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Structural Design and Analysis of a 50 m Fully Steerable Pulsar Radio Telescope

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Abstract A radio telescope of 50 m in diameter, basically, for pulsar observation, is to work at multi-wave bands among which the shortest wavelength is 13 cm. Proposed is a fully steerable exposed truss structure scheme of the telescope. The design is essentially a wheel-on-track style radio telescope with 6 rollers in three bodies for azimuth drive and support, while two sets of gear wheel for elevation drive. The main reflector is a mesh with crimped stainless steel wire spanned on a “bowl-like” back-up truss structure which is supported by 6 points on its bottom. After discussion of structural design and related dead-load analysis, wind and thermal disturbances are estimated. Particularly, response spectrum seismic hazard is performed with response spectra analysis. The results confirm that the 50 m radio telescope can meet the observational requirements and survive seismic hazard of acceleration of 0.1 gravity with a light and cost-effective structure.

Key words: pulsars: general — telescopes

1 INTRODUCTION

Thanks to the extremely stable nature of the periodicity of pulsar radio, some milli-second pulsars can be observed with radio telescopes for timing service and for crosschecking with atomic clocks (Ni et al. 1994). A 50-m pulsar telescope, as a large radio astronomical facility, will enable Chinese astronomers to extend their research range much wider, say, gravitational wave detection based on long-term observations of pulsars.

As proposed, the radio telescope has an aperture of 50 meter with focal ratio of 0.4, and both primary and Cassegrain foci are employed. The shortest working wavelength is 13 cm, as defines that the reflector surface can not run out of 7 mm (RMS) in any working cases.

As seen in Figure 1, basically, a full truss structure concept is adopted, and the telescope design presented in this paper is a wheel-on-track alt-azimuthal mounting configuration with two elevation gear pairs and three azimuth supporting and driving mechanisms. Bowl-like reflector backup structure supported on 6 points and crimped-wire-meshed reflecting paraboloidal surface are considered for the telescope (Yang et al. 2002). Aided with finite element method software, the design is evaluated by performing dead-load analysis at typical working cases, further wind and thermal estimation is also discussed. Specifically,seismic hazard of the telescope under acceleration of 0.1 g is analyzed by adapting the conventional seismic response spectrum in civil engineering code. It is confirmed that the design meets technical specification very well and exhibits good performance in weight, cost and safety.

2 THE REFLECTOR STRUCTURE DESIGN

The backup structure has a profile like a bowl, refer to Figure 1, outwards from center, it consists of four circumferential ring groups, the inner ring, the support ring, the secondary outer ring and the outer ring.

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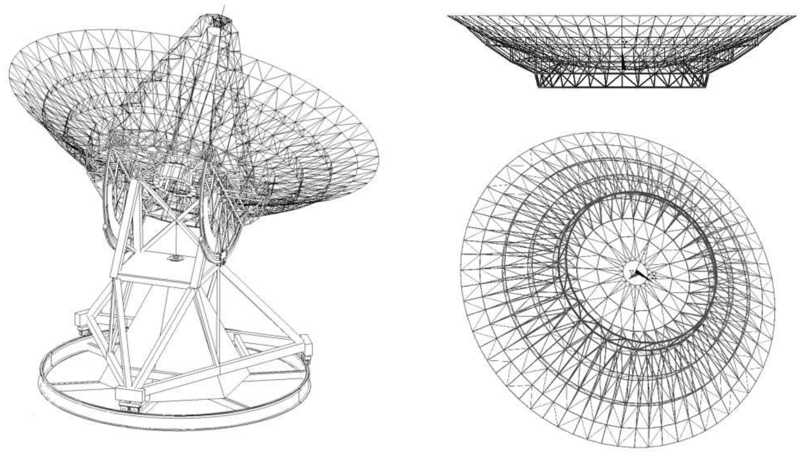

Fig. 1 Left: The 50-m radio telescope. Right: The backup bowl.

From the theory of reflection of radio wave and design tolerance of paraboloidal reflector, generally, the tolerance of reflector surface can not run out of one sixteenth of the shorted observed wavelength, and normally, it requires higher precision for inner part of aperture while coarser for outer aperture, particularly for reflector edge region, the precision tolerance can be much more looser thanks to the radio field over the reflector aperture has much weaker distribution towards reflector edge (Zhou et al. 1994). As permits and drives light flexible design for outer ring of telescope backup structure. Seeing these facts, among the four rings of the 50 m telescope, the inner ring and the outer ring are deliberately designed with single layered trusses. For the inner ring is smaller, 18 m in diameter, with better outer circumferential support condition, single layer truss is promising to achieve necessary accuracy. For the outer ring, it may deform more but still within global tolerance of the reflector. Different from the existing large truss radio telescopes in China, the above features drives the 50 m reflector to have a lighter structure and hence a lower cost. Particularly, the support ring is a triangularly cross-sectioned circular truss under which there is an auxiliary conic girder ring so as to form the strengthening "bowl bottom". The elevation axis and the big gearwheel pairs are to be connected only to the bottom ring but separate from the backup structure, such that the backup structure is settled on a six-point support system.

The reflecting surface is to be a wire mesh with ø0.55 mm crimped stainless steel wire easily available on industrial market. In order to enable observation at the shortest waveband of 13 cm, the wire mesh size of 8 mm is patterned for the inner aperture within diameter of 25 m while 15 mm for the outer part. In addition to its inherent feature of corrosion proof, crimped stainless steel wire is securing the mesh joints against movement and helpful to give a more even mesh than plain wire is. The sub-meshes are spanned on lightweight steel frames as panels which are normally shaped in trapezoid or triangle with sides of about 3 m.

The gravity deflection of feed quadrapod is directly related to the spanning angle of the legs along gravity plane, the larger is the angle, the less is the deflection and vice versa. In this design scheme, the quadrapod legs, stretching through the reflecting meshed surface without contact with wires, are rooted on the four vertexes/points of a rectangle instead of a traditional square. Actually, the four points are the very four ends of the elevation rack gearwheels attached on the bottom ring of the reflector backup structure.

3 THE DRIVING SYSTEMS

As alt-azimuthal mounting configuration is adopted, the driving system consists of the elevation driving system, the azimuth driving system and the alidade.

Refer to Figure 2 left, the body of the both rack gearwheels are a halved circle of spokes and braces. Each of the two big gears is connected to the bottom of the backup structure bowl only on the two ends.

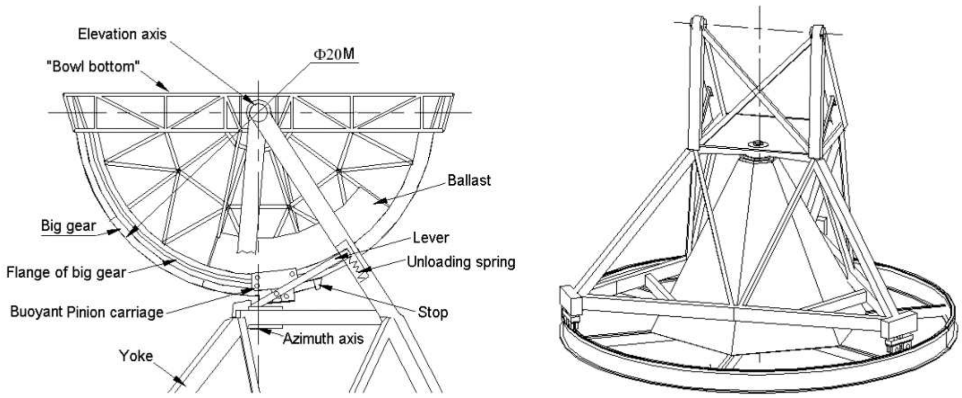

Fig. 2 Left: Buoyant elevation driving system. Right: the three-point-driven alidade.

Reversing torque motor technique is used to eliminate backlash. For telescopes as big as 50 m in diameter with big driving gear of 20 m, it is of utmost importance to beware of gravitational deflections in the meshed gears due to gravity load as well as heat effect from the sun radiation. Therefore, in order to keep the gears in well meshing state, a buoyant pinion carriage elastically unloaded with spring is designed for each of the big rack gears. The elevation shaft is essentially a truss structure that is comparatively pliable and not able to structurally/rigidly synchronize the two separated gear drives on the two ends of elevation shaft. Instead, the task of synchronizing the two sets of gears is fulfilled by electronic control effort with elevation axis encoders. Refer to Figure 2 right, different from large traditional radio telescopes in China, the azimuth driving unit is actually friction driving system. It is a bogie combination of three couples of rollers orbiting on a track of 35 m in diameter and centered by a pintle bearing. The three couples are installed on the three corners of the equilateral-triangle-based alidade. For the sake of compactness and stability, the alidade is designed as two parts, the upper triangular yoke and lower triangle-based platform (Kärcher 2000). The upper yoke arms stretch into between the two elevation drive gearwheels and make a big space for cassegrain feeds and other backend instruments. To minimize wind turn-over moments and to directly transfer lateral loads to the concrete foundation, the pintle bearing is elevated as high as possible to the upper square platform of the alidade. The structure configuration has realized the elevation axis to be perpendicular to and intersectant with the azimuth axis, as makes the whole telescope well balanced without need of extra counterweight and the three azimuth driving units burden even vertical loads. It is seen also that the three-bogie azimuth drive scheme and compact alidade design introduce excellent structural performance with lighter wight and lower cost to the 50 m telescope.

4 STRUCTURAL ANALYSIS

4.1 Dead-load Analysis

The full telescope is modeled with finite element method (FEM) software at two extreme working positions to evaluate dead-load effect due to its own dead weight. See Figure 3, virtual shell with zero density and zero young’s modulus is paved over the reflector to facilitate vivid result plots. In the zenith position, the maximum gravitational deflection occurs at the edge of the dish, it is about 11 mm (RMS 1.3 mm). In the position of elevation angle 15 degree, the value turns to be 13.7 mm (RMS 1.5 mm). From the deformation contours, the effect of a rigid-body rotation is present, and thanks to the predictable linear elastic telescope system, it is possible to be partly compensated by elevation rotation and to find a best paraboloid with least square fit.

4.2 Wind and Thermal Effect Analysis

The required operational wind speed is specified as $17\,\mathrm{m\,s^{-1}}$ and survival wind2 speed $40\,\mathrm{m\,s^{-1}}$. By assuming equivalent wind loads are evenly distributed onto the nodes over the reflector surface, four cases of

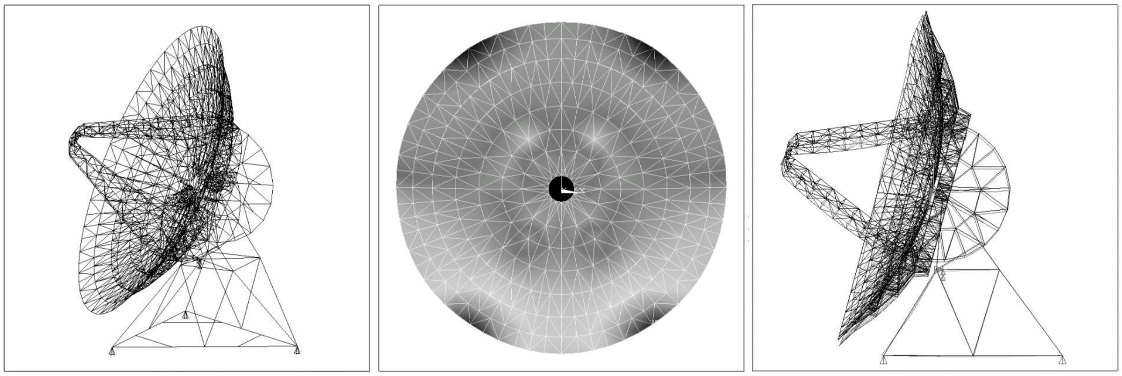

Fig. 3 Left: The FEM of the 50 m telescope (pointing to 15 deg.). Right: results under dead-weight.

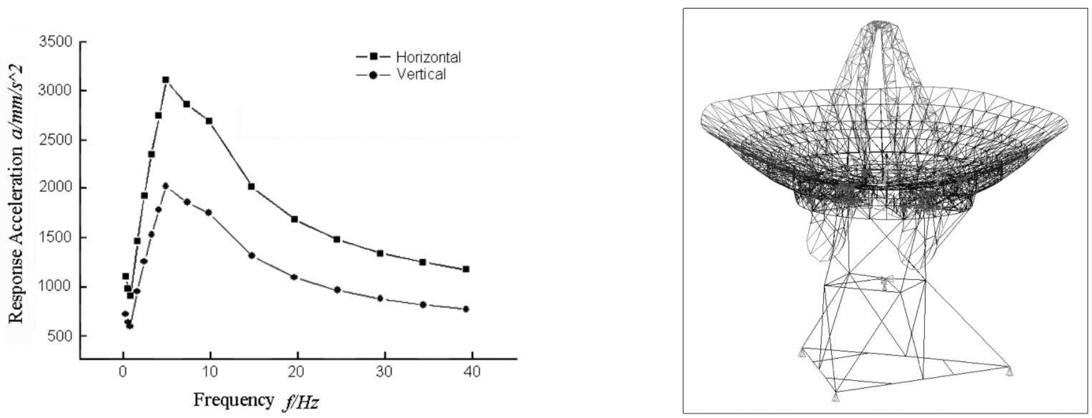

Fig. 4 Left: Acceleration response spectra. Right: Seismic displacement response.

load are calculated at the two extreme working positions: wind comes from the front of the reflector dish and wind comes from the side of the dish, respectively. With effect of gravity included, the RMS deflection over the reflector is 2.5 mm which implies that the telescope is able to work well with full aperture under the required operational wind speed. Further calculation indicates that to survive in the wind of $40\,\mathrm{m\,s^{-1}}$, the reflector dish has to be elevated towards zenith to minimizing wind load and consequent turn-over moment.

As for an exposed large radio telescope, sun radiation is the major heat generator during daylight observation, while during dusk towards night, the emission of the telescope structure to cold sky again affects observation, as mainly deteriorates the pointing accuracy of telescope. Nevertheless, taking advantage of the slow temporal nature of thermal effect on the telescope structure, it is possible to correct the pointing error by alt-azimuth control electronics in real-time mode.

4.3 Response Spectrum Seismic Analysis

Due to suddenness and devastation of seismicity, and also due to delicateness of telescope, seismic hazard analysis is of great importance for large astronomical telescopes (Yang et al. 2004). In response spectrum analysis of seismic hazard, acceleration response spectra are most frequently used, which is related to damping ratio of measuring/recording system. Normally, the design acceleration response spectra in conventional construction code are given with damping ratio of 0.05. While damping ratio of a astronomical telescope is 0.01, therefore, it is necessary to adapt the spectra. According to the design code, the technically required design acceleration, 0.1 g, is approximately equivalent to that generated by seismicity of magnitude 7. And additionally, an importance factor 1.3 is chosen for telescope analysis as special engineering. Finally, the adapted acceleration spectra are shown in Figure 4 left. The seismic analysis is conducted for the telescope in its stowed state, i.e., pointing to zenith. Maximum seismic displacement response is 36.5 mm, occurring at the quadrapod, and maximum seismic stress response is 212 MPa, occurring at the four lower ends of the quadrapod, which is though safe within the allowable stress limit, it is practical to be mitigated to a much lower level by local mechanical design.

5 CONCLUSIONS

The design scheme of the 50 m pulsar telescope features in the lightweighted bowl-like backup structure supported by six points at bottom. With unloaded buoyant pinion carriages for elevation driving system, it solves structural deflection due to gravity and thermal effect. The quadrapod is laid out with rectangle-based support to minimize gravity deflection. Special alidade layout is introduced with three azimuth driving units, which lowers telescope cost and structure complexity. The results of dead-load, wind and thermal analyses, and of further seismic acceleration response spectrum analysis confirm that the design of the 50-m radio telescope exhibits excellent performance within technique specification.

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