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DYNAMIC RESPONSE ANALYSIS ON FLEXIBLE RISER WITH DIFFERENT CONFIGURATIONS IN DEEP-WATER BASED ON FEM SIMULATION

Shuangxi Guo
a. Key Laboratory of Mechanics in Fluid Solid Coupling System, Institute of Mechanics, Chinese Academy of Sciences
Beijing 100190, China
b. AVIC Composite Corporation LTD, National Key Laboratory of Advanced Composites
Beijing 100095, China

Yilun Li
Sino-French Engineering School, Beihang University
Beijing 100191, China

Min Li
School of Aeronautics Sciences and Engineering, Beihang University
Beijing 100191, China
limin@buaa.edu.cn

Weimin Chen*
a. Key Laboratory of Mechanics in Fluid Solid Coupling System, Institute of Mechanics, Chinese Academy of Sciences
Beijing 100190, China
b. School of Engineering Science, University of Chinese Academy of Sciences
Beijing 100049, China
wmchen@imech.ac.cn

Yue Kong
School of Aeronautics Sciences and Engineering, Beihang University
Beijing 100191, China

ABSTRACT

For case of oil/gas exploitation and mining in deep water, the length of riser is pretty large and, consequently, it brings huge challenges in both offshore installation and production operations and results in significant cost elevation due to the factors such as extreme tension loads induced from riser suspended self-weight and large structural flexibility. Therefore, there are several alternative riser configurations, e.g. lazy wave, hybrid tower and lazy-wave riser beside free hanging catenary, which have been proposed. In this paper, the dynamic characteristics and responses of several risers with typical configurations are considered and compared with each other based on our numerical simulations. Firstly, the nonlinear dynamic model of the riser systems are developed based on our 3d dynamic riser equations along with the modified FEM simulations. Then the dynamic response is analyzed based on our 3d curved flexible beam approach where the structural curvature changes with its spatial position and time in terms of vector equations. Compared with the linear approach, the nonlinear FEM method is used so as to consider large displacement/deformation, configuration geometry and structural stiffness changing with body motion. Moreover, the hydrodynamic force is considered as being related to body motion too.

Based on the FEM numerical simulations, the influences of the amplitude/frequency of the top vessel motion along with the buoyancy modules/tower distribution along structural length on riser's dynamic responses, in terms of the temporal-spatial evolution of displacement, curvature/bending stress and dynamic tension, are studied for different riser's configurations. Our results show that the dynamic responses, particularly the maximum top tension, of different riser systems significantly change. Among the examined riser configurations, the response of the riser with more buoyancy modules may have lower value, and buoyancy distribution along structural length can influence the top tension and curvature.

Key Words: lazy-wave riser; hybrid tower; tension; bending stress; curvature

1 INTRODUCTION

To explore and exploit the resources in deep-water and ultra-deep-water of ocean, the traditional fixed platform is no

longer economical to endure to the harsh marine environment and is replaced by floating systems such as the semi-submersible, Floating Production Storage (FPSO), spar platform and Tension-Leg Platform (TLP). Risers, as an important part of the floating system, transform the oil and gas from subsea production system to the upper vessel. At present, there are mainly four types of riser configurations, including flexible riser, hybrid tower riser, steel catenary riser (SCR), and top tension riser (TTR). Among these risers, the catenary riser and lazy-wave riser are mostly used, particularly in deep or ultra-deep water, due to its simple structure and installation. As the water depth gets larger, the structural length and weight of risers get larger, and consequently it costs much economic expenses. Moreover, its structural strength design and safety assessment of different configurations become more challenging.

One of important issues of structural safety of deep-water risers is: when the water depth is large and the length of the pipe increases, the tension at the top point of the riser will be too large[1]. In some way, this problem can be effectively solved by installing buoyant modules on a section of the riser so that the riser forms a wave-shaped layout. Several variations of the step riser configurations, include lazy-wave riser, free hanging riser, double wave configuration and hybrid tower configuration, have been presented and discussed[2]. Comparing these risers, we can see that the top tension of free hanging riser is larger and the configuration of double wave riser is a little complex. In this study, the two configurations, i.e. lazy-wave riser and hybrid tower, are considered. And the distributions of the buoyancy along riser's length, in terms of buoyancy length and number and dimension of every segment, are explored to assess the riser's performances under top-end motion and ocean current.

As for the response of these risers, there are a plenty of researches. For examples, by using finite difference method, Jain[3] gave the static analysis of the of the overhang section of s lazy-S riser. Chatjigeorgiou[4] analyzed the dynamic response of a two-dimensional catenary riser based on the Box approximation finite difference method which can give satisfied solutions of complete nonlinear model and simplified linear equation. To model the bending stiffness of risers, some professional codes, such as Orcaflex[5], use short rod element plus torsion spring-damping systems at both ends of the rod. And, Raman-Nair and Baddour[6] derived the equivalent bending force in the local coordinate system to consider the bending stiffness of flexible riser. In this study, the nonlinear dynamic model of the riser systems are developed based on 3d dynamic riser equations along with the modified FEM simulations. Then the dynamic response is analyzed based on our 3d curved flexible beam approach where the structural curvature changes with its spatial position and time in terms of vector equations. Compared with the linear approach, the nonlinear FEM method can consider large displacement/deformation, configuration geometry and structural stiffness changing with body motion. Moreover, the hydrodynamic force is considered as being related to body motion too.

Based on the FEM numerical simulations, the dynamic responses of two riser configurations, i.e. the lazy-wave riser and hybrid tower riser designed for ultra-deep-water industry, caused by top-end motion are examined. The influences of the amplitude/frequency of the top vessel motion along with the buoyancy modules distribution along structural span on riser's dynamic responses, in terms of the temporal-spatial evolution of displacement, curvature/bending moment and dynamic tension, are studied for different riser's configurations. Our results show that the dynamic responses, particularly the maximum top tension, of different riser systems significantly change. Among the examined riser configurations, the response of the riser with more buoyancy modules may have lower value, and buoyancy distribution along structural length can influence the riser tension and curvature.

2 THE STRUCTURAL MODELS AND CASES

2.1 The considered cases

The riser models are shown in Fig.1, i.e. 1) the modified lazy-wave risers (Model A, Model B and C) and hybrid risers (Model D and E). To study and compare the influences of the buoyancy modules distribution and buoyancy modules number on the riser's response, three distributions of buoyancy modules for the modified lazy-wave risers and two distributions for the hybrid tower risers are examined respectively. For cases of modified lazy-wave risers, in Model A, the 500m-long buoyancy modules are continuously distributed along the riser length, and the overall buoyancy force is 286ton; in Model B, the same length of buoyancy modules and same equivalent buoyancy force are considered, but the buoyancy modules are separated into two parts, i.e. the upper part is 300m long and the lower part is 200m long; in Model C, only the buoyancy force remains same while the length of upper part is 400m and the lower part is 200m long. For cases of hybrid risers, in Model D, the buoyancy modules are continuously distributed at the middle of the vertical riser; in Model E, the same length of buoyancy modules is considered, but it is divided into two parts which are mounted along the lower and upper middle span of the vertical riser. The structural parameters[1] of the risers and the buoyancy modules, the equivalent buoyancy forces are listed in table 1 and table 2 respectively.

TABLE 1. PARAMETERS OF THE RISER

Parameter	Value
Outer Diameter	393.95 mm
Inner Diameter	203.20 mm
Nominal Bend Stiffness	275.09 kN*m2
Axial Stiffness	949775.00 kN
Unit weight, empty in air	272.49 kg/m
Lazy-wave riser length	4000 m

TABLE 2. THE BUOYANCY MODULES PARAMETERS

Items	Total length	Equivalent buoyancy
Model A	500m	286 ton
Model B	500m	286 ton
Model C	600m	286 ton
Model D	576m	301 ton
Model E	576m	301 ton

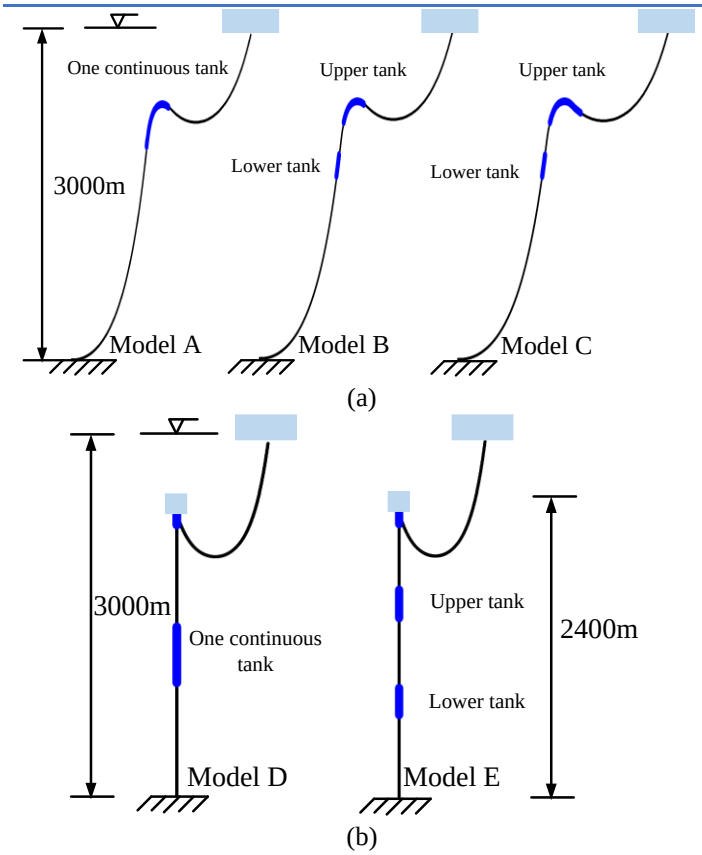


FIGURE 1. THE CONFIGURATION OF DIFFERENT RISER MODELS (a) MODIFIED LAZY-WAVE CONFIGURATIONS (b) HYBRID TOWER CONFIGURATIONS

2.2 The FEM models

In order to consider the nonlinear geometry, structural inertial and damping and the fluid drag forces, the dynamic governing equations of the riser was developed. The dynamic response can be analyzed based on our 3d curved flexible beam approach where the structural curvature changes with its spatial position and time in terms of vector equations. For a 3d riser (see Fig.2), the governing equations of dynamics in terms of vectors[7,8] can be written as:

$$\vec{F}' + \vec{q} = \rho A \ddot{\vec{r}} \tag{1}$$

$$\vec{M}' + \vec{r}' \times \vec{F} + \vec{m} = 0 \tag{2}$$

where $\boldsymbol{F}$ and $\boldsymbol{M}$ are respectively the total force and moment of the catenary. $\boldsymbol{q}$ and $\boldsymbol{m}$ are respectively the outer force and moment acted on per unit length of the catenary. ρ and $\boldsymbol{A}$ are structural mass density and area respectively. $\boldsymbol{r}$ represents the position vector.

Then the expression of the bending moment and curvature is:

$$\vec{M} = \vec{r}' \times (B\vec{r}'') + H\vec{r}' \tag{3}$$

where $\boldsymbol{B}$ is the structural stiffness and $\boldsymbol{H}$ is the torsion moment. Substituting Eq.(3) into (2), we have:

$$\vec{r}' \times [(B\vec{r}'')' + \vec{F}] + H'\vec{r}' + H\vec{r}'' + \vec{m} = 0 \tag{4}$$

and:

$$H' + \vec{m}\vec{r}' = 0 \tag{5}$$

where $\vec{m}$ is the averaged rotation moment whose value will be zero if $\vec{m}\vec{r} = 0$, then $\boldsymbol{H}$=0, that means the torsion moment is independent on the structural arc length. Generally, the rotation moment can be neglected, or the values of both $\boldsymbol{H}$ and $\vec{m}$ are zero. Then Eq.(4) can be rewritten as:

$$\vec{r}' \times [(B\vec{r}'')' + \vec{F}] = 0 \tag{6}$$

or:

$$\vec{F} = -(B\vec{r}'')' + \lambda\vec{r}' \tag{7}$$

Substituting Eq. (7) into (1) will yield:

$$-(B\vec{r}'')'' + (\lambda\vec{r}')' + \vec{q} = \rho A \ddot{\vec{r}} \tag{8}$$

and the deformation equation is:

$$\vec{r}' \cdot \vec{r}' = (1+\varepsilon)^2 \tag{9}$$

where ε is the strain of the catenary. If the value of the bending moment in Eq.(7) is zero, we will have the dynamic equation of a catenary of which the external loads include the gravity, buoyancy and hydrodynamic forces. The hydrodynamic force acted on per unit riser length is calculated by the Morison formula. And only the damping term related to the structural velocity is considered as external force, and the inertial term is considered by using the equivalent density which includes both the structural and added masses. The damping coefficient used here is 1.2[9].

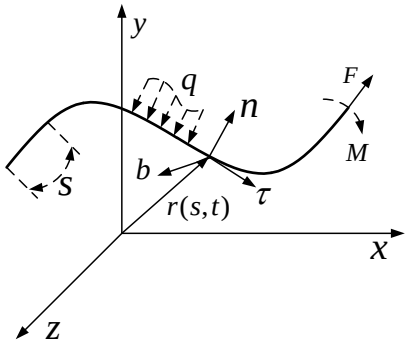


FIGURE 2. THE ELEMENT OF 3D FLEXIBLE RISER

To run the dynamic response analysis, a numerical simulation is used to solve the FEM dynamic equations. Among those direct numerical integration methods like the Newmark and the Finite Difference methods, the Newmark method is employed here so as to adjust the distribution of the structural acceleration and the nonlinearity of the catenary during the integration range by properly changing the integration parameters. The interpolation functions of the displacement and acceleration are written as:

$$\dot{U}_{t+\Delta t} = \dot{U}_t + [(1-\beta)\ddot{U}_t + \beta\ddot{U}_{t+\Delta t}]\Delta t$$
$$U_{t+\Delta t} = U_t + \dot{U}_t\Delta t + [(\frac{1}{2}-\alpha)\ddot{U}_t + \alpha\ddot{U}_{t+\Delta t}]\Delta t^2 \quad (10)$$

where the values of α and β are respectively 1/6 and 1/2 at every time step during the dynamic response.

2.3 The natural dynamic characteristics of the risers

Using the presented finite element model, the natural dynamic characteristics of the two kinds of riser configuration, i.e. the five riser models, are calculated and the first-five frequencies of each modes are shown in Table 3. It can be seen that, the buoyancy modules installed in different positions can change the natural frequency of the structure by around 15%, though their equivalent forces are same. And, the longer of the buoyancy modules distribution length is, the lower of the structure natural frequency is. Because the local tension of the riser gets smaller as the buoyancy modules length gets larger.

TABLE 3. FREQUENCIES OF DIFFERENT RISER MODELS (UNIT, Hz)

Mode	Model A	Model B	Model C	Model D	Model E
1	0.00617	0.00612	0.00593	0.00519	0.00489
2	0.01072	0.01052	0.00912	0.00905	0.00884
3	0.01793	0.01671	0.01558	0.01634	0.01317
4	0.02547	0.02497	0.02422	0.02236	0.01777
5	0.02963	0.02896	0.02707	0.02598	0.02534

3 THE DYNAMIC RESPONSES

The responses caused by top-end motion of the two kinds of risers with different configurations, as shown in Fig.1, are calculated. The displacement, tension and bending stress along the riser length are studied. The influences of the buoyancy modules distribution on the riser's response are investigated.

3.1 The responses of the modified lazy-wave risers

Firstly, to analyze the responses of the modified lazy-wave risers with different buoyancy modules distributions, the responses of Model A and Model B, caused by top-end motion with 100m amplitude and 100s period, are calculated. The time history and spectrum of top tension are shown in Fig.3 and Fig.4.

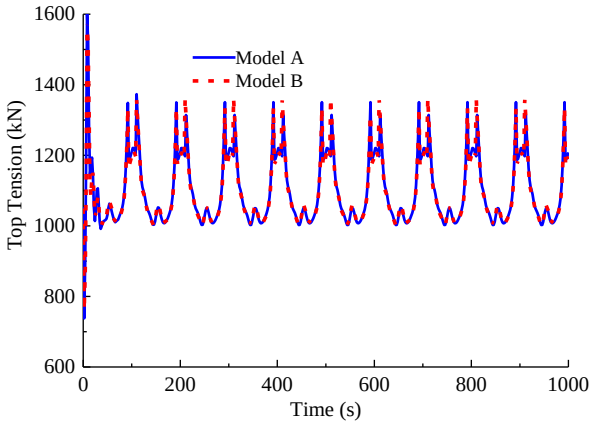


FIGURE 3. TIME HISTORY OF THE TOP TENSION

It can be seen that the buoyancy modules distribution has almost little effect on the top tension, because the initial static states of the two riser's spatial position location are almost the same. Thus the static tension components in the tension spectrum of the two models are almost same too, while the dynamic tension component is much smaller than the static tension, e.g. about 10% of the static value.

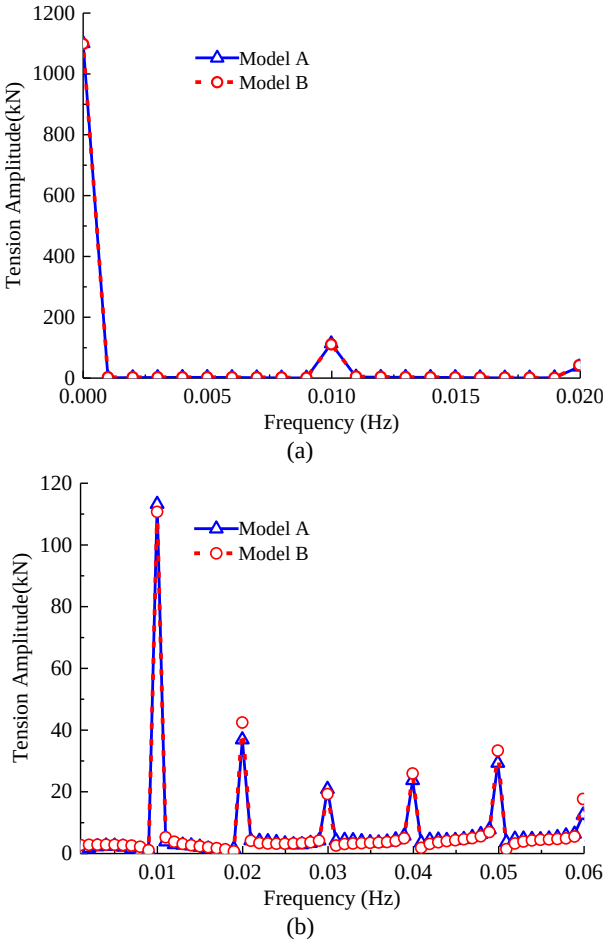
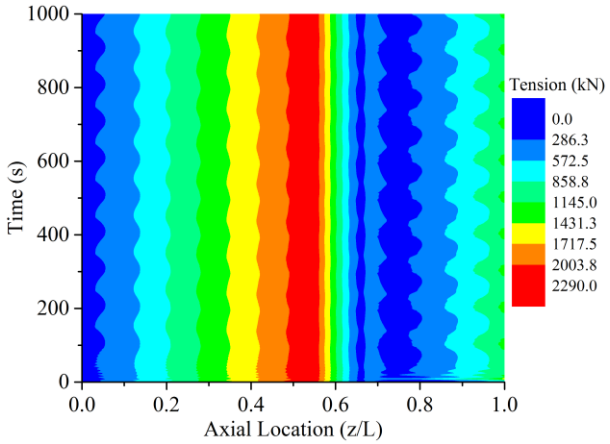
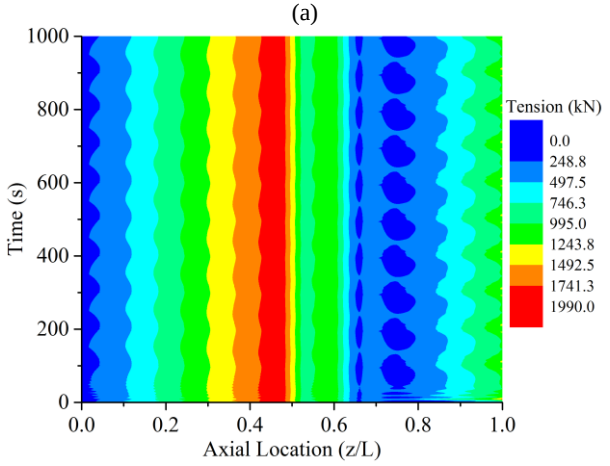


FIGURE 4. THE SPECTRUM OF THE TOP TENSION (a) FREQUENCY RANGE 0-0.2HZ (b) FREQUENCY RANGE 0.01-0.06HZ

The temporal-spatial evolutions of the tension for Model A and Model B are presented in Fig.5. The maximum tension of Model B is 1990.0kN, which is about 13.1% lower than 2290.0kN of Model A. It shows that the maximum tension of the riser can be reduced by changing the distribution of the buoyancy modules. In addition, it can be seen that the maximum tension of the riser occurs near the bottom end of the lower buoyancy modules which is at the middle of the overall riser. Or, below the bottom end of the lower buoyancy modules, only the tension, without any additional buoyancy force, should balance all the structural gravity force which accounts for around half of the total structural gravity. Fig.6 shows the comparison of the tension distributions along the riser length, it is also seen that the maximum tension of Model B is lower than that of the Model A.



(a)



(b)

FIGURE 5. TEMPORAL-SPATIAL EVOLUTION OF RISER TENSION (a) TENSION OF MODEL A (b) TENSION OF MODEL B

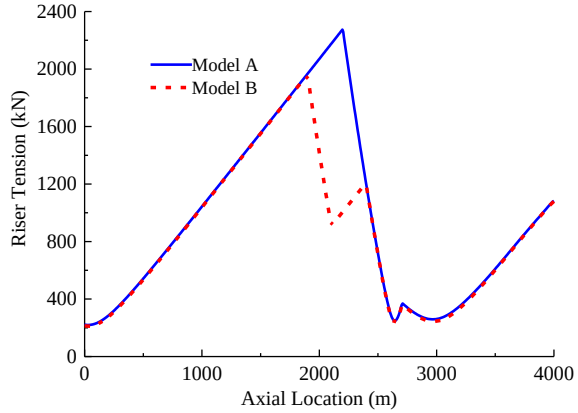
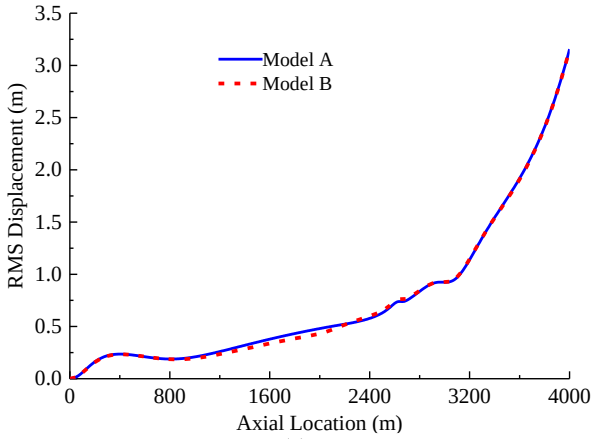
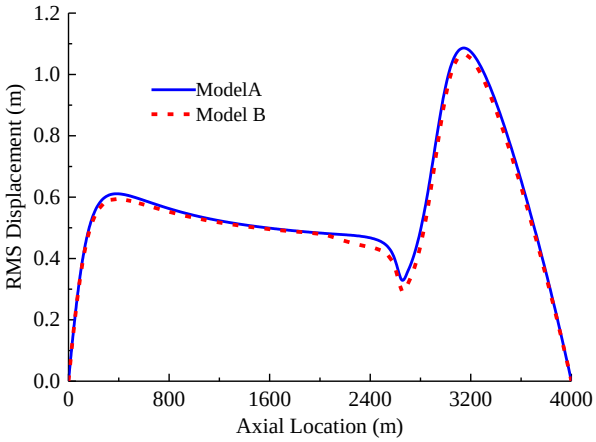


FIGURE 6. COMPARISON OF THE TENSION DISTRIBUTION ALONG THE RISER LENGTH

The RMS (root mean square) displacements of Model A and Model B are shown in Fig.7 where the displacement of Model B is slightly smaller than Model A. The horizontal displacement of the riser, as shown in Fig.7a, gradually increases along the riser's length from the bottom end, i.e. on the seafloor, to the up end. The maximum vertical displacement is at the bottom of the catenary part of the riser. The structural bending stress and curvature of Model A and Model B are shown in Fig.8. It can be seen that the bending stress around the highest point of the riser wave is obviously higher than that of the other parts. The maximum bending stress of Model B is 43.2MPa which is slightly higher than 41.0MPa of Model A, the values of which are far lower than the material yield strength. As the top-end reaches its maximum displacement, the values of structural curvature are less than 0.02.

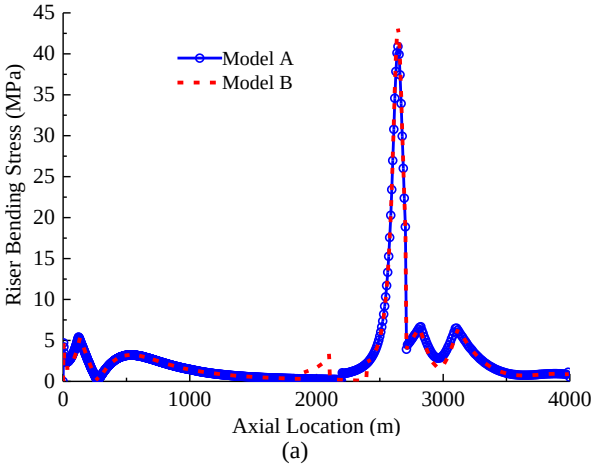


(a)

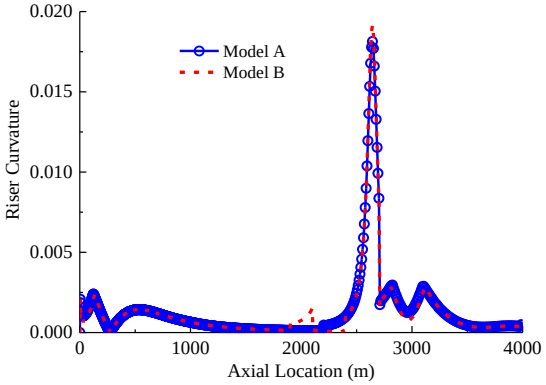


(b)

FIGURE 7. THE RMS DISPLACEMENT (a) HORIZONTAL DISPLACEMENT (b) VERTICAL DISPLACEMENT



(a)



(b)

FIGURE 8. THE BENDING STRESS AND CURVATURE DISTRIBUTING ALONG THE RISERS LENGTH (a) BENDING STRESS DISTRIBUTION (b) CURVATURE DISTRIBUTION

Secondly, to analyze the responses of the modified lazy-wave risers with different buoyancy modules lengths, the responses caused by top-end motion of Model B and Model C are calculated. The comparisons of top tensions, in terms of time history and spectrum, are shown in Fig.9 and Fig.10 respectively. It is seen that the top tension of Model C, with 600m long buoyancy modules, is smaller than Model B, with 500m long buoyancy modules, while the equivalent buoyancy forces of the two cases are same. The tension spectrum (Fig.10) shows that tension of Model C, in terms of both the static tension and the tension corresponding to the excitation frequency, is smaller than Model B.

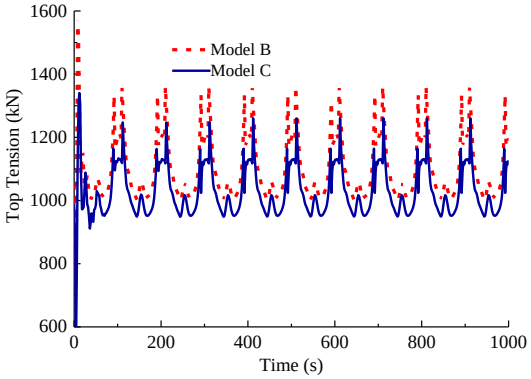
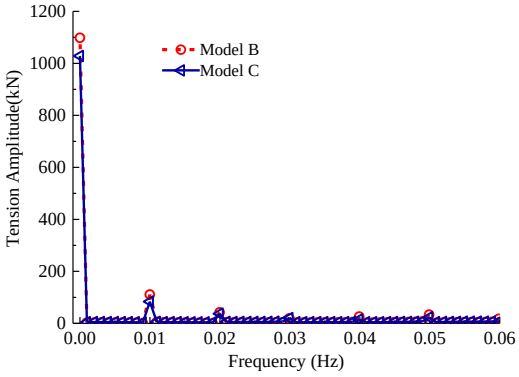
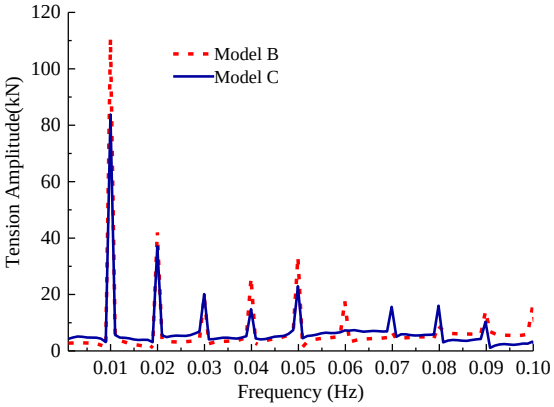


FIGURE 9. COMPARISON OF THE TIME HISTORY OF TOP TENSION



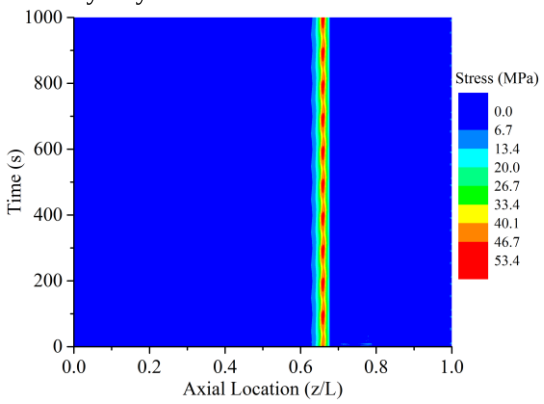
(a)



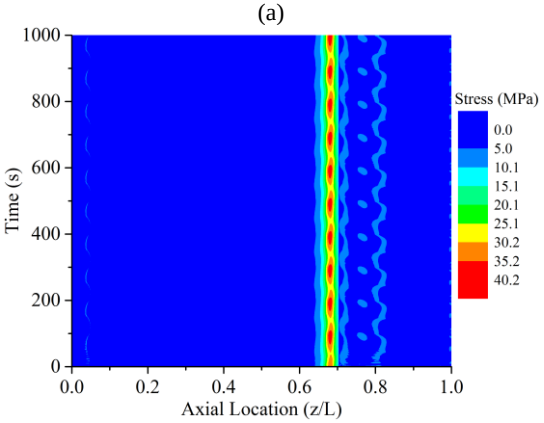
(b)

FIGURE 10. SPECTRUM OF RISER TOP TENSION (a) FREQUENCY RANGE 0-0.06HZ (b) FREQUENCY RANGE 0.01-0.1HZ

The temporal-spatial evolutions of the bending stress for Model B and Model C are presented in Fig.11. As the buoyancy modules length increases, the maximum structural bending stress decreases by about 24.7%. That is to say that the bending stress and curvature of the riser can be reduced by increasing the distribution length of the buoyancy modules under the same equivalent buoyancy force.



(a)



(b)

FIGURE 11. TEMPORAL-SPATIAL EVOLUTION OF BENDING STRESS (a) BENDING STRESS OF MODEL B (b) BENDING STRESS OF MODEL C

3.2 The responses of the hybrid tower riser

Fig.12 and Fig.13 show the time history and spectrum of the top tension for Model D and Model E, under the condition of 100m amplitude and 100s period of the top-end motion. We can see that the top tensions of the two models are almost same. And the amplitude value of the dynamic tension is much lower than static tension, e.g. only about 4% of the static one.

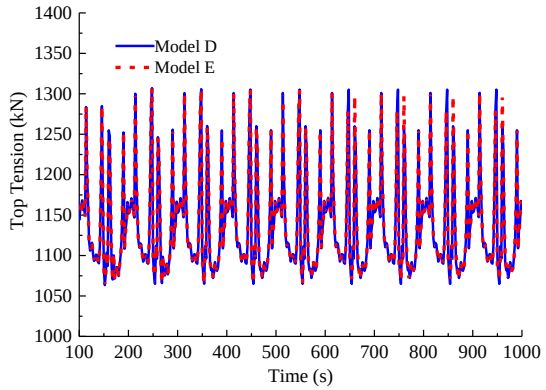


FIGURE 12. COMPARISON OF TIME HISTORY OF THE TOP TENSION

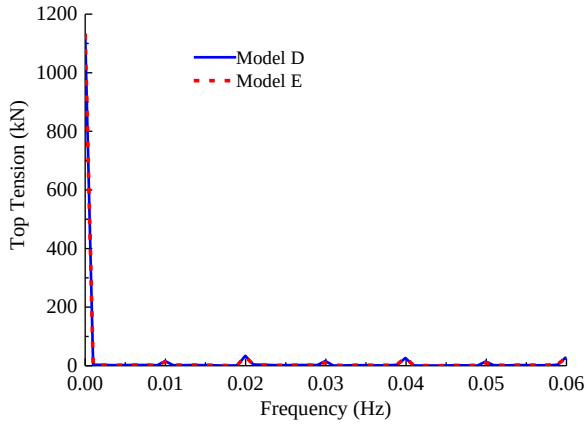


FIGURE 13. THE SPECTRUM OF TOP TENSION (a) FREQUENCY RANGE 0-0.06HZ (b) FREQUENCY RANGE 0.01-0.2HZ

But interestingly (see Fig. 13), the value of the dynamic tension corresponding to 2 times of the excitation frequency, at 0.02Hz, is higher than that corresponding to the excitation frequency 0.01Hz. And, the tension values corresponding to the higher frequency (around 3-8 times of the excitation frequency) are close to, even sometimes higher than, that corresponding to the excitation frequency. The tension distributions along the riser at the condition that the top float reaches its maximum displacement are presented in Fig.14. The bending stress along the catenary riser when the displacement of up-end is maximum is shown in Fig.15.

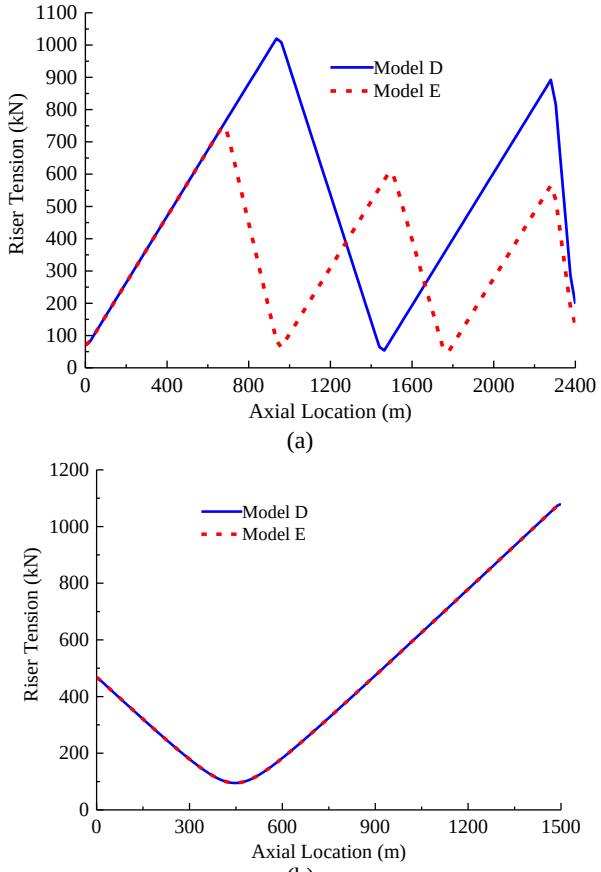


FIGURE 14. COMPARISON OF THE TENSION ALONE THE RISER (a) TENSION ON THE STRAIGHT SECTION (b) TENSION ON THE CATENARY SECTION

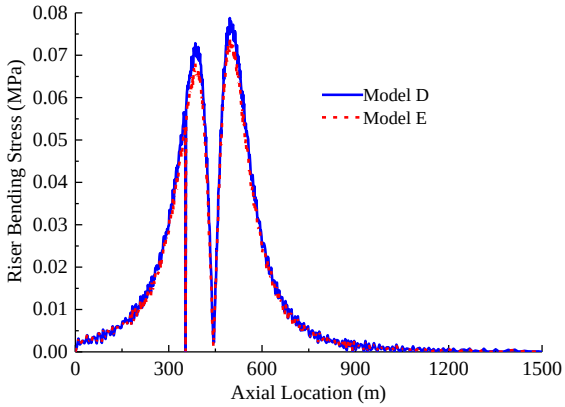


FIGURE 15. BENDING STRESS ALONG THE CATENARY PART RISER

The maximum bending stress is smaller than 0.1MPa, that indicates the bending stress along the catenary riser can be neglectable compared to that of axial tension. It can be seen that the difference between the tensions along the catenary part of the two risers is very small. That is because the catenary parts of the two risers are almost same. However, the difference of the mounting position of the buoyancy modules has a significant influence on the tension of the straight line part of the risers, see Fig. 14a. More specifically, in Fig. 14a, the maximum tension of Model E drops by about 26% compared with Model D, and the tension distribution of Model E is more moderate (flattened but more peaks) than Model D.

3.3 Discussions on different riser configurations

To examine and compare the performances of the modified lazy-wave riser and hybrid riser, the globally dynamic responses of Model B and Model E are further analyzed. Considering firstly the time history and spectrum of top tension, the results at different top-end amplitudes are respectively presented in Fig.16 and Fig.17. The dynamic top tension of Model E rises significantly when the top-end amplitude increases from 100m to 150m. For Examples, the tension component at the excitation frequency increases to 4 times, and the tension at 2 times excitation frequency increases to twice times.

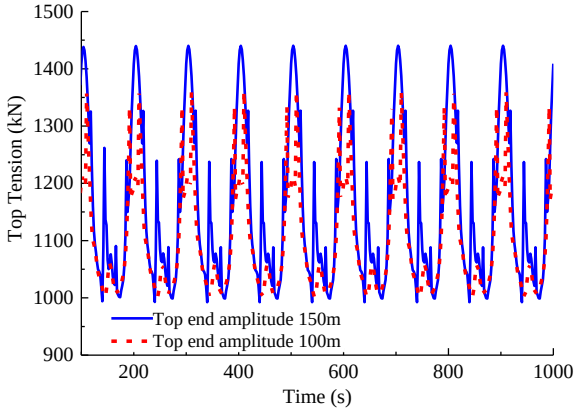


FIGURE 16. TOP TENSION OF MODEL B AT DIFFERENT TOP END AMPLITUDES (a) TIME HISTORY OF THE TOP TENSION (b) SPECTRUM OF TOP TENSION

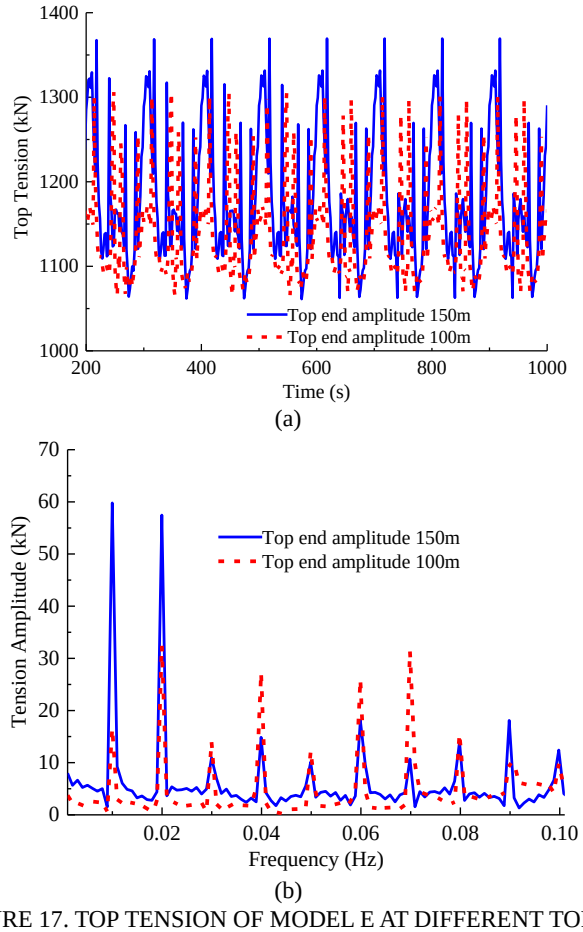
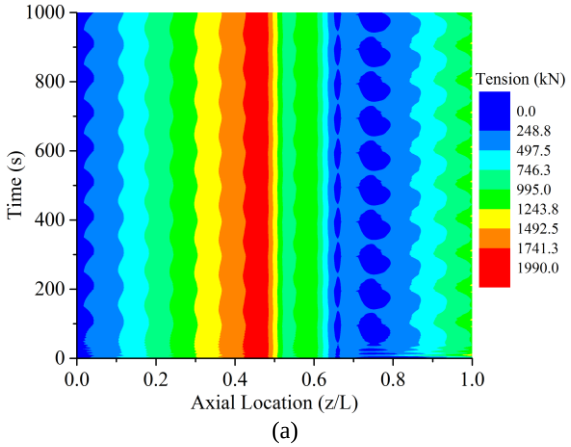
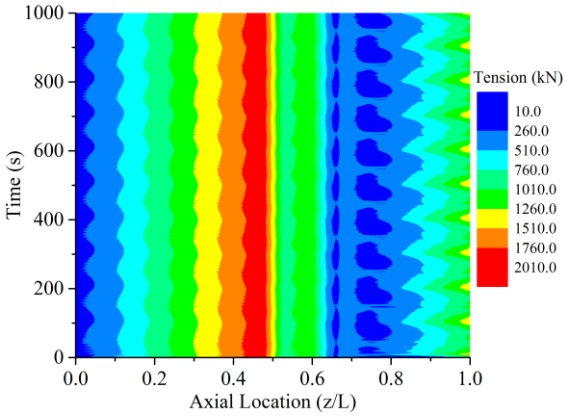


FIGURE 17. TOP TENSION OF MODEL E AT DIFFERENT TOP END AMPLITUDES (a) TIME HISTORY OF THE TOP TENSION (b) SPECTRUM OF TOP TENSION

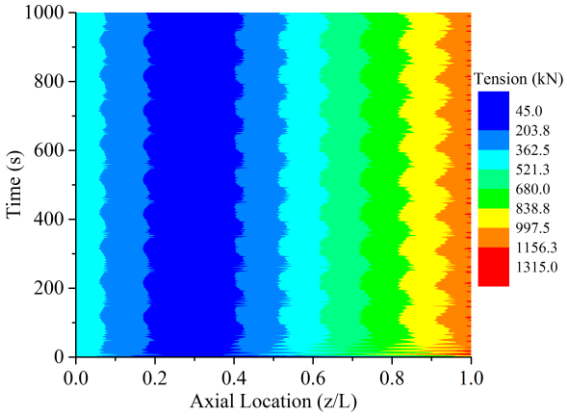
Further considering the temporal-spatial evolutions of the riser's tension, the results at different top-end amplitudes of Model B and Model E (the catenary part) are presented in Fig.18 and Fig.19 respectively. It can be seen that as the amplitude of the top-end motion increases, both the maximum tension and the tension distribution along the riser of Model B increase, comparing Fig. 18a with Fig. 18b.



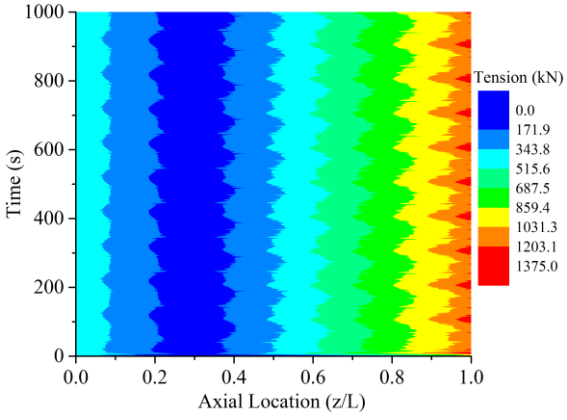


(b)

FIGURE 18. TEMPORAL-SPATIAL EVOLUTIONS OF TENSION FOR MODEL B (a) 100M TOP-END AMPLITUDE (b) 150M TOP-END AMPLITUDE



(a)



(b)

FIGURE 19. TEMPORAL-SPATIAL EVOLUTIONS OF TENSION FOR MODEL E (a) 100M TOP-END AMPLITUDE (b) 150M TOP-END AMPLITUDE

Differently, for Model E, the maximum tension, occurring at riser's top (or top tension), rises with the increase of top-end, but the minimum tension drops with the increase of top-end. When the top-end amplitude is 150m, the value of minimum tension of Model E is zero, that means slack may happen to the catenary part of the hybrid tower riser, under the condition of a larger top-end motion. And then, the catenary part riser may clash with the straight part and the buoyancy modules, especially the upper tower.

The main responses of the five riser models caused by top-end motion with 100m amplitude and 100s period is compared in table 4. It can be seen that if the riser lengths, and consequently the cost of the configurations, are almost same, the responses, in terms of the maximum tension, maximum bending stress and curvature, of the hybrid tower riser is lower than the lazy-wave riser. But, the catenary part of the hybrid tower may clash with the other part under the condition of larger top-end motion. And, although the response of the lazy-wave configuration is larger, the values are still acceptable, i.e. smaller than the material strength limitation. Moreover, riser the responses can be decreased by changing the distribution of the buoyancy modules, such us changing the length or number of segments. In general, the lazy-wave riser might be more acceptable than the hybrid tower riser.

TABLE 4. RESPONSES AND PARAMETERS OF THE MODELS

Model	Total length	Maximum tension	Maximum bending stress	Maximum curvature
Model A	4000m	2290.0kN	51.2MPa	0.0227
Model B	4000m	1990.0kN	53.4MPa	0.0237
Model C	4000m	1940.0kN	40.2MPa	0.0178
Model D	3900m	1315.0kN	15.4MPa	0.0068
Model E	3900m	1315.0kN	15.4MPa	0.0068

5 CONCLUSION

The dynamic response of two kinds of risers, i.e. modified lazy-wave riser and hybrid tower riser, are analyzed based on the presented FEM numerical simulations. And different buoyancy modules installation positions and its distribution length are considered. To compare the performances of different risers' configurations under top-end motions, the dynamic responses, such as the structural top tension, tension distribution, bending stress and curvature are presented and discussed. The maximum tension, maximum bending stress and curvature of hybrid tower riser is lower than the lazy-wave riser. But it should be noted that clash may happen to the hybrid tower riser under larger top-end motion. The riser's responses can be decreased by changing the distribution of the buoyancy modules.

The influences of riser configuration on dynamic response is discussed by considering different top-end amplitudes. The results show that:

1) Under the condition of same equivalent buoyancy force, the structural curvature and bending stress of the risers get smaller as the distribution length of the buoyancy modules gets larger. As the buoyancy modules length increases, the maximum structural bending stress decreases by about 24.7%.

2) Under the conditions of same distribution length of buoyancy modules and same equivalent buoyancy force, the configuration of multi-segment buoyancy modules can decrease structural maximum tension, compared to the configuration of one continuous buoyancy modules. For the lazy-wave configuration the maximum tension decreases by 13.1%, and

for the hybrid tower configuration the tension decreases by 26%.

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