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Prognostics and health management of FAST cable-net structure based on digital twin technology

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Abstract The Five-hundred-meter Aperture Spherical radio Telescope (FAST) will be fully commissioned later in 2019. Once commissioned, operation and maintenance of FAST will be the most prominent task. The unique working mode of active shape-changing of FAST cable-net structure makes the traditional maintenance way, which combines routine inspection with preventive maintenances not only expensive, but also unable to effectively avoid potential risks in operations. Therefore, it is necessary to develop an economical and reliable operation/maintenance technology for FAST cable-net structure. In this paper, a Prognostics and Health Management (PHM) system is proposed based on the advanced Digital Twin (DT) technology. Through the finite element analysis of DT model, the current safety status of FAST cable-net is evaluated, and the fatigue life of components in the cable-net is predicted. Hence Condition-Based Maintenance (CBM) of FAST cable-net structure can be realized. The PHM system described in this paper can effectively guarantee the healthy and safe operation of the FAST cable-net structure, greatly improve the maintenance efficiency and reduce the cost for maintenance works.

Key words: telescopes — astronomical instrumentation, methods and techniques — methods: analytical — methods: data analysis

1 INTRODUCTION

The Five-hundred-meter Aperture Spherical radio Telescope (FAST), which is one of the key scientific projects of the national 11th Five-year Plan, is the largest single-aperture radio telescope in the world. The total investment of FAST is 1.2 billion RMB, and it has a designed life of 30 years. FAST performs observations at frequencies from 70 MHz to 3 GHz, with designed resolution and pointing accuracy of 2.9′ and 8″ respectively (Nan et al. 2003, 2011). The construction of FAST was completed on 2016 September 25. It is predicted that FAST will maintain the status of world-class equipment in the next 20 to 30 years.

Currently, FAST is still in its commissioning stage. The commissioning procedures are going through smoothly, with the main technical specifications being achieved (Jiang et al. 2019; Lu et al. 2019a,b; Qian et al. 2019; Yu et al. 2019). Over 80 high-quality pulsar candidates have been found during the commissioning period, with more than 55 being confirmed, which shows the superb prospect of FAST. It is expected that FAST will pass the national acceptance in 2019, and will be officially commissioned later in 2019.

2 OPERATION AND MAINTENANCE OF FAST CABLE-NET STRUCTURE

2.1 Configuration of FAST Cable-net Structure

FAST has adopted a flexible cable-net structure as the main support structure of the active reflector. Rigid panels are connected to the cross nodes of flexible cable-net through adaptive connecting mechanisms. The cable-net structure is comprised of 6670 steel cables and 2225 down-tied cables (see Fig. 1), with one of the terminals of the down-tied cable connecting to the cross node, and the other fixed on the ground with an actuator (Li et al. 2001; Luo et al. 2000a,b; Ren et al 2001; Lu et al. 2007). The outer edge of the cable-net is fixed on the ear-plate joints of the ring beam by 150 borderline main cables. With an interior di-

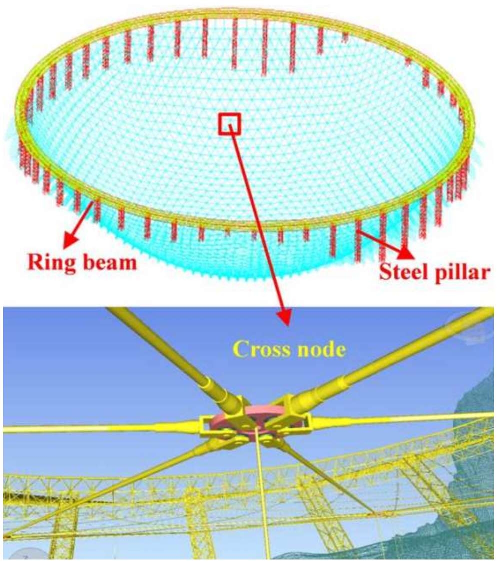

Fig. 1 Sketch of FAST cable-net structure.

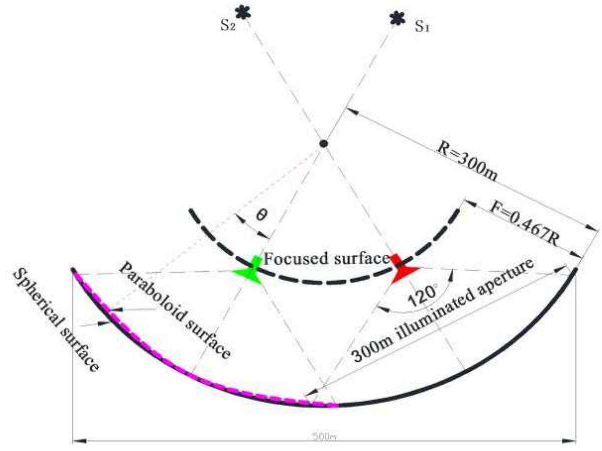

Fig. 2 Geometric optical principle of FAST.

ameter of 500.8 m and a total weight of 5350 tons, the ring beam is constructed with 11 m × 5.5 m ring truss structure. The ring beam, sitting on the sliding bearings, is supported by 50 steel pillars with varied heights, and the pillars are evenly distributed around the ring beam.

As one of the major sections of FAST, the cable-net structure features super-long span and real-time adjustable shape. The positions of the cross nodes can be adjusted to form a 300m-aperture paraboloid by actuator operations (Jiang et al. 2017; Li et al. 2017a,b). The cable-net structure, with its ability of active shape-changing, distinguishes itself remarkably from traditional structures. Thus once FAST is commissioned, the safe operation and maintenance of its cable-net structure will be the focus and sticking point of FAST's operation and maintenance.

2.2 Safe Operation of FAST Cable-net Structure

In the design stage of FAST cable-net structure, the possible adverse conditions in operation have been considered in detail. However, these based on design model. In FAST's 30-year design lifespan, the actual structure will inevitably become different from the original design model, such as, (1) because FAST construction site is karst depression, there are many karst caves and fissures in the ground, which leads to several down-tied cable foundations that are just located on the fissures are not strong enough. At present, a few such foundations have been pulled out, and the re-construction of the foundation position is bound to have deviated from the original position; (2) during the long-term operation of FAST, the uneven force leads to the overall slip of the ring beam on the sliding bearings, etc. In addition, the failure of some actuators in FAST operation will also lead to the inconsistency between the actual working conditions and the design conditions. These differences may result in safety problems that cannot be considered in the design stage. The results show that under the most unfavorable conditions, the failure of some actuators may cause the load on the corresponding down-tied cables to exceed their ultimate bearing capacity, which may result in the breakage of the down-tied cables (Jiang et al. 2013).

More than 500 sensors have been arranged on FAST cable-net and the ring beam, to monitor the safety of the cable-net structure. However, there are nearly 10 000 components just in the cable-net, the effective evaluation of the cable-net structure safety cannot be achieved just by the arrangement of about 500 sensors. Therefore, a more reliable strategy is required (Jiang et al. 2015).

In observations, a series of paraboloids should be formed at different locations of the spherical surface by pulling down the down-tied cables with the actuators (see Fig. 2) to meet the pointing requirements of the targeting objects (Qian et al. 2005a,b). Obviously, long-term observations can lead to long-term and frequent shape-changing operations of the cable-net. This can lead to cyclically variable loads in the cable-net endure over long terms, which may result in fatigue failures of the steel cables in the structure.

The fatigue failures of these steel cables in the cable-net are the key technical problem that decides the success or failure of FAST. According to the estimations done in the design stage, the fatigue stress amplitude of FAST steel cables can be as high as 500 MPa, which is nearly twice the authorized standard value (Jiang et al. 2013, 2015; Kong et al. 2013), and far beyond the fatigue performance index of conventional steel cables. Thus, the FAST-technical team has spent many years developing high-fatigue performance index steel cable, and have successfully addressed this problem.

However, the uncertainty in observation arrangements and the changes in the actual cable-net can all make the actual stress spectrum deviate from the predicted stress spectrum during the design stage, which will lead the cables in the cable-net to face the risk of fatigue failure. Of course, such brittle fatigue failures of the steel cables may cause the damage of the reflector and the actuators in adjacent area, or even result in casualties. Considering the great social influence of FAST, these accidents should absolutely be avoided.

In addition, fatigue failures of steel cables could also decrease the efficiency of astronomical observation in the relevant areas. However, there are nearly 10 000 steel cables in the cable-net of FAST, all with varying lengths and specifications. Therefore, it is impossible to have all types of cables as replacements for the damaged ones ready on site. Due to the uniqueness of these cables, it could take a long time to get such replacements if current cables got damaged.

Therefore, we need to know which steel cables in the cable-net of FAST may suffer from fatigue damage, as well as when such things may happen, in advance. In case of the brittle fatigue failure of the steel cables, great losses may be caused, and the repair and maintenance works may take as long as several months. Of course, these accidents would severely affect the normal operations of FAST.

For the safe operation and maintenance problems faced by FAST cable-net structure, the traditional maintenance strategy, which combines routine inspection with preventive maintenance, cannot meet our requirements. Thus in this paper, a Prognostics and Health Management (PHM) system is designed based on the advanced Digital Twin (DT) technology. Through the finite element analysis of DT model, the near-real-time safety status of FAST cable-net can be evaluated, and the fatigue life of each component in the structure can be predicted. With such information, the PHM system can inform operators to make maintenance plans in advance; thus nipping any possible accidents in the bud.

2.3 Basic Concept of Digital Twin

DT technology is a novel technology that combines digital information of a certain equipment with real-time data stream acquired from it during operations. Through analysis of the DT model, the real-time status of the actual equipment can be obtained. With the help of improvements of simulation software, hardware and computer processing speed, as well as the advent of Internet of Things, it is possible to apply DT technology widely. Unlike traditional simulation technologies and CAE technology, DT technology can provide dynamic, evolving images based upon historical data and current data, and can map physical entities in the real world digitally (Jin et al. 2019).

In recent years, DT technology has achieved great developments and is widely used due to its huge economic benefits. For example, the U.S. Department of Defense first proposed to use DT technology in the maintenance of aerospace vehicles in 2010 (Tao et al. 2017). In 2015, GE applied DT technology to its GE90 engine, thus significantly reducing the number of engine overhauls, and minimizing premature replacements of spare parts. The use of DT technology has saved tens of millions of dollars in costs (Warwick 2015). Gartner, the world's leading IT research and consultancy firm, has ranked DT as one of top 10 strategic technologies in 2017, and envisaged that this technology will be one of the leading technologies in the Internet of Things environment. According to Gartner's predictions, by the year of 2021, more than half of the major industrial companies will adopt and rely on DT technology (Tao et al. 2018).

In this paper, we use DT technology to obtain real-time data that either cannot be collected when FAST is observing, or the amount of the real-time data collected cannot meet the requirements of prognostics. Through analysis of these data, we can evaluate the real-time operation safety status of cable-net structure, predict the fatigue life of the steel cables in the cable-net, thus realize the Condition-Based Maintenance (CBM) of FAST cable-net structure.

3 CONSTRUCTING THE DIGITAL TWIN OF FAST CABLE-NET STRUCTURE

The construction of DT model consistent with actual structure for FAST cable-net is the core to establish the prognostics and health management system. Thanks to the forward-looking vision of FASTs designers, high-precision sensors and measuring equipments have already been installed on the key elements of the cable-net structure during the construction phase. For example, magnetic flux sensors for measuring the borderline main cables forces have been installed on 150 borderline main cables; reflective targets for laser measurements have been distributed on the ear-plate pinholes of the ring beam to make sure that the coordinates of these pinhole can be automatically measured with laser total stations; magnetostrictive sensors have been set up on each actuator to provide the strokes of these equipments, and so on. These high-precision sensors and measuring equipments enable us to construct DT model of FAST cable-net structure at a low cost.

Considering the powerful programming ability of ANSYS Parametric Design Language (APDL), we use APDL to construct the DT model of FAST cable-net structure. Figure 3 shows an integral finite element model of

FAST cable-net structure, which includes the ring beam and all the steel pillars. We use BEAM44 element to simulate components of the ring beam as well as the pillars, and LINK10 element to simulate the main and down-tied cables. The actual weights of the reflector panels are applied to the cross nodes in the form of loads.

As mentioned above, DT can be seen as a dynamic, evolving image based on historical and current data, and a digital mapping of physical entities in the real world. To construct the DT model of FAST cable-net structure, this needs to be updated in time according to the actual changes of the physical entities on site. By the time-varying speed of data, we divide the data in need two categories: real-time feedback data and periodically-measured data. Real-time feedback data indicate that data change rapidly and have a significant impact on the stress of the cable-net structure. It is necessary to update such data in DT model in real time. Periodically-measured data indicate that the data change slowly, and the effects of such changes on the stress of cable-net structure is not as obvious as the former type in a shorter time scale. Thus, measuring and updating such data to the model regularly is sufficient enough.

Real-time feedback data, including actuator strokes, numbers of abnormal actuators, and ambient temperatures, are the most important factors affecting the stress state of cable-net. In fact, during tracking observations a series of paraboloids should be shaped by changing strokes of 2225 actuators. Thus, the strokes of these actuators directly determine the stress state of the cable-net. The failed actuators also have significant effects on the stress of the surrounding main and down-tied cables. In addition, because of the huge scale of FAST, the influence of ambient temperature on the stress state of cable-net cannot be ignored. Such real-time feedback data need to be updated to DT model as soon as possible.

The real-time feedback data can be obtained by digital communications between OPC module of MATLAB and PLC. The time for each round of data by this way is less than 1 second. New data obtained each time will be stored in a .txt file of a specified folder, replacing the old data file. Thus, ANSYS can update the DT model in real time by calling the .txt file.

The updating process is shown as follows. The strokes of actuators represent the deformations of the down-tied cable elements, which can be transformed into the temperature changes of the corresponding element by Equation (1), together with the ambient temperature applied to the DT model in the form of temperature loads:

$$\Delta T_i = \frac{\Delta L_i}{\alpha \times L_i}\,. \tag{1}$$

Here ΔT_i is the temperature changes when deformation value of the ith down-tied cable is ΔL_i. ΔL_i represents the deformation of the ith down-tied cable, that is also the stroke of the corresponding actuator; L_i represents the length of ith down-tied cable; and α represents the coefficient of linear expansion of steel.

According to the actual response mode of abnormal actuator on site, the abnormal actuators can be simulated either by inputting the last non-zero strokes, or killing the corresponding down-tied cable elements in the DT model.

For periodically-measured data, we get measured data and update them to DT model every three months. The periodically-measured data include: (1) the center coordinates of each ear-plate pinhole, which can show the position drifts of the connecting junctions between the borderline main cables and the ring beam (for example, such effects can be caused by the slip of the ring beam); (2) the coordinates of cross nodes and the strokes of actuators under the basic sphere (Here "basic sphere" refers to the standard spherical state of the FAST reflector with a curvature radius of 300 m, which provides a benchmark for reference during cable-net structure's shape-changing operations), which can reflect the changes of main cables and down-tied cables; (3) the coordinates of the anchorages of down-tied cables, which is used to reflect the position changes of the down-tied cables' foundations; (4) The force of the 150 borderline main cables, which can be used to check the updated DT model. The periodically-measured data obtained every three months are also stored in a .txt file in a specified folder. The relevant data can be updated to the ANSYS model by calling a special APDL program.

The real-time feedback data are applied to the model in the form of loads, and will not change the geometry of the finite element model. By comparison, the periodically-measured data could modify the geometry of the finite element model.

FAST cable-net structure is a complex coupling structure. Modifying the geometric model along cannot guarantee the accuracy of the finite element simulation results, it is also necessary to modify other parameters of the finite element model by iterative process according to the comparisons between measured data and simulated results.

The manufacturing process of the main cables of FAST cable-net structure has strict quality control, the error length for each single main cable is less than 1 mm. Considering the stress of the steel cables in the cable-net of FAST are all elastic, as long as the cross node positions of the DT model is consistent with the measured positions on site, the main cables forces calculated by the model should also be consistent with the forces experienced by actual main cables on site under the same working conditions.

Since the basic sphere provides the benchmark for cable-net structure's shape-changing, we update the DT

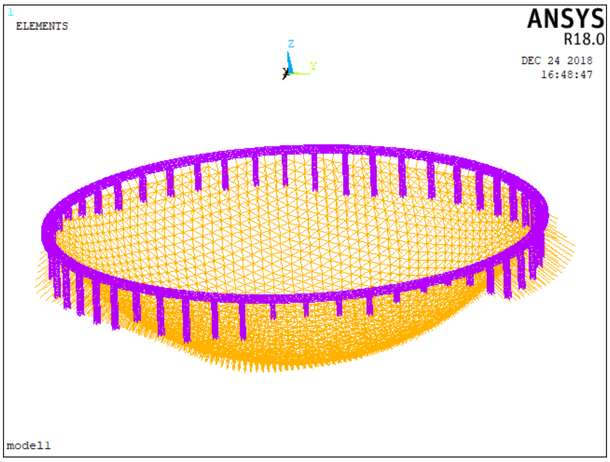

Fig. 3 The integral finite element model of FAST cable-net structure.

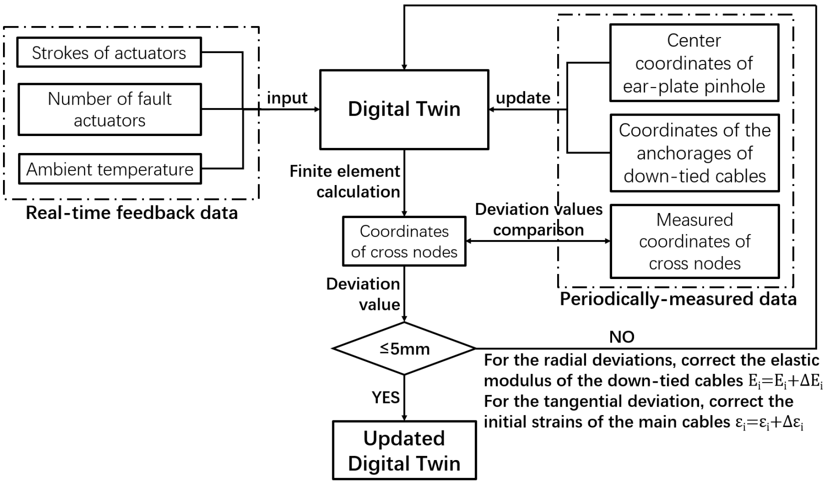

Fig. 4 The flow chart of updating process.

model under such state. The specific updated method of DT model is as follows.

In non-observing time of FAST, the basic sphere can be calibrated by an automatic calibration system at optimum working hours for the total station on site, which is around 4:00 a.m. The measured root-mean-square value of the out-of-plane error for the calibrated basic sphere's deviation from the theoretical sphere should be less than 2 mm. While the strokes of 2225 actuators, the numbers of the abnormal actuators and the ambient temperature can be obtained by the sensors on site. At the same time, the coordinates of 2225 cross nodes, the center coordinates of the ear-plate pinholes and the force of the 150 borderline main cables can be measured. The changed coordinates of the anchorages of the down-tied cables should also be measured, if changes are shown.

Using the measured center coordinates of the ear-plate pinholes and the coordinates of the down-tied cables anchorages, we modify the geometry of DT model, and then carry out finite element analysis of the model. From the analysis results, the deviations between calculated and measured positions of the cross nodes should be divided into radial and tangential deviations.

Considering the high accuracy in manufactures and installations of the cable-net structure, the radial deviations of the cross nodes is mainly related to the stiffness change caused by the catenary action of down-tied cables. Therefore, according to Equation (2), we calculate the correction of elastic modulus caused by catenary action and correct the elastic modulus of the corresponding down-tied cable elements in the DT model:

$$\Delta E_i = \frac{F_i \times L_i}{\Delta L_i \times A_i}\,. \tag{2}$$

Here ΔE_i represents the elastic modulus correction of the ith down-tied cable; F_i is the calculated cable force of the ith down-tied cable; L_i the length of ith down-tied cable; ΔL_i the radial deviation value between the calculated and measured positions of the cross nodes at the ith down-tied cable; A_i means the area of cross section of the ith down-tied cable.

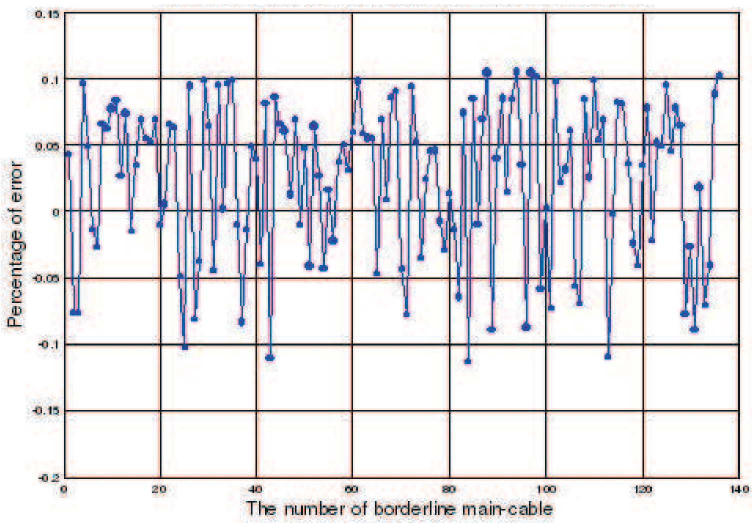

Fig. 5 Force errors between the measurement and the calculation.

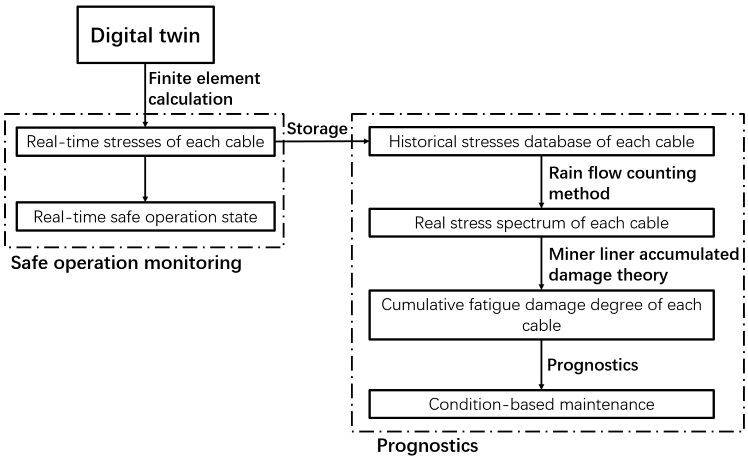

Fig. 6 Prognostics and health management architecture of FAST cable-net structure.

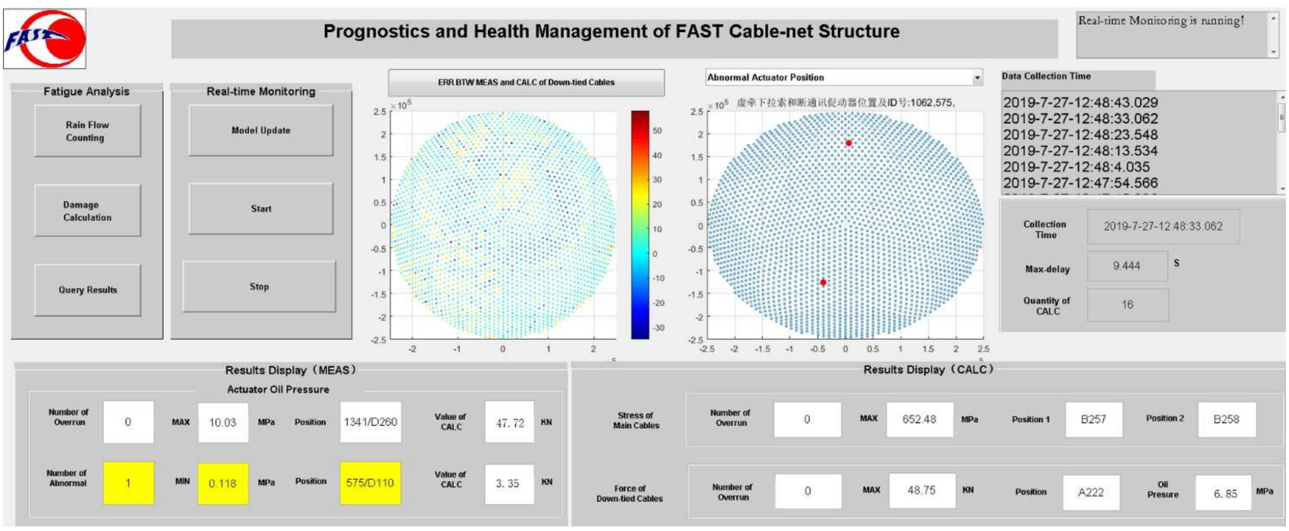

Fig. 7 The user's interface of PHM system.

The tangential deviations mainly arises from the initial strains of the main cables predetermined in the model. According to the measured and the calculated coordinates of the cross nodes, we can get the measured length and the model length of each cable under the same working conditions. Then, the initial strain corrections of the main cables can be calculated with Equation (3) to correct the initial the main cable strain in the DT model:

$$\Delta\epsilon_i = \frac{L_{i1} - L_{i2}}{L_{i2}}\,, \tag{3}$$

where $\Delta\epsilon_i$ represents the initial strain correction of the ith main cable; L_{i1}represents the measured length of the ith main cable; and L_{i2} is the calculated length of ith main cable.

According to this method, the relevant parameters can be updated iteratively, until the deviations between the calculated and measured positions of the cross nodes are all less than 5 mm. The updated model will be the new model for DT until three months later. We have compiled the finite element program using APDL language of ANSYS software, and made the automatic update of DT model possible. The flow chart of updating process is shown as follows (see Fig. 4).

Since the outer edge of the cable-net is fixed on the earplate joints of the ring beam by 150 borderline main cables, the errors between the measured and calculated forces of the 150 borderline main cables can be best used to prove the accuracy of the DT model.

Based on the Code of Technical Specification for Cable Structures (JGJ 257–2012), the safety factor for steel cables in FAST's cable-net structure should be 2.5. Considering that the self-weight loads and active displacement loads of FAST are more accurate than those of common civil engineering structures, the safety factor of the cables in the cable-net structure can be lowered down to 2.0, if it is designed by allowable stress method (Luo et al. 2015).

Considering the measurement errors of the magnetic flux sensor is $\sim$ 3%, the errors between calculated and measured forces of the 150 borderline main cables are less than 15% under the basic sphere configuration, which shows that the DT model can be updated successfully.

In September 2018, we made a complete measurement of the relevant data, updated the DT model for the first time, and checked the accuracy of the DT model by measuring the 150 borderline main cables forces under the basic sphere state. Figure 5 shows force errors between the measurement and the calculation. Since there are 14 failed measurements, only 136 cable force errors are given in Figure 5.

It can be seen that most of the errors between measurements and computations are less than 10%, and the maximal error is only 11.21%. Thus, the accuracy of the updated DT model can meet the requirements of the FAST cable-net structure's PHM system.

4 PROGNOSTICS AND HEALTH MANAGEMENT OF FAST CABLE-NET STRUCTURE

Based on the DT model, we design a prognostics and health management system of the FAST cable-net structure. The system is divided into two parts: safe operation monitoring and prognostics. The specific architecture of this system is shown in Figure 6.

4.1 Safe Operation Monitoring of FAST Cable-net Structure

Through the real-time finite element analysis of the DT model, we can obtain real-time stresses of each steel cable, which are closely consistent with the actual structure, and grasp the real-time safe operation status of the cable-net structure, hence make the health management of the FAST cable-net structure possible.

Since it takes about 10 seconds for each round of finite element analysis, the stress of the cable-net structure that we obtain at present actually reflects the status at 10 seconds ago. However, the maximal speed of the actuator is only 1.6 mm s^{-1}, thus the maximal stroke incremental of the actuators in this period is about ± 16 mm, which cannot cause great changes in the stress status of the cable-net. We calculated that the maximal incremental in cable forces caused by ± 16 mm actuator stroke is about ± 20 MPa only, which is far less than the yield strength of the steel cables (1860 MPa). It is still feasible to use this method to monitor the safe operation status of FAST cable-net structure.

4.2 Prognostics of FAST Cable-net Structure

The real-time stress of each cable obtained during the safe operation monitoring process are stored in a specialized database as a time sequence. Through statistical analysis of historical stresses in the database, the real stress spectrum of each cable can be obtained with rain flow counting method. Hence we can get the cumulative fatigue damage degree for each cable up to the present time by using the miner liner accumulated damage theory, which is internationally accepted at present (MOHURD 2017).

Assuming that a cable endures n_i cyclically varying loadings in the stress amplitude level of $\Delta\delta_i$, according to S-N curve, we can get the fatigue life corresponding to $\Delta\delta_i$ is N_i, then the damage degree caused by stress amplitude $\Delta\delta_i$ is n_i/N_i. If we perform similar calculations for all these stress amplitudes over a statistical stress spectrum, we can get Equation (4):

$$F = \frac{n_1}{N_1} + \frac{n_2}{N_2} + ... + \frac{n_n}{N_n} = \sum_{i=1}^{n} \frac{n_i}{N_i} . \quad (4)$$

Here F is the cumulative fatigue damage degree of the cable up to the present time. From the point of engineering application, it can be assumed that fatigue failure occurs at the corresponding position when $F = 1$. Thus from the cumulative fatigue damage degree, we can predict the fatigue life of each cable. For the cables with fatigue damage risk, we can devise maintenance plans, and order the corresponding types of cables in advance, in order to replace them in time, so as to truly achieve CBM.

At present, the PHM system of FAST cable-net structure has been deployed on site. This system, especially the safe operation monitoring part has played a very important role during the commissioning phase of the FAST. The user's interface of PHM system is shown in Figure 7.

5 CONCLUSIONS

To meet the actual requirements of FAST operators, an economical and efficient operation and maintenance system suitable for the cable-net structure is established by using the advanced DT technology in this paper. The main work and achievements of this paper can be summarized as follows.

(1) In this paper, the latest DT technology is applied to the operation and maintenance of the FAST cable-net structure for the first time.

(2) The DT model of the FAST cable-net structure has been constructed, which is highly consistent with the actual structure on site and can be updated with time.

(3) According to the constructed DT model, a PHM system which including safe operation monitoring and prognostics has been designed. The PHM system can make CBM of the FAST cable-net structure possible, thus greatly improving the maintenance efficiency and reducing its maintenance cost. The PHM system has achieved good results during the commissioning of the FAST.

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