea | 0.56 | 0.62 | 0.66 |

Fig. 10. Models of subsea suspended manifold system lowering system.

Fig. 11. System dynamic responses with different wave return periods.
of the fiber cable, the offset of the subsea suspended manifold, and the tilt angle of the installation attitude are constantly increasing. When the wave height is of a 50-year return period, the x-direction offset, the fiber cable force and inclination angle have the maximum values, which are 12.71 m, 8313.2 kN, and 14.85°, respectively.

4.3 Effect of current velocity

As can be seen from Fig. 12, the current velocity has little effect on the force of the fiber cable and the motion response of the subsea suspended manifold. The force of the fiber cable is about 6970 kN, the inclination angle is about 11°, the x-direction offset and the y-direction offset are about 9.1 m and 4.1 m, respectively.

Comparisons with the influence of currents and waves on the lowered process installation system are shown in Fig. 13. The influence of waves on the extreme force of the fiber cable, the offset of the subsea suspended manifold and the inclination angle of the installation attitude are all greater than the influence of the sea current velocity. Therefore, in the process of the splash zone, it is necessary to pay special attention to the changes of the waves to avoid the occurrence of the overturning of the manifold and blast damage.

4.4 Effects of environmental load direction

Due to the different directions of the environmental loads, the installation vessel and the subsea suspended manifold will have different motion responses and coupling effects, which will have a great impact on the lowering installation system. In this paper, environmental load directions of 0°, 45°, 90°, 135° and 180° are selected for simulation analysis, as shown in Fig. 14.

The different environmental load directions have a great influence on the force of the fiber cable and the motion response of the subsea suspended manifold. When the environmental load is perpendicular to the direction of the installation vessel, the force of the fiber rope, the installation attitude and offset of the subsea suspended manifold all become larger. When the environmental load is along with the direction of the hull of the installation vessel, the force of the fiber rope, the installation attitude and offset of the subsea suspended manifold all appear to be relatively smaller values. The effective tension of the fiber rope appears to be zero during the entry into the seawater, which indicates slack phenomenon. Thus, during engineering operations, the bow of the installation vessel should be aligned with the direction of the environmental loads, which can reduce the maximum force of the fiber cable and avoid the generation of cable slack.

5 Conclusions

This paper establishes a mathematical model of the water flowing into the single-layer cabin with different posi-
tions of the center of gravity, along with the software to carry out a flow simulation. Meanwhile, the installation numerical model of the multi-body lowering system in the splash zone is established and the simulation is conducted. Some conclusions are listed as follows:

1) The mathematical model of seawater ingress of the different centers of gravity of the single-layer cabin was proposed. The initial flow at the inlet of the single-layer cabin below the sea level is 276.75 kg/s, which exist a 5.47% relative error in the simulation result. The correctness of the model is verified, and the time required for four pontoons to be filled with seawater is calculated, so as to determine the locations where the subsea suspended manifold is filled with seawater.

2) The wave height has a positive influence on the extreme force of the fiber cable, the offset of the subsea suspended manifold and its inclination angle greater than the impacts on the current velocity. For the case of 50-year return period, the maximum force of the fiber cable is 8313.2 kN, the maximum offset and inclination angle of the manifold can reach 12.71 m and 14.85°, respectively.

3) When the environmental load direction is parallel to the installation vessel, its effects on the multi-body coupled system is the smallest, which is conducive to the installation of the splash zone. It can effectively avoid the slack phenomenon of the cable, and reduce the maximum force of the fiber cable and the motion response of the subsea suspended manifold.

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