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Simulation and Experiment Research on Fatigue Life of High Pressure Air Pipeline Joint

Jin Shang, Jianghui Xie, Jian Yu, Deman Zhang
Wuhan Second Ship Design and Research Institute, Wuhan, 430064, PRC

Abstract. High pressure air pipeline joint is an important part of high pressure air system, whose reliability is related to the safety and stability of the system. This thesis developed a new type-high pressure air pipeline joint, carried out dynamics research on CB316-1995 and new type-high pressure air pipeline joint with finite element method, deeply analysed the join forms of different design schemes and effect of materials on stress, tightening torque and fatigue life of joint. Research team set up vibration/pulse test bench, carried out joint fatigue life contrast test. The result shows: the maximum stress of the joint is inverted in the inner side of the outer sleeve nut, which is consistent with the failure mode of the crack on the outer sleeve nut in practice. Simulation and experiment of fatigue life and tightening torque of new type-high pressure air pipeline joint are better than CB316-1995 joint.

Key words: high pressure air joint; fatigue analysis; design optimization.

1. Foreword
High pressure air pipeline joint is an important part of high pressure air system, its function is sealing medium, connecting system pipeline, whose reliability is related to the safety and stability of the system. In the process of working, the joint usually subjects to the pre-tightening force, shear stress caused by the pipeline deformation and internal and external pressure, resulting in a high stress concentration phenomenon. This phenomenon not only affects the statics strength of the joint, but also reduces the fatigue life of the joint, which leads to the leakage of the air and the failure of the connection. As shown in fig 1, is outer sleeve nut fatigue damage. Therefore, it is important to analyze the stress distribution characteristics of the joints under different conditions, and improve the design to improve the fatigue life of the joints.

At present, the finite element simulation research of the joint has achieved some results. Chen Tie Yun [1] carried out research on elastic-plastic behavior, hot point strain of four kinds of joints with finite element method. Research shows: T style joint’s hot point position doesn't change in deformation process, but Y, K style joint’s change. Xi Jun Tong [2] set up a finite element model for the contact of casing joints based on characteristics of its structure and load with finite element contacts problem blenders method. Carried out finite element analysis on casing joints under 3 kinds of loads. Research shows: heterogeneity of loads has important effect on casing joint performance. Chen Yin Jie[3,4] carried out research on distribution rule of casing joint's contract pressure, displacement field, stress field under different loads. Research shows: distribution rules of contract pressure, displacement field, stress field under different
loads are basically consistent. Meanwhile, Tian Zeng [5], Xiang Heng Fu [6] and Zhang Zong Feng [7] have carried out thorough analysis on different structure quick joints stress under different loads with finite element method, the research results have a certain guiding role for the optimization design of the quick joints. For marine high-pressure air pipeline joint, Chen Sheng [8], Li Jun Chu [9] carried out numerical analysis and optimization design on high pressure air pipeline joint with finite element method. Research shows: optimized joint can withstand greater loads, maximum stress reduced. Li Yan [10] developed a kind of Fe based shape memory alloy joint with a good mechanical properties, in view of the failure of marine high-pressure air pipeline joint.

On the basis of existing research, the thesis focuses on the phenomenon of high pressure air pipeline joint damage. First, research team carried out optimization design on existing joints structure. Secondly, research team analyzed mechanics on joints under different conditions with finite element method. research team made the estimation of fatigue life of joints based on S-N fatigue curves of different materials. Thirdly, research team set up vibration/pulse test bench, carried out joint fatigue life contrast test, verified the new developed joint has better fatigue life than CB316-1995 joint.

2. Mechanical analysis model and boundary condition

2.1. design scheme

Existing high-pressure air uses CB 316-1995 joint, its style B is shown in fig 2, including rotary joint, right flat shoulder joint, left flat shoulder joint, outer sleeve nut, shim.

As shown in fig 3, is developed new joints structure, including rotary joint, flat shoulder joint, outer sleeve nut, shim (3,4). Design scheme combines rotary joint and left flat shoulder joint, to reduce the coaxial error of assembly. Set new shim (4) to reduce tightening torque. The outer sleeve nut material is replaced by anti occlusai, high strength alloy KA145 instead of QAL9-2.

Fig. 1 Fatigue crack damage of outer sleeve nut

![Fatigue crack damage of outer sleeve nut](image1)

Fig. 2 Structure of CB 316-1995 style B joint

![Structure of CB 316-1995 style B joint](image2)
2.2. Material model
In this study, we use the bilinear constitutive model of isotropic hardening to define the material properties of the joint. The material of each part of joint is: 1) rotary joint: HDR; 2) outer sleeve nut: QAL9-2, KA145; 3) shim: T2; 4) flat shoulder joint: HDR. Material models are shown in fig 4. Mechanical properties of materials is shown in table 1.

\[
\Delta \sigma (N_f)^{0.071778} = 832.87 \\
\Delta \sigma (N_f)^{0.055383} = 1423.96
\]

\(\Delta \sigma\): Stress (MPa); \(N_f\): Fatigue life.

2.3. Mechanical model
As shown in fig 6, the joint mainly affected by the shearing force, internal and external pressure, and the retightening force in operation. In this study, we fix one end of the pipeline, and load the total amount of deformation to the other end of the pipeline.
The retightening force on outer sleeve nut is 1kN. Pipeline radius deformation amount $\Delta \delta$ is 4mm, 6mm, 10mm as separately. The skip distances of pipeline are 2m, 3m as separately.

2.4. Mesh division

In order to better capture the chamfer of the stress distribution, the component is used to segment the hexahedral mesh and other regions take tetrahedral meshes. Mesh division of the joint is shown in fig 5.

![Mesh division of the joint](image)

Tab. 1 Mechanical properties of materials

| Material | $\rho$ [kg/m$^3$] | E [GPa] | $\lambda$ [-] | $R_{P0.2}$ [MPa] | $R_m$ [MPa] | A [%] | $\sigma_{\text{f1}}$ [MPa] |
|----------|------------------|---------|--------------|-----------------|-------------|-------|-------------------|
| HDR      | 7890             | 206     | 0.31         | 400             | 650         | 25    | 283.5             |
| QAL9-2   | 8300             | 110     | 0.34         | 430             | 540         | 15    | 261.9             |
| T2       | 8300             | 120     | 0.34         | 103             | 240         | 62    | 92.61             |
| KA145    | 8250             | 200     | 0.31         | 855             | 1305        | 20    | 583.2             |

(a) Loads on pipeline
3. Simulation result

We use ANSYS 14.5 to simulate stress and deformation distribution of CB316 and new joints. As shown in fig 7, maximum deformation of the pipe is at joint. As shown in fig 8, the maximum stress of the joint is inverted in the inner side of the outer sleeve nut, which is consistent with the failure mode of the crack on the outer sleeve nut in practice.

Calculation result is shown in table 2. The result shows:

1) The maximum deformation and stress of the joint are increased with the increase of the deformation of the pipe.
2) The maximum stress of the joint is reduced with the increase of the length of the pipe.
3) The maximum stress of the new joint is large than CB316-1995 joint.
4) The fatigue life of the CB316-1995 joint of QAL9-2 meets the 1 million design requirements under L=3m, Δδ=4mm condition.
5) The fatigue life of the new joint of KA145 meets the 1 million design requirements under all the condition.
Fig. 8 Stress distribution of outer sleeve nut ($\Delta \delta = 6$mm)

| Working condition | Pipeline deformation (mm) | Maximum stress of outer sleeve nut (MPa) | Fatigue life ($N_f$) |
|-------------------|---------------------------|------------------------------------------|---------------------|
|                   |                           | 4m | 6mm | 10mm | 4mm | 6mm | 10mm | 4mm | 6mm | 10mm |
| Design scheme     | Material of outer sleeve nut | Pipeline length (m) |                    |                    |      |      |      |      |      |      |
| CB316 - 1995      | QAL9-2                    | 2  | 6.95| 9.97|14.51|460.6|477.0|500.2|5.21E+05|1.16E+04|5.77E+01|
|                   |                           | 3  | 8.49|12.15|18.05|447.6|464.5|490.9|1.00E+07|2.07E+05|4.88E+02|
| New joint         | KA145                     | 2  | 6.83| 9.85|15.70|472.2|494.3|542.1|1.00E+07|1.00E+07|1.00E+07|
|                   |                           | 3  | 8.36|12.01|19.01|461.2|476.1|510.5|1.00E+07|1.00E+07|1.00E+07|
4. Experiment research
For comparie the fatigue life of two types of joint, we simplified the simulation working condition, with reference to 《Steel ships into grade standard Part 3》, built the vibration/pulse test bench. As shown in fig 9, the test bench is composed of hydraulic device, vibration source, control software, valves, pressure gauges, pipes. The test joint joins two pipes, one end of pipe is rigid fixed, the other end of the pipeline is provided with a power source, and the hydraulic device provides shock pressure. Operation interface of the control software is shown in fig 10.

Test condition:
1) Test medium: water
2) Amplitude: 0.4mm
3) Frequency: 20～50Hz
4) Shock pressure: 0～37.5MPa
5) Shock frequency: 0.5Hz

Qualified index: joint keep seal under condition of vibrate $10^7$ times with amplitude 0.4mm, Shock $10^4$ times with pressure 0～37.5MPa.

![Fig. 9 The vibration/pulse test bench](image1)

![Fig. 10 Operation interface of the control software](image2)

Test result is in tab 3.
Tab. 3 Test result

| Joint                  | Test result                                                                 |
|------------------------|-----------------------------------------------------------------------------|
| The new joint          | Meet the qualified index with tightening torque 550N.m                       |
| CB316-1995             | Leak at vibrate 90 times with tightening torque 900N.m; Meet the qualified index with tightening torque 1180N.m. |

5. Conclusion
This thesis carried out dynamics research on CB316-1995 and new type-high pressure air pipeline joint with finite element method, deeply analyzed the join forms of different design schemes and effect of materials on stress, tightening torque and fatigue life of joint. Research team set up vibration/pulse test bench, carried out joint fatigue life contrast test. The experiment research shows:

1. The maximum stress of the joint is inverted in the inner side of the outer sleeve nut, which is consistent with the failure mode of the crack on the outer sleeve nut in practice.

2. The maximum deformation and stress of the joint are increased with the increase of the deformation of the pipe. The maximum stress of the joint is reduced with the increase of the length of the pipe.

3. The fatigue life of the CB316-1995 joint of QAL9-2 meets the 1 million design requirements only under L=3m, Δδ=4mm condition. The new joint of KA145 meets the requirements under all the condition.

4. In the vibration/pulse test, the new joint meets the qualified index with tightening torque 550N.m, CB316-1995 joint leaks at vibrate 90 times with tightening torque 900N.m, meet the qualified index with tightening torque 1180N.m.

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