PIPELINE LEAKAGE ANALYSIS AND VIBRATION STUDY OF A REFRIGERATION SYSTEM

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Aiming at the vibration leakage phenomenon of refrigeration system pipeline of a civil space equipment, the main leakage location was tested and analyzed. To obtain the cause of leakage, the finite element model of the fusion pipeline installation state was constructed, and modal vibration simulation analysis of the pipeline structure was carried out. Using three axial random response and harmonic response to simulate the actual vibration condition of the product. Under the actual vibration condition, the main stress concentration point of the designed structure is the joint of square tube and circular tube, and the maximum equivalent stress cloud and displacement cloud diagram of X-direction, Y-direction and Z-direction of the vibration of pipeline was obtained under vibration excitation. The main stress concentration point of the structure was the joint of square and circular tube, and the maximum three-direction stresses of the pipeline are 8.15 MPa, 9.19 MPa and 7.05 MPa, which are much lower than the yield strength (165 MPa) and tensile strength (235 MPa) of 6063 aluminum alloy material. The simulation results verify the rationality of the design and provide an effective method for pipeline optimization design in complex environment.

Keywords: Pipeline; Harmonic Response; Random Vibration; Stress Nephogram; Element Mesh

1. Introduction

The refrigeration system is an important part of the normal operation of the equipment under many complex working conditions. Its stability and reliability are one of the key factors for the normal and efficient operation of the equipment. Hot and cold pipes are important components of the cooling system. Under environmental vibration conditions, its anti-fatigue characteristics will be

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greatly affected, leading to problems such as equipment operating efficiency, equipment failure, and pipeline leakage. Damage caused by fatigue is the most important cause of mechanical structure failure. The statistical results show that, among various fracture accidents of machinery, the accidents caused by fatigue failure account for about 80% [1]. Therefore, it is necessary to analyze the fatigue characteristics of the pipeline under the vibration environment.

Scholars at home and abroad have done a lot of research on pipeline fatigue damage and vibration, and have been widely used in aerospace, automotive, ship and mining machinery, and have achieved fruitful results. Menshykova and other researchers had compared the stress distribution of composite pipes under different pipe diameters. The function relationship between pipeline stress and material characteristics under different parameters was obtained [2]; Wu Xiao Nan et al. established a stress analysis model for gas pipelines in shield tunnels and obtained the location of stress-sensitive sections in the pipeline [3].Qu Wei et al. used the bidirectional fluid-solid coupling finite element method to solve the stress of the curved pipe based on the dynamic characteristics of the curved pipe of the hard rock tunneling machine [4]; Chen Guo et al.Effect of fluid velocity on pipe vibration [5].

Aiming at the leakage problem of the heat pipe of the refrigeration system of a certain space equipment, this paper uses the test method of test paper to find the leak point, simulates the actual environment, establishes a random and harmonic vibration model, construction of finite element model for vibration analysis of heat pipe,and obtain the fatigue characteristics of the pipe. Find out the cause of heat pipe leakage and damage, and provide reference for the design and improvement of heat pipe.The layout of pipeline system is shown in Fig.1, the system uses a total of four external heat pipes, including one visible heat pipe, one compressor heat pipe, and two expander heat pipe. The heat pipe material is 6063 aluminum alloy, and its elastic modulus is as follows: the elastic modulus is 70Gpa, the yield strength is 165Mpa, and the tensile strength is 235MPa [6].

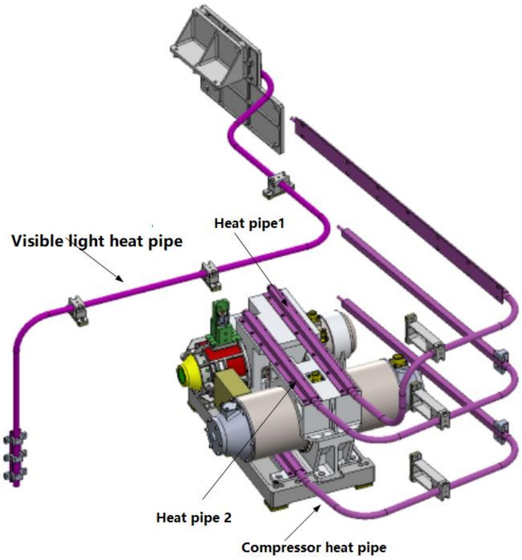


Fig. 1. Heat Pipe Layout

2. Heat Pipe Leakage Analysis

2.1 Leak Location Analysis

The heat pipe leakage occurred during the vibration test of the equipment refrigeration system. In order to find out the cause of the heat pipe leakage, the investigation was performed. The main process is described below.

1) First, use a heat pipe test paper to screen the suspected leaking heat pipe area [7]. Visible light heat pipe area discoloration test paper is not obvious, refrigerator heat pipe area test paper color continues to deepen, so it can be inferred that the refrigerator heat pipe area leaks.

2) Remove the multiple layers outside the heat pipe area of the refrigerator,use a hot air fan to heat the hot ends of the three heat pipes of the refrigerator. The cold ends of the three heat pipes have temperature rises. Therefore, it can be judged that there is still residual ammonia working medium in three heat pipes even if they leak.

3) Test the three heat pipe welds with a test paper. The color of the test paper has no change. It can be judged that the leak is not a weld.

4) Continue to use the test paper to test the whole body of three heat pipes. The test paper quickly changes color at the corner of the rear end of the heat pipe mounting the surface of expander heat pipe 1, and the other two heat pipes also

change color at the same position, but the change is slow and the color changes. The location is not directly opposite the pipe body. Given that the three heat pipes are close to each other, it can be determined that the leak of the expander heat pipe 1 may affect the vicinity of the other two heat pipes.

5) The final leakage is basically located at the transition section of the rear end of the expander heat pipe 1 and the compressor heat pipe installation surface, the three location are shown in Fig. 1.

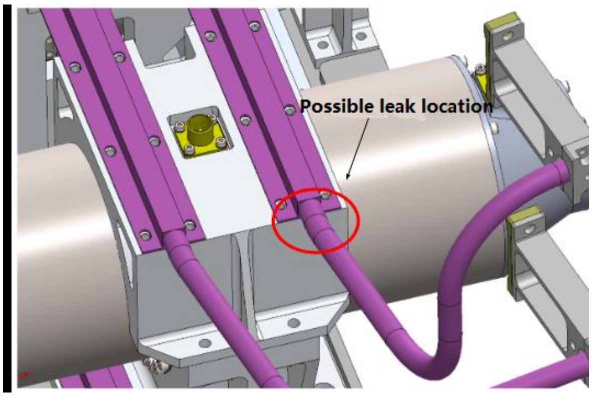


Fig. 2. Location of Leakage Point of Refrigeration System

2.2 Causes of Leakage

Through the above analysis, the system has leaked during the vibration test, combined with the leak point, it is mainly between the curved section of the pipeline and the rear end of the installation surface. After consulting a large amount of literature, it is found that when the vibration magnitude is large, the structural fatigue strength fatigue damage is easy to occur when it is insufficient. Structural vibration fatigue damage occurs frequently in complex vibration environments. The essence of vibration fatigue is that there are overlapping areas or intersections between the excitation frequency of equipment components and the natural frequency of the equipment itself, which causes resonance fatigue failure [8-10], therefore, the preliminary analysis shows that some parts of the heat pipe used in this system have structural fatigue failure.

3. Theory of Vibration Analysis

When the space running equipment is working, it mostly bears nonlinear vibration load, which includes low-frequency vibration and high-frequency vibration. Generally, random vibration and harmonic vibration can be used to comprehensively reflect its working condition. Therefore, this paper analyzes the harmonic vibration and random vibration response.

3.1 Harmonic Vibration Response

Sinusoidal vibration mainly comes from changes in engine thrust pulsation, equipment rotation imbalance [11], and interactions between equipment. Its main frequency range is 5~1000Hz [12]. In order to perform stress analysis on the heat pipe and apply harmonic load to it, the harmonic response of each degree of freedom is obtained. The original mechanical model of free vibration is [13-15]:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\} \tag{1}$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness of the tested object respectively; $\{u\}$ and $\{F\}$ are displacement vector and load function respectively.

$$\begin{aligned}\{F\} &= \{F_{max}e^{i\psi}\}e^{i\omega t} = (\{F_1\}+i\{F_2\})\ e^{i\omega t}\\ \{u\} &= \{u_{max}e^{i\psi}\}e^{i\omega t} = (\{u_1\}+i\{u_2\})\ e^{i\omega t}\end{aligned} \tag{2}$$

where F_{max} is the magnitude of the load and ψ is the phase angle of the load function; F_1 is the real part that is $F_{max}\cos\psi$, F_2 is the imaginary part that is $F_{max}\sin\psi$; u_{max} is displacement amplitude; u_1 is displacement amplitude that is $u_{max}\cos\psi$; u_2 is the imaginary part that is $u_{max}\sin\psi$.

Obtain the dynamic equation of the harmonic load by eq. (1) and eq. (2):

$$(\omega^2[M]+i\omega[C]+[K])(\{u_1\}+i\{u_2\})=(\{F_1\}+i\{F_2\}) \tag{3}$$

According to the harmonic response analysis, the eq. (2) and eq. (3) are comprehensively applied, and the limit values of stress and displacement response can be obtained in the corresponding frequency range, so the weak nodes of fatigue failure of the heat pipe can be found.

3.2 Random Vibration Response

Random vibration mainly comes from the exhaust noise of the air-conditioning equipment and the noise of high-speed airflow in the space. It belongs to broadband vibration, and its frequency range is about 0.5~10 KHz [11].

Random vibration is a type of vibration that cannot be expressed with precise mathematical formulas. Most of the random vibrations in engineering problems are due to random responses caused by random excitation. In order to facilitate analysis, most of the system parameters are considered to be definite. Therefore, the stochastic response calculation process of the deterministic system under various conditions is [16,17]:

$$S_y(w) = |H(w)|^2 S_i(w) \tag{4}$$

where $S_y(\omega)$ is the system response power spectrum, $|H(\omega)|$ is the system response function modulus ,and $S_i(\omega)$ is the excitation power spectrum density.

Then the mean square power density value of the random vibration response is:

$$\Psi_y{}^2 = \frac{1}{\pi}\int_0^\infty S_y(\omega)d\omega \tag{5}$$

Generally, in practical engineering applications, input power spectral density is used for calculation according to eq. (5), the solution setting is completed in the workbench. The calculation results can directly obtain the deformation displacement cloud map and equivalent stress cloud map of the heat pipe in three directions.

4. Construction of Finite Element Model

In order to analyze the cause of leakage in a deeper level, the vibration modal analysis is performed on the system. A finite element model of the pipeline system must be constructed before the modal analysis. The heat pipe finite element model is built using Solid hexahedron elements, consisting of 26494 solid elements and 58 rigid elements. The actual geometry of the heat pipe is a special-shaped hole, which is equivalent to a circular hole, as shown in Fig. 3.

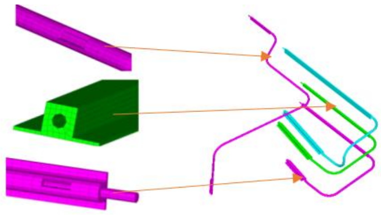


Fig. 3. Details and general diagram of the heat pipe grid model unit

In the model construction, the model is fully considered and meets the actual requirements, and the model is optimized. In the mesh division, the node between the cylindrical and square of the heat pipe is directly fused together to make it a whole. The actual working conditions are more consistent, and the main details are shown in Fig. 4.

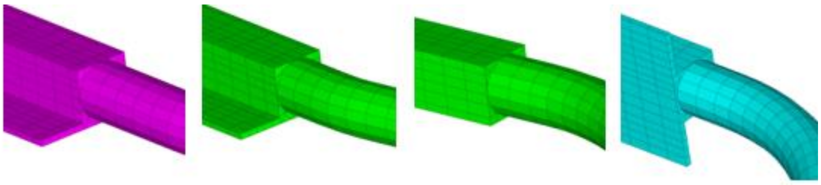


Fig. 4. Fusion details of round and square heat pipe nodes

In the analysis of the entire system, the interaction between the pipeline and the connector is fully considered. The number of rigid units connected to other parts is strictly based on the actual number of bolts. As shown in Fig. 5, the connection details of the heat pipe and other parts are compared with the CAD model.

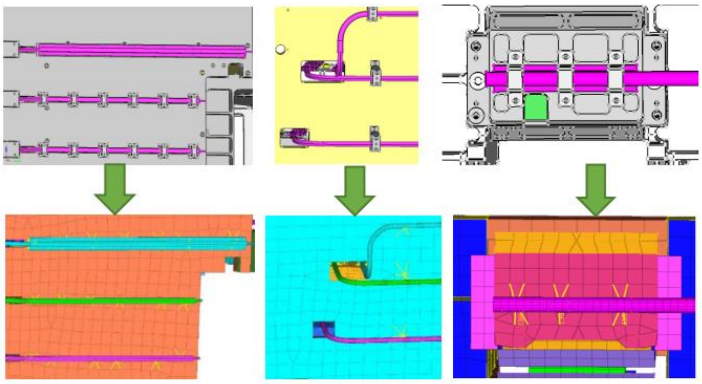


Fig. 5. Grid Model of Major Node Connections

5. Heat Pipe Vibration Analysis

This design is based on Workbench software, which simulates the various vibration environments encountered by the product under transport, installation and operating conditions. It is used to test whether the product can withstand various vibration environments. The most commonly used vibration mode is sinusoidal vibration, scanning vibration, random vibration, and compound vibration. Sinusoidal vibration is often used in experimental test analysis to simulate the excitation response of the product under periodic vibration, pulsation and vibration. It is mainly used for resonance analysis. Random vibration simulates the strength of the entire structure of the product during installation, transportation and operation. Comprehensively consider and analyze the system environment where the heat pipe is located. In order to more effectively assess the product's vibration resistance and quickly obtain product defects and weak links, this paper mainly uses a random vibration and harmonious response for simulation and comprehensive analysis.

5.1 Harmonic Response Analysis

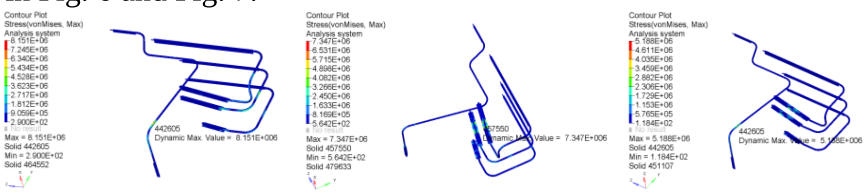
According to the working environment of the heat pipe, the working parameters of the system are set as shown in Tab. 1.

Table 1

Sine vibration test conditions

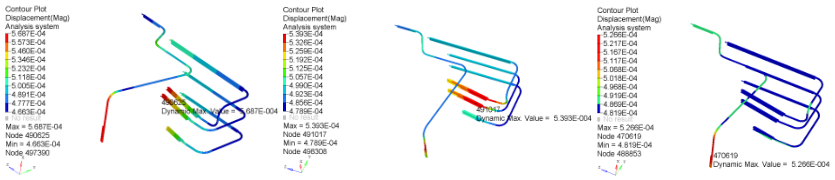
Serial number	Test conditions	Parameter requirements
1	10 ~ 20Hz	5.625mm (0-P)
2	20 ~ 100Hz	9g
3	Scan rate	2oct / min
4	Loading direction	Three axes

According to the working conditions required in Table 1, sinusoidal vibration loads in the three directions of X, Y, and Z are applied to the fixed end of the pipe model in Fig. 2, and the harmonic response of the heat pipe is calculated to obtain the stress and displacement cloud diagrams of the model, as shown in Fig. 6 and Fig. 7.



X direction Y direction Z direction

Fig. 6. Stress cloud diagrams of the heat pipe in three directions



X direction Y direction Z direction

Fig. 7. Cloud diagram of displacement of heat pipe in three directions

It can be seen from the sinusoidal vibration stress cloud Fig. 6 and displacement cloud Fig. 7 that the X direction has a large displacement at the end of the heat pipe, and the stress is greater at the bolt connection and the transition between the round pipe and the square pipe; the Y direction is at the bolt connection and the round pipe The part where the transition with the square pipe is relatively stressful, and the displacement in the transition area between the circular pipe and the square pipe is relatively large; the Z direction is relatively more stressed at the bolt connection site and the transition area between the circular pipe and the square pipe, at the end of the heat pipe and the circular pipe The transition area with the square tube is relatively large.

5.2 Random Response Analysis

Compared with harmonic vibration, random vibration is more severe. Random vibration is a kind of statistical forced vibration, which reflects the probability statistics of the structure's response to random dynamic loads. The response is expressed by the mean value of stress.

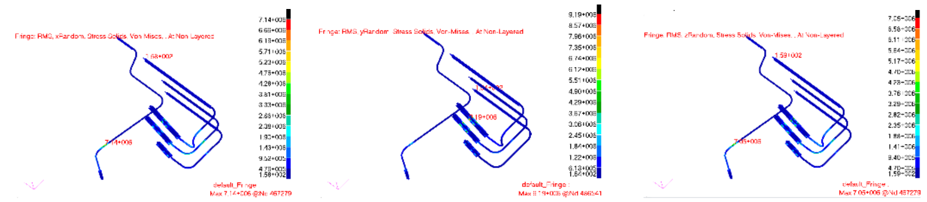
According to the working environment of the heat pipe, the working conditions of the system are set as shown in Table 2.

Table 2

Random vibration test conditions

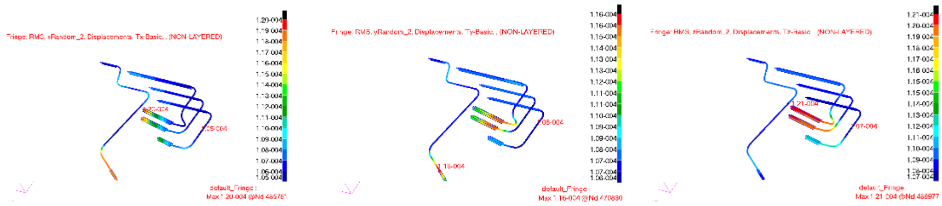
Serial number	Test conditions	parameter	Serial number	Test conditions	parameter
1	10 ~ 65Hz	+ 6dB/oct	5	450~2000Hz	-18dB / oct
2	65~100HZ	$0.8g^2$ /Hz	6	Total root mean square value	10Grms
3	100~200Hz	0.8～$0.08g^2$ / Hz	7	Loading time	2min
4	200~450Hz	$0.08g^2$ / Hz	8	Loading direction	three axial

According to the working conditions required in Table 2, the random vibration characteristics of the model in Fig. 2 were simulated, and the stress and displacement clouds of the model were obtained, as shown in Fig. 8 and Fig. 9.



X direction Y direction Z direction

Fig. 8. Stress cloud diagrams of the heat pipe in three directions



X direction Y direction Z direction

Fig. 9. Cloud diagram of displacement of heat pipe in three directions

From the random vibration stress cloud Fig. 8 and displacement cloud Fig. 9, it can be seen that the stress of the bolt connection part, the transition part between the round pipe and the square pipe are relatively large in X, Y and Z direction, and the displacement are also relatively large at the end of the heat pipe in X, Y and Z direction.

5.3 Analysis of Simulation Results

The stress cloud diagram and displacement cloud diagram of the three-way vibration are extracted and analyzed in Fig. 6 to Fig. 9, and the maximum stress and maximum displacement data are obtained shown in Table 3.

Table 3

Maximum stress and displacement

Serial number	direction	Sinusoidal vibration		Random vibration	
		Maximum stress (MPa)	Maximum displacement (mm)	Maximum stress (MPa)	Maximum displacement (mm)
1	X	8.15	0.65	7.14	0.15
2	Y	7.35	0.64	9.19	0.13
3	Z	5.19	0.76	7.05	0.20

From the analysis results of the table, the maximum value of the vibration stress in the three directions is 9.19 MPa, and the maximum value of the vibration displacement in the three directions is 0.76 mm, but it is still far less than the yield strength (165 Mpa) and tensile strength of the 6063 aluminum alloy used in the heat pipe. Strength limit (235 MPa), the maximum displacement mainly occurs at the joint of the end face of the pipe and the transition position of the round square pipe, which is also far less than the physical distance of the pipe.

6. Conclusion

Combining the results of leak investigation and simulation analysis data can be inferred:

1) The maximum stress appears between the round and square of the heat pipe, and there will be slight stress concentration in the transition area, especially in the two heat pipes of expander, which are easy to release under the complex vibration and impact load environment, leading to the fatigue failure of the pipe;

2) The maximum equivalent stress and strain of the pipeline appear at the fixed position of the bolt connection, which indicates that the support of the pipeline is a dangerous section of stress, but the simulation results are far from reaching the yield deformation limit and no plastic deformation occurs. However, in order to prevent the local stress of the heat pipe from expanding, it is suggested to adopt the soft connection support in the design, so as to reduce the additional stress concentration as much as possible;

3) The location of the heat pipe bend also has different degree of stress concentration, but they are far below the stress limit of the material selection. The simulation results also exclude that the leakage of the heat pipe is due to the excessive stress of the pipeline itself, which verifies the correctness of the overall design of the pipeline system;

4) The large displacement of the heat pipe mainly occurs at the end face and transition position of the pipe. And the maximum displacement in three directions is far less than the physical distance of the pipeline, its structural strength meets the engineering requirements.

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