J. Electrical Systems 20-10s (2024): 5994-6003

[1]Y. Song
[2]Y. Gu
[3]X. Y. Wan*

Mechanical Analysis of Deepwater Drilling Bulkheads

Abstract: - The Earth's oceans cover about 75% of the surface and contain 34% of global oil resources, with some reserves deeper than 1,000 meters. Deep-sea drilling encounters challenges due to the harsh marine environment. A key component is the water distribution pipe, which links offshore platforms to the seabed. This study examines the environmental loads on these pipes using a nonlinear finite element model. It finds that maximum deformation and internal stress occur near the water surface due to seawater flow and waves. Therefore, the design should enhance resistance to bending, shear, and tensile forces in these upper regions. These findings improve the design of water separators for ultra-deepwater conditions and support offshore oil and gas development.

Keywords: ANSYS, Modal Analysis, Riser Pipe, Statics, Spectral Analysis

I. INTRODUCTION

With the rapid development of China's economy, the demand for oil has risen sharply, a trend that has prompted the urgent need for exploration of new oilfields, and the seabed, especially the deep-sea region, has naturally become a hot spot for exploration because it contains rich oil resources that account for about 34 per cent of the global total. The South China Sea region, an important base for China's oil and gas resources, holds considerable oil and natural gas reserves, and most of them are located in the deep sea, has an inestimable strategic value for the maintenance of China's energy security. Considering that China's land-based oil and gas resources are depleting, oil dependence on foreign countries is as high as about 70%, and there are a lot of uncertainties in the import path, therefore, to increase the exploration and development of deep-water oil and gas resources has become the main direction of China's marine energy strategy, which aims to enhance the energy self-sufficiency, to ensure the country's energy security.

In deepwater oil and gas exploration and development, as the core equipment connecting the drilling platform and submarine equipment, the stability of the offshore drilling spacer is directly related to the safety and efficiency of the whole drilling operation. The complexity and variability of the deep-sea environment, such as strong waves, currents and wind and other external loads, make the platform movement extremely irregular, and thus exert complex and variable mechanical effects on the watertight pipe. Due to the extreme environment, the deep water bulkhead has become one of the weakest links in the drilling system, and any failure may bring serious consequences and even endanger the safety of the platform. Especially in the South China Sea and other deep-water areas, the length of the water separator in drilling operations often exceeds 1,000 metres, and the stress situation is even more intricate and complex, which significantly increases the risk of accidents. A number of major offshore drilling accidents in history have highlighted the extreme importance of improving the stability of water separator pipes.

In order to meet this challenge, scholars at home and abroad have carried out extensive and in-depth research in the field of offshore drilling watertight pipe research. Foreign research not only covers a full range of contents from nonlinear vibration analysis to performance evaluation of deep-sea drilling watertight pipe, but also reveals the mechanical behaviour of watertight pipe in complex environment through the combination of advanced theoretical methods and on-site measurement data, providing a solid empirical basis for design optimization. Especially, the application prospect of composite water separator pipe in deep water drilling is widely favoured due to its unique performance advantages, and its lightweight, high strength and optimized stress distribution have been verified through simulation and experiments.

[1, 3] School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia

[2] School of Safety Science and Engineering, Civil Aviation University of China, Dongli Campus, 300300, Dongli District, Tianjin, China.

*Corresponding author Email: wanxinyu@student.usm.my

In recent years, domestic research has also followed the international pace, focusing on the mechanical properties and safety analysis of deepwater drilling water separators. Through the construction of fine finite element models, it is found that waves, flow velocity and platform motion have significant effects on the bending moment and overall dynamic response of the bulkhead. Meanwhile, the potential threat of vortex-excited vibration to the strength and fatigue life of the isolation pipe is also deeply analysed, and a strategy to avoid resonance by adjusting the top tension and other effective measures is proposed. In addition, for the safety of the flange joints, the connecting part of the watertight pipe, the study evaluates its safety performance by simulating the stress changes under different loading conditions, while the study based on the hydrostatic model further reveals the specific effects of wind and waves on the bending moments and lateral displacements of the watertight pipe. In specific environments such as high-pressure conditions, the performance of the watertight pipe has also been analysed in comparison with conventional working conditions, providing valuable data for a comprehensive understanding of its complex stress conditions.

In summary, the research on offshore deepwater drilling watertight pipe at home and abroad has been continuously deepened, providing solid theoretical support and technical support for improving the stability of the watertight pipe and guaranteeing the safety of deepwater mining. In the future, with the continuous deepening of research and technological innovation, marine oil and gas extraction is expected to expand to deeper and farther waters, contributing more clean energy to the sustainable development of human society.

II. MODEL ESTABLISHMENT AND METHOD

As an important conduit system connecting the subsea wellhead with the drillship, the watertight pipe system covers various types such as steel, flexible and hybrid, which are widely used in drilling, oil production, water injection and well maintenance. The drilling spacer is particularly critical, as it not only carries the burden of circulating drilling fluids between the blowout preventer and the drillship, but also supports auxiliary piping, guides the drilling tools, and serves as a carrier for the operation of the blowout preventer team. The deepwater version of the system is significantly more complex, integrating numerous key components such as deflectors, chucks, universal joints, shunts, flexible joints (top and bottom), expansion joints, fill valves, isolation tubing singles, throttling and pressurisation lines, hydraulic lines, drilling fluid pressurisation lines, buoyancy blocks, terminal stubs, bottom isolation manifolds (LMRPs), and isolation pipe fittings. Each of these components has its own role to play, such as chucks to support the weight of the bulkhead and quickly connect and disconnect the fittings; universal joints to support the entire bulkhead column and compensate for deflection; flow dividers to direct drilling fluids and divert shallow gas; tensioners to apply vertical force and control axial tension; expansion joints to balance the platform's displacement; a single piece of the bulkhead to isolate the seawater, connect to the pipeline, introduce drilling tools and form a mud circulation channel; and buoyancy blocks, flexure joints and bottom bulkhead assembly to solve the problems of the hydraulic line, the hydraulic line, the terminal nipple, the bottom bulkhead assembly (LMRP), and other key components respectively. The buoyancy blocks, flexible joints and bottom bulkhead assembly solve the problems of bulkhead self-loading, vibration control and anti-spray protection respectively. In the complex subsea environment, the coordinated work of these components ensures the stable operation of the watertight pipe system, thus guaranteeing the safety and high efficiency of deep-sea drilling operations.

For structural analysis and calculation of the marine drilling water separator using ANSYS 19.0, selecting the appropriate element type from the ANSYS element library is essential to accurately simulate the actual drilling separator. The PIPE288 element, suitable for elongated to moderately short pipe structures, is based on Timoshenko beam theory and accounts for shear deformation effects. It is a three-dimensional, two-node pipeline element capable of handling linear, large rotation, or large strain applications, including stress stiffness terms. This element supports various material models such as elasticity, hyper-elasticity, plasticity, and creep, and can be used to analyze bending, transverse, and torsional stability issues. (Common types of units used to simulate marine drilling hots are shown in Table 1 below.)

Table 1: Common unit type

Sequence number	Unit type	Feature
1	PIPE288	A two-node direct tube unit with plasticity and creep characteristics can be considered

2	PIPE289	The three-node straight pipe unit with plasticity and creep characteristics can be considered
3	ELBOW290	A three-node bending unit with plasticity and creep can be considered

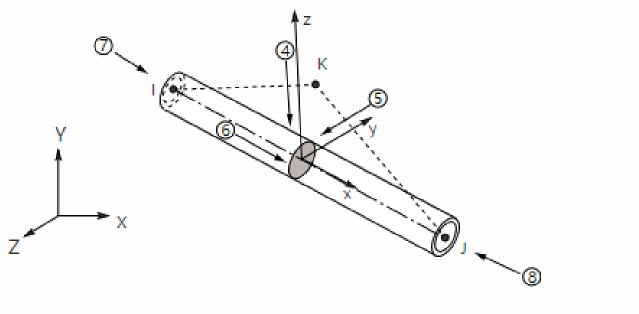


Figure 1. PIPE288 cell configuration

(2) PIPE288 Instructions for unit use

PIPE288 Is based on the Timoshenko beam theory, a first-order shear deformation theory. The transectangent strain is constant in the cross section, meaning that the cross section remains flat and unchanged after deformation. This element can be used for elongated or robust pipes, due to the limitations of the first-order shear deformation theory. The length to length ratio (GAL ^{2} / (EI)) can be used to determine the applicability of elements, where:

G—— modulus of shearing

A—— cross-sectional area

L —— Actual tube length (non-unit length)

EI—— flexural rigidity

For pipelines, (GAL^2/EI) can be simplified to: $2L^2/((1+\nu)(R_o^2+R_i^2))$, for thin-walled pipes: $L^2/((1+\nu)R^2)$, where ν = Poisson's ratio, Ro= outer radius, Ri= inner radius, R= average radius. The figure figure provides an estimate of lateral shear deformation in the cantilever tube bearing the tip load, although the results cannot be extrapolated to other applications, the example is generic. ANSYS recommends a length ratio greater than 30.

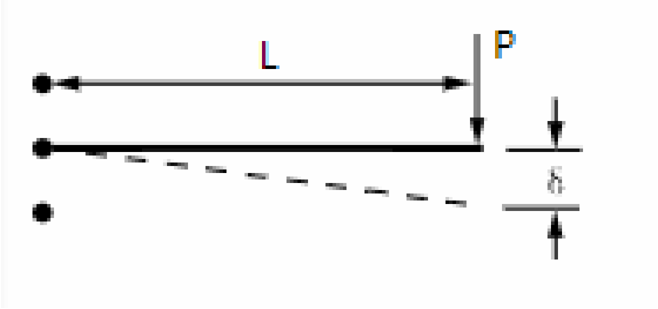


Figure 2. Horizontal deformation estimation

Figure 2 In deep water conditions, the force of the water divider becomes very complicated. Therefore, when establishing its mechanical model, it is necessary to grasp the main factors while ignoring some secondary factors. The following basic assumptions are hereby made:

1) Within each cell, the geometric characteristics and the material characteristics remain unchanged.

2) The lower end of the partition pipe is connected with the ball hinge, which is simplified to the fixed end support.

3) The upper end of the partition pipe is connected with the floating drilling device, which is simplified to the movable hinge support.

4) The partition pipe belongs to the category of small strain and large deformation under the action of dead loads and external loads.

5) No influence of the drill column on the bending stiffness of the partition.

Based on the above assumptions, the mechanical model of the ultra-deep water offshore drilling water divider can be obtained as shown in the figure below. Apply lateral load to it, mainly including wind load and ocean current load. Both wind load and ocean current load are equivalent to static load.

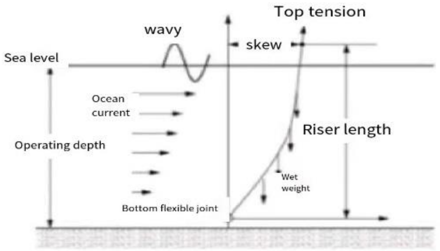


Figure 3. Schematic diagram of static force bearing of deep water divider

2.1 *Basic theory of modal analysis*

Modal analysis is used to determine the vibration characteristics of the designed structure, specifically its natural frequency and vibration patterns, namely, the natural frequency and pattern of the structure, which are important parameters in the design of the dynamic load. At the same time, it is also the early analysis process of the following spectral analysis.

According to D'Alembert's principle, the equilibrium equation of any vibrational system can be written in the following form

$$\{F_t\}+\{F_D\}+\{F_s\}=\{P\} \tag{1}$$

Where $\{F_t\}$, $\{F_D\}$, $\{F_S\}$ represent the inertial, damping and elastic force vectors of the structure, respectively, as the external load vector. $\{P\}$ is the external load vector. Inertial force and elastic force vector can be further expressed by acceleration and displacement vector:

$$\{F_t\}=-[m]\{\ddot{\delta}\} \qquad \{F_S\}=-[K]\{\delta\} \tag{2}$$

When the assumption of viscous damping is adopted, the damping force is proportional to the velocity, so that the damping force vector can be expressed as:

$$\{F_D\}=-[C]\{\dot{\delta}\} \tag{3}$$

Adding the inertial force, damping force and elastic forces by unit, the displacement equation of the finite element node is:

$$[M]\{\ddot{\delta}\}+[C]\{\dot{\delta}\}+[K]\{\delta\}=\{P\} \tag{4}$$

Where[K] is the elasticity coefficient; [C] is the damping coefficient, [M] is the mass and P is the external load vector. The $\{\ddot{\delta}\}$ mean the six-dimensional displacement vector of the nodes at both ends of the divider, x, y, z, rot x, rot y, rot z, respectively. When assuming viscous damping, the damping force is proportional to velocity, leading to the damping matrix [C]. By combining the inertial, damping, and elastic forces, the displacement equation for the finite element nodes is derived. When there is no external load action and the damping is ignored, the upper formula becomes:

$$[M]\{\ddot{\delta}\}+[K]\{\delta\}=0 \tag{5}$$

This is the free vibrational equation of the system. If all the nodes of the whole structural system have n degrees of freedom, then this equation is the free vibration equation of the system of n degrees of freedom. Let the displacement of the structure at the free vibration be as follows $\{\delta\}=\{A\}\cos\omega t$ After the substitution formula (5), the following system of homogeneous equations can be obtained:

$$([K]-\omega^2[M])\{A\}=0 \tag{6}$$

Due to the amplitude of each junction at free vibration $\{A\}$ it is impossible to be all zero, so the condition that the formula (6) has non-zero solutions is that the value of its coefficient matrix determinant must be zero, namely:

$$|[K]-\omega^2[M]|=0 \tag{7}$$

2.2 The spectral analysis theory

Spectral analysis is an analytical technique that relates the results of a modal analysis to a known spectrum to compute the displacement and stress of a model. Spectral analysis alternative time-course analysis to mainly determine the dynamic response to random load or time-varying load over time. In this paper, vibration type decomposition reaction spectroscopy is used to determine the dynamic response of this intermittent load.
The natural frequency f and the intrinsic form function $\Phi(x)$ of the model are:

$$f=\frac{\pi}{2l^2}\sqrt{\frac{EI}{\rho A}} \tag{8}$$

$$\Phi(x)=\sin\left(\frac{\pi x}{l}\right) \tag{9}$$

The moment of inertia $I_y=\frac{\pi}{64}\left[1-\left(\frac{d}{D}\right)^4\right]$, the natural frequency of the model is $f=0.028$ Hz. Modality participation coefficients Γ:

$$\Gamma=\frac{\int_0^L m\Phi(x)dx}{\int_0^L m[\Phi(x)]^2dx} \tag{10}$$

Maximum displacement of the model relative to the base δ_{max}:

$$\delta_{max}=\Gamma\delta_{max}^0 \tag{11}$$

III. SIMULATION SETTINGS

3.1 Hydrostatic analysis of water pipe

By assuming only the transverse load from the offshore current, this study examines the deformation of the deepwater water distribution pipe and the internal force characteristics of the sea flow rate of 1.5m / s and the lateral load of the assumed drilling water distribution pipe by the sea current and the sea wind, and study the deformation and internal force characteristics of the deepwater water distribution pipe under the sea current force and the sea wind force. The wind speed is 24.5m/s and the ocean current velocity is 1.5 m/s for calculation.

3.2 Dynamic analysis of the drain pipe (modal analysis)

The self-oscillation frequency, period, and mode of vibration, as obtained from the modal analysis of the watertight pipe, express the structure's inherent dynamic characteristics, which is an inherent property of the structure itself. In order to obtain the self-oscillation frequency and vibration mode of the water trap structure. In this paper, ANSYS is used to extract the first twelve orders of intrinsic frequency and vibration pattern of the water pipe, and the same solution is removed, leaving six orders of intrinsic frequency and vibration pattern, because the vibration pattern can be displayed in the even order, so the frequency is also selected as the even order, as shown in the following Table 2 and Figure 4.

Table 2: First six orders of intrinsic frequency of the model

Modal order	2	4	6	8	10	12
Natural frequency (Hz)	0.025	0.082	0.17	0.29	0.45	0.63

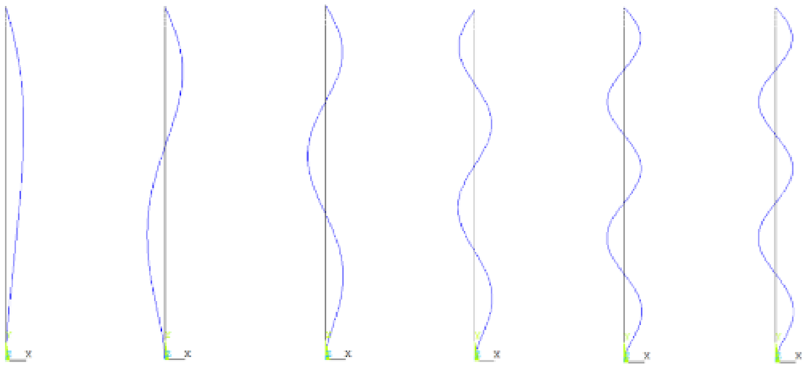


Figure 4. Sixth order intrinsic modes of vibration of water pipes

It can be seen that the natural frequency of the divider increases with the increase of the order, and with the increase of the order of the partition pipe, the mode vibration of the divider becomes more and more tortuous, the more bending number.

3.3 *Analysis of dynamics analysis (calculation of ANSYS spectrum analysis)*

Compared with time-course analysis, spectral analysis requires less hardware resources. Compared with time-course analysis, which can obtain the complete time course of the structure response, spectral analysis can only obtain the maximum response of the structure. Compared with time-range analysis, it can consider a variety of nonlinear factors, and spectral analysis cannot consider the nonlinear factors, namely linear analysis. In the actual calculation, the second order pattern and frequency are selected for analysis. Through the literature, the shaking frequency is 0~4Hz and the amplitude is 22 m to obtain the maximum displacement map.

IV. NUMERICAL CONCLUSION

4.1 *Hydrostatic analysis of water pipe*

The calculation results of the static analysis of the partition pipe are introduced. The maximum deformation of the partition pipe is near the water surface, and the maximum internal force is at the fixed place near the sea surface of the sea floor, and the internal force value near the sea level. Therefore, the carrying capacity of the bending, shear and tensile bearing capacity of the partition pipe near the water surface and the fixed place of the sea floor should be improved. Moreover, compared with the calculation results of the transverse load only the sea current force and sea current force and sea wind force, it can be seen that the deformation and internal force of the deep water ocean drilling separation pipe are mainly dependent on the sea current force. However, the sea wind force is less affected due to the small action area and small force.

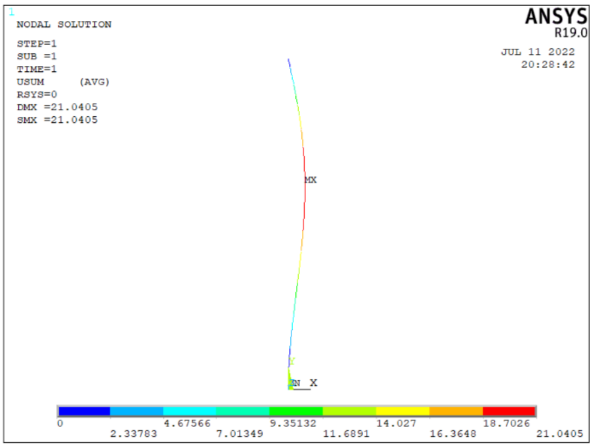


Figure 5. Shift diagram

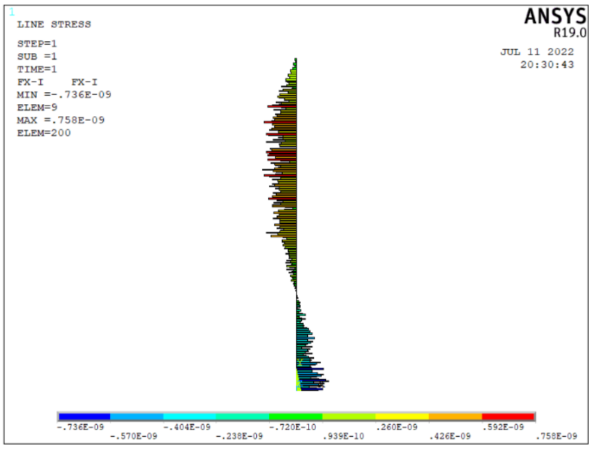


Figure 6. Axial force diagram

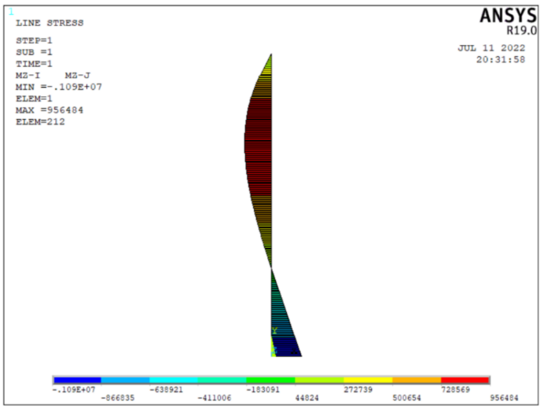


Figure 7. Bending moment diagram

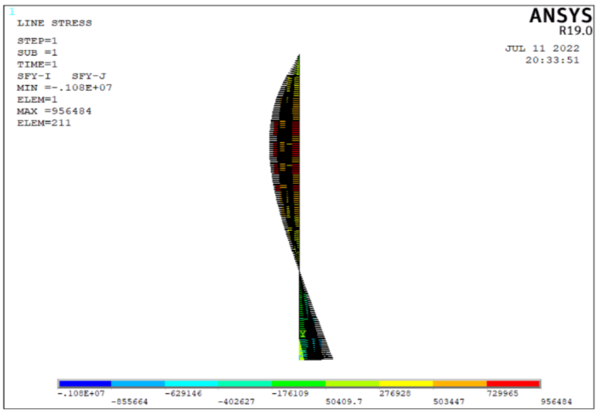


Figure 8. Shearing force diagram

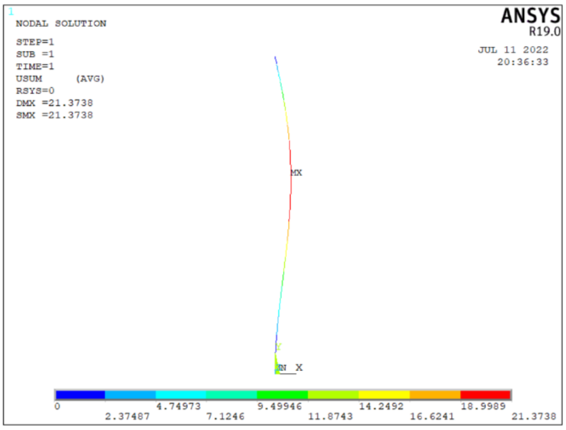


Figure 9. Shift diagram

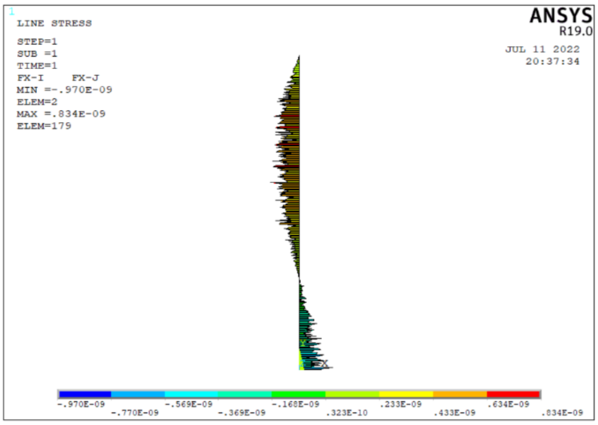


Figure 10. Axial force diagram

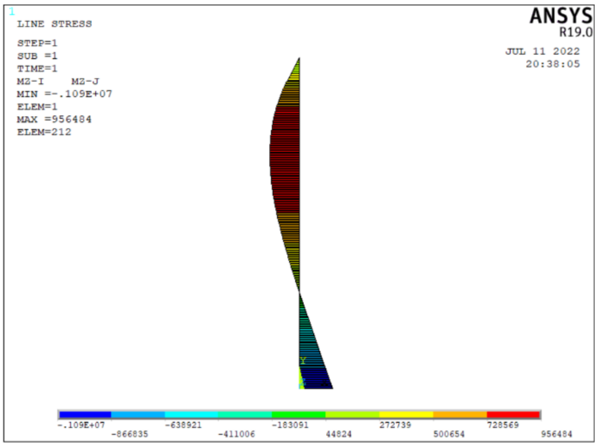


Figure 11. Bending moment diagram

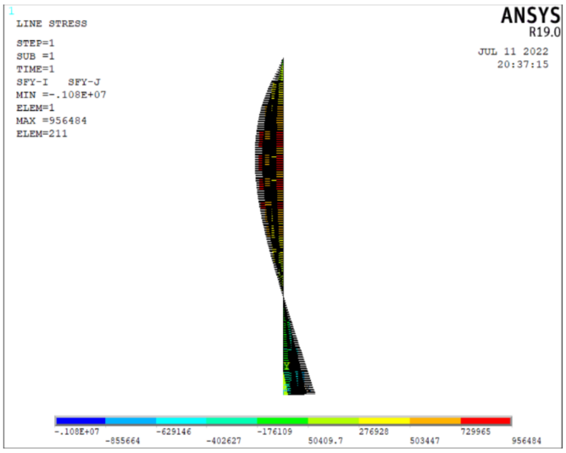
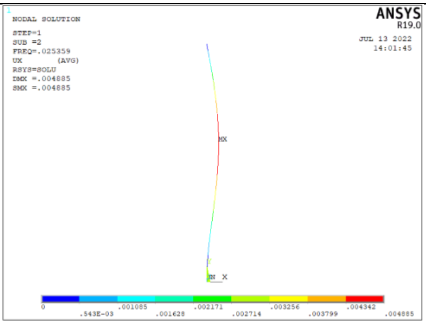
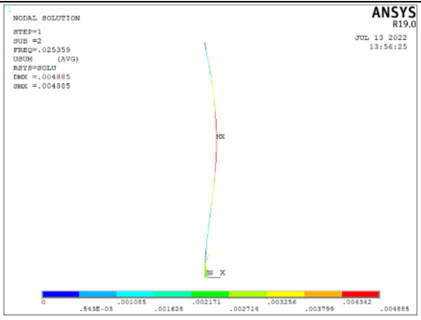
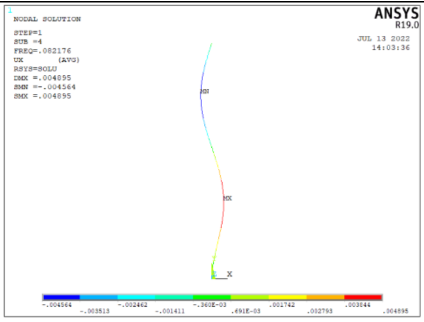
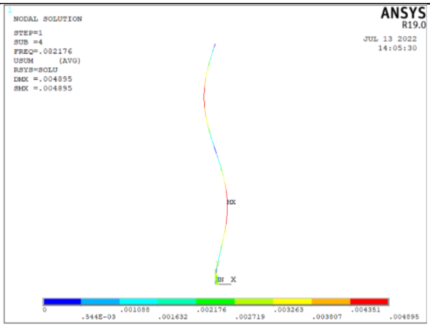
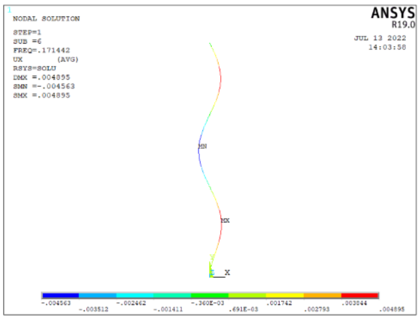
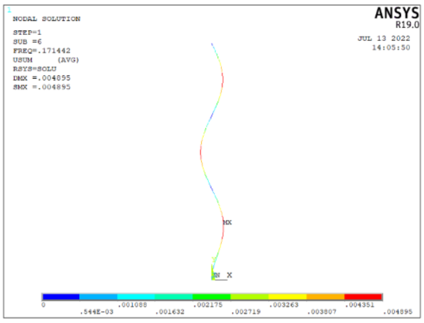
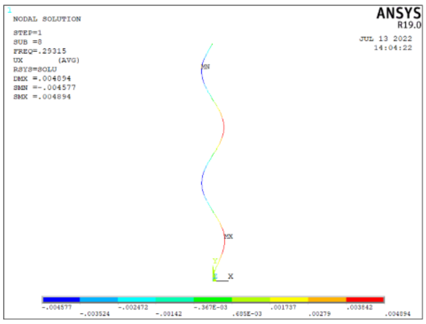
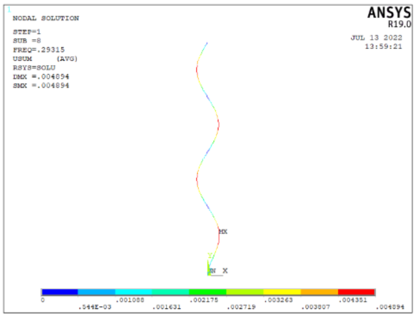
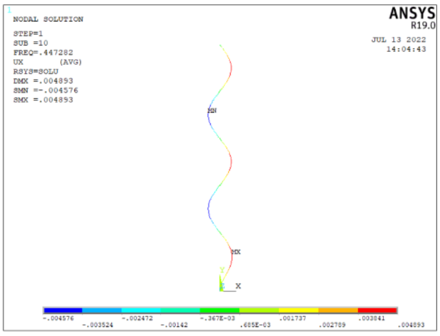
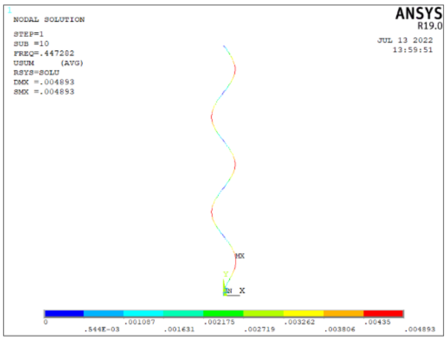


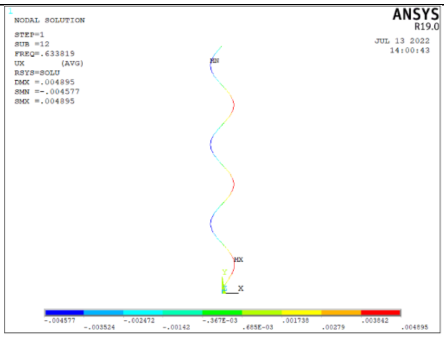
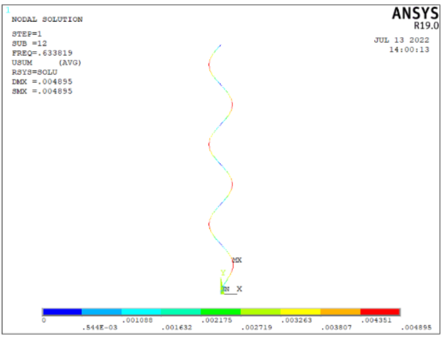
Figure 12. Shearing force diagram

4.2 Modal analysis of water: Analysis of the displacement diagram for modal analysis of water trap

Dynamic analysis of the water pipe from the water pipe modal analysis concluded that the second order of the intrinsic frequency of 0.025Hz, the maximum displacement of 4.885× 10-3m, the deformation mainly occurs in the middle of the water pipe in the upper part of the water pipe. The fourth order of the intrinsic frequency of 0.082Hz, the maximum displacement of 4.895× 10-3m two bends. Sixth-order intrinsic frequency of 0.17Hz, the maximum displacement of 4.895× 10-3m, the maximum displacement is still in the bend, and then with the increase in frequency of the maximum displacement basically unchanged, the maximum displacement are in the bend. Derived to pay attention to the part of the water separator pipe bending, the bending part of the reinforcement to avoid bending

Table 3: Displacement diagram for modal analysis of water trap

Modal order	The displacement diagram of x direction	Total displacement diagram
2	 NODAL SOLUTION STEP=1 SUB =2 FREQ=.025359 UX (AVG) RSYS=SOLU DMX =.004885 SMX =.004885 JUL 13 2022 14:01:45 	 NODAL SOLUTION STEP=1 SUB =2 FREQ=.025359 USUM (AVG) RSYS=SOLU DMX =.004885 SMX =.004885 JUL 13 2022 13:56:25
4	 NODAL SOLUTION STEP=1 SUB =4 FREQ=.082176 UX (AVG) RSYS=SOLU DMX =.004895 SMN =-.004564 SMX =.004895 JUL 13 2022 14:03:36 	 NODAL SOLUTION STEP=1 SUB =4 FREQ=.082176 USUM (AVG) RSYS=SOLU DMX =.004895 SMX =.004895 JUL 13 2022 14:05:30
6	 NODAL SOLUTION STEP=1 SUB =6 FREQ=.171442 UX (AVG) RSYS=SOLU DMX =.004895 SMN =-.004563 SMX =.004895 JUL 13 2022 14:03:58 	 NODAL SOLUTION STEP=1 SUB =6 FREQ=.171442 USUM (AVG) RSYS=SOLU DMX =.004895 SMX =.004895 JUL 13 2022 14:05:50
8	 NODAL SOLUTION STEP=1 SUB =8 FREQ=.29315 UX (AVG) RSYS=SOLU DMX =.004894 SMN =-.004577 SMX =.004894 JUL 13 2022 14:04:22 	 NODAL SOLUTION STEP=1 SUB =8 FREQ=.29315 USUM (AVG) RSYS=SOLU DMX =.004894 SMX =.004894 JUL 13 2022 13:59:21
10	 NODAL SOLUTION STEP=1 SUB =10 FREQ=.447282 UX (AVG) RSYS=SOLU DMX =.004893 SMN =-.004576 SMX =.004893 JUL 13 2022 14:04:43 	 NODAL SOLUTION STEP=1 SUB =10 FREQ=.447282 USUM (AVG) RSYS=SOLU DMX =.004893 SMX =.004893 JUL 13 2022 13:59:51

Modal order	The displacement diagram of x direction	Total displacement diagram
12		

4.3 Spectral analysis of water dynamics

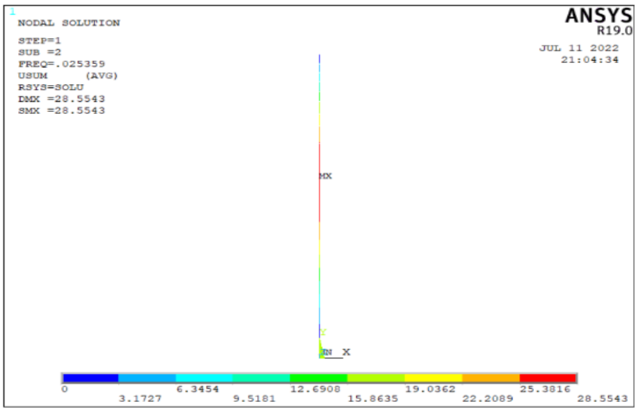


Figure 13. Maximum displacement diagram

From the above figure 13, the largest displacement of the spectral analysis is 28.5543m, and the maximum displacement from the analytical solution is 28.025m, with an error of 1.85%, which is basically consistent.

The modal and spectral analysis of the water er using ANSYS software yielded the following conclusions:

1) The natural frequency and natural vibration pattern will change with the cross section. The maximum displacement of the riser in the mode analysis is at the bend of the tube.

2) In the kinetic calculation, the spectral analysis shows that the impact of ocean current transient change is greater than the impact of continuous applied load.

V. CONCLUSION

Static and dynamic analyses of the deep-water offshore drilling partition pipe show that the greatest deformation occurs in the middle section of the pipe, with peak internal forces at the seabed fixation and near the sea surface, highlighting the need for enhanced resistance to bending, shear, and tensile forces. Sea current forces are the primary influence on deformation and internal forces, while wind forces have a minimal effect. The natural frequency increases with the modal order, with the second and fourth order frequencies at 0.025 Hz and 0.082 Hz, respectively, corresponding to displacements of 4.885 × 10-3 m and 0.4895 × 10-3 m. Cross-sectional changes affect natural frequencies and mode shapes, with maximum displacement occurring at pipe bends. Spectral analysis further shows that transient changes in ocean currents have a more significant impact on the pipe than continuous loads. These findings emphasize the need for robust structural design, particularly in the middle section and at the seabed fixation, to account for dynamic conditions and ensure structural integrity.

REFERENCES

[1] Klaycham K， Athisakul C， Chucheepsakul S .Nonlinear vibration of marine riser with large displacement[J].Journal of Marine Science&Technology, 2016, 22(2):1-15.

[2] Grytoyr,G,L.E.Eilertsen, et al.Full Scale Measurements of Cyclic Bending Moments on Subsea We1lHeads on the Norwegian Continental Shelf[C].in SPE International Conference and Exhibition on Health, Saftey, Security, Environment,and Social Responsibility, 2016.

[3] Chiemela Victor Amaechi,Xiaonan Hou,Jianqiao Ye,et al.Local and Global Design of Composite Risers on Truss SPAR Platform in Deep waters[D]. Institute Superior Tecnico, Lisbon, Portugal, 2019.

[4] VALENTIN-PAUL TUDORACHE,LAZAR AVRAM NICULAE-NAPOLEON ANTONESCU. Aspects on offshore drilling process in deep and very deep waters[J].Journal of Engineering Sciences and Innovation, 2020, 5(02):157-172.

[5] Chiemela Victor Amaechi,Nathaniel Gillet,Idris Ahmed Ja’e,et al.Tailoring the Local Design of Deep Water Composite Risers to Minimise Structural Weight[J]. Journal of Composites Science, 2022, 103(06).

[6] Chiemela Victor Amaechi,Cole Chesterton,Harrison Obed Butler,et al.Review of Composite Marine Risers for Deep-Water Applications:Design, Development and Mechanics[J]. Journal of Composites Science, 2022, 96(06).

[7] Li D. Mechanical analysis of ultra-deepwater drilling bulkhead based on ANSYS[D]. Hainan: Hainan University, 2013.

[8] GAN Wuxiang, ZHAO Honglin, DUAN Menglan. Mechanical performance analysis of deepwater drilling water separator[J]. Petroleum Machinery, 2018, 46(03):48-52.

[9] SHEN Guohua,WANG Rupeng. Vortex vibration analysis of deepwater watertight pipe based on finite element[J]. Tianjin Science and Technology, 2018, 45(03):43-45.

[10] LIU Qingyou, HE Junjiang, MAO Liangjie. Analytical study on the safety of compression collapse of flange joints of watertight pipe for deep water drilling[J].Journal of Southwest Petroleum University(Natural Science Edition), 2018, 40(05):163-169.

[11] Liu Lujiang. Research on mechanical properties and application of deepwater drilling water separator pipe[D]. Chengdu:Master's thesis of Southwest Petroleum University,2018.

[12] Jun Li. Research on mechanical properties and safety analysis of high-pressure drilling water separator pipe[D]. Chengdu:Master's thesis of Southwest Petroleum University,2018.

[13] WU Yongzhao,LI Zhenkun,CHAI Longshun et al.Stability analysis study of 30" watertight pipe joint[J]. China Petroleum and Chemical Standards and Quality, 2019, 39(15):150-151.

[14] Wang Rupeng. Static analysis of deep water bulkhead based on ANSYS[J]. Offshore Engineering Equipment and Technology, 2019, 6(S1):86-89.

[15] Xu Wenwen. Mechanical analysis of three-dimensional vibration of a watertight pipe when the wave direction is different from the current direction[D]. Qinhuangdao:Yanshan University Master's thesis,2019.

[16] Liu YJ. Analysis of deepwater drilling bulkhead tensioning system and its backlash control[D]. Qingdao:Master's thesis of China University of Petroleum (East China), 2019.

[17] Liao Maolin, Zhou Yingcao, Su Yiming et al. Research on dynamic analysis and design method of deepwater drilling tubular column system[J]. Oil Drilling Technology, 019, 47(02):56-62.

[18] CHEN Kun, HUANG Jian, HAN Xueying et al. Mechanical characterisation of marine watertight pipe systems[J]. Marine Engineering, 2021, 43(12):6-13.

[19] ZHANG Caiying, LI Xiankun, WANG Chuan et al. Research on pressure-bearing performance of bimetallic composite sealing structure based on ABAQUS[J].PetroleumMining Machinery, 2021, 50(02):7-11.

[20] YE Rui, LI Ruidong, GAO Cheng et al. Research on sealing test technology of deepwater drilling watertight pipe under ocean dynamic load[J]. Mechanical Engineer, 2021, (09):120-121+124.

[21] LI Yanjun, GUAN Shen. Mechanical characterisation of double-layer pipe column based on contact collision[J]. Science and Technology Innovation, 2021, (32):45-47.

[22] GUO Ming. Study on the vibration law of deepwater drilling watertight pipe[D]. Daqing: Northeast Petroleum University, 2021.

[23] HE Yufa, GUO Xiaoqiang, LIU Qingyou et al. Nonlinear dynamic modelling of deepwater bulkhead-test pipe system[J]. Vibration and Shock, 2022, 41(11):104-113.