Study on the Leakage Mechanism of Cone Sealing Structure in Metal Tube

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Abstract. Cone seal structure is widely used in metal tube connection of industrial equipment and ground vehicle. In vibration environment, the leakage failure of cone seal occur frequently, which will affect the function and reliability of the product directly. In this paper, the contact stress for typical cone sealing structure in low pressure metal tube under vibration loading is analyzed and the mechanism of liquid leakage failure is discussed using the finite element numerical method. Results show that the circumferential contact stress distribution is uneven on the interface of cone sealing structure under the cyclic load introduced by local vibration. The contact stress is significantly lower than the initial pretension stress in some areas, which will result in the leakage failure of cone sealing structure.

1. Introduction
The cone sealing structure is widely used in metal tube connection of industrial equipment and ground vehicle for it is easy to assemble, costs less, and can be used in conjunction with the rubber ring. However, leakage failure of cone seal occur frequently under vibration and other external loads due to the local pressure change on the conical sealing surface, which will influence the function and reliability of the product [1]. In this paper, the contact mechanics model for a 24 degree cone sealing structure containing rubber ring is established, the temporal and spatial distribution of pressure on the interface under typical external load is determined through finite element calculation, and the effects of vibration amplitude and the fastening torque on the leakage failure of the cone sealing structure are analyzed [2].

2. Finite element model
A half model is established according to the symmetric geometry of the cone sealing structure and the uni-directional vibration load. The 8 nodes linear hexahedral element is adopted to get the meshes, as shown in Figure 1.
Materials of cone tube, fastening nut and joint body are steel, whose elastic modulus is 210000MPa, Poisson's ratio is 0.3, yield strength is 355 MPa, tensile strength is 600MPa and elongation percentage is 16%. The bilinear elastic-plastic constitutive model is adopted in the calculation. Material of rubber ring is treated as super elastic model, and the Mooney-Rivlin polynomial strain potential energy model is used to describe the stress-strain relationship:

\[
U = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \frac{1}{D_1}(J_{el} - 1)^2
\]

where \(U\) is the strain potential energy, \(J_{el}\) is the elastic volume ratio, \(I_1\) and \(I_2\) are the deformation measurement of the material, \(C_{ij}\) and \(D_i\) are the temperature dependent material parameter. For the rubber ring in this paper, \(C_{10}\) is 1.34, \(C_{01}\) is 0.33, and \(D_1\) is 0.0001.

The assembly process and pre-stress of the rubber ring are simulated by the cold contraction and re-expansion of the cone tube. The thermal expansion characteristics of cone tube are defined as anisotropic. The fastening nut, rubber ring, and joint body have no thermal expansion. The thermal expansion coefficient is 0.01 along the radial direction, the initial temperature, intermediate temperature, and final temperature are set to 0°C, -25°C, and 0°C respectively. During the cooling process, the outer diameter contraction of the groove can make the rubber ring assemble correctly, and the sealing components will contacted effectively when the temperature reaches 0°C.

The boundary conditions are shown in Figure 1. The symmetric constraints are applied to x-y plane, and the freedom of x and y directions at the right end cone of the joint are constrained. The pretension load of the nut is 3000N. The triangular wave cycling displacement with the amplitude of 0.3mm and mean value of 0 is applied to the left end surface of the cone tube.

The surface-to-surface contact is set between the cone tube and the nut, the cone tube and the rubber ring, the rubber ring and the joint body, the cone tube and the joint body, the internal threads of the nut and the external threads of the joint body. The sliding mode is set to be finite sliding. The contact behavior between each contact pair is simulated by a penalty friction in the contact interaction property definition [3]. The friction coefficient is set to 0.1, and the hard contact is applied to the normal contact.

3. Results and Discussions
To discuss the influence of vibration load on the sealing performance of this cone sealing structure, the overall stress distribution and the contact pressure distribution in the sealing area are calculated.

The Mises stress distribution of the structure under the pretension load when the left end of the cone tube reaches the displacement of 0.3mm, 0 and -0.3mm are shown in Figure 2 (a) - (d), respectively.
The overall stress distribution of the cone sealing structure is axially symmetrical about the tube axis under the pretension load. The relatively uniform high stress distribution exists around the rubber ring. When the displacement of cone tube end is 0.3mm, the overall stress around the rubber ring is still large, but some local stress concentration areas can be observed. When the displacement of the cone tube end is back to 0, the local stress concentration reduced significantly. However, compared to the stress field under the pretension load, the stress distribution around the rubber ring is no longer uniform, which indicate that the material undergoes irreversible elastic-plastic cyclic process. When the displacement of the cone tube end is -0.3mm, the stresses of the whole structure have symmetry distribution with the displacement of 0.3mm for the cone tube end. Based on the above analysis, the repeated alternating displacement process are simulated, and the maximum Mises stress of the structure is extracted, as shown in Figure 3.

**Fig.2.** Mises stress distribution of cone sealing structure

![Mises stress distribution of cone sealing structure](image)

**Fig.3.** Maximum Mises stress of cone sealing structure under different working conditions

It can be seen that the maximum Mises stress of the cone seal structure is basically the same when the displacement of the cone tube end reaches the forward and reverse maximum values in an alternating displacement cycle, respectively. However, the maximum Mises stress in the second alternating displacement cycle is significantly greater than that of the first cycle, which indicates that the local concentrated stress of the cone seal structure under vibration trend to be serious, namely the uniformity of the internal stress distribution in the structure is enhanced. At this situation, it is difficult to maintain a stable sealing performance for this structure.

Taking into account the influence of the contact pressure on the seal performance, the contact pressure distributions under different load conditions are analyzed. When only pretension is applied, the distribution of the contact stress on the contact surfaces is shown in Figure 4. The contact pressure on each contact surface is symmetrically distributed. The contact pressure on the rubber ring groove at the cone surface reaches 580Mpa, and the contact pressure on the rubber ring is about 380Mpa.
These two components work together to realize the sealing function. From the view of contact pressure, the rubber ring is mainly used to dynamically compensate the radial displacement between the cone tube and the joint body, and it does not take the main sealing effect.

The contact stress distribution on the cone surface with displacement 0.3mm, 0, -0.3mm and 0mm are shown in Figure 5(a) - (d) respectively.

It can be seen that the inhomogeneity of the circumferential stress distribution in the effective seal area of the cone surface increases remarkably under the action of cycling displacement. The contact stresses in some areas can reach 620Mpa which are greater than the initial contact stresses, but stresses in other areas are less than 400Mpa which are much less than the initial contact stresses. In this case, the leakage possibility of the cone sealing structure will increase greatly.

4. Conclusion
The cone seal structure relies on the plastic deformation in the contact area between the cone tube and the joint body to achieve sealing function. The contact stress in the rubber ring is far below the stress in groove area, so it is mainly used to compensate for the radial displacement between the cone tube and the joint body. The contact pressure in the sealing area along the circumferential direction is non-uniform under the cycling displacement caused by the vibration load. The contact pressure in some sealing torus areas will be significantly lower than the contact pressure under the preload condition, which will result in the leakage failure of cone sealing structure.
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