Finite Element Analysis for Harmonic Oscillator of Acceleration Seismic Geophone

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***Abstract*—In the oilfield development stage, more recoverable reserves can be found by using the more sophisticated seismic methods with stimulation. Three-component seismic exploration technology comes into being, and it is becoming a major oil exploration seismic technology currently. As the sensitive element of seismic geophone, the performance of the harmonic oscillator is vitally important to the entire seismic exploration. The working principle of the harmonic oscillator is introduced, the solid model of harmonic oscillator mass is created by using the finite element method, and its three-dimensional static analysis and modal analysis are carried out. Load is applied and solved. The first fourth-order model is taken for analysis. The frequency of twentieth order vibration mode of physical model is 78 kHz; the total displacement of twentieth order is 0.122×10^{-6}μm; and the total displacement of the solid model is 0.236×10^{-19}μm.**

***Index Terms*—three-component, harmonic oscillator, msss, finite element**

I. Introduction

Three-component acceleration seismic geophone mainly includes harmonic oscillator, optical waveguide polarizer, optical detector and digital signal processing circuit. In order to build the corresponding contact between output signal and acceleration, and use computer to process, harmonic oscillator is the key component of the whole geophone, which is mainly composed of the mass, $LiNbO_3$ base and dual M-Z interferometer, whose design, production, sensitivity and performance play a crucial role to the whole geophone. High-quality harmonic oscillator should meet the demand that edges and corners are clear; the whole part is neat and clear; and the edge of mass and base are without patterns and spots.

Finite element method is a numerical method to solve mathematical equations, and it is a powerful engineering tool for numerical calculations. This method was originally used to study the stress of the structure of plane, which organically combines the computer software, computational mathematics and the theory of elasticity. Later, as this approach is effective, swift and flexible, it is rapidly developed as a general approximation method to solve the mathematical equations in various fields. At present, this method is widely used in many practical engineering problems and subject areas. The subject takes finite element method for the structure analysis of harmonic oscillator.

II. Working Principle of Harmonic Oscillator

The working principle of three-component acceleration seismic geophone is that when the geophone suffers an external seismic wave, the mass deforms in the bending beam due to the vibration, causing the optical phase change in the signal arm, and then stimulates detector along three directions of X, Y, Z. The interference light intensity is detected by the dual M-Z interferometer, and its phase is further detected by digital signal processing circuit. Finally, the sensed acceleration signal is extracted from the output light of the dual M-Z interferometer.

The motion of classical harmonic oscillator follows the equation

$$F = -kx = m\frac{\mathrm{d}^2 x}{\mathrm{d}t^2} \tag{1}$$

Where, m is the mass of harmonic oscillator, and k is elasticity constant. Its solution is

$$x(t) = A\sin(\omega t) + B\cos(\omega t) \tag{2}$$

Where, $\omega=(k/m)^{1/2}$ is the angular frequency of vibration; potential energy $V(x)=1/2kx^2$ is the parabolic form.

Of course, in practice, harmonic oscillator is an ideal system. However, any potential energy can be approximated as a parabolic form in the vicinity of its minimum value. When it is spread by Taylor series form at the minimum value of $V(x)$, then it can be gotten

$$V(x) = V(x_0) + V'(x_0)(x - x_0) + \frac{1}{2}V''(x_0)(x - x_0)^2 + \mathrm{L} \tag{3}$$

As $V(x_0)$ is constant, it can be removed. $V''(x_0)$ (because x_0 is minimum point), ignore higher order terms, the potential energy function becomes

$$V(x) \approx \frac{1}{2}V''(x_0)(x - x_0)^2 \tag{4}$$

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It describes harmonic vibration moving around the point x_0, and the force constant is $k=V''(x_0)$. The reason of harmonic oscillator so important is that any vibration can be approximated as harmonic oscillator as long as amplitude is small.

The harmonic oscillator of three-component acceleration geophone is shown in Fig.1, and its structure is: dual M-Z interferometer is independently produced on the three X-cut Y-propagation $LiNbO_3$ crystals, and then the three disconnect-type dual M-Z interferometer is mounted on a fixed core body, which constitutes the harmonic oscillator of three-component geophone accelerometer. The mutually perpendicular polarized light in the vibration direction reflects from the X, Y, Z three directions. In essence, the harmonic oscillator of combined type three-component acceleration seismic geophone is combined by three single-component acceleration harmonic oscillator. In every dual M-Z interferometer, the polarized light TE propagates along the optical axis of LiNbO3, and it induces the changes in refractive index of extraordinary light ne.

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta n_e l \tag{5}$$

It can be gotten according to (5)

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta n_e l \tag{6}$$

Then, the phase sensitivity is $\Delta\varphi/\Delta a$.

If $\Delta a_{\text{spindle}}$ is the acceleration in the measured direction, and $\Delta a_{\text{cross-axis}}$ is the acceleration perpendicular to $\Delta a_{\text{spindle}}$, the corresponding light position changes are $\Delta\varphi_{\text{spindle}}$ and $\Delta\varphi_{\text{cross-axis}}$.

$$\Delta\varphi_{\text{spindle}} = \frac{2\pi}{\lambda} n_e^3 l \tag{7}$$

The phase sensitivity of the spindle is

$$K_{\text{spindle}} = \frac{\Delta\varphi_{\text{spindle}}}{\Delta a_{\text{spindle}}} \tag{8}$$

Because the TE light propagating along the optical axis cannot be induce the changes in refractive index, which is perpendicular to the vibration direction, i.e., the changes of Δn_0 will not result in changes in $\Delta\varphi$. So $\Delta\varphi_{\text{cross-axis}}=0$. Thus, the transverse sensitivity ratio (TSR) of combined type three-component acceleration seismic geophone is

$$\text{TSR} = \frac{K_{\text{cross-axis}}}{K_{\text{spindle}}} \tag{9}$$

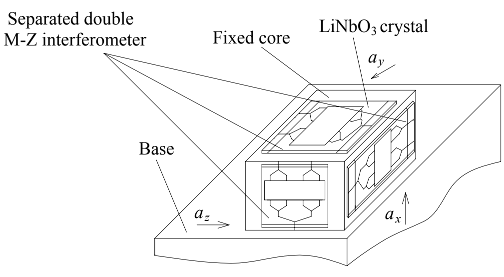

Fig. 1. The harmonic oscillator of combined type

The harmonic oscillator of this structure has the advantages of wide response frequency band, low cross-sensitivity, good anti-electromagnetic interference capability, small size and so on.

III. Three-Dimensional Finite Element Analysis For Harmonic Oscillator

Starting a finite element analysis is very simple. As long as there are a geometric structure, the basic knowledge of material deformation properties, a finite element analysis software and computer hardware platform, it can be implemented following the normative procedure: geometry (drawing) description, unit selection and subdivision, the set of geometry constraints and the imposition of external forces, algorithms selection, run, observation of the calculation results, visualization output and other steps.

ANSYS is developed by the ANSYS Corporation in United States. It provides a platform, and it is a finite element analysis (FEA) software, which can make coupling analysis for structure, heat transfer, fluid and other issues. It is one of the largest and most popular commercial software internationally. The greatest feature of the software is that it provides both direct operation mode based on graphical interface and command-flow language of finite element analysis process. The user can use the top of the finite element language of the command stream to model and control processes, and it has good portability.

IV. Create The Finite Element Model Of Harmonic Oscillator

The self-modeling methods of ANSYS can be divided into two ways: top-down modeling and bottom-up modeling. Top-down model is modeled based from body to surface, from face to line, from line to point. Because the line is composed of the points; the surface is constituted by the lines, while the body is constituted by the surfaces. So this order is from top to bottom to model. Bottom-up modeling is just opposite to the top-down modeling. In the modeling process, top-down is not absolute, and the bottom-up approach is used sometimes.

For papers published in translated journals, first give the English citation, then the original foreign-language citation [6].

A. Create the Physical Model of the Harmonic Oscillator

The solid model of mass in the harmonic oscillator is established by the top-down modeling approach. The size of the model of the mass is shown in Table I.

TABLE. I

THE SIZE OF THE MODEL OF MASS

Length/μm	72
Width/μm	48
The whole height/μm	48
the height of both sides /μm	15

The solid model of mass generated by ANSYS is shown in Fig. 2.

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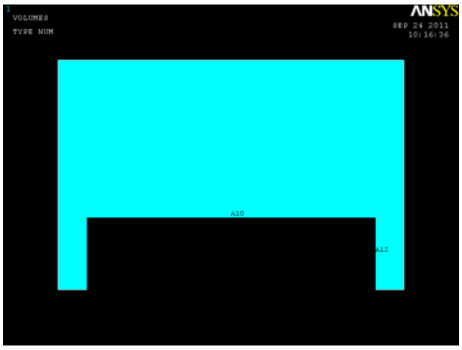
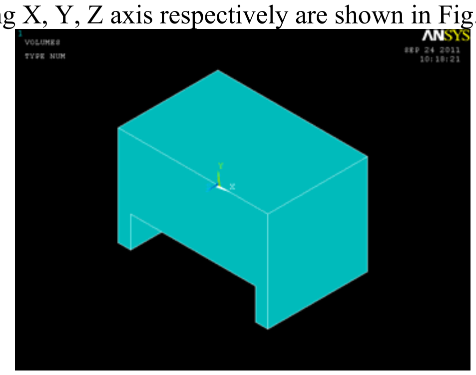
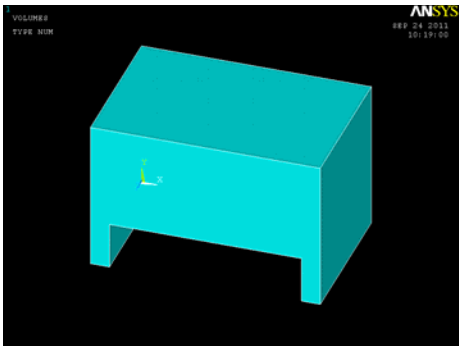


Fig.2 The solid model of mass of harmonic oscillator

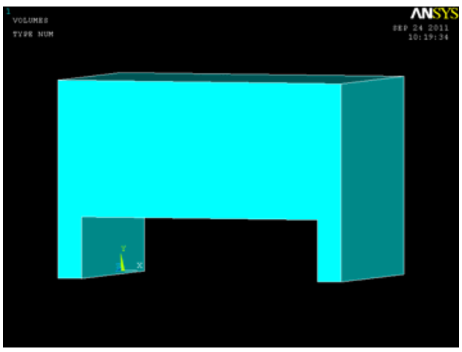
The three-dimensional diagrams of solid model in different angles and the three-dimensional diagrams after rotating X, Y, Z axis respectively are shown in Fig.3.



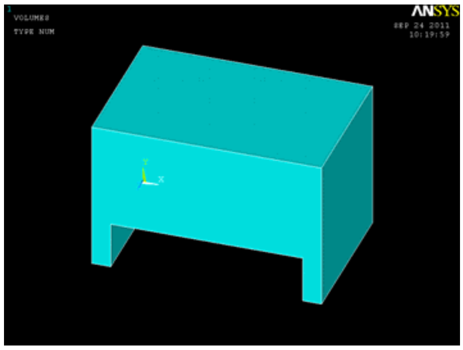
(a)Isometric view



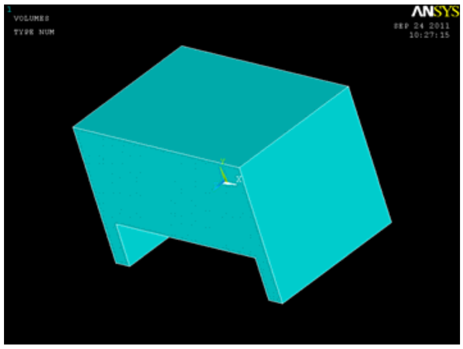
(b)Oblique view



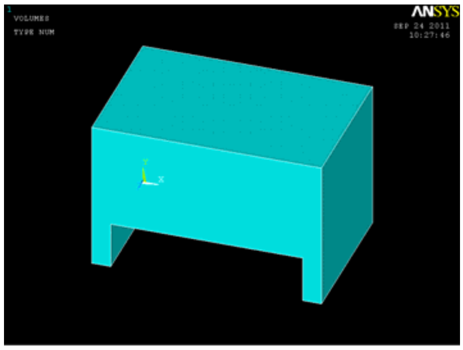
(c)Rotate −X



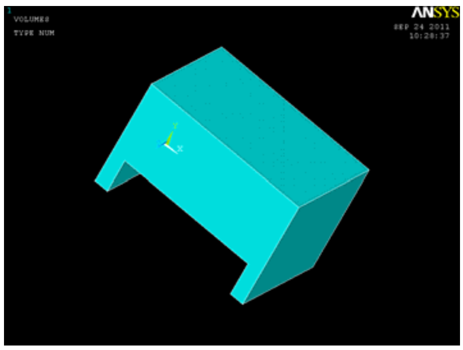
(d) Rotate +X



(e)Rotate −Y



(f) Rotate +Y



(g) Rotate −Z

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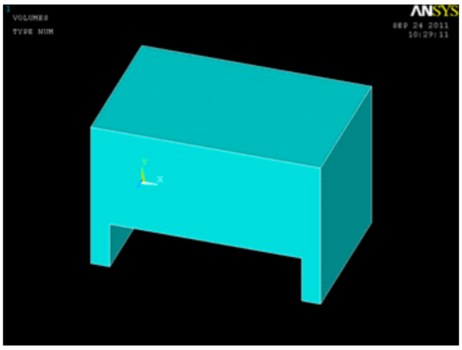


(h) Rotate +Z

Fig. 3. Three-dimensional diagrams of the solid model under different angles

B. *Choice of the Material of Harmonic Oscillator*

Taking into account the requirements of integration of three-component acceleration seismic geophone and the corrosion quality of harmonic oscillator, monocrystalline silicon is selected as the material of the mass of harmonic oscillator. Silicon is one of the most abundant elements on earth, accounting for about 26% of the weight of the crust, only less than oxygen. The simple substance of silicon doesn't exist on the earth, it basically exists in silicate or silica as oxidation states, which forms for a variety of stones such as granite, quartzite, and so on.

The hardness of silicon is high, but brittleness is large and easily broken. As a brittle material, the anti-tensile stress of silicon is much larger than that of anti-shear stress, and it has no ductility at room temperature. When the heat treatment temperature is higher than 750℃, the silicon material converts from brittle material into plastic material. Slip dislocations are produced under the effect of external applied stress, and the plastic deformation is formed [7].

Except that silicon can produce oxidation reaction at room temperature, its chemical properties are stable. High-purity silicon surface can react with oxygen in the air to form several nm thick oxide layer under normal atmospheric temperature and constant pressure. However, it can react with almost all substances and chemical reactions at high temperatures, especially the oxygen. Although silicon is not soluble in a single acid at room temperature, it is soluble in the mixture of alkaline and acid.

Monocrystalline silicon takes the high purity polycrystalline silicon as raw material, which is usually growed by the Czochralski method and Float-Zone method.

C. *Meshing*

Meshing control technology mainly relates to cell shape, location of the intermediate nodes, cell size, etc., which directly affects the size of the finite element model, and plays a decisive role in the accuracy and economy of the calculation of finite element model.

Before meshing of geometric model, first, the properties of unit should be defined, which include the determination of element types, definition of material properties and real constants. Second, the geometric model needs to meshing to give the corresponding unit attributes. And finally the meshing density is set. Thus the preparatory work is completed before meshing.

First the unit type is selected, and Solid Brick 8node 45 is selected, which is a parabolic curve solid tetrahedral element. Then the material properties are defined. The elastic modulus, Poisson's ratio and density are set in accordance with Table.1 in turn. Finally, smart meshing is adopted to mesh. In order to improve the calculation accuracy, set the grid size 1. The solid model after meshing is shown in Fig.4.

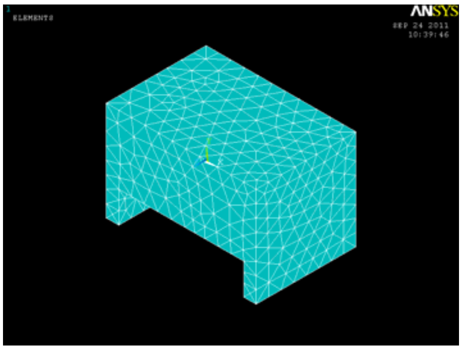
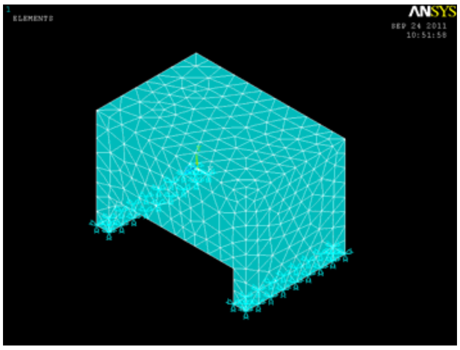


Fig.4 The result of free meshing division

D. *Apply Load and Solve*

Load refers to the displacement, force, temperature, etc. of the physical model. The selection of appropriate load makes great impact on the analysis results, and the key is to determine the load type.

As the mass is associated with the substrate, displacement constraints are imposed on the two bottom sides of the geometric model, as shown in Fig.5(a). Then the force is applied on the number of 414 node on the right side of the model along the horizontal direction, i.e. X-axis direction. The results are shown in Fig.5(b).



(a) Imposimg displacement constraint

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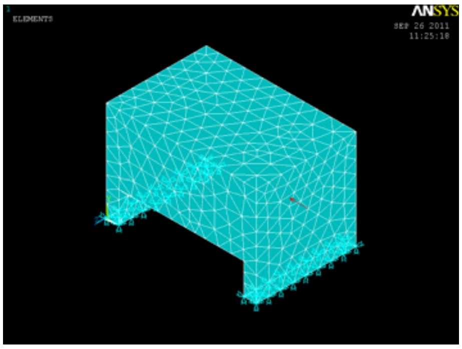


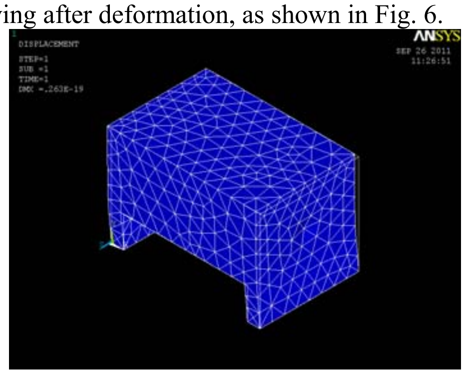
(b) Imposimg concentrated load

Fig.5 Diagrams after the applied load.

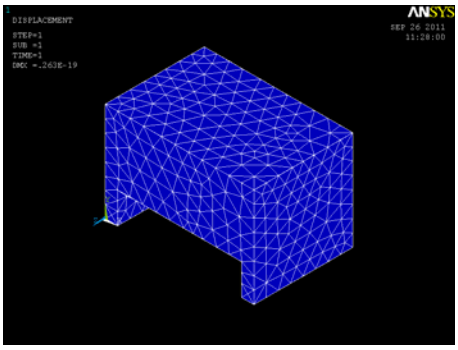
E. Static Analysis Results

Static analysis is used to calculate the structure effect under fixed loads, regardless of the displacement, stress, strain and force caused by the load inertia and damping effects acting on the structure or components. Fixed load and response are the assumption that assuming loading and structural response changes very slowly over time.

First check the structure deformation diagrams of the solid model, and choose the border line and boundary line displaying after deformation, as shown in Fig. 6.



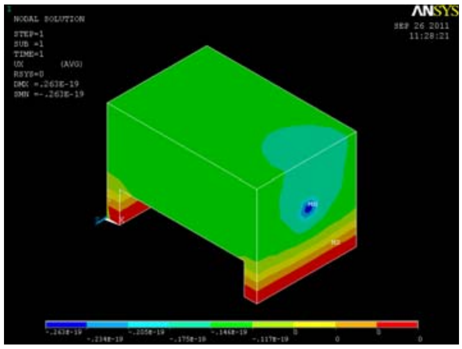
(a) The deformation diagram with a large scaling



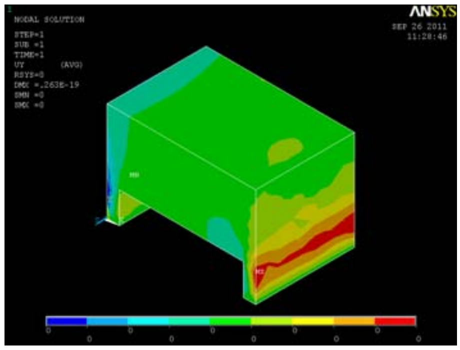
(b)The deformation diagram with a true ratio (1:1)

Fig.6 Structural deformation diagrams of solid model

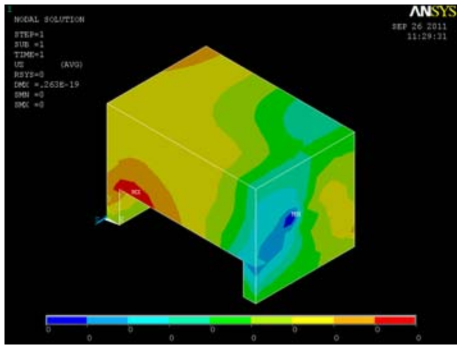
Then look over the stress nephograms of X component, Y component and Z component three components total displacement of the solid model respectively, as shown in Fig.7.



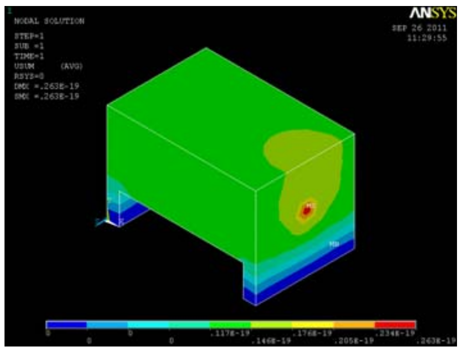
(a)Displacement of X component



(b) Displacement of Y component



(c) Displacement of Z component



(d) The total displacement of X, Y, Z three components

Fig.7 The stress nephograms with stress and after calculation

Fig. 7(d) shows that the total displacement of the solid model is 0.236×10^{-19}μm.

F. Modal Analysis Results

Modal analysis determines the vibration characteristics of the structure, by which to determine the mode shapes, natural frequencies and modal participation factor.

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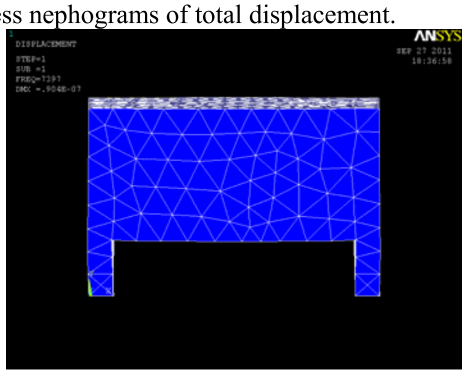
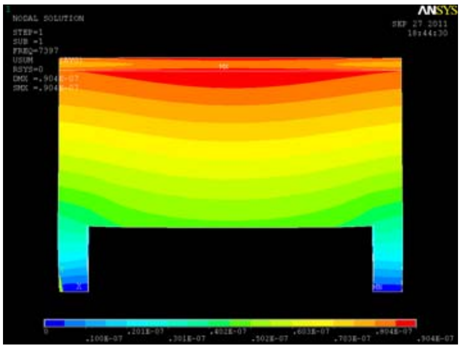
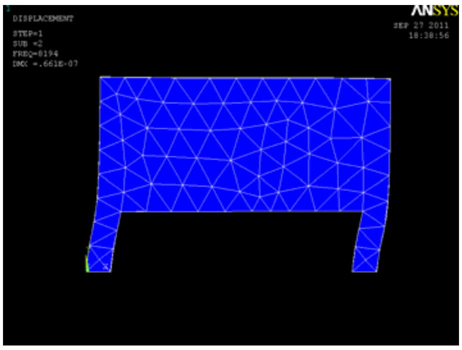
Vibration mode refers to the displacement ratio relationship of each particle when the structure vibrates with the first order frequency, i.e., the maximum displacement is 1. A value is gotten by comparing the displacement of other particle and the maximum displacement. Then the deformation diagrams are drawn according to these values are the vibration mode diagrams Modal analysis can help in estimating and solving the control parameters (such as the time step) in other power analysis [8].

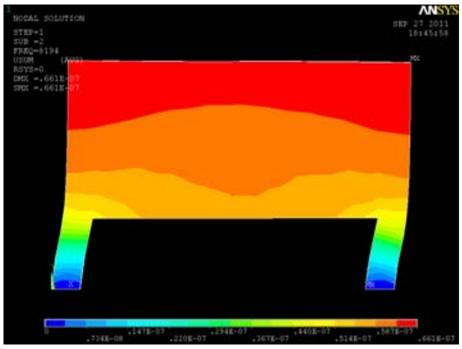
The modals are expanded to 20 orders, and the frequency range is set to 0~100kHz. As the fifth-order vibration mode repeats the first-order vibration mode, it only needs to look over the fourth-order vibration mode diagrams. Fig.8 shows the vibration mode diagrams and the stress nephograms of total displacement.



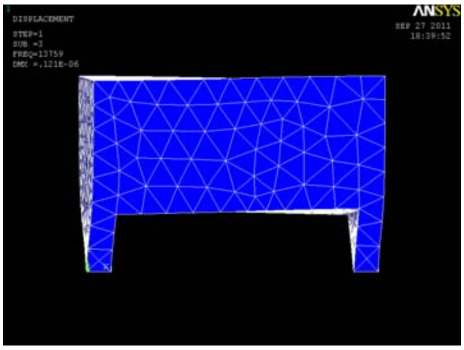


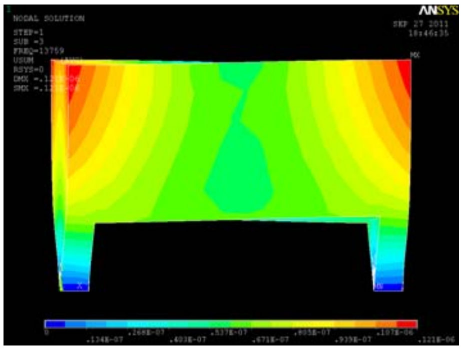
(a)First-order vibration mode and its stress nephogram



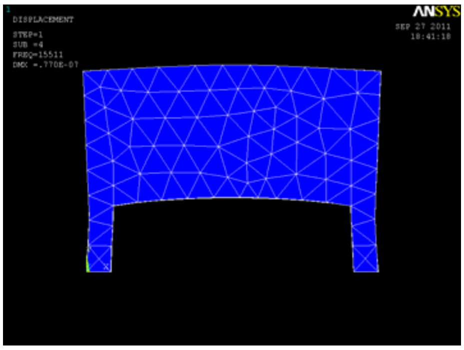


(b)Second-order vibration mode and its stress nephogram





(c)Third-order vibration mode and its stress nephogram



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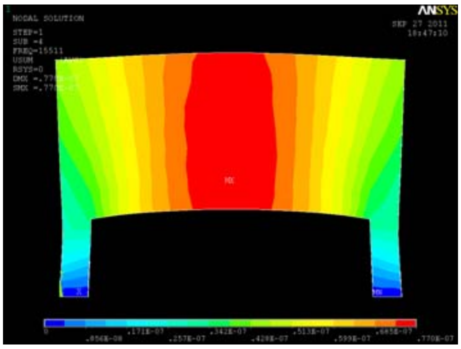

(d)Fourth-order vibration mode and its stress nephogram

Fig.8 The first fourth-order vibration mode and the stress nephograms

It can be known from the fourth-order vibration mode diagrams that the first-order vibration mode vibrates front and back along the Z axis; the second-order vibration mode vibrates left and right along the X axis; the third-order vibration mode makes bending vibration in the X-Z plane; and the fourth-order vibration mode makes bending vibration in the X-Y plane. Therefore, the stiffness of the model structure is the worst when it suffers the load along the X axis direction, which is the weak direction of the structure.

Fig.9 is the total displacement deformation diagram of the twenty-order vibration mode (stress nephogram), where contains the border lines after deformed and unreformed, and the chromatogram on the bottom shows that different colors correspond to different values (signed).

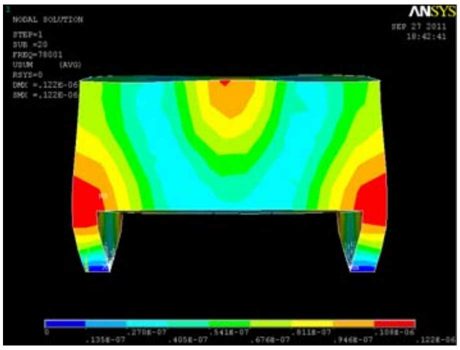

Fig.9 Total displacement deformation diagram of twenty-order

Fig.9 shows that the tenths-order vibration mode frequency of solid model is 78001Hz, and the total displacement of the twentieth order is 0.122×10^{-6}µm. The changing curve of elastic equivalent strain versus time of 414 nodes of the twentieth is shown in Fig. 10.

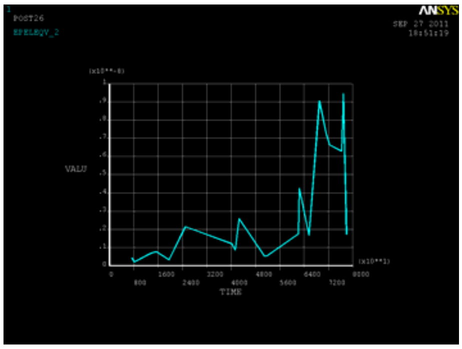

Fig.10. The changing curve of elastic equivalent strain versus time

V. CONCLUSION

Static analysis and structural modal analysis are made for the harmonic oscillator of three-component acceleration seismic geophone. The geometrical model of mass in the harmonic oscillator is created by using ANSYS, and load is applied and solved. The first fourth-order model is taken for analysis. The twentieth-order vibration mode frequency of physical models is 78001Hz; the total displacement is 0.122×10^{-6}µm; and the total displacement of the solid model is 0.236×10^{-19}µm.

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