Design and analysis of cushioning packing box for Chinese Small Telescope Array

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ABSTRACT

Dome C and A of the Antarctic plateau is considered to be the best astronomical site on the earth because of extremely cold, dry weather, low wind speed and atmospheric turbulence overhead. CSTAR (Chinese Small Telescope ARray), which is composed of four small telescopes with 100mm clear aperture, has been accomplished in August and shipped to Antarctic at November 2007. Then, from the Zhongshan station, Chinese traverse team sledged it by snow tractor to Dome A through about 20 days hard trip and erected in January 2008. In this paper, the vibration proof design of packing box of CSTAR is introduced based on vibration theory and the analysis of power spectrum density is done to verify parameter selection. Finally, transport experiment is done to prove that packing box is suitable for the inclement and various transport condition.

Keywords: Antarctic telescope-Dome A-Packaging dynamics-Finite element analysis

1. INTRODUCTION

Now South Pole and Dome C are considered the better sites for astronomy than existing mid-latitude sites, with exceptional coldness, low sky brightness and low content of water vapor. Dome A, the highest point on the Antarctic plateau, is expected to experience colder atmospheric temperatures, lower wind speeds, and thinner turbulent boundary layer, so could outperform Dome C in many aspects for astronomical observations.

The Dome A site was first visited in January 2005 via an overland traverse, conducted by the Polar Research Institute of China (PRIC). PRIC plans to return to the site to establish a permanently manned station within the next decade. Chinese Small Telescope Array--CSTAR (Fig.1), which consists of four individual telescopes each of 14.5-cm aperture and a field of view of 4.5°×4.5°, is to be used for transient searches and monitoring at Dome A. Each telescope is attached to a 1K × 1K CCD with frame transfer readout capabilities. This set of telescopes has been shipped to Antarctica in November 2007, and installed at Dome A in January 2008 by Chinese traverse team. Astronomers have got the images sent back by CSTAR now and start analysis of data.

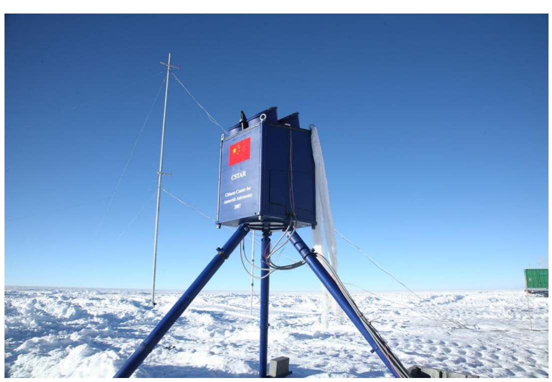

Figure 1 CSTAR at Dome A

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From Chinese workshop to Dome A, CSTAR has to be transported by truck, ship and sledge successively and endure change of temperature about from 20 to -40℃. During the thousands miles trip, it also was suspended by crane, helicopter and other hoist. On the other hand, because of extremely environment of Dome A, CSTAR is transported totally with optical components and expected to work with very limited adjustment in situ, it demands very elaborate packing to prevent mirror fracture and misalignment. A detailed design, analysis and test of cushioning packing box for CSTAR are introduced in the following section.

2. DYNAMIC MODEL OF CUSHIONING PACKING SYSTEM

Vibration and shock is the main reason to cause damage on product in transportation. In the case of resonance vibration, damage usually happens while resonance acceleration exceeds the limits. It's particularly important to optical precision instruments such as telescope. In order to reduce the impact from outside, product needs to be isolated from the support while transportation. Here, product is considered to be rigid, the mass and flexibility of the packing box is also neglected. Thus, the linear model of single degree of freedom is shown as Fig.2.

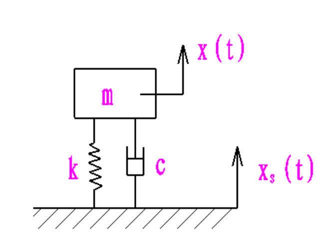

Figure 2 Linear model of single degree of freedom

In the research of practical cushioning packing system in transportation, interference displacement is always recognized as the typical half-sine wave. It is given in the form: $x_s = a\sin(\omega t)$

According to Newton's Law of Motion, the differential equation of vibration of the single degree system is given by:

$$m\ddot{x} = -c(\dot{x} - \dot{x}_s) - k(x - x_s)$$

Where m is the mass of the system, c is the damping of the system, k is the stiffness of the system and x is the generalized coordinate of the system.

The stable solution of the above differential equation is following formula: $x = B\sin(\omega t - \phi)$

Where,

$$B = a\sqrt{\frac{k^2 + c^2\omega^2}{(k - m\omega^2)^2 + c^2\omega^2}} = a\sqrt{\frac{1 + (2\zeta\lambda)^2}{(1-\lambda^2)^2 + (2\zeta\lambda)^2}} ,$$

$$\phi = \arctan\frac{mc\omega^3}{k(k - m\omega^2) + c^2\omega^2} = \arctan\frac{2\zeta\lambda^3}{1 - \lambda^2 + (2\zeta\lambda)^2} ,$$

Where,

ω is the angular frequency of the system;

ω_n is the natural frequency of the system, $\omega_n = \sqrt{k/m}$;

λ is the ratio of the frequencies, $\lambda = \omega/\omega_n$;

ζ is the ratio of damping, $\zeta = c/2m\omega_n$;

Usually, the acceleration response is used to evaluate the influence of vibration; it can be derivative by stable solution of displacement.

3. DESIGN OF CUSHIONING PACKING BOX

CSTAR has been transported to Dome A in the inclement and various transport condition on the whole journey. Therefore, the cushioning packing box for CSTAR is required to be able to resist long-term vibrations with low frequencies caused by waves from the oceans. On the other hand, it is also asked for suitable elasticity against the random shock with high amplitude on the snow way to Dome A. The design and analysis of the cushioning packing box is based on the above two main points.

CSTAR is composed of two parts: mirror box and tripod. Mirror box contains four tubes, support legs and box (Fig. 3). Due to the long and complicated trip, packing box of CSTAR needs not only vibration isolation and cushioning but also waterproof, fireproof and anti-corrosive. Vibration isolators have many types such as air damping shock absorber, rubber, hydraulic and metal spring. For different size and weight of product, the distributions of isolator also have different methods. According to volume of CSTAR, the tripod and mirror box were divided into different packing box. The tripod just needs normal wooden box and mirror box should be packed more carefully. Considering inclement whether on Antarctica, air damping and hydraulic is not suitable for us; on the other hand, CSTAR is not so big and heavy, hence, metal tension spring is used to hang mirror box of CSTAR.

We designed outside frame and sealed inside case through elastic connection to protect mirror box of CSTAR (Fig. 4). Firstly, the mirror box of CSTAR is put into a steel case, the space between mirror box and steel case are chocked up by vibration-proof rubber so mirror box has no any shake relative to steel case. Then steel case is covered and bolted, the gap between cover and case is sealed by silica gel to resist ingress of moisture and water spray. And then whole steel case is suspended on outside frame by eight canting pull springs so it can endure vibration of any direction. Finally, some damping block made by sponge is embedded between inside case and outside frame to resist unexpected shock.

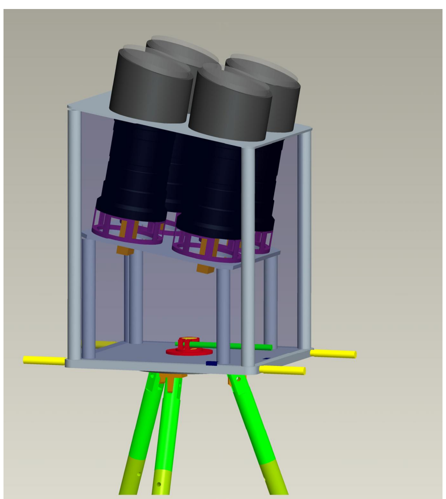

Figure 3 Mirror box of CSTAR

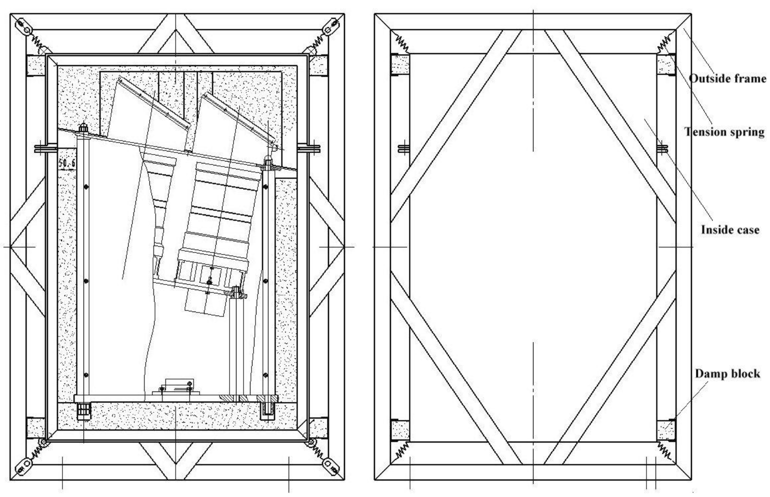

Figure 4 Cushioning packing box of CSTAR

Spring is key of design of packing box; proper spring can absorb vibration and consequently protect precise instruments during transportation. Either too stiff or flexible ones are useless. Stiffness of tension spring can be calculated by following formula:

$$k = \frac{Gd^4}{8nD^3}$$

K: Stiffness of tension spring;
G: Coulombs modulus, Mpa;
d: Diameter of materials;
D: Pitch diameter of spring;

Considering self-weight of mirror box, the upper spring should be stiffer than inferior ones. Consequently, elastic force of upper spring equal sum of inferior ones and weight of mirror box under steady state. In this way, both upper and inferior springs have suitable stretch so active for vibration-proof. Two materials, spring steel and stainless steel wire is used to twist tension spring. After probation and test, stainless steel wire is selected because of corrosion proof and good performance under low temperature.

4. PSD ANALYSIS OF THE CUSHIONING PACKING BOX

4.1 Model of the cushioning packing box

Size of the cushioning packing box is shown as Tab.1 and finite element model in ANSYS is shown as Fig.5. In order to keep the accordance between the packing box and the model in analysis process, the inside case is built with element Solid 45, the outside frame is built by element Beam 188 with L section and the springs between the inside case and the outside frame are built by element Combin 14 (Solid 45, Beam 188 and Combin 14 are the selectable elements in ANSYS).

Table 1 Size of the packing box

	Size/*mm*	Weight/*kg*
Inside case	670×630×980	250
Outside frame	1030×970×1450	96

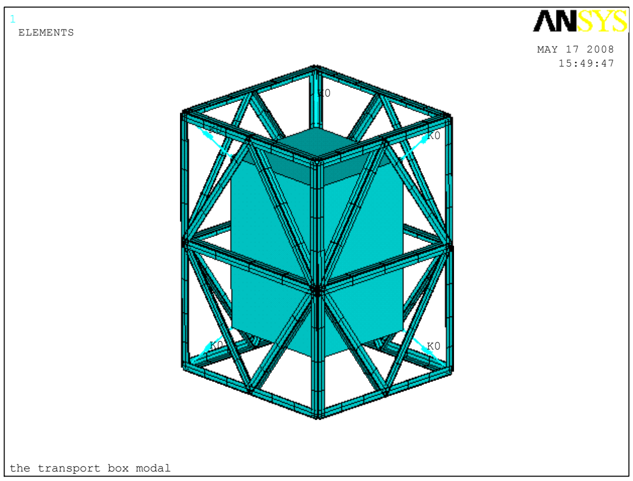

Figure 5 Finite element model of the packing box

Generally speaking, the anti-vibration result of the system is performed better while the natural frequency of the system f_n is lower. However, it is easier to vibrate under outer excitation if f_n is too low. Thus, the suitable range of f_n is between 2Hz and 6Hz. As noted above, based on the equation $f_n = \frac{\omega_n}{2\pi} = \frac{1}{2\pi}\sqrt{k/m}$, the range of the stiffness of the system listed as follows: $40 \le k \le 355$ (*N/mm*), where $m = 250$ *kg*, the total weight of the inside case. After calculation, the stiffness of the upper ones is 30*N/mm*, and of the inferior ones is 15*N/mm*.

4.2 Modal analysis

Modal analysis is the first step in a dynamic analysis, as the response of the structure to different frequencies must be determined. It is crucial in understanding how the structure will respond during vibration, and to prevent premature failure. Natural frequency and modal shape is the important preprocess in PSD analysis. In ANSYS, the Block Lanczos method is chose because of high precision and rapid calculation speed. The first three steps of natural frequencies and modal shapes are listed in Tab.2 and shown as Fig.6.

Table 2 Natural frequencies and modal shapes

Set	Natural frequency/*Hz*	Modal shape
1	2.121	swing forward and backward
2	2.245	swing leftward and rightward
3	2.951	swing upward and downward

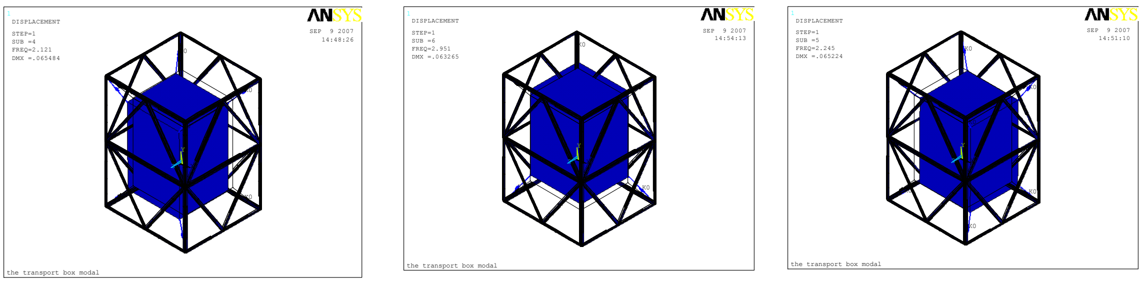

Figure 6 Modal results from the first to the third (from left to right)

From Tab.2 and Fig.6, it comes to the conclusion that the stiffness of springs is appropriate and the design of the cushioning packing box for CSTAR is rational.

4.3 PSD analysis

Random vibration (PSD) analysis is a qualitative analysis. The result of PSD analysis only stands for the possibility of occurrence under a particular value. In this paper, acceleration power spectral density (see Fig.7) is considered as a base excitation coming from truck, which was obtained from the vibration measurer in the vertical direction of the packing box. Through measure of vibration of truck, which runs in normal suburb road with 40-60 *km/h* speed, excited acceleration spectrum is acquired and shown in Fig.7, the unit of horizontal axis and vertical axis is *Hz* and $(m/s^2)^2/Hz$. The result of PSD analysis is probability statistics, which includes displacement, velocity and acceleration of each node and stress of each element within 1σ range. Every parameter is supposed as standard Gaussian distribution and 1σ response is the RMS value in Gaussian distribution. The vertical acceleration PSD response to the random vibration is mostly concerned, hence the corner point of the packing box is picked out with No.270, and the vertical acceleration response is shown as Fig.8. It can be concluded that PSD response is a narrow-band spectrum nearby 2.9*Hz* that is the natural frequency of system in vertical direction.

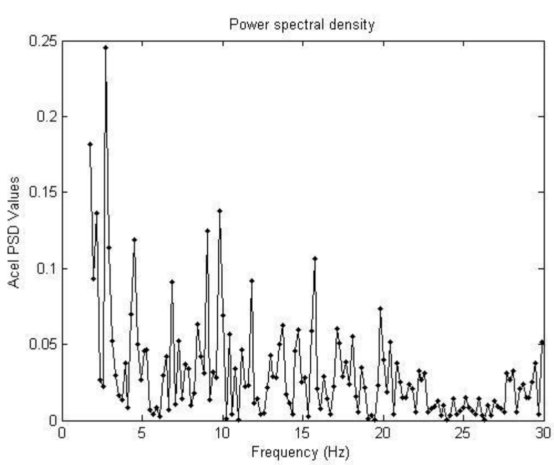

Figure 7 Y direction input PSD

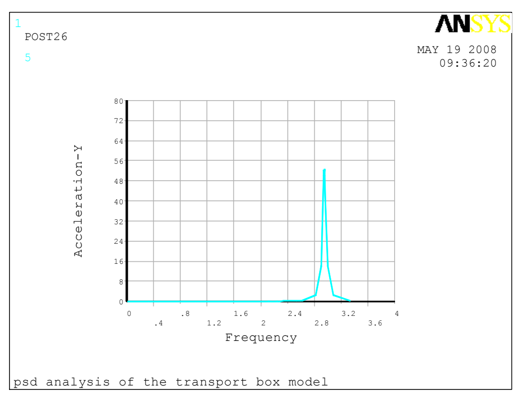

Figure 8 PSD result of node No.270

5. TEST AND TRANSPORTATION OF PACKING BOX

5.1 Transport experiment

With this cushioning packing box, experiment of vibration was done at September 10, 2007. During experiment, the packing box was fixed on the truck in speed of 40~ 60 *km/h* in suburb. The peak value of acceleration of inside case in vertical direction, which is the direction in which the highest loads are believed to typically occur, is measured and listed in Tab.3. The vibration meter is TV300 of Time group incorporation and sample interval is about 5s.

Table 3 Sample data of acceleration (m/s^2)

0.67	0.41	0.38	0.62	0.51	0.31	0.62	0.38	1.09	0.94
0.76	0.66	0.39	0.32	0.26	0.37	0.33	0.30	0.22	0.26
0.23	0.84	0.61	0.60	0.51	0.39	0.32	0.36	0.59	0.34
0.39	0.47	0.68	0.29	0.49	0.63	0.46	0.43	0.64	0.46
0.65	0.32	0.72	0.57	0.58	0.58	0.69	0.50	0.71	0.46
0.40	0.72	0.62	0.44	0.46	0.40	0.63	0.62	0.50	0.60
0.94	0.98	0.58	0.38	0.30	0.28	0.51	0.75	0.51	0.47
0.52	0.26	0.56	1.33	0.46	0.63	0.59	0.49	0.48	0.35
0.59	0.41	0.46	0.53	0.60	0.68	0.31	0.34	0.40	0.67
0.82	0.47	0.46	0.47	0.23	0.30	0.21	0.41	0.54	0.59
0.41	0.31	0.61	0.33	0.83	0.40	0.68	0.77	0.49	0.31

From the table above, the maximal acceleration of the inside case is 1.33 m/s^2. It is much smaller than the empirical safety value-1*g* (*g*, the gravity acceleration). Thereby, the stiffness of the springs is proved to be suitable, so as well as the design of the packing box.

5.2 Transportation and Installation

After CSTAR had been split into two parts and packed in Nanjing Institute of Astronomical Optics and Technology (NIAOT), it was been conveyed to Polar Research Institute of China, Shanghai by truck at October 2007. The packing box was put into standard container and fixed by adjacent box and wood block (Fig.9). At the bottom of outside frame, four caoutchouc pads are glued to vibration proof and anti-slip. With about 13000 sea miles voyage including hundreds sea miles ice-break, the Xuelong ship carried container to Chinese Antarctic Zhongshan Station at Dec. 2007. The traverse team, consisted of 17 members and transported by an over-ice tractor convoy, arrived at Dome A on 11 January 2008, after about 1300 km journey taking 22 days. The expedition spent 15 days at the Dome A site, during which time CSTAR was assembled and tested, before the team returned to the coast. Figure 10 to 12 show state of transportation and assembly.

Complicated transport condition with road, sail and sleigh did no any damage to mirror box and optical mirror, furthermore, subsequent installation and calibration indicated that CSTAR could be started and operated successfully. It means that cushioning packing box of CSTAR have a good performance during long and hard journey. Two vibration meter are used to record data of vibration and shock on the way from coast to Dome A, it will be very useful for next simulation and analysis. When the expedition return back china, CSTAR start to work and send observation data back with darker and darker sky.

Figure 9 CSTAR in container

Figure 10 Swing by helicopter

Figure 11 CSTAR and jerrican on sleigh

Figure 12 lifting by CAT

6. CONCLUSIONS AND PROSPECT

Compared with the PSD analysis result, the measure result of vibration test matches well. The error mainly comes from the error of vibration meter as well as measuring method and interference of environment. The design of packing box is shown to be suitable based on the analytical and testing data. Finally, CSTAR is transported to Dome A safely under the protection of the packing.

For the remote and hard site such as Dome A, precise optical instruments need more careful packing and handling than normal. Even it has become the most important factor for Antarctic telescope. Large sea wave, lifting and dropping, snow bump and other unexpected shock, all of them possibly result in failure of instrument. At the same time, extreme environment and inaccessibility in winter make it very difficult to assemble and maintain telescope at Dome A. Because CSTAR is relatively small device, more test and analysis, especially for shock during icebreaking and sledge trips, still need to be done for next large telescope. Meanwhile, considerate and gentle handing in each step also is critical factor for safe of instruments.

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