Numerical investigation on fatigue problem of cable net structure of Five-hundred-meter Aperture Spherical radio Telescope

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Abstract

The reflector of Five-hundred-meter Aperture Spherical radio Telescope (FAST) is supported by cable-net structure, so that to enable its reflector surface to form a paraboloid from a sphere in real time through active control. However, such form-changing operation would lead to about 500MPa stress range for the cable-net structure. Such stress range is nearly twice as much of that defined by the relative standard. So the cable-net structure is the most critical and expendable part of FAST reflector system. The service life of FAST would directly depend on the residual fatigue life of its cable-net structure. Then, the present paper would make an effort to find a more appropriate deformation strategy to decrease the stress amplitude of the cable during form-changing operation.

Key words: FAST engineering, cable net structure, active reflector, mechanical analysis

1. Introduction

The project of Five-hundred-meter Aperture Spherical radio Telescope (abbreviated as FAST), belongs to the national "11th Five-Year Plan" Key scientific projects, has been approved for construction by the National Development and Reform Commission in July 10, 2007. (Nan et al, 2003) FAST working frequency can cover the range of 70MHz to 3GHz. The design resolution and point accuracy are respectively 2.9′ and 8″. (Nan et al, 2003; Qiu, 1998).

The FAST reflector is designed to be supported by cable-net structure. The outer edge of cable-net is suspended from the steel ring beam, whose diameter is 500m. (Qian, 2007) The crossed nodes of the cable-net are used as control points. Each of them is tied to control actuator by down tied cable. By controlling the actuator using the feedback from the measurement and control system, the position of these cross nodes can be adjusted to form an illuminated aperture with 300m diameters. And this illuminated aperture can move along spherical surface according to the zenith angle of the target objects. Later, an extensive numerical comparative analysis has been performed among several different grid types, such as three-dimensional grids, kiewitt grids and geodesic triangle grids. Finally, the last one is selected because of its more uniform of cable stress and cable length. (Qian, 2007; Jiang, 2009)

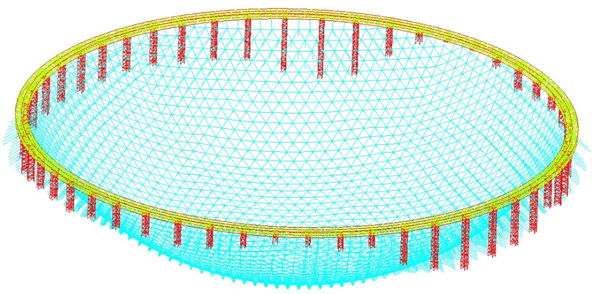

Fig. 1. Concept of the adaptive cable-net structure

From above-mentioned description, it can be easily seen that the long-term observation process of FAST would lead to long-term frequent shape-changing operation of cable-net structure. Previous research results have shown that such shape-changing operation would lead to about 500MPa stress range. Such stress range is nearly twice as that required by the relative standard (ISO 15630-3, 2001). So, the cable-net structure would be the most critical and expendable part of the FAST reflector system. Thus, the present work, based on the preliminary design,

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would make an effort to decrease the stress range of the cable caused by shape-changing operation.

2. The stress range optimization

2.1 The main influence factor analysis

The cable-net is consisting of about 7000 steel cables and about 2300 cross nodes. Each cross node is tied to one actuator on the ground. The length of cables is from 10.5m to 12.5m. In general, the illuminated aperture is a paraboloid surface, whose profile can be expressed by

$$x^2=2py+c \tag{1}$$

The variables and parameters of this problem can be summarized as follow: the weight of reflector element w, the density of the cable ρ, the elastic modulus of cable E, the area of cable cross section A_i, the geometric parameters of illuminated aperture p and c, the diameter of the illuminated aperture d, the radius of the cable-net structure R, the diameter of the ring beam D. So, the stress amplitude can be expressed by

$$\Delta\sigma=f\,(w, E, \rho, A_i, p, c, d, R, D) \tag{2}$$

In our preliminary design, w, E, ρ, A_i, d, R, D have already been determined as a certain value. The weight of reflector element w is about 17kg/m^2, the diameter of the illuminated aperture d is 300m, the radius of the cable-net R is 300m, and the diameter of the ring beam D is 500m, and all cable's cross section A_i have also been determined according its load. For steel cable, ρ is about 7850Kg/m^3. Thus, Eq(2) can be simplified as

$$\Delta\sigma=f\,(E, p, c, d) \tag{3}$$

Among these four governing parameters, two of them, namely E and d have independent dimensions. By applying the π theorem in dimensional analysis (Barenblatt 1996), we obtain

$$\frac{\Delta\sigma}{E}=f\left(\frac{p}{d},\frac{c}{d^2}\right) \tag{4}$$

Furthermore, the nodes of the outer edge of the cable-net are fixed to the ring beam, and their position cannot be adjusted by the actuator like other cross nodes can do (See Fig. 1). In order to expand the observation zenith angle of FAST as large as possible, outer edge of illuminated aperture should coincide with basic spherical surface. Only then can outer edge of illuminated aperture arrive at the outer edge of the cable-net. With such constraint, we can derive that

$$c=22500+519.6p \tag{5}$$

Then, the Eq(3) can be further simplified as

$$\frac{\Delta\sigma}{E}=f\left(\frac{p}{d}\right) \tag{6}$$

For the steel cable, the elastic modulus is about 200GPa, thus the only variable remained in this implicit function is p/d, which is the focal ratio of this telescope.

From Eq(6) we can know that the fatigue stress range of FAST cable is most dependent on the focal ratio of this telescope. The different focal ratio would lead to the different relative position between the illuminated aperture and the base plane, which is directly related to internal forces of cable-net and stroke of actuator.

In our early work (Qian, 2007; Jiang, 2009), three kinds of deformation strategies, namely the strategy Ⅰ, the strategy Ⅱ, and strategy Ⅲ, have been proposed. The relative positions of these three strategies to the spherical base plane are shown in Figure. 2. The focal ratios corresponded to these three strategies are respectively 0.4665, 0.4611, and 0.4613.

In the preliminary design of FAST cable-net structure, the deformation strategy Ⅰ was recommended as the prefer control scheme just because of its shortest actuator stroke. Obviously, it is unreasonable to omit the fatigue problem in the deformation strategy optimization, especially for the present case of about 500MPa stress range.

So the present work would make an effort in establishing the relation between the focal ratio and the deformation stress range. And then, by considering both factors of the actuator stroke and the stress range of the cable, we would re-recommend deformation strategy for FAST future observation.

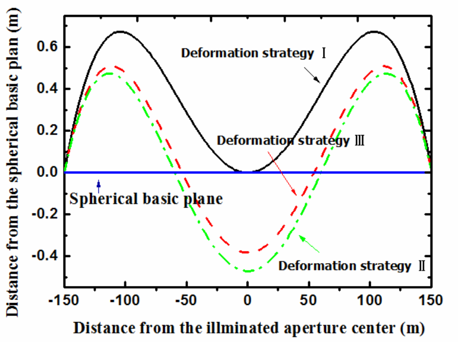

Fig. 2. The relative positions between the paraboloid and base spherical surface for three previous proposed deformation strategies.

2.2 Numerical analysis

For the FAST condition, the maxmium distance between the spherical and the paraboloid surface is no more than 1m. As we known, the angular velocity of celestial body is about 15 degrees per hour. Accodingly, the radial velocity of the cross node during FAST tracking observation is less than 1mm/s.The deformation procedure of the reflecter system in the tracking observation can be taken as quasi-static state procedure. Thus, we can replace a continuous observation procedure with a set of sequential discrete observation states. By comparing with the time history analysis method, this method would be capable of saving a lot of calculation time.

For FAST observation, the illuminated aperture is restricted within the scope of the cable-net. Consequently, we can easily deduce the movement range of the illuminated aperture center, which has been illustrated by Fig. 3. This region contains 550 cross nodes, the interval of any two adjacent ones is no more than 13m which corresponds about only one degree-center angle of 300m radius of reflector.

In the present work, these 550 cross nodes are taken as the discrete points, which is used to describe the continuous trajectory path of the illuminated aperture center. Thus, any possible observation state during FAST observation can be approximately recognized as one of those 550 observation states, whose centers are corresponding to these 550 cross nodes. By using the finite element analysis method, we can simulate these 550 observation states. With the simulation results, stress data of all cables under those 550 cases can be saved as two-dimensional array data. By processing this two-dimensional array data, the maximum stress range of each cable during FAST observation can be easily derived.

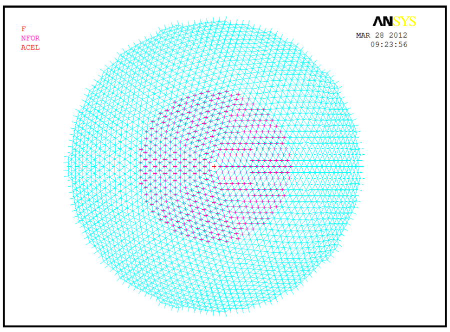

Fig. 3. Illustration of range of cross nodes used as discrete points to describe continuous trajectory path of the center of the illuminated aperture

Utilizing the same procedure, the distribution of the stress range for other two types of deformation strategies can be derived. The peak stress range of the strategy Ⅰ and strategy Ⅲ are respectively 547MPa and 482MPa. By using the least square method, the relation of the focal ratio and the peak stress range can be fitted by quadratic polynomial, from which we can predict that the focal ratio value corresponding to the minimum stress range is about 0.4633. The corresponding profile shape of the illuminated aperture can be determined by Eq(1) and Eq(5).

We input this new deformation strategy into the above analysis procedure, we can derive that the maximum stress range of this deformation strategy is 488MPa, which is same to that of the focal ratio of 0.4613. Then, by repeating the above steps with interpolation of this new data point, the focal ratio of 0.4621 can be further achieved. The further simulation result has shown that the maximum stress range corresponding to the focal ratio of 0.4621 is 459MPa, which is about 90MPa beneath that of deformation strategy Ⅰ and 30MPa beneath that of the strategy Ⅱ.

However, it is difficult to say whether 0.4621 is the optimum focal ratio for the fatigue problem of the cable-net. For this reason, other two strategies with 0.4620 and 0.4622 of focal ratios have also been investigated in the present work. And the simulation results have shown that the peak stress ranges leaded by these two deformation strategies are respectively 462MPa and 460MPa, both of them are slightly higher than that caused by the deformation strategy with focal ratio of 0.4621. So, we have reasons to believe that the deformation strategy with focal ratio of 0.4621 is very close to the deformation strategy corresponding to the minimum stress range.

It also should be noted that the actuator stroke of this strategy is 0.89m, which is also 50mm beneath the strategy Ⅱ. By comparing the stress range and actuator stroke of these deformation strategies (see Table. 1), we would recommend the strategy with focal ratio of 0.4621 for FAST application.

Table. 1. Comparison of the fatigue stress range of the cable and the stroke of the actuator caused by different deformation strategies.

Focal ratio	0.4603	0.4611	0.4613	0.4620	**0.4621**	0.4622	0.4633	0.4665
Maximum stress range (MPa)	512	488	482	462	**459**	460	488	547
Actuator stroke (m)	0.9890	0.9450	0.9341	0.8966	**0.8914**	0.8861	0.8291	0. 6741

3. Conclusion

During FAST observation procedure, the stress range borne by its cable is more than twice as that provided by the relative standard. In order to improve the reliability of FAST and extend its service life, the present work has performed an extensive numerical investigation to decrease the stress range, the research results has shown that the focal ratio is the key influence factor of the stress range of FAST cable-net structure caused by shape changing operation. And 0.4621 is suggested as the most appropriate focal ratio, which would lead to about 30MPa reduction of the stress range and 50mm reduction of actuator stroke.

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