Structural Analysis of FAST Reflector Supporting System and Its Joints

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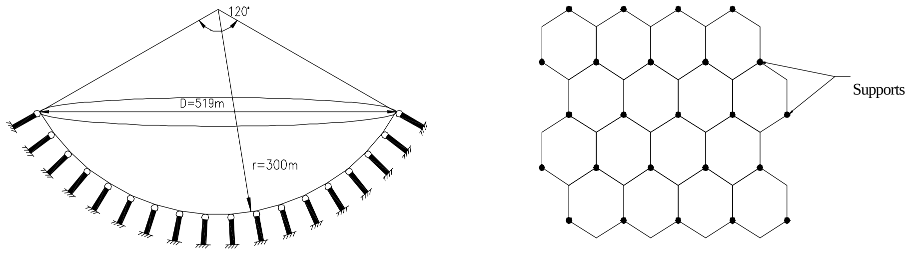
Abstract: According to the deformation and movement requirements of FAST reflector, a multi-purpose analysis, including the load-bearing behavior, deformation, construction cost of the reflector supporting structure and its model, is presented in this paper. The advantages and disadvantages of the steel structure and the aluminum alloy structure are also discussed and compared through detail design calculation. A novel joint system of the reflector is proposed to meet the strict requirements on the shape accuracy of the reflector. The joint system comprises structural joint and reflector panel-fixing joint for both steel structures and aluminum alloy structures.

Keywords: reflector supporting structure, steel, aluminum, deformation, joint system, shape accuracy

1.Introduction

The FAST[1] (**F**ive-hundred meter **A**perture **S**pherical **T**elescope) project is now a world-wide well-known astronomical project in China. Its reflector is a spherical surface with 500 m aperture and 300 m radius of curvature (Fig.1a). According to the requirement of fitting a moving paraboloid of revolution, FAST reflector must be continuously adjustable while tracking a celestial object. To this purpose, FAST reflector is divided into approximately 1788 elementary units. An elementary unit is a virtual spherical hexagon of about 7.5 m in edge length. It is realized by a structural unit composed of aluminum panels and a stiff supporting structure. The structure is attached to three servo controlled actuators that can drive the structure to move in the direction normal to the spherical surface. The real time movement of every elementary unit is in coordination with all adjacent units while fitting the required paraboloid. The relationship between elementary units is shown in Fig1b.



a) Reflector surface b) Relationship between elementary units

Fig.1. FAST reflector

2.The aluminum panels of the reflector

An elementary unit is further divided into 54 plane triangles. All apexes of a triangle are on the reflector spherical surface and its edge length is not greater than 2.5 m. A typical elementary unit is shown in Fig. 2.

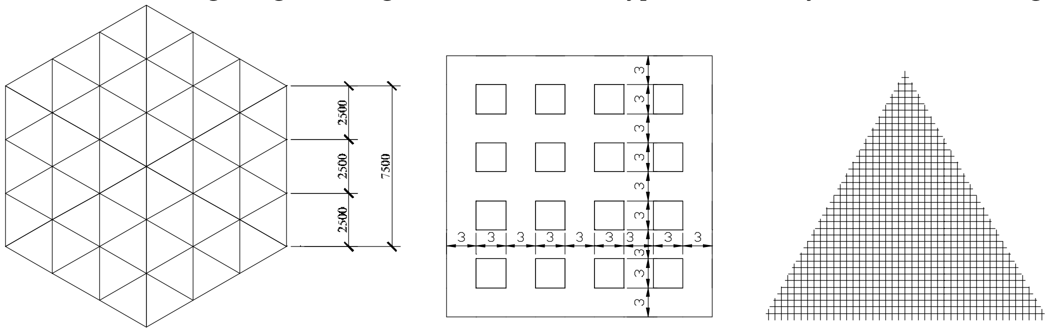


Fig.2. An elementary unit and perforated aluminum triangle-panels

The reflector surface is made of perforated aluminum panels. The thickness of the panel is t≤1 mm. Each hole in the panel is a 3 mm by 3 mm square hole or d=3 mm circular hole spaced 6 mm between two adjacent hole centers. The net area of the panels is almost 75% of the gross area of the reflector. The surface area of an elementary unit is 146.142 m^2. The total area of the reflector surface is approximately 261300 m^2. The aluminum density is 2.8 t/m^3. If the thickness of the panel is 1 mm, the total aluminum quantity needed for the reflector panels is 558.7 t.

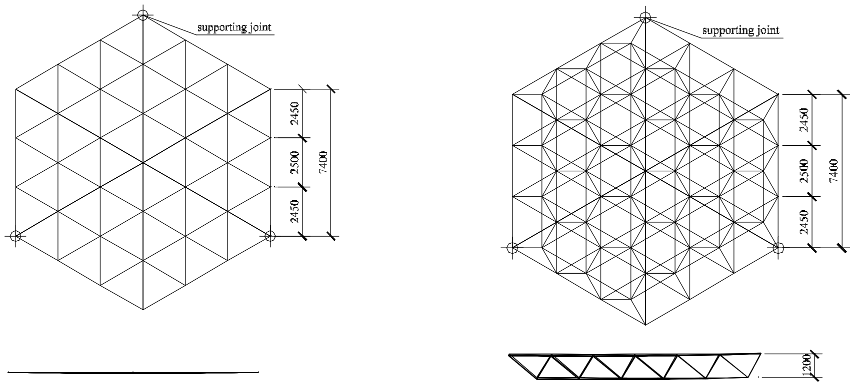
3. The supporting structure of the reflector

According to the astronomy requirement for the working accuracy of the reflector[1], the reflector must possess enough spatial stiffness, integrity and service reliability. The reflector supporting structure must ensure the fitting accuracy. On the other hand, the construction cost and the service durability of the supporting structure are also major control factors for the structure design.

There are two alternative supporting structure systems, i.e., plane structures and space structures. Most of the traditional structures are practically plane structures. Their out-plane stiffness and integrity are insufficient and their joint systems are complicated for forming space structures. The advantages of space structures over plane structures are better spatial stiffness, better integrity, lighter self-weight, easier fabrication and lower construction cost. Modern reticulated (or grid) shells are inherently space structures.

Two types of grid shells can be selected for the reflector structure, i.e., single layer grid shell (Fig.3a) and double layer grid shell (Fig.3b). The strength of the first type may be sufficient for the reflector, but the spatial stiffness is hard to satisfy the FAST requirement. The second type has better spatial stiffness, integrity, and reliability. Although the number of joints and members is more than that of single layer grid shell, the self-weight of the double layer grid shell will be lighter and the total construction cost will be lower. Therefore, double layer grid shell is better and more suitable for the supporting structure of the FAST reflector.

The double layer grid shell with triangular-pyramid patterns is finally selected for the supporting structure of the reflector. A typical grid shell is shown in Fig.3. All upper joints are on a spherical surface and all lower joints are on a concentric spherical surface. The triangle grid size of the shell is not greater than 2.5 m. The structure height is chosen between 1.2 m and 1.5 m to achieve a balance between stiffness requirement and construction cost.



a) Single layer grid shell b) Double layer grid shell

Fig.3. A typical grid shell as a supporting structure

4. Design and analysis of the supporting structure

The construction quality and geometry accuracy of FAST reflector have direct effect on its operation. Possible structure systems are compared to yield the optimal design of the supporting structure. Two different structural materials – steel (Q235, Chinese standard steel) and aluminum alloy (AA 6061 T6) – are selected here for comparison. The advantages and disadvantages of the structures are listed and compared. Stainless steel as a weather proof structural material is not discussed in detail here because of its high construction cost.

Steel grid shell has the advantages of high spatial stiffness, integrity, low cost, small deformation and convenient manufacture, but it has the disadvantages of heavy self-weight, unbalanced thermal deformation with the aluminum reflector panels, low corrosion resistance, heavy maintenance work and high service cost.

Aluminum alloy grid shell has the advantages of light self-weight, high corrosion resistance, little maintenance work (no maintenance at all if the service environment is favorable) and identical thermal deformation with the aluminum reflector panels, but it has the disadvantages of difficult and deficient welding and high construction cost.

Two different structural limit states, i.e., load-bearing capacity limit state and deformation limit state under normal working condition, and twelve different load combinations are considered in the analysis and design of the supporting structure.

4.1. Load-bearing capacity of the structure

Under the load-bearing capacity limit state, the supporting structure is mainly subject to self-weight, ultimate wind load (average wind speed v=20.0 m/s), temperature change (±30°C) and possible snow load. The structural analysis is conducted under possible load combinations based on the factorized values of these loads, and the strength and stability of members are checked against relevant design codes[2,3]. The major results are listed in Table 1 and Table 2.

Table 1. Material consumption of the structure

Materials	Consumption per unit area (kg/m^2)		An elementary unit consumption (t)	Unit price (10^3RMB/t)	Total cost (average for all units) (10^6RMB)
Steel (Q235)	Bottom (0°)	9.78	1.43/1.41	6.5 7.0	16.50 17.77
	Edge (60°)	9.65			
	Average	9.715			
Aluminum alloy (AA6061-T6)	Bottom (0°)	4.947	0.723/0.925	25 35	36.83 51.56
	Edge (60°)	6.329			
	Average	5.638			

Note: The cost of steel structure is only the initial construction cost and does not include maintenance cost. The coating of steel structure costs about 2.54 (10^6RMB) and may last 5 to 10 years.

Table 2. Reactions at the supporting joints

Materials	Tangential reaction (kN)		Normal reaction (kN)			
	Bottom (0°)	Edge (60°)	Bottom (0°)		Edge (60°)	
Steel	0	20.539	-6.535	10.836	-15.127	11.448
Aluminum alloy	0	12.934	-3.814	13.563	-14.089	11.811

Note: - is for compression and + is for tension.

It is shown in Table 2 that reactions of steel structure are higher than those of aluminum structure. This will increase the cost of mechanical and electronical systems.

4.2. Deformation analysis under normal working condition

The supporting structure must ensure the geometry accuracy of the reflector surface under normal working condition: the structure is subject to self-weight, working limit wind load (average wind speed v=4.0 m/s), and temperature change (±20°C). The structural analysis is conducted under possible load combinations based on the standard values of these loads. The major results are listed in Table 3.

Table 3. The largest displacements of the upper joints (mm)

Materials	Bottom (0°)	Edge (60°)
Steel	0.43	0.15
Aluminum alloy	0.54	0.20

5. Design of the test model

5.1. Test model

In order to investigate the loading behavior of the supporting structure, the functionality and the reliability of different mechanical devices, and the weathering effect on the whole reflector, a 1/3 scaled test model composed of four elementary units is designed. The principle of analogy is applied in the design. Twelve load combinations are also considered. Because the original grid size is much irregular, it is adjusted for optimal design and convenient construction. Two different structural materials are also used in the test model, i.e., three different steel grid shell structures are used in three units and an aluminum alloy grid shell structure is used in one unit.

5.2. Joint system

The theoretical shape of FAST[1] reflector is a spherical surface with 300 m radius of curvature. The deviation of the practical shape from the theoretical shape has direct effects on FAST performances of astronomical observation and deep space survey. High shape accuracy of the reflector surface is a major consideration in the design of the joint system of the reflector supporting structure. The joint system should allow adjustment of the position of the reflector panels, so that the shape of the reflector may be checked and adjusted on a regular basis.

There are a number of practical joint types used in space frames and grid shells. The most common joint types found in practice are Mero joint (bolted solid hub) and ball joint (welded hollow ball). It can not be directly used in the supporting structure of FAST reflector. To meet the FAST requirements, a novel and simple joint system is developed on the basis of investigation and improvement of existing practical joint systems. The joint system comprises structural joint and reflector panel-fixing joint for both steel structures and aluminum alloy structures.

5.2.1 Structure joint

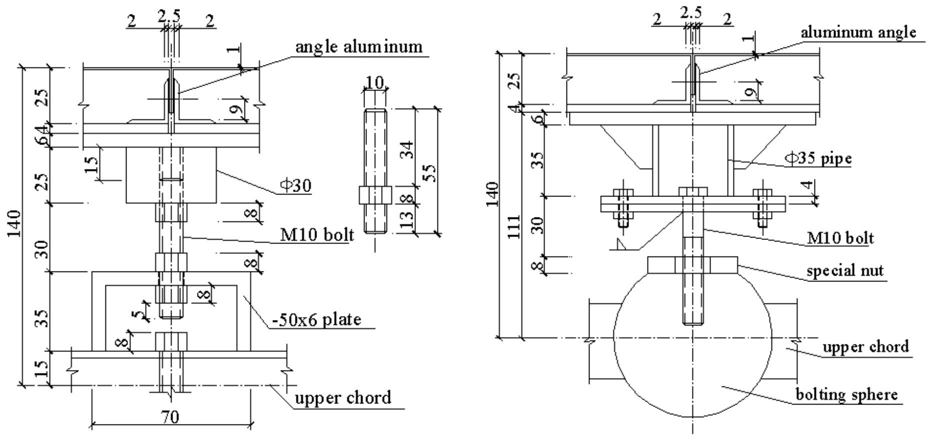
The welded joint has heavy work of site welding. It is not adjustable during structure assembly. The welding deformation is hard to control during construction. Therefore, the welded joint is not suitable for FAST reflector.

The bolted joint has little work of site welding. Most components are prefabricated in factory. The structure members are assembled on site with bolts. This joint type is ideal for FAST reflector. Mero joint[4,5] that was early invented by a German engineer is a kind of bolted joint that is now found widely in space frames and grid shells. The original Mero joint can be directly adopted as lower chord joints of FAST reflector structure. Then it should be improved for the upper chord joints. An adjustable part for controlling the shape of the reflector surface is put on the top cap (facing the reflector sphere center) of the upper chord, shown in Fig.4.

5.2.2 Adjustable panel-fixing joint

The shape accuracy of the reflector is controlled in two steps. The error produced in the structure assembly procedure is controlled through the structure joint system, but it is usually not easy to meet FAST requirement. High shape accuracy is much difficult to reach during structure assembly. It needs a compensation adjustment. The joint system for fixing the panels to the supporting structure must be adjustable. The final error of the reflector surface can be adjusted and controlled through panel-fixing joints.

The adjustable joints for fixing panels on the upper chord joints of the structure is shown below. There are two alternative joints. The first joint shown in Fig.4(a) can be adjusted continuously. The reflector panels can be adjusted exactly to fit the required surface, but its structure is complex. The second joint shown in Fig.4(b) is relatively simple. The reflector panels can be adjusted step by step. The increment of the bolt height within one step is 0.25 mm. The reflector panels can not be adjusted to the exact surface, but they can be adjusted within permission error.



(a) Continuously adjustable joint (b) Step adjustable joint

Fig.4. Adjustable panel-fixing joint

6. Conclusions and suggestions

(1) Double layer grid shell is better for the reflector structure to obtain better spatial integrity, stiffness, reliability.
(2) Steel structure generates larger tangential reactions on the mechanical devices than aluminum alloy structure does. This will increase the cost of the mechanical devices and the servo controlled actuators.
(3) Aluminum alloy structure has many advantages that just meet all the requirements of the supporting structure of the reflector. Although its cost in the construction period is higher than steel structure, its maintenance cost in service stage is much lower. In general, the total costs of these two structural systems are equally matched. In conclusion, aluminum alloy structure should be the best choice.
(4) The shape accuracy is most important for FAST reflector. The joint system of the reflector is critical to FAST working accuracy. The panel-fixing joint system must be adjustable. It makes the reflector accuracy easy to control during construction and in service.

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References

[1] Y.H. Qiu: 1998, 'The Novel Design for a Giant Arecibo-type Spherical Radio Telescope with an Active Main Reflector', *Mon. Not. Astron. Soc.*, **301**, pp.827-830.
[2] China Academy of Building Research: *Regulations for Design and Construction of Space Frame (JGJ7-91)* (in Chinese), 1991.
[3] The Aluminum Association: *Specifications for Aluminum Structures*, The Aluminum Association, USA, 1986.
[4] A. Hanaor: 1995, 'Characteristics of Prefabricated Spatial Frame Systems', *Int. J. of Space Structures*, **Vol.10**, **No.3**, pp.151-173.
[5] C.Q. Zhao, W.X. Liu and H.L. Zhao: 1998, 'Experimental Study on a New Joint of Space Truss', *J. of Shandong Institute of Arch. and Eng.* (in Chinese), **Vol.13**, **No.4**, pp.8-11.