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Effects of stiffening rings on the dynamic properties of hyperboloidal cooling towers

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Abstract. As hyperboloidal cooling towers (HCTs) growing larger and slender, they become more sensitive to gust wind. To improve the dynamic properties of HCTs and to improve the wind resistance capability, stiffening rings have been studied and applied. Although there have been some findings, the influence mechanism of stiffening rings on the dynamic properties is still not fully understood. Based on some fundamental perceptions on the dynamic properties of HCTs and free ring structures, a concept named "participation degree" of stiffening rings was proposed and the influence mechanism on the dynamic properties was illustrated. The "participation degree" is determined by the modal deform amplitude and latitude wave number of stiffening rings. Larger modal deform amplitude and more latitude waves can both result in higher participation degree and more improvement to eigenfrequencies. Also, this concept can explain and associate the pre-existing independent findings.

Keywords: hyperboloidal cooling towers; stiffening rings; participation degree; dynamic properties; modal deform amplitude; latitude wave number

1. Introduction

As the largest spatial thin-wall and high-rise reinforced concrete (R.C.) structure, hyperboloidal cooling towers (HCTs) are used in a wide industrial range especially for power plants. For economical and environmental benefits, HCTs are growing taller, bigger and relatively thinner consistently, owning to the planning of new thermal power plants and the renewal of existing fossil-fueled power plants (Busch *et al*. 1998, Harte and Wittek 2009, Zhang *et al*. 2013). The present HCTs are always 160~200m high with shell thickness merely about 200~250mm, which makes the structures even slender relatively. Their fundamental eigenfrequencies are always less than 1Hz and are growing closer to the neighboring maximum of the power spectral density function of the wind. Therefore, the dynamic responses under wind loads (Abu-Sitta 1973, Niemann 1980, Niemann and Zerna 1986, Ke *et al*. 2012, Babu *et al*. 2013), as well as the stability problem (Mungan and Lehmkämper 1979, Medwadowski 2004, Noh 2006, Sabouri-Ghomi *et al*.

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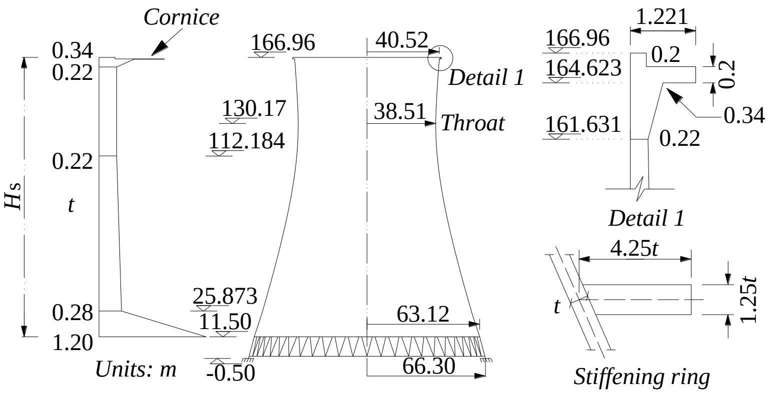


Fig. 1 Dimensions of the representative cooling tower

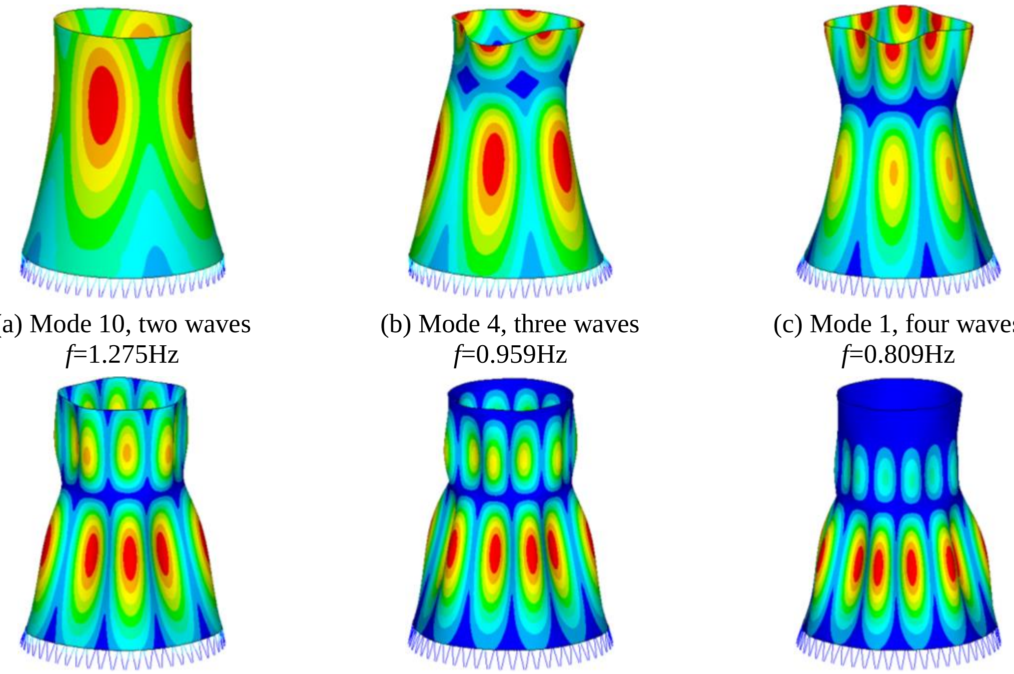
2006, Gopinath *et al*. 2012), become more significant and attract more attention. There is no way to change the spectrum characteristics of the wind, so increasing the stiffness and eigenfrequencies of HCTs would be the fundamental method to reduce the wind-induced dynamic responses.

As an innovative method, stiffening rings have been used on several HCTs, both new built and repaired, mainly to improve the stability (Mungan and Lehmkämper 1979, Form 1986, Niemann and Zerna 1986, Eckstein *et al*. 1987, Gould and Guedelhoefer 1989, Bosman *et al*. 1998, Meschke 1999, Sabouri-Ghomi *et al*. 2006). Meanwhile, stiffening rings' contribution to dynamic properties was also investigated in several parallel studies (Form 1986, Eckstein *et al*. 1987). Both of these applications have been proven to be economical and practicable (Peters 1986). Here are some preliminary instructive conclusions for the effects on dynamic properties. Compared with the original unstiffened structure, stiffening rings' influences on eigenfrequencies could be classified into two separate series. For a specified mode, the stiffening ring's effect is related to its location: the eigenfrequency would be increased most if it locates at the maximum modal displacement, which is quite similar to the buckling problem (Mungan and Lehmkämper 1979, Form 1986, Eckstein *et al*. 1987, Gould and Guedelhoefer 1989, Bosman *et al*. 1998). For different modes, the stiffening ring's effect is related to the latitude wave number: the mode which has more latitude waves will show more remarkable increase on eigenfrequency (Form 1986, Eckstein *et al*. 1987).

However, these two existing conclusions are just findings but with no theoretical explanations, and there seems no relation between each other (Form 1986, Eckstein *et al*. 1987). In fact, they can both be explained by a concept named "participation degree" of the stiffening ring. So, the main purpose of this paper is not only to state the stiffening rings' contributions to dynamic properties, but try to propose the concept mentioned above and illustrate how it works. A representative R.C. HCT was analyzed in this study using the finite element (F.E.) method.

2. Dynamic properties of the unstiffened HCT

All subsequent numerical investigations are carried out for a HCT shown in Fig. 1, which locates at Xuzhou, Jiangsu Province, China. The dimensions of the selected sample HCT are typical in current practice. Fig. 1 shows schematically the elevation and pertinent details of this HCT. It's made of continuous cast-in-place R.C. shell and is supported by 52 'V'-shaped columns



(a) Mode 10, two waves f=1.275Hz
(b) Mode 4, three waves f=0.959Hz
(c) Mode 1, four waves f=0.809Hz
(d) Mode 2 five waves f=0.811Hz
(e) Mode 3, six waves, f=0.930Hz
(f) Mode 6, seven waves f=1.155Hz

Fig. 2 Mode shapes of the unstiffened cooling tower

with a circular cross-section of 1000 mm in diameter. The R.C. cornice at the top, also known as the top stiffening ring, is 200 mm thick and 1221 mm wide. This is an inherent part of the original design. So, the cooling tower with the top stiffening ring (as shown in Fig. 1) is referred to as the unstiffened HCT and used as the benchmark for comparisons with other configurations.

The F.E. instrument used in this study is a commercial software ANSYS. The cooling tower shell is modelled by Shell181 element. The columns, the top stiffening ring and other additional rings were modelled by Beam188 element.

To avoid the influences of the circular strip foundation and piles, the F.E. model just consists of the shell and columns, with the columns constrained at the bottom. According to the casting procedure, shell-column connection, computation accuracy and F.E. modeling instruction, the number of elements (or mesh) was optimized after numerous trials. The shell was meshed into 416 and 106 shell elements in latitude and meridian direction respectively. Another, each column was meshed into 8 beam elements. The top stiffening ring and other additional rings were meshed into 416 beam elements as well to match with the shell meshing.

According to the F.E. model, several low order modes and eigenfrequencies were shown in Fig. 2. The dynamic properties of HCTs are characterized by complex spatial mode shapes and close eigenfrequencies. Moreover, most modes are coupling of latitude and meridian waves and the number of latitude waves is always bigger than the meridian's. As shown in Fig. 2, the latitude waves vary from two to seven, but the meridian waves are just one or two. In order to facilitate the following illustration of stiffening rings' effects, the modes in Fig. 2 were listed in the sequence of the latitude wave number but not the mode order. Furthermore, in subsequent high order modes,

Table 1 Eigenfrequencies of a free ring which has the same size of the stiffening ring located at the throat of the HCT shown in Fig. 1

Circular wave number	2	3	4	5	6	7	8
Eigenfrequency (Hz)	0.160	0.577	1.215	2.058	3.101	4.341	5.776

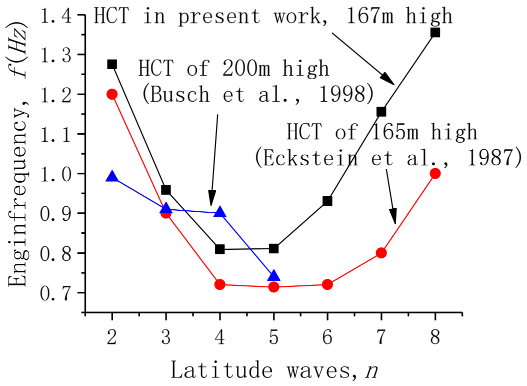


Fig. 3 Eigenfrequencies and latitude wave numbers

there will be some modes whose latitude wave number is equal to a previous mode but have different meridian waves. So, what showed in Fig. 2 are the modes with a specified number of latitude waves appearing for the first time.

Besides the overwhelming majority modes characterized by coupling waves, there are still several global displacement modes in high order. These modes are crucial for earthquake responses but not for wind because of their high eigenfrequencies. Therefore, these modes are not involved in this study.

It should be noted that the latitude waves of HCTs are still similar to those of free rings, although there are certain differences. HCTs can also be regarded as many free rings connected along the height in some sense. Therefore, analogous analyses would be reasonable. For free rings, it’s well known that the circular wave numbers of modes start from two and increase along the mode order sequentially. Another, the eigenfrequencies also increase rapidly along the mode order (Table 1). For HCTs, however, the mode with two or three latitude waves hardly appears at the lowest order as free rings because of the constraints at the column bottom and the hyperbolic meridian curve. The mode with six, seven or even more latitude waves hardly appears at the lowest order either, because these wave number are located at high orders for free rings and difficult to be excited at the lowest order. Consequently, the latitude wave number of the lowest mode is always four or five for large HCTs, which is a general features for HCTs (Fig. 3).

HCTs are three dimensional spatial structures but always are described by the latitude and meridian directions. Before the further investigation into how to increase eigenfrequencies, it should be identified in which direction the stiffness provides more contribution to the whole structure.

A rough but valid and simple method was employed here: change the elastic modulus of the two directions artificially. Reinforced concrete is always regarded as isotropic material in linear elastic analysis; the elastic modulus of shell material for HCTs in latitude, meridian and through-thickness directions are identical and can be expressed by E_0. In this rough method here, however,

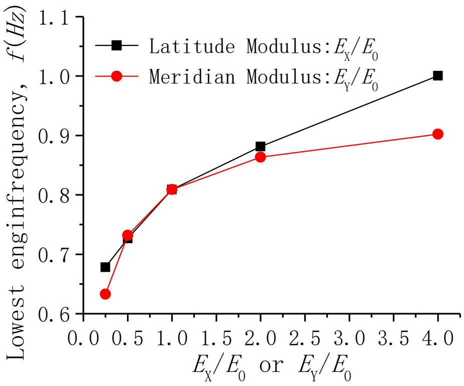


Fig. 4 Effects of stiffness in the two directions on the fundamental eigenfrequency

the shell material is regarded as orthotropic, and the elastic modulus in the two directions, E_X for latitude direction and E_Y for meridian direction, are adjusted individually. When E_X is adjusted, E_Y remain the original value E_0 and vice versa. Then, a fundamental eigenfrequency can be obtained accordingly for each combination of E_X and E_Y. According to the relationship between the shell elastic modulus in two directions and the corresponding fundamental eigenfrequencies, the more crucial direction can be identified.

Based on this method, the results were shown in Fig. 4 and apparently the E_X or the stiffness in the latitude direction contributes more to the whole structure. That's why latitude rings but not meridian ribs are always used for stiffening. In fact, meridian ribs are always used as aerodynamic measures to reduce the wind loads, or just as ancillary measures to support slip forms during construction (Farell *et al*. 1976, Niemann 1980, Goudarzi and Sabbagh-Yazdi 2008), but not as structural measures.

3. Improvement of the eigenfrequencies by one stiffening ring

Among the questions for stiffening rings such as location (along the height), size, amount and inner or outer surface, only the first is related directly to the influence mechanism on dynamic properties. Therefore, just the location will be discussed and there will be just one stiffening ring located at the outer surface. The location is expressed by the relative height of the shell, h_S/H_S, in which H_S represents the whole shell height and h_S is the height of the stiffening ring. Its size is expressed by the multiple of shell thickness where it locates: 1.25 times for thickness and 4.25 times for wideness (Fig. 1). This is determined according to primary optimizing design with both the dynamic properties and stability problems involved. This size is a little smaller compared with some existing application cases which always target only one issue: the dynamic properties or the stability problems (Form 1986, Eckstein *et al*. 1987, Sabouri-Ghomi *et al*. 2006).

3.1 Improvement of the fundamental eigenfrequency

Fig. 5 shows the improvement of the fundamental eigenfrequency by one stiffening ring at different locations, which is labeled by curve A. The stiffening ring's contribution varies greatly along the height, and the maximum improvement is 4.1%, seemingly quite limited. However, the improvement is only about 15% even if the shell latitude stiffness is doubled (Fig. 4). Another, the improvement is only about 12% if the shell thickness increases 80mm uniformly, 36% of the original minimum thickness which is 220mm. So, compared with other methods, the stiffening ring's contribution is still appreciable relatively. Also, it should be noted that the improvement due to additional ring stiffness has been partly compensated by the opposite trend due to additional ring masses.

Accompanied with curve A is the first order modal displacement of the unstiffened HCT, labeled by curve B. Curve B was drawn from Fig. 2(c) and also along the meridian direction. Apparently, two curves show a certain analogy except in the top shell, and the similarity is one of the important finding in pre-existing studies but there is still no explanation (Form 1986, Eckstein *et al*. 1987). For comparison and illustration, the latitude wave number of the stiffened HCT was also shown in Fig. 5: except in the top shell where there would be five waves, the wave number would still be four when the stiffening ring locates in other region, just as the original unstiffened HCT. In addition, several representative mode shapes for different locations of the stiffening ring were given in Fig. 6. Because the size of stiffening ring is not remarkable, its existence is always unable to alter the mode shape of the lowest mode. Therefore, the lowest mode shape of the stiffened HCT is almost identical to the unstiffened except when the stiffening ring is located in the top shell.

Based on the phenomena stated above, the following is the reason for the similarity of curve A and B. Apparently, in the stiffened HCT or ring-shell structure, the stiffening ring's circular modal deform will be excited along with the shell. The wave number of the ring will always be equal to that of the shell but will be different for different locations, just as shown in Figs. 5-6. If the stiffening ring always shows the same wave number no matter where it locates, the higher modal deform amplitude of the stiffening ring, the more modal energy and more contribution to the whole ring-shell structure, i.e., the participation degree of the stiffening ring in the stiffened HCT is higher. For this example, when the stiffening ring locates in the middle and bottom shell, the stiffened HCT shows almost identical mode shape with the unstiffened and both have four latitude waves. Therefore, the modal deform amplitude and contribution of a stiffening ring could be approximately presented by the modal displacement of the unstiffened HCT, and thus curve A and B are similar in these two regions.

For the top shell, however, curve A and B are quite different. The maximum modal displacement of the unstiffened HCT appears in top shell (Fig. 2(c)). However, when a stiffening ring is located here, the modal displacement amplitude in this region turns out quite slight (Fig. 6(c)), which results in a limited participation degree and contribution of the stiffening. Nevertheless, the lowest eigenfrequency is still improved because of the alteration of mode shape: from four latitude waves to five.

Finally, although the two curves in Fig. 5 show certain similarity, especially in the bottom and middle shell, the contribution of a stiffening ring at different locations is not characterized by the modal shape of the unstiffened HCT but the stiffened HCT. That's because the contribution or participation degree of a stiffening ring can only be discussed in the ring-shell structure. In fact, the similarity of curve A and B stems from the similar mode shapes of the unstiffened and stiffened HCT, only when the stiffening ring is located in the bottom and middle shell. The similarity will vanish if the mode shape is altered greatly by the stiffening ring, just like in the top shell. Therefore, the location where the maximum modal displacement of the unstiffened HCT appears would not always be the most effective place for an additional stiffening ring, as shown in Fig. 5.

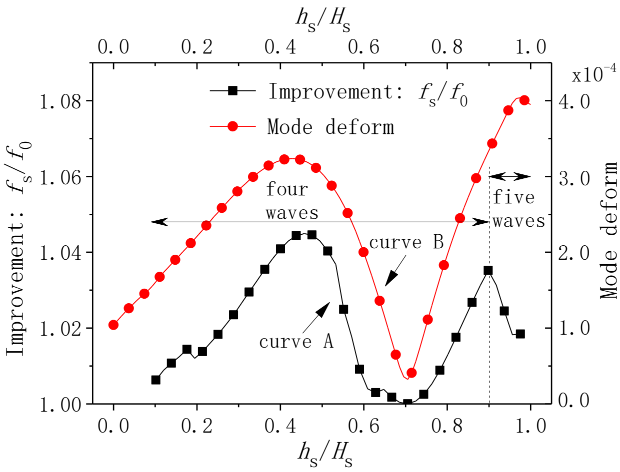
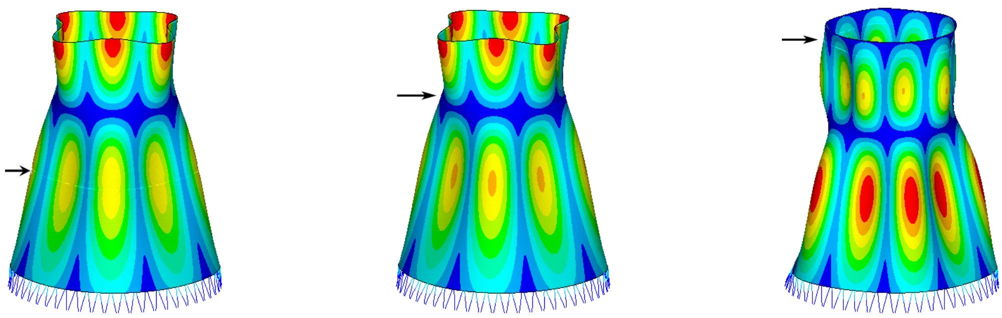


Fig. 5 Improvement of the fundamental eigenfrequency by one stiffening ring



(a) Location h_S/H_S=0.45 (e) Location h_S/H_S=0.70 (f) Location h_S/H_S=0.95

Fig. 6 Representative mode shapes for different locations of the stiffening ring

On the other hand, locations where remarkable modal displacement of the unstiffened HCT appears are still critical options for stiffening rings, because stiffening rings in moderate size will not always alter the mode shape. For this example, the top shell region for five waves only accounts for 10% of the whole shell height.

Consequentially, for a specified mode, i.e., the lowest mode, with a definite latitude wave number, the contribution or participation degree of a stiffening ring can be measured by the modal deform amplitude of the stiffening ring in the ring-shell structure. Only when the stiffening ring doesn't alter the mode shape obviously, its contribution will show similarity with the modal displacement of the unstiffened HCT.

Furthermore, the unstiffened HCT still has a cornice, or inherent stiffening ring, on the top. The cornice's contribution can also be explained by the concept of participation degree. If this cornice is removed, the lowest mode shape shows almost no change and the maximum modal displacement is still on the top, so the participation degree and contribution of the cornice would be quite high. This is confirmed by the drop of fundamental eigenfrequency when the cornice was removed: from 0.809Hz to 0.734Hz, nearly 9%, two times of the maximal effect of an additional stiffening ring.

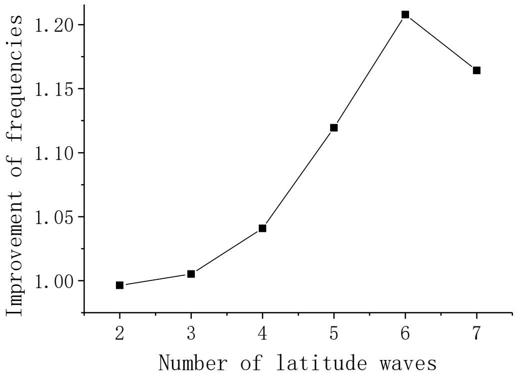
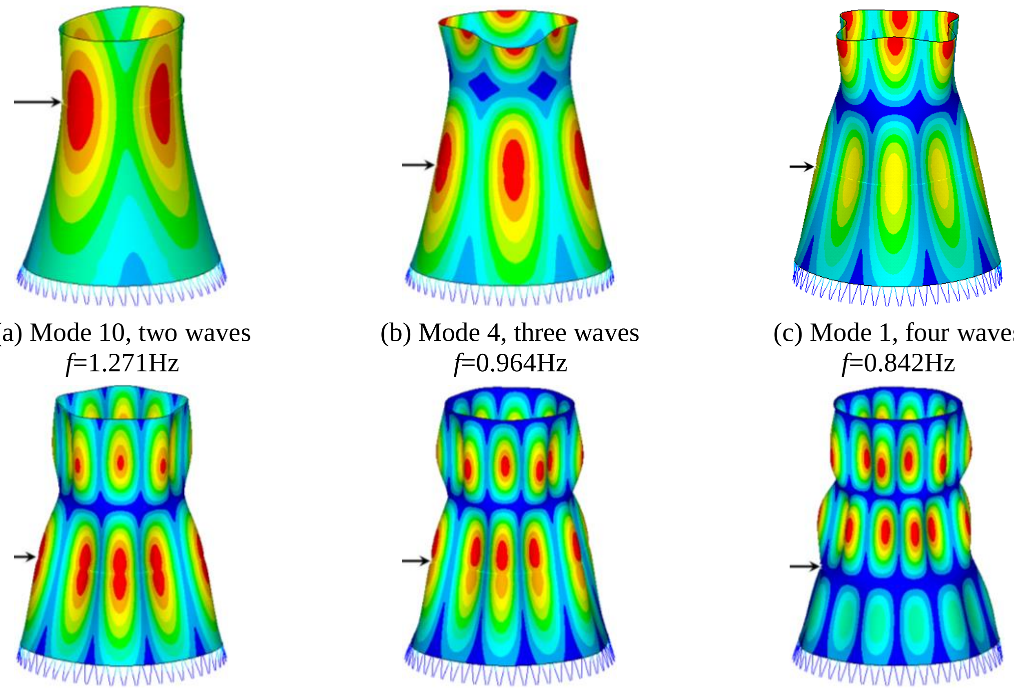


Fig. 7 Improvement of different mode eigenfrequencies by one stiffening ring



(a) Mode 10, two waves
f=1.271Hz

(b) Mode 4, three waves
f=0.964Hz

(c) Mode 1, four waves
f=0.842Hz

(d) Mode 2 five waves
f=0.908Hz

(e) Mode 3, six waves,
f=1.123Hz

(f) Mode 6, seven waves
f=1.345Hz

Fig. 8 Mode shapes of the stiffened cooling tower

3.2 Improvement for modes with different latitude waves

What stated above is just about the contribution to a specified mode with a definite latitude wave number. For different modes with different latitude waves, does the concept of participation degree still work?

Fig. 7 shows the improvement of eigenfrequencies of several lower modes with different latitude waves by one stiffening ring. The corresponding mode shapes were listed in Fig. 8, in the same sequence of Fig. 2. For integrity and comparison, the lowest mode with four latitude waves was also listed here as Fig. 8(c). For each mode, the stiffening ring is located at the most effective location. For example, as shown in Fig. 7 and Fig. 8(c), the improvement is 4.1% for the mode with four latitude waves, and this value is the maximal value of curve B in Fig. 5.

Evidently, the contribution of a stiffening ring increases fast with the number of latitude waves until six, but deceases when the number is seven. As said previously, the stiffening rings are located at the most effective location for each mode, so they all exhibit great amplitudes of modal deform, more or less in the same level. Another, the stiffening rings will show the same circular wave number as the shell, as shown in Figure 8. For a free ring, its eigenfrequency increases substantially with the modal wave number which increases along the mode order sequentially (Table 1). In other words, the mode would be more difficult to be excited if it has more modal waves, and there will be more modal energy restored in this mode. Analogously, this is also reasonable for stiffening rings in the ring-shell structure. It also means that the wave number would be another index of the participation degree of stiffening rings. As a result, the more wave number, the more contribution from the stiffening ring: for the mode with six latitude waves, its eigenfrequency increases more than 20%, much higher than the mode with two or three waves.

Another, for the mode with just two waves, Figs. 2(a) and 3(a), the eigenfrequency even drops when a stiffening ring is added to the original unstiffend HCT. That's because the stiffness contribution from the stiffening ring are even less than its opposite trend due to additional masses. However, when the waves are too many, for example seven for this HCT, the maximal modal displacement will not appear around the stiffening ring no matter where the stiffening ring locates. That's because the stiffness of the stiffening ring in this mode is too high compared with the shell and, therefore, the stiffening ring can't be excited to give a remarkable modal deform. As a result, the contribution or participant degree decreases: large wave number but much slight modal deform.

Consequently, according to the effects of stiffening rings on a specified mode and different modes, which are always discussed separately (Form 1986, Eckstein *et al*. 1987), the contributions can both be explained by the concept of participation degree, which is related to the dynamic properties of free rings: the modal deform amplitude and the circular wave number.

4. Conclusions

Dynamic properties of HCTs are characteristics of complex spatial mode shapes and close eigenfrequencies. Most modes are coupling of latitude and meridian waves, the number of latitude waves is always higher than the meridian's, and the latitude wave number of the lowest mode is always four or five for large HCTs. For the latitude and meridian directions, the stiffness in the latitude direction contributes more to the whole structure. That's why latitude rings but not meridian ribs are always used for stiffening. Stiffening rings' contribution to the eigenfrequencies is limited in quantity, but it is still an effective and economical method compared with the increase of shell thickness.

The stiffening rings' improvement to the dynamic properties was illustrated and a concept of "participation degree" was proposed. The "participation degree" is determined by the modal deform amplitude and latitude wave number of the stiffening ring. The higher modal deform amplitude and larger latitude wave number, which mean more modal energy, will give higher participation degree in the ring-shell structure and more improvement to the eigenfrequencies.

Also, this concept can explain and associate the pre-existing independent findings about stiffening rings.

In some other studies, it was pointed out that the contribution of stiffening rings to a specified mode was related to the modal deform amplitude of the unstiffened HCT. In fact it was related to the modal deform amplitude of the stiffened HCT. The misunderstanding was brought about because the stiffening ring in moderate size usually doesn't alter the mode shape of a specified mode. Therefore, the location where the maximum modal displacement of the unstiffened HCT appears will not always be the most effective place for an additional stiffening ring unless the mode shapes of the unstiffened and stiffened HCTs are similar.

Acknowledgments

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