Research on Frame Size of Vehicle Mounted Hydrogen Supply System Based on Parametric Design

Jinhao Huang\(^a\), Chenghong Duan\(^b\), Minghuang Zhao\(^c\) and Xiangpeng Luo\(^*\)

College of Mechanical and Electrical Engineering, Beijing University of Chemical Technology, Beijing, China

*Corresponding author e-mail: xpluo@mail.buct.edu.cn, \(^a\)18811406593@163.com, \(^b\)duanchenghong@163.com, \(^c\)zhaomh26@163.com

Abstract. The hydrogen supply system is the energy supply of hydrogen-powered vehicle. The failure of most parts in the hydrogen supply system is due to the impact and vibration caused by complex road conditions. Therefore, it is required that the hydrogen supply system should have good impact and vibration resistance. In this paper, the Design Exploration module in ANSYS Workbench is used to study the multi-objective optimization about the stiffness and strength of a two-bottle horizontal hydrogen supply system under impact and vibration conditions. The responding surface between the width and length of the frame and the stiffness and strength of the system under different conditions is developed. The optimal frame size which can effectively reduce the stress state of the system structure under impact and vibration condition is obtained.

1. Introduction

Many studies have been conducted on new energy systems as alternatives to exiting fossil-fuel-based energy systems [1]. Hydrogen has become a new energy source for its advantages of high efficiency, cleanliness, low carbon or carbon free, and it is one of the promising alternatives to conventional fuel in road transportation [2]. As a carrier of energy, the storage and transportation of hydrogen becomes very important. Failure of most parts of hydrogen system is due to random vibration which is resulted from road surface roughness and impact acceleration caused by complex road conditions [3]. Once the system fails, hydrogen leakage and structural strength or stiffness failure will happen [4]. Therefore, for vehicle hydrogen supply system, good anti-vibration and impact resistance is required.

In the optimization design of frame structures, scholars from both domestic and foreign countries have conducted some research and exploration. Zhong [5] took structural stiffness, weight and cost of a high-rise frame-core tube structures as control objectives, and meeting the requirements of structural specifications and oversize examination. Zhang et al. [6] used PKPM to establish several models of frame structure, frame shear wall structure, frame bracing structure, frame shear wall + bracing structure, and compared their use function, seismic force, cost and energy dissipation characteristics to optimize the structure. Aiming at safety and maximum stress, Changizi and Jalalpour [7] optimized the steel structure frame by using the method of topology optimization. Changizi et al. [8] proposed a stress topology optimization method for frame structures based on geometrical uncertainty. But when
synthesizing all the literatures, it is found that there was a lacking of research on the optimization of hydrogen system frame size.

In this paper, Design Exploration module in ANSYS Workbench is used. The length and width of the hydrogen system frame are taken as research variables, the stress and the deformation under the impact condition and the Power Spectral Density (PSD) random vibration condition are taken as target parameters. By parameterizing the process of impact analysis and random vibration analysis, and combining with response surface optimization module, the relationship between stress, deformation and frame size under the two working conditions is obtained. And then the optimized frame size is obtained.

2. Finite element model

2.1. Basic parameters
The research object of this paper is a two-bottle group horizontal hydrogen supply system, whose main components include hydrogen cylinder (aluminum and carbon fiber), frame (6063 aluminum), saddle (6061 aluminum), gasket (rubber), bandage (stainless steel), pin (45 Steel) and bolt (35 Steel), etc. The impact analysis applies an inertial acceleration of 8g in the horizontal X direction, and the PSD random vibration applies the PSD curve in the standard GB/T 4857.23-2012.

2.2. Analysis model
The key parts need to be checked are frame, saddle and connecting bolt. Therefore, mesh refinement of these three parts is carried out. And the cylinders which are not the concerned part are roughly divided. Fig. 1 shows the finite element mesh model of the whole hydrogen system, which is swept by solid186. The edge length of the element ranges from 5 mm to 10 mm.

![Figure 1. Finite element model.](image)

2.3. Boundary conditions and loadings

2.3.1. Impact analysis. Step 1: 1) Applying bolt pretension force with a displacement of 0.178 mm on the cylindrical surface of the eight connecting bolts; 2) Applying fixed restraint on the bottom of the frame; 3) Applying a gravity acceleration of 10 m/s². Step 2: 1) Setting the bolt pretension force to LOCK state; 2) Applying an inertial acceleration of 80 m/s² to the hydrogen system in X direction.

2.3.2. PSD random vibration analysis. Step 1: 1) Applying bolt pretension force with a displacement of 0.178 mm on the cylindrical surface of the eight connecting bolts; 2) Applying fixed restraint on the bottom of the frame. Step 2: 1) Reading the prestress field of static solution in Step 1; 2) Setting the frequency range of modal analysis 1-200 Hz; 3) Applying fixed restraint on the bottom of frame. Step 3: 1) Reading the modal solution in modal analysis in Step 2; 2) Applying a vertical vibration excitation of PSD power spectral density on the fixed restraint surface.
2.4. Optimizing parameter settings

The frame structure size B and L are set as input parameters, which are called driving parameters. L is the total length of the frame of the hydrogen system, and B is the 1/2 total width of the frame of the hydrogen system. In the input parameter field, the range of the parameters should be given. The range of parameter B is 200-250mm, and parameter L is 1316-1516mm. And there are eight output parameters in the optimization design of responding surface. They are the maximum stress of hydrogen system, the maximum stress of saddle, the maximum stress of frame, the maximum deformation of frame under impact condition; and the maximum stress of hydrogen system, the maximum stress of saddle, the maximum stress of frame and the maximum deformation of frame under PSD random vibration condition.

3. Results analysis and discussion

3.1. Impact condition

![Figure 2. Maximum stress responding surface of system.](image1)

![Figure 3. Maximum stress responding surface of saddle.](image2)

![Figure 4. Maximum stress responding surface of frame.](image3)

![Figure 5. Maximum deformation responding surface of frame.](image4)

| Objectives               | System stress | Saddle stress | Frame stress | Frame deformation |
|--------------------------|--------------|--------------|--------------|------------------|
| **Input parameters**     | B/mm         | L/mm         |              |                  |
| 227.31                   | 1316.00      |              |              |                  |
| 200.00                   | 1316.00      |              |              |                  |
| 227.31                   | 1316.00      |              |              |                  |
| 207.51                   | 1316.00      |              |              |                  |
| **Output parameters**    |              |              |              |                  |
| System stress/MPa        | **153.79**   | 244.85       | 153.79       | 216.31           |
| Saddle stress/MPa        | 101.95       | **59.03**    | 101.95       | 69.78            |
| Frame stress/MPa         | 153.79       | 244.85       | **153.79**   | 216.31           |
| Frame deformation/mm     | 0.42         | 0.40         | 0.42         | **0.39**         |
The most dangerous condition is selected when the parameterized frame size is studied under impact condition, and an 8g acceleration is applied in +X direction. From Fig. 2, it is noted that the maximum stress of the whole system decreases with the increment of the frame width B. The maximum stress of the system decreases first and then increases with the increment of frame length L. When the frame length is about 1415 mm, the stress reaches its minimum value. From Fig. 3, it is observed that the saddle stress increases first and then decreases with the increment of the frame width B, and it reaches its maximum value at B=225mm. However, the frame length L almost has no effect on the saddle stress value. It can be noted from Fig. 4, the change trend of the maximum stress of the frame is the almost the same as that of the whole system stress. As presented in Fig. 5, with the increment of frame width, the maximum deformation of the frame decreases slightly at first and then increases, and its minimum value appears at B=207.51mm. Meanwhile, the maximum deformation of the frame increases slowly with the increment of the frame length. The optimal dimensions of the frame structure are designed respectively for the four optimization objectives that is reducing the maximum stress of the system, the maximum stress of the saddle, the maximum stress of the frame and the maximum deformation of the frame, as shown in Table 1. Considering the four optimization objectives, Design Exploration module in ANSYS Workbench can obtain the optimal frame size, for frame length B is 202.73 mm, and for frame width L is 1400.5 mm.

3.2. Random vibration condition

![Figure 6. Maximum deformation responding surface of frame in Y-direction.](image1)

![Figure 7. Maximum stress responding surface of system.](image2)

![Figure 8. Maximum stress responding surface of saddle.](image3)

![Figure 9. Maximum stress responding surface of frame.](image4)
Table 2. Optimal size of frame under different objectives in PSD random vibration analysis.

| Input parameters | Objectives |
|------------------|------------|
|                  | Deformation in Y-direction/mm | System stress/MPa | Saddle stress/MPa | Frame stress/MPa |
| B/mm             | 0.017      | 22.70           | 12.132           | 22.70          |
| L/mm             | 1452.50    | 1458.60         | 31.16            | 1458.60        |
| Output parameters|            |                  |                  |                |
|                  | Deformation in Y-direction/mm | 0.017           | 0.017            | 0.020          |
|                  | System stress/MPa | 22.69           | 31.16            | 22.69          |
|                  | Saddle stress/MPa | 12.133          | 10.712           | 12.133         |
|                  | Frame stress/MPa | 22.69           | 31.16            | 22.69          |

As can be seen from Fig. 6, with the increment of the frame width, the frame deformation in Y-direction decreases, but when the frame length L increases, the frame deformation in Y-direction decreases with a rising rate with the increment of frame width B. When the frame width B is less than 230mm, the frame deformation in Y-direction increases with the increment of frame length L. When the frame width B is greater than 230mm, the frame displacement in Y-direction of decreases with the increment of frame length L. It is seen that from Fig. 7, the maximum stress of the system decreases with the increment of the frame width B. The maximum stress of the system decreases first and then increases with the increment of frame length L. When the frame length L is about 1420 mm, the stress reaches its minimum value. However, with the increment of frame width, the frame length L has less effect on the maximum stress of the system. It can be observed that from Fig. 8, with the increment of the frame width, the saddle stress decreases first and then increases, and it reaches its maximum value at B=225mm. Meanwhile, the frame length L almost has no effect on the saddle stress. As can be seen from Fig. 9, the variation trend of the maximum stress of the frame is the same as that of the whole system stress, which means that the maximum stress of the whole system occurs at the frame under vibration condition. The optimal dimensions of the frame structure are designed respectively for the four optimization objectives that is reducing the maximum deformation in Y-direction, the maximum stress of the system, the maximum stress of the saddle and the maximum stress of the frame, given in Table 2. Design Exploration module in ANSYS Workbench can obtain the optimal frame size, for frame length L is 245.48 mm, and for frame width B is 1455 mm.

4. Conclusion

1) Under the impact condition, the maximum stress of the whole system and the maximum stress of the frame decreases with the increment of the frame width B, and decreases first and then increases with the increment of the frame length. The saddle stress increases first and then decreases with the increment of the frame width B. The frame length L almost has no effect on the saddle stress value.

2) Under the random vibration condition, the frame deformation in Y-direction decreases with the increment of the frame width B, and increases first and then decreases with the increment of the frame length L. The maximum stress of the system and the maximum stress of the frame decrease with the increment of the frame width B, and decreases first and then increases with the increment of the frame length L. The saddle stress decreases first and then increases with the increment of the saddle width B.

3) According to all the optimization objectives under different working conditions, the optimal frame size B is 202.73 mm and L is 1400.5 mm under impact condition, and the optimal frame size B is 245.48 mm and L is 1455 mm under random vibration condition.

Acknowledgments

This work was financially supported by the National Key Research and Development Program of China (No. 2016YFB1100202).
References

[1] Y. B. Woo, B. S.Kim, A genetic algorithm-based matheuristic for hydrogen supply chain network problem with two transportation modes and replenishment cycles, Computers & Industrial Engineering, 2019, 127: 981-997.

[2] A. Lahnaoui, C. Wulf, H. Heinrichs, D. Dalmazzone, Optimizing hydrogen transportation system for mobility via compressed hydrogen trucks, International Journal of Hydrogen Energy, 2018.

[3] B. Cao, Z. H. Wang, Research on Random Vibration Characteristics of the Bus Frame based on Displacement PSD, New Technique and New Process, 2014, 06: 87-90.

[4] Y. He, X. H. Li, Random Vibration Response Analysis of Longitudinal Roadheader, Industry and Mine Automation, 2018, 44 (03): 87-91.

[5] J. M. Zhong, Optimum design of a high-rise frame-core tube structure, Structural Engineer, 2018, 34 (02): 33-40.

[6] J. Y. Zhang, C. Y. Liu, Y. W. Wang, Optimum Design of Reinforced Concrete Frame Shear Wall + Supporting Structures in Public Buildings, Structural Engineer, 2018, 34 (04): 14-20.

[7] N. Changizi, M. Jalalpour, Topology optimization of steel frame structures with constraints on overall and individual member instabilities, Finite Elements in Analysis and Design, 2018, 141: 119-134.

[8] N. Changizi, H. Kaboodanian, M. Jalalpour, Stress-based topology optimization of frame structures under geometric uncertainty, Computer Methods in Applied Mechanics & Engineering, 2017, 315: 121-140.