Research Article
Finite Element Analysis of Flat Spiral Spring on Mechanical Elastic Energy Storage Technology

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Abstract: Energy storage technology has become an effective way of storing energy and improving power output controllability in modern power grid. The mechanical elastic energy storage technology on flat spiral spring is a new energy storage technology. This study states the mechanical elastic energy storage technology, models the mechanical model. Aimed to three kinds of structure and size of flat spiral spring, the finite element model are modeled, modal analysis is completed and the natural frequencies and the first 10-order vibration modes of the spring are analyzed, the relationship of natural frequency and vibration mode of spiral spring and structure and size is analyzed. The research results can provide the reference for the structure design and dynamics analysis.

Keywords: Finite element, flat spiral spring, mechanical elastic energy storage technology, modal analysis

INTRODUCTION

The new energy, such as wind power and solar energy, is randomness, intermittent, volatility energy which gives the huge change of the voltage, frequency and phase on the power grid. The application of new energy will affect the stability of the power grid (Jia *et al*., 2009; Georgescu *et al*., 2010). The energy storage technology can improve the new energy technology controllability, realize the new energy power generation smooth output and improve the quality of power supply (Mohod and Aware, 2008; Jin, 2009; Zhang *et al*., 2008). The energy storage technology is a technology that the energy can be stored up with chemical or physical methods and released out with needed energy when needed. Now the energy storage methods have not unified division standard. According to the energy conversion way, the energy storage methods can be divided into physical energy storage, electromagnetic energy storage, electrochemical energy storage and phase change energy storage. The physical energy storage, also called mechanical energy storage, mainly includes pumped storage, compressed aie energy storage and flywheel energy storage. The mechanical energy storage has advantages of high capacity, high efficiency, low cost, no pollution (Veszpremi and Schmidt, 2007; Tang *et al*., 2007; Aboul-Seoud and Jatskecich, 2008).

The flat spiral spring is a elastic element widely used in machinery industry. When loaded, the flat spiral spring can occur large elastic deformation, the mechanical energy or kinetic energy can be turned into elastic potential energy. When unloaded, the deformation of the spiral spring restores, the elastic potential energy can be turned into needed forms of energy. This study states an energy storage technology with flat spiral spring as the basic energy storage element, as called mechanical elastic energy storage technology. In this study, the mechanics model of the flat spiral spring is established. Aimed to three kinds of structure and size of flat spiral spring, the finite element model are modeled, modal analysis is completed and the natural frequencies and the first 10-order vibration modes of the spring are analyzed, the relationship of natural frequency and vibration mode of spiral spring and structure and size is analyzed. The research results can provide the reference for the structure design and dynamics analysis.

MECHANICAL ELASTIC ENERGY STORAGE TOCHNOLOGY

The diagram of the mechanical elastic energy storage technology is shown in Fig. 1. In the process of storing energy, the double-fed motor is controlled in the condition of electric motor and the breaker is locked. The power from grid drives the motor to run and the spiral spring in the energy storage device is coiled tightly through the transmission system and the deformation energy is stored by spiral spring. In the process of releasing energy, the control system controls the double-fed motor to work as a power generator and
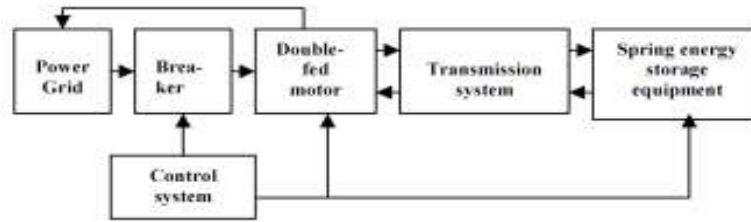
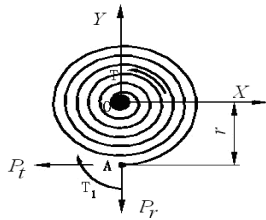Fig. 1: Diagram of mechanical elastic energy storage technology

Fig. 2: Force analysis of flat spiral spring

control the spiral spring to release the deformation energy to put the double-fed motor in motion by transmission system. Then it realizes the transform from deformation energy to electrical energy (Duan *et al*., 2011).

Mechanical elastic energy storage technology is a new energy storage method which takes the flat spiral spring as important storage element. According to the Fig. 1, the base principle of the mechanical elastic energy storage technology is that various forms of energy can be turned into elastic potential energy of the flat spiral spring and stored in spring energy storage equipment. In time of need, the elastic potential energy of the spring can be released and turned into appropriate forms of energy. The core element of the mechanical elastic energy storage technology is the flat spiral spring, which directly affects the reliability and security of the mechanical elastic energy storage technology.

The geometry of the flat spiral spring is very complex, there is lots of surface. So analytic method is not applicable all over the spring for the stress distribution and natural frequency. This study uses the finite element numerical analysis method to establish the mechanics model. The cross section of commonly used spiral spring is rectangular. For increase storage density, the cross section of flat spiral spring can adopt special structure. This study establishes three forms of spiral spring to model the finite element models for the mode analysis, which include two kinds of rectangular cross section spiral spring with different size and one kind of special cross section spiral spring.

Mechanics model: The flat spiral spring is a spring that is winded along the spiral with slender spring material. When one end of the spring is fixed and the other
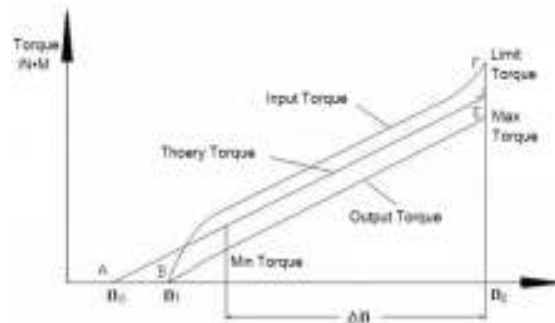

Fig. 3: Relationship of torque and work angle

end is exerted by torque, the spiral spring will occur large elastic deformation and store the elastic potential energy.

Shown in Fig. 2, one end of spring is fixed, the fixed point is A, the other end is fixed at point O. The distance from point A to point O is r. When the torque is loaded at point O, the loads at point A include torque T_1, tangential force P_t and Radial force P_r.

The energy storage process of mechanical elastic energy storage technology can be boiled down to the energy process of the spiral spring. So the energy storage capacity of the spiral spring is equivalent to the study W that the torque T drives the spring rotating angle φ, the φ is the product of spring's work turns n and 2π. Thus there is formula (1) as follow:

$$W = T \times \phi \tag{1}$$

The torque of spiral spring changes with the study angle, the curve is shown in Fig. 3.

The spring's turns in Free State are shown as n_0, the turns released in spring equipment is n_1 and the turns rolled tightly on shaft is n_2. The study turns of spring is $\Delta n = k_4 (n_2-n_1)$. Here, k_4 is effective coefficient on the diameter of spring's shaft and the thickness of spiral spring (Jiang *et al*., 1994).

As shown in Fig. 3, the curve of spring work torque is divided into theory torque curve AJ, input torque curve BF and output torque curve BE. In this study, only the input torque curve BF is analyzed. Because of the friction, the left end of input torque curve BF has a curve that means the spring is gradually
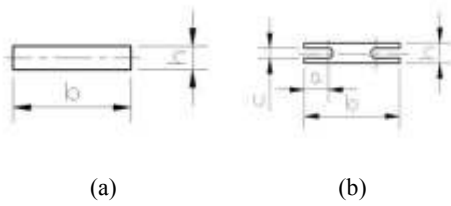
(a) (b)

Fig. 4: Cross section of spiral spring

Table 1: Design data of flat spiral spring

Data	Spring 1	Spiral 2	Special spring
Section size (mm×mm)	40×2 (b×h)	10×2 (b×h)	10×2 (b×h), a = 2.5, c = 1
Length (m)	20	20	20
Shaft diameter (m)	0.08	0.08	0.08
Released turns (r)	22	22	22
Work turns (r)	15	15	15

released. The right end of input torque curve has a curve that means the torque of spring rapidly raise after the spring is tightened round the shaft. In fact, during the process of energy storage, only the torque is used while the spring deforms all over the spring. Shown in Fig. 3, this stage of the curve is the Δn. This time, the curve tends to straight line. In the Δn stage, the curve of work torque is approximately linear.

The work torque of spiral spring can be calculated as formula (2) and (3). Elastic modulus E and moment of inertia I am proportional to work torque. The limit torque T_{max} of spiral spring is checked by the tensile strength limit value $[\sigma_b]$ of spring's material. Z_m is the section coefficient of bending:

$$T = \frac{EI}{l}\varphi = \frac{2\pi nEI}{l} \tag{2}$$

$$\frac{T_{max}}{Z_m} \leq [\sigma_b] \tag{3}$$

The commonly cross section of spiral spring is rectangular. The moment of inertia I and the section coefficient of bending Z_m of spring can be calculated as formula (4) and (5). In formulas, b is the width of cross section and h is the thickness of cross section:

$$I = \frac{bh^3}{12} \tag{4}$$

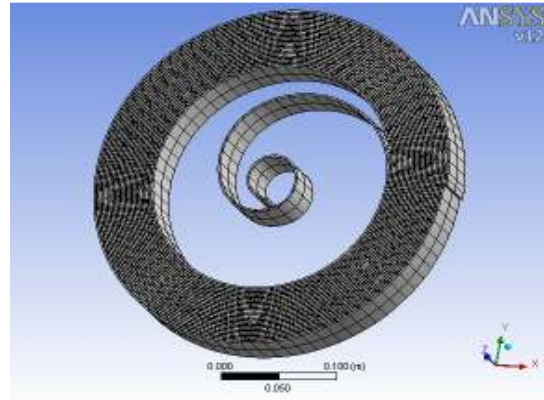$$Z_m = \frac{I}{y_{max}} = \frac{bh^3/12}{h/2} = \frac{bh^2}{6} \tag{5}$$

Spiral spring model:
Finite element model: According to the flat spiral spring winded along the spiral of Archimedes, this study establishes finite element models of three forms of spiral spring. Two kinds of rectangular cross section spiral spring with different size and one kind of special cross section spiral spring. The rectangular cross section is shown as Fig. 4a and the special cross section is shown as Fig. 4b.
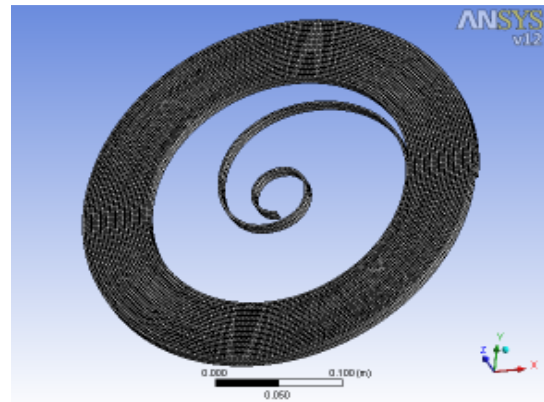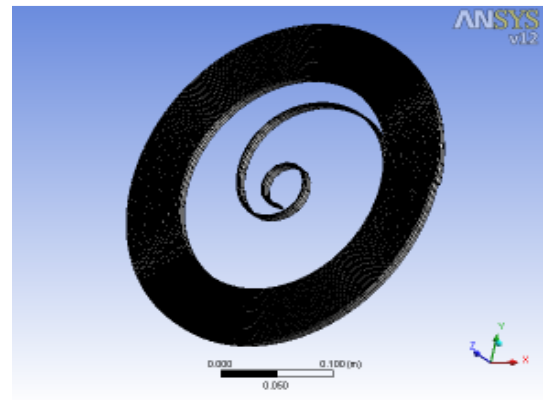
In this study, the material of spiral spring is 55 CrMnA, the value of elastic modulus E is 197 GPa, the value of tensile strength limit value $[\sigma_b]$ is 1653 MPa, the value of density ρ is 7800 kg/m³. The design data of spiral spring is shown as Table 1.

(a) Finite element model of flat spiral spring

(b) Finite element model of flat spiral spring

(c) Finite element model of flat spiral spring

Fig. 5: Model of flat spiral spring

Because of special section spring, the spring models are built with three-dimensional modeling software Pro/engineer and then the models are imported into ANSYS system for finite element analysis. In ANSYS environment, the spring models are established by the default three-dimensional entity unit types. The finite element models are shown as Fig. 5.

Boundary conditions: The boundary condition is set as Fig. 6. According to the character of spiral spring, one end of spring is fixed on the shaft as B in Fig. 6 and the other end is fixed on the equipment as An in Fig. 6. During the process of energy storage, the A end of spring is fixed, the B end of spring is rotated by the torque of shaft. When setting the boundary condition, the A end and B end can be set fixed constraint.

MODAL ANALYSIS

The finite element analysis of the flat spiral spring can be considered as a huge deformed problem, different from the analysis of other springs (Qu and Chao, 2005; Lan, 2010; Guo *et al*., 2010). Because the deformation of the spring belongs to elastic deformation, the spring is analyzed with general linear analysis method.

The modal analysis about spiral spring is finished while the spring is released in energy storage equipment. The two ends of spring are fixed. The modal number is set as 10 and the frequencies and modes of vibration about 1, 6 and 10 orders, respectively are extracted and contrasted each other.
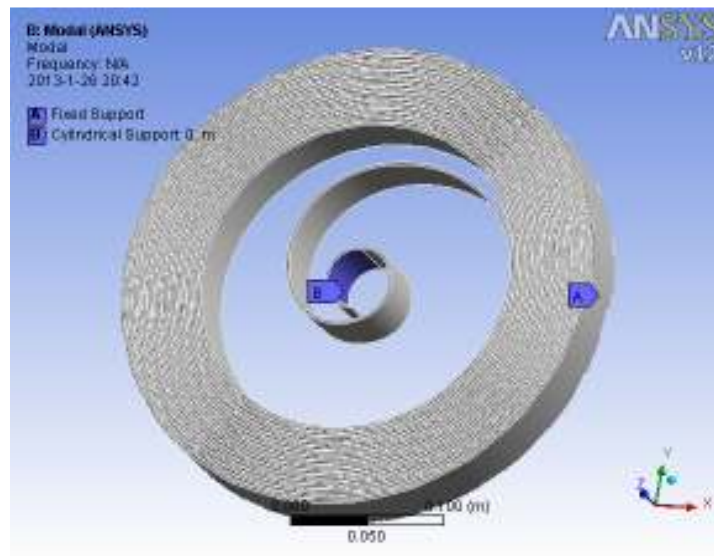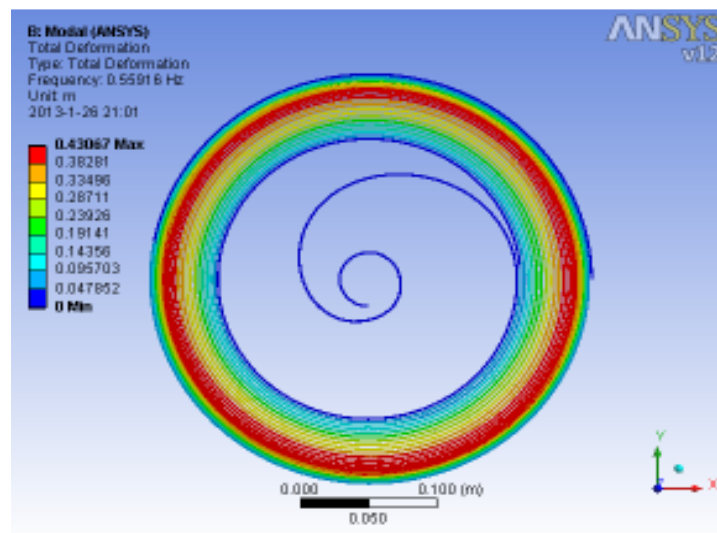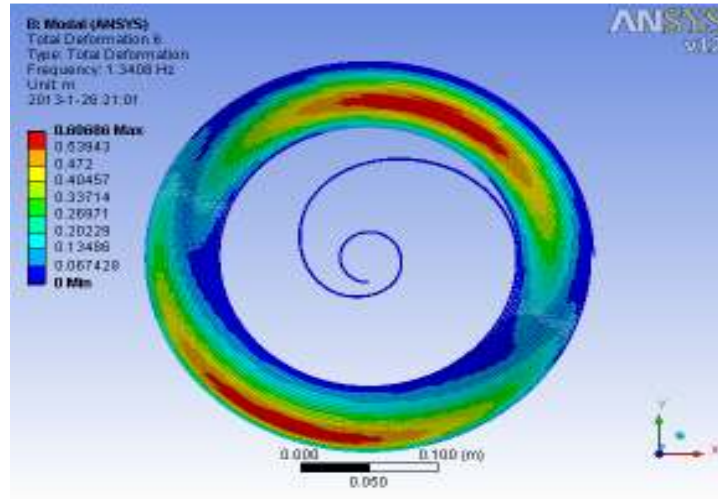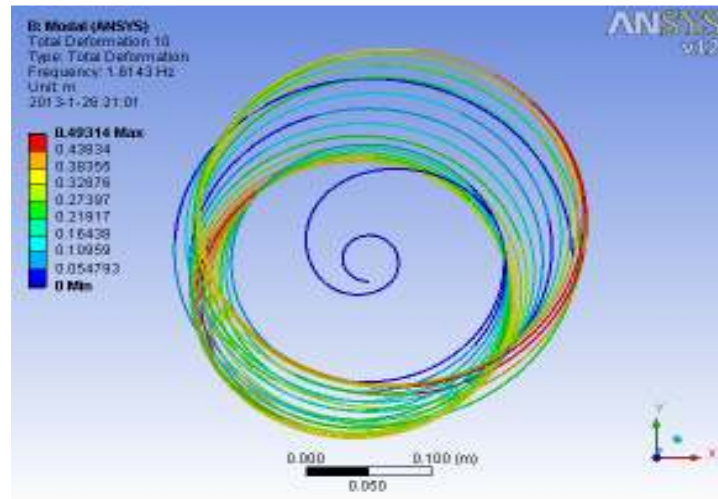

Fig. 6: Boundary conditions

(a)

(b)

(c)
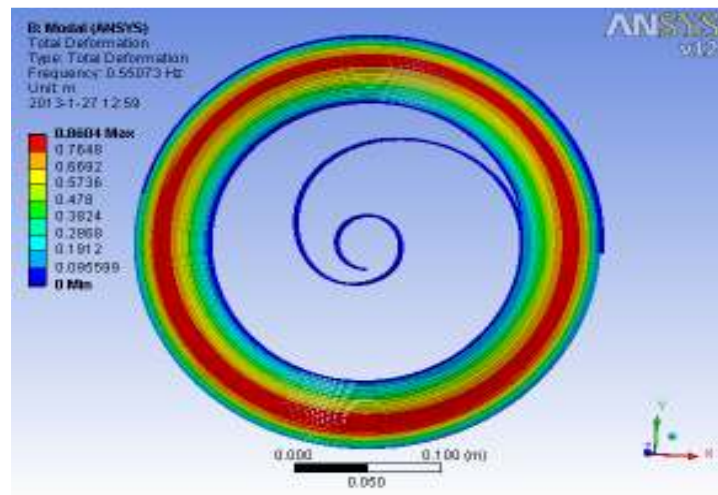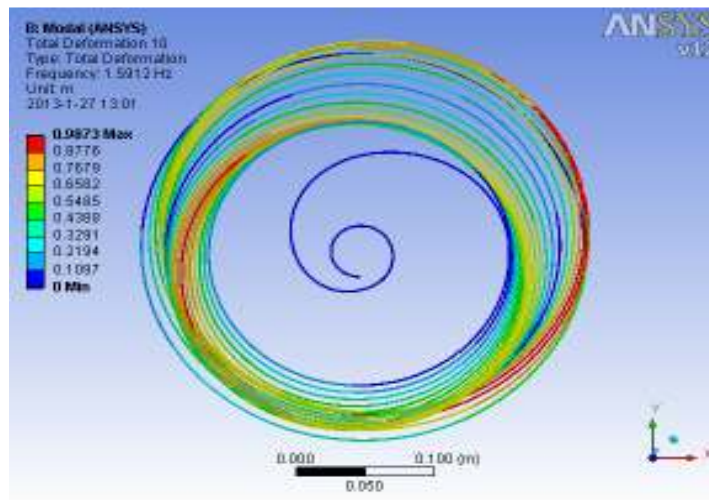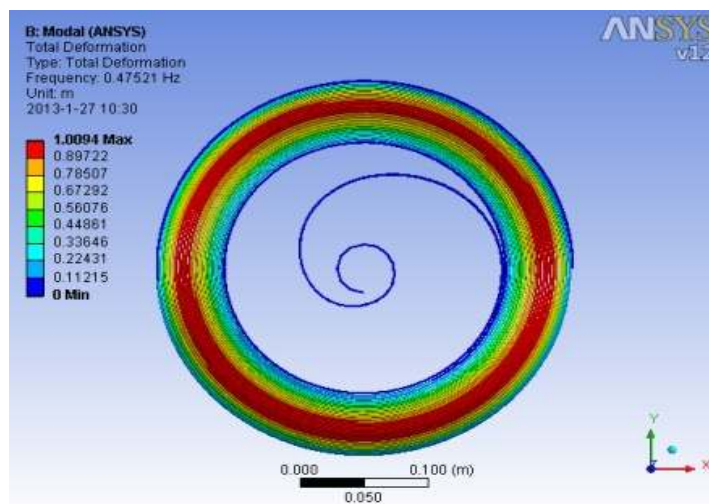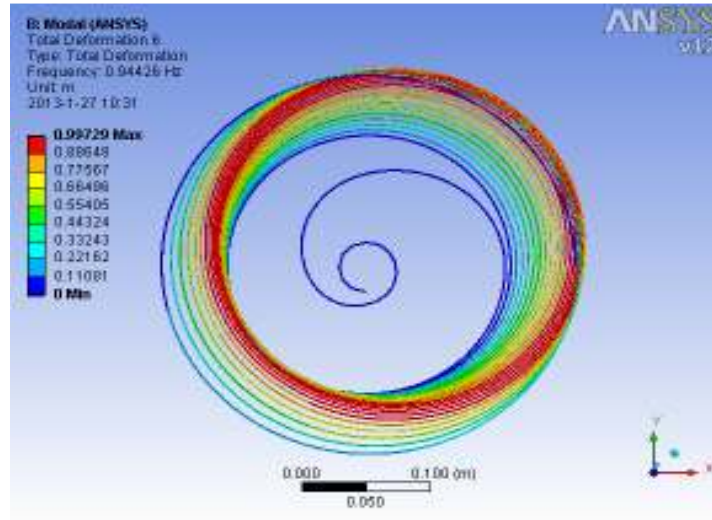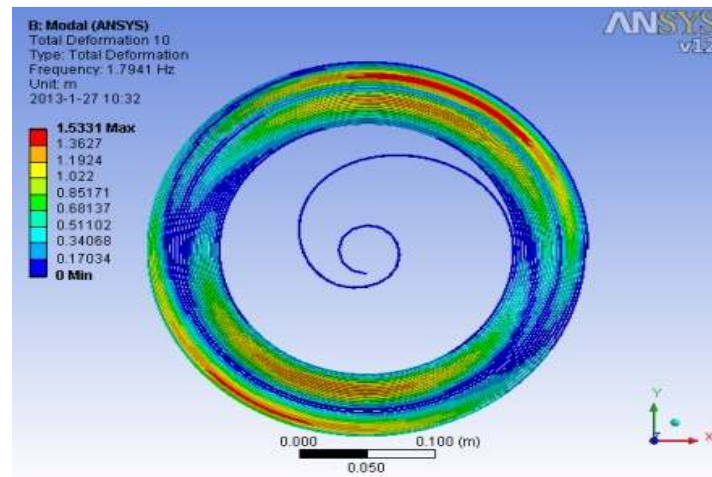

(d)
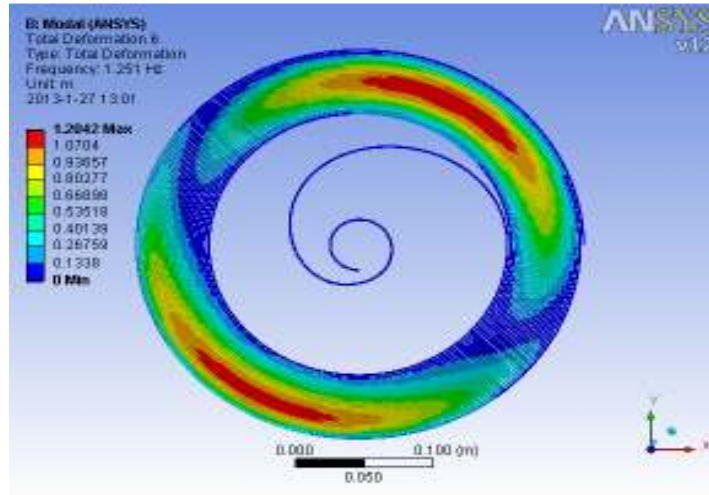
(e)

(f)

(g)

(h)

(i)

Fig. 7: Modes of vibration of spiral spring

The modes of vibration about three kinds of spring are shown as Fig. 7.

The modes of vibration of rectangular section spring1 is shown as Fig. 7a to c, the display scale is 0.1. The max value is 0.60686 m. The modes of vibration of rectangular section spring 2 is shown as Fig. 7d to f, the display scale is 0.02. The max value is 1.2042 m. The modes of vibration of special section spring are shown as Fig. 7g to i, the display scale is 0.002. The max value is 1.5331 m.

The natural frequencies of spiral spring 1 are shown as Table 2.

The natural frequencies of spiral spring 2 are shown as Table 3.

The natural frequencies of special spiral spring are shown as Table 4.

Table 2: Natural frequencies of 3 orders modal

Mode	1	6	10
Frequency [Hz]	0.55073	1.251	1.5912

Table 3: Natural frequencies of 3 orders modal

Mode	1	6	10
Frequency [Hz]	0.55916	1.3408	1.6143

Table 4: Natural frequencies of 3 orders modal

Mode	1	6	10
Frequency [Hz]	0.47521	0.9442	1.7941

We can draw a conclusion from the above: Comparing two rectangular section springs, the mode of vibration of spring 1 is half of that of spring 2, which means that the width greatly influences the mode of vibration. Comparing rectangular section spring to special section spring, the mode of vibration of special

section spring is bigger than that of the rectangular section spring, which shows that the material at neutral axis has great influence for mode of vibration. The frequencies of rectangular and special section spring are similar. This result shows that the change of width and section shape has very small effect to the frequency of spring.

CONCLUSION

This study expounds the basic concept of mechanical elastic energy storage technology on flat spiral spring. Aiming to the spiral spring, the mechanical models are established. This study establishes three forms of spiral spring to model the finite element models for the mode analysis, which include two kinds of rectangular cross section spiral spring with different size and one kind of special cross section spiral spring. The research results can provide the reference for the structure design and dynamics analysis.

ACKNOWLEDGMENT

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