Fault Diagnosis of Gas Engine Bellows
Yu-shan JIN\textsuperscript{1,}*, Qing-ren ZHAO\textsuperscript{2}, Shou-le WANG\textsuperscript{3}, Xu-wei HU\textsuperscript{3} and Dan SUN\textsuperscript{4}
\textsuperscript{1}Shanghai Marine Diesel Engine Research Institute, Shanghai, China
\textsuperscript{2}College of Aerospace and Civil Engineering, Harbin Engineering University, Harbin, China
\textsuperscript{3}College of Power and Energy Engineering, Harbin Engineering University, Harbin, China
\textsuperscript{4}Harbin Marine Boiler& Turbine Research Institute, Harbin, China
*Corresponding author

Keywords: Fault diagnosis, Vibration test, Bellows expansion joint, Fatigue fracture.

Abstract. A bellow of an waste gas exhaust system has cracks after working 80 hours. Modal test and force source analysis were carried out for the system. It was found that cracks of the bellow was caused by resonance. The system dynamics model is established by using finite element software. The exciting force is introduced into the model. The load on bellows exceeds the maximum permissible stress. The bellow will have cracks in this state. The resonance region is avoided by modifying the structure. After structural adjustment, the bellow did not break again.

Introduction
The steel bellows has good ductility, high tensile strength, light weight, good durability and fast construction speed. It is widely used in engineering\cite{1}. The performance and reliability of steel bellows is highly dependent on the design. Hamada\cite{2} provided theoretical design formulas and standards for bellows designers. In connection with the unreinforced U-shaped titanium bellows, Qin\cite{3} deduced the fatigue life design formula accordingly and analyzed its fatigue fracture form. Ghader Faraji\cite{4} described the relevant finite element parameter extraction in the process of manufacturing metal bellows. He gave specific description of the relevant parameters. Tu\cite{5} found that the bellows expansion process is equivalent to the secondary processing of itself. There are residual stresses on the inner and outer surfaces of the approximate round tube after forming. Mehrabadi\cite{6} found that the stress of the bellows after expansion focus on the inner side of the original wave peak. The outer side of the trough and the stress value is related to the cross-section shape of the bellows. The more the number of flaps, the denser the residual stress distribution.

Fault Situation and Analysis
Fault Situation
During the test of the bellows of a gas turbine waste bypass system, two fractures were reported. The first was found after 320 hours of durability. The second was discovered after 80 hours of replacement.

![Figure 1. Schematic diagram of waste gas bypass system and broken bellows photos.](image-url)
Fig. 1 (a) is a schematic view of the waste gas bypass system; Fig. 1 (b) (c) is a physical photograph of a damaged bellows which is located on the right side in Fig. 1 (a).

It can be seen from Fig. 1(b)(c) that the damaged bellows has multiple cracks. The crack A and the crack B are spaced apart by about 180°.

**Waste Gate Bypass System Modality and Response Test**

The figure below shows the test site and measuring point layout of the waste gate system.

![Figure 2. Modal test.](a)

The xy3 three-way definition is shown in Fig2(b). The main test instruments are B&K3560C tester, normal temperature acceleration sensor and so on. The modal test results are shown in Table 1.

<table>
<thead>
<tr>
<th>Modal</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>55.8</td>
<td>69.9</td>
<td>102.9</td>
<td>111.7</td>
<td>131.6</td>
<td>143.0</td>
</tr>
</tbody>
</table>

It can be seen from the response results that the main peak of the response in the X direction is at 58.5 Hz (3.5 times ultimate frequency). The main peak of the response in the Y direction is at 67 Hz (4 times ultimate frequency). The main peak of the response in the Z direction is at 58.5 Hz (3.5 times ultimate frequency). The above multiple axial frequencies are close to the first-order and second-order natural frequencies. It is estimated that the bellows resonates at these natural frequencies.

**Modal and Response Calculation of Waste Gate System**

**Establishment of Finite Element Model**

This paper mainly analyzes the waste gas bypass system. So we just need mainly model and calculate it. Some simplifications are made to ensure that the quality and center of gravity of the model are consistent with the actual structure. The simplified model is shown in Fig.3. The simplified geometric model is imported into the Hypermesh software for meshing. Solid part adopts Solid185 unit. The two bellows flanges are bolted to the bypass valve flanges where the BEAM188 unit is used to simulate the bolts. The finite element model is shown in Fig.4.
Boundary Conditions

1) The connection relationship between the inlet and outlet of the system and the boundary. Bracket and boundary is simulated by the three-way spring unit. The stiffness of the three springs is identified by the modal test and assigned to the properties of the Combin14 unit.

2) Free boundaries are set in other locations.

Analysis of Modal Results of Waste Gas Bypass System

The comparison of calculation the modal results with the test modal results.

<table>
<thead>
<tr>
<th>Modal order</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured mode (Hz)</td>
<td>55.83</td>
<td>69.88</td>
<td>102.94</td>
<td>111.74</td>
<td>131.57</td>
</tr>
<tr>
<td>Computational mode (Hz)</td>
<td>43.00</td>
<td>59.97</td>
<td>75.29</td>
<td>107.58</td>
<td>126.67</td>
</tr>
<tr>
<td>Error (%)</td>
<td>7.41</td>
<td>7.74</td>
<td>3.72</td>
<td>3.72</td>
<td>3.72</td>
</tr>
</tbody>
</table>

Among them, the calculation of 59.97Hz is basically consistent with the test of the 55.83Hz mode. The calculation of 75.29Hz is basically consistent with the test of the 69.88Hz mode. The calculation of 107.58Hz is basically consistent with the test of the 111.74Hz mode.

Response Calculation

The result is shown in the calculated stress cloud and time-stress curves. The maximum stress at the groove of the two bellows in the calculation time has exceeded the allowable stress of 44 MPa. The bellows work in this state for a long time, and thus fatigue fracture occurs.

Improvement Measures and Verification

1) Improve the installation accuracy of the bellows and minimize or even eliminate the initial deformation.

2) Strengthen the restraining stiffness of the bracket and the turbine end.

3) Add high temperature resistant lightweight gaskets at the left and right ends of the bellows.

After the gas bypass system of the gas machine has been adjusted, the bellows has not been damaged at present. In order to verify the improved reliability and durability of the structure, the modal and response test of the adjusted waste gas bypass system is performed. The results of the two modal tests are shown in Table 3 below.

<table>
<thead>
<tr>
<th>Modal</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>First modal result (Hz)</td>
<td>41.8</td>
<td>72.5</td>
<td>94.9</td>
<td>100.7</td>
<td>133.9</td>
<td>150.6</td>
</tr>
<tr>
<td>Second modal result (Hz)</td>
<td>55.8</td>
<td>69.9</td>
<td>102.9</td>
<td>111.7</td>
<td>131.6</td>
<td>143.0</td>
</tr>
</tbody>
</table>

It can be found that the modified structure has changed the natural frequency. Compared with the previous structure, the frequency values in the first six steps are different, and the frequency that may
cause resonance is avoided. By comparing the results of the two response tests, it is found that the amplitude of the second response under the 100% operating condition is lower than that of the first time, and the frequency with higher amplitude basically avoids the natural frequency of the structure. This shows that under this condition, the adjustment of the structure is beneficial to prolong the service life of the bellows.

Conclusion

1) Under the dynamic load, the bellows expansion joint is subjected to stress exceeding its allowable value. The bellows works in this state for a long time, and fatigue fracture occurs.

2) The bellows resonates at 58.5 Hz (3.5 times the axial frequency) and 67 Hz (4 times the axial frequency) caused the bellows to be coupled by lateral bending and axial compression. The fatigue is broken and cracks are generated.

3) After modification and adjustment, the overall natural frequency and mode of the first seven steps of the structure have changed. The frequency which may cause resonance is avoided.

4) After rectification, the amplitude of each measuring point is reduced. The connection between the gas machine and the whole is more stable.

Acknowledgement

The paper is founded by Marine Low-Speed Engine Project Phase I.

References


