ANALYSIS OF STIFFNESS CHARACTERISTICS OF BALANCED ARC FLEXIBLE PIPES

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Balanced arc flexible pipe joint is an important connecting part of the pipeline vibration isolation system. It can effectively isolate the structural vibration, compensate displacement between pipelines without additional force and displacement under the action of working pressure and other advantages. In this paper, a certain kind of balanced arc flexible pipe is taken as the research object and a theoretical calculation model is established to analyze its axial static stiffness. By using ABAQUS to create its three-dimensional solid simulation model, the relationship between the axial static stiffness and the number of cord layers, the spacing between the cord layers and the working pressure was obtained. Compared with the experimental results, the accuracy of the model was proved. This method has certain reference value for the calculation of the axial stiffness of arc pipe. It provides a theoretical basis for the development of high-performance arc pipe.

Keywords: Arc body; Flexible pipe; Stiffness analysis; Cord

1. Introduction

In order to meet acoustic stealth design requirements, a large number of flexible vibration isolation devices, such as single-layer vibration isolation, double-layer vibration isolation, and floating buoyancy are used in the main engines, auxiliary engines and other equipment of ship power plants. Because of this, higher requirements are imposed on the displacement compensation of the external piping of the isolated equipment.

In order to isolate the structural vibrations transmitted along the pipeline system and compensate for the displacement and deformation caused by impacts between pipeline systems, various types of flexible joints are used on ships [1,2]. Balanced arc body flexible pipe (hereinafter referred to as arc pipe) is a new type of flexible pipe, which has the advantages of self-balancing, simple structure, relatively small size, high compressive strength and compensation displacement [3,4]. Balancing performance refers to the measurement of the change in the axial length under the working pressure or the force to prevent its axial deformation under normal working conditions of the flexible pipe [5].

The stiffness of the arc pipe is an important indicator of the performance. This article addresses traditional stiffness design methods such as the graphical solution method and the empirical formula method are difficult to predict the stiffness of the arc pipe accurately and there are also issues such as high costs and limitations. Using the finite element software ABAQUS modeling simulation method to obtain the relationship between the axial static stiffness characteristics of the arc pipe and the working pressure, the number of cord layers, and the density of the cord. An experiment was designed to verify the results. The experimental results agree well with the simulation results which prove the accuracy of the model. The conclusions obtained in this paper can provide theoretical basis for the development of high-performance arc pipes.
2. Parameterization calculation

This article takes a certain type of arc pipe as the research object, and its structure is shown in figure 1. The arc pipe is mainly composed of four parts: an inner rubber layer, a skeleton layer, an outer rubber layer and a joint structure. Skeleton layer is composed of cords and it is the main bearing component. Skeleton layer is composed of multiple layers between inner and outer rubber layers. Each layer is cross-covered at a certain angle and exhibits anisotropic characteristics. The rubber used for each adhesive layer is a vulcanize containing various fillers. The joint structure uses a three-flange structure which not only ensures the ability of the joint to resist pulling out, but also improves the displacement compensation ability and vibration reduction performance by increasing the relative length of the flexible section of the pipe body.

Studies have shown [6] that the arc pipe static stiffness $K$ is:

$$K = E_t l / B - \frac{R_2}{R_1} \frac{1}{\sin^2 \alpha} \left[ \frac{R_2}{R_1} \frac{1}{\sin \alpha} 1 + \frac{\mu R_2}{R_1 t g^4 \beta} \right] \left[ \frac{R_2}{R_1 t g^4 \beta} \mu + \frac{R_2}{R_1 t g^4 \beta} \right] \left[ \frac{1}{2 \pi R_2 \sin^2 \alpha} \right]$$

Among them:

$$B = \int_{\alpha}^{\beta} \frac{R_1}{\sin \alpha} \left[ 1 + \frac{\mu R_2}{R_1 t g^4 \beta} \right] \left[ \frac{R_2}{R_1 t g^4 \beta} \mu + \frac{R_2}{R_1 t g^4 \beta} \right] \left[ \frac{1}{2 \pi R_2 \sin^2 \alpha} \right] d\alpha$$

Figure 1: Arc pipe structure and pipe model

In the formula, $\alpha$ is the radial coordinate that is the normal direction of the outside of the pipe body and the right angle of the axis in Figure 1. $R_1$ and $R_2$ are respectively the radial and circumferential densification coefficients that is the radius of curvature of the pipe body and the radius of curvature are taken by the distance between the busbar and the axis; $N_1$ and $N_2$ are the radial and circumferential internal forces; $p$ is the static pressure on the pipe body, $\mu$ is the Poisson's ratio, $E_t$ is the radial macro elastic modulus of pipe body material, $t$ is the thickness of the pipe body, $E_f$ is the product of the area of a cord and its elastic modulus, $\rho$ is the average linear density of the circumferential axis, $\beta$ is the cord angle. Because the $\beta$ value of the arc pipe varies little, it can be considered as a constant.

The formula shows that the axial stiffness of the arc pipe is positively related to the distance between the cord layer and the number of cord layers. Under certain geometric parameters, the axial
deformation is proportional to the internal pressure and the axial force, that is, the static stiffness is a certain value.

3. Finite element simulation analysis

Because the arc pipe wall is a rubber-cord composite material. A rubber-cord rib model can be used to treat cord rubber and cords as two materials. The mechanical properties of cord fabrics are anisotropic and need to be described using nonlinear materials [9]. The constitutive relation of rubber material is very important for the finite element simulation of arc pipe, and it is usually described by the strain energy function of Mooney-Rivlin model [7,8]:

$$W(I_1, I_2) = C_{01}(I_1 - 3) + C_{02}(I_2 - 3)$$

(4)

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$

(5)

$$I_2 = \lambda_1^{-2} + \lambda_2^{-2} + \lambda_3^{-2}$$

(6)

In the formula: $W$ is the strain energy function; $C_{01}$, $C_{10}$ is the Rivlin coefficient; $I_1$, $I_2$ are the first and second Green strain invariants; $\lambda_1$, $\lambda_2$ and $\lambda_3$ are the elongation rates in the three stretching directions. The cord is a skeleton material in the wall of the arc pipe, and is a main load-bearing part, which is made of Kevlar fiber. The Rebar element M3D4R was used in the finite element software ABAQUS to simulate the cords, the three-dimensional stress element C3D8RH was used to simulate the rubber, and the three-dimensional stress element C3D8R was used to simulate the upper and lower covers. The cord winding angle was arranged according to the calculated theoretical winding angle 52°. At this winding angle, the arc pipe will not generate axial force and displacement when only internal pressure is applied and has a good balance.

Figure 2: Axial static stiffness finite element calculation model

Create a load step. First, create an inflation step, fix the displacement of the upper and lower cover plates of the arc pipe, and apply a certain pressure to the model. Due to the good balance of the arc tube, the displacement change is very small, and the volume of the arc tube basically does not change so the gas pressure is used directly. The surface forces acting on the arc pipe wall are replaced by equivalent ones to simplify the calculation. Next, the assembly step is created, the displacement constraint of the upper cover plate in the axial direction is released, and the constraint in the other direction is not changed. The reading vertical direction is different from the following upper cover plate reaction force.

3.1 Study on the Influence Factors of Working Pressure

In the finite element model of the arc pipe, the area of the cord is 0.567mm$^3$. The spacing between the two layers of the ply is 1mm. The number of cord layers is four. Two different initial pressures of 2MPa, 2.5MPa, and 3MPa are set in the cavity. Set the displacement load for vertical compression -2mm, stretch 2mm. By reading the displacement and reaction force at the reference
point of the cover plate of the arc pipe, the axial load-displacement curve under different working pressure conditions is shown in Figure 3.

![Figure 3: Displacement load curve at different pressures](image)

As can be seen from Figure 3, the axial characteristic curve of the arc pipe is approximately a straight line at the same working pressure. It shows that the arc pipe is proportional to the internal pressure and the axial load under certain geometric parameters. That is, the static stiffness is a certain value which is consistent with the previous conclusion. Second, when the working pressure increases from 2 MPa to 3 MPa, the slope of the axial displacement-load curve increases. That indicates the axial static stiffness increases with the increase of working pressure, and the axial static stiffness is positively correlated with the working pressure.

### 3.2 Study on the Influence Factors of Cord Layer Spacing

In the finite element model, the distance between adjacent two cord layers is defined as the cord layer spacing. When the working pressure was set to 2.5 MPa and the other conditions stay unchanged, the cord layer spacings were changed to 0.8 mm, 1.0 mm, and 1.2 mm, respectively, and the load-displacement characteristics curve at different layer spacings was shown in Figure 4.

![Figure 4: Displacement load curve with different cord spacing](image)

From Figure 4, it can be seen that when the working pressure is determined, the load-displacement curve of the arc pipe under different cord layer spacing almost completely coincides with the increase of the distance between the cord layers. Although the arc pipe stiffness increases synchronously with the increase in the spacing of the line layers, but the degree was very small. That phenomenon indicates that the spacing of the cord layers had a relatively small effect on the arc pipe.
3.3 Study on the Influence Factors of Cord Layers Number

Changing the number of Rebar layers in the model can change the number of cord layers of the arc pipe. When the working pressure is 2.5MPa and the distance between cord layers is 1mm, the number of cord layers is set to 2 layers and 4 layers respectively. The load-displacement curve is shown in Figure 5.

As can be seen from the figure, as the number of cord layers increases, the slope of the load-displacement curve rises, the axial stiffness of the arc pipe increases. It indicates that the axial static stiffness has a positive correlation with the number of cord layers. However, the increase in static stiffness is not significant. In engineering practice, the cost required to change the number of cord layers is high. It is not economical to develop low-rigidity high-performance flexible joints by this method.

4. Axial static stiffness test

In order to verify the accuracy of the finite element model of the axial static stiffness simulation of the arc pipe established in the previous article, the axial static stiffness test of the flexible internal pressure of the arc body was carried out at 2 MPa and 3 MPa, respectively. The test platform is shown in figure 6. The arc pipe is pressed through the seal ring and clamped on the MTS tester through a clamp. Underneath it, a nitrogen bottle with a pressure gauge is connected through a pipe joint to pressurize. During the test, the internal pressure of the arc pipe is kept constant. After the pressure is filled, the reaction force is read by loading the displacement load and effective test data is recorded.

Axial static stiffness simulation and test results are shown in Figure 7. It can be seen that the simulation results are very close to the experimental results and the relative errors are calculated to be 6.5% and 3.6%, respectively (Table1). This shows that the method for calculating the axial static stiffness of the arc pipe studied in this paper is feasible.
5. Conclusion

In this paper, the stiffness characteristics of a certain type of arc-shaped flexible pipe are studied. In view of the defects of the traditional calculation methods, the correctness of the theoretical model is proved through the finite element simulation. Axial stiffness test was designed and carried out. The comparison between the experimental data obtained and the simulation data shows that the finite element model has a good accuracy and at the same time it proves the effectiveness of the research method. The conclusions are as follows:

1. In the case of the geometric parameters of the arc pipe body, the axial deformation of the arc pipe is directly proportional to the axial force, i.e., the axial static stiffness is a certain value. The higher the working pressure of the arc pipe is, the greater the axial static stiffness is, and the axial static stiffness is positively related to the working pressure. As the number of cord layers increases, the axial stiffness of the curved tube increases, but the increase is not significant. In engineering practice, the cost required to change the number of cord layers is high. It is not economical to develop low-rigidity and high-performance flexible joints by this method. Increasing the spacing between the cords will increase the static stiffness of the shaft slightly, but the increase is almost negligible.

2. Compared with the traditional method of combining mathematical models and experiments, the calculation of the finite element method is more convenient and rapid for high-performance arc pipe design, providing a more economical and effective method for modern design. The results in this paper can provide a theoretical basis for the selection of the stiffness design parameters of arc pipe and provide theoretical guidance for the production of high-performance arc pipe.
REFERENCES


