Stability analysis of optomechanical system in SGII facility

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ABSTRACT

In SHENGUANGII (SGII) facility, the optomechanical system is the optics and optomechanical support hardware which necessary to transport the laser beams through the system from the laser drivers to the target. In order to satisfy the laser beam accurately positioned, the system must provide a stable platform for the optical elements before and during a shot. While the ambient vibration such as thermal impact, ground borne, acoustic and noise usually disturbs the stability of the system when the facility on working. This paper put forward the concept of system stability, and the method of test and vibration isolation control presented. The finite element analysis has been used to analysis the stability of the typical system. Base on the result, the working performance of system can be confirm, even the stability of SGII facility in future long-time work can be estimated, also the key points of stability design for the important parts and system can be suggested. It offers design guidance on the next upgrade of SG facility design and guarantee for the procedure of facility's precision. This information also can be used to the structure and system of the similar facilities.

Keywords: ICF, SGII facility, Optomechanicl system, stability, vibration isolation, structure design

1. INTRODUCTION

SGII facility is a unique high power Inertial Confinement Fusion (ICF) laser facility which is running in China, it is an all-round high-tech project which integrated the most advanced technology of our country including optics, fine mechanics, energy sources and computer control system. Fig.1 is the 9th beam of SGII facility. In the facility, the optomechanical system is the optics and optomechanical support hardware which necessary to transport the laser beams through the system from the laser drivers to the target[1]. As the support hardware, the optomechanical system must assure the position on target with a very high degree of accuracy. In order to satisfy the facility requirement for optical system positioning, the optomechanical must provide a stable optical support structures for the optical elements and the accuracy of alignment process before and during a shot[2].

Considering in the really condition, the ambient vibration such as due to thermal impact, ground borne, acoustic and noise influence the stability of the system when the facility on working. All these would weaken the accuracy of alignment process, influence the stability of the laser system, induce laser excursion, structure drift, and ultimately influence the accuracy of the target. To guarantee the accuracy of target position, each large scale ICF facility set the positioning error tolerance, and the total tolerance of laser system of SGII facility is 25*u*rad[3].

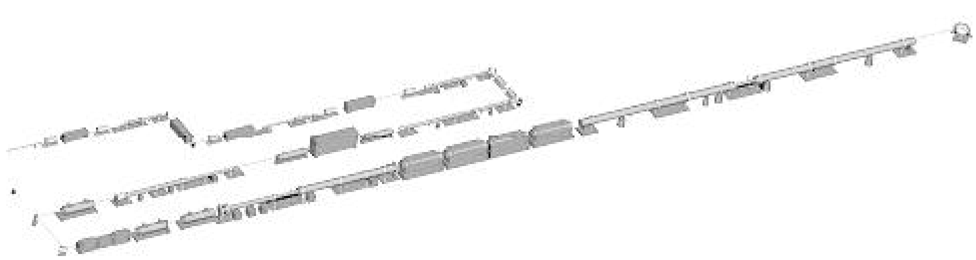

Fig.1.The 9th beam of SGII facility

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For the discussion in this paper, the concept of system stability put forward, and the method of test and vibration isolation control presented. Finite element analysis has been used to analysis the stability of the typical system. Base on the result, the working performance of system can be confirm, even the stability of SGII facility in future long-time work can be estimated, also the key points of stability design for the important parts and system can be suggested. It offers design guidance on the next upgrade of SG facility design and guarantee for the procedure of facility's precision. This information also can be used to the structure and system of the similar facilities.

2. CONCEPT OF SYSTEM STABILITY

For a system, stability is a basic requirement for the system function, which including space stability and time stability. Space stability fulfils by the system framework and ensures the time stability. While time stability determines by the system natural frequency, and the system must have high enough stiffness to ensure the stability of system. To any system, the measure characteristic of the requirement stability design is the natural frequency, and in ICF experiences, the characteristic quantity usually is displacement. So usually, we use the compliance, which is a measure of the susceptibility of a structure to moves as a result of an external force, to measure dynamic of a vibrating structure. Compliance curves show the displacement amplitude of a point on a body pre unit force applied, as a function of frequency. Expresses as formula[4]:

$$C=\frac{|x|}{|F|} \tag{1}$$

where C denoted the compliance, $|F|$ is the magnitude the applied sinusoidally varying force , $|x|$ is the magnitude of resulting amplitude of the displacement.

For a simple system, the transfer function is:

$$\frac{x}{F}=\frac{1}{\sqrt{(k-M\omega^2)^2+(c\omega)^2}} \tag{2}$$

where M is the mass being moved, c is the damping, k is the stiffness, and ω is the frequency of the applied force F. Use the Eqs.(1) and Eqs.(2), the compliance C can be expressed as:

$$C=\frac{1}{\sqrt{(k-M\omega^2)^2+(c\omega)^2}} \tag{3}$$

From the Eqs.(3), the relation of the compliance C and stiffness k can be know. To a system, when the system mass, damping made certain, the compliance is dominated by the stiffness.

Base on the above analysis, to the optomachanical system, the stability is determined by the system natural frequency which can be achieve through a combination of facility design, optics support structure design, and passive damping. To assure each laser beam is successfully positioned on target, the error which due from the system structure should be smaller than the positioning error stability budget. In the ICF experiences, structure drift is the major contributor to the error summation of the beam position on target. Conditions that can cause structure drift include ambient vibration input, wind fluctuations, thermal variations, acoustical input, and HAVC pressure fluctuation. The stability allocation for the structure response due to different input loads is specifies as follows[5~6]:

$$\Delta_{Drift}=\Delta_{structural}+\Delta_{thermal\ Transient}+\Delta_{Contingency} \tag{4}$$

where Δ_{Drift} is the total budget for drift of the structure, $\Delta_{structural}$, $\Delta_{thermal\ Transient}$ and $\Delta_{Contingency}$ is the allocation portion caused by structure, thermal and contingency respectively. In the system, the stability is connection with the time and the requirement of system stability is provide a stable platform in during a period of time. So the Eqs.(4) can be expressed as:

$$\Delta_{Drift}(t)=\Delta_{structural}(t)+\Delta_{thermal\ Transient}(t)+\Delta_{Contingency}(t) \tag{5}$$

The compliance of the structure can be understand the mass point oscillate in the circle of the radius $\Delta_{Drift}(t)$. To the facility, the stability requirement is sum of the compliance of each structure no more than the total budget at one point time. In facility, the system stability is the basic guarantee for the procedure of facility precision, and the total target error budget of main laser beam system is 25*u*rad[3].

3. SYSTEM STABILITY TEST AND CONTROL

To confirm the stability of optomechanical system in SGII facility, the test should be taken. It not only can be estimated the stability of SGII facility in future long-time work performance, also can verify the result of numerical simulation. Base on the test result, some control methods should be taken to attenuate the amplitude which due from the ambient vibration. The following introduce the test which use in SGII facility and some control methods which widely used in vibration isolation control.

3.1 System stability test

For a system, the stability can be use the system stiffness as the characteristic quantity. So usually, experimental modal analysis would be undertaken to determine the modal parameters (frequencies, damping factors, and modal vectors) of linear, time invariant system. The transfer function that defining as the measure of response of a system to a given input also can be obtained using a digital signal analyzer.

In SGII facility, experimental modal analysis is undertaken using the "China orient Institute" vibration test system, and the layout measurement system in Fig.2. The exciter such as a hammer excites the signal on the test object, then transducer pick up output response. The power amplifier uses to strengthen the small signals generated be the transducers so that they can be fed to the analyzer for measurement. The role of the A/D converter switches the analog signals to digital signals for computer processing. In the computer, the special analysis soft processes the signal to get the system parameters.

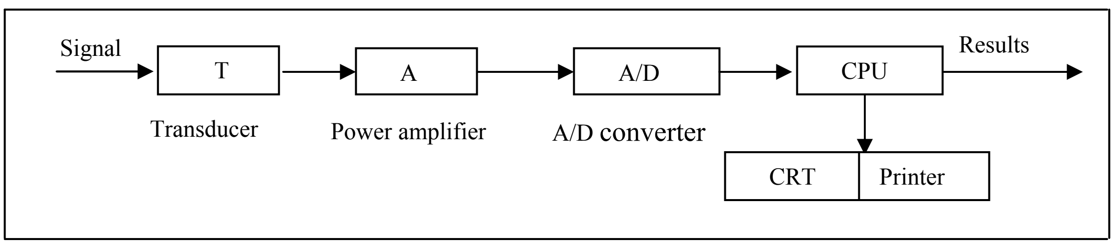

Fig.2. Procedure of experimental model test

From the test data, the system natural frequency can easily obtain. To evidently show the system stability in really application, compliance curve usually use from the data processing. It not only more easily reflects the system vibration dynamic character, also can show the structure resonant frequencies and its amplitude at resonant. With other information, compliance curve can also make a reliable estimate of how a particular system with perform in your application[4]. Fig.3 is experimental compliance curve of a tabletop which dimension 900mm×600mm×50mm,and freely suspended when testing. The dashed curve is the idea rigid tabletop line. From the figure, the natural frequency of this tabletop is about 295Hz. It is fairly high and can provide a stable platform for facility optical elements. To some high precision optical position system, some vibration control methods should be taken to satisfy the system requirement.

3.2 Vibration isolation for stability

The aim of vibration control is to damp vibration and reduce noise to push the system resonance to a higher frequency and lower amplitude. According to have a source or no source, the vibration isolation control can be classed the passive vibration isolation and active vibration isolation. There are three passive vibration isolation approaches to vibration isolation. The first approach to vibration isolation is to reduce ambient vibration and acoustic noise from external sources. The second one is to increase the system rigidity to avoid the resonance. The last one is to use the damp to attenuate the resonance amplitude.

In SGII facility, the location of laboratory is on a vibration isolation concrete floor to weaken the vibration source to attenuate the resonance. The damp material has the character of consuming and transfer energy that usually used on the optomechanical system. If a substructure cannot meet performance specifications, an increased value for the system damping can be used to reduce the relative motion between optical components on the system.

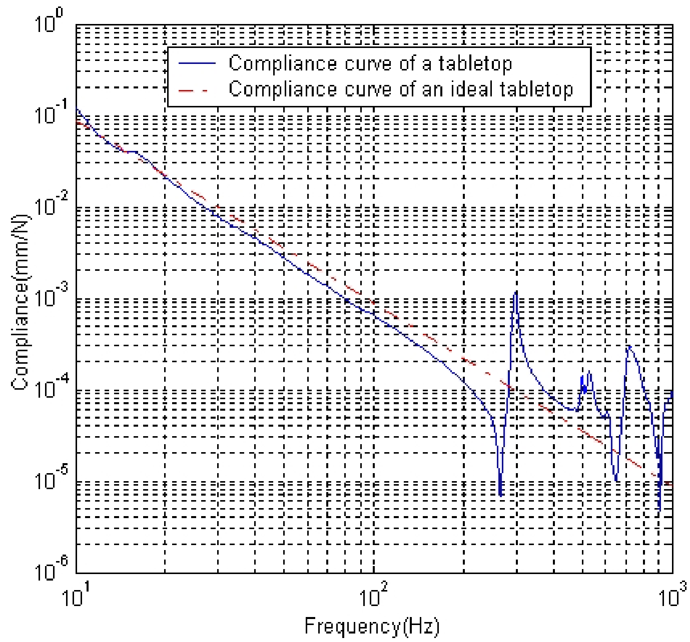

Fig.3. Compliance curve of an aluminum honeycomb core tabletop

Although, the passive isolation control methods mentioned above can satisfied the most optomechanical system which the requirements of precision is general high and attenuate the vibration resonant amplitude mostly. For some high precision positioning systems, such as interferometer positioning system, synchrotron radiation positioning, the stable requirement demands more strictly range in the low frequency and ultra-low frequency. So the active isolation control methods are adopted to satisfy the requirements. As to active vibration isolation, the different algorithm of active isolation control would get different effect, so selecting the good algorithm of active control is the most important point in active control. Sometimes, hybrid control has been taken to achieve wanted control.

4. STABILITY ANALYSIS OF TYPICAL ELEMENTS

The optomechanical system in SGII facility can be classified two types, the foundation structures and optics element. The foundation structure includes sub-truss, beam path tubes, fix mechanism and other structure about vacuum, water, energy and gas equipments. These type structures usually one-time assemble, fix and adjust[7]. The optics element includes any component necessary to transport the laser beams through the system from the laser drivers to the target. In order to overall confirm the system stability, the typical foundation structure optical table and the main important optical element spatial filter and its system carry out the numerical simulation. And other typical systems take the modal test. The results can guide the future design of the systems has typically been controlled by stability in order for the large laser system to meet its performance for alignment and positioning.

4.1 Optical table

An optical table is support structure in SGII facility which provides platforms for slab amplifiers, spatial filter and other optical equipments. Fig. 4 is sketch of an optical table with a honeycomb core between the bottom and top skin. In order to provide a rigid platform for high precision experiments and system, they are designed to eliminate errors caused by relative motion between optical components in the beam path. So table rigidity is the primary consideration in optical table. The table rigidity can be quantified in terms of static or dynamic rigidity. Static rigidity describes the ability of an optical table to resist the changed load distribution and in facility the equipments usually one-time fix and adjust. While dynamic rigidity describes the ability of an optical table to resist the deflection in response to ambient vibration, acoustic noise or mechanical excitation[4]. The design goal of any optical table is to be as stiff and light as possible. It must be stiff to ensure that the resonant frequencies are high, but light to ensure that the amplitude of vibration at the resonant frequency is low .The stability of optical table is to analysis its dynamic characteristic.

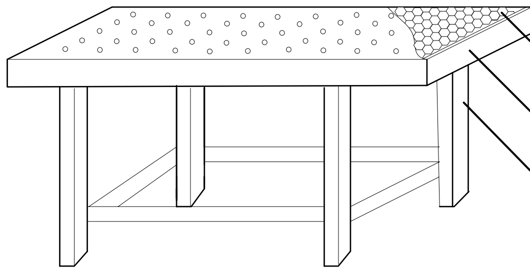

Fig.4. Sketch of an optical table

Usually, the optical tables using in the facility are the honeycomb comb tables, as shown in Fig.4. The tabletop provides the rigidity of the table. So the finite element analysis of an optical table usually takes on analysis the tabletop. The Fig.5 is the analysis result of the three lowest natural frequencies of model analysis the tabletop, and Fig.6 is the experimental modal analysis of the transfer function of the optical table. In the low frequency, there are many disturb signal in the response. From analysis the factor of coherence, the true natural frequency can be select. The differences between the simulation and experimental be explained by the test environment which having disturbance vibration and predigest about the simulation model.

First bend mode (246Hz) First torsion mode (299Hz) Second bend mode (422Hz)

Fig.5. Three lowest modes of tabletop

Serve as foundation structure in the facility, the mode of bend and twist of the tabletop will bring the displacement of relative optics elements which on the tabletop. The damper that is typically a sealed vessel fills with oil and containing a weight on a spring and the frequency of the spring is design to match a resonant frequency of the table used to apply to attenuation the bending or twist mode. Selecting different location for the damper to absorb would take different effective. For example, the most effective location for bending mode is in each end of table. The compliance curve of tabletop with damping level has lower peak in resonance and more approach the idea rigidity body line.

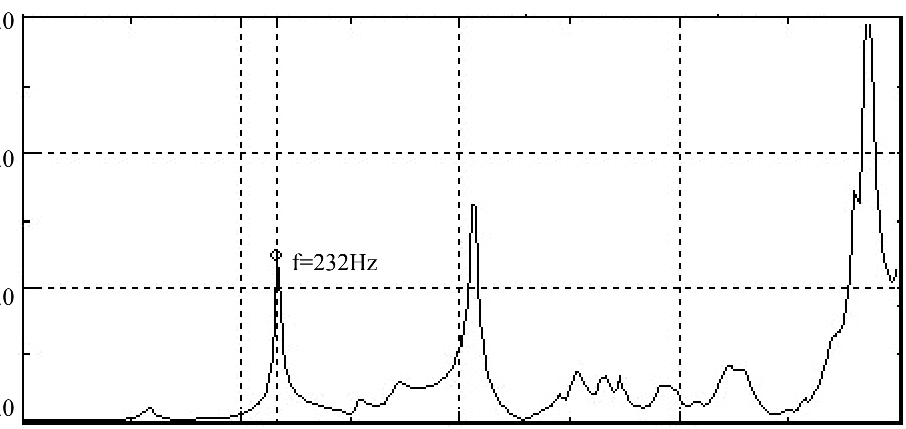

Fig.6.The transfer function of tabletop

When application, the select the support legs of the optical table also play important role in isolation the ambient vibration. To the general support table, the rigid legs be used for economical and maneuverability. But in the especial application, the pneumatic support as high performance vibration isolation systems counteract both the vertical and horizontal components of ground based noise. The most advanced models use air springs to support load carrying pistons as well as dual air chamber to eliminate vertical vibration, while damped pendulums reduce the horizontal component.

4.2 Spatial filter system

In ICF facility, the amplifiers and spatial filters are the most important elements in laser system. The main role of amplifiers is power amplification. And the spatial filter is to enlarge beam, image transfer, filter to assure the quality of beam in the near-field, significant improvements in the laser chain focusable power also can be chieved[8]. So in the facility, the stability is more important to the spatial filter, and it is necessary to carry out analysis for spatial filter system.

The spatial filter system is an integration system use in the facility and consists of a spatial filter, tube carriage, optical table and isolation foundation, as shown in Fig.7. While the spatial filter structure is fairly simply, which consist of a pair of confocal lens, pinhole which position on the focal surface and vacuum tube.

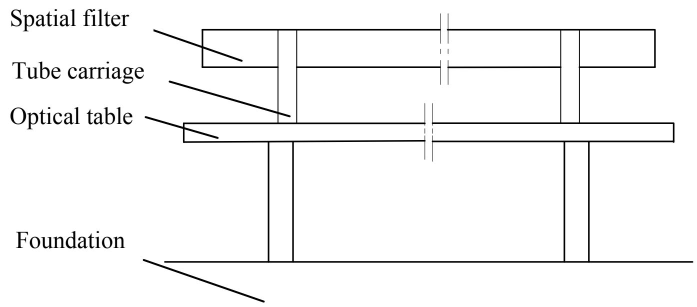

Fig.7. Sketch of spatial filter system

For a system, the whole rigidity is mainly decided by the element which is much weak in the system. Firstly, the spatial filter, spatial filter with two carriages, spatial filter with two carriages put on the table optical are taken on analysis solely. In the finite element modal, the foundation is assumed to be rigid, therefore no flexibility of the foundation in included in the analysis. The natural frequency of substructure in spatial filter lists in the table 1.

Table1. The natural frequency of the substructure of spatial filter system

Substructure	Natural frequency
Spatial filter vacuum tube	43Hz
Spatial filter with carriage	87Hz
Optical table	246Hz
Spatial filter system	66Hz

From the table 1, it shows that the spatial filter vacuum tube has low natural frequency in the whole system, and its natural frequency is 43Hz. By adding the carriage, the natural frequency is pushed highly and up to 87Hz. And then spatial filter tube supported by the carriage which is fixed on the optical table by bolt. The foundation assumed be rigid and restrict the support legs, the natural frequency of spatial filter system is 66Hz. In facility, the horizontal and vertical translation of the spatial filter would lead angle deviation and change the beam path. So the design and fix the spatial filter should eliminate both directions mode. The following approaches can improve the distortion of spatial filter. Firstly, altering the spatial filter structure, such as reinforced, can transfer the mode energy to others mode which influence the beam path slightly to reduce the beam angle deviation effectively. The second one is to control the displacement distortion of the element material can fulfill the spatial filter. The last one is to select the optimize location of the carriage can reduce the distortion. Otherwise, the degree of parallelization and perpendicularity should be control when the process the vacuum tube to avoid the decline of the system structure. The corrugated connection tubes acting as adjust compensating elements are also used to reduce the transfer energy.

Fig.8 is the transfer function of spatial filter by experimental test. The natural frequency is 70.4Hz and according the result of simulation. It can assume that the result of simulation is valid.

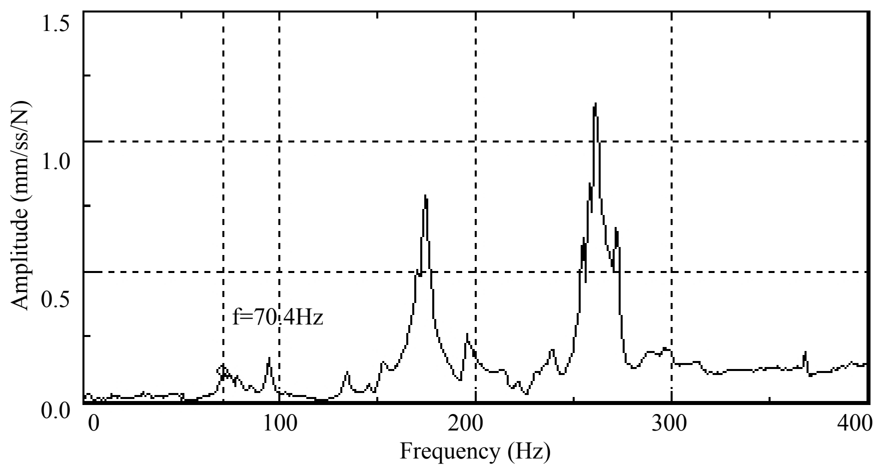

Fig.8.The transfer function of spatial filter system

The spatial filter system will be subjected to the low-lever ambient vibration from external such wind and impact from the upside. Fig.9 is the input PSD force spectrum on the spatial filter. Fig.10 is the displacement spectrum of one point on the spatial filter tube.

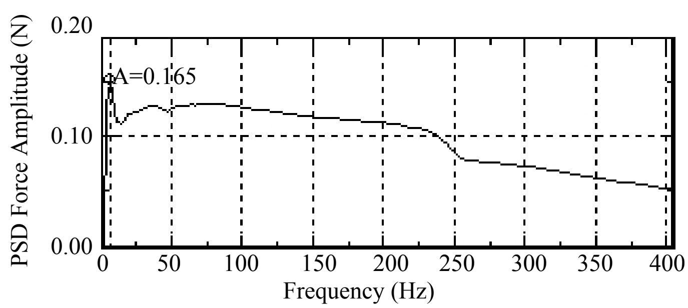

Fig.9.The input PSD force spectrum on the spatial filter

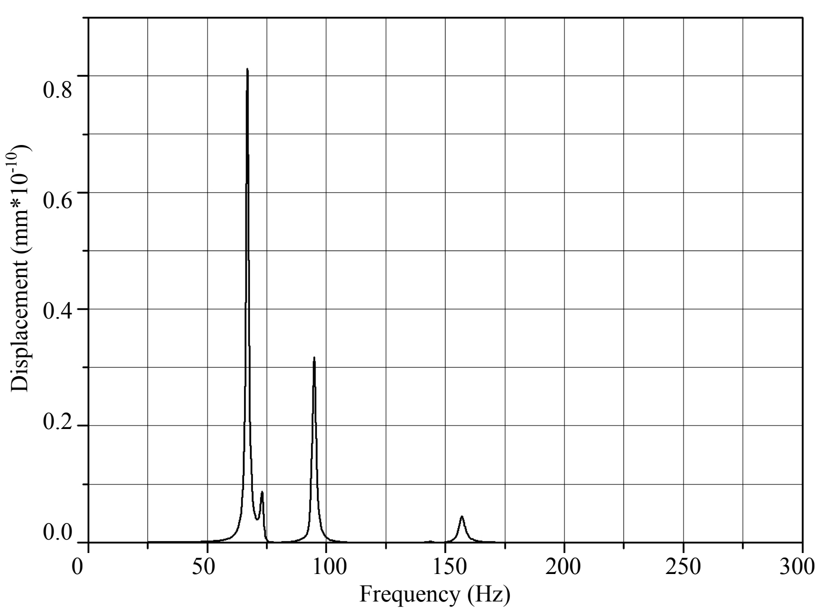

Fig.10. Displacement spectrum response of a point on spatial filter tube

As shown in Fig.10, there is peak value at the natural frequency. The peak value is much higher than the following peaks in the other natural frequencies. So in the spatial filter, the high natural frequency is, the small disturb would influence the system.

5. CONCLUSIONS

In this paper, the concept of system stability is put forward, and the method of test and vibration isolation control presented. Finite element analysis has been used to analysis the stability of the typical system in SGII facility. The results of test and simulation show that both the optical table and spatial filter have high enough natural frequency and satisfy the requirements of the facility.

All work can offer design guidance on the next upgrade of SG facility design and guarantee for the procedure of facility's precision. This information also can be used to the structure and system of the similar system and facilities.

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